GIS-based Modeling of Nyiragongo's Lava Flow Inundation Probability And Mazuku : A Spatial Environment for a Successful Evacuation Plan for Goma City

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Abstract. The densely populated city of Goma in the Democratic Republic of Congo is highly vulnerable to volcanic hazards from the Nyiragongo volcano. However, these threats are not taken into account in land use and urban planning. In fact, a contingency plan for evacuating people in the event of a volcanic disaster cannot be successful if the evacuation environment is not known and properly simulated, as it may change over time.

Based on the Mazuku distribution map and lava flow inundation probabilities, this study aimed to suggest the possible evacuation scenarios from the drown up models. The Q-LavHA tools were used to simulate the lava flow from 8 selected vents on the flank of Nyiragongo towards the city of Goma, using data from past eruptions in 1977, 2002 and 2022. Thus, based on certain volcanic hazard criteria related to the dataset analysis, the exposure to hazards was assessed.

The result shows that more than half of the city of Goma is highly exposed to the volcanic hazards of Nyiragongo. Unfortunately, this is also where the majority of the population, the commercial centre and the main public and private institutions are located.

Therefore, taking into account the level of exposure to mazuku and lava flows, a spatial evacuation environment that could support a successful evacuation was proposed. This environment is essential for an ongoing study on a spatially explicit agent-based simulation related to the evacuation of people.

Keywords: Nyiragongo · volcanic crisis · spatial environment · lava flow simulation · Mazuku · evacuation plan · Q-LavHA

1 Introduction

Evacuation planning is a complex and challenging task as it requires an integrated approach to heterogeneous spatial datasets, including population, road network, and facilities [9]. Evacuation management in emergencies is often based on the description of evacuation circumstances and spatial analysis of the datasets[9].

Nyiragongo is an effusive volcano, well known for its persistent lava lake activity which has fascinated scientists[13]. It is also famous for its magma composition, which produces extremely fluid lava flows, capable of descending the

crater flanks at speeds of up to 100 km per hour on certain slopes[13]. Furthermore, the population living near Nyiragongo is growing quickly, from about 50,000 when 1977 eruption occurred to 500,000 in 2002 eruption[12][13], and to about 1,000,000 in 2021 eruption.

It was suggested by [2] that the modeling of the spatio-temporal variations of the population is crucial information for quantifying the resources needed to manage a future sudden crisis in Goma. Indeed, the knowledge of the evacuation spatial environment and its probable or possible variation matters a lot. Certainly, an emergency evacuation plan in case of a sudden disaster such as flood, volcanic lava flow cannot be successful if the spatial data is not known and properly simulated as it can change over the time. As suggested by [10], knowing the study context is essential at all stages of vulnerability analysis.

The three previous eruptions of Nyiragongo, in 1977, 2002, and 2021, were real disasters and caused many losses. Lava flows killed people, destroyed homes, roads and commercial facilities, and left many families homeless [2] [4] [12] [13].

CO2 rich gas location, known at Goma as Mazuku, is another dangerous hazard related to volcano that is killing silently animals and people[5]. In addition to their high concentration of CO2, Mazuku give a false impression of warmer temperatures, making them the shelter of choice for refugees [5]. Between 1994 and 1996, many Rwandan refugees died while sheltering in mazuku without knowing their toxicity. Local military officials have also reported the death of soldiers in mazuku during wartime operations[5].

Therefore, to prepare for any coming volcanic crisis, the proposed models would be one of the key elements on which evacuation and emergency plans would be based. GIS data model enables a computer to represent real geographical datasets as graphical elements. Two representational models are mostly used; raster (grid-based) and vector (line-based).

Knowing the extend of lava flow is a critical information for anyone interested in modeling/simulation studies, response plans and mitigation measures implementation for saving lives during volcanic crisis(source). Thus, to better understand the spatial distribution of lava flow hazard, it was important to identify accurately the area that can be inundated by the lava flow.

Talking about the spatial environment, it is important to know where objects are, how they relate to each other, and how to avoid dangerous places, to find one's way to a familiar or unfamiliar location [14]. However, it is stressful when the spatial environment has been threatened by a disaster, for example topographical changes or road blockage[14].

This study aimed at suggesting the potential evacuation scenarios based on Mazuku distribution and on accurate simulations of lava flow extend relying on data form 1977, 2002 and 2021 Nyiragongo past known eruptions.

The objectives of this study are as follows:

- simulating the lava flow inundation probabilities
- assessing the potential exposure of the city of Goma to Mazuku and volcanic lava flow hazards

– proposing evacuation routes, assembly points, evacuation route sign's loca-
tion and temporary refuge areas.

