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Geospatial analysis of population exposure associated with lava flow and Mazuku hazard at Nyiragongo, and implications for evacuation planning for Goma, D.R. Congo

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Abstract

The city of Goma in the Democratic Republic of Congo faces significant volcanic hazards from Nyiragongo volcano, yet these dangers are largely overlooked in urban planning and land use strategies. Effective evacuation plans for potential volcanic disasters depend on a thorough understanding of the geospatial characteristics of the evacuation environment, which can change over time. This study assesses risks associated with volcanic hazards in Goma, focusing on exposure to lava flows and the dangers of CO_2-rich gas emission areas known locally as Mazuku. Using QGIS and Q-LavHA tools, mapping and simulations were conducted based on historical eruption data from 1977, 2002, and 2021 to model lava flow paths towards Goma from eight eruption vents. The findings indicate that over half of Goma is at high risk from volcanic hazards, particularly in areas where the majority of the population and critical infrastructure are located. To enhance community resilience in line with the eleventh Sustainable Development Goal (SDG 11), this paper proposes evacuation scenarios and mitigation strategies based on a detailed hazard and exposure assessment. The result of this study shows that eleven neighborhoods in the east of Goma city are located in the potential lava flow corridor and that roads, lake ports and part of the airport are potentially exposed to volcanic hazards. This study contributes to global methodologies for assessing volcanic hazard exposure in data poor regions. In addition, the proposed geospatial environment model is crucial for developing agent-based simulation studies to improve evacuation effectiveness during volcanic events.

Keywords Nyiragongo, Volcanic crisis, Geospatial analysis, Geospatial environment, Lava flow simulation, Mazuku, Evacuation plan, SDG 11

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Introduction

Geospatial analysis has become a cornerstone for understanding and managing exposure to volcanic hazards at global, regional, and local scales. At the global level, Freire et al. (2019) estimate that over one billion people, 14.3% of the world's population in 2015, live within 100 km of a Holocene volcano, with population growth near volcanoes often exceeding global averages, particularly in Southeast Asia. Case studies further confirm the utility of such approaches. For instance, research around Mount Semeru in Indonesia shows how detailed surveys and statistical methods identify high-risk neighborhoods and vulnerability factors, enabling informed preparedness (Thouret et al. 2023). Similarly, Reyes-Hardy et al. (2021) conducted the first GIS-based risk assessment for Guallatiri volcano in Chile, while Biass et al. (2012) examined Cotopaxi in Ecuador, integrating hazard modeling with vulnerability analysis to reveal potential widespread impacts.

Regional-scale assessments have further expanded volcanic risk knowledge. Meredith et al. (2024) compiled the first global dataset of lava flow impacts on infrastructure, though most records lacked detail on damage intensity, limiting their operational value. Similarly, Kervyn et al. (2024) mapped susceptibility at Nyiragongo and Nyamulagira in the DRC, validated by the 2021 eruption, although these analyses were not integrated into Goma's contingency planning. While such studies offer valuable methodologies for advancing volcanic risk science, they reveal a persistent gap in connecting hazard assessment to evacuation planning at the local level.

Despite these broader efforts, the hazards of Mount Nyiragongo in the DRC demand urgent attention. Located just 18 km north of Goma, Nyiragongo is notorious for its exceptionally fluid lava capable of advancing at speeds up to 100 km/h (Tedesco et al. 2007; Boudoire et al. 2022). Eruptions in 1977, 2002, and 2021 devastated Goma, causing loss of life, extensive damage to homes and businesses, and disruption of essential road infrastructure (Baxter et al. 2003; Tedesco et al. 2007; Balagizi et al. 2018; Adalbert et al. 2021). These disasters unfolded in parallel with rapid urban growth, as Goma's population expanded from roughly 50,000 in 1977 to more than one million by 2021 (Tshiswaka-Tshilumba and Nagamatsu 2024). Alongside lava flows, the city is threatened by Mazuku, which refer to areas where CO_2, a dense and odorless asphyxiant gas, accumulates, creating potentially lethal conditions for inhabitants. In addition to their high concentration of CO_2, Mazuku give a false impression of warmer temperatures, making them a preferred shelter for refugees (Balagizi et al. 2018). Between 1994 and 1996, many Rwandan refugees died while sheltering in Mazuku, unaware of their toxicity (Balagizi et al. 2018). Local military officials have also reported the deaths of soldiers in Mazuku during wartime operations (Balagizi et al. 2018). In February 2023, Joseph Makundi, the civil protection coordinator for North Kivu, died of asphyxiation in Bulengo, in the "Lac Vert" neighborhood west of Goma (Gouvernorat de la Province du Nord-Kivu 2024; Kapinga 2024). In April 2023, at least five people were reported to have died of suffocation due to Mazuku exposure in Goma (Kapinga 2024). Mazuku are recognized as the most persistent natural hazard in the North-Kivu region of the Democratic Republic of Congo, continually threatening human life and resulting in multiple fatalities each year (Wauthier et al. 2018). The coexistence of rapid lava flows and ongoing Mazuku exposure creates a multi-hazard risk environment for Goma.

Previous research has yielded many insights into these hazards. Favalli et al. (2009) simulated the 1977 and 2002 eruptions to produce hazard maps, while Chirico et al. (2009) tested protective barriers in digital terrain models. Recent studies have offered more nuanced perspectives on eruption dynamics: Kyambikwa et al. (2025) measured eruption volumes and viscosity changes; Mutima et al. (2024) analyzed seismicity and geothermal shifts preceding the 2021 eruption; and Muhindo Musubao (2022) documented fissures and lava pathways aligned with the East African Rift. These contributions substantially improve hazard characterization but largely exclude urban exposure and evacuation feasibility. Parallel hazard assessments have emphasized multi-hazard dimensions. Balagizi et al. (2018) examined Nyiragongo's combined threats, including possible CO_2 and CH_4 release from Lake Kivu, while Smets et al. (2010) identified Mazuku as a recurrent lethal hazard in southern Goma. In terms of social exposure, Adalbert et al. (2021) highlighted daily population mobility patterns, and Michellier et al. (2020) mapped household vulnerability using Social Vulnerability Index (SoVI) and Operational Vulnerability Index (OVI) indicators. Abdelhamid et al. (2025) advanced this body of work by integrating field observations, GIS, and satellite remote sensing to map lava flows and gas emissions during the 2021 eruption, while also documenting infrastructure damage and proposing geospatial tools for urban planning. Yet, despite these valuable contributions, most studies remain static when considering the infrastructural and spatial dynamics that shape evacuation.

Taken together, past research has generated hazard maps, Mazuku surveys, eruption analyses, and vulnerability indices. Yet a crucial shortcoming persists: no study has systematically integrated lava flow and

Mazuku hazard modeling with a holistic view of urban exposure, encompassing both population vulnerability and transport infrastructure (roads, airport, lake port). Across the reviewed studies, scientific insights into volcanic hazards have not been translated into operational evacuation strategies, such as mapping of safe routes, installation of signage, designation of assembly points, or identification of refuge areas. This persistent gap forms the basis of the present research.

This study addresses these limitations while aligning with SDG 11 of the 2030 United Nations Agenda, which emphasizes making cities and human settlements inclusive, safe, resilient, and sustainable (Krellenberg et al. 2019; Abubakar and Aina 2019; Ariyanti et al. 2020; Jain et al. 2023). Although SDG 11 does not explicitly reference volcanic hazard assessment, it encompasses critical aspects of natural hazard management, including volcanic risks and population exposure. Consequently, effectively assessing and managing exposure to volcanic hazards becomes fundamental for strengthening community resilience to natural hazards and to fully realizing the objectives of SDG 11.

Leveraging QGIS and Q-LavHA, this study aimed to explore the spatial distribution of lava flow and Mazuku hazards, evaluate their implications for human safety, and propose actionable insights for evacuation planning in one of the world's most volatile regions. It also provides a replicable methodology for other data-scarce volcanic regions. Accordingly, the objectives of this study are to:

- Simulate the probability of lava flow inundation using geospatial analysis and historical eruption data.
- Evaluate the exposure of Goma's population and key infrastructure (roads, airport, lake port) to lava and Mazuku hazards.
- Identify safe evacuation routes, assembly points, signage, and temporary refuge areas to improve preparedness.
- Recommend mitigation measures for volcanic emergencies, while ensuring alignment with disaster risk reduction frameworks.

Materials and methods

Study approach

The methodology follows a structured, GIS-based approach to volcanic hazard assessment and evacuation planning, progressing from conceptual design to actionable strategies. The process is divided into three main phases: preparation, simulation and analysis, and strategic response.

Preparation phase

This phase establishes the foundational framework for the study. It begins with (1) defining key GIS parameters critical for evacuation planning, followed by (2) selecting the study area, and (3) identifying appropriate software tools. Next (4), comprehensive data collection is conducted, encompassing both geospatial and hazard-related datasets. Finally (5), simulation parameters are specified, including eruption source characteristics (e.g., number of vents, proximity to Lake Kivu, lava flow thickness, topographic correction factors, and the number of iterations, to support accurate modeling of hazard scenarios).

