RESEARCH ARTICLE

VOLCANICA

Submitted: 2024-01-31 | Accepted: 2024-09-05 | Published: 2024-12-03

Assessing accessibility to critical resources for volcanic risk management in Goma, Democratic Republic of Congo

Adalbert Muhindo Syavulisembo*† [α,β,γ], François Kervyn[δ], Moritz Lennert[γ], Eléonore Wolff[γ], and Caroline Michellier[δ]

[α] OVG, Observatoire Volcanologique de Goma, Quartier Les Volcans, Avenue du Rond-Point 142, Goma, Democratic Republic of Congo.
[β] UNIGOM, Université de Goma, Department de Géologie, Quartier Katindo, Avenue Ishasha 32, Goma, Democratic Republic of Congo.
[γ] ULB, Université Libre de Bruxelles, ANAGEO/IGEAT, CP130/03, Av. F.D. Roosevelt 50, B-1050 Brussels, Belgium.
[δ] MRAC, Royal Museum for Central Africa, Department of Earth Sciences, Leuvensesteenweg 13, B-3080 Tervuren, Belgium.

Abstract

In many administrative entities, there is little information on the accessibility of critical resources such as food, water, healthcare and fuel. Yet the lack of accessibility to critical resources can be a risk-mitigating factor. Indeed, people who are not physically threatened by a hazard can be put at risk by the fact that they lack critical resources. In the specific context of an area threatened by lava flows and characterized by a scarcity of accessible and reliable data, we assessed the accessibility of critical resources in Goma, in the Democratic Republic of Congo (DRC), a densely populated city located at the foot of the Nyiragongo volcano. Our study shows that by mapping the location of critical resources and characterizing their accessibility, we can systematically identify underserviced urban areas that are consequently more vulnerable to risks, and in our study to volcanic risks.

Résumé

Dans de nombreuses d'entités administratives, il n'existe que peu d'informations sur l'accessibilité aux ressources critiques telles que la nourriture, l'eau, les soins de santé et le carburant. Pourtant, l'absence d'accessibilité aux ressources critiques peut être un facteur d'atténuation des risques. En effet, les personnes qui ne sont pas physiquement menacées par un aléa peuvent être mises en danger par le fait qu'elles ne disposent pas de ressources critiques. Dans le contexte particulier d'une zone menacée par une coulée de lave et caractérisée par une rareté de données accessibles et fiables, nous avons évalué l'accessibilité aux ressources critiques à Goma, en République démocratique du Congo (RDC), une ville densément peuplée, localisée au pied du volcan Nyiragongo. Notre étude démontre que la cartographie de l'emplacement des ressources critiques et la caractérisation de leur accessibilité permettent d'identifier systématiquement les zones urbaines mal desservies qui sont de ce fait plus vulnérables aux risques, et dans notre étude spécifiquement aux risques volcaniques.

Keywords: Disaster risk management; Critical resources; Population mobility; Nyiragongo volcano; Spatio-temporal analysis; Goma.

1 Introduction

Resource availability is crucial for natural disaster risk management in normal periods, crisis periods, and recovery periods [Lutoff et al. 1998a; Demoraes and d'Ercole 2009; Brunet et al. 2012; Leone et al. 2013; Laganier and Veyret 2023]. This is particularly true when the area concerned is densely populated, as is the case in urban areas. The term 'normal' means that the population has not yet been affected by a (natural) phenomenon, and the functioning of the city is still effective. During a crisis, activities and services are affected to varying degrees, depending on their level of vulnerability and the intensity of the hazard. Finally, during recovery, the city begins to function on its own again to meet basic needs, and redevelop external relations [Brunet et al. 2012; Leone et al. 2013; Crozier et al. 2017; Laganier and Veyret 2023].

The primary concern of crisis managers is to ensure that the resources needed in a period of 'crisis' (referred to as 'critical resources' in the remainder of this article) are both sufficient and accessible to meet the needs of the population [Brunet et al. 2012; Laganier and Veyret 2023]. Indeed, identifying and quantifying critical resources, as well as assessing their accessibility on foot and by car are fundamental priorities for the implementation of the Sendai Framework for Disaster Risk Reduction [UNDRR 2015]. The accessibility of a place, relying on mobility on a road and path network combined with traffic speeds, is generally defined according to the ease with which it can be reached from one or more other places, by one or more individuals, who can travel using all or part of the existing means of transport [Demoraes and d'Ercole 2009; Leone 2018]. Road networks are crucial in economic systems, logistic chain continuity, mobility and evacuation of the population during and after extreme events [Chamorro et al. 2023]. In the context of reducing the disaster risk drivers, it is advisable to integrate human mobility into disaster risk reduction (DRR) policies and measures, and to ensure, where appropriate, that programs for displaced persons do not increase risk and vulnerability to hazards [Yamamoto et al. 2018].

In areas prone to hazards, such as volcanic eruptions, low accessibility to critical resources can generate a secondary disaster. Barclay et al. [2019] point out that during a volcanic cri-

* adalmuhindo@gmail.com
† Permanent address: Observatoire Volcanologique de Goma, Quartier Les volcans, Avenue du Rond-Point 142, Goma, Democratic Republic of Congo.

Editor: A. Donovan | Typesetter: J. Farquharson

sis, the impact on livelihoods can be the origin of fatalities. Indeed, their global survey conducted over the period from 1986 to 2015, reveals that 63 % of primary volcanic deaths occur after the first week of activity, with >44 % of these deaths associated with citizens returning to an established high-hazard zone [Barclay et al. 2019]. Between 1600 and 2010, more than 24 % of human deaths caused by volcanic eruptions (66,931 deaths) were due to secondary effects such as starvation and diseases [Auker et al. 2013]. Moreover, Gaillard [2008], Mei et al. [2013], and Connell and Lutkehaus [2016] all show that during a crisis, the population is often forced to go to dangerous areas to meet their basic needs. This brief review of volcanic crisis situations suggests that the need to preserve critical resources and their accessibility plays an important role in protecting life while lava flows destroy everything in their path [Auker et al. 2013; Barclay et al. 2019]. Understanding the accessibility of critical resources is crucial when planning for and responding to volcanic crises. To do this, we first need to identify where critical resources are located, and then model the accessibility of these resources for the population.

The case study of the Nyiragongo volcano (DRC) is particularly interesting to study; indeed, during its three historical eruptions in 1977, 2002, and 2021, the high number of casualties and the impacts felt on the long term were not only related to the high speed of lava [Morrison et al. 2020], its fluidity and the eruption near inhabited areas [Michellier et al. 2020; Syavulisembo et al. 2021], but also the accessibility of resources likely to meet basic needs during the crises [Syavulisembo 2019].

To fully determine the accessibility to critical resources in disaster risk management in the Goma region, the aim of this study is to identify the areas with the fastest access to resources, as well as the best way to access them, and thus highlight the most vulnerable areas. Although the study was initiated in 2017, we considered both the lessons learned from the 2002 and 2021 eruption crises.

2 Background

2.1 Goma and the flank eruptions of Nyiragongo volcano since the 1970s

The city of Goma (DRC), capital of the province of Nord-Kivu and approximately one million inhabitants [de Goma 2020], is built in the lava field of the Nyiragongo volcano (DRC). It is a significant economic hub for the region, with the convergence of several commercial routes. Goma is also a place of refuge for the population from the rural surroundings, which are themselves not secure due to the presence of many rebel groups. Within the city administrative boundaries, the population distribution, which reflects its exposure to volcanic risk, is characterized by very high density in the eastern part, decreasing towards the west and the north [Michellier et al. 2020]. However, its strong attractiveness is bounded to the east by the national border with Rwanda, to the west by the Virunga national park, to the south by Lake Kivu, and to the north by Nyiragongo territory, towards which it is expanding recently (Figure 1A–1C).

During the last three flank eruptions of the Nyiragongo volcano, lava flows spread to the outskirts of Goma in 1977 and 2021, and into the city in 2002. Due to limited disaster risk reduction measures, impact on critical resources and economic consequences of these volcanic eruptions have been significant and felt over the long term in this densely populated region.

On January 10, 1977, north-south fissures opened simultaneously to the northwest and south of the main crater of Nyiragongo volcano and emitted a volume of lava of approximately 2×10^7 m^3 for about an hour [Pottier 1978; Durieux 2003]. Government sources reported that 554 people lost their homes, 6.6 km^2 of fields were destroyed by lava flows, and 193 cattle and 1,584 goats were killed (North Kivu Sub-Regional Office Report, cited by Katamba [1978]). Following this crisis, DRC authorities attempted to relocate the population affected by the Nyiragongo volcano from the path of the lava to Katoyi locality (located approximately 80 km west of the city of Goma). Unfortunately, due to the lack of essential infrastructure in Katoyi locality, including sufficient housing, health facilities, and roads, evacuees returned to Goma within a few months of the 1977 eruption.

On January 17, 2002, a set of fissures from the 1977 eruption reopened at about 8:35 a.m. (local time = GMT+2), and spread as far as the center of Goma city, emitting about 2.5×10^7 m^3 of lava in complex flows [Komorowski et al. 2002; Kavotha et al. 2003]. During this eruption, no official evacuation orders were issued. Approximately 400,000 people fled and took refuge mainly in Rwanda (Pole Institute 2004). Lava flows destroyed the houses of about 120,000 people, a third of Goma's airport, the city's commercial center, numerous public service infrastructures (45 schools, 3 hospitals, 27 clinics), and the power supply of about 21 % of the official customers of the Congolese national electricity company [Komorowski et al. 2002]. Altogether, 10 % of the urban area was destroyed [Syavulisembo et al. 2017]. According to official figures, about 40 people died directly from lava flows, and 30 to 60 people were victims of indirect causes, such as the explosion of a fuel depot on January 21, 2002 [Baxter et al. 2002; Komorowski et al. 2002]. Several testimonies reported that those who fled to Rwanda found no food nor water, and spent the night out of the country [Institute 2004]. Two days after the lava flows crossed the city, the displaced population decided, on its own, to return to Goma [Komorowski et al. 2002; ISIG-Goma 2003], despite the risks and the advice of the authorities to wait at least 10 days before returning [Kayser 2002]. As a result, following the volcanic crisis of January 17, 2002, the population of Goma mainly used the remaining critical resources located within the city [Institute 2004; Syavulisembo 2019].

About 20 years later, on May 22, 2021—while the COVID-19 pandemic was restricting the movement of the population and the province of North Kivu was under military authority due to unrest generated by armed rebel groups— Nyiragongo volcano erupted again, in the early evening [GVP 2021; UNICEF 2021b; OCHA 2021a; Musubaho 2022; Nyandu Kubuya-Shamavu 2022; Smittarello et al. 2022]. For about six hours, it drained a volume of lava in the order of 1–1.5×10^7 m^3 on its southern flank towards Goma [Smittarello et al. 2022]. This eruption was a surprise. The confusion and

