Multihazard Risk Mitigation Strategy for Goma, Democratic Republic of the Congo

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Abstract

Goma, a city in the North Kivu province of the Democratic Republic of the Congo, is situated in a complex multihazard environment. Volcanic and limnic eruptions, CO_2 emissions, tsunamis, flooding, and landslides all threaten the city and its inhabitants, the risks from which are compounded by the region's political instability and socioeconomic vulnerability. This report models the risks posed by each of these hazards using both quantitative and qualitative assessments. Spatial patterns of risk and vulnerability across Goma and the surrounding area were analysed using the Pressure and Release framework originally proposed by Wisner et al. (2003). The region's key hazards include effusive volcanic and limnic eruptions (stemming from the nearby volcano of Mt. Nyiragongo), CO_2 emissions (locally Mazuku), tsunamis, flooding, earthquakes, and landslides. The distinct spatial inequalities within the city and its wider catchment make hazard planning and mitigation measures more difficult to design and implement. Due to the complex nature of this region's hazards, combined with these inequalities, this report advocates for a focus on resilience building and increasing community preparedness, in addition to efforts to directly reduce the impacts of these hazards. Indeed, in the context of Goma's complex multi-hazard environment, this report advocates for a similarly interconnected multi-response plan to mitigate against them.

1. Introduction

The 2015 Sendai Framework proposed four pillars of improving disaster risk reduction, notably focusing on strengthening governance and increasing resilience (United Nations, 2015). This report will build upon this framework, applying its principles to the city of Goma in the Democratic Republic of the Congo (hereafter DRC). As shown in Figures 1, 2 & 3, the city's location in close proximity to the volcano Mt. Nyiragongo to the North and Lake Kivu to the South situates Goma at the confluence of two major hazard sources (Michellier et al., 2020). Hazards include effusive volcanic and limnic eruptions, CO_2 emissions (locally Mazuku),

tsunamis, flooding, earthquakes, and landslides; visual representations of which are shown in Figure 4.

Goma's population of approximately 2 million makes it one of the most densely populated areas in the world that is routinely exposed to volcanic hazards (Kakozi et al., 2023). Goma also has a precarious sociopolitical situation: civil unrest, stemming from rebel groups, has led to widespread violence, causing a 'major humanitarian crisis', with shortages of food, clean water, and medicine (CAFOD, 2025, :np). This has resulted in prominent refugee camps, characterised by overcrowding and poorly-constructed buildings, often located in locations that are particularly vulnerable to hazards (Balagizi et al., 2018). Furthermore, much of Goma's population lives below the poverty line: 90% of households receive <US$2 daily (Nzanzu et al., 2021; World Bank, 2022). Weak governance and conflict in the area have severe implications for the population's capacity to cope with natural hazards (Wisner, 2017). Tensions with Rwanda have historically led to influxes of refugees across the border, most notably in 1994 (Pierret, 2024). These tensions have been exacerbated in recent years amid reports that Rwanda is funding rebel activity in the country (Zane, 2025).

The combination of these socioeconomic and political factors, in addition to the broad threats posed by the intersection of the region's natural hazards, makes Goma a unique case study for multihazard management strategies. Whilst much research has either assessed the hazards in the area (for example Balagizi et al. (2018)), or proposed and evaluated existing mitigation schemes (for example Mafuko- Nyandwi et al. (2024)), there is little literature combining the two. This article aims to address this gap by creating a holistic and comprehensive hazard management and mitigation strategy for the wider Goma region, assessing the risks posed by the region's varied hazards by integrating remotely-sensed primary data with secondary data from pre-existing studies. This enables the widespread analysis of hazards such as landslide risk, limnic eruptions, and tsunamis using remotely sensed data, and the assessment of hazards such as effusive volcanic eruptions, Mazuku, and earthquakes using the data and assessments of pre-existing literature. Following these assessments of hazard risk, this article formulates realistic policy recommendations for the addressing of these hazards.
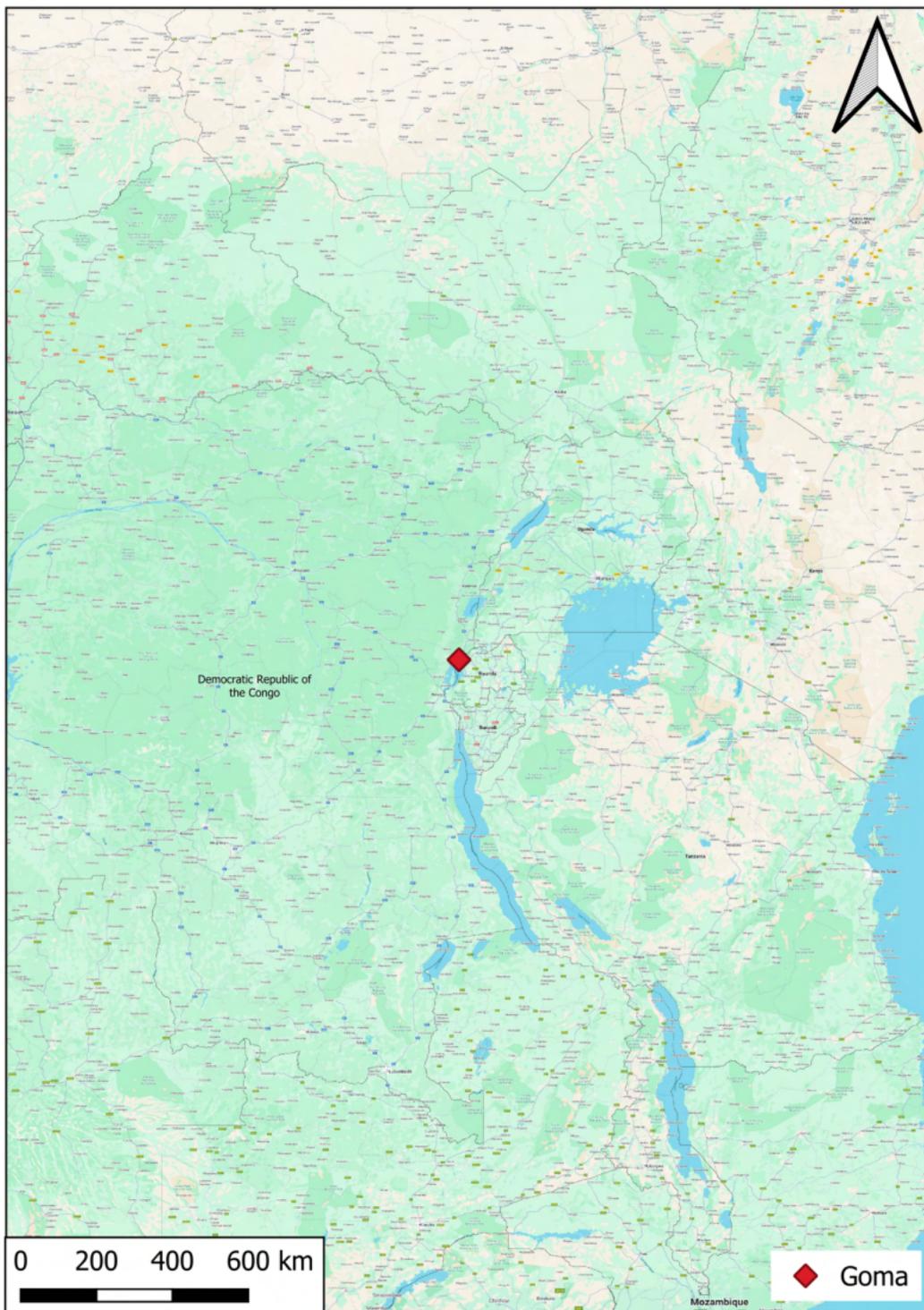
Figure 1: A map showing Goma's location in central Africa, situated on the border between the DRC and Rwanda. Created by the author using a basemap from (Google Maps, 2025).

