

# Impacts of volcanic hazards on rural communities and adaptative strategies: a case study of the Virunga Volcanic Province (Democratic Republic of Congo)

Patrick Habakaramo Macumu<sup>1,2,3\*</sup>, Guillaume Boudoire<sup>4,5\*\*</sup>, Sergio Calabrese<sup>5,6</sup>, Francesco Rufino<sup>8</sup>, Rachel M. Coyte<sup>7</sup>, Dario Tedesco<sup>1,8,9</sup>

<sup>1</sup> DISTABIF, Università degli Studi della Campania Luigi Vanvitelli, Via Vivaldi 43, 81100 Caserta, Italy

<sup>2</sup> Geochemistry and Environment Department, Goma Volcano Observatory, 142, Avenue du Rond point, Quartier Les Volcans, Goma, Democratic Republic of Congo.

<sup>3</sup> Département de Biologie-Chimie, Institut Supérieur Pédagogique d'Idjwi (ISP-Idjwi), RD. Congo

<sup>4</sup> UCA, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, 6 avenue Blaise Pascal, 63178 Aubière, France

<sup>5</sup> Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, Italy

<sup>6</sup> Dipartimento di Scienze della Terra e del Mare - DiSTeM, Università degli Studi di Palermo, Italy

<sup>7</sup> School of Earth Sciences, The Ohio State University, Columbus, 43210, OH, United States

<sup>8</sup> Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli-Osservatorio Vesuviano, Via Diocleziano 328, 80124 Naples, Italy

<sup>9</sup> Mission de l'Organisation des Nations Unies pour la stabilisation en RD Congo, Democratic Republic of Congo

\* Corresponding author. Present address: DISTABIF, Via Vivaldi 43, 81100 Caserta, Italy. Telephone: +39 (0)371 443 2036. E-mail: [patrick.habakaramomacumu@unicampania.it](mailto:patrick.habakaramomacumu@unicampania.it); [phabakaramo2@gmail.com](mailto:phabakaramo2@gmail.com)

\*\* Corresponding author. Present address : Laboratoire Magmas et Volcans, Campus universitaire des Cèzeaux, 6 Avenue Blaise Pascal, 63170 Aubière, France. Telephone: +33 (0)4 73 34 67 23. E-mail: [guillaume.boudoire@uca.fr](mailto:guillaume.boudoire@uca.fr)

## Abstract

Active volcanoes are a continuous threat for several regions worldwide and cause socio-economic and environmental issues, including the Virunga Volcanic Province (D.R. Congo). There, more than 2 million people are permanently exposed to the hazards of the most active volcanoes in Africa: Nyiragongo and Nyamulagira. However, there is a clear lack of information regarding the impacts of these hazards and how they may be affected by social vulnerability. In this study, a household survey based on semi-structural interviews was performed for rural communities in Virunga. This research aims to (i) investigate the impacts of volcanic hazards on rural communities facing distinct levels of social vulnerability, (ii) understand the adaptive strategies developed by these communities to address these impacts, and finally (iii) identify the main grievances with respect to volcanic hazards raised by these rural communities. The most vulnerable households are those directly affected by volcano-tectonic hazards such as lava flows, mazukus, volcanic gases, ash fallout, and seismic activity. Indirect dangers related to water and food contamination by volcanic emissions are also stronger for the most vulnerable households. Respondents reported that most edible plants and waters are strongly affected by direct volcanic emissions. Drinking

waters, which come from traditional drainage, rainfall, and streams, are generally not suitable for human consumption in the study area. Community suggestions for addressing issues related to volcanic-tectonic hazards include efforts to improve water and food quality, enhancement of the sanitary system, timely information on the volcanic activity, volcano monitoring, and capacity building for volcanologists.

**Keywords:** Volcanic hazards, Social vulnerability, Risks perception, Nyiragongo, Nyamulagira.

## 1 Introduction

Volcanic hazards are of concern worldwide, causing severe damage to infrastructure and loss of human life. In volcanic provinces, hazards related to lava flows, volcanic ash, and particulate fallout can lead not only to socio-economic losses but also to adverse effects on human health and damages on livestock (Gudmundsson, 2011; Hansell et al., 2006; Horwell and Baxter, 2006; Markantonis et al., 2012). Active volcanoes, such as those of the VVP, emit huge amounts of particulates and gases into the atmosphere, which threaten the human life at both regional and global scales. More than 600 million people live less than 100 km from an active volcano (Auken et al., 2013; Gudmundsson, 2011; Hansell and Oppenheimer, 2006; Lara et al., 2021; Schuster and Highland, 2001; Small and Naumann, 2001; Tesone et al., 2018; Freire et al., 2019). Threats associated with volcanic hazards around the globe are increasing with population growth, while the lack of awareness, preparedness, and resilience capability among citizens remains a concern (Antronico et al., 2020; Wiley et al., 2017).

In low- to middle-income countries fertile volcanic soils tend to favor agricultural activities and the settling of rural communities (Dibben and Chester, 1999; Lowe, 2010). However, there is little research being done on vulnerability and risk perception of these rural communities in volcanic provinces, especially in the Global South. According to the United Nations Development Program (UNDP) (2015) and Prelog and Miller (2013), the most vulnerable rural communities live in the less developed countries of Asia, Latin America, and Africa, with many rural communities facing different and at times more severe disadvantages related to natural disasters than their urban counterparts (Firdhous and Karuratane, 2018). Rural risk factors include limited access to primary resources, high levels of poverty, inadequate and underdeveloped infrastructure, and lack of access to public services (e.g., hospitals, schools, markets, roadway networks).

While exposure to volcanic hazards may be the same for distinct social groups or households, the actual impacts will strongly depend on the social vulnerability of each group

(Cutter et al., 2008; Hummell et al., 2016). The concept of vulnerability is defined as the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of a hazard (Gaillard, 2008; Antronico et al., 2020). Traditional vulnerability approaches in volcanic provinces are focused on the vulnerability of buildings (physical destruction of buildings and inventories) and the probabilities of loss of life given to the proximity to a volcanic hazard. Such evaluations calculate the expected damages, or the degree of damage based on the monetary values of assets (Blong et al., 2017; Hopkins et al., 2021; Jenkins et al., 2014, 2017; Markantonis et al., 2012; Meyer et al., 2013; Michellier et al., 2020) or the direct loss of life. These, however, neglect the continual human and environmental risk from volcanic activity. There is an additional strong vulnerability component to volcanic multi-hazards that includes socio-economic considerations, known as social vulnerability. Only a few studies have evaluated the social vulnerability and community resilience of populations facing volcanic hazards in the Global South (Michellier et al., 2020; Tedesco, 2002, 2003). Resilience refers to the ability of communities exposed to hazards to anticipate, prepare for, reduce the impact of, cope with, and recover from the effects of shocks and stresses without compromising their long-term prospects (De Iuliis et al., 2019; Marasco et al., 2022; Mitchell and Harris, 2012). In this respect, resilience can provide a way to overcome vulnerability to a hazard and prioritize mitigation actions among communities to decrease the vulnerability level. Therefore, studying the social vulnerability and resilience of people living in the vicinity of an active volcano regarding volcano-tectonic hazards can inform sustainable strategies for living in volcanic provinces.

In this study, we lead an innovative approach to investigate the impacts of volcanic hazards on rural communities responding to distinct levels of social vulnerability. We explore the adaptive strategies intuitively developed by these communities to address these impacts. Finally, we identify the main grievances raised by rural communities, to aid future efforts at improving quality of life and resilience in volcanic environments. This study is focused on rural communities present in the vicinity of the very active and dangerous Nyiragongo and Nyamulagira volcanoes in the Democratic Republic of Congo (DRC). To our knowledge, this is the first study to deal with vulnerability and resilience related to volcanic hazards as experienced by exposed rural communities in the Virunga Volcanic Province (VVP).

## **2 Context of the study**

The Virunga Volcanic Province (VVP) in Africa lies within the western branch of the East African Rift System between the Democratic Republic of Congo (DRC), the Republic of Rwanda and the Republic of Uganda (Pouclet and Bram, 2021; Poppe et al., 2014) (Fig. 1). The area is continuously

threatened by the activity of the Nyiragongo (Latitude 1.52°S, Longitude 29.25°E, Altitude 3470 m a.s.l. at the rim of the summit crater, 1240-1345 m in diameter) and Nyamulagira (Latitude 1.41°S, Longitude 29.20°E, Altitude 3058 m a.s.l. in height at the edge of a large caldera which is 2150 m in diameter) volcanoes, two of the most active volcanoes in Africa, and worldwide (Pouclet and Bram, 2021) (Fig. 1). Other dormant volcanoes are present in the VVP setting up the Central and Eastern volcanoes groups: Mikenko (4437 m a.s.l.), Karisimbi (4508 m a.s.l.), Visoke (3911 m a.s.l.), Sabinyo (3647 m a.s.l.), Gahinga (3474 m a.s.l.), and Muhabura (4127 m a.s.l.) (Le Guern, 1987; Pouclet and Bram, 2021). Even in a quiescent state of activity, these dormant volcanoes are still a source of concern for local populations and authorities. For instance, Mikenko drained sludge flows in the villages of Rugari and Jomba in the territory of Rutshuru, between July and September of 2021.

Nyiragongo is a stratovolcano well known worldwide for the semi-permanent active lava lake that has repeatedly formed in its main crater (Pouclet and Bram, 2021). Documented records of Nyiragongo go back to 1894 and have been summarized by several previous works (Sahama and Meyer, 1958; Sahama, 1962), most recently by Tazieff (1977, 1984, 1985). In recent times, Nyiragongo has erupted only three times outside of the summit crater: on January 10, 1977, January 17, 2002, and on May 22, 2021. The first lateral eruption drained lava from the lava lake towards Goma (50,000 inhabitants; Tedesco et al., 2007) and the lava flows stopped in Munigi village, covering between 16 to 20 km<sup>2</sup> in around 32 minutes (Tazieff, 1977), and killing about 70 people (Pottier, 1978). In 1982, the lava lake appeared again (Durieux, 2002, 2003) and remained active for a short period: in August 1995, the lava lake activity stopped, and the lava solidified until a second flank eruption in 2002 (Tedesco et al., 2007). Meanwhile, the population of Goma had increased to ~ 400,000 inhabitants. About 15% of the city was destroyed by the lava flows from the two main fissures opened during the 2002 eruption (Komorowski et al., 2002; Tedesco et al., 2002, 2007; Wauthier et al., 2012). A part of Goma airport runway and ~120,000 households were destroyed. Around 300,000 people were evacuated and ~140 people were killed (Komorowski et al., 2002; Tedesco et al., 2007). The latest lateral eruption of Nyiragongo on May 22, 2021, surprised people and scientists due to the apparent absence of precursory signs preceding the eruption recorded by the volcanic monitoring network. The subsequent seismic events and associated surface fracturing surprised and scared the population (Boudoire et al., 2022). In the meantime, the population in Goma and the surrounding villages had increased to about 2 million. The eruption led to a very disorderly displacement of more than 500,000 individuals from the surroundings areas of Goma, Sake, Minova, Kiwanja, Bukavu as well as Rwanda (Boudoire et al., 2022). The lava flows, subsequent ash fallout (mainly due to chunks of the crater collapsing within

the same crater), and the long-lasting seismic activity have been a stressful and traumatic experience for many people in the region. The official report from the Congolese civil protection stated that 23,045 individuals were impacted by the eruption: among those, 22,395 individuals lost their home or had them heavily damaged by the earthquakes that followed the eruption, while 650 lost their fields. A new magmatic event with a proto-lava lake started forming in September 2021 and in December 2021/January 2022, with small degassing vents developing and intermittent eruptive activity.