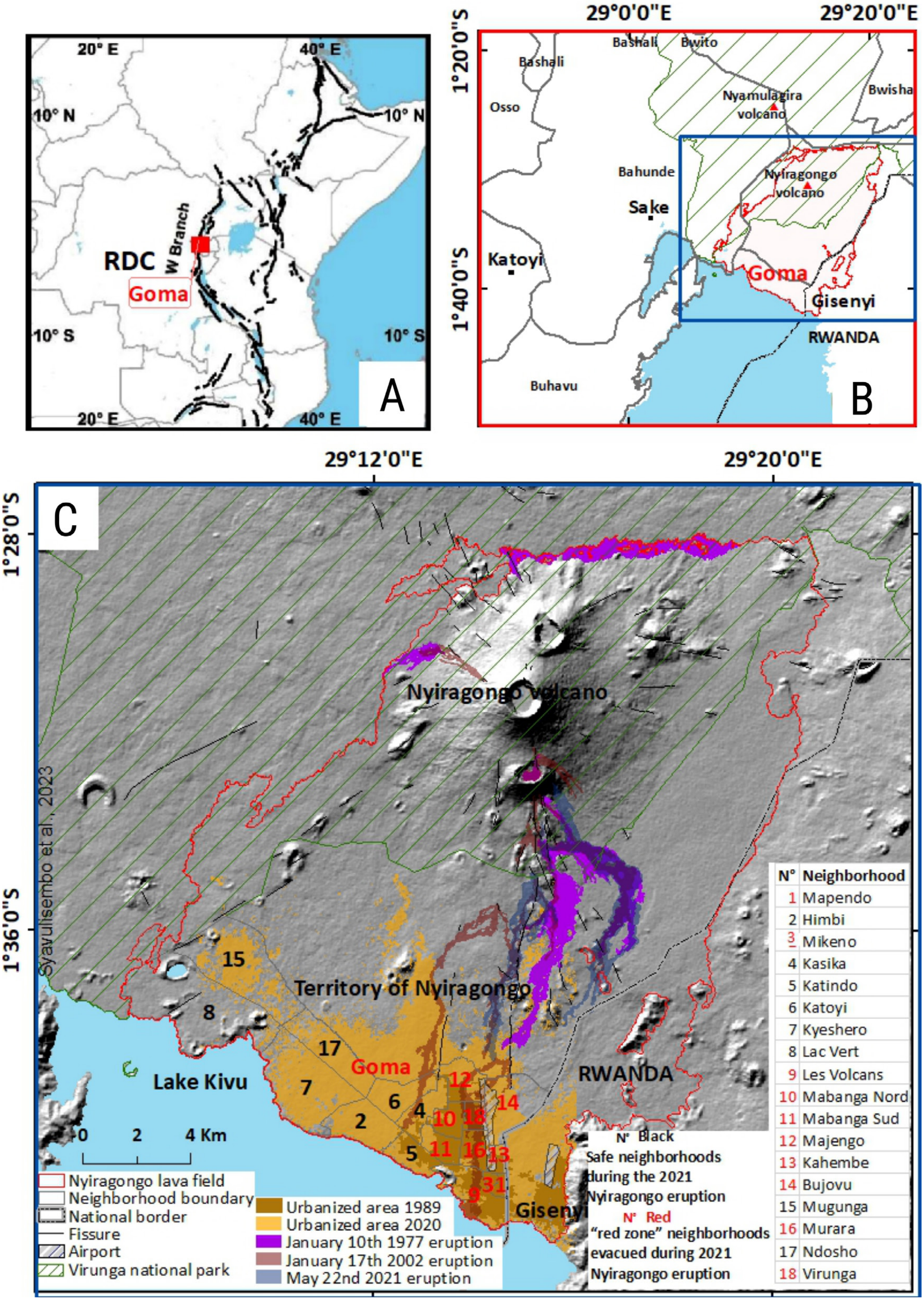

Figure 1: Overview of flank eruptions of Nyiragongo volcano since the 1970s: [A] the East African Rift System, [B] the Katoyi locality and lava field of the Nyiragongo volcano, and [C] Goma city and its surroundings, characterized by a strong urban expansion (source of GIS urban expansion layers: Mboga [2021]) including in the area affected by the three past eruptions of Nyiragongo volcano (source of GIS lava flow layers: Syavulisembo et al. [2015], GeoRiskA MRAC [2016], Michellier et al. [2020], and Smittarello et al. [2022]).

lack of precursory activity and warning signs greatly complicated the first few hours of eruption response and crisis management. Residents of the Nyiragongo territory (i.e. the administrative unit located north of Goma city; Figure 1) who witnessed the eruption onset raised an informal alert via word of mouth and social media. Panic-stricken and without any official instructions for several hours, a large proportion of the population spontaneously evacuated, mainly towards the western town of Sake, and towards Rwanda [OCHA 2021a; Syavulisembo et al. 2022]. A peri-urban area and several villages located north of the city of Goma were devastated. Although the economic impacts of this eruption were limited, the lava flows decimated more than 3,500 houses, 9 schools, 4 health centers, 10 km of road and about half a million people were deprived of access to drinking water [Smittarello et al. 2022; Syavulisembo et al. 2022]. According to OCHA [2021b], 31 people died in incidents related to the eruption. After six hours, lava stopped erupting and intense seismicity began. The seismicity was caused by dike propagation underneath the city of Goma towards Lake Kivu About 20 years later, while the COVID-19 pandemic was restricting the movement of the population and the province of North Kivu was under military authority due to a lack of security generated by armed rebel groups, on May 22, 2021, in the early evening, the Nyiragongo volcano erupted again [GVP 2021; UNICEF 2021b; OCHA 2021a; Musubaho 2022; Nyandu Kubuya-Shamavu 2022; Smittarello et al. 2022]. For about six hours, it drained a volume of lava in the order of 1–1 × 10^7 m^3 on its southern flank towards Goma [Smittarello et al. 2022]. This eruption was a surprise. The confusion and lack of precursory activity and warning signs greatly complicated the first few hours of eruption response and crisis management. Residents of the Nyiragongo territory (i.e. the administrative unit located north of Goma city; Figure 1) who witnessed the eruption onset raised an informal alert via word of mouth and social media. Panic-stricken and without any official instructions for several hours, a large proportion of the population spontaneously evacuated, mainly towards the western town of Sake, and towards Rwanda [OCHA 2021a; Syavulisembo et al. 2022]. A peri-urban area and several villages located north of the city of Goma were devastated. Although the economic impacts of this eruption were limited, the lava flows decimated more than 3,500 houses, 9 schools, 4 health centers, 10 km of road and about half a million people were deprived of access to drinking water [Smittarello et al. 2022; Syavulisembo et al. 2022]. According to [Smittarello et al. 2022]. As a result of this persistent seismic activity, the military governor ordered the evacuation of the population of the 10 'red zone' districts, in the east of the city on May 27, 2021. More than 232,000 people were forced to move to shelters, where they stayed for several days in schools, in churches, or in host families [UNICEF 2021c; OCHA 2021a; b].

2.2 Availability and accessibility of critical resources in disaster risk management

Several different frameworks have been published to identify critical resources in the event of a crisis. They consider that the importance given to a resource is not constant during the three crisis management periods that urban functioning can experience: the normal period, the period of crisis linked to the occurrence of a hazard, and the period of recovery following a disaster [Lutoff et al. 1998a; Demoraes and d'Ercole 2009; Leone et al. 2013].

Lutoff et al. [1998a] were interested in studying vulnerability to several natural hazards (earthquake, flood, storm, tsunami, land movement) in Nice (France). According to them, a city can be characterized by seven types of resources and the relative importance of each of them can be assessed using seven indicators: 1) market price, 2) human lives, 3) economic importance, 4) identity or external influence, 5) functional usefulness in normal period, 6) functional usefulness in crisis period and finally, 7) functional usefulness in recovery period. On the one hand, some resources, such as economic, political, cultural and functional ones, are predominant in the normal functioning of the city, but they take a secondary role in a crisis situation, during which they are no longer used by the population. On the other hand, as soon as the crisis breaks out, the demand for critical resources is suddenly very high.

In Quito (Ecuador), D'Ercole and Metzger [2009] have prioritized the areas in which mitigation measures for several hazards (earthquakes, volcanic hazards, flooding, landslides, and torrential flooding) would be most effective. They considered sixteen resources being critical for the normal period. Some of them (e.g. education, recreation, heritage, culture, business, and land value) are not considered during the crisis period and are therefore considered less critical in the short term. Moreover, to understand the situation in some areas of Quito exposed to natural hazards (earthquake, volcanic eruption, flooding and landslides), Demoraes [2004] and Demoraes and d'Ercole [2009] selected only four critical resources, namely water, food, medical capacity, and the possibility of taking care of the victims (number of ambulances, number of shelters). In contrast to Lutoff et al. [1998a] and D'Ercole and Metzger [2009] who identified resources in the face of different hazards during the three periods (normal, crisis, and recovery), they focused on the issue of reduced accessibility to few resources types, during the crisis period.

Leone et al. [2013], who studied population mobility in a tsunami-threatened area, quantified the different forms of accessibility in Mayotte (France) for six groups of resources, specifically water, energy, administration and school, security and healthcare, commercial and agro-industrial infrastructures, and long distance transportation (port and airport). The forms of territorial accessibility are modeled using graphs in a Geographic Information System (GIS) environment. The maps and indicators created provide local authorities with strategic information for enhancing official emergency plans, including road network obstructions, number of people to be evacuated, estimated evacuation times, suggested locations for safe zones, and the amounts and types of resources available for residents following a tsunami.

Demoraes [2004], Demoraes and d'Ercole [2009], and D'Ercole and Metzger [2009] all focus on non-tsunami hazards, and subsequently these studies focus on different types of critical resources compared with those that are of relevance herein. In addition, Comparing these approaches, we can highlight that Lutoff et al. [1998a] emphasize that some resources vary from one city to another, depending on their specific characteristics, and that it is important to validate the list of critical resources with stakeholders who have in-depth knowledge of their city. For example, based on the specific context of their respective study, Leone et al. [2013] give importance to school and agro-industrial resources during the crisis period, while these are discredited (zero weight) by Lutoff et al. [1998a] and D'Ercole and Metzger [2009]. To summarize, the selection of critical resources depends on the hazard type (e.g. some critical resources appropriate for a flood crisis may not be appropriate for a volcanic crisis), the purpose of the study, the crisis management period (normal, crisis, recovery) to analyze, and the study area [Lutoff et al. 1998a].

Studies that focus on the location of resources in Sub-Saharan Africa [Vennetier 1989; Diop 2007; Issaka 2007; Cappelle 2008; Michellier et al. 2020] stress that the majority of resources (e.g. schools, hospitals, markets, factories and skilled personnel) are located in urban areas, while rural and peri-urban areas remain under-equipped. Diop [2007] noted that all of Senegal's large health facilities are in urban areas and, even within the city of Dakar, the main urban functions are in the central district of *Le Plateau* only. Thus, if a natural hazard were to destroy or isolate the area where critical resources are concentrated, risk management in the rest of the city, or even the rest of the country, could become problematic.

2.3 Road networks in sub-Saharan Africa with a focus on the city of Goma

Mobility in Sub-Saharan African cities generally takes place in a challenging context characterized by unsatisfactory, poorly maintained, and poorly distributed traffic lanes, insufficient and poorly organized public transport, and traffic jams on certain roads during rush hours [Vennetier 1989; Plat 2003; SITRASS 2004; Diaz Olvera et al. 2007; Diop 2007; Kumar and Barrett 2008].

Mondzech and Sester [2011], Neis et al. [2013], and Syavulisembo [2019] all assess travel velocities according to road classification. As a consequence, some roads are mistakenly classified as passable, and restrictions are rarely incorporated. As a result, it is difficult to measure the spatial and temporal mobility of the population in the region in the absence of such data. To assess the territorial accessibility, a digital map of a road network cataloging elements such as road sections, junctions, and traffic flow direction is often used; element attributes can include travel time and time-varying road restrictions [Sevtsuk and Mekonnen 2012]. In Sub-Saharan African countries, and particularly in DRC, data on road network elements and measurements of variations in population mobility speeds are still scarce, or of questionable quality. Indeed, OpenStreetMap [OSM, OpenStreetMap 2017] is the main source of road network data. Unfortunately, OSM, which is mainly based on visual interpretation of satellite imagery to create road network data, has limited reliable information concerning road practicability and travel velocity or time.

The city of Goma faces all the road network use and characterization challenges described in the previous two paragraphs. In addition, the road network of Goma is exposed to lava flows. Lava flows from the three flank eruptions of Nyiragongo volcano destroyed roads, which were then always rebuilt in the same locations because of their crucial role in the urban and regional road networks.

Like many cities in sub-Saharan Africa [Vennetier 1990], Goma has developed since independence with less and less planning and implementation of plans by the public authorities. With population growth inducing a strong spatial expansion of the city, some unplanned constructions are narrowing or even obstructing certain roads listed as operational routes by the *Office des Voiries et Drainage*, the DRC public company that manages the urban road network [OVD 2016]. Several times, city authorities have initiated road "reopening" operations, but rarely successfully, as the population refused to move. Politicians, urban planners, regional entrepreneurs, development experts, and residents have different and often contradictory visions of their city [Förster and Ammann 2018]. The authorities did not take action early enough to control land use and urban development [Vennetier 1990]. Our study contributes to determining the location and access to critical resources for managing a volcanic crisis in such a data-poor context.