Simulation & analysis phase

This phase forms the core of the hazard assessment, with (6) the simulation execution: Probabilistic modeling is conducted to generate lava flow inundation probability maps for each potential eruption vent. Then, in (7) result presentation, simulation outputs inform actionable planning through:

- Lava flow invasion probability maps.
- Assessment of volcanic hazard exposure.
- Analysis of exposure across Goma's critical infrastructure, including roads, Lake Kivu ports, and the airport.
- Identification of evacuation routes and best placement of route signage, and designation of assembly points and temporary refuge areas.

Strategic response

This final phase translates analytical findings into practical strategies for risk mitigation. At step (8), interpretation of results, the hazard maps and simulation outputs are critically analyzed to identify patterns of exposure, assess vulnerability, and understand the spatial dynamics of lava flow and Mazuku threats. Finally, in the last step (9), mitigation measures are formulated and proposed to enhance community preparedness and response capacity.

The overall workflow is illustrated in Fig. 1.

Definition of key GIS parameters for evacuation planning

Geospatial analysis often employs GIS-based modeling and simulation to explore diverse phenomena. In this study, four distinct categories of parameters were employed, as outlined in Table 1.

Study area

Goma, the capital city of North Kivu province, is located in eastern Democratic Republic of Congo (DRC), bordering Rwanda. It is situated between 1.59° north and 1.70° south and between 29.11° and 29.26° east. Nyiragongo is situated within the East African Rift Valley, a tectonically

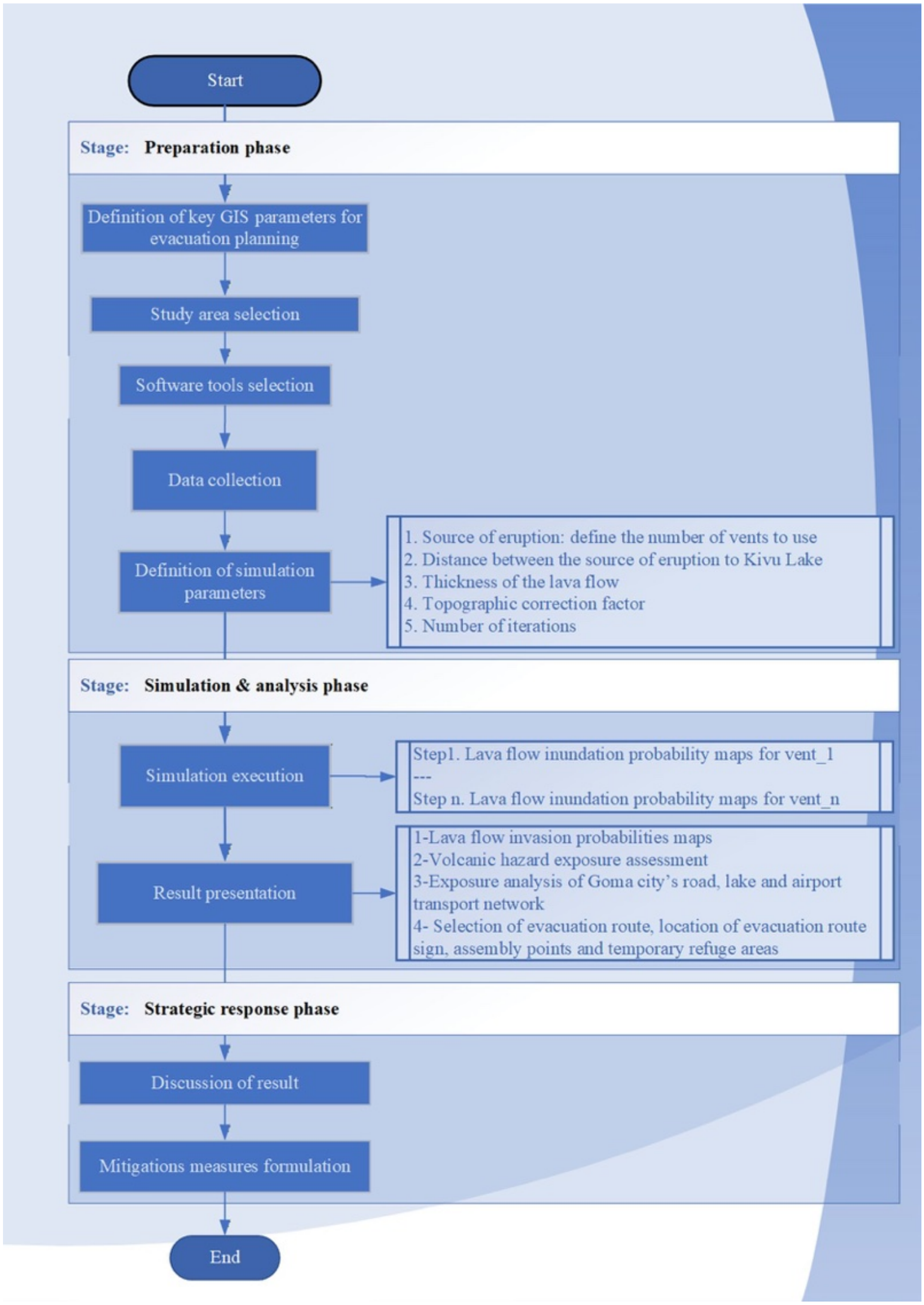

Fig. 1 Step-by-step flowchart of the study's approach. Workflow for GIS-based volcanic hazard assessment and evacuation planning. The flowchart outlines a three-phase methodology: Preparation, simulation & analysis, and strategic response, used to model lava flow hazards, assess exposure of critical infrastructure, and design evacuation strategies. It integrates geospatial tools and historical eruption data to support decision-making in volcanic risk management

Table 1 Key analytical parameters for GIS-based volcanic hazard modeling and evacuation planning. this table categorizes the Geospatial inputs used to simulate lava flow and Mazuku hazards, assess infrastructure vulnerability, and optimize evacuation logistics in Goma. It includes data layers, hazard metrics, network analysis tools, and safe zone identification criteria essential for integrated risk assessment

Parameter Category	Parameter	Definition	Usage
Geographical	Digital Topography, expressed as DEM	A digital elevation model (DEM) is a georectified grid-based representation of surface elevation. Most DEMs use rectangular arrays stored as raster images (Guth et al. 2021).	Supports simulation of lava dynamics and identification of evacuation routes.
	Land use	Classification of surface areas (urban, vegetation, water) reflecting human settlements and natural features.	Informs safe zone selection and accessibility assessment.
	Infrastructure	Spatial data on critical physical facilities and transport networks (roads, airports, lakes ports).	Assists in planning evacuation routes and identifying key access points.
	Volcanic vent	Natural geological features representing openings or fractures on the Earth's surface through which magma and gases erupt.	Critical for identifying eruption sources, lava flow modeling, and hazard mapping.
Hazard Assessment	Volcanic activity	Spatial and temporal records of volcanic phenomena such as seismic activity, gas emissions, and surface deformation.	Defines hazard zones for evacuation and informs eruption impacts.
	Exposure level	Classification of exposure indicating how severely populations and assets are exposed to volcanic hazards, typically categorized as "Very high," "High," "Moderate," or "Low."	Used to prioritize evacuation efforts and tailor risk communication strategies.
	Analysis criteria	Rules and thresholds for defining hazard severity and exposure, used to guide evacuation triggers.	Guides classification of exposure levels and timing of evacuation orders.
Evacuation Route Analysis	Network model	Network representation of critical infrastructure exposed to volcanic hazards.	Determines evacuation route feasibility and optimizes escape paths.
	Route optimization	Algorithms for analyzing network optimization such as network flow, ant colony optimization, and Dijkstra's algorithm (Liu et al. 2023).	Facilitates planning of signage, assembly points, and shelter access.
Safe Zones	Assembly point	Locations designated for gathering evacuees for transport to shelters, selected based on access and capacity.	Coordinates evacuation logistics, particularly for vulnerable populations.
	Refuge zone (Temporary/Permanent)	Designated shelters with known capacity and facilities for evacuees.	Guides evacuees to safe locations and assists in emergency shelter management.

active region. Its eruptions are generally effusive, meaning they are characterized by lava flows rather than explosive ash eruptions (Yeo et al. 2022). However, the volcano's steep slopes and the low viscosity, fluid nature of its alkaline lava can lead to rapid and destructive flows. Between the Nyiragongo eruptions of 1977, 2002, and 2021, the city's area expanded to 17.6 km^2, 52.6 km^2 and 76 km^2 respectively (Tshiswaka-Tshilumba and Nagamatsu 2024). The location of the study area is shown in Fig. 2 below.

Geospatial software tools and data

This study used Quantum Geographic Information System (QGIS) for mapping and Quantum-Lava Hazard Assessment (Q-LavHA) for simulating lava flow propagation. Q-LavHA is a freeware plugin for QGIS designed to simulate the probability of lava flow inundation from single or multiple regularly distributed eruptive vents on a DEM. It combines established probabilistic and deterministic models, including the FLOWGO thermo-rheological model, to improve calculations of lava flow spatial propagation and terminal length (Mossoux et al. 2016). Designed for scientists and stakeholders facing imminent or long-term lava flow hazards from basaltic volcanoes, Q-LavHA aids in understanding the spatial distribution of lava flow hazards, informs land use decisions, and supports evacuation planning during volcanic crises (Mossoux et al. 2016). Developed in Python, its flexible code can be adapted to user needs, and its user-friendly interface facilitates widespread use within the QGIS platform.