Figure 2: A map of the region immediately surrounding Goma, highlighting the major hazard sources of Mt. Nyiragongo and Lake Kivu, as well as the nearby village of Bambiro to Goma's North-West, and Gisenyi in Rwanda to the East. Created by the author using a basemap from (OpenStreetMap, 2025).
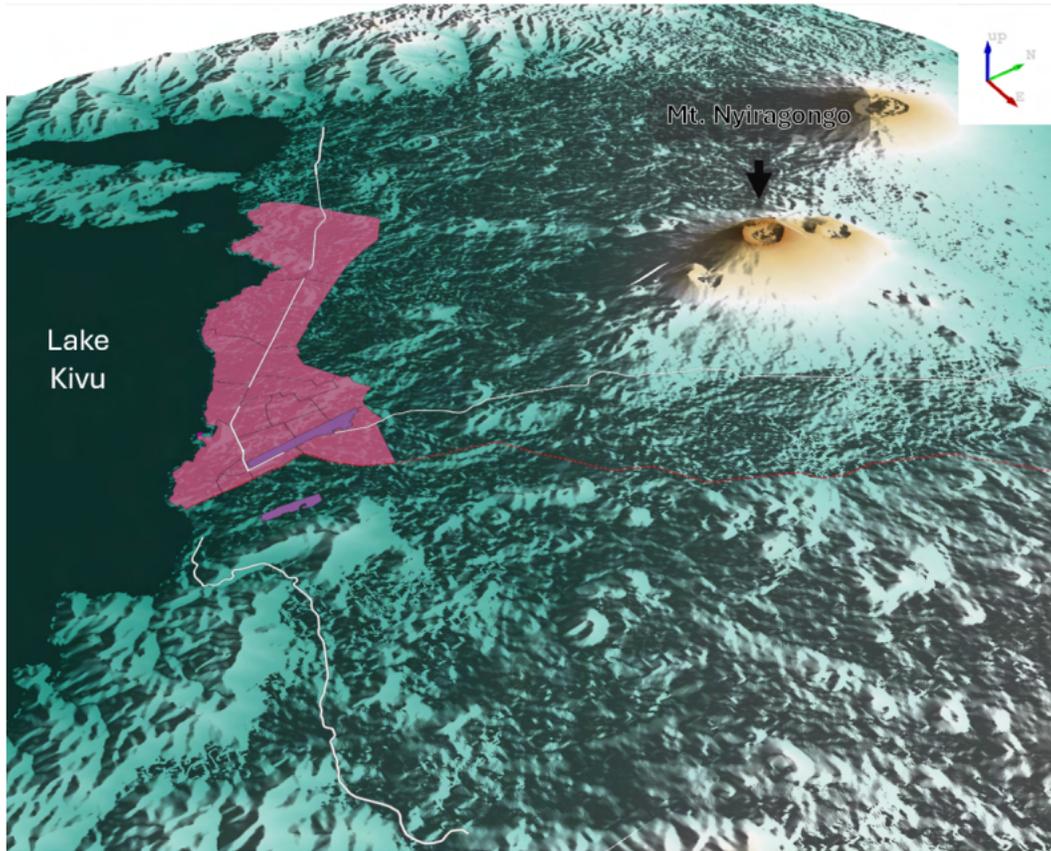
Figure 3: A 3-Dimensional elevation map of the region immediately surrounding Goma, highlighting Lake Kivu and Mt. Nyiragongo. Created by the author using a Digital Elevation Model from the SRTM (2013). A shapefile for Goma's extent was taken from OCHA (2025).

Figure 4: A figure providing a visual representation of the hazards present in the region immediately surrounding Goma: Lava Flows, Limnic Eruptions, Flooding, Landslides, and Earthquakes. Created by the author, using images credited in the figure.

2. Methods

The wide variety of hazards present around Goma presents challenges to their effective modelling and mapping. Each individual hazard requires a unique methodology to appropriately categorise the risks it creates; volcanic hazards were assessed using the digitisation of past eruption maps, in particular highlighting volcanic vents, fissures, and lava flows. Landslide hazards were assessed by creating an empirical model of landslide risk, accounting for factors such as slope, soil bulk density, vegetation density and soil moisture.

2.1. Lava Flow, Vent and Fissure Digitisation

Maps of past lava flows, vents, and fissures in 1977 and 2002 (Komorowski and Karume, 2015) were digitised using QGIS, then integrated into a pre-digitised lava flow map of the 2021 eruption taken from UNOSAT (2024). Whilst this article does not attempt to quantitatively model potential future vent or fissure locations, it does offer insight into past eruption patterns and severity, which are still useful in informing future management practices. Given Mt. Nyiragongo's effusive nature, and the lack of summit glaciers, volcanic hazards such as tephra, ash fall or lahars are unlikely or impossible in this region, meaning they are not assessed here.

2.2. Landslide Risk Modelling

This method created a quantitative map of landslide risk at a resolution of 30m2 , that assigned areas a level of risk between zero and one, with higher values indicating a greater risk of slope failure. This model utilised elevation data from SRTM (2013), as well as remotely-sensed satellite data from European Space Agency (ESA) (2025) to calculate vegetation indices. Normalised Difference Vegetation Index (NDVI) is a vegetation index which measures the 'greenness' of vegetation by calculating the difference in reflectance of the red and near infrared (NIR) bands of satellite imagery (Rouse et al., 1973). Chlorophyll effectively absorbs red light, whilst healthy leaves tend to reflect light in the NIR spectrum due to their mesophyll cavities, hence making the difference between red and NIR reflectance a good indicator of leaf health.. Normalised Difference Moisture Index (NDMI), by contrast, infers leaf water content by calculating the difference between the NIR and short wave infrared (SWIR) spectra (Gao, 1996). Leaves with high water concentrations effectively absorb light in the SWIR spectrum, enabling an inference of the moisture content of the leaf (Gao, 1996). NDMI, in the absence of highresolution precipitation or soil moisture data (as is the case for the Goma region), is used here as a proxy for soil moisture.

Slope was calculated using the integrated Earth Engine function ee.Terrain.slope(), the documentation for which can be found at Google Earth Engine (n.d.).

This method was adapted from Shah (2021), and limited by data scarcity for historical landslides in Goma, making self-determined weightings, and indeed weightings specific to Goma, impossible. Instead, weights were adapted from Getachew and Meten (2021):
   1. Slope: 50%
   2. Soil bulk density: 30%
   3. Vegetation density: 10%
   4. Soil moisture: 10%

Areas with a slope of less than 5° were excluded (landslides cannot occur in areas with very small or non-existent slope values), resulting in the following overall equation being used:

$$L_R = (nSlope_{>5°} \times 0.5) + (nSBD \times 0.3) + (iNDVI \times 0.1) + (NDMI \times 0.1)$$

Where LR = landslide risk, nSlope = normalised slope values, nSBD = normalised soil bulk density, and iNDV I = inverted NDVI - increased vegetation coverage reduces landslide risk; roots increase soil cohesion and shear strength (Li and Duan, 2024).

2.3. Limnic Eruption Modelling

The potential extent of a limnic eruption from Lake Kivu was determined by creating a flat plane at a known elevation above the lake in QGIS, using a DEM provided by SRTM (2013). This process was repeated at differing heights until the volume enclosed between the flat plane and the lake/ground surface equalled Balagizi et al. (2018)'s estimate that there is 300 km^3 of dissolved CO_2 in Lake Kivu. This assumes a 'worst-case' scenario; an eruption of the full 300km^3 of CO_2, and fails to explicitly account for other factors, such as wind speed and direction, nor does it account for potential CH_4 efflux.