3 Methodology

Our study focuses on the potential impact of a 2002-like eruption, which was the most devastating flank eruption of Nyiragongo volcano since the 1970s. During the crises of the January 17, 2002, and May 22, 2021, volcanic eruptions, the first author stayed in the city of Goma and his empirical knowledge of the terrain allowed him to identify the critical resources which remained accessible and their use during the crisis. This is one of the strengths of our study and we believe that it is essential for the transferability of the methods used.

Below, we present the methodology implemented regarding the identification and mapping of the critical resources, their accessibility based on the road and paths network, and the approach used to assess the population spatio-temporal mobility, in such a context of data scarcity.

3.1 Critical resources identification and mapping

Based on referenced studies on crisis management following natural hazards [Lutoff et al. 1998a; Demoraes 2004; D'Ercole and Metzger 2009; Demoraes and d'Ercole 2009; Leone et al. 2013; Yu and Welch 2022; Alegría and Vergara-Pinto 2024], we compiled a list of critical resources that could be used during a volcanic crisis. This list was validated and contextualized by eighteen semi-structured face-to-face interviews (Table 1) with individuals who managed resources during the crises caused by the 1977, 2002, and 2021 eruptions. Among the interviewees, two participants had experienced the three eruptions. They recommended other stakeholders to be interviewed (snowball method), identified by their role, their knowledge of Goma, and their experience in recent volcanic crises. These interviews led to the selection of five critical resource types during a future Nyiragongo eruption crisis. Critical resources were located respectively in 539 places for shelter, 360 places for food, 18 places for water, 58 places for healthcare, and 62 places for energy.

Aside from the interviewers used to measure population mobility in Goma, seventeen interviews (Table 1) were conducted with persons who have managed resources during historical crises. For all the research steps detailed below, ethical approval was granted by the North Kivu provincial disaster prevention council. Moreover, prior to the interviews and population mobility measurement campaign, the first author reminded participants that their contribution was voluntary, that no data likely to identify them would be used, and that the interview and data collection were aimed at improving volcanic crisis management. All participants gave their consent.

To geolocate and collect descriptive information on the available critical resources, the first author conducted a twenty-day field campaign (June 5-30, 2017), with the help of six interviewers, all of whom were students or graduates of Goma universities. He trained them for two days in the use of a hand-held GPS (GARMIN GPS portable eTrex 32x), the list of critical resources, and an eight-columns survey form including the identifier of the GPS point, the name of the establishment, the type of resource, the subcategory of resource, the capacity or quantity of critical resources, the management (public, private, religious), the number of staff and some observations.

Schools and places of worship were identified as potential **shelters**. Regarding schools, only those run by religious organisations were considered, because those were the only ones to open their doors during the previous eruptions. We considered all classrooms to have the same capacity. According to the report of IPEPSP Nord Kivu (*Inspection Provinciale de l'Enseignement Primaire, Secondaire et Professionnel du Nord Kivu*), the number of students in a classroom is limited to fifty students or fewer (IPEPSP Nord Kivu 2016). The capacity of the schools was assessed based on the number of classrooms (C_{school}). It was estimated that if a classroom is normally occupied by 15 benches; each displaced person should have a space equivalent to that occupied by one bench to be able to sleep during the emergency stage of the crisis. In other words, the capacity of a school was estimated according to the equation $Cap_{school} = 15 \times C_{school}$. The same evaluation was made for the places of worship according to the seating capacity (C_{church}). The number of places of worship and its number of seats were counted or provided during the campaign. We considered that the space occupied by 50 seats would be the space equivalent of a classroom space, i.e. a room for displaced persons. The capacity of a church was then estimated according to the equation $Cap_{church} = 15 \times C_{church}/50$. We finally determined the city's total shelter capacity as follow: $Cap_{displaced\ persons} = Cap_{school} + Cap_{church}$. In addition, the population unable to find shelter inside the city were evacuated to camps located beyond its administrative boundaries (interviews 4, 5, and 6). The contingency plan provides evacuation routes in the event of an eruption of the Nyiragongo volcano (Protection civile du Nord-Kivu 2015). Further in this paper, we will assess the minimum travel time from each district to its closest exit point from Goma.

The second step was to assess the **quantity of food available** in Goma. In Goma the food is stocked and sold from food depots. Each depot may host agricultural produce collected by several traders, who obtain their supplies from surrounding villages and sell agricultural products at the depot independently. As for food shop traders, they mainly buy their supplies from neighboring countries, such as Rwanda and Uganda. To estimate the total stock of food available in Goma, we assumed that the number of traders in the depots and the one of the food shops would be proportional to a certain quantity of food. We determined how long this stock would feed the population on the assumption that a person consumes an average quantity of 0.5 kg of food per day (dry weight). This assumption was based on an interview with a resident of the Virunga district having a family of seven persons (interview 1). He told us that with a stock of 50 kg of corn flour, 25 kg of beans, 10 kg of rice, 10 kg of fish, and 10 kg of vegetables and condiments, he manages to feed his family for a month; this corresponds to an average daily consumption of about 0.5 kg per person (dry weight).

In terms of **water supply**, the lake Kivu is the only guaranteed resource in the event of a volcanic crisis in Goma. Indeed, the water supply network could be destroyed by the lava flow; water pumping stations, which depends on electricity for their functioning, could be cut off due, for instance, to damage to the power network, which also remains vulnerable to lava flows. Moreover, when a volcano erupts, the use of rainwater is not recommended, as it can contain chemical pollutant [Nyandu Kubuya-Shamavu 2022]. Although the lake's water is unsafe for consumption and its untreated use can lead to disease outbreaks, we believe that collecting water (consumed after boiling or with chlorine tablets) should be the most viable and sustainable solution.

With regard to **healthcare facilities**, our assumption is that they will be used during a future volcanic eruptions in the same way as during previous events, i.e. only public health centers and those managed by the religious will treat and host victims of the eruption and people who would need any kind of healthcare (interviews 2 and 3). We estimated the the capacity of these healthcare facilities based on the number of hospital beds.

As for **energy sources** (which we consider for cooking only), we assume that the main source would be charcoal. Shelters (schools or places of worship) do not have the equipment, and sometimes not even the power supply for displaced persons to cook; and these shelters could also be disconnected from the electricity network by the lava flow. According to Lejeune et al. [2013], Goma consumes over 105,000 tons of charcoal each year, or 286 tons per day. We considered that the amount of charcoal available in each depot is proportional to the number of staff. Therefore, we assumed that each of the 215 charcoal traders identified during the campaign to locate critical resources in Goma supplies the population with about 1.4 tons per day. While the 215 traders may not be solely charcoal suppliers, our assumption is that their location is representative of Goma. Furthermore, despite the high

Table 1: List of interviewees with their specifications.

Interview	Person specifications
Interview 1	A resident (2001–present) of the Virunga district, March 16, 2017
Interview 2	An official (1998–present) in a general hospital destroyed in 2002 by the lava flow from the Nyiragongo volcano, March 6, 2018
Interview 3	An official (2000–present) in a hospital destroyed in 2002 by the lava flow from the Nyiragongo volcano, September 1, 2022
Interview 4	An official (1990–present) in a primary school in Goma, March 7, 2018
Interview 5	A pensioner living in Goma who has worked as an official (1974–2010) in a secondary school in Goma, March 7, 2018
Interview 6	An official (2001–present) in a primary and secondary school coordination in Goma, March 7, 2018, and April 14, 2022
Interview 7	A displaced person of the 2002 and 2021 Nyiragongo volcano eruptions, March 18, 2022
Interview 8	An official (1975–present) in Goma city public administration, March 7, 2018, and September 5, 2022
Interview 9	A pastor (1995–present) of a Protestant church in Goma, March 8, 2018
Interview 10	An official (1992–present) of humanitarian affairs in North Kivu based in Goma, July 26, 2022
Interview 11	An official (1999–present) in a hospital destroyed in 2002 by the lava flow from the Nyiragongo volcano, September 1, 2022
Interview 12	An official (1996–present) in a food depot in the Kahembe district
Interview 13	a trader (2000–present) in Virunga market (located in Murara district), March 9, 2018
Interview 14	An international official of humanitarian affairs based in Goma during the eruption of the Nyiragongo volcano in 2021, May 30, 2021
Interview 15	An official (2018–present) in an electricity supply company in Goma, June 30, 2021
Interview 16	A co-founder of a new electricity supply company in Goma, February 5, 2020
Interview 17	A pensioner woman living in Goma who worked as a nurse's aide (1978–2007)
Interview 18	A resident (1994–present) of Majengo district, September 5, 2022

number of generators used by the population of Goma, fuel stations will not be considered as energy resources, as they may generate an additional risk of fire and explosion during the volcanic crisis.

3.2 Characterizing accessibility on the road and path network of Goma

When we undertook this work in 2017, the only publicly available geospatial database of the road network was Open Street Map (OSM), which was incomplete and inaccurate (Figure 3A), as in many regions of the world [Mondzech and Sester 2011; Neis et al. 2013]. We therefore combined the data available on OpenStreetMap (OSM) with field surveys and satellite imagery interpretation to update and complete the road network and its physical characteristics.

The downloaded OSM road data does not distinguish between the ones for vehicles from the others for pedestrians only, which is a key factor in terms of travel speed. To update and complete the road network, participatory mapping sessions were organized. These sessions were based on the visual interpretation of a Pleiades image with 50 cm spatial resolution (Figure 2A and 2B).

For an area of 73 km^2 subdivided into 18 districts and 10 villages, the first author organized eighteen participatory mapping sessions in the district offices. Participants from the villages joined those from neighboring districts. Before scheduling the participatory mapping sessions, we visited each district office to explain to the district heads and their staff the importance of the activity, the criteria for effective participation and to make an appointment with the participants. There were around ten participants per district/village, and each session took more or less four hours. We prepared a working map for each district/village featured the 50 cm spatial resolution Pleiades multispectral image (September/October 2014), with administrative boundaries. Each participant then took it in turns to draw on the map, according to a unique legend (red for asphalted roads, blue for paved roads, black for road passable by vehicle but not asphalted and not paved, and green for foot path), the roads they knew. At the end of the participatory mapping session, each head of the district/village and their team was thanked with a copy of the map of their administrative area.

3.3 Quantifying vehicle and pedestrian mobility in Goma

Given the lack of reliable mobility data, we organized the collection of empirical data to derive realistic average vehicular and pedestrian speeds for all road segments. To this end, we recruited 10 public transportation bus drivers and 10 pedestrians to carry the *USB GPS GT-730* unit with them from 6 a.m. to 8 p.m. These units recorded the location and speed at five second intervals. This field campaign ran from February until August 2017. With 10 GPS units available, we first assigned them to bus drivers from February to mid-August, and then reassigned them to pedestrians.

To select the bus drivers, the first author met with the head of a drivers' association in Goma to explain the objectives of the measurement campaign, and to reassure him that the data would be used with the strictest respect for privacy. This per-

Figure 2: Participatory mapping sessions (© A.M. Syavulisembo, 2017)

son then invited volunteer drivers to meet the first author for further explanations and to carry out the measurement campaign throughout the city of Goma and surrounding villages. As for pedestrian mobility, the first author chose from among his acquaintances volunteers who live in the outlying districts of the city of Goma and who make their daily journeys to services in the city center on foot.

The data were anonymized and stored electronically. This campaign provided approximately 1.3 million speed measurements for buses, and 11,600 for pedestrians.

When checking the vehicle data, we noticed that a bus driver could have left the vehicle without switching off the GPS, which continued to record information. To clean up the database, we created a sixteen-meter buffer, corresponding to the sum of the average road width in Goma plus the GPS location error. We then excluded measurements outside these buffers and kept around 900,000 speed measurements for buses.

The direction of the vehicle movement was derived from the GPS identifiers incrementally attributed according to the time and the geographic locations of the measurement. In other words, measurements with identifiers 1, 2, 3, 4, etc., were taken chronologically, with measurement 1 was taken before 2, and 2 before 3, and so on. Next, we compared the geographic locations of measurements n (the waypoint number for a trip) and $n + 1$ to calculate the angle of movement direction. The angles range from 0 to 360°, but in practice, two groups of directions (forward and backward) were identified for each road section. We separated them into two files. A few measurements, generally corresponding to the records during direction change maneuvers, were removed from the data file to be processed.