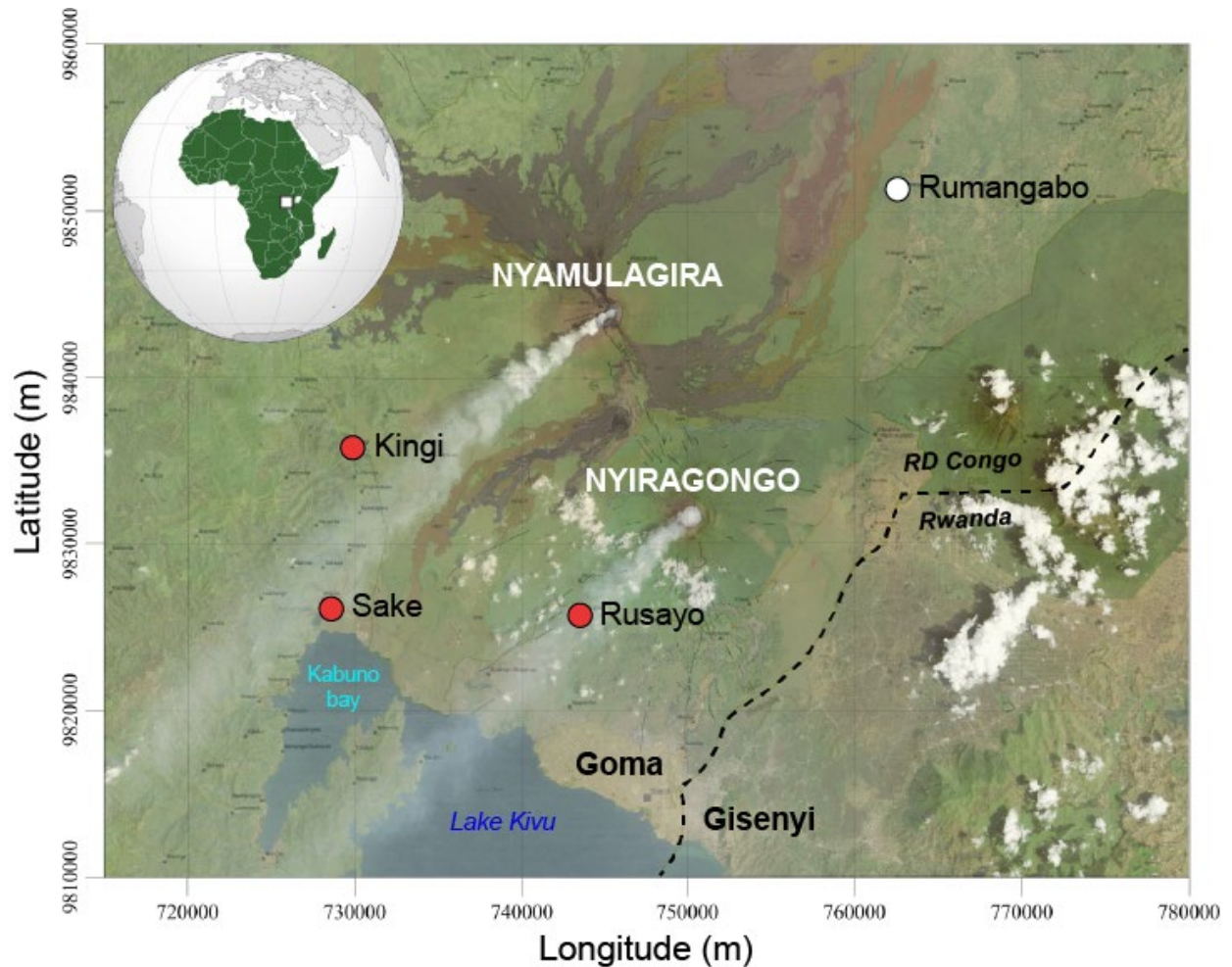
Nyamulagira is the second active volcano in VVP. It is a shield volcano located 13 km North-West the Nyiragongo, well known by natives and first explored by Europeans in 1880s (Pouclet and Bram, 2021). It is marked by eruptive cycles averaging 1-4 years throughout the last century (Burgi et al., 2020; Pouclet and Bram, 2021; Smets et al., 2015; Syavulisembo et al., 2015). It has erupted at least 40 times since 1865 (see table 1 in Pouclet and Bram, 2021; Smets et al., 2015; Mavonga et al., 2010). In 1938, eruptive fractures opened on the southwest slope of the volcano and drained a lava lake which has persisted in its main crater since 1913, impacting several areas including Sake, Rusayu, and Kingi villages (Fig. 1). The drained lava reached the westernmost part of Lake Kivu and separated one small area from the rest of the lake, today called the Bay of Sake. The eruption stopped 3 years later in 1940 (Pouclet et al., 1983, 2016). This historically long eruption of Nyamulagira completely disrupted patterns of land cover and land use, including the destruction of important infrastructure for several villages. Nyamulagira eruptions are generally preceded by several month of abnormally high seismicity (mainly earthquake swarms) (Mavonga et al., 2010), and include lava fountaining and lava flows, gas plumes, scoria, Pele's hair, and ash injected into the atmosphere, which can generate serious consequences for human health and the environment (crops yields, livestock, infrastructure, etc.) (Vaselli et al., 2007). The intense activity of Nyamulagira is usually reported by local inhabitants living southwest of the volcano downwind of the gas plume, as a permanent danger to the whole community, especially to children under 10 years old and the elderly. Nyamulagira volcano is nowadays characterized by an intermittent lava lake in the central part of the crater, the so-called "pit-crater" which collapsed after the eruption that occurred from November 6, 2011, to mid-April 2012 (Balagizi et al., 2017; Cuoco et al., 2013a, b; Pouclet and Bram, 2021). The Goma Volcano Observatory (GVO) reported a new active lava lake in the Nyamulagira central caldera on June 23, 2014, which remained active until April 26, 2017 (Report GVO, 2014). One month after (May 26, 2017), only fumaroles inside the main crater were documented and the lava lake was not active. A new lava lake reappeared early in January 2018 and remains today (Burgi et al., 2020). However, the insecurity caused by several armed groups within the Virunga National Park does

not allow researchers to reach the Nyamulagira crater regularly to make direct field observations inside the crater. This is possible only with help from the Virunga National Park rangers and/or the MONUSCO (United Nations) helicopters, which supports the GVO for field work once or twice a month.

It is clear that both Nyiragongo and Nyamulagira volcanoes present a permanent danger for local populations. The most exposed areas are those close to the lake Kivu, threatened both by lava flows and by a potential gas release from Lake Kivu where an important reservoir of CH<sub>4</sub> and CO<sub>2</sub> is stored within (Tassi et al., 2009). The VVP is a densely populated area with more than 2 million people, most of them living in Goma, the main regional city, located 18 km from the summit of Nyiragongo (Arellano et al., 2017; Liotta et al., 2017; Poppe et al., 2016 ) (Fig. 1). In the VVP, rural communities face volcano-tectonic dangers related to lava flows, cold dry CO<sub>2</sub> emissions (so-called “mazukus”), seismicity, and volcanic gas plume/ash emissions causing multiple health, environmental, and socio-economic damages (Balagizi et al., 2018; Tedesco et al., 2007, 1995, 1996; Vaselli et al., 2002). Exposure to volcanic emissions can threaten the health of inhabitants in many ways, depending on the physical and chemical characteristics of these emissions. Among volcanic hazards, lava flows and tephra deposits can seriously damage land, buildings, and ecosystems, triggering fires and leading to socio-economic losses. The health effects can be acute or chronic, being a consequence of inhalation either of particles directly emitted from the volcanoes, or from the re-suspension of the soil ashes during clean-up, agriculture, construction, quarrying, vehicular movements, etc. Ash-fall is of concern because of the wide areas that can be covered by fallout that may remain in the local environment for years to decades being remobilised by human activity or re-suspended by the wind (Horwell and Baxter, 2006). Acute effects of ash exposure can include eye, skin and throat irritation, cough, dyspnoea, chronic obstructive disease, cardiovascular events, psychological stress, reversible changes in healthy lung function, and asthma (Hansell et al., 2006; Horwell and Baxter, 2006). A second major volcanic hazard for local communities and ecosystems is the permanent volcanic plumes, a mixture of gas, liquid and solid particles continuously injected in the atmosphere that become more intense during eruptive phases, mainly at the beginning of each eruptive phases or cycle. Volcanic plumes affect the lower part of the troposphere and strongly influence the chemistry of rainwaters (the most important source of drinking water for Virunga inhabitants), often producing acid rains. Acid rains lead to lower crop yields and hinder meat and milk production which are crucial for the survival of local populations (Cuoco et al., 2013a, b; Yalire et al., 2010). The most exposed areas are located downwind the volcanic gas plumes that regularly blow south-southwest (Fig.1). Surveys

conducted in the VVP have indicated a significant number of diseases and damages induced by volcanic emissions, with a higher exposure among rural communities (Balagizi et al., 2018).

As the VVP is one of the most densely populated areas in Africa, with an extremely high rate of population growth, data scarcity related population vulnerability and exposure in the face of volcanic hazards is a major concern (Michellier et al., 2020). This concern is amplified by the fact the VVP is also the locus of (i) many epidemics such as Malaria, Ebola, Cholera, measles, respiratory tract infections, and diarrhoea (Arie, 2019; Annelies et al., 2020), and (ii) persistent insecurity for decades due to armed rebel groups that have forced thousands of people to flee their homes leading to massive migratory flows (Arie, 2019). It is important to note that both epidemics and migratory flows are also related to the state of volcanic activity (Boloweti et al., 2020; Burgi et al., 2020). This makes the VVP a complex area, subject to multiple and often interconnected natural and anthropological risks. In this context, defining the vulnerability of rural communities to volcanic hazards is a crucial task for the development of well-targeted remediation actions among communities, stakeholders, and the government. It should lead to the implementation of common strategies, as effective as possible, to manage volcanic risks, by means of the integration of (structural and non-structural) preventive actions and adaptive strategies which might help to decrease vulnerability levels. Whereas social vulnerability to volcanic hazards was recently investigated in the city of Goma (Tedesco, 2002; Michellier et al., 2020;), little is known about how the rural communities in the VVP perceive, prioritize, and face multiple volcanic hazards. Most of the studies led in the VVP focus either on volcanic hazards (Favalli et al., 2006; Syavulisembo et al., 2015) or vulnerability (Michellier et al., 2020), but, at our knowledge, no study deals with the real impact of volcanic hazards as felt, undergone, and faced by local people. The presented results constitute thus an essential background for an integrated assessment and key awareness of volcanic risks in the rural areas neighbouring VVP active volcanoes.



**Fig. 1.** Location map of the investigated areas (VVP, Eastern DRC, satellite image captured by Landsat 8) with (i) Nyiragongo and Nyamulagira volcanoes, (ii) the cities of Goma (DRC) and Gisenyi (Rwanda), and (iii) the rural communities involved in this study, the villages of Kingi, Sake, Rusayo and Rumangabo.

### 3 Methodology

#### 3.1 Rural communities interviewed in the survey

Rural communities interviewed in this study include 119 households randomly sampled from three villages exposed to multiple volcanic hazards (red circles on Fig. 1) and one village relatively less exposed to volcanic hazards (white circle on Fig. 1). The choice of these villages from among several in the vicinity of Nyiragongo and Nyamulagira relates to two criteria: (1) being exposed or impacted by distinct volcanic hazards to compare the perception of rural communities facing the presence or the absence of each volcanic hazard identified in the area (Balagizi et al., 2018) and (2) allowing for interviews to be conducted in safe conditions considering the security issues in the area raised by the presence of several armed groups (Boudoire et al., 2022). For example, at the time of writing, the village of Rumangabo is no longer accessible due to intense fighting between the FARDC (Forces Armées de la République Démocratique du Congo) and the M23



rebel movement north of the City of Goma. All the villages are exposed to latent seismicity related to the tectonic activity of the East African Rift System and to several recurrent attacks by armed groups or political instability that has occurred in the region since 1996. The region has also been the site of multiple epidemics including measles, cholera, and Ebola (Boudoire et al., 2022). In addition, each village is characterized by the presence or absence of specific hazards:

- Sake (30 households) is the most economically rich and densely populated village (after the City of Goma) located 25 km southward of Nyamulagira, in front of the Kabuno bay. The village may be impacted by lava flows (cf. 1948 eruption of Nyamulagira; Smets et al., 2015), volcanic gas (plume) and particles from Nyamulagira (under the prevailing winds; Fig. 1), and mazukus (Smets et al., 2010).
- Kingi (20 households) is a small remote village almost continuously impacted by volcanic gas (plume) and particles mainly from Nyamulagira (under the prevailing winds; Fig. 1). However, the village is not exposed to either mazukus (mainly on the shoreline of Lake Kivu; Smets et al., 2010) or lava flows (due to its elevation, almost 500 m more than Sake).
- Rusayu (33 households) is a village close to Goma that is highly threatened by the volcanic gas (plume) and particles from both volcanoes. Several eccentric eruptive cones are present in the vicinity of the village (Pouclet & Bram, 2021) that testify to the possibility of future eruptive events in the area even if no lava flow has affected the village in the last century. No mazuku is described in the village, but the closest ones on the shoreline of Lake Kivu are less than 5 km from the village (Smets et al., 2010).
- Rumangabo (36 households) is located North-East of Nyiragongo and is marginally to not at all affected by volcanic hazards identified for the other villages (far from the shoreline of Lake Kivu, in the opposite direction of the prevailing winds). Note that the village is close (less than 1 km) to the lava flow emitted during the 1981-1982 eruption at Nyamulagira. However, compared to the other three villages, Rumangabo represents our “background area” in this study, i.e., a place where rural community is scarcely exposed to volcanic hazards.

Note that all villages exposed to volcanic gas and particles emissions from the plume of either Nyiragongo and/or Nyamulagira volcanoes are also potentially faced with derived hazards, like the contamination of local water and food resources (Balagizi et al., 2018). Therefore, the perception of the degree of contamination of local water and food resources is investigated in this study.

### 3.2 *The Questionnaire*

The survey was conducted from July to December 2020 (before the last eruption of Nyiragongo on May 22, 2021) by means of a structured interview using an anonymous questionnaire composed of 30 questions organized into six sections (Appendix 1) to obtain both quantitative and qualitative data on social vulnerability, severity of the impacts of volcanic hazards, and resilience strategies developed by rural communities in the VVP. People were informed about the final purpose of their answers and gave their consent to use the data in general terms. Neither name nor physical address were collected. The respondents were either met at their homes or at their workplace during daily activities. Most of the participants were not able to read the survey, so questions were directly asked by the first author of this study, translating the English into Swahili or local dialects. The household socio-economic variables (e.g., time in village, level of education, number of people in the household, number of dependents in the household, main source of income, annual income, means of transport, means of communication; see Appendix 1) were investigated in the first part of the questionnaire, based on the main recommendations and results discussed by Michellier et al. (2020). The second part of the questionnaire was developed to evaluate (i) the experience of the respondent regarding volcanic hazards, (ii) respondent impression regarding the impact on local resources such as drinking waters and food plants, and (iii) the preparedness and resilience actions deployed to face these volcanic-related issues. Interviews lasted 15-20 minutes, on average. Responses were then compiled in a table on an electronic worksheet (Appendix 2).

### 3.3 *Definition of the vulnerability classes*

To study the impacts of volcano-tectonic hazards on rural communities, we analysed the questionnaire responses by both village and group vulnerability using an Operational Vulnerability Index (OVI) that was developed for studying social vulnerability within the city of Goma (Michellier et al., 2020). The OVI is recognized as an index that can “help to communicate more easily a certain message to political authorities for risk management actions” and is adapted to contexts for data availability may be an issue (de Assis Dias et al., 2020; Michellier et al., 2020). To construct the OVI, the first step was to aggregate individual socio-economic data for each household. In our case, eight variables were selected based on both previous work by Michellier et al. (2020) and also our knowledge of the local social context in VVP: (i) the time in village, (ii) the educational level, (iii) the household size, (iv) the number of dependents, (v) the main income, (vi) the average annual income, (vii) the means of transport, and (viii) the means of communication. These variables, previously identified as relevant for the City of Goma (Michellier et al., 2020) were applied in our study to rural communities because urban and rural areas are

mixed in the VVP due to continuous population movements triggered by economic interests or  
 insecurity issues (Verhoeve et al., 2004; Syavulisembo Muhindo et al., 2021). Moreover, except  
 for the (remote) village of Kingi, the other villages are either in the immediate vicinity of Goma  
 (Rusayu) or well connected to Goma by national roads of interest related to local trade (Fig. 1). A  
 value between 0 and 1 (from the lowest to the highest vulnerability) was assigned to each socio-  
 economic variable, as reported in Table 1. The selection of the main variables of interest for  
 defining the OVI was based on results obtained from a Principal Component Analysis (PCA),  
 which is a widely used multivariate statistics technique for reducing the dimensionality of data  
 sets with many input variables (Wold et al., 1987; Reimann et al., 2008) (Fig. 2). Tests of reliability  
 (Kaiser-Meyer-Olkin (KMO) test; see Shrestha (2021) for a review) and of sampling adequacy  
 (Cronbach's alpha; see Taber (2018) for a review) were performed for the PCA of the whole  
 dataset. The value of the KMO test is 0.69 (i.e., >0.60 retained as acceptable value for the sampling  
 size; Shrestha, 2021) and the Cronbach's alpha is 0.58 (range of confidence of 0.45-0.68, i.e.,  
 slightly beneath acceptable values). Optimized indicators (value of the KMO test equal to 0.72 and  
 Cronbach's alpha equal to 0.66 with a range of confidence of 0.56-0.75) are obtained by removing  
 the variables "household size" and "number of dependents". Actually, these two variables are  
 known to trigger either positive or negative benefits on vulnerability, especially in rural  
 communities (Kakota et al., 2015). In the absence of clear statement about the impact of these two  
 variables on the evaluation of the local vulnerability, we decided to exclude them in the PCA.  
 PCAs performed individually for each village do not satisfy the tests of reliability and of sampling  
 adequacy and were thus not retained timely. The first two axes (or principal components: PCs)  
 have eigenvalues ( $\lambda$  on Fig. 2a) greater than 1 and are thus significant (cf. eigenvalue-one  
 criterion). We also retained the third axis (even if the eigenvalue is slightly lower than 1) bringing  
 the cumulative variance of the PCA from 56 % (with the first two axes) to 71 % (with the first  
 three axis) (cumulative proportion of variance criterion) (Fig. 2b). The other axes have a very low  
 eigenvalue (<0.8) and do not contribute enough to the cumulative variance (<10 %) to be retained.