Therefore, mapping works and simulation were undertaken to get the MAZUKU
distribution and lava flow invasion probabilities relying on Nyiragongo volcanic
crisis data of 1997, 2002 and 2021. Furthermore, assessment of potential exposure
of Goma city to lava flows and MAZUKU hazards were undertaken. Lastly, based
on hazard exposure assessment and vulnerability analysis, evacuation routes, lo-
cation of assembly points, evacuation route, location of evacuation route sign,
and temporary refuge were selected.

The result shows that eleven neighborhoods in the east of Goma city are
located in the potential lava flow corridor and that roads, lake ports and the
part of the airport are potentially exposed to volcanic hazards.

The following sections of this study are: 2. materials and methods 3. results
4. discussion. 5. conclusion, recommendations and future work.

2 Materials and Methods

2.1 Study area

Goma, the capital city of the province of North Kivu, is located in the east of
the Democratic Republic of Congo (DRC) on the border with Rwanda. It is
situated between 1.59° North and 1.70° South latitude and between 29.11° and
29.26° East longitude.

During the eruptions of 1977, 2002 and 2021, the city covered 17.6 km2, 52.6
km2 and 76 km2 respectively [6]. It now covers an area of 66.45 km2. Figure 1
below shows the location of the study area.

2.2 Software tools

This study used Quantum Geographic Information System (QGIS) for map-
ping and Quantum-Lava Hazard Assessment (Q-LavHA) for simulating lava flow
propagation.

Q-LavHA is a freeware QGIS plugin that simulates lava flow invasion prob-
ability from single or regularly distributed eruptive vents on a Digital Elevation
Model. It combines existing probabilistic and deterministic models for lava flow
hazard assessment[11] and proposes some improvements to calculate the proba-
bility of lava flow spatial propagation and terminal length.

Q-LavHA is intended for scientists and stakeholders facing imminent or long-
term lava flow hazard from basaltic volcanoes [11]. Q-LavHA can improve their
understanding of the spatial distribution of lava flow hazards, influence their
land use decisions and support evacuation planning during a volcanic crisis [11].
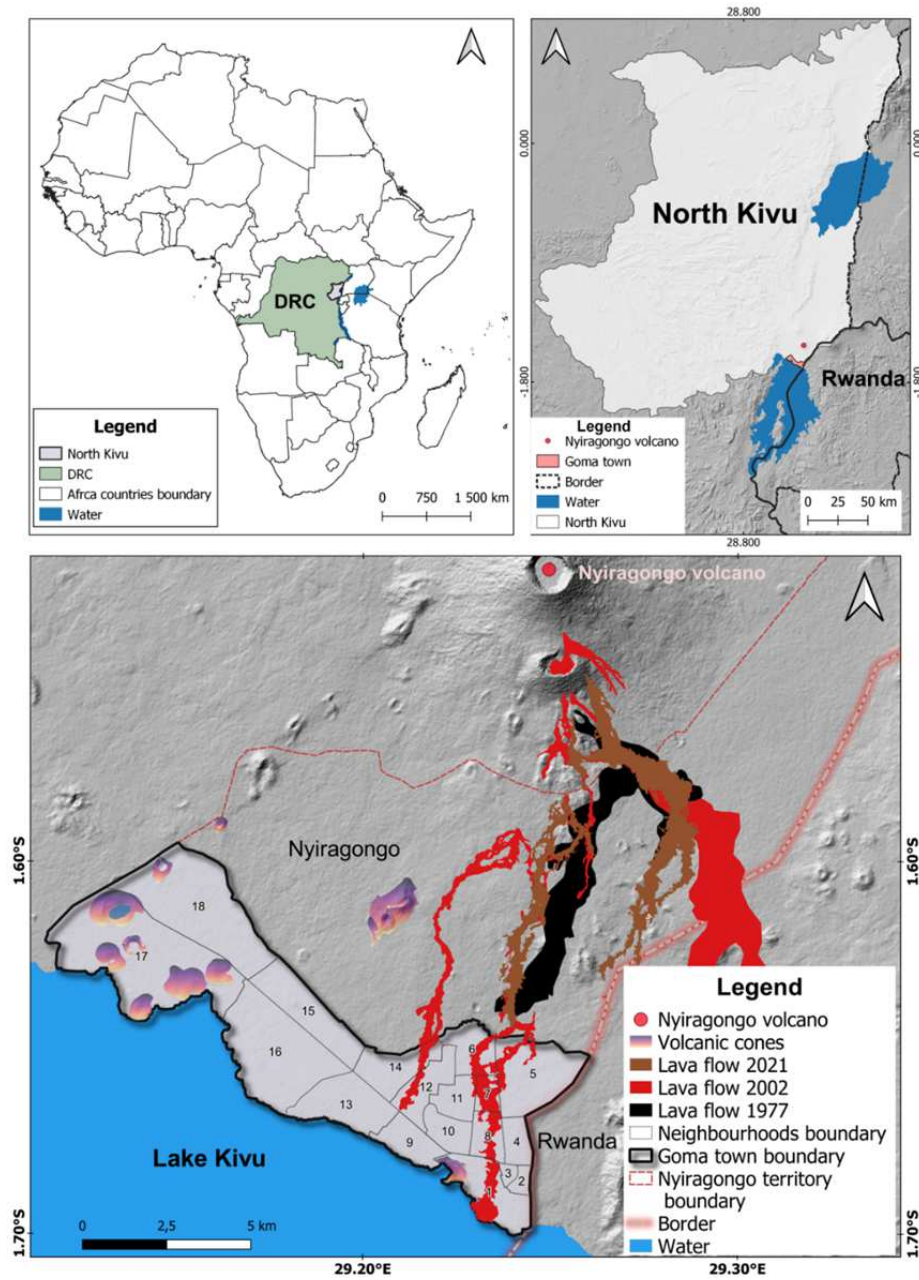
Fig. 1. Location maps of the study area
(Neighborhoods: 1= Les Volcans, 2 = Mapendo, 3 = Mikeno, 4= Kahembe, 5 = Bujovu, 6 = Majengo, 7=Virunga, 8 = Murara, 9 = Katindo, 10 =Mabanga-Sud, 11= Mabanga-Nord,12 = Kasika, 13 = Himbi, 14 = Katoyi, 15 = Ndosho, 16 = Kyeshero, 17 = Lac-Vert, 18 = Mugunga)