For pedestrian mobility, we first excluded zero speeds and movements off roads, paths, and sidewalks, since it was possible for the person carrying the GPS to stop or leave the road for various reasons without switching off the GPS. The pedestrian mobility analysis refers to 11,600 speed measurement points (Table 2). We considered pedestrian mobility speed to be defined by the medians calculated by each road type.

Finally, to be used in the modeling software, the 465 km-long road network was divided into 7,753 interconnected sections, to facilitate links between sections and routes. Divisions were based on the location of intersections. Vehicle and pedestrian mobility on a road section was defined by the average speeds calculated according to the direction of movement.

We used `ArcGIS Network Analyst` [Sevtsuk and Mekonnen 2012; Lacroix 2013; Lamine and Mahdi 2015] to analyze the spatio-temporal variations of speeds in Goma. These speeds characterize the mobility of the population between various places. This approach allows determining the fastest routes to a location and identify less accessible areas, therefore allowing for more efficient implementation of activities and better decision making [Sevtsuk and Mekonnen 2012]. We used the `ArcMap` GIS route calculator to assess the population's accessibility to critical resources. This calculator is based on the Dijkstra algorithm, which is based on graph theory [Sevtsuk and Mekonnen 2012].

4 Results

4.1 Use of critical resources during previous eruptions of Nyiragongo volcano

We identified five types of critical resources that could be used during a future crisis due to the Nyiragongo volcano eruption (Table 3).

4.1.1 *Shelters*

In 2002, a large number of the schools and places of worship that were not inundated by lava flows were used as shelters or as distribution centers for humanitarian aid to the victims, until classes resumed about a month after the eruption (interviews 4, interviews 5, interviews 6). After the 2021 eruption, it took between three weeks and five months, depending on the district, for the school to restart (interviews 4, 5, and 6). However, following both eruptions, the public schools did not make their buildings available as shelters, because they feared their property would be damaged; moreover, the victims did not voluntarily move into these schools, because they feared that they would not be supported by humanitarian aid (in-

Table 2: Number of speed measurement points for pedestrians and description of roads.

Description of roads OSM characterized by local administrative officials in Goma	Number of speed measurement points
Roads in the opposite direction to the slope	55
Flat roads	223
Roads in the direction of the slope	301
Unpaved, flat roads	2704
Unpaved, uphill roads	709
Unpaved, downhill roads	3008
Paved, flat roads	3215
Paved, uphill roads	567
Paved, downhill roads	801

Table 3: Critical resources for managing a volcanic crisis in Goma.

Resource	Criteria of validity	Number of locations	Inventory
Shelter	Places of worship for Catholics, Protestants, Muslims, Kimbanguists and Jehovah's Witnesses, as well as primary and secondary schools run by these religious groups.	539	Total capacity of accommodation: 64,000 places.
Healthcare facilities	Public health centres and those managed by the religious.	58	Hospitalization capacity: 2589 beds
Food	Sale and food storage points.	360	2300 tons of food that could feed the population of Goma for five days.
Water	Water chlorination points installed on the northern shore of Lake Kivu.	19	19 water chlorination points.
Energy	Charcoal sale and storage points.	62	1434 tons of charcoal.

terviews 4, 5, 6, 7, and 8). Indeed, along with local NGOs, religious people (with the exception of the revival churches) were the first to organize the distribution of humanitarian aid [Kayser 2002]. According to those who managed critical resources during the crises that followed the 2002 and 2021 volcanic eruptions, the population feels that they belong to the churches and to church-run schools, and during difficult times they do not hesitate to turn to them. The population is convinced that taking refuge in a place of worship or in a church-run school increases their chances of benefiting from humanitarian assistance (interviews 9 and 10).

4.1.2 *Healthcare facilities*

Healthcare facilities are essential to manage the impacts of a volcanic crisis, as people can get burned or injured, particularly in areas inundated by lava flows. Further, those in hospital prior to the eruption need to continue receiving medical care. In 2002, the lava flow destroyed 80 % of private pharmacies, one hospital, and three health centers [Baxter and Ancia 2002; Médecins du Monde 2002]. In 2021, it devastated four health centers. Following both eruptions, healthcare was provided free of charge for all patients, whatever their pathology [Baxter and Ancia 2002; OCHA 2021a]. It led to a massive increase in attendance at health centers (interviews 2 and 3). In 2002, medical staff were encouraged to continue working, in exchange of food rations ('food for work'; interviews 2 and 11). In 2021, with the mass evacuation of the population from the ten 'red zone' districts, health facilities in the west of the city received hundreds of additional patients, affecting their ability to provide effective medical care. These facilities received support from the International Committee of the Red Cross (ICRC) to maintain the supply of electricity, water and medicines (interview 10). Until August 31, 2022, patients were treated free of charge in health centers located around the area invaded by lava flows (interview 3).

4.1.3 *Food*

Although Goma is supposed to be a food basket for the region, it faces chronically low food stocks, because agricultural areas are insecure and many farmers no longer have access to their fields because of the insecurity. Therefore, supplying the population during a volcanic crisis could be difficult without rapid external support. According to a manager of a food depot and a trader in a market, the 2002 eruption destroyed food stored in the lava flow area, but food stored outside this area was consumed in Goma (interview 12, interview 13). On January 17, 2002, outside the lava flow area, the World Food Program (WFP) had a stockpile of 1000 tons of food [Baxter and Ancia 2002; Kayser 2002]. However, the population had to wait until January 23 (five days after the eruption) for the first distributions to take place, as the WFP feared that this would draw even more people into the area at risk [Kayser 2002]. In the meantime, local and international NGOs, as well as churches had created a 'Nyiragongo 2002 crisis committee' to begin distributing food found in Goma stores [Kayser 2002]. It is worth mentioning that at that time, the presence of humanitarians and their food stocks in Goma was linked to other humanitarian situations (wars and epidemics) in the region [Kayser 2002], so that if these situations were fortunately to improve, they might no longer be around for the next eruption. In 2021, the sudden evacuation of the 'red zone' temporarily displaced approximately 400,000 people from their homes to the areas surrounding Goma [WFP 2021]. Although the lava flow stopped 500 m from the Goma airport, it had burned agricultural fields in Nyiragongo territory and blocked the main food supply road north of Goma. In addition, to avoid plane crashes, the Goma airport was closed for several days. Although food stocks in Goma were not directly affected by the lava flow, the airport closure and the road blockage north of Goma have affected food accessibility. To meet the needs of the thousands of displaced people to towns near Goma, the Congolese government and humanitarian aid agencies have distributed food and non-food items (interview 14).

4.1.4 *Water*

In 2002, the water distribution system was severely damaged by the lava flow and was almost unusable during the crisis. Besides, the city of Goma has only two natural water sources: Lake Kivu and rainwater. Chlorination points were then installed on the shore of Lake Kivu to meet the demand of the population who drew water directly from there. In addition, plastic tanks with a capacity of approximately 20 m^3 were installed in the city and supplied by tanker trucks from international and local NGOs [Baxter et al. 2002; UNICEF 2021a]. In 2021, the lava affected the water supply pipes of the city's main reservoir, which served about 500,000 people in the northern districts of Goma [UNICEF 2021a]. On June 30, 2021, the Virunga Foundation NGO, funded by the European Union, completed the rehabilitation of the destroyed water supply pipes, replacing 1,300 and 300 meters of 500-millimeter main and secondary pipelines respectively (interview 15). As the majority of REGIDESO's pipes are in an area at high risk of lava flows, it cannot be excluded that, in the event of a future eruption, the water distribution network could once again be severely damaged. Finally, imported bottled water could also be used, but at a cost that most of the Goma's population cannot afford.

4.1.5 *Energy*

In terms of energy resources, in the early 2010s, only 30 % of households in Goma were connected to the electricity grid of the national electricity company (SNEL), which until 2015 held a state monopoly in the electricity sector; despite the recurrent daily power cuts suffered by the customers [Muhindo Kambumbu 2010; Kakule Kisenge 2013]. Since 2020, because of the market liberalization in the supply of electrical energy in the DRC, the city of Goma is supplied by four companies (SNEL, Nuru, SOCODEE SA and the VIRUNGA ENERGIE). However, only 35 % of the estimated 80 megawatts required by the city of Goma are available (interview 16). Looking back at the impact of past eruptions, in 2002, lava flows damaged the power supply, depriving about 21 % of SNEL's customers. In May 2021, the power transmission infrastructure of SOCODEE SA and VIRUNGA ENERGIE were cut off by the lava flow, depriving more than ten thousand households, two water pumping stations and dozens of public lighting lines of electricity for ten days (interview 15). Consequently, during the two crisis periods that followed these events, the population relied primarily on charcoal for cooking.

4.2 Road characterization

Thanks to their knowledge, local administrative officials (district chiefs, heads of avenues, district development officer) were able to easily identify the traffic routes in their districts and characterize them (footpath, paved or unpaved road, mobility restrictions, flat road and sloping road). According to 2017 OSM data (Figure 3A), Goma's roads had at that time a total length of 745 km classified as passable roads (86 %), footpaths (9 %) and unclassified roads (5 %). Validation of these roads by local administrative officials brought the total length of roads to 664 km, of which 7 % are paved, 63 % are passable and unpaved, and 30 % are footpaths (Figure 3B and 3B). In addition, Goma's road network is characterized by a lower density of roads in the northern and western parts of the city. This is due to the more recent development in these districts, in contrast to the southeastern part of the city, which corresponds to the oldest districts (Figure 3B and 3B).

4.3 Accessibility of exits points and critical resources

All travel times to exit points and critical resources calculated here are based on road network conditions as they are during 'normal' times (i.e. without road obstructions, traffic intensification due to a disaster, or extraordinary fuel shortages) and following network use by locals who know the roads better than displaced people. The results should therefore be considered as minimum travel times. As the accessibility to the various exit points and critical resources was calculated along existing roads and paths, white areas on the maps below (Figure 4, Figure 5) are most probably very difficult to cross because they are inaccessible by car and so one must travel exclusively by foot.

To address potential crisis situations, the existing population evacuation plan identifies one 'departure point' in each district of the city, often district offices or district centers (Protection civile du Nord-Kivu 2015). Using these starting points and applying calculated travel times, we estimated pedestrian travel time on officially designated evacuation routes and also identified the fastest route and its travel time (Figure 4 and Table 4). Of the 20 routes identified in the current evacuation plan, seven are slower than the fastest paths identified from this study.

To reach one of the five land exit points of the city of Goma, the maximum computed travel time is about 160 minutes for pedestrians and 60 minutes for cars (Figure 5A, 5B). Nyiragongo territory, Kyeshero and Ndosho stand out as the most disadvantaged districts if an evacuation was necessary.