For this study, Q-LavHA was implemented using a DEM with a 30-m resolution and shapefiles of eruptive vents from the 1977, 2002, and 2021 eruptions, sourced from the Goma Volcano Observatory (in French, Observatoire Volcanologique de Goma, OVG). The DEM was freely downloaded from https://dwtkns.com/srtm30m/. Additional spatial data, including roads, lakes, and air traffic networks, were incorporated from OpenStreetMap, https://extract.bbbike.org/.

Q-lavHA simulation of lava flow propagation

Data pre-processing

Prior to the simulation, several pre-processing steps are necessary for the raster data: reprojection of the DEM into the UTM (Universal Transverse Mercator) coordinate reference system, cropping to the area of interest, and filling of depressions. These operations help prevent the simulation from failing due to errors

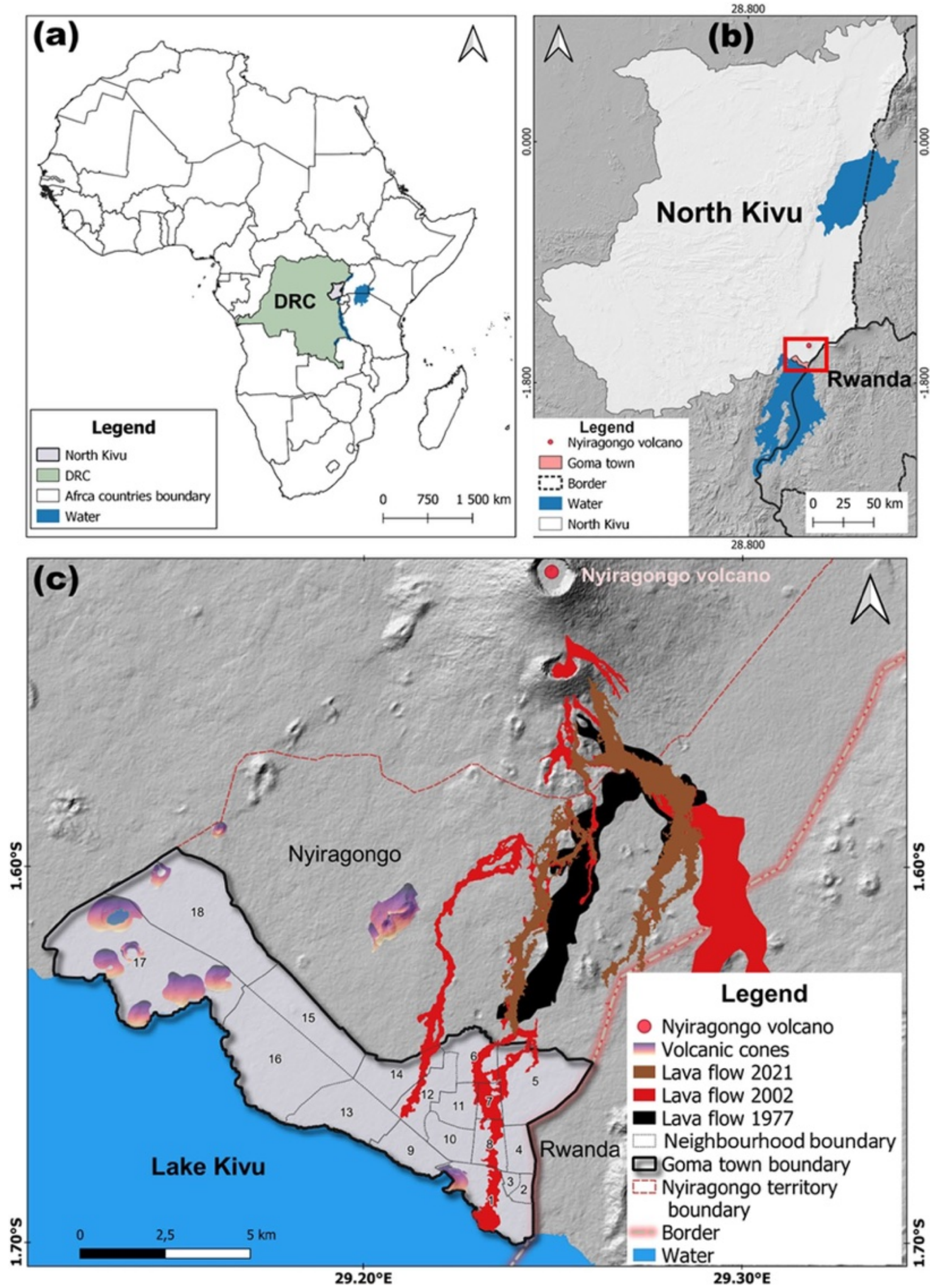

Fig. 2 Location of the study area and geological context of Nyiragongo volcano and surrounding hazard zones. (a) Map of Africa showing the Democratic Republic of Congo (DRC), (b) Regional map showing North Kivu province and Nyiragongo volcano, with a bounding box indicating the study area, and (c) Detailed map of the study area showing the spatial distribution of lava flows from the 1977, 2002, and 2021 Nyiragongo eruptions, volcano boundaries, and the layout of Goma's neighborhoods and critical infrastructure. 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

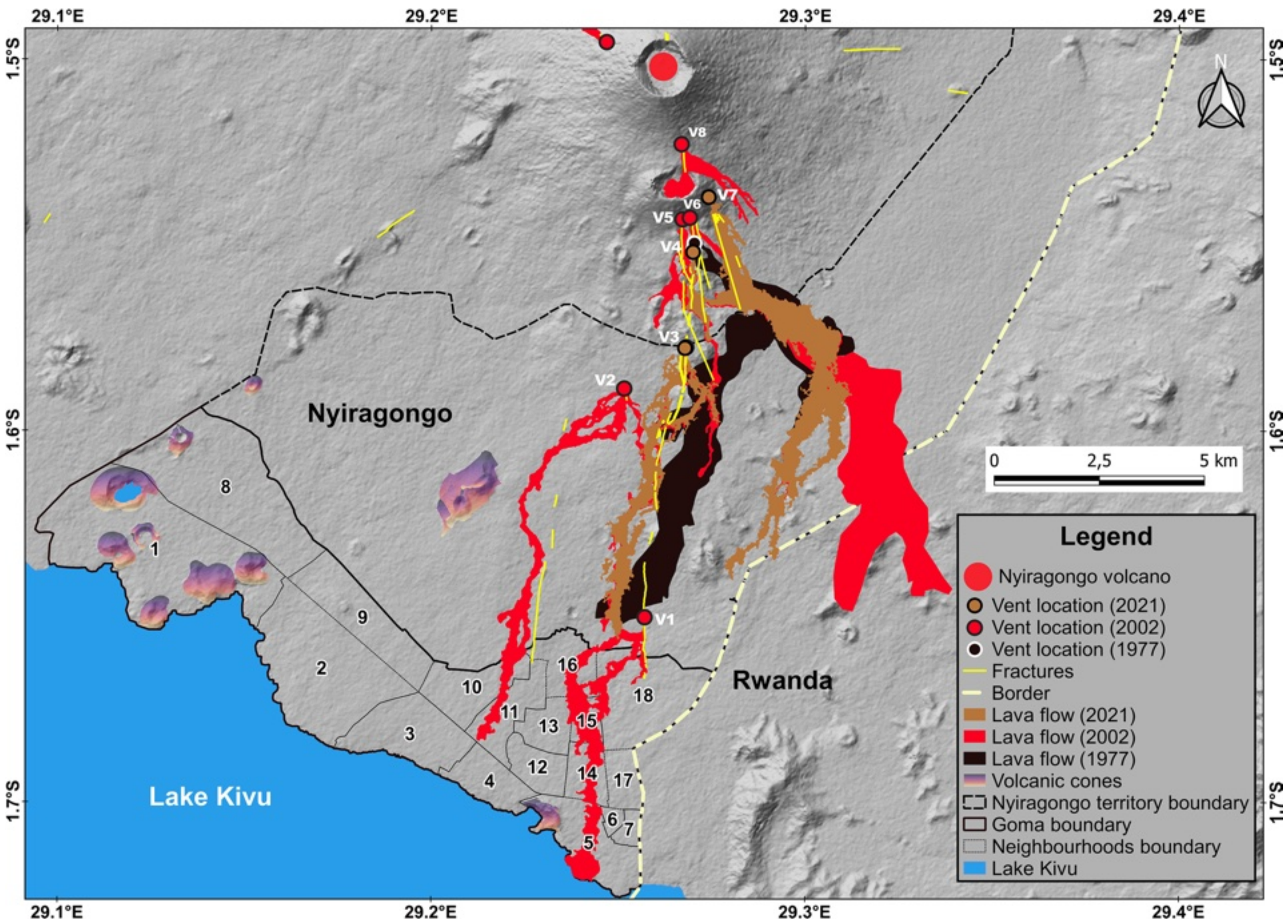

Fig. 3 Vent locations for eruptions in 1977, 2002, and 2021, alongside the resulting lava flows and their paths toward the city of Goma and Lake Kivu

Table 2 The Geospatial location of eruption vents in universal transverse mercator (UTM) format, along with their respective distances to lake Kivu (in meters)

Vent No	Northing(m)	Easting(m)	Altitude	Distance (m)	Eruption/s
1	749,851	9,818,568	1598	8000	2002
2	749,366	9,824,019	1855	12,000	2002
3	750,815	9,824,982	1965	14,000	2002, 2021
4	751,024	9,827,312	2260	19,000	1997, 2021
5	750,755	9,828,051	2423	17,000	2002
6	750,932	9,828,088	2405	17,000	2002
7	751,382	9,828,579	2484	18,000	2021
8	750,736	9,829,841	2816	19,500	2002

in the DEM. While Q-LavHA requires input data in the .asc format, it can also accept .tiff files, which are automatically converted to .asc within the plugin. Accordingly, null values (NoData) and anomalous depressions (sinks) in the DEM were filled. The study area was then projected using the WGS 84 / UTM zone 35 S coordinate system.