Representative variables to define the OVI were chosen with respect to two main criteria:  
 (1) a unique variable selected from each axis and usable only once, and (2) a score of the variable  
 along the axis greater than 0.5 or lower than -0.5 (practically, the variable with the maximum score  
 was chosen for each axis; Fig. 2c,d). In total, three variables were retained to define the OVI (one  
 for each axis). Then the OVI, for each household, was calculated by summing (for the three first  
 retained PCs;  $n = 3$ ) the products of the PC variance by the value of the selected variable for the  
 household following the equation:

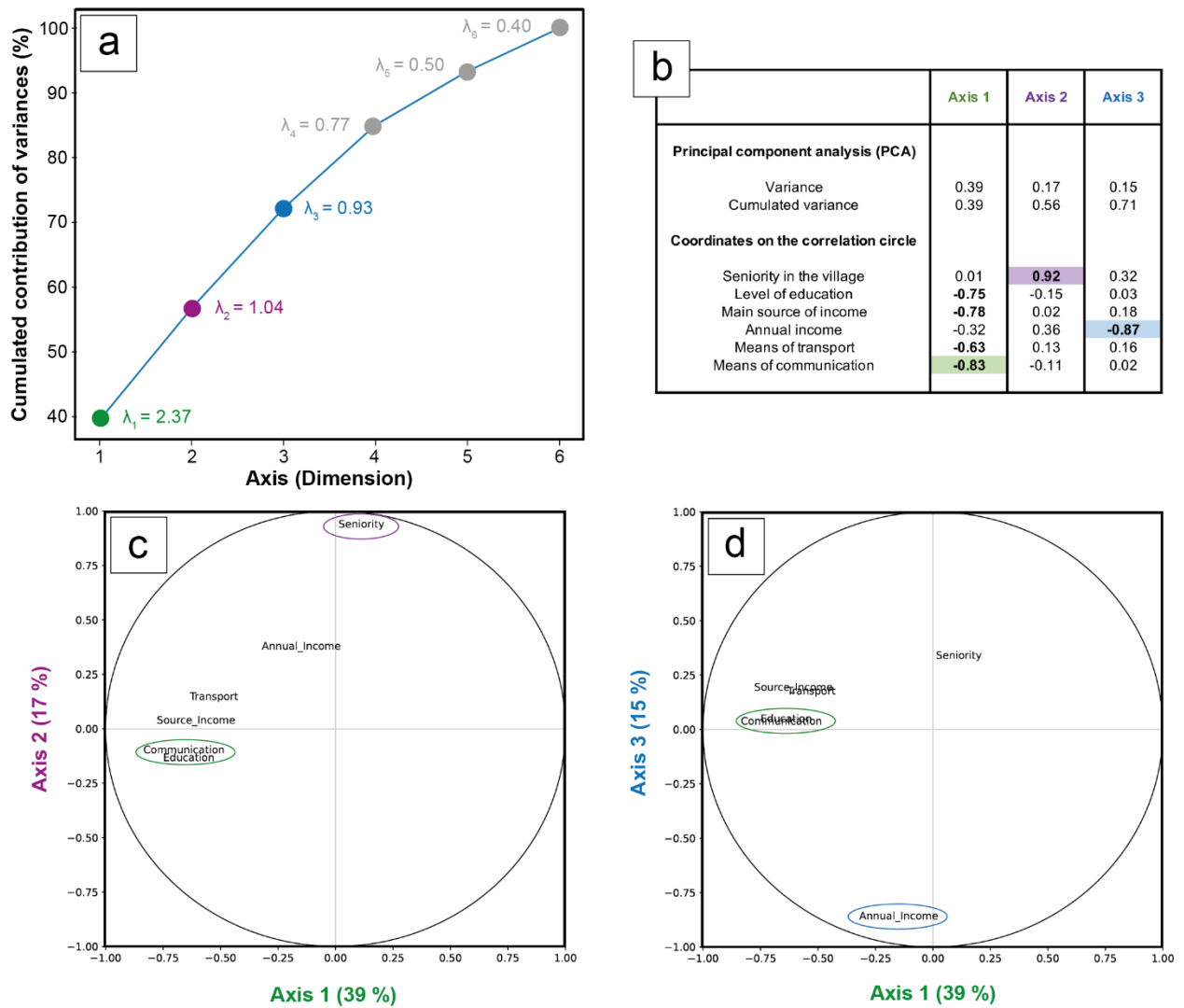
$$OVI = \sum_{i=1}^{n=3} variance_i \times value_i$$

Where “ $variance_i$ ” corresponds to the variance of each axis (i.e., 0.39, 0.17, and 0.15 for the first three axes) and “ $value_i$ ” corresponds to the value set for the household for each variable representative of the axes (i.e., value of the variable “means of communication”, “time in village”, and “annual income”; more information is provided in the following parts about the choice of these variables). Finally, the OVI was normalized to between 0 and 1 for the whole sampling group (see Appendix 2 for the OVI for each household). This approach captures the social vulnerability for each household of the survey. Finally, the 119 households were assigned to one of three groups of vulnerability according to their OVI. We applied a maximum-likelihood method using a Gaussian Mixture Model (GMM) implementing an expectation maximization (EM) algorithm developed in Python to distinguish the populations (see Boudoire et al. (2018) for details): the low vulnerability population (OVI between 0 and 0.5), the medium vulnerability population (OVI between 0.5 and 0.9), and the high vulnerability population (OVI between 0.9 and 1).

Variable of social vulnerabilty	Threshold	Scale of vulnerability
Time in village	>2017 2003-2017 1978-2002 <1978	1 0,66 0,33 0
Level of education	No formal education Primary Secondary University	1 0,66 0,33 0
Number of people in the household	>9 6-9 2-5 1	1 0,66 0,33 0
Number of dependents in the household	>9 6-9 2-5 1	1 0,66 0,33 0
Main source of income	Agriculture Market	1 0,75

	Private sector Liberal profession Public sector	0,5 0,25 0
Annual income (USD)	<528 (national average) 528-1278 (SMIG) 1278-2556 >2556	1 0,66 0,33 0
Means of transport	None Bicycle Motorcycle Car	1 0,66 0,33 0
Means of communication (Radio - TV - GSM)	0 1 2 3	1 0,66 0,33 0

**Table 1.** Variables used to define the Operational Vulnerability Index (OVI). The scale of vulnerability ranges from 0 to 1 (most vulnerable) and is based on 4 to 5 thresholds.



**Fig. 2.** (a) Cumulated contribution variance of the PCA axis (e.g., Principal Component: PC). The eigenvalue ( $\lambda$ ) is highlighted for each PC (in green for the first axis, in purple for the second axis, and in blue for the third axis). The last three axes (in grey) were not retained being characterized by low eigenvalues and contribution to the cumulative variance. (b) Statistics of the PCA for the three retained axes (eigenvalue, variance, cumulated variance) and score of the variables along each axis. In bold: significant variables for each axis (score greater than 0.5 or lower than -0.5). The variable retained for each axis to define the OVI is highlighted in green, purple, and blue for the first, second, and third axis, respectively. (c) PCA circle defined by the first and second PC (56 % of the cumulated variance) with the main representative variables (the closest ones to 1 or -1 along each axis) surrounded in green and purple for the first and second axis, respectively. (d) PCA circle defined by the first and third PC (54 % of the cumulated variance) with the main representative variables surrounded in green and blue for the first and third axis, respectively.

## 4 Results and Discussions

### 4.1 Vulnerability of rural communities

Eight socio-economic variables were defined in this study: (1) time in village (with respect to historical eruptions at Nyiragongo in 1977 and 2002, and considering that people already affected

by a natural disaster have developed a higher level of preparedness), (2) education level (from no formal education to university), (3) household size, (4) number of household dependents (non-working people like children or retired persons who increase the number of people physically present at home in case of a hazard event), (5) main source of income (from agriculture, which is strongly threatened by volcanic emissions, to public sector, which is less affected), (6) annual income (defined according to the national average and the minimum salary defined by the state or SMIG), (7) the means of transport (relevant to escaping dangerous situations), and (8) the means of communication (to be informed about dangerous situations). The results of PCA have highlighted three main axes (PC) that explain 71 % of the total variability of the dataset (Fig. 2). The first axis explains 39 % of the total variance and shows a close correlation between the means of communication (score along the first axis = -0.83), the main source of income (-0.78), the level of education (-0.75) and the means of transport (-0.63). The second axis explains 17 % of the total variance and is mainly defined by the time in village (so-called “seniority” in Fig. 2) with a score along the second axis = 0.90 whereas scores of the other variable along this axis are <0.4. The third axis explains 15 % of the total variance and is mainly defined by the annual income (score along the third axis = -0.87 whereas scores of the other variable along this axis are <0.4). All other PCs were considered as “scree” due to the eigenvalues largely lower than 1 together with a low contribution to the total variance of the dataset (<10 %). With respect to the methodology described above, the PCA allows us to restrict our dataset to the use of 3 main variables representative of the 3 retained axes: means of communication, time in village, and the annual income.

The first axis of the PCA reveals a strong and interesting correlation between the level of education, the main source of income and the kind and number of means of communication and transport available for the household. In urban areas, Michellier et al. (2020) highlighted that bicycles or motorcycles are the most important means of transport for people that can be used to evacuate household’s dependents to low-risk areas if they are prepared in for eruptive events. The PCA suggests that the absence of means of communication and transport, which increases the vulnerability of individuals faced with volcano-tectonic hazards, is strictly dependent on the respondent’s job and thus indirectly of his/her education level. It is consistent with previous studies showing that individual income and the education level are the most important key factors for assessing social vulnerability within rural communities facing natural hazards (Qureshi et al., 2021).

The second axis of the PCA is essentially defined by the time in village which reflects household experience with past eruptive events and volcano-tectonic hazards. Past experiences will positively influence preparedness and favor the development of preventive actions by the

household (Michellier et al., 2020; Wiley et al., 2017). People living for a long time in the villages who have already experienced volcano-tectonic hazards (like the Nyiragongo eruptions in 1977 and 2002) are less vulnerable than individuals living in the same area for shorter times (with similar characteristics for the other variables).

Finally, the last axis of the PCA shows that social vulnerability to volcano-tectonic hazards is influenced by the household economic features. Households with economic stability (the richest ones) are less vulnerable due to their ability to access primary resources more easily (Hummell et al., 2016). According to Antronico et al. (2020), natural hazards affect society by disrupting utility services and local business, thereby leading to lost revenue, and limiting the access to primary resources. These observations from the PCA are in line with several prior works (Zêzere et al., 2007; Schuster and Highland, 2001; Schuster and Fleming, 1986) suggesting that the indirect socio-economic loss is fundamental in understanding social vulnerability within the communities.

#### ***4.2 Perception of the impacts of volcano-tectonic hazards in the VVP***

In this study, the impact of direct volcano-tectonic hazards (lava flows, mazukus, ash fallout, seismicity, volcanic gas plume) and derived hazards (drinking waters and edible plants contamination, diseases, and insecurity) were discussed with rural communities.

##### ***4.2.1 Evaluation of the impacts of volcano-tectonic hazards on VVP rural communities***

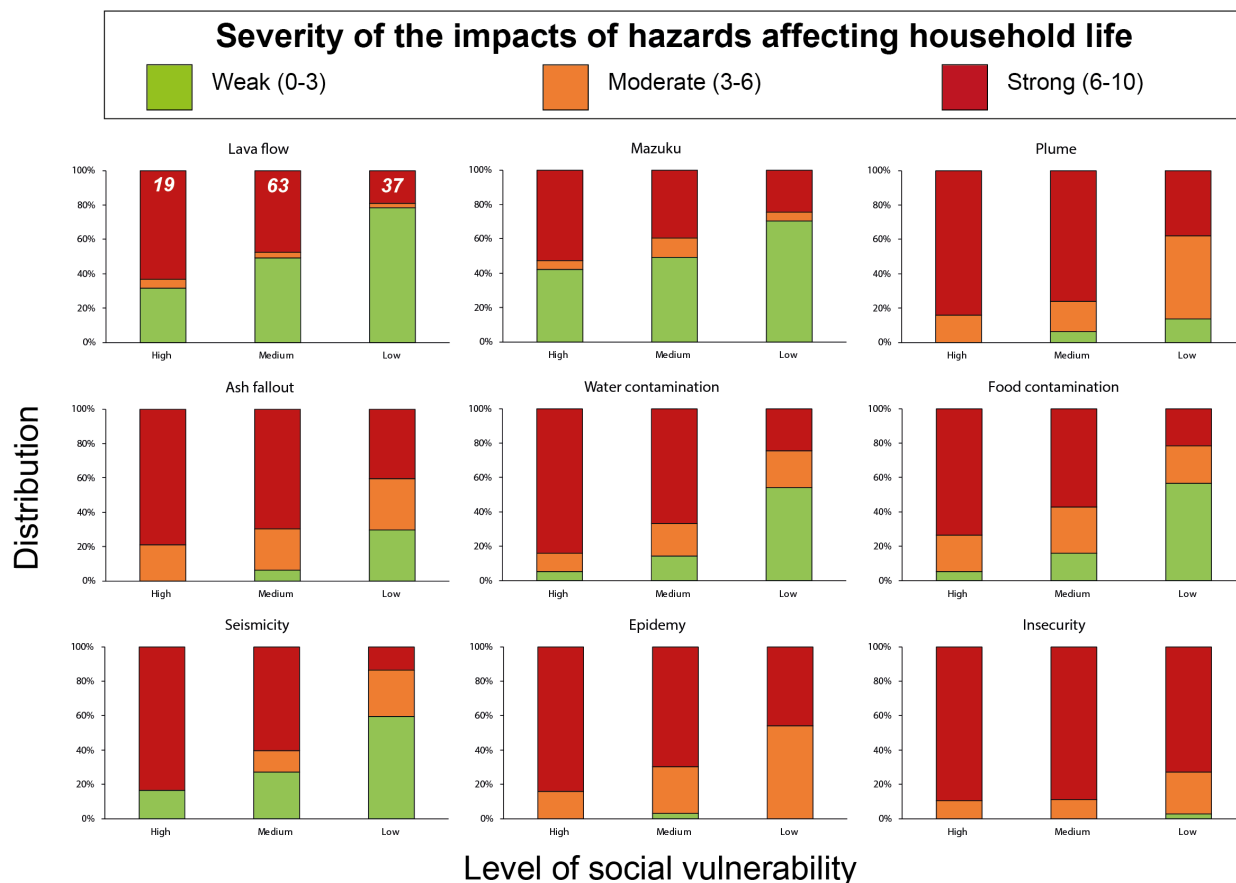
The impacts of epidemics and insecurity are major concerns in rural communities, independent of the level of social vulnerability (Fig. 3). It is important to note that both insecurity and epidemics (sustained by migratory flows) are accentuated by the volcano-tectonic activity in the VVP (Boloweti et al., 2020). The attention paid to epidemics and insecurity may be due to several reasons including the absence of adequate health infrastructure in rural areas, the inaccessibility of health care, and the absence of public medical insurance in the VVP. Furthermore, the VVP has experienced insecurity since the 1996 wars of “liberation” with the presence of multiple armed groups spread in the rural surroundings of Nyiragongo and Nyamulagira volcanoes.