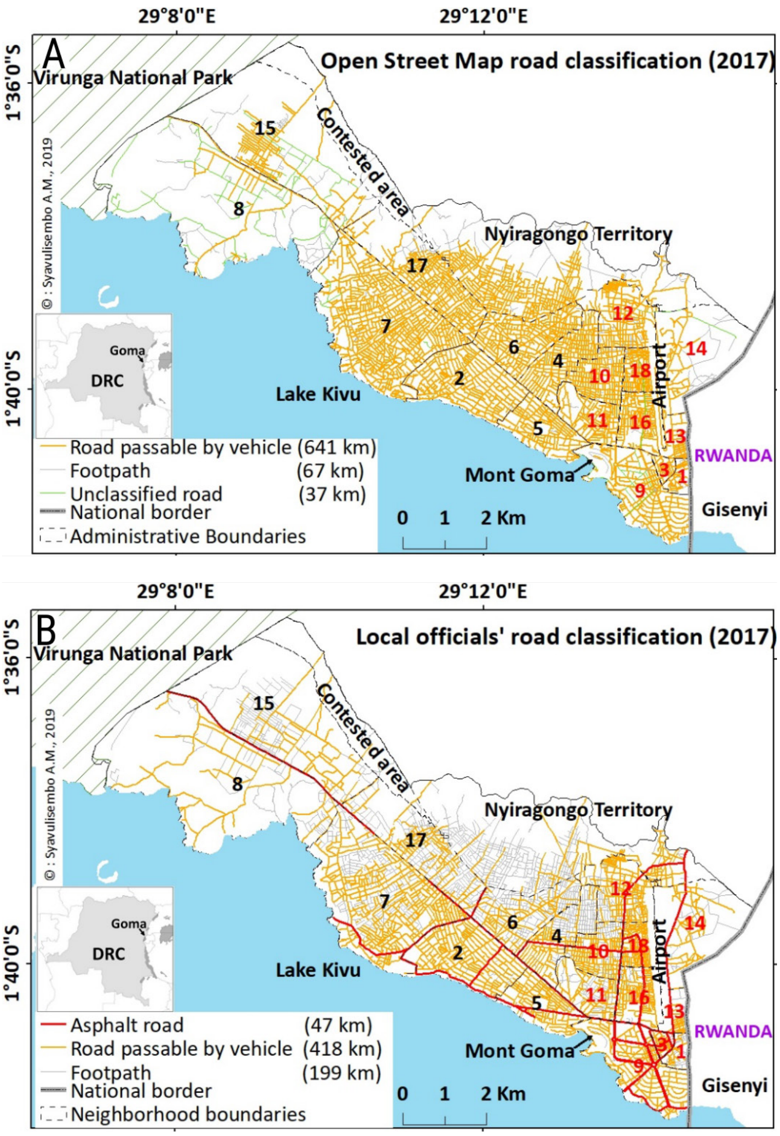

Figure 3: Goma's road network: [A] as characterized by OSM vs. [B] as characterized by local administrative officials.

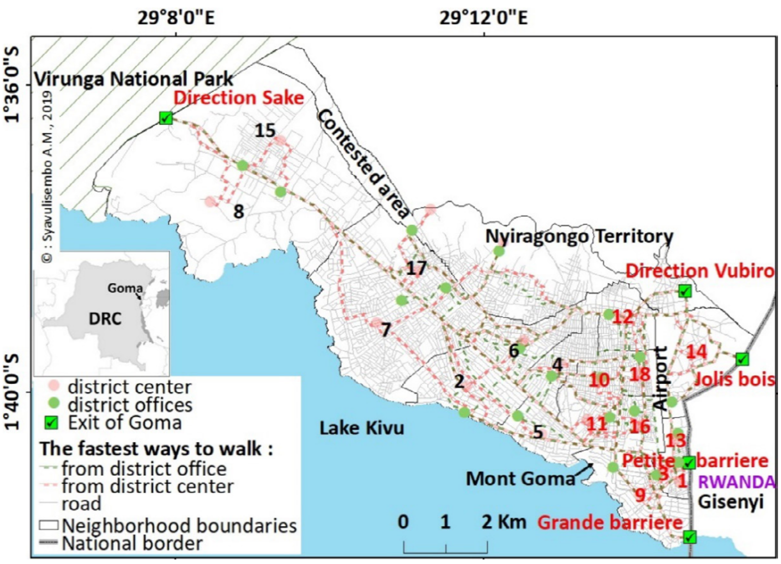

Figure 4: Fastest footpath from districts to city exit points.

Table 4: Minimum travel times (all in units of minutes) from district offices (A) / district center (centroid) (B) to city exits (the travel time for the itinerary indicated in the contingency plan is colored orange).

Districts	Direction Sake		Direction Vubiro		Grande Barrière		Jolis bois		Petite Barrière	
	A	B	A	B	A	B	A	B	A	B
Bujovu	251	258	43	29	61	85	51	33	28	52
Nyiragongo Territory (western part: Kiziba)	167	173	119	127	158	171	156	168	138	150
Nyiragongo Territory (eastern part: Muja)	132	144	158	163	179	190	196	204	159	170
Himbi	171	156	115	99	106	116	152	140	85	96
Kahembe	240	237	56	57	51	47	66	69	17	15
Kasika	180	184	73	67	93	97	110	108	73	76
Katindo	176	191	99	96	90	76	136	124	69	55
Katoyi	160	163	80	69	113	119	118	110	92	99
Kyeshero	116	130	134	135	148	160	171	176	128	139
Lac vert	53	59	192	219	206	244	229	260	186	224
Les volcans	214	227	79	88	42	28	99	100	32	29
Mabanga nord	197	196	54	56	81	81	92	97	59	60
Mabanga sud	210	203	65	81	63	73	102	121	43	52
Majengo	198	214	32	28	101	97	70	69	78	75
Mapendo	231	236	66	73	40	35	76	85	4	12
Mikeno	227	228	74	70	32	36	84	82	15	13
Mugunga	34	60	207	208	221	233	244	249	201	213
Murara	217	221	63	69	59	51	96	98	36	29
Ndosho	132	115	123	130	146	156	160	171	125	135
Virunga	215	213	40	49	77	70	72	86	54	48

Considering that, as during the 2002 eruption, a significant proportion of the population could take **refuge in schools and places of worship** in case of a new crisis, analysis of accessibility to these places of refuge shows that the maximum travel time is 60 minutes for pedestrians and 20 minutes for cars (Figure 5C and 5D). The districts with the least access to shelters are Lac Vert and Mugunga, as they have few shelters and few roads.

With regards to the population's accessibility to healthcare, the maximum travel time is 60 minutes for pedestrians and 30 minutes for cars (Figure 5E and 5F). Access times to healthcare are longer for inhabitants of Nyiragongo territory, Lac Vert, Mugunga and Bujovu than for the rest of the city's inhabitants.

In terms of accessibility to food depots, the maximum travel time is 120 minutes for pedestrians and 40 minutes for cars (Figure 6G and 6H). Access to the food depots takes more time from Nyiragongo territory, Lac Vert and Mugunga districts than from other parts of the city.

The shoreline of Lake Kivu (i.e. the main natural water source) is enclosed by hotels and fenced private plots. The population has only a few sites through which it can freely access the lake; only the latter were considered in the analysis. The maximum travel time to the lake is 120 minutes for pedestrians and 40 minutes for cars (Figure 6I and 6J). Nyiragongo territory, Mugunga, Ndosho, Majengo, and Bujovu districts show longer access times than the other Goma districts.

The population's access to charcoal depots requires a maximum travel time of 120 minutes for pedestrians and 40 minutes for cars (Figure 6K and 6L). Lac Vert, Mugunga, Kyeshero, Himbi districts and Nyiragongo territory have the longest access times to charcoal depots, due to the limited number of roads to access these places (Figure 3).

Table ?? summarizes the maximum travel time on foot and by vehicle for each district and for each type of critical resource and exit points. Disadvantaged districts are the ones generally located in peri-urban areas. Mobility on foot covers larger areas than mobility by vehicle. Districts located further west (Lac Vert and Mugunga) and north (Nyiragongo territory, Ndosho, Bujovu) have large inaccessible areas and longer maximum travel times than districts located in the east and center of the city. This reflects the city's development which is expanding more recently to the west and north with fewer critical resources.

5 Discussion

A rapid onset major crisis, such as a volcanic eruption, requires a rapid and effective response to not only allow for the evacuation of the population at the time of the event [Mei et al. 2013; Leone et al. 2018; Wild et al. 2021], but also to facilitate the response to their critical needs [Auker et al. 2013; Leone et al. 2014; Barclay et al. 2019]. In a context of data scarcity and at the scale of a city like Goma, the objective of this study was to analyze both (1) the evacuation routes accessible and usable by the threatened population, but also (2) the accessibility to critical resources during an eruption crisis of the Nyiragongo volcano. Both of these crucial pieces of infor-

Table 5: Access to critical resources in Goma districts (estimated travel time in minutes).

Districts	Area (km^2)			Maximum estimated travel time (minutes)											
	Total	Accessible by car	Accessible on foot	Shelter		Charcoal depots		Water at lake Kivu		Healthcare		Food depots		Exit points	
				by car	on foot	by car	on foot	by car	on foot	by car	on foot	by car	on foot	by car	on foot
Lac Vert	12.09	3.81	6.92	25	60	40	120	40	120	30	60	40	120	60	160
Kyeshero	7.80	6.85	7.32	25	60	40	120	40	120	30	60	40	120	60	160
Himbi	3.40	3.29	3.35	25	60	40	120	40	120	30	60	40	120	60	160
Katindo	1.83	1.59	1.70	25	60	40	120	40	120	30	60	40	120	60	160
Les Volcans	3.43	3.22	3.36	25	60	40	120	40	120	30	60	40	120	60	160
Mapendo	0.41	0.29	0.40	25	60	40	120	40	120	30	60	40	120	60	160
Mikeno	0.26	0.26	0.26	5	10	5	20	15	40	5	10	5	5	10	25
Mabanga Sud	1.45	1.45	1.45	5	10	10	15	20	55	10	15	5	15	25	80
Mabanga Nord	1.37	1.37	1.37	5	5	10	15	25	75	10	15	5	15	25	75
Murara	1.48	1.44	1.48	25	10	15	25	25	65	10	20	10	15	20	50
Virunga	0.89	0.86	0.89	25	10	15	20	30	80	15	25	5	10	20	60
Kasika	1.94	1.94	1.94	5	10	25	30	35	85	10	20	15	20	40	100
Majengo	2.17	2.15	2.17	25	15	25	35	40	105	25	35	20	25	40	65
Katoyi	2.52	2.20	2.52	25	10	40	35	40	95	30	25	40	20	60	115
Kahembe	0.66	0.46	0.66	25	60	40	120	40	120	30	60	40	120	60	160
Bujovu	4.13	2.19	3.17	25	60	40	120	40	120	30	60	40	120	60	160
Ndosho	4.36	2.15	3.57	25	60	40	120	40	120	30	60	40	120	60	160
Mugunga	11.22	2.84	5.79	25	60	40	120	40	120	30	60	40	120	60	160
Nyiragongo	10.05	1.82	6.31	25	60	40	120	40	120	30	60	40	120	60	160