Simulation

– *Eruption sources (vent locations)*

Considering the last three eruptions (1977, 2002, and 2021), eight potential vents were identified on the south flank of Nyiragongo volcano. All of these vents are situated along fractures, as shown in Fig. 3. Additionally, most of the vents are clustered in the same area, with some sources overlapping. Therefore, eight vents representing the most active and relevant lava flow sources-were selected for the simulation.

The geographical coordinates (in UTM) of the vents used in simulations are provided in Table 2 and their locations are illustrated in Fig. 3.

In Table 2, "distance" is one of the parameters used to simulate lava flow propagation. It represents the user-defined maximum length over which the lava flow can extend. To identify the potential lava flow corridor, we considered a scenario in which the lava reaches Lake Kivu. For each vent, the distance between the source and Lake Kivu was determined by following the direction of past lava flows.

Table 3 Additional input parameters for the lava flow propagation simulation

Parameter	Symbol	Value	Unit	Source
Characteristic thickness of the lava flow	Hc	1.5	m	(Kamate Kaleghetso 2018)
Topographic correction factor	Hp	7	m	(Kamate Kaleghetso 2018)
Number of iterations	-	1500	-	(Mossoux et al. 2016)

Table 4 Criteria for volcanic hazard zonation used in risk assessment and evacuation planning

Level of hazard	Analysis criteria
Very high	Areas directly impacted by past lava flows, indicating a high likelihood of future inundation. Area in the potential lava flow corridor (with high probability of inundation based on modelling).
High	Area within the potential lava flow corridor (with medium to low probability of inundation based on modelling). Areas with high CO_2 concentration (Mazuku), as identified in the hazard assessment by Balagizi et al. (2018).
Moderate	Areas outside the potential lava flow corridor. Areas adjacent to the exposed area (high), maximum distance: 500 m.
Low	Zone outside the potential lava flow corridor. No previous lava flows, no Mazuku.

This table outlines the parameters and thresholds applied to classify hazard zones based on lava flow intensity, proximity to eruption vents, topographic features, and exposure of critical infrastructure. These zonation criteria support the delineation of exposure levels and guide strategic evacuation decisions

- *Other parameters used for the simulation*

The other parameters used to simulate lava flow propagation are shown in Table 3. Correction factors have been included to allow the lava to overcome small topographic obstacles or pits (Mossoux et al. 2016).

Analysis criteria used to assess the relative levels of volcanic hazard

Zoning of potential volcanic hazards in the city of Goma was performed based on the criteria listed in Table 4.

Based on the description of hazard levels provided above (Table 4), individuals located within these zones are classified as having very high, high, moderate, or low exposure, respectively. This categorization reflects the spatial severity of volcanic threats and informs subsequent evacuation planning by identifying priority zones for intervention and resource allocation.

Exposure analysis of goma's roads, lake and air transport network

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.

Results

Lava flow invasion probabilities maps

Using the eight vents considered in this study, we modelled the potential paths that lava flows could take if an eruption were to occur on the flanks of Nyiragongo toward the city of Goma. The probability of lava inundation ranged from very low (indicated by white areas) to very high (indicated by dark red areas), as detailed in Figs. 4, 5, 6 and 7; Table 5.

The results of the lava flow simulations are shown in Figs. 4, 5, 6 and 7.

Volcanic hazard exposure assessment

Results show that the city of Goma is exposed to volcanic hazards from Nyiragongo volcano, which threatens the city's rapidly growing population, as shown in Table 6; Fig. 8. Using hazard zones delineated based on the criteria in Table 6, an estimate of the proportion of the urban area in each zone was carried out (Table 6).

A map of volcanic hazard (Fig. 9) reveals critical insights into the exposure of the urban area to the dangers of Nyiragongo volcano. In fact, more than half of the urban area, specifically 51.3%, corresponding to 30.2 km^2, is classified as highly exposed to volcanic hazards. An additional 7.4% of the city is very highly exposed, and the remaining parts of the city are either moderately exposed (18.0%) or weakly/not exposed (23.2%). High hazard exposure areas are located in the eastern part of the city, which includes the most ancients neighbourhoods. Importantly, the majority of the population, the commercial centre and the main public and private institutions are located in this area.

More specifically, the findings of the lava flow modelling (Figs. 4, 5, 6 and 7) 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 (Fig. 9). However, 7 of these 11 neighborhoods, namely Majengo, Virunga, Murara, Bujovu, Les Volcans, Katoyi and Kasika are more exposed to lava flow inundation than others (Fig. 9).

Exposure analysis of Goma city's road, lake and airport transport network

By overlaying the exposure map (zoning) with the road network, Fig. 10 highlights areas of potential risk. Using the geoprocessing tool 'clip', the road network was segmented according to hazard levels (Very High, High, Moderate, Low). Subsequently, the total length

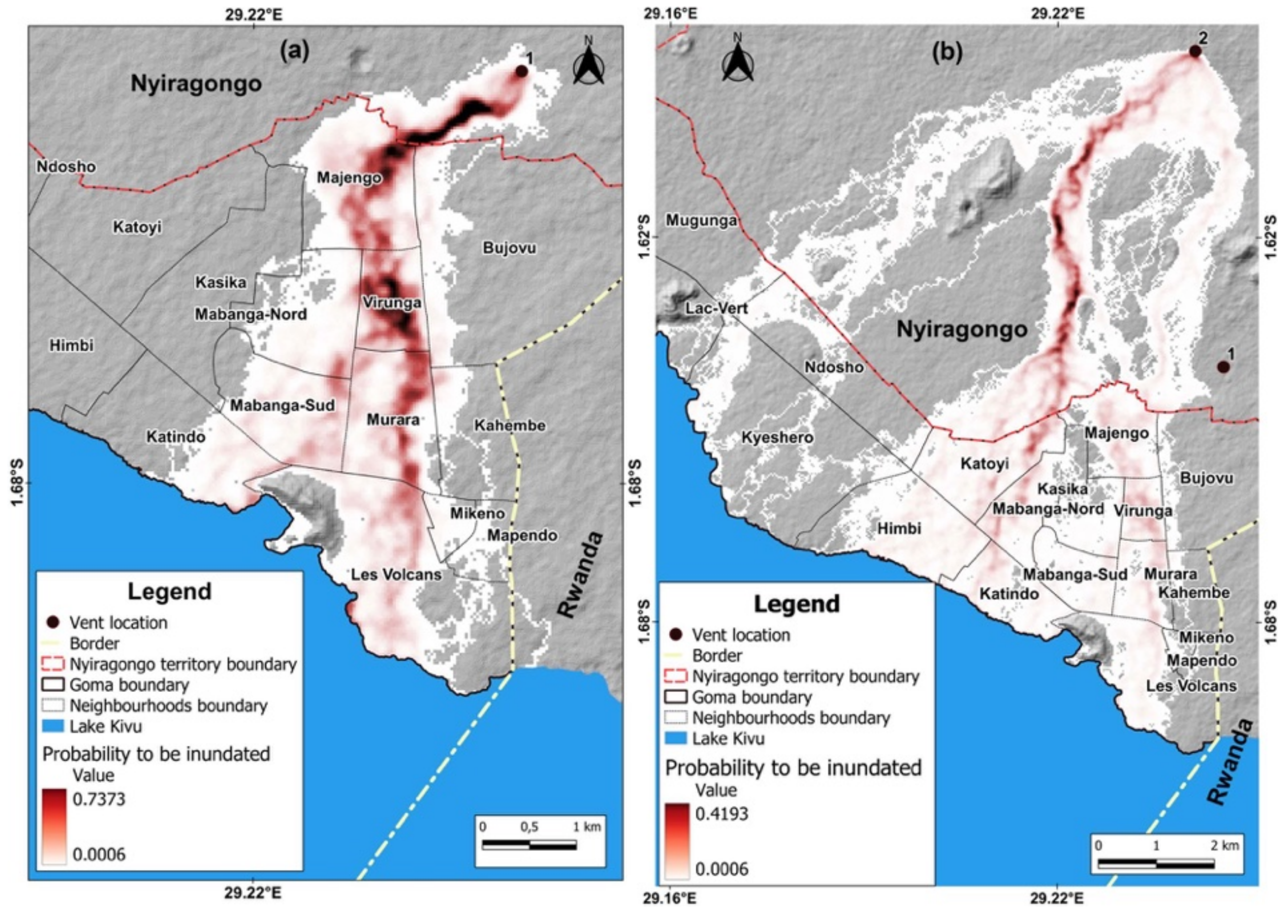

Fig. 4 Lava flow inundation probability maps for Nyiragongo eruption simulations: (a) from vent 1 and, (b) from vent 2

of roads within each zone was calculated by road type, as detailed in Tables 7 and 8. Figure 10 illustrates road network exposure to lava and Mazuku (CO_2) hazards in Goma city, highlighting segments ranging from very high to low risk. Color-coded lines differentiate how various road types intersect hazard zones, offering a clear spatial overview for evacuation planning and infrastructure protection. Table 7 presents a detailed breakdown of the road network in Goma city according to hazard levels and road types. Table 8 complements the category-based breakdown in Table 7 by summarizing the total length of roads affected across hazard zones, regardless of classification.