2.4. Tsunami Modelling

Potential future tsunami heights were assessed in relation to lacustrine tsunamis in the historical record, in particular in Lake Lauerz and Lake Lucerne, the data from which was taken from Schnellmann et al. (2002) and Bussmann and Anselmetti (2010) respectively. In particular, tsunami heights of 1-2 metres, 10 metres, and 20 metres were assessed; with heights of 10m being recorded in Switzerland, the 20m wave height assessment is more an illustration of a potential worst-case scenario, whereby earthquakes in the region could trigger widespread sub-lacustrine and surface landslides from the slopes within and surrounding the lake.

This article did not attempt to mechanistically model lacustrine tsunami paths, or risk for Lake Kivu due to technological limitations. However, the hazard zoning presented here in Figure 11 still offers useful insight into future urban planning and hazard management schemes.
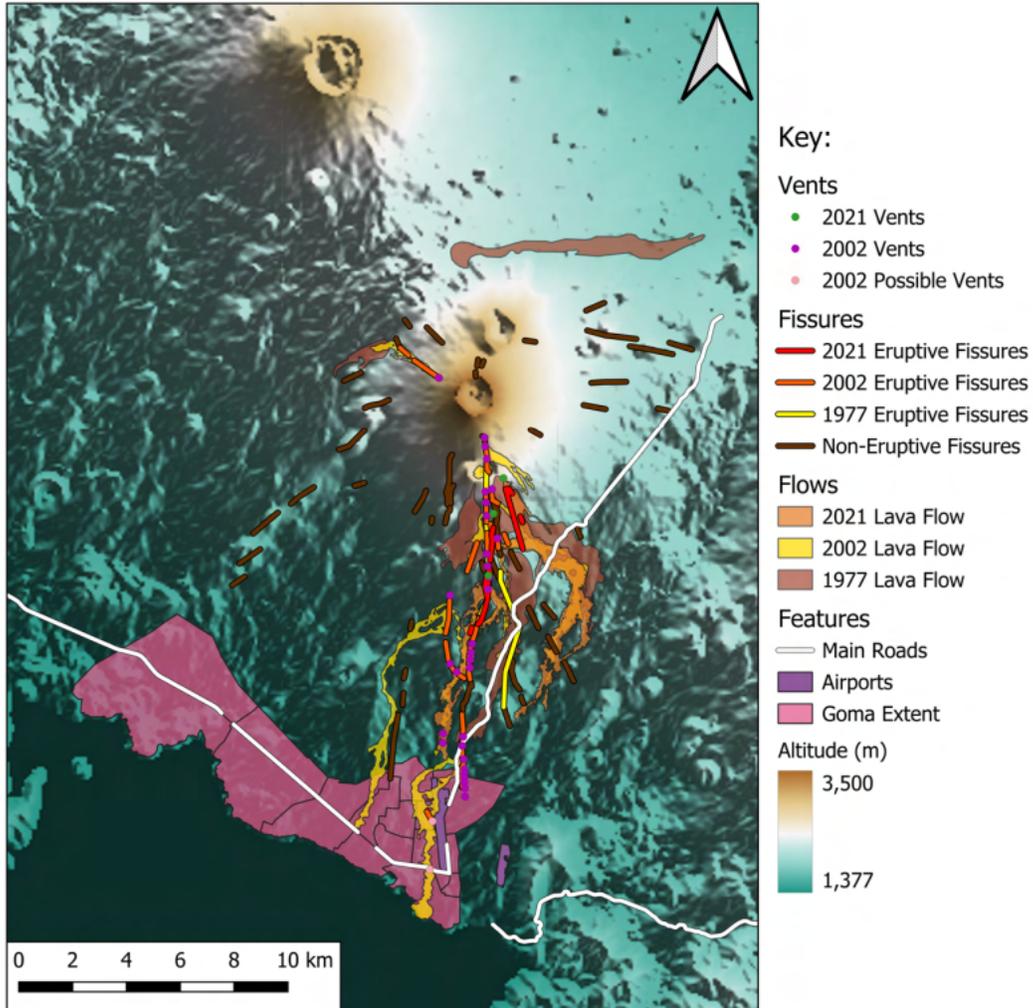
3. Results

3.1. Volcanic Hazards

Figure 5: A map of lava flows, fissures and vents from previous eruptions of Mt. Nyiragongo. Created by the author. Features from the 1977 and 2002 eruptions were digitised from a map found in Komorowski and Karume (2015), and shapefiles for the 2021 eruption were taken from UNOSAT (2024). The DEM used was from SRTM (2013).

Eruptions from Mt. Nyiragongo are characterised by low viscosity lava causing rapid lava flows, and eruptions which have not exceeded an intensity of 2 on the Volcanic Explosivity Index (VEI) (Program, 2025). The region experiences fairly continuous eruptions, with the Program (2025) reporting regular activity since records began in 1884.

The 1977 eruption resulted in the draining of the lava lake at the volcano's summit, releasing approximately 2.2×10^7 m3 of lava, covering over 20km2 , with lava flows being released from both the Northern and Southern flanks of the volcano (Sawyer et al., 2008; Tazieff, 1977). The Southern flows affected the Northern highway out of Goma, and almost reached the city limits, as shown by Figure 5.

The 2002 eruption released between $14–34 \times 10^6$ m3 of lava, resulting in two lava flows inundating the city. One of these flows reached Lake Kivu, forming an outcropping of material into the lake, which can be seen on the South-Eastern edge of Goma's boundary in Figure 5. This poses a distinct threat for a potential limnic eruption of CO_2 from the lake, the consequences of which are discussed later in this article. This eruption also affected key city infrastructure such as the airport in the East, and central infrastructure such as roads, with Figure 5 clearly showing the lava flows over the larger of the region's two airports.

The most recent 2021 eruption released 2.2×10^7 m3 of lava, with flows following similar paths to previous eruptions; the more Western flow following one from 2002, and the more Eastern flow following one from both 2002 and 1977. These flows are likely topography constrained, with the elevation map indicating that the flows are largely directed by the volcano's surrounding terrain.