By car: 0 | 5 10 15 20 25 30 35 40 45 50 55 60 minutes

By foot: 0 | 20 40 60 80 100 120 140 160 minutes

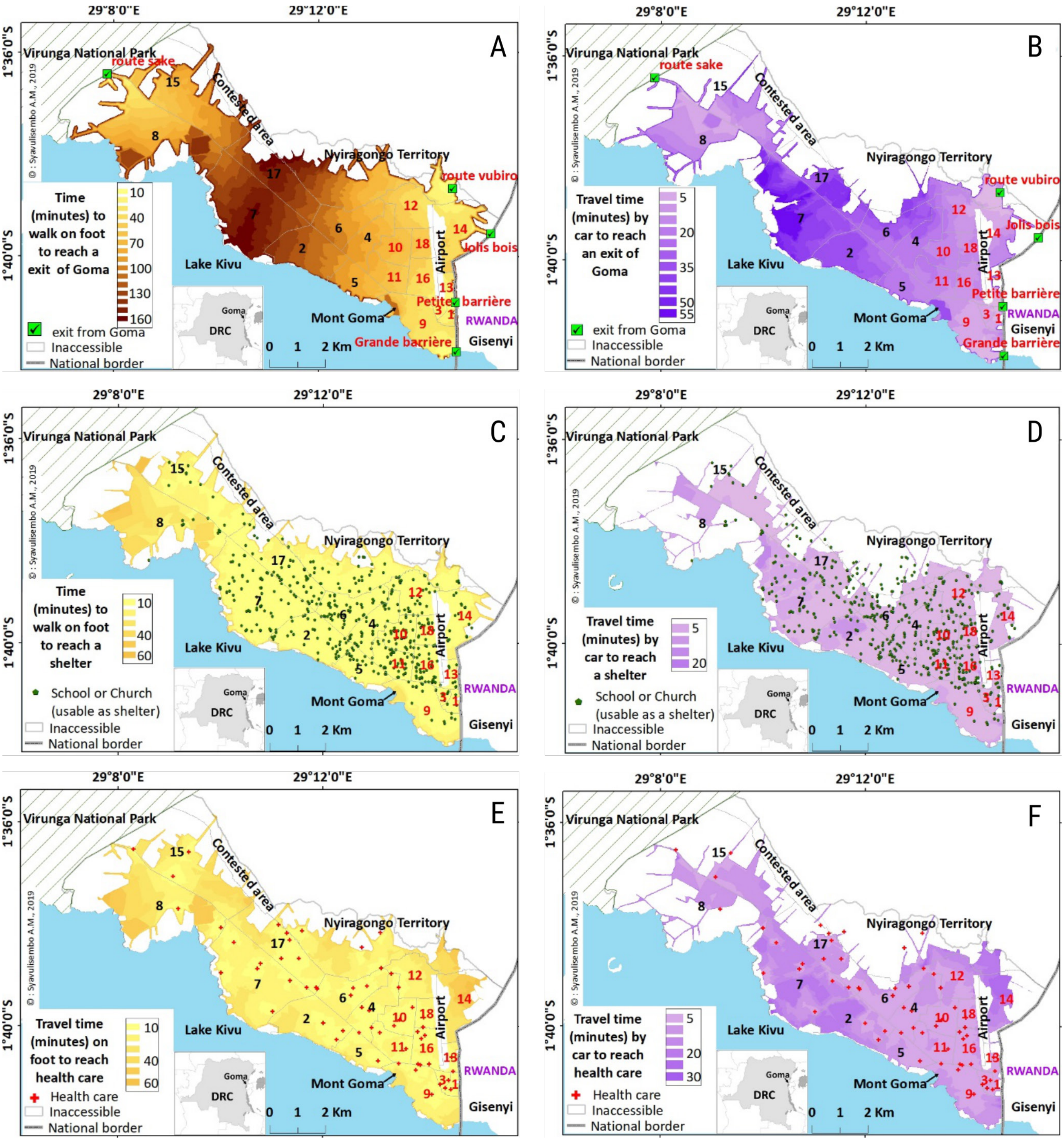

Figure 5: Minimum travel times by foot or car to different features or facilities. [A]–[B] Travel time to land exit points from Goma, by foot [A] and by car [B]. [C]–[D] Travel time to shelters (schools or churches), by foot [C] and by car [D]. [E]–[F] Travel time to healthcare locations, by foot [E] and by car [F].

mation in the response phase of a volcanic crisis depend first and foremost on mobility on path and road networks [Leone et al. 2013]. Several parameters, based on flank eruptions of Nyiragongo since the 1970s and the daily life of the population of Goma, were used to measure the accessibility, quantify critical resources, and determine how they would be used in the event of a large-scale eruptive crisis, like the one in 2002.

Officially, the evacuation plan for the population of Goma states that in the event of an eruption of the Nyiragongo volcano, the evacuation of the population is based on each individual's place of residence [Ministère de l'intérieur 2015]. In our study, the accessibility measures are read from the isochrones, the critical resources taken as the destination points for mobility. Isochrones provide a measurement of the population's accessibility to resources from any point in

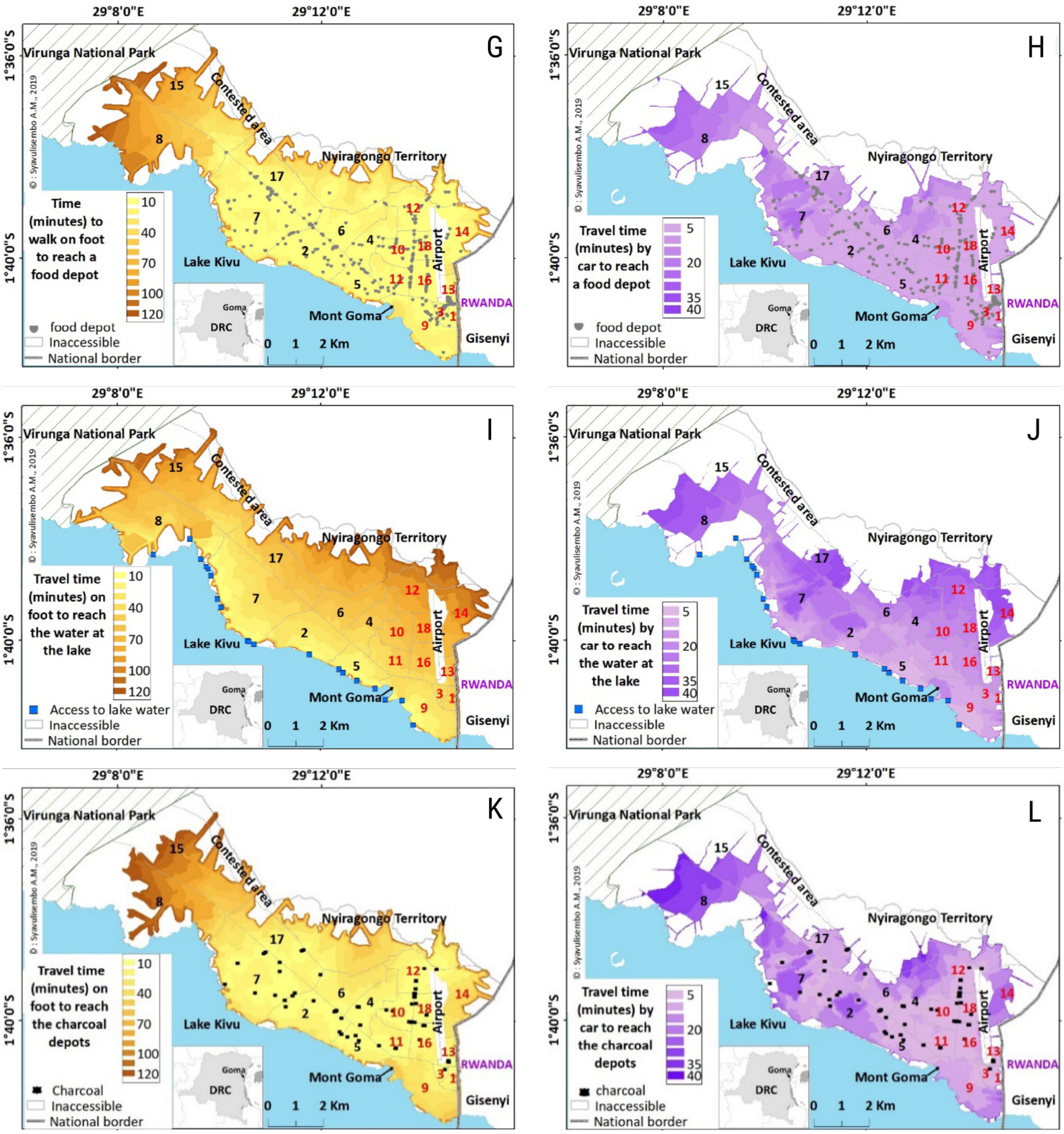

Figure 6 (cont.): Minimum travel times by foot or car to different features or facilities. [G]–[H] Travel time to food depots, by foot [G] and by car [H]. [I]–[J] Travel time to lake, by foot [I] and by car [J]. [K]–[L] Travel time to charcoal depots, by foot [K] and by car [L].

the study area [Sevtsuk and Mekonnen 2012; Lacroix 2013; Lamine and Mahdi 2015]. While we were able to determine the travel times required for the population to reach the point of exit from the city from their district of residence, this nevertheless highlights an initial paradox. Indeed, as the departure point and route depend primarily on the location of the population at the time of the alert, if an eruption warning was triggered during service hours, the travel times to reach the city exit points would probably be very different from the results presented in our study.

The spatio-temporal location of the population shows, during the day, a high concentration of individuals along major traffic routes [Syavulisembo et al. 2021]. Therefore, at the time of the alert, a large part of the population could choose the same evacuation routes and cause traffic congestion, slowing down the evacuation [Provitolo et al. 2015; Hayes et al. 2022;

Wild et al. 2023], if they have not been informed beforehand of the preferential routes they should use.

Thus, a person will not only be at-risk because of its vulnerability depending on their socioeconomic status, level of education, or experience with their local environment [Michellier et al. 2020], but also because of its exposure which depends on its location at the time of the disaster [Aubrecht et al. 2012; Syavulisembo et al. 2021]. Despite the magnitude of the flank eruptions in Goma, urban land use planning has not taken this into account. As a result, the peri-urban districts of Goma (Lac Vert, Mugunga, Majengo, Bujovu, and Nyiragongo territory) are doubly vulnerable: vulnerability due to socio-economic conditions, which was highlighted by Michellier et al. [2020], and vulnerability related to access to critical resources.

Indeed, regarding measures of population accessibility to critical resources via a road network, they are associated with mobility which is generally very specific, as it does not only take into account the length of the route, but also possible speed variations along the route [Sevtsuk and Mekonnen 2012; Lacroix 2013; Lamine and Mahdi 2015]. In our study, these measures allowed us to highlight that the accessibility of the population to the critical resources available for the management of a volcanic eruptive crisis is decreasing from the southeast to the north-northwest, going from the central districts - where the majority of critical resources are located—to the peri-urban districts—close to the Virunga National Park.

In order to cope with a crisis situation, it is crucial to assess key parameters for access to critical resources including estimated needs, overall costs (purchase and freight), timeframes for next deliveries, available and usable stocks, stocks on order, supplier delivery times, maximum and minimum stock levels for the supply/purchase plan, and storage areas [WFP 2013; Persha and Farrell 2017]. However, we were constrained to consider only information that was available and/or collected in the field. International Alert (2010) demonstrated that the informal sector is by far the largest provider of resources in Goma whereas it is the more difficult to measure. Moreover, Michellier et al. [2020] and Syavulisembo et al. [2021] reported that, within this city, data on quantitative parameters are still scarce or of uncertain quality, even on formal activities.

Regarding the critical resources to analyze, we faced some significant constraints and limitations. To assess the amount of food available, we inventoried traders' warehouses (i.e. the number of traders). We could also have looked at the size of food storage areas [WFP 2013], but in the case of Goma, this option did not seem appropriate. Indeed, some warehouses in outlying districts are spacious, but have a small number of resellers, and thus little stock. In practice, they are also little used by traders because of their distance from the center of activity (i.e. the city center). To refine our estimates, it would be relevant to take into account agricultural seasons, which affect the supply of depots [Reyns and Willekens 1973; Bako et al. 2019].

In addition, to estimate the capacity of health facilities, we referred to the number of beds for inpatient care. The number of medical staff, their categorization, and medical equipment could improve the comparison [Lutoff et al. 1998b; WHO 2021]. However, in the case of Goma, a doctor may serve in several health centers (interview 2). Therefore, it would have been difficult to define which health center to attach them to.

During humanitarian crises in general, and volcanic eruption-related crises in particular, in the Virunga region, victims typically seek refuge in informal sites such as schools and places of worship [Komorowski et al. 2002; Institute 2004; OCHA 2015]. However, living conditions in shelters can be very difficult, especially when they are collective. The main problems are insecurity, overcrowding, and lack of access to water and sanitation [OCHA 2014]. Moreover, the proportion of displaced persons accommodation in host families is even much higher than in collective accommodation [OCHA 2015]. For reasons of insecurity in eastern DRC, from January to November 2014 for example, OCHA [2015] estimated that 78 % of IDPs in North Kivu province were in host families and 22 % in collective shelters. During the Nyiragongo volcano eruption crisis in 2021, a resident of Majengo districts took refuge in his aunt's family in Kyeshero with his wife and five children. He was afraid of the poor conditions in the collective shelters (interviews 17 and 18). Therefore, an improved study on shelter capacity could consider the distribution of the displaced population according to the places available in shelters and host households.

Finally, we can highlight that some roads were insufficiently visited during the speed measurement campaign. Moreover, the data collected did not take into account certain factors, such as the purpose of mobility, physical interactions between pedestrians, and the age of the respondent, which would also influence walking speed [Knoblauch et al. 1996; Sugimoto et al. 2003; Imamura et al. 2012]. In addition, the speed measures obtained in this study reflect the quality of the roads, but they do not take into account the "panic" that the population might feel and that could have consequences on the way they move. Finally, in a context of very rapid demographic and spatial expansion, the road network and the critical resources database require regular updating. New roads may be built, or resources moved. Updating the resource accessibility analysis would be key for improving the response to future volcanic crisis.