Regarding the main roads, approximately 12.6 km, or 53%, including segments of National Road 2, fall within the high exposure zone, representing about 3% of the entire road network. An additional 3.2 km (14%) of main roads lie in the very high exposure zone, accounting for 4% of the total network; these segments are directly intersected by simulated lava flows and rendered largely unusable. In contrast, only 15% and 18% of main roads are situated in moderate and low exposure zones, respectively, corresponding to 3% and 2% of the total road network.

Overall exposure levels indicate that 52% of main roads are classified as highly exposed, followed by 23% with low exposure, 16% as moderate, and 9% as very highly exposed. For secondary roads, 6.5 km (8% of the total road network and14% in the eastern part of the city) fall within very high exposure zones and are at significant risk of disruption by lava flows. Additionally, 27.8 km (60%) of eastern secondary roads lie in high exposure zones, while 17% and 10% fall within moderate and low exposure areas, respectively, making them comparatively less threatened.

The lake transport network is centred on the infrastructure of the national 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.

Goma’s international airport, covering 217,530 m^2 with a 2,800-meter runway, lies within a high lava flow

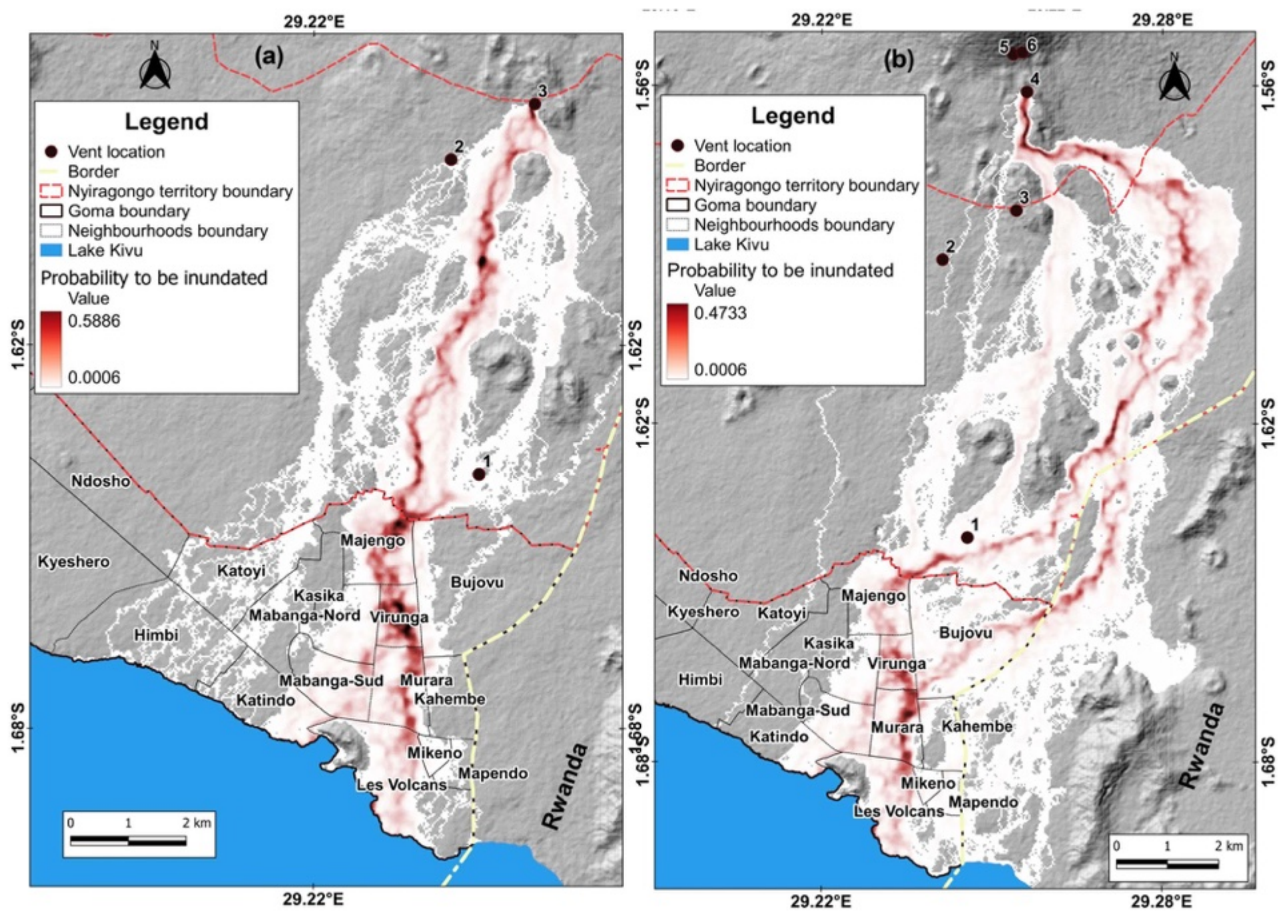

Fig. 5 Lava flow inundation probability maps for Nyiragongo eruption scenarios: (a) Simulated probability of lava flow inundation from vent 3. (b) Simulated probability of lava flow inundation from vent 4

exposure zone, posing a critical vulnerability. Its scale and strategic role in regional and international connectivity make it indispensable for emergency response and evacuation logistics.

Land, lake, and air transportation infrastructure are vital before and during a volcanic crisis, ensuring safe evacuation and rescue operations. In the aftermath, they become essential for recovery and reconstruction. The vulnerability of these key infrastructures is illustrated in Figs. 8 and 10. Accordingly, hazard mitigation measures, particularly preparedness, must be proactively planned by all stakeholders involved in emergency evacuation management taking into consideration identified highly exposed areas and assets.

Evacuation routes, location of evacuation route signs, assembly points, temporary refuge areas

Based on the volcanic hazard map (Fig. 9) and lava flow probability maps in Figs. 4, 5, 6 and 7, an Evacuation infrastructure map was developed (Fig. 11). In this map, we propose temporary refuge areas, assembly points and evacuation routes, and location of evacuation signs in the event of a volcanic crisis. Six evacuation routes out of Goma were identified: (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, and (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 (UCS), and (5) E.P. NENGAPETA. These sites are primarily located in zones with moderate or low exposure to volcanic hazards. For the selection of evacuation route signage locations, exit points from areas with very high exposure to lava flow hazards were considered. When installing the route signs, it would be advisable to include dual messages: “Exit” to guide people evacuating from danger zones, and “No Entry” to warn those approaching the very high hazard areas.