More vulnerable rural communities are the most concerned about the impact of volcano-tectonic hazards, with concern progressively declining in the less vulnerable populations (Fig. 3). This trend is even more pronounced for the perception of the impacts related to volcanic plume gas and particle emissions, and to a lower extent, to their derived impacts on water and food quality that pose several health problems among the end users (Arellano et al., 2017; Cuoco et al., 2013a,b; Tedesco, et al., 2013; Kasereka et al., 2021; Tedesco et al., 2007; Yalire et al., 2010; Habakaramo et al., 2019). The most severe impacts related to volcanic plume gas and particle emissions



identified by rural communities are the loss of farming activities and livestock together with  
sanitarian issues (burns, skin and eyes irritation) (Table 1). When impacting water and food  
quality, local inhabitants raise various health problems, in particular tooth diseases (mostly linked  
to dental fluorosis due to the fluoride enrichment in drinking waters; Vaselli et al., 2007; Balagizi  
et al., 2018) and diarrhoea-nausea (Table 1). Similar fluorosis and diarrhoea-nausea issues have  
also been reported in other places along the East African Rift System since colonial times  
(MacQuillan, 1944; Onipe et al., 2020). Remedial actions implemented by rural communities  
consist in (i) protecting water and food resources, (ii) washing food before eating, and (iii)  
protecting the skin or staying inside during intense periods of volcanic gas and particle emissions.

The study reveals that both lava flows and mazukus are of minor concern with respect to  
volcanic plume gas and particle emissions (Fig. 3). This mirrors the narrow impact of lava flow  
(in time) and of mazukus (in space) in contrast to persistent volcanic gas and particle emissions  
from the summit craters of Nyiragongo and Nyamulagira that affect large-scale areas (Balagizi et  
al., 2018). In the case of the mazukus, local inhabitants are mostly aware of asphyxia issues and  
thus most of them can avoid them (Table 1). Regarding the impact of lava flows, the respondents  
mostly evoked the loss of farming activities, livestock, and homes rather than human loss. Faced  
with lava flows, many of the respondents mentioned migration on the highlands or the building of  
wooden and thatched houses that are more economic and easier to rebuild (Table 1).



**Fig. 3.** Perception of the severity of the impacts of hazards affecting household life for VVP rural communities. Answers provided by the household respondents are clustered in three distinct groups of social vulnerability (see Methodology) from high to low vulnerable populations. The number of respondents in each group of social vulnerability is shown in white italic bold.

Hazard	Impact	Remedial action
Lava Flow	#1 – Loss of farming activities and livestock (32) #2 – Loss of home (30) #3 – Human loss (4)	#1 – Migration on the highlands (27) #2 – Wooden houses (24) #3 – Thatched houses (19)
Mazukus	#1 – Asphyxia (46) #2 – Loss of farming activities and livestock (8) #3 – Pollutants (7)	- - -
Plume	#1 – Loss of farming activities and livestock (54) #2 – Pollution and contamination (45) #3 – Sanitarian issues : diseases (21)	#1 – Protecting water and food ressources (57) #2 – Washing food before eating (49) #3 – Bringing children indoors or protecting the skin during high peaks of activity (41)

Ash fallout	#1 – Sanitarian issues: burns, skin and eyes irritations (49) #2 – Loss of farming activities and livestock (42) #3 – Pollution and contamination (27)	#1 – Protecting water and food resources (51) #2 – Washing food before eating (38) #3 – Protecting the skin and staying inside (38)
Seismicity	#1 – Loss of farming activities and livestock (32) #2 – Loss of home (31) #3 – Change in the volcanic activity (21)	- - -
Water contamination	#1 – Various health problems (33) #2 – Tooth problems (12) #3 – Diarrhea and nausea (4)	- - -
Food contamination	#1 – Diarrhea and nausea (31) #2 – Loss of quality and reduced stock (20) #3 – Various health problems (10)	- - -
Epidemy	#1 – Mortality (35) #2 – Major diseases (37) #3 – Origin from waters (18)	- - -
Insecurity	#1 – Looting and rape (89) #2 – Kidnapping (44) #3 – Attacks by animals (7)	- - -

**Table 2.** Main three impacts and remedial actions raised by household respondents in the VVP faced with regional dangers. The number of respondents is shown in parenthesis (for a total of 119 respondents).

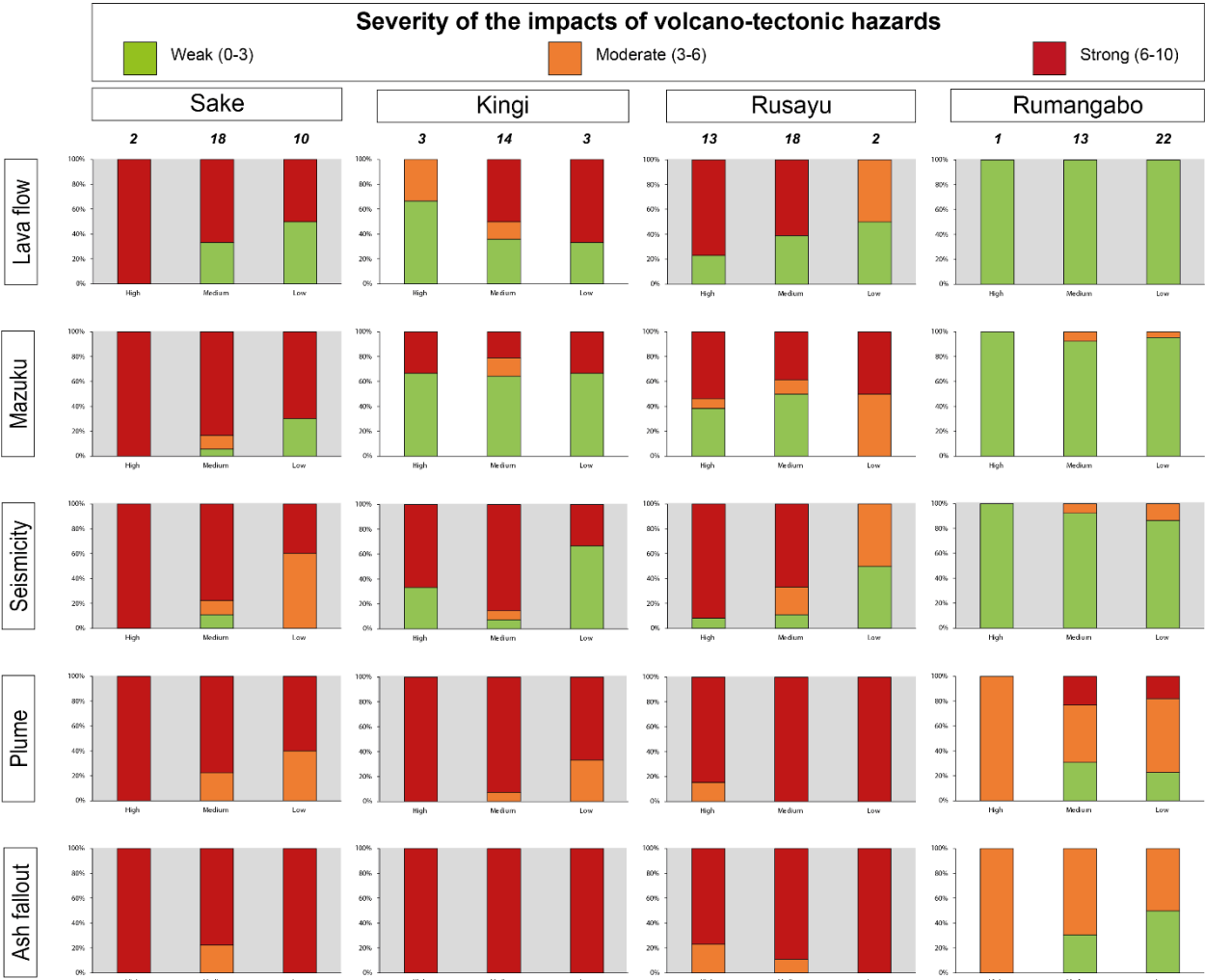
#### 4.2.2 Geographical variability of the perception of the impacts of volcano-tectonic hazards

The perception of the impacts of volcano-tectonic hazards for each village was surveyed (Fig. 4). There is a clear difference between the responses provided by the inhabitants of Rumangabo (“background area”) and those from Sake, Kingi and Rusayu (“gas and particulate plume affected areas”). Rumangabo is located to the North-East of the Nyiragongo and Nyamulagira volcanoes, in the opposite direction of the prevailing winds (Fig. 1). Consequently, whatever the level of social vulnerability of the respondents, the severity of the impacts of volcano-tectonic hazards is considered weak to moderate for the volcanic gas and particle emissions. Unsurprisingly, local perceptions of derived hazards, such as food and water contamination, are weak (Fig. 5). Only the impacts of epidemics and insecurity are felt moderately to strongly by the respondents, independently of the level of social vulnerability. Interestingly, the perception of the impacts of

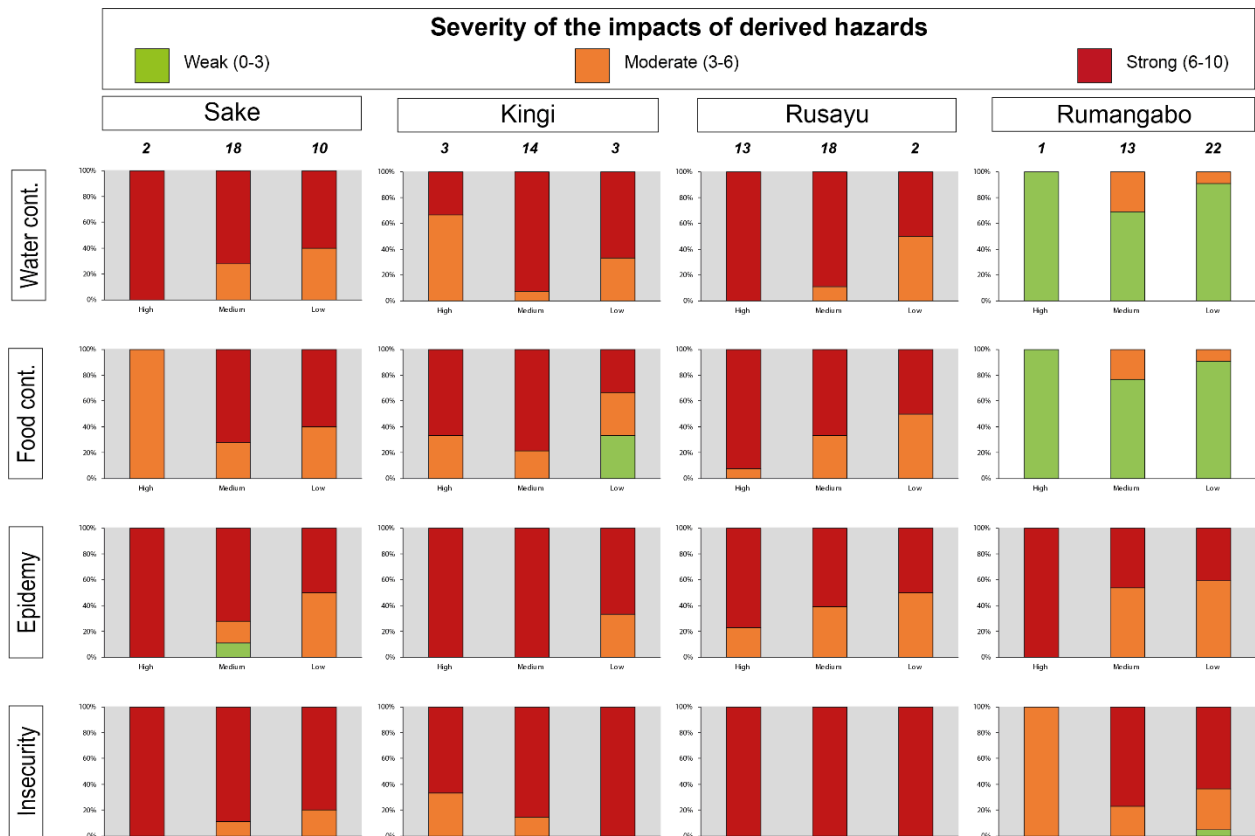
lava flows is considered weak at Rumangabo. This contrasts with the fact that the village is exposed as evidenced by the lava flow from the 1981-1982 eruption at Nyamulagira that passed less than one kilometer far from the village.