Each of the three most recent eruptions have notably affected Goma's North-East and the key Northern highway (Balagizi et al., 2018). The 2002 eruption also destroyed part of the airport, and saw lava flows reach Lake Kivu. Research also suggests that there are fractures extending below Goma and Lake Kivu, at a depth of ~ 3km (Wauthier et al., 2012; Balagizi et al., 2018). This could increase the possibility of a limnic eruption from the lake.
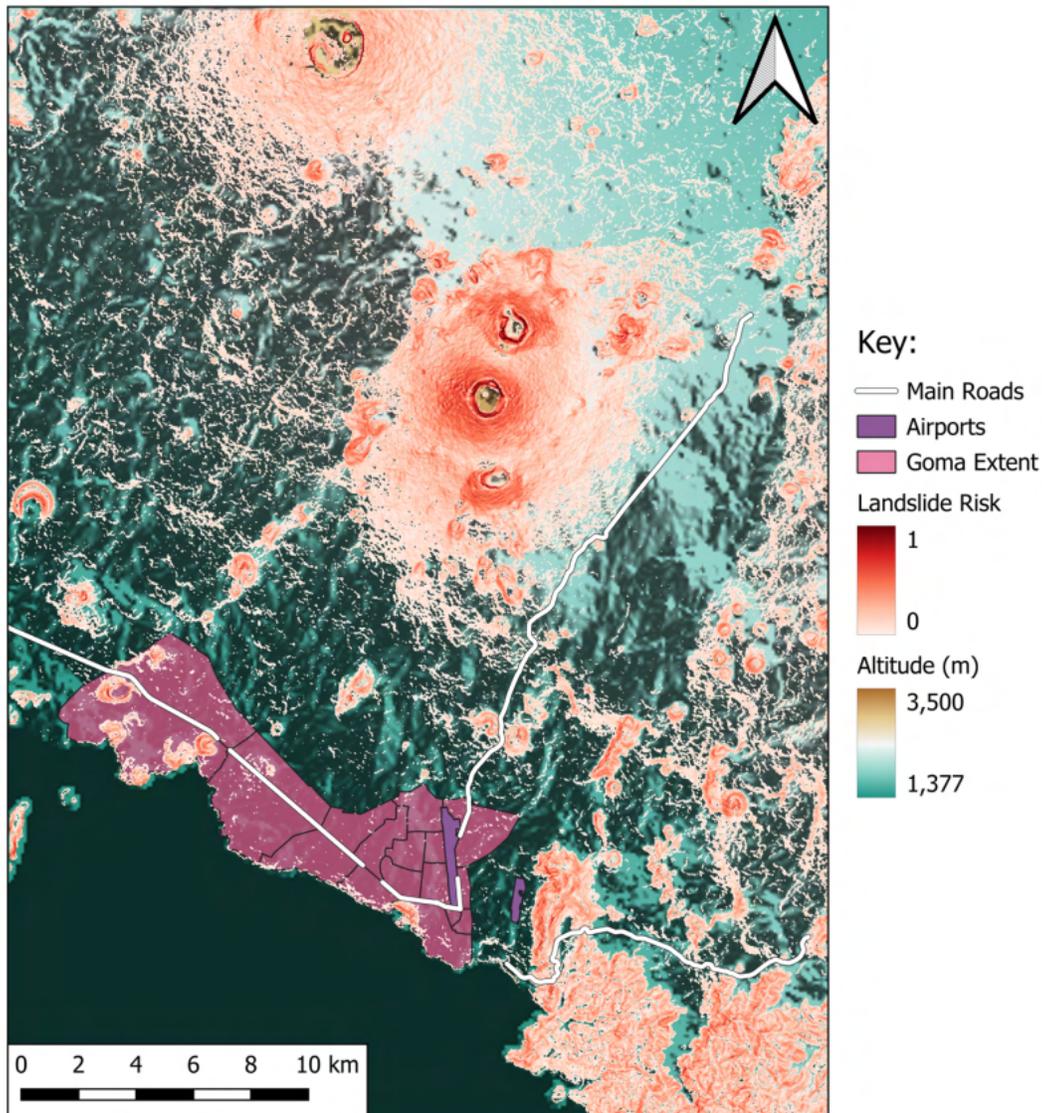
3.2. Landslides

Figure 6: A map showing landslide risk across the region surrounding Goma. Landslide risk models were created by the author, and a DEM was taken from SRTM (2013), with a shapefile for Goma's extent and location being used from OCHA (2025).

As Figure 6 demonstrates, there are also significant landslide risks across the region. Landslide risk is centred around both volcanoes, with Mt. Nyiragongo experiencing greater risk than Nyamuragira. This is primarily influenced by the steeper slope angles found around the volcanoes; particularly around the rims of their crater lakes; soil bulk density around the two volcanoes is actually higher (the more densely-packed soil particles are more cohesive, and therefore more resistant to failure). NDVI and NDMI (two other predictors of landslide risk used in this model)

are also higher in the areas around the volcanoes, meaning the higher landslide risk is entirely slope-driven.

The Northern highway out of Goma also lies between two areas of elevated landslide risk to its East and West, having potential consequential impacts for aid.

Within Goma, landslides most prominently affect the Western areas of the city. The central areas of the city suffer relatively little risk from landslides, a fact mirrored for the larger of the two airports found in the region. These Western landslide hotspots are in fact driven by all four predictive factors; with steep slopes, lower soil bulk density, and low NDVI and NDMI. Each of these contributes to an increased likelihood of slope failure, and thereby an increase in landslide risk for these areas.