2.3   Data

Data including a Digital Elevation Model (DEM) was implemented in Q-LavHA with a spatial resolution of 30 m and shapefiles of eruptive lava vents from the 1977, 2002, and 2021 eruptions (data source: the Goma Volcano Observatory, that is "Observatoire Volcanologique de Goma" (OVG) in french). A DEM is a satellite image (raster data) that represents the bare earth topographic surface of the Earth, excluding trees, buildings, and other surface objects.The DEM used in this study was freely downloaded from https://dwtkns.com/srtm30m/. The road, lake, and air traffic network shapefiles were freely downloaded from OpenStreetMap https://extract.bbbike.org/.

2.4   Simulation of lava flow propagation

Data pre-processing Prior to the Q-lavHA simulation, pre-processing operations on the raster data are necessary: reprojection of the DEM into the UTM (Universal Transverse Mercator) coordinate reference system, cropping to the area of interest, and filling of depressions. These pre-processing operations help to avoid the simulation from getting stuck due to errors in the DEM. Q-LavHA requires a .asc format. However, a .tiff format can be used in the plugin, which is automatically converted to a .asc format.

Therefore, the null values (nodata) and the anomalous depressions in the DEM (fill sink) were filled in. The WGS 84 / UTM zone 35S value of the study area was then used for projection.

Simulation

  − *Eruption sources (vents location)*

Taking into account the last three eruptions (1977, 2002, and 2021), 11 vents were identified, including 2 vents for 1977, 6 vents for 2002, and 3 vents for 2021. All these vents are located on fractures (Figure 2). In addition, most of the vents are located in the same area and some sources overlap. As a result of this overlap, 8 vents were selected for the lava flow simulation. The geographical coordinates (in UTM) of the vents used are given in Table 1.
In this table, "distance" is one of the parameters used to simulate lava flow propagation. It represents the maximum length of the lava flow (the length over which the lava flow can propagate). To identify the potential lava flow corridor, we considered the scenario where the lava reaches Lake Kivu. Thus, for each eruptive source (vent), we determined the distance between the source and Lake Kivu by following the direction of past lava flows (1977, 2002 and 2021 volcanic eruptions) (Table 1).

  − *Other parameters used for the simulation in this study*

The other parameters that were used in the simulation of the propagation of the lava flow are shown in Table 2. Correction factors were included to allow lava to overcome small topographic obstacles or pits [11].
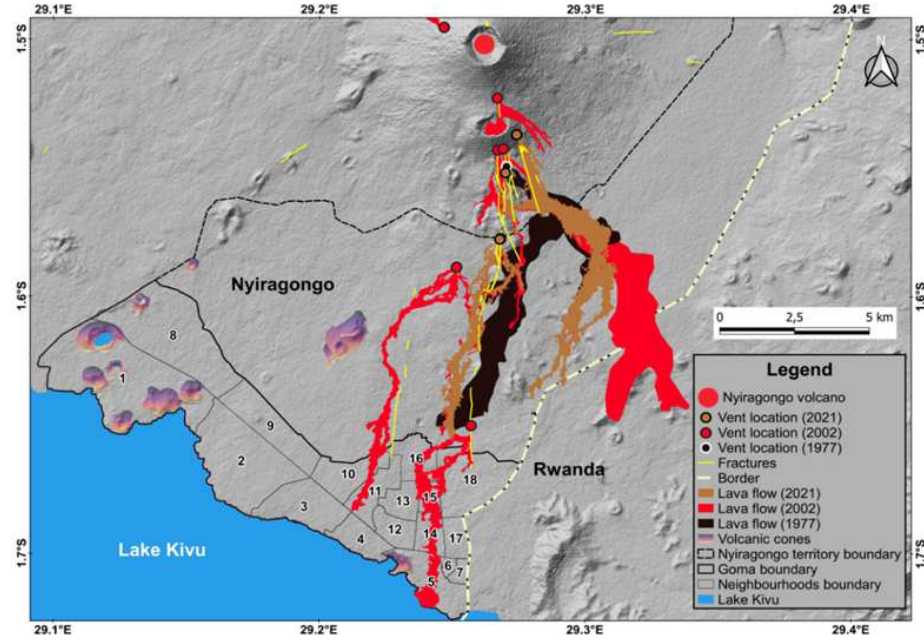
Fig. 2. Vents location.