6 Conclusions

In this study, we propose two methods for understanding population accessibility to critical resources: locating critical resources and measuring population mobility on the road network. In a context of scarcity of data, we demonstrate it is possible, through intensive field campaign, to collect geographical information, to improve the contingency plan of areas threatened by natural hazards, and to contribute to disaster risk reduction (DRR). The campaign periods may depend on several parameters, including the size of the agglomeration and the availability of reference data. Moreover, To identify critical resources that could be used during a future natural hazard crisis, it is essential to consider the opinions of stakeholders who have managed resources during historical crises. We have stressed how short field campaigns can greatly improve understanding of travel times between any location and critical resources. In conclusion, the results of this work can not only guide the selection of locations for new investments and serve as a decision-support tool for assessing the population's accessibility to a site but can also be integrated into crisis management tools, such as emergency plans and land-use plans.

Author Contributions

AMS, FK and CM conceived the study. AMS carried out the field work, including tool/questionnaire development and data collection, and the analytical calculation and numerical simulations. FK, LM, EW and CM validated the analytical methods. AMS and CM wrote the manuscript. All authors discussed the results and reviewed and edited the manuscript.

Acknowledgements

This publication was made possible thanks to the field support of Goma authorities and the Goma Volcano Observatory. We also benefited from the financial support of the North Kivu provincial government's Vision 2020, and the technical and financial support of the Université Libre des Bruxelles and the Royal Museum for Central Africa.

Data Availability

The data are available from the corresponding author. However, part of these data are currently used in population modeling and lava flow scenario analysis, and will be made available only at the end of the study.

Copyright Notice

References

Alegría, C. and F. Vergara-Pinto (2024). "Living In-between: Implications of Local Risk Perceptions for the Management of Future Eruptions at the Calbuco and Osorno Volcanoes (Ensenada, Chile)". *Andean Geology* 51(1), page 63. DOI: 10.5027/andgeov51n1-3668.

Aubrecht, C., S. Freire, C. Neuhold, A. Curtis, and K. Steinnocher (2012). "Introducing a Temporal Component in Spatial Vulnerability Analysis". *Disaster Advances* 5(2), pages 48–53.

Auker, M. R., R. S. J. Sparks, L. Siebert, H. S. Crosweller, and J. Ewert (2013). "A Statistical Analysis of the Global Historical Volcanic Fatalities Record". *Journal of Applied Volcanology* 2(1). DOI: 10.1186/2191-5040-2-2.

Bako, R. U., F. D. Ibrahim, U. S. Mohammed, C. O. Adebayo, A. A. A. Coker, and A. I. Oseghale (2019). *Analysis of Growth Rate in Price of Local and Imported Rice in Rural and Urban Markets of Niger State, Nigeria.* http://ageconsearch.umn.edu.

Barclay, J., R. Few, M. T. Armijos, J. C. Phillips, D. M. Pyle, A. Hicks, S. K. Brown, and R. E. A. Robertson (2019). "Livelihoods, Wellbeing and the Risk to Life During Volcanic Eruptions". *Frontiers in Earth Science* 7. DOI: 10.3389/feart.2019.00205.

Baxter, P., P. Allard, M. Halbwachs, J.-C. Komorowski, A. Woods, and A. Ancia (2002). "Human Health and Vulnerability in the Nyiragongo Volcano Eruption and Humanitarian Crisis at Goma, Democratic Republic of Congo". *Acta Vulcanologica* 14.

Baxter, P. and A. Ancia (2002). *Human Health and Vulnerability in the Nyiragongo Volcano Crisis Democratic Republic of Congo 2002 Final Report to the World Health Organisation.*

Brunet, S., C. Fallon, P. Ozer, N. Schiffino, and A. Thiry (2012). *Articuler Risques, Planification d'urgence et Gestion de Crise.* De Boeck Supérieur.

Cappelle, F. (2008). *Polycentralité et Gouvernance: Quelles Relations?* Université de Tours.

Chamorro, A., T. Echaveguren, C. Pattillo, M. Contreras-Jara, M. Contreras, E. Allen, N. Nieto, and H. de Solminihac (2023). "SIGeR-RV: A Web-Geographic Information System-Based System for Risk Management of Road Networks Exposed to Natural Hazards". *Transportation Research Record: Journal of the Transportation Research Board* 2677(12), pages 754–769. DOI: 10.1177/03611981231169532.

Connell, J. and N. Lutkehaus (2016). *Another Manam? The forced migration of the population of Manam Island, Papua New Guinea, due to volcanic eruptions 2004–2005.* International Organization for Migration, Geneva, Switzerland.

Crozier, D., G. Jouannic, C. Tran Duc Minh, Z. Kolli, E. Matagne, and S. Arbizzi (2017). "Reconstruire Un Territoire Moins Vulnérable Après Une Inondation: Une Fenêtre d'opportunité Encore Difficilement Mobilisable". *Espace-Populations-Societes* 2016(3). DOI: 10.4000/eps.7033.

D'Ercole, R. and P. Metzger (2009). "La Vulnérabilité Territoriale: Une Nouvelle Approche Des Risques En Milieu Urbain". *Cybergeo: European Journal of Geography.* DOI: 10.4000/cybergeo.22022.

De Goma, M. (2020). *Rapport Annuel 2020, Goma, République Démocratique Du Congo.*

Demoraes, F. (2004). "Mobilité, enjeux et risques dans le District Métropolitain de Quito (Equateur)". PhD thesis. Université de Savoie.

Demoraes, F. and R. d'Ercole (2009). "Risques et accessibilité des lieux dans le District Métropolitain de Quito (Équateur)". *Mappe Monde* 95(3), pages 1–20.

Diaz Olvera, L., D. Plat, and P. Pochet (2007). "Mobilité quotidienne en temps de crise". *Belgeo* (2), pages 173–188. DOI: 10.4000/belgeo.11255.

Diop, A. A. (2007). "Quelles Centralités Pour La Ville de Dakar, Sénégal?" *Rives Méditerranéennes* (26), pages 75–92. DOI: 10.4000/rives.921.

Durieux, J. (2003). "Nyiragongo: The January 10th, 1977, Eruption". *Acta Vulcanologica* 14.

Förster, T. and C. Ammann (2018). "Les Villes Africaines et Le Casse-Tête Du Développement". *Revue Internationale de Politique de Développement* (10). DOI: 10.4000/poldev.3352.

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), pages 315–328. DOI: 10.1016/j.jvolgeores.2007.12.036.

GeoRiskA MRAC, M. r. d. l. c. (2016). *Rapports Du Département Des Sciences de La Terre*.

Global Volcanism Program (GVP) (2021). "Report on Nyiragongo (DR Congo)". *Bulletin of the Global Volcanism Network*. Edited by E. Venzke. Volume 46. 6. Smithsonian Institution. DOI: 10.5479/si.gvp.bgvn202106-223030.

Hayes, J. L., S. Biass, S. F. Jenkins, E. S. Meredith, and G. T. Williams (2022). "Integrating criticality concepts into road network disruption assessments for volcanic eruptions". *Journal of Applied Volcanology* 11(1). DOI: 10.1186/s13617-022-00118-x.

Imamura, F., A. Muhari, E. Mas, M. H. Pradono, J. Post, and M. Sugimoto (2012). "Tsunami Disaster Mitigation by Integrating Comprehensive Countermeasures in Padang City, Indonesia". *Journal of Disaster Research* 7(1), pages 48–64. DOI: 10.20965/jdr.2012.p0048.

Institut supérieur d'informatique et de gestion de Goma (ISIG-Goma) (2003). *Étude Globale Sur La Situation Des Ménages Dans La Ville de Goma Après l'éruption Du Volcan Nyiragongo Le 17 Janvier 2002. Rapport d'analyse*. ISIG-Goma, Ministère de la Région Wallone Goma, and Namur.

Institute, P. (2004). *Spécial Nyiragongo (No. 6), Regards Croisés*. Goma.

Issaka, H. (2007). "L'habitat informel dans les villes d'Afrique subsaharienne francophone à travers l'exemple de Niamey (Niger)". Master's thesis. Université de Pau et des pays de l'Adour.

Kakule Kisenge, V. (2013). *Problématique de l'utilisation des énergies polluantes sur le réchauffement climatique. Â« Cas du mazout dans les groupes électrogènes communautaires : BI groupe Â»*. Institut supérieur de développement rural des Grands Lacs (ISDR/GL).

Katamba, M. T. (1978). "Les Conséquences Des Éruptions Volcaniques Dans La Région de Goma 1976-1977". Master's thesis. Institut Supérieur Pédagogique de Bukavu.

Kavotha, S. K., T. Mavonga, J. Durieux, and K. Mukambilwa (2003). "Towards a More Detailed Seismic Picture of the January 17th, 2002 Nyiragongo Eruption". *Acta Vulcanologica* 14.

Kayser, C. (2002). "Les Gomatraciens entre le volcan et l'humanitaire". *Politique africaine* 85(1), pages 152–154. DOI: 10.3917/polaf.085.0152.

Knoblauch, R. L., M. T. Pietrucha, and M. Nitzburg (1996). "Field Studies of Pedestrian Walking Speed and Start-up Time". *Transportation Research Record* (1538), pages 27–38. DOI: 10.3141/1538-04.

Komorowski, J.-C., D. Tedesco, M. Kasereka, P. Allard, P. Papale, O. Vaselli, J. Durieux, P. Baxter, M. Halbwachs, M. Akumbe, B. Baluku, P. Briole, M. Ciraba, J.-C. Dupin, O. Etoy, D. Garcin, H. Hamaguchi, N. Houlié, K. S. Kavotha, A. Lemarchand, J. Lockwood, N. Lukaya, G. Mavonga, M. de Michele, S. Mpore, K. Mukambilwa, F. Munyololo, C. Newhall, J. Ruch, M. Yalire, and M. Wafula (2002). "The January 2002 flank eruption of Nyiragongo volcano (DRC): Chronology, evidence for a tectonic rift trigger and impact of lava flows on the city of Goma". *Acta Vulcanologica* 14, pages 25–57.

Kumar, A. and F. Barrett (2008). *Coincés dans les embouteillages : Le transport urbain en Afrique*. Banque mondiale, SSATP.

Lacroix, P. (2013). "Contributions of GIS to Efficient Mine Action". PhD thesis. Université de Genève. DOI: 10.13140/RG.2.1.4104.4888.

Laganier, R. and Y. Veyret (2023). *Gestion Des Crises Territoriales: De l'urgence à La Reconstruction*. ISTE group.

Lamine, B. M. and K. Mahdi (2015). "La mobilité motorisée dans la ville de Batna, étude de la répartition spatiale des établissements de santé vis-à-vis du CHU : approche par scénarios". *Bulletin de la Société Géographique de Liège* 64(1), pages 83–92.

Lejeune, G., F. Ansay, M. V. Geit, and T. Lusenge (2013). "ECO-makala: Répondre à La Demande Énergétique Pour Protéger Les Forêts Du Parc National Des Virunga Au Nord-Kivu (RDC) et Lutter Contre La Pauvreté". *World Wildlife Fund (WWF) Technical Guide*.

Leone, F. (2018). "Territorial Accessibility and Volcanic Crisis Management in the French West Indies (Guadeloupe & Martinique): Contribution to Evacuation Planning". *Cyber-Geo. Geographie-Cites*. DOI: 10.4000/cybergeo.29425.

Leone, F., J.-C. Komorowski, M. Gherardi-Leone, G. Lalubie, T. Lesales, J.-R. Gros-Désormeaux, and J. Deymier (2018). "Accessibilité territoriale et gestion de crise volcanique aux Antilles françaises (Guadeloupe & Martinique) : contribution à la planification des évacuations". *Cybergeo*. DOI: 10.4000/cybergeo.29425.

Leone, F., M. Péroche, and R. Gutton (2014). "Le Risque Tsunami En Martinique: Planifier Une Évacuation Préventive En Optimisant l'accessibilité de Sites Refuges". *VertigO* 14(2). DOI: 10.4000/vertigo.15046.

Leone, F., M. Péroche, E. Lagahé, M. Gherardi, A. Sahal, F. Vinet, S. Hachim, and F. Lavigne (2013). "Territorial Accessibility Modeling Serving Tsunami Crisis Management (Mayotte, France)". *Annales de Géographie* 123(693), pages 502–524. DOI: 10.3917/ag.693.0502.