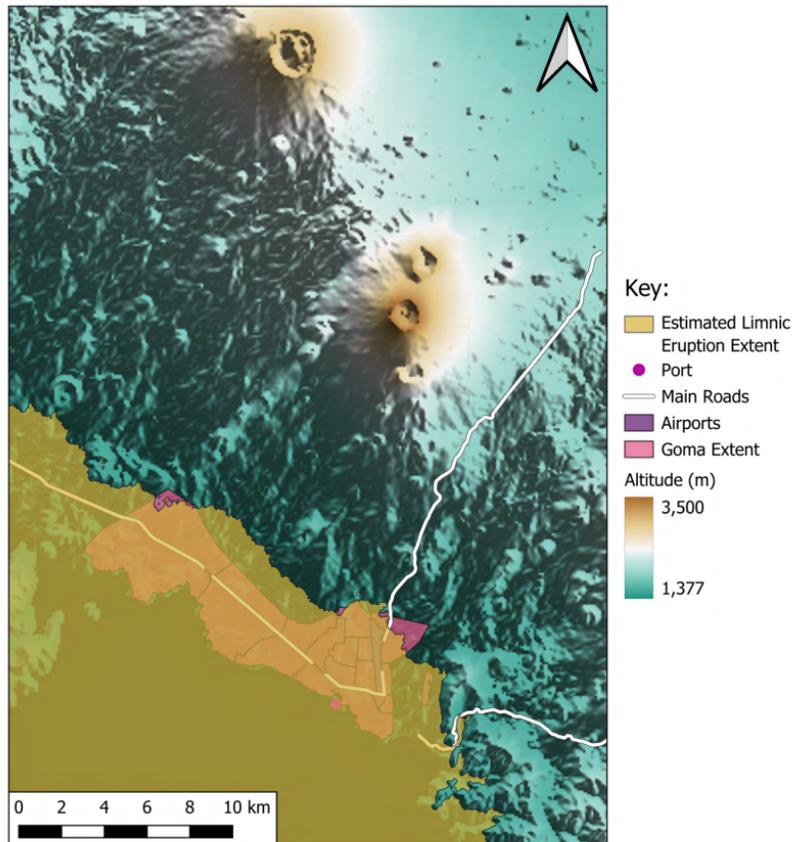*3.3. Limnic Eruption & Mazuku*

Figure 7: A map showing the possible extent of a limnic eruption from Lake Kivu. Created by the author. The DEM was taken from the SRTM (2013), and the shapefile for Goma's location and extent from OCHA (2025).
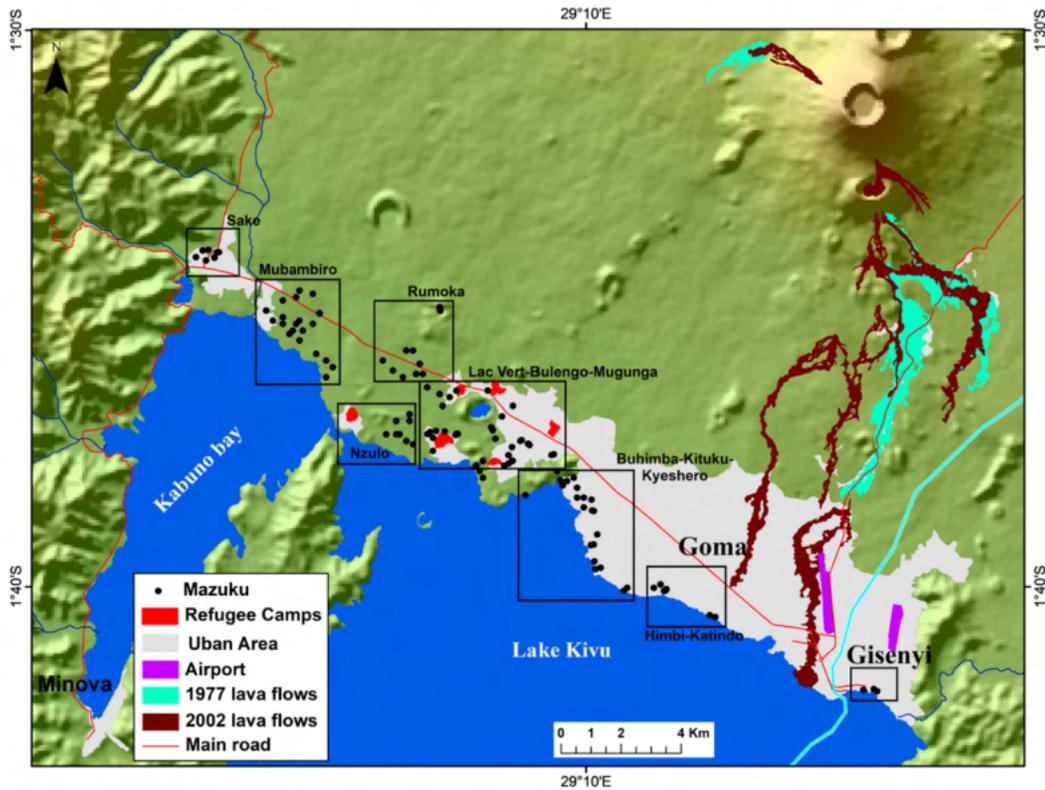
Figure 8: A map showing the verified sources of Mazuku around Goma. Created by and taken from Balagizi et al. (2018). The author did not make this figure.

Modelling indicates that a limnic eruption could engulf the majority of Goma, affecting up to 2.5 million people (Jones, 2021). As shown by Figure 7, under a worst-case, maximum-volume eruption, only the furthest North-East and North-West regions of Goma would remain unaffected. This, however, is an unlikely scenario - much more likely would be a partial eruption - indeed, studies (Zhang and Kling, 2006; Bärenbold et al., 2020; Hirslund and Morkel, 2020) have shown that a full degassing of a saturated lake is unlikely - requiring highly saturated water, and little vertical stratification of gas concentrations. Indeed, the continued gas extraction from the lake has been cited as causing the lake to reach a near-stable state, with little change to CO_2 or CH_4 levels since 1974 (Bärenbold et al., 2020).

Although the informal settlements to the North of the city are less vulnerable, they could still be impacted; wind direction in Goma demonstrates distinct seasonality, most often coming from the South during summer, and from the North during winter (Weather Spark, 2024). Thus, a summer eruption could result in CO_2 being blown further North, whereas the severity of a winter eruption could be lessened by the northerly wind most common during those months. It is important to note that, despite these seasons predominantly experiencing these wind conditions, daily

conditions vary, not necessarily following these seasonal averages, making the impacts of an eruption dependent on that day's wind conditions.

As shown by Figure 8, Mazuku is most prevalent in the Western side of the city, along the lakeside, and in the villages and refugee camps to Goma's North-West. Data sparsity makes it difficult to spatially quantify the volume of gas being released at each of these locations, or indeed to determine the type of vent at each location: much of the data included here (from Balagizi et al. (2018)) is based upon verified in-situ measurements. In the past, these marked locations have been recorded with CO_2 concentrations of up to 70%, far exceeding the lethal threshold of approximately 10% (Smets et al., 2010).
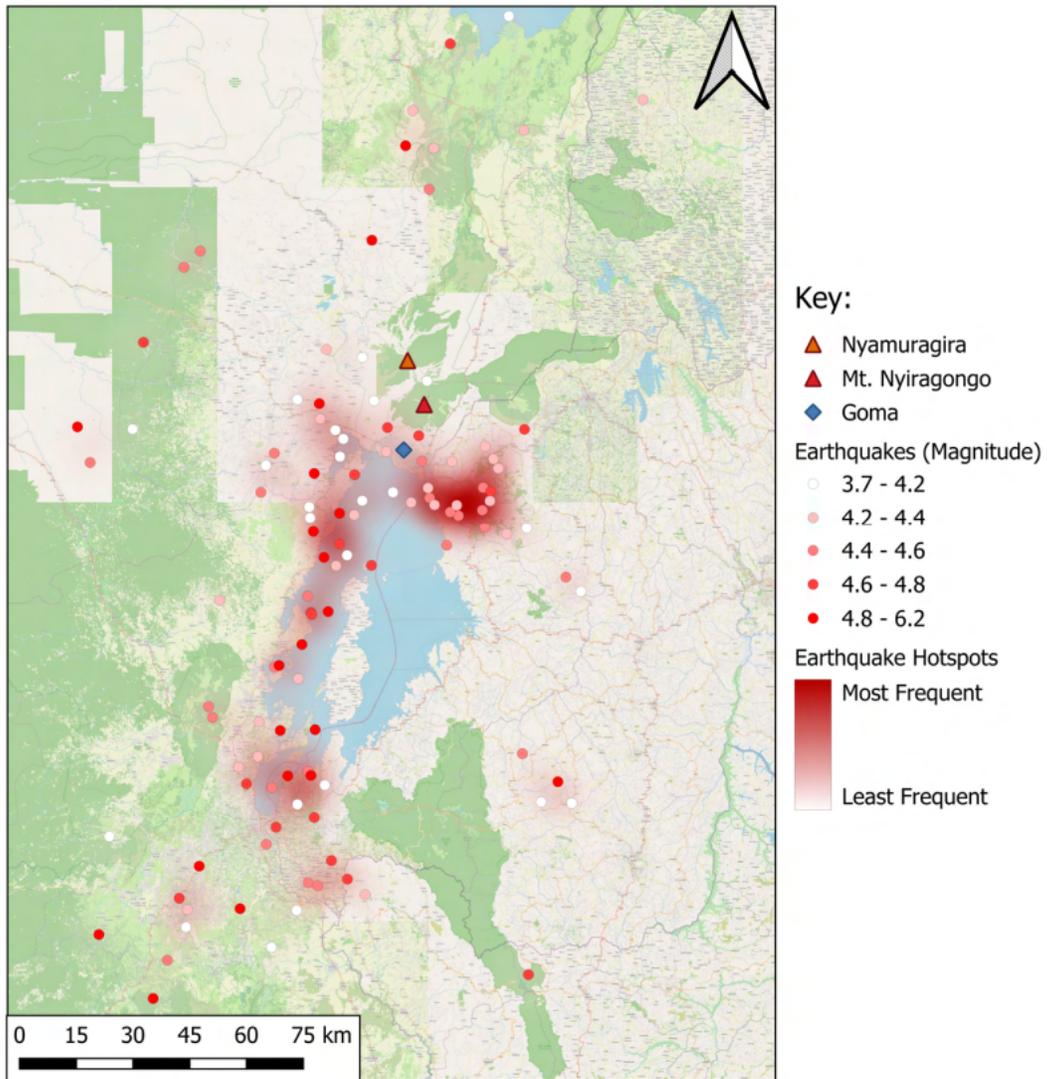
3.4. Earthquakes

Figure 9: A map showing the epicentre location and magnitudes of all earthquakes since 2000 in the region surrounding Goma. Earthquake data was taken from USGS (2025), and the basemap was taken from (OpenStreetMap, 2025).