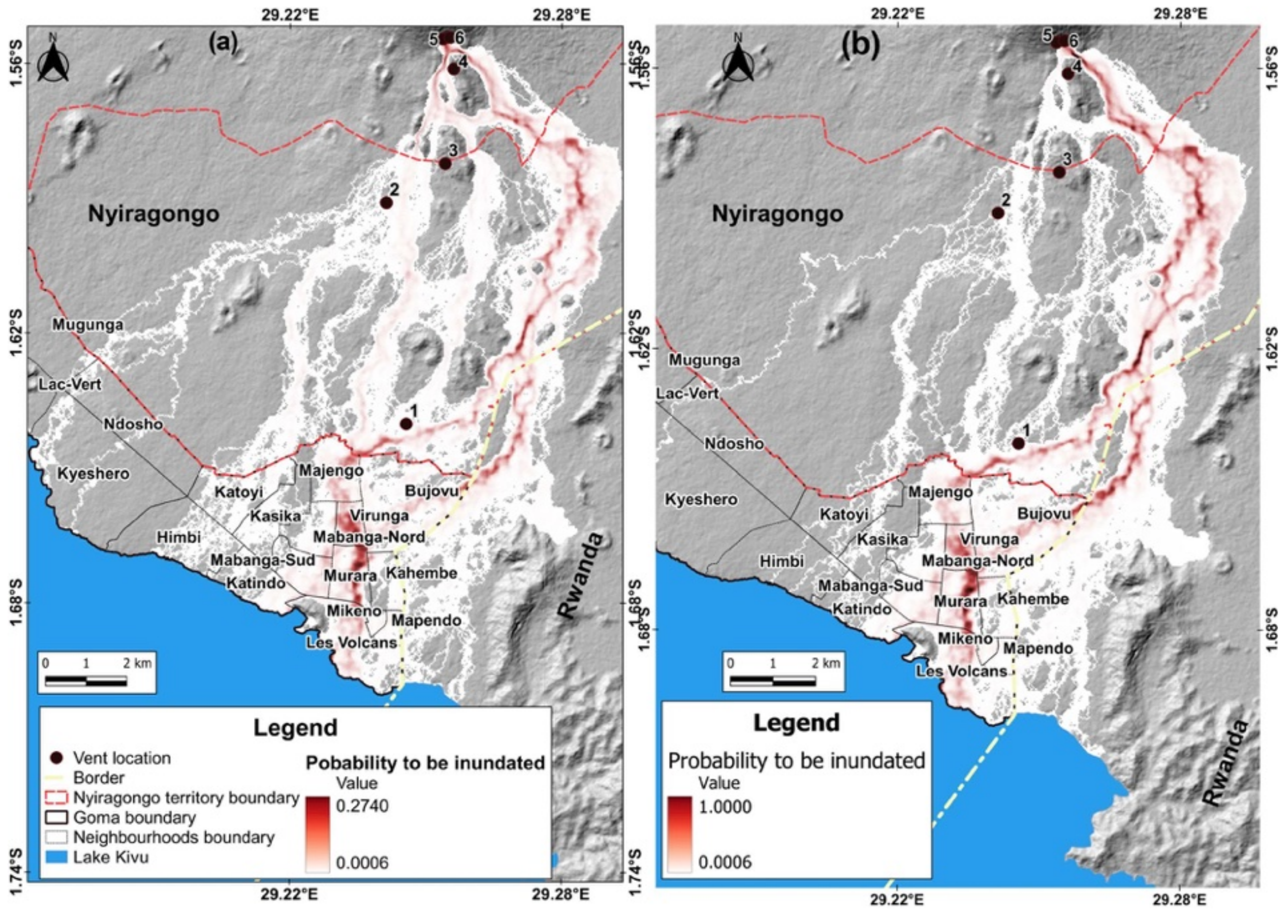

Fig. 6 Lava flow inundation probability maps for Nyiragongo eruption scenarios: (a) Simulated probability of lava flow inundation from vent 5. (b) Simulated probability of lava flow inundation from vent 6

Discussion

Analysis of lava inundation probabilities based on eruptions from eight vents reveals significant spatial variability in volcanic hazard. While all vents show areas with very low chance of being covered by lava (0.06%), the maximum probability of inundation varies widely, from 27.4% for Vent 5 to a full 100% for Vent 6. This indicates that some vents, particularly Vent 6, pose an extreme hazard to certain areas, where lava inundation is virtually certain if an eruption occurs. In contrast, other vents, such as 5 and 8, present lower likelihood of inundation, suggesting more limited potential impact zones. These findings highlight the importance of vent-specific risk assessments in volcanic hazard planning and emergency preparedness. High-probability zones, especially those associated with Vent 6 and Vent 1, should be prioritized for monitoring, evacuation planning, and public awareness campaigns. Overall, the results highlight the importance of implementing targeted mitigation strategies that address the specific hazard profiles of each vent.

The distribution in volcanic hazard exposure, as depicted in Figs. 8 and 9, highlights a considerable portion of the urban population living under significant volcanic threat. Urban planners, emergency responders, and policymakers should prioritize areas of high exposure for their hazard mitigation strategies, including land use planning, early warning systems, and community education. The findings emphasize the importance of integrating volcanic risk assessments into urban development to reduce potential loss of life and property.

Figure 10 offers a spatially explicit view of transportation network vulnerability to both lava and Mazuku hazards. By mapping hazard intensity across different road types and urban zones, it provides a practical tool for identifying critical infrastructure at risk. This geospatial insight is essential for evacuation planning, emergency logistics, and infrastructure reinforcement. When interpreted alongside Tables 7 and 8; Fig. 10 translates raw exposure data into actionable intelligence, supporting multi-level decision-making for urban planners and disaster response teams. The

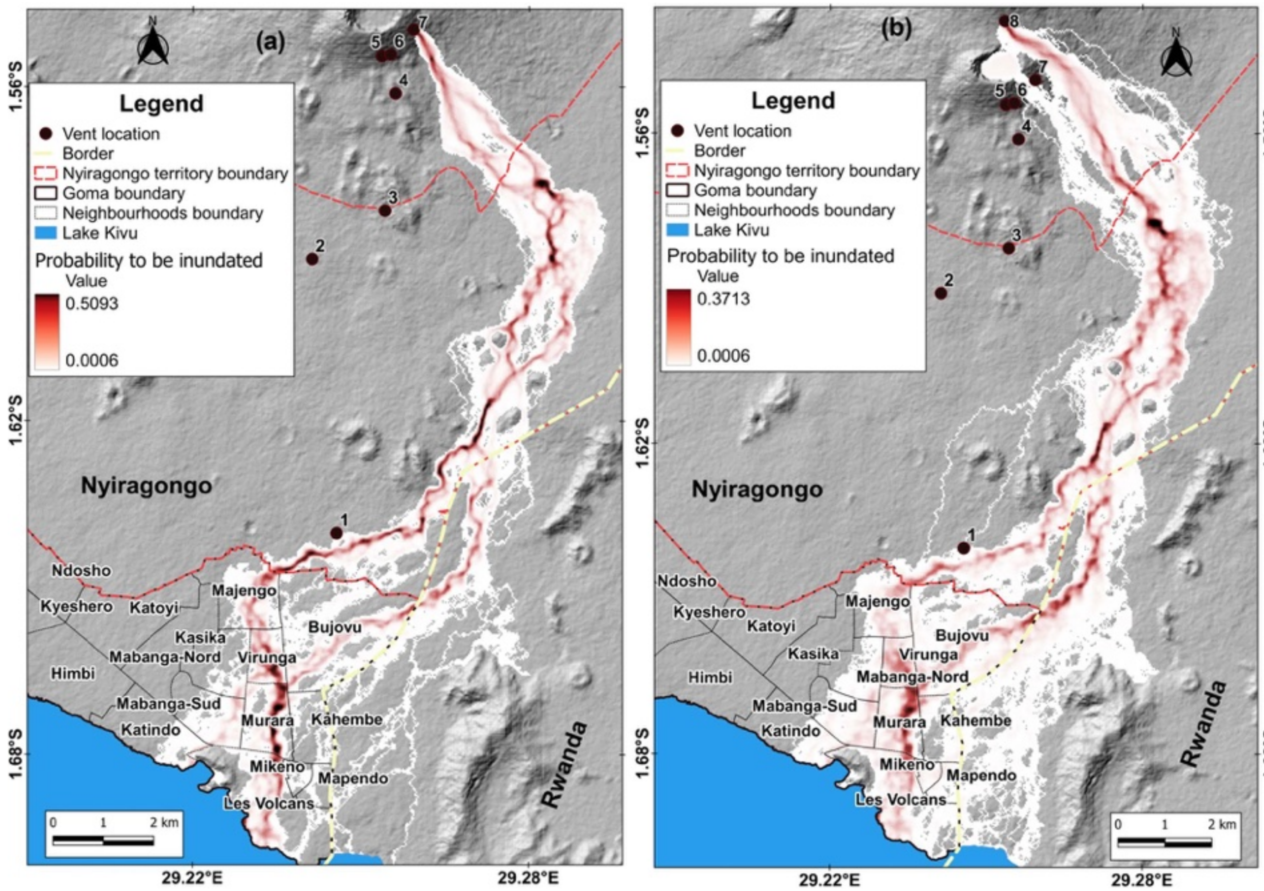

Fig. 7 Lava flow inundation probability maps for Nyiragongo eruption scenarios: (a) Simulated probability of lava flow inundation from vent 7. (b) Simulated probability of lava flow inundation from vent 8

Table 5 Simulated probabilities of lava inundation from Nyiragongo eruption scenarios

Vent	Minimum (%)	Maximum (%)
1	0.06	73.73
2	0.06	41.93
3	0.06	58.86
4	0.06	47.33
5	0.06	27.4
6	0.06	100.00
7	0.06	50.93
8	0.06	37.13

This table presents modeled probabilities of lava flow inundation from different vents, based on Geospatial simulation outputs

Table 6 The Spatial distribution of goma's urban area across four hazard zones - very high, high, moderate, and low - based on lava flow inundation probability and Mazuku distribution (Table 4)

Hazard zone	Area (m2)	Proportion (%)
Very high	4,375,665	7.4
High	30,240,388	51.3
Moderate	10,669,509	18.1
Low	13,695,360	23.2
Total	58,980,922	100.0

It quantifies the exposed urban surface area (in m²) and proportional share of the exposed urban footprint, supporting risk prioritization and evacuation planning

concentration of critical infrastructure in hazard-prone areas increases the risk of road disruptions during volcanic events and can severely hinder evacuation efforts and the delivery of emergency aid, exacerbating the impact of volcanic disasters.

Six corridors are initially selected as potential evacuation routes. However, if the main road to Kibumba is cut off and the commercial port is severely threatened, only four locations will remain viable: (1) the route toward Sake town, (2) the route toward South Kivu via Kituku port, (3) the route toward Rwanda via Grande-Bariere, and (4) the route toward Rwanda via Petite-Bariere.

These findings situate the present study within, and extend, the existing body of Nyiragongo research, which has predominantly emphasized hazard characterization (Favalli et al. 2009; Chirico et al. 2009; Mutima et al. 2024; Kyambikwa et al. 2025) or vulnerability indices without translating them into operational evacuation planning (Smets et al. 2010; Balagizi et al.