Table 1. Geographic coordinates (in UTM) of the vents (eruption sources) and distance of the vents from Lake Kivu (m) used for the simulation.

No	L a t i t u d e	L o n g i t u d e	Altitude	Distance (m)
1	749851.18	9818568.07	1598	8000
2	749366.49	9824018.58	1855	12000
3	750814.98	9824981.52	1965	14000
4	751023.56	9827312.31	2260	19000
5	750755.09	9828051.06	2423	17000
6	750931.67	9828088.30	2405	17000
7	751382.14	9828579.29	2484	18000
8	750735.87	9829840.87	2816	19500

Table 2. Parameters used for lava flow propagation simulation in this work.

Parameter	Symbol	Value	Unit	Source
Thickness of the lava flow	Hc	1,5	m	[7]
Topographic correction factor	Hp	7	m	[7]
Number of iterations	-	1500	-	[11]

2.5   Analysis criteria used for volcanic hazard exposure assessment

Zoning of potential exposure to volcanic hazards in the city of Goma was performed based on the criteria listed in Table 3:

Table 3. Parameters used for lava flow propagation simulation in this work.

Level of exposure	Analysis criteria
Very high	-Lava flow (area that has already been inundated by lava)
	-Area in the potential lava flow corridor (with high probability of flooding)
High	- Area in the potential lava flow corridor (path)
	(with medium to low probability of inundation)
	-Areas with high CO_2 concentration (MAZUKU)
Moderate	-Area outside the potential lava flow corridor
	-Area adjacent to the exposed area (high), maximum distance: 500m.
Low	-Zone outside the potential lava flow corridor
	-No lava flows, no MAZUKU

2.6   Vulnerability analysis of the road, lake and air traffic network of Goma city

To highlight the potential exposure of roads, ports and airports to volcanic hazards, the volcanic hazard level map was overlaid on the road, lake and air network map. The mileage (length) of roads potentially exposed to lava flows was then calculated using QGIS geoprocessing tools.

3   Results

3.1   Lava flow invasion probabilities maps

The results of the lava flow simulation are shown in Figures 3 to 6: Figure 3.1 for vent 1, Figure 3.2 for vent 2, Figure 4.1 for vent 3, Figure 4.2 for vent 4, Figure 5.1 for vent 5, Figure 5.2 for vent 6, Figure 6.1 for vent 7, Figure 6.2 for vent 8.

From the 8 vents considered in this paper, these maps show the path that the lava flow could potentially follow if an eruption occurred on the flank of Nyiragongo towards the city of Goma.

The probability of the lava flow path being inundated varies from:

– 0.06% (areas colored in white) to 73.73% (areas colored in dark red) for vent 1,
– 0.06% to 41. 93% for vent 2,
– 0.06% to 58.86% for vent 3,
– 0.06% to 47.33% for vent 4,
– 0.06% to 27.4% for vent 5,
– 0.06% to 100.00% for vent 6,
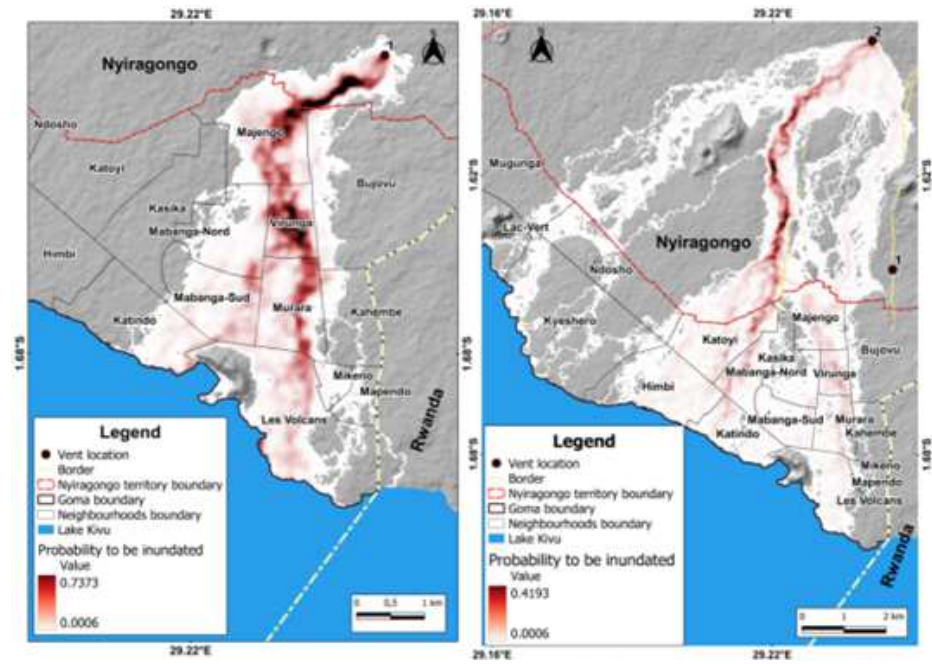– 0.06% to 50.93% for vent 7 and
– 0.06% to 37.13% for vent 8.

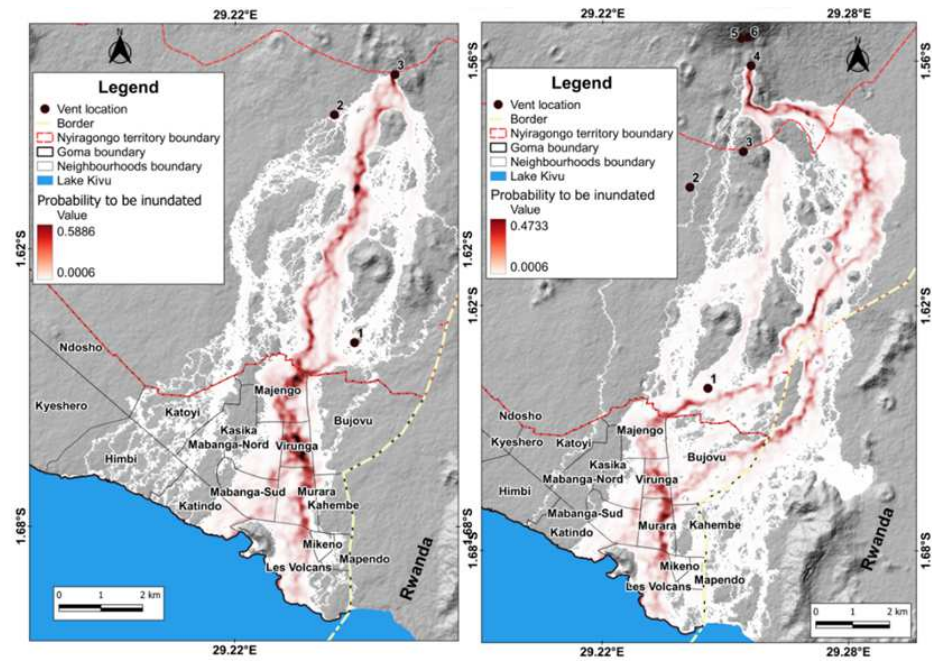**Fig. 3.** (3.1) and (3.2). Lava flow inundation probability maps