Lutoff, C., P. Masure, C. Arnan, and P. Thierry (1998a). *Gestion des risques majeurs dans les villes européennes. Analyse des enjeux dans les villes. Application à la ville de Nice et comparaison avec les pratiques en Italie et en Espagne*.

Lutoff, C., P. Masure, A. C, and P. Thierry (1998b). *Gestion des risques majeurs dans les villes européennes. Analyse des enjeux dans les villes. Application à la ville de Nice et comparaison avec les pratiques en Italie et en Espagne*. Bureau de recherches géologiques et minières.

Mboga, N. O. (2021). "Long-term mapping of urban areas using remote sensing: Application of deep learning using case-studies of data from Central Africa". PhD thesis. Université libre de Bruxelles.

Médecins du Monde (2002). *Urgence Volcan Nyiragongo Conséquences de l'éruption Volcanique à Goma*. URL: https://reliefweb.int/report/democratic-republic-congo/urgence-volcan-nyiragongo-cons%C3%A9quences-de-l%C3%A9ruption-volcanique-%C3%A0 (visited on 04/02/2002).

Mei, E. T. W., F. Lavigne, A. Picquout, E. de Bélizal, D. Brunstein, D. Grancher, J. Sartohadi, N. Cholik, and C. Vidal (2013). "Lessons Learned from the 2010 Evacuations at Merapi Volcano". *Journal of Volcanology and Geothermal Research* 261, pages 348–365. DOI: 10.1016/j.jvolgeores.2013.03.010.

Michellier, C., M. Kervyn, F. Barette, A. M. Syavulisembo, C. Kimanuka, S. K. Mataboro, F. Hage, E. Wolff, and F. Kervyn (2020). "Evaluating Population Vulnerability to Volcanic Risk in a Data Scarcity Context: The Case of Goma City, Virunga Volcanic Province (DRCongo)". *International Journal of Disaster Risk Reduction* 45. DOI: 10.1016/j.ijdrr.2019.101460.

Ministre de l'Intérieur Sécurité, D. e. A. c. (2015). "Plan Provincial de Contingence En Prévision Des Éventuelles Éruptions Volcaniques Au Nord-Kivu 2014-202". *Plate-forme Nationale de Réduction des Risques et Gestion des Catastrophes*, pages 1–33.

Mondzech, J. and M. Sester (2011). "Quality Analysis of OpenStreetMap Data Based on Application Needs". *Cartographica* 46(2), pages 115–125. DOI: 10.3138/carto.46.2.115.

Morrison, A. A., A. G. Whittington, B. Smets, M. Kervyn, and A. Sehlke (2020). "The Rheology of Crystallizing Basaltic Lavas from Nyiragongo and Nyamuragira Volcanoes, D.R.C." *Volcanica* 3(1), pages 1–28. DOI: 10.30909/vol.03.01.0128.

Muhindo Kambumbu, E. (2010). "Étude de Faisabilité d'une Centrale Électrique à Gaz Méthane En Vue d'alimenter Les Installations Production d'eau Potable de La REGIDESO/Centre de Goma". Master's thesis. Institut international d'ingénierie de l'eau et de l'environnement (2iE).

Musubaho, M. B. (2022). *Cartographie Des Coulées de Lave et Fissures de l'éruption Volcanique Du Nyiragongo Du 22/05/2021*. Goma.

Neis, P., D. Zielstra, and A. Zipf (2013). "Comparison of Volunteered Geographic Information Data Contributions and Community Development for Selected World Regions". *Future Internet* 5(2), pages 282–300. DOI: 10.3390/fi5020282.

Nyandu Kubuya-Shamavu, P.-C. (2022). "Des bénéfices des interventions des ONG internationales en RDC : A partir d'une étude de la distribution de l'eau aux sinistrés et de la remise en fonctionnement des écoles, dans le territoire de Nyiragongo, au lendemain de l'éruption volcanique du 22 mai 2021, par les ONG internationales". Master's thesis. Université catholique de Louvain.

Office des Voiries et Drainages (OVD) (2016). *Rapport Annuel 2016. Goma, République Démocratique Du Congo*. Kinshasa: Ministère des infrastructures et travaux publics.

OpenStreetMap (2017). *Geofabrik*. URL: https://www.geofabrik.de/ (visited on 08/30/2024).

Persha, L. and W. Farrell (2017). *Rapport final de l'analyse de la diversification des moyens de subsistance (LDA)*. United States Agency for International Development (USAID). URL: https://pdf.usaid.gov/pdf_docs/PA00N5SR.pdf (visited on 04/25/2017).

Plat, D. (2003). "Mobilités Quotidiennes En Afrique Subsaharienne". PhD thesis. Université Lumière-Lyon II.

Pottier, Y. (1978). "Première Éruption Historique Du Nyiragongo et Manifestations Adventives Simultanées Du Volcan Nyamulagira (Chaîne Des Virunga-Kivu-Zaire: Décembre 76-Juin 77)".

Provitolo, D., E. Dubos-Paillard, N. Verdiere, V. Lanza, R. Charrier, C. Bertelle, and M. A. Aziz-Alaoui (2015). "Les Comportements Humains En Situation de Catastrophe: De l'observation à La Modélisation Conceptuelle et Mathématique". *CyberGeo*. DOI: 10.4000/cybergeo.27150.

Reyns, A. and F. Willekens (1973). "Le Mouvement Saisonnier Des Prix Des Produits Agricoles Sur Les Marchés de Kinshasa".

Sevtsuk, A. and M. Mekonnen (2012). "Urban network analysis. A new toolbox for ArcGIS". *Revue internationale de géomatique* 22(2), pages 287–305. DOI: 10.3166/rig.22.287-305.

Smittarello, D., B. Smets, J. Barrière, C. Michellier, A. Oth, T. Shreve, R. Grandin, et al. (2022). "Precursor-Free Eruption Triggered by Edifice Rupture at Nyiragongo Volcano". *Nature* 609(7925), pages 83–88. DOI: 10.1038/s41586-022-05047-8.

Solidarité internationale sur les transports et la recherche en Afrique subsaharienne (SITRASS) (2004). "Pauvreté et mobilité urbaine à Conakry". (Rapport SSATP No 09/04/CKR).

Sugimoto, T., H. Murakami, Y. Kozuki, K. Nishikawa, and T. Shimada (2003). *Natural Hazards* 29(3), pages 587–602. DOI: 10.1023/a:1024779724065.

Syavulisembo, M. A., H.-B. Havenith, B. Smets, N. D'Apos;Oreye, and J. Marti (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 Sciences* 15(10), pages 2391–2400. DOI: 10.5194/nhess-15-2391-2015.

Syavulisembo, M. A. (2019). "La Variation Spatio-Temporelle de La Population et l'analyse de l'accessibilité à Ses Ressources Vitales: Vers Une Meilleure Gestion Du Risque Volcanique à Goma, République Démocratique Du Congo". PhD thesis. Bruxelles: Université libre de Bruxelles, Faculté des Sciences.

Syavulisembo, M. A., F. Kervyn, L. Moritz, É. Wolff, and C. Michellier (2021). "Spatio-Temporal Location of Population: Strengthening the Capacities of Sudden Hazards Risk Management in Goma, DRC". *International Journal of Disaster Risk Reduction* 66. DOI: 10.1016/j.ijdrr.2021.102565.

Syavulisembo, M. A., C. Michellier, É. Wolff, and F. Kervyn (2017). *Analyse Spatio-Temporelle de La Vulnérabilité de La Population Face à l'aléa Volcanique: Le Cas de Goma, République Démocratique Du Congo*. 99e Journées Luxembourgeoises de Géodynamiques-Luxembourg.

– (2022). "The Challenging Crisis Management during the Nyiragongo 22nd May 2021 Eruption (D.R. Congo)". Cities on Volcanoes 11. International Association of Volcanology and Chemistry of the Earth's Interior. Heraklion, Crete.

United Nations Children's Fund (UNICEF) (2021a). *Eruption Du Volcan Nyiragongo: L'après-Crise*. URL: https://www.unicef.org/drcongo/recits/eruption-du-volcan-nyiragongo-lapres-crise (visited on 07/08/2021).

– (2021b). *Eruption Du Volcan Nyiragongo: Rapport de La Situation Éducation No 2 - Au 06 Juin 2021*.

– (2021c). *UNICEF Democratic Republic of Congo: Humanitarian Situation Report No. 5 - May 2021*. URL: https://reliefweb.int/report/democratic-republic-congo/unicef-drc-humanitarian-situation-report-no-5-may-2021#:~:text=As%20of%20May%2031st%20%2C%202021,2.7%25%20from%202020%20to%202021. (visited on 07/19/2021).

United Nations Office for Disaster Risk Reduction (UNDRR) (2015). "Sendai Framework for Disaster Risk Reduction".

United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (2014). *Conditions de Vie Des PIDs En Milieu Urbain - Résumé Du Rapport En Français*.

– (2015). *Rapport Sur La Situation Des Mouvements de Population Au Nord-Kivu*. URL: https://www.unocha.org/publications/report/democratic-republic-congo/rapport-sur-la-situation-des-mouvements-de-population-au-nord-kivu (visited on 01/31/2015).

– (2021a). *Eruption Volcanique Nyiragongo: Rapport de Situation - Goma, RDC (Le 05 Juin 2021)*. URL: https://reliefweb.int/report/democratic-republic-congo/eruption-volcanique-nyiragongo-rapport-de-situation-goma-rdc-le-05 (visited on 06/05/2021).

– (2021b). *OCHA RDC Sitrep Inondations Dans Le Territoire de Masisi*. URL: https://reliefweb.int/report/democratic-republic-congo/r-publique-d-mocratique-du-congo-nord-kivu-inondations-dans-le (visited on 10/09/2020).

Vennetier, P. (1989). "Centre, Périphérie et Flux Intra-Urbains Dans Les Grandes Villes d'Afrique Noire". (547), pages 257–285.

– (1990). "Que Faire Des Villes d'Afrique Tropicale? Ou: Les Problèmes d'une Urbanisation Galopante". *Bulletin de La Société Géographique de Liège* 26, pages 63–75.

Wild, A. J., M. S. Bebbington, J. M. Lindsay, and N. I. Deligne (2023). "Cost-benefit analysis for evacuation decision-support: challenges and possible solutions for applications in areas of distributed volcanism". *Journal of Applied Volcanology* 12(1). DOI: 10.1186/s13617-023-00133-6.

Wild, A. J., M. S. Bebbington, J. M. Lindsay, and D. H. Charlton (2021). "Modelling spatial population exposure and evacuation clearance time for the Auckland Volcanic Field, New Zealand". *Journal of Volcanology and Geothermal Research* 416, page 107282. DOI: 10.1016/j.jvolgeores.2021.107282.

World Food Programme (WFP) (2013). *Gestion de La Chaîne d'approvisionnement Des Aliments Nutritifs Spécialisés*. URL: https://fsnetwork.org/gtranslate/gtranslate.php?glang=fr&gurl=resource/managing-supply-chain-specialized-nutritious-foods.

– (2021). *Rapport de Situation Externe #25*. URL: https://reliefweb.int/report/democratic-republic-congo/pam-rd-congo-rapport-de-situation-externe-25-08-juin-2021 (visited on 07/08/2021).

World Health Organization (WHO) (2021). *The selection and use of essential medicines: report of the WHO Expert Committee on Selection and Use of Essential Medicines, 2021 (including the 22nd WHO model list of essential medicines and the 8th WHO model list of essential medicines for children)*. WHO technical report series;1035. World Health Organization, xlviii, 829 p.

Yamamoto, L., D. Andreola Serraglio, and F. de Salles Cavedon-Capdeville (2018). "Human Mobility in the Context of Climate Change and Disasters: A South American Approach". *International Journal of Climate Change Strategies and Management* 10(1), pages 65–85. DOI: 10.1108/IJCCSM-03-2017-0069.

Yu, S. and E. W. Welch (2022). "Responding strategically to natural hazards: the role of hazard experience, infrastructure vulnerability, and risk perception in transit agency coordination with stakeholders". *Journal of Environmental Planning and Management* 67(1), pages 108–130. DOI: 10.1080/09640568.2022.2100246.