The villages of Sake, Kingi, and Rusayu are located to the South-West of the Nyiragongo and Nyamulagira volcanoes, downwind the volcanic gas and particulate plumes (Fig. 1). Note that these villages, known to be poor areas economically, host a majority of medium to highly vulnerable inhabitants compared to those from Rumangabo. This strongly increase the level of risk and danger in the face of volcano-tectonic hazards and derived hazards (Fig. 4). These villages are constantly affected by tectonic earthquakes or volcano-tectonic seismic events (Mavonga et al., 2010; Pouclet et al., 2016; Pouclet and Bram, 2021) and by the lava flows coming from several eruptions of the Nyamulagira volcano since 1865 to 2019 (~ 40 eruptions; see Table 1 in Pouclet & Bram, 2021). Consequently, the severity of the impacts related to lava flows and volcanic gas and particulate emissions is strongly felt by the inhabitants (Fig. 4). This is thought to be of direct concern for food and water quality (Fig. 5), especially considering that drinking water in these villages generally comes from rain, streams, or rivers (Vaselli et al., 2007) and are generally stored and continuously accumulated in traditional containers such as tanks and canisters (Balagizi et al., 2017, 2018; Cuoco et al., 2013a,b). The impact of the mazukus is of major concern for the inhabitants of Sake (and of Rusayu to a lesser extent). This is consistent with the fact that many mazukus have been inventoried within Sake (and close to Rusayu) leading to frequent human and animal fatalities by CO<sub>2</sub>-asphyxiation (Kasereka et al., 2017; Smets et al., 2010).

One peculiarity of the survey lies on the concern for the seismicity. Although this concern should be common to the four villages because of the regional impact of seismicity related to the opening of the East African Rift (Burgi et al., 2020; Mavonga et al., 2010), the severity of the impact of the seismicity at Rumangabo is weakly felt by local respondents. We think this may be related to the fact that the other villages are close to Lake Kivu and Kabuno bay and may reflect the fear that regional earthquakes could trigger a limnic eruption or a tsunami (see Balagizi et al. (2018) for a review of the potential effects of earthquakes on the stability of Lake Kivu). The lake contains high quantities of dissolved gases: ~250 km<sup>3</sup> of CO<sub>2</sub> and ~ 55 km<sup>3</sup> of CH<sub>4</sub> stored in deeper water layers (Schmid et al., 2004; Baxter et al., 2004), which might be catastrophic for the population living on its shores. Recently, Boudoire et al. (2022) highlighted that earthquakes were strongly felt by the inhabitants of Goma and Gisenyi, located on the shores of Lake Kivu (Fig. 1), a few hours after the last Nyiragongo eruption. They significantly damaged infrastructure and generated panic among local inhabitants due to the fear of the opening of eruptive fissures within the cities and of the impact on the stability of water layers in Lake Kivu.



**Fig. 4.** Evaluation of the severity of the impacts of volcano-tectonic hazards by rural communities for distinct villages in the VVP (more details in Methodology). Grey background highlights the villages where each volcano-tectonic hazard is considered as a major concern for local inhabitants (moderate to strong impact; Smets et al., 2010, 2015; Balagizi et al., 2018). The number of respondents in each group of social vulnerability and for each village is shown in black italic bold.



**Fig. 5.** Evaluation of the severity of the impacts of derived hazards by rural communities for distinct villages in the VVP (more details in Methodology). Grey background highlights the villages where each volcano-tectonic hazard is considered as a major concern for local inhabitants (moderate to strong impact; Smets et al., 2010, 2015; Balagizi et al., 2018). The number of respondents in each group of social vulnerability and for each village is shown in black italic bold.

### 4.3 Effects on local resources (edible plants and drinking water) sustaining rural communities

In this study we investigated in more detail the effects reported by local inhabitants from rural communities of the VVP on the quality of water and food. In particular, we have surveyed the main edible plants used locally (Fig. 6) as well as the main sources of drinking waters (Fig. 7). Based on respondents' answers, the most common edible plants grown and eaten by rural communities include three main genera (Fig. 6): *Amaranthus* (31%), *Brassica* (25%) and *Cucurbita* (17%). In Rumangabo, these three genera represent 99% of the plants. *Amaranthus* genus is the most common edible plant grown and eaten by respondents (Fig. 6). The only major difference is the predominance of the *Amaranthus* genus (>29%) together with the use of the *Manihot* genus (up to 26%) in the villages located downwind the volcanic plume. In Rumangabo, *Brassica* genus is more widely grown than *Amaranthus* genus and the *Manihot* is almost absent from crops (1%). Not surprisingly, village inhabitants downwind of volcanic plume expressed strong concern for the severity of the impacts of volcanic gas and particulate emissions (>7.6 on a

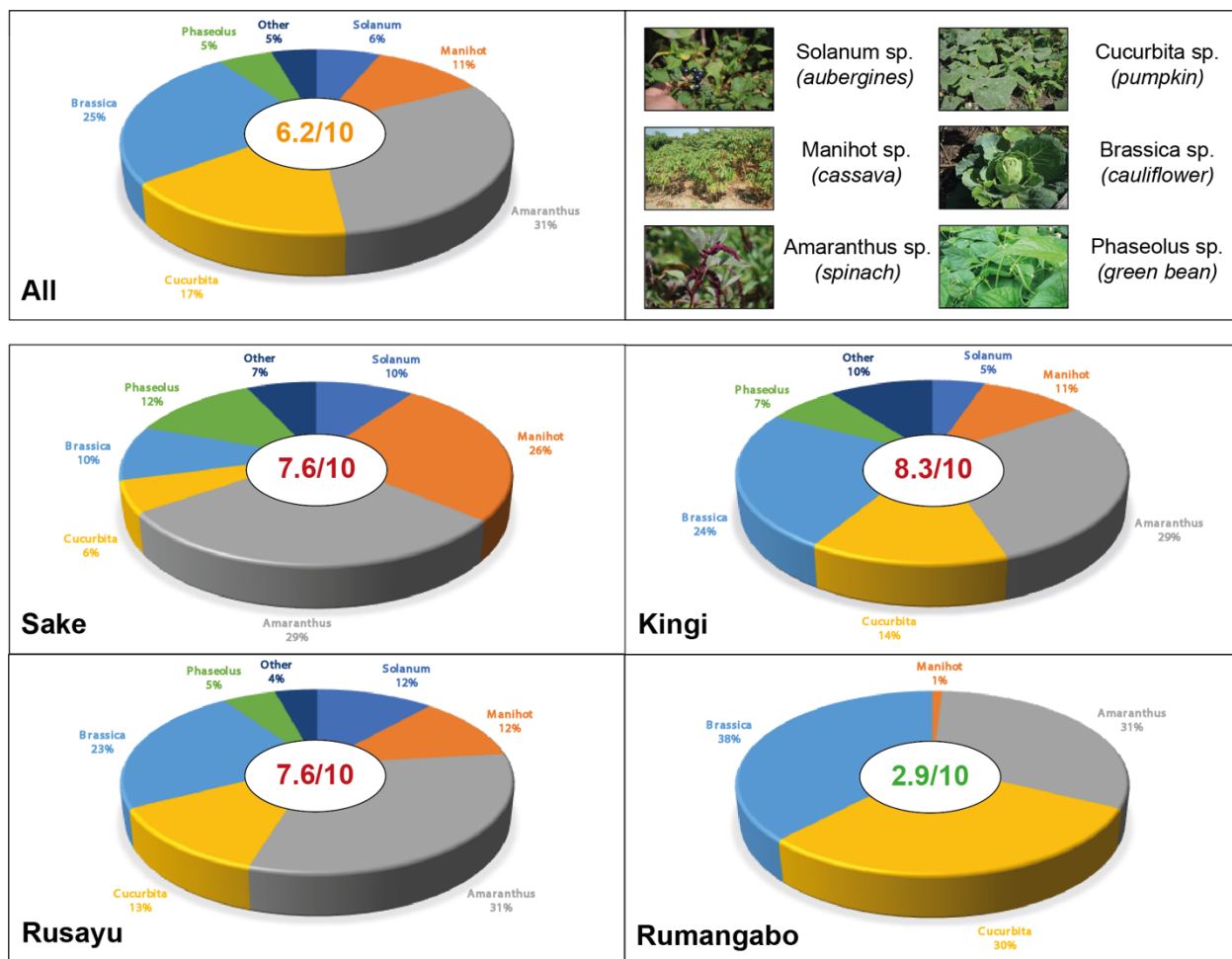
scale of 10). There, respondents have reported may issues mainly related to diarrhea, nausea, and to the loss of farming activities and livestock (Table 2). At Rumangabo, these impacts are judged weak by the inhabitants (2.9/10). These results highlight the need for targeting these edible plants to assess environmental health and to develop public health initiatives in the VVP considering the impacts of volcanic emissions on food contamination. Several studies revealed that temporary or continuous exposure to volcanic gas and particulate emissions has harmful effects on vegetation, since gases (and/or chemical compounds) exchange across plant stomata and are directly absorbed onto the leaf surface with a potential impact for human consumption (Kabata-Pendias and Pendias, 2001; Martin et al., 2012).

Three main sources of drinking waters reported by the respondents are (Fig. 7): *traditional drainage through a pipe system* (55%), *rainwater/meteoric* (29%) and *rivers/surface water* (16%). Rainwater is directly collected from the house rooftops and continuously stored using plastic tanks or traditional collectors (see more details in Balagizi et al., 2017). It should be emphasised that 100% of the respondents using *rainwater* as their primary drinking water believe the water is contaminated (acidity, high fluoride concentrations, volcanic particles, etc.). 95% of the respondents believe that waters from *rivers* are also contaminated, whereas this percentage falls to 14% for *drained* waters (less prone to contamination according to local users). Among the main impacts reported by the respondents consuming contaminated waters, the development of various health issues including teeth problems (known locally and in other volcanic provinces along the East African Rift System as fluorosis; Onipe et al., 2020) is of most concern (Table 2). At Rumangabo, which is our reference site, there is a clean and safe water system. This village has benefited of financial support from the Virunga National Park (PNVi), the Great Virunga Transboundary Collaboration (GVTC) and other multiple donors to improve basic infrastructure, including drinking water, farming, and environmental maintenance (Karume et al., 2019). In contrast, our survey reveals a strong perception by rural communities of the severity of the dangers related to water quality in the villages located downwind the volcanic plumes (Sake, Rusayu, Kingi) that are continuously threatened by volcanic gas and particle emissions. This spatial distribution shows that water contamination is not only associated with naturally occurring toxic elements in groundwaters (such as fluoride) triggered by geothermal temperature and rock leaching as frequently reported in sub-Saharan African countries (Onipe et al., 2020). In our case, the source of toxic elements seems to also come from volcanic plume – rainwaters interactions (Calabrese et al., 2014). The absence of artificially *drained* filtered waters for the villages located downwind the volcanic plume (with respect to Rumangabo) is a major issue. For instance, our survey reveals that all the respondents of Rusayu use *rainwater* as drinkable water (no draining

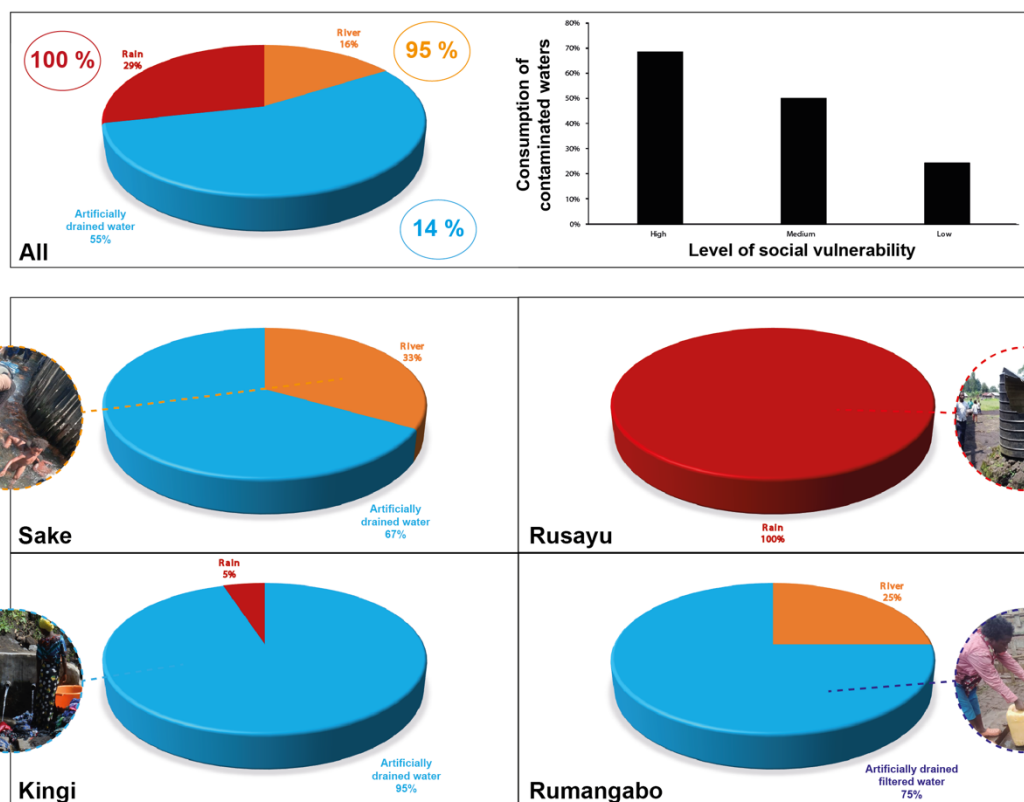
system, no river) and at the same time are aware it is contaminated (Fig.7). Finally, we note that the higher the level of social vulnerability of the respondents, the higher reported consumption of contaminated waters (Fig.7). In VVP, Habakaramo et al. (2019) highlighted multiple disadvantages of volcanism including death of human beings, wild animals, water contamination and plant decay due to high volcanic degassing as well the conversion of arable soils into rocks after lava flow events; that lead to poverty and famine for the local population.

These results are important to guide strategies of local sanitarian agencies, public services, and authorities: it strongly emphasizes that rural communities are aware of the level of water contamination but cannot avoid its use due to the lack of public alternative, or to economic issues at the household level (high vulnerability). To our knowledge, there is currently no local program for rural communities living downwind the volcanic plumes that aims to minimize the impacts of volcanic gas and particle emissions on food and water quality, nor are there programs aiming to decrease the level of social vulnerability of exposed population. Future studies based on chemical analyses of both edible plants and water used for drinking purpose are required to (i) quantify the level of contamination of these staple products with respect to sanitarian thresholds and (ii) foment the development of adapted sustainable strategies.





**Fig. 6.** Edibles plants commonly used as food by rural communities in the VVP. The first three genera listed by the respondents were considered. The severity of the impact of volcanic emissions on food quality is described from 0 to 10. Pictures from personal collection and Google Images.