Figure 10: A map showing the epicentre location and year of all earthquakes since 2000 in the region surrounding Goma. Earthquake data was taken from USGS (2025), and the basemap was taken from (OpenStreetMap, 2025).
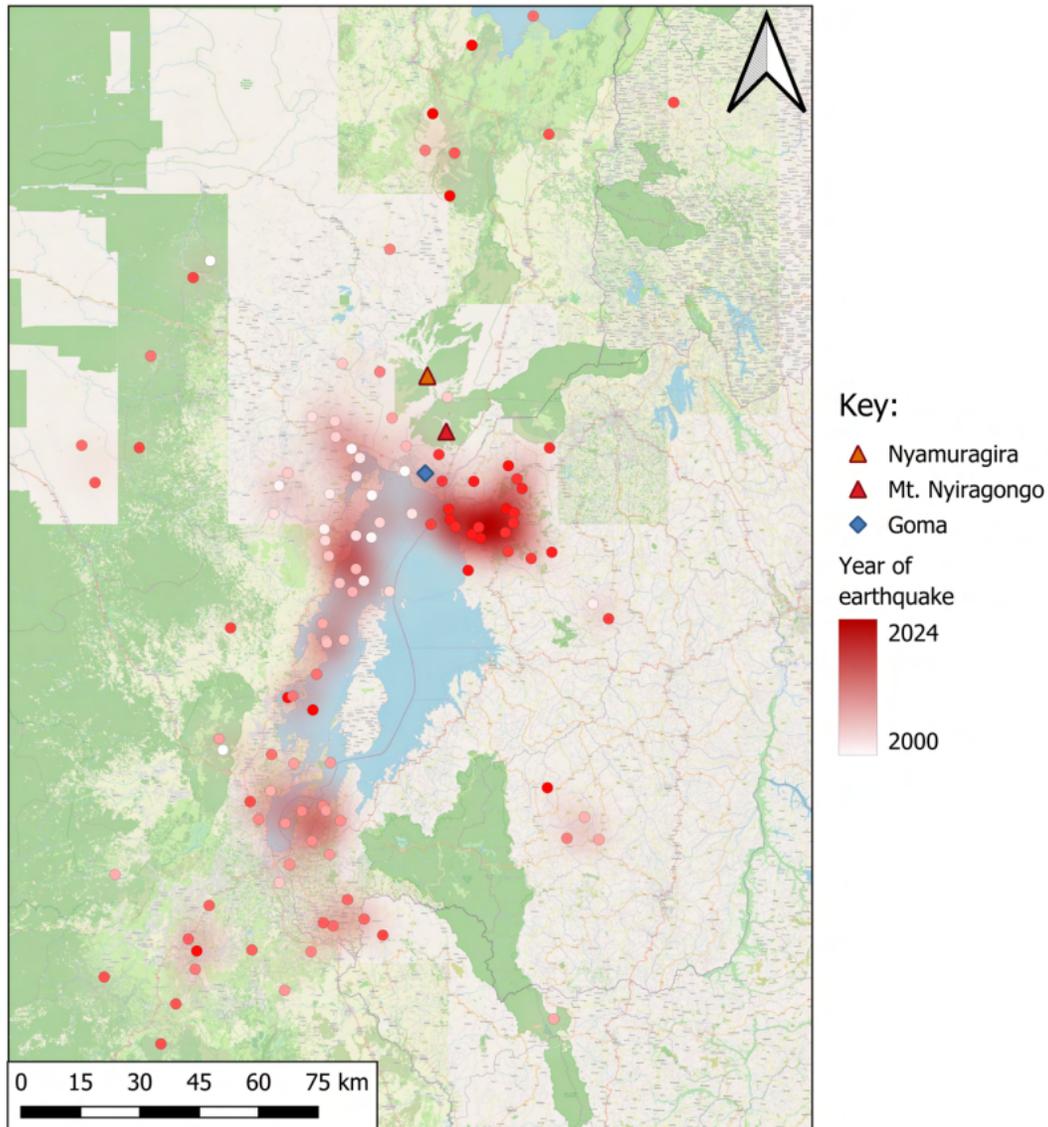
This region experiences frequent seismicity, with an average of 4.5 earthquakes above magnitude 2.5 (Richter scale) annually since 2000, as demonstrated in Figure 9 (USGS, 2025). Earthquakes had a mean magnitude of 4.5, with the most powerful being magnitude 6.2 in 2002, part of a period of elevated seismicity following the eruptions early in the same year (USGS, 2025). There is also a temporal pattern to the region's seismicity; Figure 9 demonstrates how epicentres of the most recent earthquakes have primarily occurred in a hotspot to Goma's South-East: a distinct spatial shift from those at the beginning of the data in 2000 to Goma's West.

Seismicity in the region is primarily resultant from the presence of the East African Rift System (EARS). Goma is situated on the Kivu Rift, opening at a rate of approximately 2mm year^{-1}, in a direction sub-orthogonal to the rift axis and a dominant normal faulting regime (Delvaux et al., 2017). This rift presents the region with regular shallow and predominantly low-magnitude earthquakes, although the volcanoes to the North create local volcanic dykes and fissures extending into the city and surrounding areas (Wauthier et al., 2012; Delvaux et al., 2017; Smittarello et al., 2022).

3.5. Tsunamis and Flooding
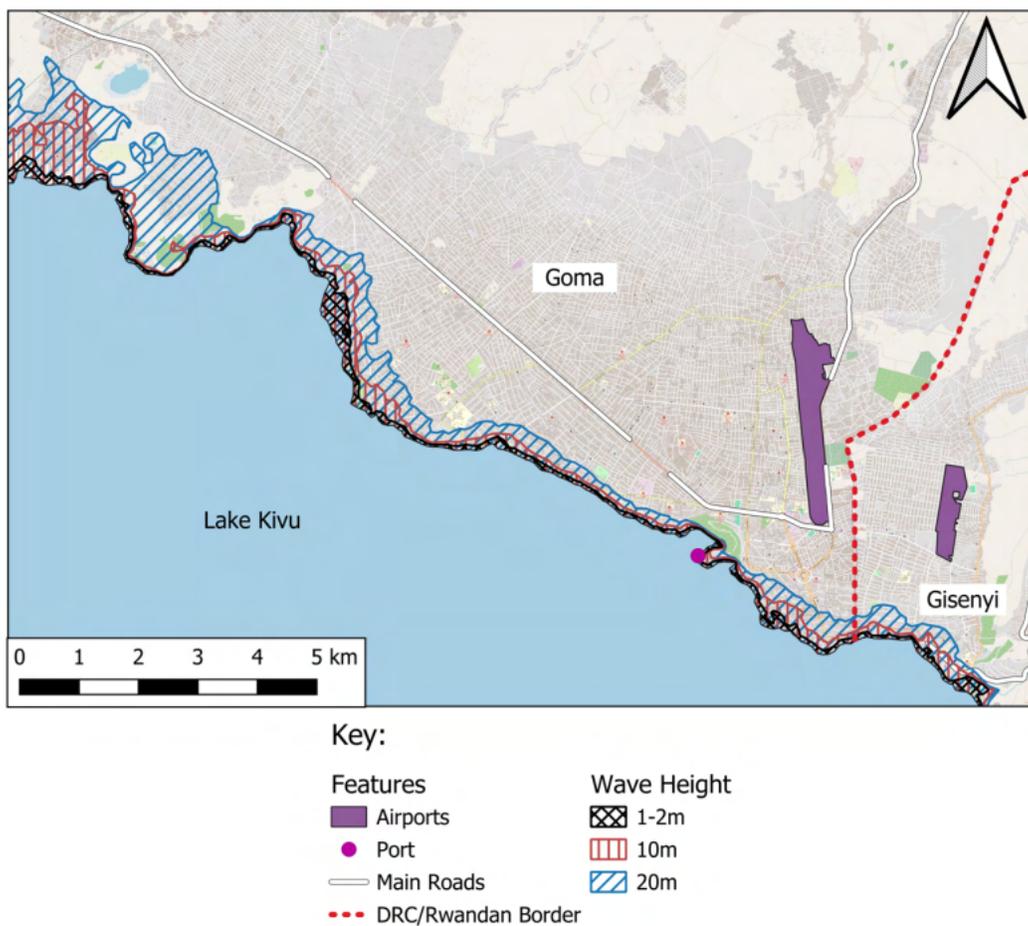
Figure 11: A map showing the areas affected by differing tsunami heights from a lacustrine tsunami. Created by the author. Basemap taken from (OpenStreetMap, 2025)

There are several examples of earthquake-induced lacustrine tsunamis in the historic record, with heights of up to 10m being recorded (Bussmann and Anselmetti, 2010). The examples used here were taken from Lake Lauerz and Lake Lucerne in Switzerland, both of which are significantly smaller than Lake Kivu. This

could impact the applicability of these examples to the lake. There is also one case of a small lacustrine tsunami in Lake Kivu, following an earthquake in 2008, the height of which was not quantified (d'Oreye et al., 2011; Balagizi et al., 2018). The lake's vulnerability to sub-lacustrine landslides also means that a larger tsunami could be generated from the low-magnitude earthquakes common in the region (Balagizi et al., 2018).