Fig. 4. (4.1) and (4.2). Lava flow inundation probability maps
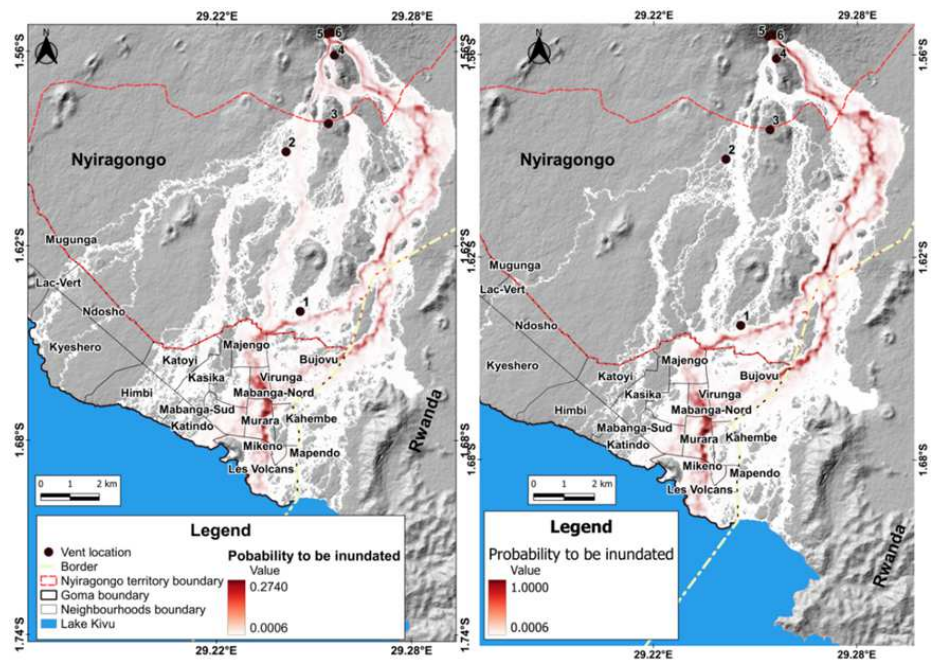
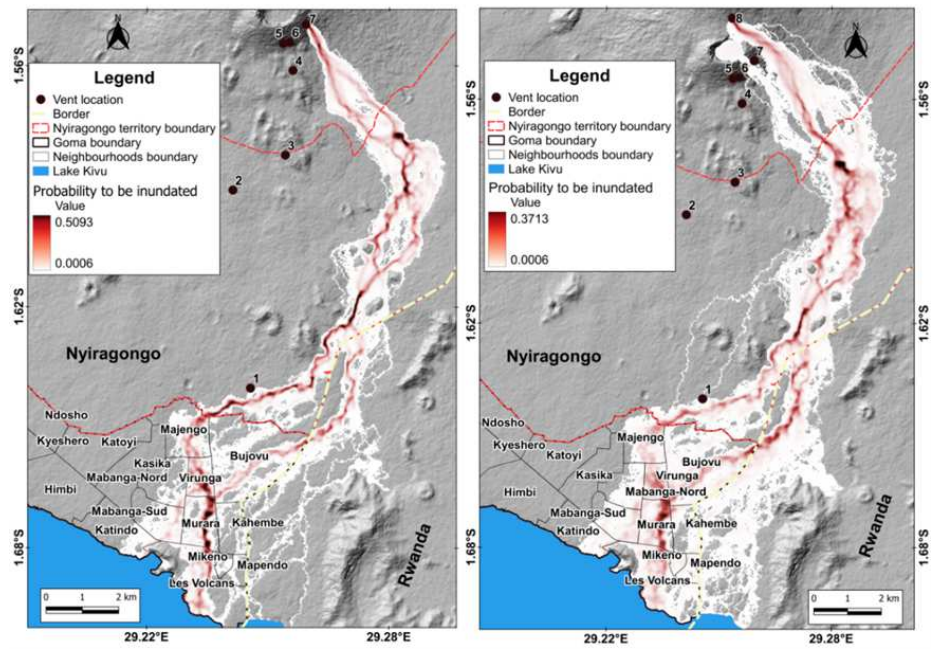**Fig. 5.** (5.1) and (5.2).Lava flow inundation probability maps

Fig. 6. (6.1) and (6.2).Lava flow inundation probability maps

3.2   Volcanic Hazard exposure assessment

The city of Goma is exposed to several types of geological hazards, including the Nyiragongo volcano, which threatens the city's rapidly growing population as shown in Table.4.

Table 4. Vulnerability of the urban area

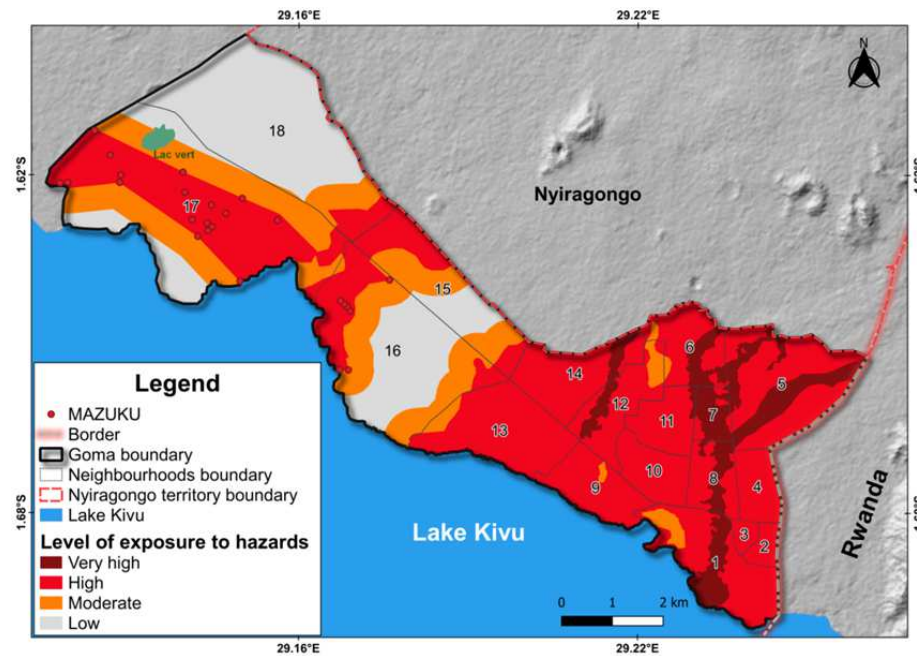| Exposure zone	Area (m2)	Proportion(%)
Very high	4375664.63	7.41877966
High	30240388.33	51,2714746
Moderate	10669508.51	18,0897622
Low	13695360.34	23,2199835
Total	58980921.81	100