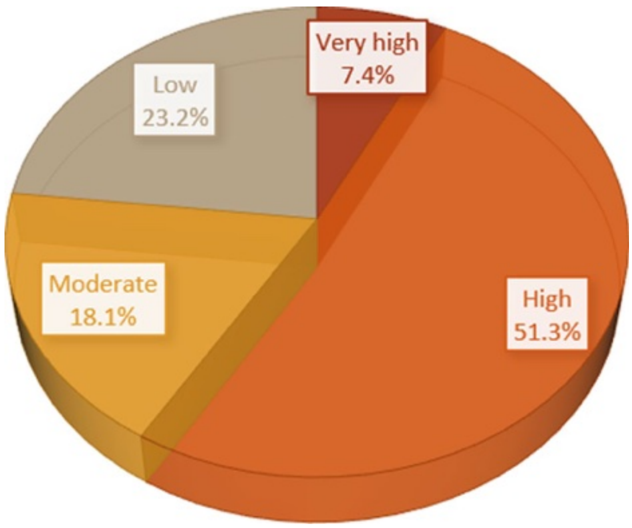

Fig. 8 Illustration of the percentage of urban land classified under four hazard levels -very high, high, moderate, and low - based on lava flow inundation probability. The chart highlights that over half of the city's area falls within the High hazard zone, underscoring the urgency for targeted evacuation planning and infrastructure resilience

2018; Michellier et al. 2020; Adalbert et al. 2021). By demonstrating vent-specific variability in lava inundation probabilities and integrating this with exposure analysis of Goma's neighborhoods and essential transport routes, the study addresses a persistent methodological gap between hazard assessment and evacuation feasibility. Beyond the local context, these results contribute to the broader international volcanic exposure and risk literature, where recent work (e.g., Meredith et al. 2024; Kervyn et al. 2024) has underscored the urgency of converting susceptibility and impact datasets into actionable crisis management tools. Accordingly, this geospatial approach not only enhances crisis preparedness for Goma but also provides a transferable framework for other rapidly urbanizing, data-constrained volcanic regions, advancing global disaster risk reduction agendas such as the Sendai Framework and SDG 11.

Conclusion

This study aimed to quantify population exposure to Nyiragongo lava flows and Mazuku hazards in Goma, addressing overlooked volcanic risks in urban planning through geospatial analysis. By linking hazard delineation to evacuation logistics, it supports SDG 11's goals for safe, resilient cities and sustainable communities, proposing actionable scenarios to protect lives and infrastructure in this high-risk setting.

Key findings reveal critical exposure patterns across Goma. GIS-based models were developed using Mazuku distribution data and simulations of lava flow inundation probabilities from the 1977, 2002, and 2021 Nyiragongo eruptions. The results show that 11 of 18 neighborhoods in eastern Goma are located within the potential lava flow corridor, including 7 neighborhoods more exposed to lava flow inundation than others. More than 51.3% (30.2 km^2) of Goma's total urban surface area is highly exposed to Nyiragongo lava flow hazards, while 7.4%, 18.0%, and 23.2% of the city is very highly, moderately, or not exposed, respectively. These findings highlight volcanic hazard and exposure as essential parameters for effective GIS-based evacuation modeling.

Contributions advance volcanic hazard assessment in data-scarce regions. This research directly supports SDG 11 for resilient cities by bridging gaps in prior hazard-focused work through refining methodologies for vent-specific lava flow and Mazuku mapping using historical data, quantifying population and infrastructure exposure in high-risk zones to inform targeted evacuation planning, and developing a replicable geospatial environment framework that integrates hazard delineation with logistics for multi-level decision-making.

Recommendations provide actionable mitigation strategies. To mitigate risks and to support resilience, authorities should integrate hazard data into urban planning and land-use strategies for Goma and surrounding areas; diversify transportation networks (roads, lake ports, airport) for crisis connectivity, considering relocation of critical assets in extreme scenarios; establish emergency infrastructure including marked evacuation routes, signage, refuge areas, community drills, and awareness campaigns; and enhance monitoring, early warning systems, institutional coordination, and plans for vulnerable groups (elderly, children, disabled) while addressing Mazuku health risks.

Future directions include enabling more advanced evacuation simulations. The proposed geospatial framework lays the foundation for an integrated GIS and agent-based modeling approach, serving as an 'evacuation simulation environment' to assess evacuation scenarios and their efficiency. Future work will incorporate real data from previous crises, such as documented lava-flow paths, including probabilistic trajectories, and mapped Mazuku locations, combined with dynamic modeling and validation to ensure generalizability to other data-poor volcanic settings, thereby strengthening global strategies for hazard exposure and crisis response.

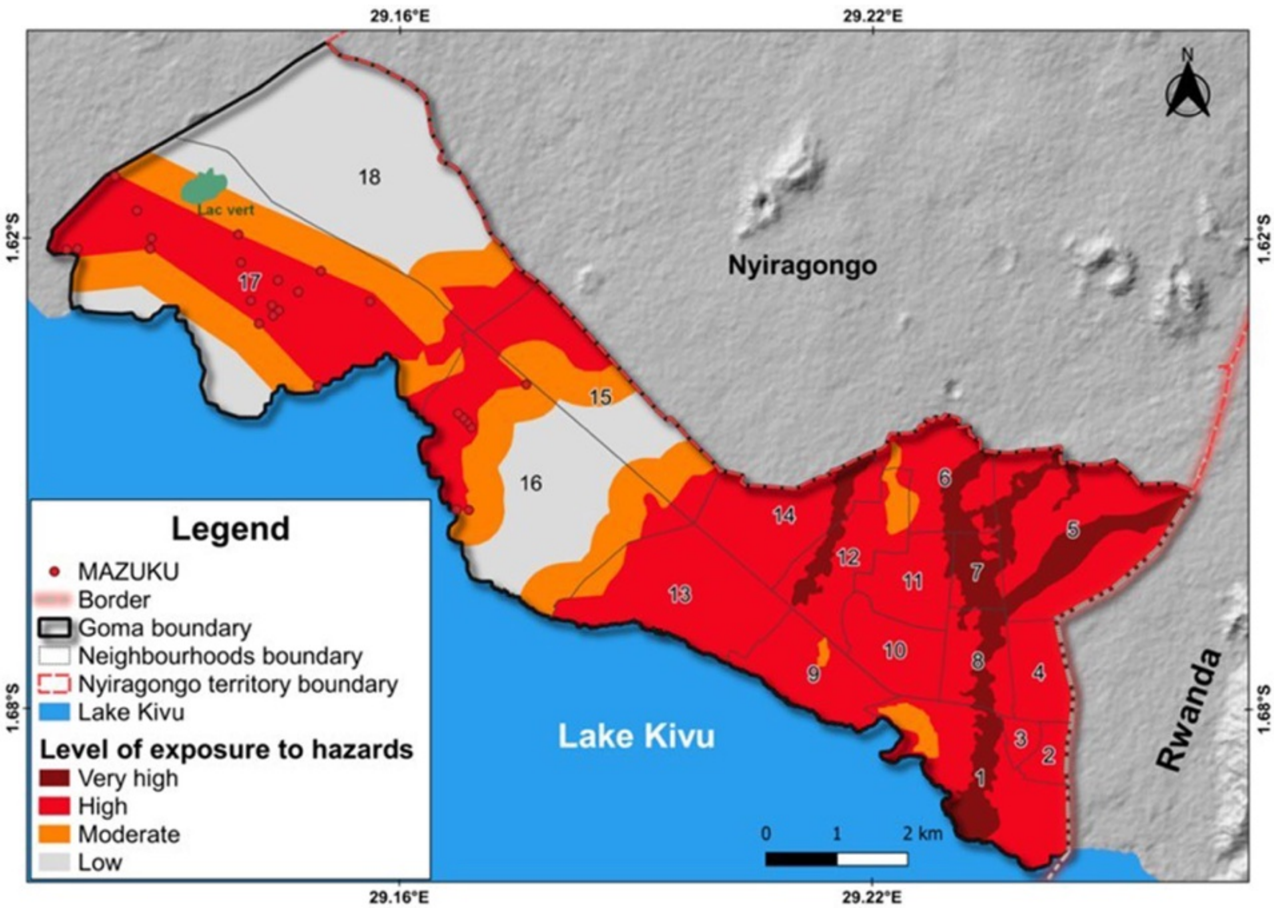

Fig. 9 The spatial extent of hazard zones within Goma, showing areas affected by historical lava flows and regions prone to Mazuku, localized CO_2-rich gas pockets. Neighborhoods are represented by the numbers. 1 = Les Volcans, 2 = Mapendo, 3 = Mikeno, 4 = Kahembe, 5 = Bujovu, 6 = Majengo, 7 = Virunga, 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