Figure 11 demonstrates the potential inundation of Goma under several different tsunami scenarios; a tsunami of 1-2 metres, of 10 metres, and of 20 metres. Given the city's location in close proximity to Mt. Nyiragongo, much of the city is situated above the lake's surface, leaving it out of reach of potential lacustrine tsunamis. The areas closest to the lake which would be affected in a tsunami event are infrastructure, such as the port, and several hospitals, such as Medical Center Cimak, located just West of the DRC/Rwanda border, or the Gisenyi District Hospital directly South of the Gisenyi airport. The Medical Center Cimak would be inundated under even the weakest of tsunami conditions assessed, whilst the Gisenyi District Hospital would be vulnerable to a ten metre wave. Likewise, the port would be vulnerable to all modelled tsunami heights, not to mention a significant number of hotels, residences, churches, and communities spread along the lake shore, all of which would be impacted by even a small lacustrine tsunami.

4. Discussion

4.1. Multihazard Interactions & Vulnerability

These results underscore the complex multihazard environment within which Goma is situated. Each of these models demonstrates the risks posed by individual hazards, but do not fully capture the true nature of the area's overall risk profile, which is rooted in multihazard interactions. Figure 12 shows how each of these hazards can be affected by another, having serious implications for the events' overall severity. The greatest risk posed by these interconnected hazards is almost certainly the possibility of a limnic eruption, triggered by a volcanic eruption from the fissures extending below Lake Kivu. Whilst monitoring does exist, and some measures are in place to manage the lake's dissolved gas concentrations, this hazard is still under-monitored and under-managed (Balagizi et al., 2018). Pilot projects for degassing solutions, such as those offered by Limnological Engineering, have seen success in the lake, particularly in shallower areas with high CO2 concentrations such as Kabuno Bay, but more widespread degassing of the lake still remains purely theoretical (Jones, 2021). Other projects, such as KivuWatt currently provide electrical power for the surrounding population through methane extraction, but this is predicted to extract only 5% of the lake's methane over the next 25 years. Other large-scale projects such as Shema Power Lake Kivu have been introduced,

but the effects of which are yet to be quantified (MWM, 2025). Continued gas extraction from Lake Kivu is critical; with a worst-case limnic eruption affecting up to 2.5 million people, this hazard cannot be ignored (Jones, 2021). Other multihazard interactions, such as volcano-earthquake-landslide hazard chains also pose a threat to the city. For example, the 2021 eruption of Mt. Nyiragongo was followed by a significant period of elevated seismicity, with a notable 5.1 magnitude earthquake occurring directly beneath Lake Kivu (USGS, 2025).

Another factor which can compound the impact of a natural hazard is the vulnerability of the population. Vulnerability encompasses physical, social, economic, and environmental factors that affect the susceptibility of an individual, community, asset, or system to the impacts of hazards (UNDRR, 2017). These factors can be understood through the Pressure and Release (PAR) model, first proposed by Wisner et al. (2003), and later built upon by other research in many different fields (see De Stefano et al. (2015), Dube (2017), Burton, Rufat and Tate (2018) and Hammer et al. (2019)). Figure 13 demonstrates an adapted version of this model which can be applied to Goma. Notably, the legacy of colonialism and neo-colonialism as a root cause, arguably resulting in the region's contemporary weak governance and political violence, significantly contribute towards the 'pressure' in the region (Wu, 2024). Indeed, Wu (2024) argues that the authoritarian power structures, 'divide-and-rule' tactics, and economic systems designed to be reliant on foreign economies induced by colonial rule have had a direct impact on political instability and violence across the continent, not least in the DRC.

		Cause				
		Volcanic Hazards	**Landslides**	**Limnic Eruptions**	**Tsunamis / Flooding**	**Earthquakes**
Effect	**Volcanic Hazards**		Landslides can trigger volcanic eruptions, often as a result of seismic activity. Examples include the 1980 eruption of Mt. St. Helens and the 2018 eruption of Krakatau, Indonesia. (Sidik, 2022)	Limnic eruptions are not known to influence any other hazards.	Flooding has been associated with causing volcanic eruptions – the 2018 rift eruption in Hawaii has been strongly linked to anomalously high levels of precipitation in its preceding months. Rainfall infiltration into the subsurface of the volcano increased pore pressure, resulting in an eruption – the same could happen here to Mt. Nyiragongo. (Farquharson and Amelung, 2020)	Earthquakes have been commonly linked to causing volcanic eruptions. Processes could include increased stress on the volcanic rock 'squeezing' magma to the surface, or stimulating fissure opening. (Seropian et al., 2021)
	Landslides	Volcanic eruptions can trigger landslides, such as through a dome collapse. (BGS, 2025)		Limnic eruptions are not known to influence any other hazards.	High soil moisture content (particularly when reaching the extreme levels found during flooding) significantly increases a slope's landslide susceptibility. (Yuliza et al., 2016)	Earthquakes commonly trigger landslides, and can weaken slopes, making landslides more likely in the future. (Qin et al., 2023; Song et al., 2022)
	Limnic Eruptions	A sub-lacustrine volcanic eruption is the most likely trigger for a limnic eruption, due to the potential sustained temperature increases which could result. (Balagizi et al., 2018)	Surface landslides and sub-lacustrine landslides in shallow water are unlikely to disturb the depths of the lake enough to trigger a limnic eruption. However, sub-lacustrine landslides at depth could trigger an eruption. (Balagizi et al., 2018)		A lacustrine tsunami is unlikely to trigger a limnic eruption, given the significant depth (>200m) at which the majority of the CO_2 is in solution, but should a sufficiently large tsunami occur, it could trigger an eruption. (Balagizi et al., 2018)	Several earthquakes since 2002 have had epicentres below Lake Kivu. Currently observed magnitudes have been insufficient to trigger a limnic eruption, but an eruption could occur with a higher magnitude earthquake directly below the lake basin. (Balagizi et al., 2018)
	Tsunamis / Flooding	Volcanic eruptions could cause a tsunami in Lake Kivu, through sub-lacustrine eruptions, or pyroclastic flows displacing water. (NOAA, 2023)	Both surface and sub-lacustrine landslides have been demonstrated to trigger lacustrine tsunamis. Examples of landslide-induced lacustrine tsunamis in Switzerland have reached up to 10m in height. (Bussmann and Anselmetti, 2010)	Limnic eruptions are not known to influence any other hazards.		Earthquakes are the most common trigger for tsunamis. There are several examples of earthquake-induced lacustrine tsunamis in Switzerland. (Schnellmann et al., 2002)
	Earthquakes	Volcanic eruptions have been linked to increased seismic activity at Mt. Etna, Sicily, where volcanic eruptions increased pressure on nearby faults, likely triggering earthquakes. (Feuillet et al., 2006)	In rare cases, landslides could trigger shallow earthquakes. Changes in fault stress fields resulting from a large movement of material could trigger a sudden release in pressure, in the form of an earthquake. (Steer et al., 2014)	Limnic eruptions are not known to influence any other hazards.	There is little literature directly linking these two hazards. However, a similar process to landslides triggering earthquakes could result in a tsunami causing an earthquake – by shifting a significant mass of material from the surface, a tsunami could alter the stress field of a fault, causing an earthquake. (Steer et al., 2014)	