**Fig. 7.** Water resources (drinking waters) used by rural communities in the VVP. For each water resources, respondents were asked if, according to them, the water was contaminated or not (the percentage of people for which the water is contaminated is shown in a circle for each water resources). The percentage of consumption of reportedly contaminated waters by households is also reported for each level of social vulnerability (high-medium-low). Pictures from personal collection.

#### 4.4 Remedial actions raised by rural populations

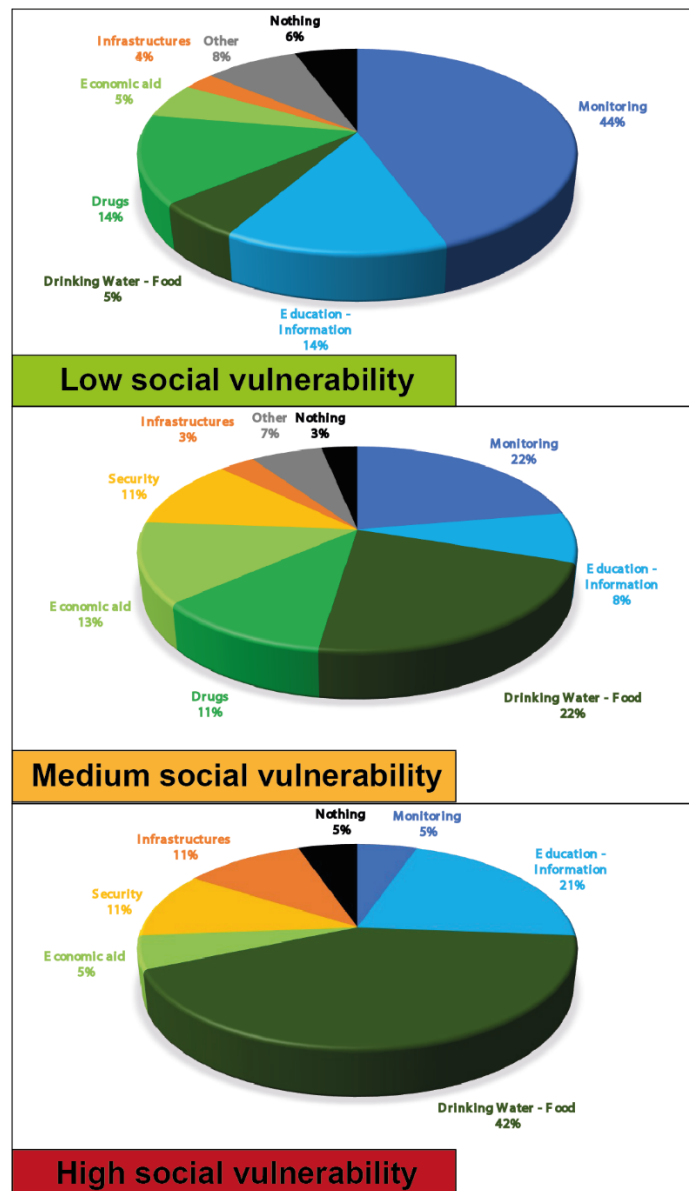
We saw that not only did people from rural communities in the VVP developed their own preventive actions when faced with volcano-tectonic hazards (e.g., cleaning edible plants after an episode of volcanic gas and particulate emissions and before eating) but they are also aware of the impact of some of them even if they do not have the tools to limit exposure to contamination (e.g., contaminated waters that are nevertheless used for drinking). Consequently, to conclude the survey, respondents were asked to propose actions and adaptations for managing and mitigating the negative effects of volcano-tectonic hazards.

The respondents suggested multiple remedial actions (for resilience and mitigation) that should be considered by local authorities, volcanologists, civil protection organizations, humanitarian groups, and other stakeholders to safeguard the lives of hundreds of thousands of people in the VVP. We notice that respondents with a low to medium level of social vulnerability primarily emphasized the need for volcanic monitoring (44 % and 22 %, respectively) and of

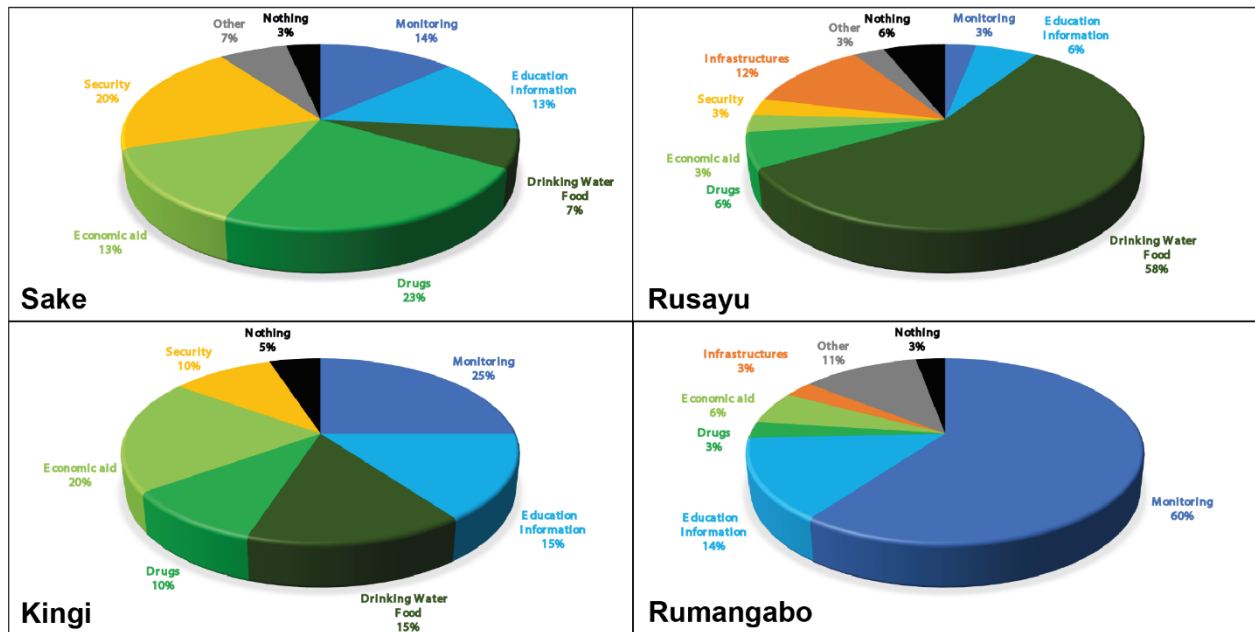
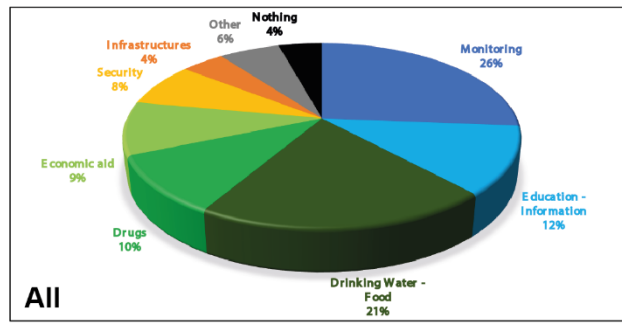
education-information (14 % and 8 %, respectively) to cope with volcano-tectonic risks (Fig. 8). In contrast, for people holding a higher level of social vulnerability, these needs are considered of less importance (26 %) than the need to have uncontaminated food and water resources available (42 %). We can directly make the link with our previous observations that respondents belonging to a higher level of social vulnerability are those who consume the most contaminated water and food resources (Fig. 7).

When looking the responses independent of the level of social vulnerability (Fig. 9), these three remedial actions remain majoritarian (59 %). The need to develop volcano monitoring includes the setting of a permanent and reliable monitoring network, as well as the adequate training of local researchers at the Observatoire Volcanologique de Goma. Following the latest eruption, Boudoire et al. (2022) strongly suggested the development of initiatives based on participatory approaches to (i) strengthen the links between researchers and citizens, (ii) propose reliable alternative to expensive monitoring stations (which are not always able to detect changes in volcano-tectonic activity), and (iii) reinforce the sustainability and resilience of local communities faced with natural hazards (in a way that also responds to the demand made in terms of educations and access to knowledge). On the basis of this survey, the improvement in the quality of drinking water and edible plants should be taken into greater consideration by the Congolese government and local authorities with the strong support of humanitarian agencies (WHO, FAO, WFP, ICRC and others). (3) Finally, the level of education and of the access to information must be improved to enhance the awareness and the preparedness of rural communities living close to the active volcanoes of VVP. This work emphasizes the need for strong communication between civil communities, researchers, and local authorities as well as the necessity to support the access to primary and high schools for children.

We note that the remedial actions proposed by the respondents of each village surveyed in this study are tightly related to the peculiar dangers affecting the villages (Fig. 9). At Rusayu, for instance, which is the village where the issues related to water contamination are the most important (Fig. 7), almost 60 % of the respondents highlight the need for access to drinkable water and uncontaminated food. It is three times more than the average calculated in this study. On the other hand, at Rumangabo, our “reference” site, no one expressed this need (due to the installation of an artificial drainage system for filtered drinking water; Fig. 7). Inhabitants of Rumangabo rather emphasize the need to improve volcano-tectonic monitoring tools and skills (60 %, i.e., almost three times more than the average calculated in this study).



**Fig. 8.** Statistical distribution of the remedial actions suggested by rural communities in the VVP to face volcanic-tectonic dangers. The statistical distribution is shown for each group of social vulnerability.



**Fig. 9.** Statistical distributions of the remedial actions proposed by all the respondents of this survey and for each village.

## 5 Conclusion

The perception of the severity of the impacts of volcano-tectonic hazards on VVP rural communities and adaptative strategies/remedial actions were discussed in this study. The main findings of the current research are summarized below:

1. An Operational Vulnerability index (OVI) was developed for each household surveyed (for a total of 119 households). Based on the OVI, low vulnerable population (OVI from 0 to 0.25), medium vulnerable population (OVI from 0.25 to 0.65), and highly vulnerable population (OVI from 0.65 to 1) were distinguished. This information can be useful to local and national authorities, volcanologists, civil protection, NGOs, and the international community to provide adapted prevention programs and/or to better target assistance to the population at risk or at the time following a crisis.
2. The severity of the impacts of epidemics and insecurity is the main concern for VVP rural communities, independently of the level of social vulnerability. A strong perception of the

impacts related to gas and particulate emissions is expressed by local communities living downwind the volcanic gas plume. These volcanic emissions are a major source of water and food contamination, leading to several sanitation issues among local inhabitants. Lava flows and mazukus are of minor concern compared to volcanic plume gas and particulate emissions.

3. Locally eaten plants include three main genera: *Amaranthus*, *Brassica* and *Cucurbita*, representing up to 99% of the edible plants at Rumangabo village. Local inhabitants living downwind the volcanic gas plume report many issues related to food quality in response to volcanic emissions. Similarly, multiple diseases related to the quality of the water are reported in the villages located downwind the volcanic plumes (Sake, Rusayu, Kingi).
4. Remedial actions are suggested by the respondents: improving monitoring, water and food quality, education, and information on volcanic risks. Preparedness to cope with the impacts of volcano-tectonic hazards is highly recommended in rural areas.

It appears that rural communities in the VVP are strongly aware of the hazards to which they are exposed. This awareness should be considered as a major advantage by stakeholders to build community resilience face to local natural hazards (Valdés et al., 2013; Burnside-Lawry and Carvalho, 2016). In this respect, we would recommend that stakeholders focus on the implementation of adapted remedial actions to enhance the ability of the rural communities to face potential natural disasters. Based on the results of this study remedial actions should be developed for:

1. Providing safe drinking water and edible plants to the most vulnerable populations who are exposed to a natural contamination of these primary resources and that are unable to access uncontaminated resources. We hope that such a study may help civil authorities, non-governmental organizations, and other intergovernmental programmes (as the World Food Programme of the United Nations) in orienting their strategy in a complex environment where, unfortunately, natural hazards are not the only sources of disasters in the area (insecurity, epidemics).
2. Promoting education and information about “good practices” to face natural hazards. For instance, the area where mazukus are present (as Sake and close to Rusayu) will benefit from better delimitating these hazardous places, indicating their presence, and excluding them from land-use plans (in the last years the City of Goma is expanding towards Sake with many new buildings in the vicinity of the mazukus) or adapting the infrastructures to these peculiar conditions (Smets et al., 2010). The reinforcement of evacuation plans and overall, their promotion in the civil society (dissemination, exercises) appear also fundamental to face potential future eruptions reaching populated areas.

3. Reinforcing local monitoring capacity. This should be done both by strengthening local skills within the relevant agencies through specific training programs and by developing new approaches in monitoring. We emphasize the need to involve civil society in local monitoring strategies by developing participatory approaches. Such approaches proved fundamental during the last eruption (Boudoire et al., 2022) in identifying early signs of unusual volcano-tectonic activity in the weeks preceding the eruption. They also help to develop the resilience of local populations and to strengthen the bond of trust between the population and the civil authorities, which is fundamental in dealing with natural disasters.

#### **Author contributions**

Patrick Habakaramo Macumu: conceptualization, methodology, data collecting, data analysis and validation, writing-original draft, writing-reviewing, and editing; Guillaume Boudoire: conceptualization, methodology, data analysis and validation, initially reviewed and edited the manuscript, supervision; Dario Tedesco and Sergio Calabrese: conceptualization, data validation, reviewing and editing, supervision; Francesco Rufino and Rachel M. Coyte: reviewing and editing. All authors read and approved the final manuscript.

#### **Acknowledgments**

This study is part of the PhD thesis of P. Habakaramo Macumu at the Università degli Studi della Campania Luigi Vanvitelli under the supervising of D. Tedesco, G. Boudoire, and S. Calabrese. Funding from the World Bank (DRC-Kinshasa) and the European Union (DRC-Kinshasa) have greatly helped PMH and DT during they stays in Italy and DRC. We thank the staff of the Observatoire Volcanologique de Goma (OVG) for their priceless support during field surveys. We are in debt with local persons who accepted to answer to the questionnaire. Data discussed in this study are fully available in Supporting Information. This research was partially supported by the French Government IDEX-ISITE initiative 16-IDEX-0001 (CAP 20-25). MONUSCO and UNDP are warmly thanked for their support in the field.

#### **Bibliography**

- Antronico, L., De Pascale, F., Coscarelli, R., & Gullà, G. (2020). Landslide risk perception, social vulnerability and community resilience: The case study of Maierato (Calabria, southern Italy). *International Journal of Disaster Risk Reduction*, 46. <https://doi.org/10.1016/j.ijdrr.2020.101529>
- Arellano, S., Yalire, M., Galle, B., Bobrowski, N., Dingwell, A., Johansson, M., & Norman, P.