Fig. 7. Hazard exposure assessment map

Neighborhoods are represented by the numbers on the map: 1 = Les Volcans, 2 = Mapendo, 3 = Mikeno, 4 = Kahembe, 5=Bujovu, 6=Majengo, 7=Virunga, 8=Murara, 9=Katindo, 10=Mabanga-Sud, 11=Mabanga-Nord, 12=Kasika, 13=Himbi, 14=Katoyi, 15=Ndosho, 16=Kyeshero, 17=Lac-Vert, 18=Mugunga.

3.3   Vulnerability analysis of the road, lake and airport traffic network in the city of Goma

Cross-referencing the level of exposure map with the road, lake and air network map highlights the roads, ports and part of the airport potentially exposed to volcanic hazards as shown in the following table and figure.

Table 5. Vulnerability of land traffic.

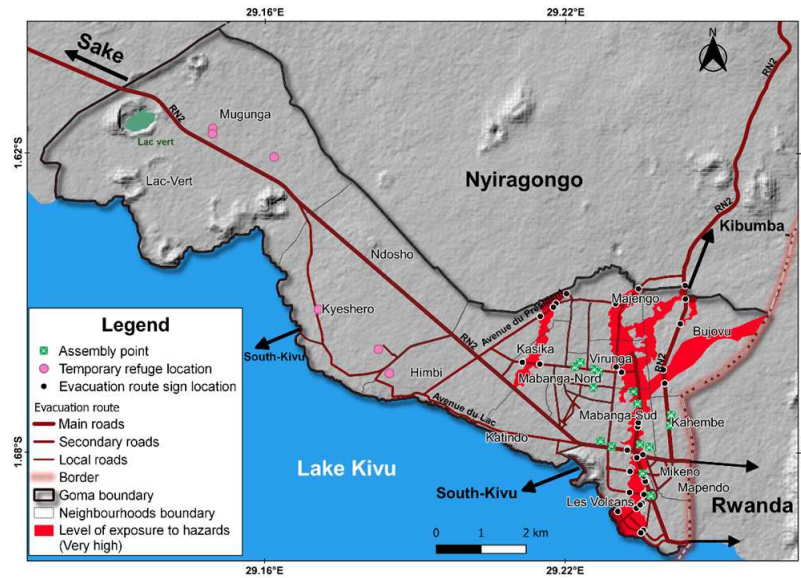| Exposure zone	Main roads (m)	Secondary roads (m)	Others roads
Very high	3226.91 (13.52%)	6451.91 (13.94%)	66343.60 (8.88%)
High	12673.98 (53.11%)	27756.82 (59.98%)	381394.76 (51.05%)
Moderate	3621.96 (15.18%)	7660.36 (16.55%)	121965.38 (16.33%)
Low	4342.60 (18.20%)	4407.38 (9.52%)	177330.24 (23.74%)
Total	23865.45 (100%)	46276.47 (100%)	747033.98 (100%)

Fig. 8. Assembly point, temporary refuge location, evacuation route sign location, Evacuation routes.

3.4   Evacuation route, location of evacuation route sign, assembly points, temporary refuge areas

Based on the volcanic hazard exposure map and lava flow probability maps, we proposed temporary refuge areas, assembly points and evacuation route, location

of evacuation sign in case of volcanic crisis similar to those of 1977, 2002 and 2021. Six locations were selected to leave Goma: (1) toward Sake town by road, (2) toward South-Kivu via Kituku beach by Boat (3) toward South-Kivu via the national commercial ports by boat, (4) toward Rutsuru/Kiwanja via Kibumba, (5) toward Gisenyi/Rwanda using "Grande bariiere, la Corniche" border (6) toward Gisenyi/Rwanda using "Petite Barierre" borders.