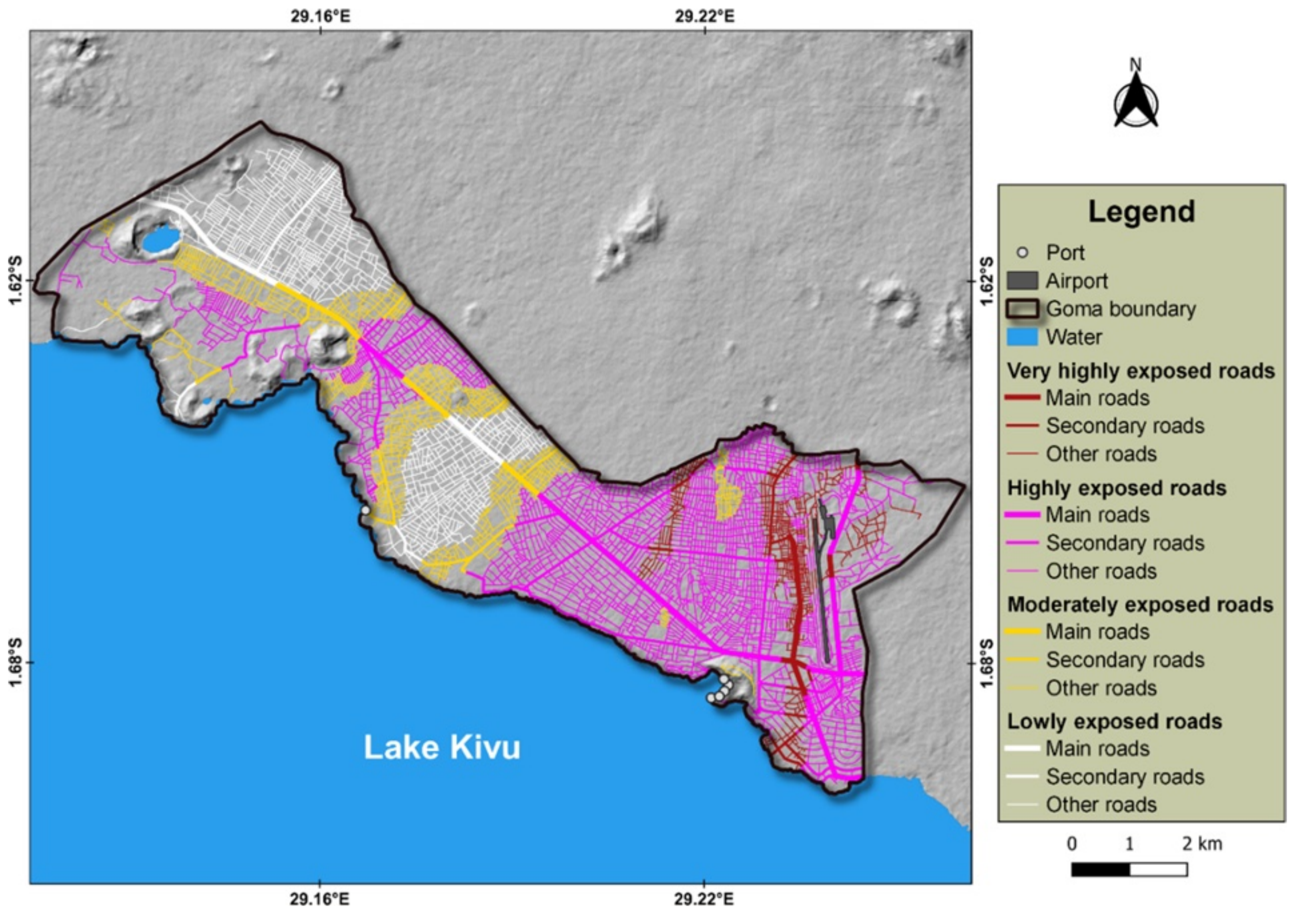

Fig. 10 Transport network exposure to lava inundation hazard in Goma city. The map displays road segments categorized by exposure level - very high, high, moderate, and low - based on proximity to past and potential lava flow zones and Mazuku distribution. Road types (main, secondary, and other) are color-coded to indicate risk intensity. Additional map features include administrative boundaries, water bodies, and geographic coordinates

Table 7 The extent of main, secondary, and other roads affected by varying levels of volcanic hazard - very high, high, moderate, and low - based on lava flow inundation probability and Mazuku distribution

Level of hazard	Main roads (m)	%	Secondary roads (m)	%	Other roads	%
Very high	3227	14	6452	14	66343.6	9
High	12,674	53	27,757	60	381394.76	51
Moderate	3622	15	7660	17	121965.38	16
Low	4343	18	4407	10	177330.24	24
Total	**23,865**	**100**	**46,276**	**100**	**747033.98**	**100**

Measurements are provided in meters and percentages, supporting infrastructure vulnerability analysis and evacuation route planning under Nyiragongo eruption scenarios

Table 8 The total length and percentage of main, secondary, and other roads exposed to varying hazard levels-very high, high, moderate, and low-based on lava flow inundation probability

Exposure zone	Main roads (m)	%	Secondary roads (m)	%	Others roads	%	Total (m)	%
Very high	3227	0	6452	1	66,344	8	76,022	9
High	12,674	2	27,757	3	381,395	47	421,826	52
Moderate	3622	0	7660	1	121,965	15	133,248	16
Low	4343	1	4407	1	177,330	22	186,080	23
Total	**23,865**	**3**	**46,276**	**6**	**747,034**	**91**	**817,176**	**100**

It provides an integrated view of road infrastructure vulnerability, supporting strategic planning for emergency access, mobility resilience, and evacuation logistics in Goma

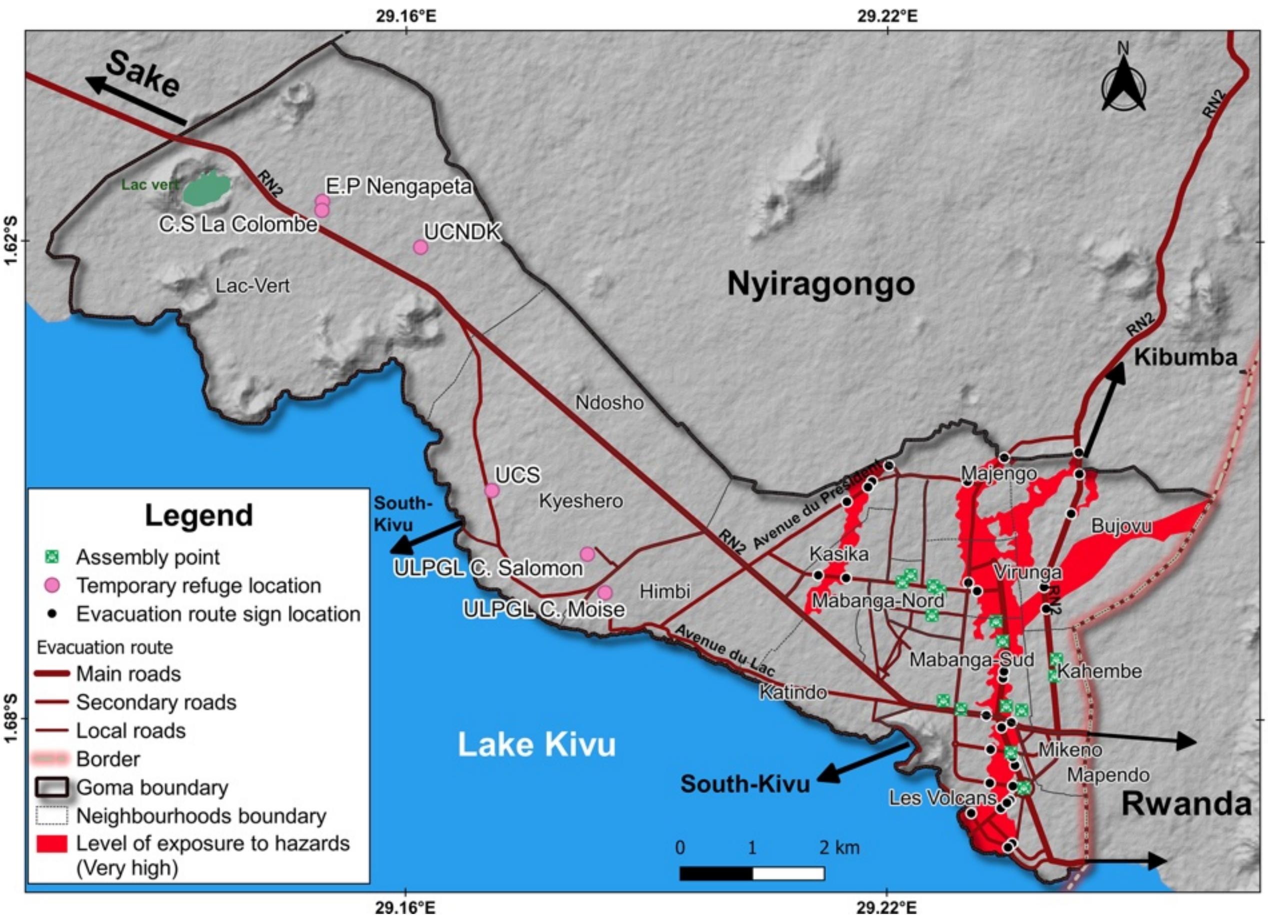

Fig. 11 The spatial configuration of evacuation infrastructure in Goma, optimized for volcanic hazard response. It includes designated assembly points, temporary refuge locations, evacuation route signage, and prioritized corridors, overlaid on hazard exposure zones and road networks. The optimization integrates geographic risk, accessibility, and population distribution

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Author contributions

K.M.: conceptualization, background, original draft, writing and editing, methodology, dataset and tools selection, mapping and simulation, analysis and discussion.N.C.K.: proof reading, project supervisor.S.K. : methodology, analysis and discussion.K.M.G.: dataset analysis, mapping and simulation.K.K.: methodology, proof reading, review, funding acquisition.

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Data availability

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Declarations

Ethics approval and consent to participate

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Consent for publication

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Competing interests

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