- (2017). Long-term monitoring of SO<sub>2</sub> quiescent degassing from Nyiragongo's lava lake. *Journal of African Earth Sciences*, 134, 866–873. <https://doi.org/10.1016/j.jafrearsci.2016.07.002>.
- Arie, S. (2019). Congo sees rise in deaths from malaria, measles, and cholera as Ebola outbreak swallows up resources. *BMJ (Clinical Research Ed.)*, 366(July), 14522. <https://doi.org/10.1136/bmj.14522>
- Auker, M. R., Stephen, R., Sparks, J., Siebert, L., Crosweller, H. S., & Ewert, J. (2013). Statistical Analysis of Fatalities. *Journal of Applied Volcanology*, 2(2), 1–24.
- Balagizi, C. M., Kasereka, M. M., Cuoco, E., & Liotta, M. (2017). Rain-plume interactions at Nyiragongo and Nyamulagira volcanoes and associated rainwater hazards, East Africa. *Applied Geochemistry*, 81(February 2018), 76–89. <https://doi.org/10.1016/j.apgeochem.2017.03.018>
- Balagizi, C. M., Kies, A., Kasereka, M. M., Tedesco, D., Yalire, M. M., & McCausland, W. A. (2018). Natural hazards in Goma and the surrounding villages, East African Rift System. *Natural Hazards*, 93(1), 31–66. <https://doi.org/10.1007/s11069-018-3288-x>
- Baxter, P., Allard, P., Halbwachs, M., Komorowski, J.-C., Woods, a., & Ancia, a. (2004). Human health and vulnerability in the Nyiragongo volcano eruption and humanitarian crisis at Goma, Democratic Republic of Congo. *Acta Vulcanol.*, 14, 8–14.
- Blong, R. J., Grasso, P., Jenkins, S. F., Magill, C. R., Wilson, T. M., McMullan, K., & Kandlbauer, J. (2017). Estimating building vulnerability to volcanic ash fall for insurance and other purposes. *Journal of Applied Volcanology*, 6(1). <https://doi.org/10.1186/s13617-017-0054-9>
- Boloweti, D. B., Giraudoux, P., Deniel, C., Garnier, E., Mauny, F., Kasereka, C. M., Kizungu, R., Muyembe, J. J., Bompangue, D., & Bornette, G. (2020). Volcanic activity controls cholera outbreaks in the East African rift. *PLoS Neglected Tropical Diseases*, 14(8), 1–20. <https://doi.org/10.1371/journal.pntd.0008406>
- Boudoire, G., Calabrese, S., Colacicco, A., Sordini, P., Habakaramo Macumu, P., Rafflin, V., Valade, S., Mweze, T., Kazadi Mwepu, J.-C., Safari Habari, F., Amani Kahamire, T., Mumbere Mutima, Y., Ngaruye J.-C., Tuyishime, A., Tumaini Sadiki, A., Mavonga T., & Tedesco, D. (2022). Scientific response to the 2021 eruption of Nyiragongo based on the implementation of a participatory monitoring system. *Scientific Reports*, 12(7488), 1–10. <https://doi.org/10.1038/s41598-022-11149-0>
- Boudoire, G., Rizzo, A. L., Di Muro, A., Grassa, F., & Liuzzo, M. (2018). Extensive CO<sub>2</sub> degassing in the upper mantle beneath oceanic basaltic volcanoes: First insights from Piton de la Fournaise volcano (La Réunion Island). *Geochimica et Cosmochimica Acta*, 235, 376–



401. <https://doi.org/10.1016/j.gca.2018.06.004>
- Burgi, P. Y., Boudoire, G., Rufino, F., Karume, K., & Tedesco, D. (2020). Recent Activity of Nyiragongo (Democratic Republic of Congo): New Insights From Field Observations and Numerical Modeling. *Geophysical Research Letters*, 47(17). <https://doi.org/10.1029/2020GL088484>
- Burnside-Lawry, J., & Carvalho, L. (2016). A stakeholder approach to building community resilience: awareness to implementation. *International Journal of Disaster Resilience in the Built Environment*.
- Cuoco, E., Spagnuolo, A., Balagizi, C., De Francesco, S., Tassi, F., Vaselli, O., & Tedesco, D. (2013a). Impact of volcanic emissions on rainwater chemistry: The case of Mt. Nyiragongo in the Virunga volcanic region (DRC). *Journal of Geochemical Exploration*, 125, 69–79. <https://doi.org/10.1016/j.gexplo.2012.11.008>
- Cuoco, E., Tedesco, D., Poreda, R. J., Williams, J. C., De Francesco, S., Balagizi, C., & Darrah, T. H. (2013b). Impact of volcanic plume emissions on rain water chemistry during the January 2010 Nyamuragira eruptive event: Implications for essential potable water resources. *Journal of Hazardous Materials*, 244–245, 570–581. <https://doi.org/10.1016/j.jhazmat.2012.10.055>
- Cutter, S. L., & Finch, C. (2008). *Temporal and spatial changes in social vulnerability to natural hazards*. [www.pnas.org/cgi/doi/10.1073/pnas.0710375105](http://www.pnas.org/cgi/doi/10.1073/pnas.0710375105)
- de Assis Dias, M. C., Saito, S. M., dos Santos Alvalá, R. C., Seluchi, M. E., Bernardes, T., Camarinha, P. I. M., ... & Nobre, C. A. (2020). Vulnerability index related to populations at risk for landslides in the Brazilian Early Warning System (BEWS). *International journal of disaster risk reduction*, 49, 101742.
- De Iuliis, M., Kammouh, O., Cimellaro, G. P., & Tesfamariam, S. (2019). Downtime estimation of building structures using fuzzy logic. *International Journal of Disaster Risk Reduction*, 34(November 2018), 196–208. <https://doi.org/10.1016/j.ijdr.2018.11.017>
- Dibben, C., & Chester, D. K. (1999). Human vulnerability in volcanic environments: The case of Furnas, Sao Miguel, Azores. *Journal of Volcanology and Geothermal Research*, 92(1–2), 133–150. [https://doi.org/10.1016/S0377-0273\(99\)00072-4](https://doi.org/10.1016/S0377-0273(99)00072-4)
- Durieux, J. (2002). Nyiragongo: The January 10th 1977 eruption. *Acta Vulcanologica*, 14–15, 145–148.
- Durieux, J. (2003). Volcano Nyiragongo (D.R.Congo): Evolution of the crater and lava lakes from the discovery to the present. *Acta Vulcanologica*, 14–15, 137–144.
- Favalli, M., Chirico, G. D., Papale, P., Pareschi, M. T., Coltelli, M., Lucaya, N., & Boschi, E. (2006). Computer simulations of lava flow paths in the town of Goma, Nyiragongo volcano,

- Democratic Republic of Congo. *Journal of Geophysical Research: Solid Earth*, 111(6).  
<https://doi.org/10.1029/2004JB003527>
- Firdhous, M. F. M., & Karuratane, P. M. (2018). A Model for Enhancing the Role of Information and Communication Technologies for Improving the Resilience of Rural Communities to Disasters. *Procedia Engineering*, 212, 707–714.  
<https://doi.org/10.1016/j.proeng.2018.01.091>
- Gaillard, J. C. (2008). Alternative paradigms of volcanic risk perception: The case of Mt. Pinatubo in the Philippines. *Journal of Volcanology and Geothermal Research*, 172(3–4), 315–328.  
<https://doi.org/10.1016/j.jvolgeores.2007.12.036>
- Gudmundsson, G. (2011). Respiratory health effects of volcanic ash with special reference to Iceland. A review. In *Clinical Respiratory Journal* (Vol. 5, Issue 1, pp. 2–9).  
<https://doi.org/10.1111/j.1752-699X.2010.00231.x>
- Habakaramo, P., Mutalegwa G., Kahuranyi J., & Karume K. (2019) Les Volcans des Virunga à l’Est de la République Démocratique du Congo, une perception populaire: un mythe ou une réalité ?. In: Gugg G, Dall’O’ E, Borriello D, Eds, Disasters in popular cultures, Lago: Il Sileno Edizioni, Geographies of the Anthropocene book series, 102–117.
- Hansell, A. L., Horwell, C. J., & Oppenheimer, C. (2006). The health hazards of volcanoes and geothermal areas. In *Occupational and Environmental Medicine* (Vol. 63, Issue 2, pp. 149–156). <https://doi.org/10.1136/oem.2005.022459>
- Hopkins, J. L., Smid, E. R., Eccles, J. D., Hayes, J. L., Hayward, B. W., McGee, L. E., van Wijk, K., Wilson, T. M., Cronin, S. J., Leonard, G. S., Lindsay, J. M., Németh, K., & Smith, I. E. M. (2021). Auckland Volcanic Field magmatism, volcanism, and hazard: a review. *New Zealand Journal of Geology and Geophysics*, 64(2–3), 213–234.  
<https://doi.org/10.1080/00288306.2020.1736102>
- Horwell, C. J., & Baxter, P. J. (2006). The respiratory health hazards of volcanic ash: A review for volcanic risk mitigation. In *Bulletin of Volcanology* (Vol. 69, Issue 1, pp. 1–24).  
<https://doi.org/10.1007/s00445-006-0052-y>
- Hummell, B. M., Cutter, S. L., & Emrich, C. T. (2016). Social Vulnerability to Natural Hazards in Brazil. *International Journal of Disaster Risk Science*, 7(2), 111–122.  
<https://doi.org/10.1007/s13753-016-0090-9>
- Jenkins, S. F., Day, S. J., Faria, B. V. E., & Fonseca, J. F. B. D. (2017). Damage from lava flows: insights from the 2014–2015 eruption of Fogo, Cape Verde. *Journal of Applied Volcanology*, 6(1). <https://doi.org/10.1186/s13617-017-0057-6>
- Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014).

- Volcanic risk assessment: Quantifying physical vulnerability in the built environment. *Journal of Volcanology and Geothermal Research*, 276, 105–120. <https://doi.org/10.1016/j.jvolgeores.2014.03.002>
- Kabata-Pendias, A., & Pendias, H. (2001). *Trace elements in soils and plants* (T. Edition (ed.)). CRC Press. <https://doi.org/0849315751>
- Kakota, T., Nyariki, D., Mkwambisi, D., & Kogi-Makau, W. (2015). Determinants of Household Vulnerability to Food Insecurity: A Case Study of Semi-Arid Districts in Malawi. *Journal of International Development*, 27(1), 73-84.
- Karume. K, Bagalwa. M, Bagula. M, Yalire. M, H. P. & J. B. (2019). A seasonal change in physicochemical, Bacteriological parameters and macroinvertebrate assemblage structure and composition in Mikenso sector, Eastern DRC. *International Journal of Environment, Ecology, Family and Urban Studies (IJEEFUS)*, 9(1), 53–70. <https://doi.org/2250-0065>
- Kasereka, M. M., Cuoco, E., Zabene, F. Z., & Balagizi, C. M. (2021). Baseline for rainwater chemistry and quality as influenced by Nyiragongo volcano permanent plume, East Africa. *Chemosphere*, 283(May), 130859. <https://doi.org/10.1016/j.chemosphere.2021.130859>
- Kasereka, M. M., Yalire, M. M., Minani, A. S., Samba, C. V, Bisusa, A. K., Kamate, E. K., Mashagiro, N., Syauswa, M., & Kavuke, J. K. (2017). Les risques liés aux Mazuku dans la region de Goma, République Démocratique du Congo (Rift Est-Africain). *J. Wat. Env. Sci*, 1, 164–174. <http://revues.imist.ma/?journal=jwes>
- Komorowski, J.-C., Tedesco, D., Kasereka, M., Allard, P., Papale, P., Vaselli, O., Durieux, J., Baxter, P., Halbwachs, M., Akumbe, M., Baluku, B., Briole, P., Ciraba, M., Dupin, J.-C., Etoy, O., Garcin, D., Hamaguchi, H., Houlié, N., Kavotha, K.S Lemarchand, A Lockwood, J., ... Wafula, M. (2002). The January 2002 flank eruption of Nyiragongo volcano (Democratic Republic of Congo): chronology, evidence for a tectonic rift trigger, and impact of lava flows on the city of Goma. *Acta Vulcanologica*, 14(1–2), 27–62.
- Lara, L. E., Flores, F., Calderón, R., & Cardona, C. (2021). Volcano hazards and risks in Chile. *Forecasting and Planning for Volcanic Hazards, Risks, and Disasters*, 617–633. <https://doi.org/10.1016/b978-0-12-818082-2.00017-2>
- Le Guern, F. (1987). Mechanism of energy transfer in the lava lake of Niragongo (Zaire), 1959-1977. *Journal of Volcanology and Geothermal Research*, 31(1–2), 17–31. [https://doi.org/10.1016/0377-0273\(87\)90003-5](https://doi.org/10.1016/0377-0273(87)90003-5)
- Liotta, M., Shamavu, P., Scaglione, S., D'Alessandro, W., Bobrowski, N., Bruno Giuffrida, G., Tedesco, D., & Calabrese, S. (2017). Mobility of plume-derived volcanogenic elements in meteoric water at Nyiragongo volcano (Congo) inferred from the chemical composition of

- single rainfall events. *Geochimica et Cosmochimica Acta*, 217, 254–272.  
<https://doi.org/10.1016/j.gca.2017.08.001>
- Lowe, C. J. (2010). *Analysing Vulnerability to Volcanic Hazards: Application to St. Vincent*.
- MacQuillan, C. J. (1944). Chronic Fluoride Poisoning in the Arasha District, Tanganyika Territory. *East African Medical Journal*, 21(5), 131–4.
- Marasco, S., Kammouh, O., & Cimellaro, G. P. (2022). Disaster resilience quantification of communities: A risk-based approach. *International Journal of Disaster Risk Reduction*, 70. <https://doi.org/10.1016/j.ijdrr.2021.102778>
- Markantonis, V., Meyer, V., & Schwarze, R. (2012). Valuating the intangible effects of natural hazards - Review and analysis of the costing methods. In *Natural Hazards and Earth System Science* (Vol. 12, Issue 5, pp. 1633–1640). <https://doi.org/10.5194/nhess-12-1633-2012>
- Martin, R. S., Witt, M. L. I., Sawyer, G. M., Thomas, H. E., Watt, S. F. L., Bagnato, E., Calabrese, S., Aiuppa, A., Delmelle, P., Pyle, D. M., & Mather, T. A. (2012). Bioindication of volcanic mercury (Hg) deposition around Mt. Etna (Sicily). *Chemical Geology*, 310–311, 12–22. <https://doi.org/10.1016/j.chemgeo.2012.03.022>
- Mavonga, T., Zana, N., & Durrheim, R. J. (2010). Studies of crustal structure, seismic precursors to volcanic eruptions and earthquake hazard in the eastern provinces of the Democratic Republic of Congo. *Journal of African Earth Sciences*, 58(4), 623–633. <https://doi.org/10.1016/j.jafrearsci.2010.08.008>
- Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Van Den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. H., & Viavattene, C. (2013). Review article: Assessing the costs of natural hazards-state of the art and knowledge gaps. In *Natural Hazards and Earth System Science* (Vol. 13, Issue 5, pp. 1351–1373). <https://doi.org/10.5194/nhess-13-1351-2013>
- Michellier, C., Kervyn, M., Barette, F., Muhindo Syavulisembo, A., Kimanuka, C., Kulimushi Mataboro, S., Hage, F., Wolff, E., & Kervyn, F. (2020). Evaluating population vulnerability to volcanic risk in a data scarcity context: The case of Goma city, Virunga volcanic province (DR Congo). *International Journal of Disaster Risk Reduction*, 45. <https://doi.org/10.1016/j.ijdrr.2019.101460>
- Mitchell, T., & Harris, K. (2012). Resilience: A risk management approach. *Overseas Development Institute, January*. <https://doi.org/ISSN 1756-7610>
- Onipe, T., Edokpayi, J. N., & Odiyo, J. O. (2020). A review on the potential sources and health implications of fluoride in groundwater of Sub-Saharan Africa. *Journal of Environmental*

*Science and Health, Part A*, 55(9), 1078-1093.