The proposed temporary refuge areas are (1) ULPGL Campus Moise, (2) ULPGL Campus Salomon, (3) UCNDK, (4) Université Catholique la Sapientia and (5) E.P. NENGAPETA. They are mainly located in areas with moderate or low exposure to volcanic hazards. Meanwhile for the location selection of evacuation route signs, the exit points from very high-level area of exposure to lava flow hazard were taken into account. When installing the route signs in modeling study, it would be advisable to indicate a double message: "Exit" for people evacuating from the danger zone and "No Entry" for people surrounding those very high-level area of exposure

4   Discussion

Results of lava flow propagation simulation show that 11 neighborhoods (out of 18 in the city), namely Majengo, Bujovu, Virunga, Mabanga-North, Mabanga-South, Murara, Les Volcans, Katindo, Himbi, Katoyi, Kasika, in the eastern part of Goma city, are located in the potential lava flow corridor. However, 7 out of thsoe 11 neighborhoods specifically Majengo, Virunga, Murara, Bujovu, Les Volcans, Katoyi and Kasika are more exposed to lava flow inundation than others. consequently, more than a half of the city of Goma is highly exposed to the Nyiragongo volcanic hazards. These high hazard exposure areas are located in the eastern part of the city, comprising with the oldest neighborhoods. Yet, this is the area where the majority of the population, the commercial center and the main public and private institutions are located.

Analysis of the hazard exposure assessment map (fig.7) shows that more than 51.3% or 30.2 km2 of the total urban area is highly exposed to the hazards of the Nyiragongo volcano, while 7.4%, 18.0% and 23.2% of the city is very highly exposed, moderately exposed, weakly exposed or not exposed to these hazards as shown in Fig.7.

Regarding the vulnerability of Goma's roads as shown in table 5 and the figure 7, it was noticed about the main roads that:

- 53.11% (12.6 km) of them, including national road number 2, are located in the high level of exposure zone (High).
- 3.2 km or 13.52% of the main roads are located in the very high exposure zone (Very high). They are cut by lava flows which make them largely unusable.
- Only 15.18% and 18.20% of the main roads are respectively in the area of medium and low exposure or not at all exposed to volcanic hazards (lava flows and Mazuku).

Considering of secondary roads, it was also noticed that:

- 6.45km or (13.94% of secondary roads) in the east of the city are mainly
  vulnerable because they are located in the zone of high exposure to volcanic
  hazards. They can be cut by lava flows.
- 16.55% and 9.52% of secondary roads located in the Moderate and Low zones
  respectively are potentially little or not at all exposed to volcanic hazards.

The maritime transport network is centred on the infrastructure of the na-
tional commercial ports: (1) Port Emmanuel, (2) Port Ihusi, (3) Port Marinette
Express Maison MI, (4) Port Etoile du Kivu/Goma and (5) the Port of Kituku.
Most of these ports (4 out of 5) are located in "Les Volcans", a neighbourhood
in the potential lava flow corridor. Only the port of Kituku has a low exposure
to lava flows.

Regarding the vulnerability of Goma's air traffic, the air network is centred
around Goma's international airport, which is unfortunately located in an area
highly exposed to lava flows.

About the evacuation route, 6 locations were selected. But, If the main road
to Kibumba is cut off and the commercial port is highly threaten, only 4 loca-
tions will remain, namely (1) location toward Sake town, (2) location toward
South-Kivu via Kituku Port (3) location toward Rwanda via Grande-Bariere,
(4) location toward Rwanda via Petite-Bariere.

Land, lake and air communication infrastructure play a strategic role before
and during a volcanic crisis for people security, evacuation, rescue and so on.
In the aftermath of a crisis, they are critical to the recovery and reconstruction
of an area. The degree of vulnerability of these key infrastructures is shown in
Figure 8. Therefore, hazard mitigation actions such as preparedness need to be
planned earlier by all actors involved in emergency evacuation management.

5   Conclusion

The eleventh Sustainable Development Goal (SDG) of the United Nations (UN)
2030 Agenda emphasizes the need to make cities and human settlements in-
clusive, safe, resilient and sustainable [8], [1]. Accordingly, this study aimed to
propose potential evacuation scenarios in the event of a volcanic crisis. To this
end, GIS-based models were developed based on Mazuku distribution and sim-
ulation of lava flow inundation probabilities.

The result shows that 11 neighborhoods out of 18 in the east of Goma city
are located in the potential lava flow corridor including 7 neighborhoods more
exposed to lava flow inundation than others.

More than 51.3% or 30.2 km2 of the total surface area of the urban area is
highly exposed to the Nyiragongo lava flow hazard, while 7.4%, 18.0% and 23.2%
of the city is respectively very highly, moderately and weakly or not exposed to
these hazards.

This study addresses risk and vulnerability assessments, one of key aspects
of natural disaster management.

Based on the results of this study, we strongly recommend:

- – people's sensitization program for awareness,
- – logistical planning, and updating of the contingency plan to take into account the proposed results
- – enforcement of land use regulations and environmental analysis studies.
- – planning of relocation of some communication infrastructures such airports and the main lake port, or in the extreme case, the relocation of the city.

More studies in modeling/simulation of evacuation for Goma case study are highly needed.

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