- Palma-Lara, I., Martínez-Castillo, M., Quintana-Pérez, J. C., Arellano-Mendoza, M. G., Tamay-Cach, F., Valenzuela-Limón, O. L., García-Montalvo, E. A., & Hernández-Zavala, A. (2020). Arsenic exposure: A public health problem leading to several cancers. In *Regulatory Toxicology and Pharmacology* (Vol. 110). Academic Press Inc. <https://doi.org/10.1016/j.yrtph.2019.104539>
- Poppe, S., Smets, B., Fontijn, K., Rukeza, M. B., De Marie Fikiri Migabo, A., Milungu, A. K., Namogo, D. B., Kervyn, F., & Kervyn, M. (2016). Holocene phreatomagmatic eruptions alongside the densely populated northern shoreline of Lake Kivu, East African Rift: timing and hazard implications. *Bulletin of Volcanology*, 78(11). <https://doi.org/10.1007/s00445-016-1074-8>
- Pouclet, A., Bellon, H., & Bram, K. (2016). The Cenozoic volcanism in the Kivu rift: Assessment of the tectonic setting, geochemistry, and geochronology of the volcanic activity in the South-Kivu and Virunga regions. *Journal of African Earth Sciences*, 121, 219–246. <https://doi.org/10.1016/j.jafrearsci.2016.05.026>
- Pouclet, A., & Bram, K. (2021). Nyiragongo and Nyamuragira: a review of volcanic activity in the Kivu rift, western branch of the East African Rift System. *International Association of Volcanology & Chemistry of the Earth's Interior*. <https://doi.org/10.1007/s00445-021-01435-6>/Published
- Pouclet, A., Menot, R. P., & Piboule, M. (1983). Le magmatisme alcalin potassique de l'aire volcanique des Virunga (Rift occidental de l'Afrique de l'Est). Une approche statistique dans la recherche des filiations magmatiques et des mecanismes de differenciation. *Bulletin de Mineralogie*, 106(5), 607–623. <https://doi.org/10.3406/bulmi.1983.7738>
- Prelog, A. J., & Miller, L. M. (2013). Perceptions of Disaster Risk and Vulnerability in Rural Texas. *Journal of Rural Social Sciences*, 28(3), 1–31. [http://www.ag.auburn.edu/auxiliary/srsa/pages/Articles/JRSS 2013 28/3/JRSS 2013 28 3 1-31.pdf](http://www.ag.auburn.edu/auxiliary/srsa/pages/Articles/JRSS%2013%2028/3/JRSS%2013%2028%203%201-31.pdf)
- Qureshi, M. I., Khan, S. U., Rana, I. A., Ali, B., & Rahman, A. ur. (2021). Determinants of people's seismic risk perception: A case study of Malakand, Pakistan. *International Journal of Disaster Risk Reduction*, 55. <https://doi.org/10.1016/j.ijdr.2021.102078>
- Reimann, C., Filzmoser, P., Garrett, R. G., & Dutter, R. (2008). Principal component analysis (PCA) and factor analysis (FA). Statistical data analysis explained: applied environmental statistics with R, 211-232
- Sahama, 1962. (1962). *Petrology of Mt. Nyiragongo: A Review*. Edinburgh Geological Society

- Sahama and Meyer. (1958). Expl , oration du Parc National Albert Exploratie van het N ationaal Albert Park. *Institut Des Parcs Nationaux Du Congo Belge*, 2(Fascicule), 18.
- Shrestha, N. (2021). Factor analysis as a tool for survey analysis. *American Journal of Applied Mathematics and Statistics*, 9(1), 4-11.
- Schmid, M., Tietze, K., Halbwachs, M., Lorke, A., McGinnis, D. F., & Wüest, A. (2004). How hazardous is the gas accumulation in Lake Kivu? Arguments for a risk assesment in light of the Nyiragongo volcano eruption of 2002. *Acta Vulcanologica*, 14/15(1–2), 115–122.
- Schuster, R. L., & Fleming, R. W. (1986). Economic Losses and Fatalities Due To Landslides. In *Bulletin of the Association of Engineering Geologists* (Vol. 23, Issue 1, pp. 11–28). <https://doi.org/10.2113/gseegeosci.xxiii.1.11>
- Schuster, R. L., & Highland, L. M. (2001). Socioeconomic Impacts of Landslides in the Western Hemisphere. *U.S. Geological Survey, August*, 1–47.
- Small, C., & Naumann, T. (2001). The global distribution of human population and recent volcanism. *Environmental Hazards*, 3(3), 93–109. <https://doi.org/10.3763/ehaz.2001.0309>
- Smets, B., Tedesco, D., Kervyn, F., Kies, A., Vaselli, O., & Yalire, M. M. (2010). Dry gas vents (“mazuku”) in Goma region (North-Kivu, Democratic Republic of Congo): Formation and risk assessment. *Journal of African Earth Sciences*, 58(5), 787-798
- Smets, B., d’Oreye, N., Kervyn, F., Kervyn, M., Albino, F., Arellano, S. R., Bagalwa, M., Balagizi, C., Carn, S. A., Darrah, T. H., Fernández, J., Galle, B., González, P. J., Head, E., Karume, K., Kavotha, D., Lukaya, F., Mashagi, N., Mavonga, G., ... Yalire, M. M. (2014). Detailed multidisciplinary monitoring reveals pre- and co-eruptive signals at Nyamulagira volcano (North Kivu, Democratic Republic of Congo). *Bulletin of Volcanology*, 76(1), 1–35. <https://doi.org/10.1007/s00445-013-0787-1>
- Smets, B., Kervyn, M., d’Oreye, N., & Kervyn, F. (2015). Spatio-temporal dynamics of eruptions in a youthful extensional setting: Insights from Nyamulagira Volcano (D.R. Congo), in the western branch of the East African Rift. In *Earth-Science Reviews* (Vol. 150, pp. 305–328). Elsevier. <https://doi.org/10.1016/j.earscirev.2015.08.008>
- Sullivan-Wiley, K. A., & Short Gianotti, A. G. (2017). Risk Perception in a Multi-Hazard Environment. *World Development*, 97, 138–152. <https://doi.org/10.1016/j.worlddev.2017.04.002>
- Syavulisembo, A. M., Havenith, H. B., Smets, B., D’Oreye, N., & Marti, J. (2015). Preliminary assessment for the use of VORIS as a tool for rapid lava flow simulation at Goma Volcano Observatory, Democratic Republic of the Congo. *Natural Hazards and Earth System*



984 *Sciences*, 15(10), 2391–2400. <https://doi.org/10.5194/nhess-15-2391-2015>

- 985 Syavulisembo Muhindo, A. M., François, K., Moritz, L., Eléonore, W., & Caroline, M. (2021).  
986 Spatio-temporal location of population: Strengthening the capacities of sudden hazards risk  
987 management in Goma, DRC. *International Journal of Disaster Risk Reduction*, 66, 102565  
988 Taber, K. S. (2018). The use of Cronbach's alpha when developing and reporting research  
989 instruments in science education. *Research in science education*, 48(6), 1273-1296.  
990 Tassi, F., Vaselli, O., Tedesco, D., Montegrossi, G., Darrah, T., Cuoco, E., Mapendano, M. Y.,  
991 Poreda, R., & Huertas, A. D. (2009). Water and gas chemistry at Lake Kivu (DRC):  
992 Geochemical evidence of vertical and horizontal heterogeneities in a multibasin structure.  
993 *Geochemistry, Geophysics, Geosystems*, 10(2). <https://doi.org/10.1029/2008GC002191>  
994 Tazieff, H. (1977). An exceptional eruption: Mt. Niragongo, Jan. 10 th, 1977. *Bulletin*  
995 *Volcanologique*, 40(3), 189–200. <https://doi.org/10.1007/BF02596999>  
996 Tazieff, H. (1984). Mt. Niragongo: renewed activity of the lava lake. *Journal of Volcanology and*  
997 *Geothermal Research*, 20(3–4), 267–280. [https://doi.org/10.1016/0377-0273\(84\)90043-X](https://doi.org/10.1016/0377-0273(84)90043-X)  
998 Tazieff, H. (1985). *Recent activity at Nyiragongo and lava-lake occurrences.*  
999 <https://doi.org/https://doi.org>  
1000 Tedesco D., Miele G., Sano Y., & Toutain J.P. (1995). Helium isotopic ratio in Vulcano island  
1001 fumaroles: temporal variations in shallow level mixing and deep magmatic supply. *J.*  
1002 *Volcanol. Geoth. Res.*, 64, 117-128. [https://doi.org/10.1016/0377-0273\(94\)00045-I](https://doi.org/10.1016/0377-0273(94)00045-I)  
1003 Tedesco D., & Nagao K. (1996). Radiogenic 4He, 21Ne and 40Ar in fumarolic gases on Vulcano:  
1004 Implication for the presence of continental crust beneath the island. *Earth & Plant. Sci. Lett.*  
1005 64, 517-528. [https://doi.org/10.1016/s0012-821x\(96\)00196-3](https://doi.org/10.1016/s0012-821x(96)00196-3)  
1006 Tedesco, D., Vaselli, O., Papale, P., Carn, S. A., Voltaggio, M., Sawyer, G. M., Durieux, J.,  
1007 Kasereka, M., & Tassi, F. (2002). *January 2002 volcano&hyphen;tectonic eruption of*  
1008 *Nyiragongo volcano, Democratic Republic of Congo.* <https://doi.org/10.1029/2006JB004762>  
1009 Tedesco, D., Vaselli, O., Papale, P., Carn, S. A., Voltaggio, M., Sawyer, G. M., Durieux, J.,  
1010 Kasereka, M., & Tassi, F. (2007). January 2002 volcano-tectonic eruption of Nyiragongo  
1011 volcano, Democratic Republic of Congo. *Journal of Geophysical Research: Solid Earth*,  
1012 112(9). <https://doi.org/10.1029/2006JB004762>  
1013 Tedesco, J. R. D. (2002). One Year After the Nyiragongo Volcano Alert: Evolution of the  
1014 Communication Between Goma Inhabitants ( Populations ), Scientists and Local Authorities.  
1015 *Acta Vulcanologica*, January, 1–5.  
1016 Tesone, A. I., Lasagni Vitar, R. M., Tau, J., Maglione, G. A., Llesuy, S., Tasat, D. R., & Berra, A.  
1017 (2018). Volcanic ash from Puyehue-Cordón Caulle Volcanic Complex and Calbuco promote

- a differential response of pro-inflammatory and oxidative stress mediators on human conjunctival epithelial cells. *Environmental Research*, 167, 87–97.  
<https://doi.org/10.1016/j.envres.2018.07.013>
- Valdés, H. M., Amaratunga, D., & Haigh, R. (2013). Making cities resilient: From awareness to implementation. *International Journal of Disaster Resilience in the Built Environment*.
- Vaselli, O., Capaccioni, B., Tedesco, D., Tassi, F., Capaccioni, B., Tassi, · Franco, Yalire, M. M., Mahinda, ·, & Kasareka, C. (2002). Mazukus Vaselli 2003 The “Evil’s winds” (Mazukus) at Nyiragongo volcano (Democratic Republic of Congo). *Acta Vulcanologica* ·, 14(2), 123–127.  
<https://www.researchgate.net/publication/236668992>
- Vaselli, O., Tassi, F., Tedesco, D., & Cuoco, E. (2007). *Environmental impact of the Nyiragongo volcanic plume after the January 2002 eruption*.  
<https://www.researchgate.net/publication/232091791>
- Verhoeve, A., Vlassenroot, K., & Raeymaekers, T. (2004). Conflict and the urban space: The socio-economic impact of conflict on the city of Goma. Conflict and social transformation in Eastern DR Congo, 103-122.
- Wauthier, C., Cayol, V., Kervyn, F., & D’Oreye, N. (2012). Magma sources involved in the 2002 Nyiragongo eruption, as inferred from an InSAR analysis. *Journal of Geophysical Research: Solid Earth*, 117(5), 1–20. <https://doi.org/10.1029/2011JB008257>
- Wilder-Smith, A., & Osman, S. (2020). Public health emergencies of international concern: A historic overview. *Journal of Travel Medicine*, 27(8), 1–13.  
<https://doi.org/10.1093/JTM/TAAA227>
- Wold, S., Esbensen, K., & Geladi, P. (1987). Principal component analysis. *Chemometrics and intelligent laboratory systems*, 2(1-3), 37-52
- Yalire, M., Galle, B., Arellano, S., Norman, P., & Johansson, M. (2010). Long-term observations of SO<sub>2</sub> gas emission rates from Nyiragongo volcano (RD Congo) during. In *Geophysical Research Abstracts* (Vol. 12).
- Zêzere, J. L., Oliveira, S. C., Garcia, R. A. C., & Reis, E. (2007). Landslide risk analysis in the area North of Lisbon (Portugal): Evaluation of direct and indirect costs resulting from a motorway disruption by slope movements. *Landslides*, 4(2), 123–136.  
<https://doi.org/10.1007/s10346-006-0070-z>

## Supplementary material

**Appendix 1.** Survey questionnaire used in this study.

**Appendix 2.** Dataset with all compiled responses from the VVP household survey.