■ / ■ = Most Hazardous

Figure 12: A table analysing the multihazard interactions in the Goma region. Darker coloured boxes are highlighted as the hazards which pose the most destructive threat, not accounting for the likelihood of such an event occurring. Created by the author.
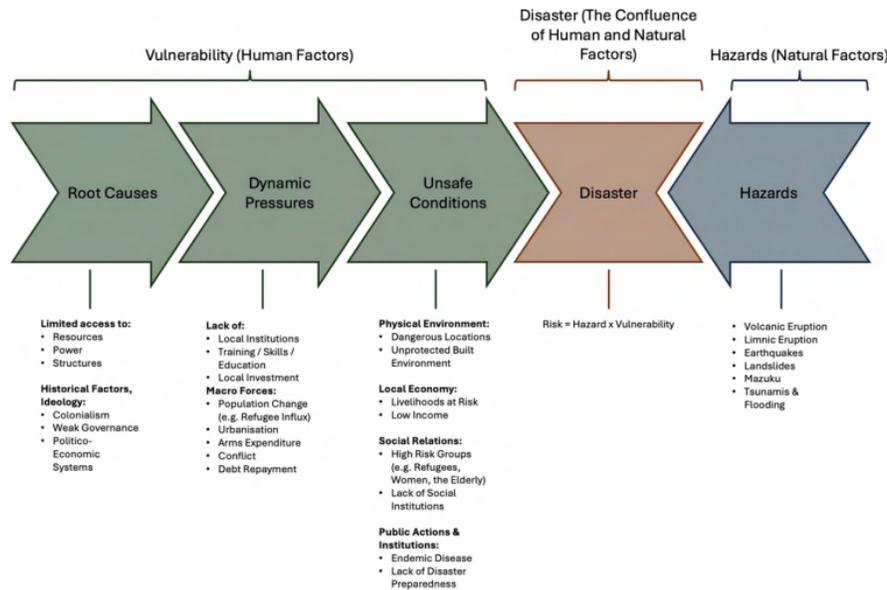

Figure 13: A diagram demonstrating the Pressure and Release model of vulnerability in relation to Goma. This model was originally proposed by Wisner et al. (2003). The figure was created by the author and adapted from figures found in Burton, Rufat and Tate (2018) and Hammer et al. (2019).

Goma's largely low-income population, combined with political instability resulting both from internal conflicts in the DRC, and from unstable relations with Rwanda, increases the population's overall vulnerability. Widespread low incomes significantly impact households' capacity to cope with hazard impacts, particularly when rebuilding (SAMHSA, 2017). Furthermore, access to technology often used in early warning systems (such as mobile phone alerts) is restricted for low-income households (SAMHSA, 2017). Fothergill and Peek (2004) found that low-income areas tend to be worse prepared for a hazard event, citing prohibitively high costs. Indeed, Balagizi et al. (2018) report that much of Goma's population regard natural hazards as less serious than 'everyday' issues such as food & water insecurity. Socioeconomic conditions within the city have also contributed to failures in hazard monitoring. Funding, provided by the World Bank, was cut for the Nyiragongo observatory in 2020 due to accusations of staff embezzlement, resulting in the observatory failing to predict the ensuing 2021 eruption, arguably exacerbating its impact (Holland, 2021; Thelwell, 2021).

There are also distinct inequalities in spatial vulnerability - Michellier et al. (2020) found that informal settlements (such as around Lav Vert or Muganga) to the North of the city experienced the most consistently high levels of vulnerability, with the furthest East and West areas of the city showing the highest absolute levels of vulnerability, as shown in Figure 13 (Michellier et al., 2020). This pattern is likely the result of several factors: firstly, areas outside the city centre are those which are fastest growing, often through the creation of informal settlements such as Lac Vert, which was created following an influx of refugees from Rwanda in 1994 (Michellier et al., 2020). Indeed, these settlements are often located in areas of high hazard prevalence, notably Mazuku, further increasing their vulnerability (Balagizi et al., 2018). Furthermore, Michellier et al. (2020) find that social vulnerability in the centre of the city, despite widespread low incomes, is moderated by high levels of hazard threat perception, fewer dependent individuals (such as women) in each household, and high levels of motorcycle ownership indicating increased economic capacity and greater mobility for evacuation in the case of a hazard event.
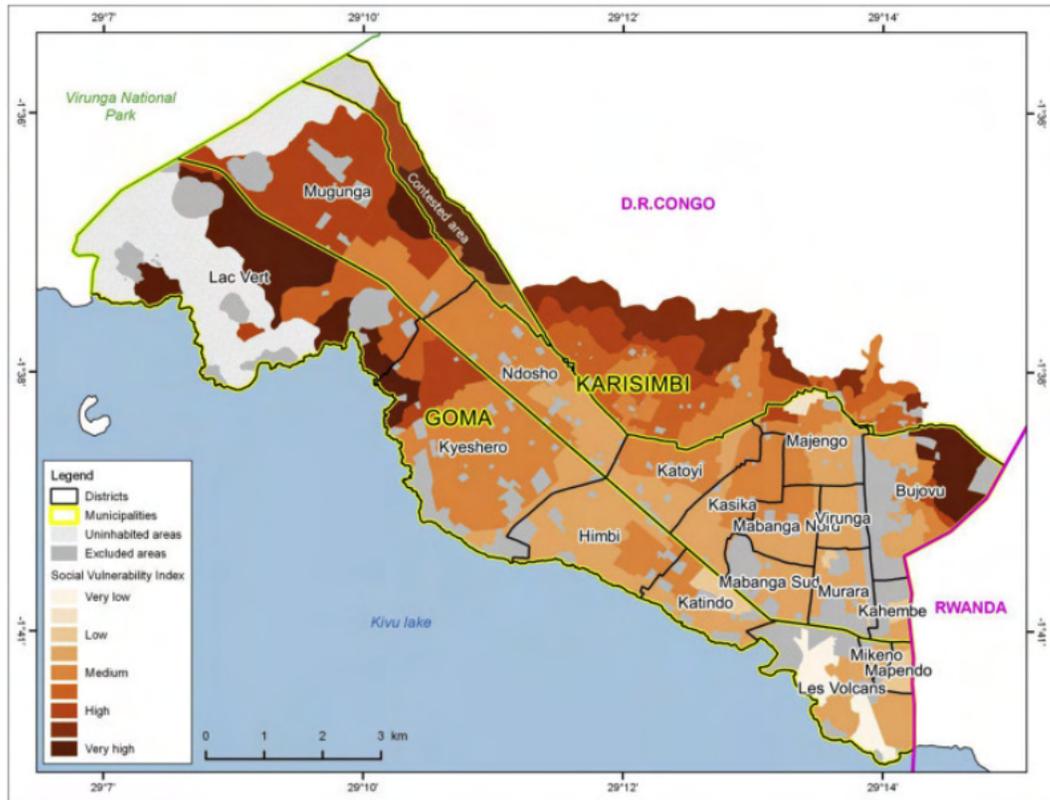
Figure 14: A map of vulnerability in Goma. Created by and taken from Michellier et al. (2020). The author did not make this figure.

The Eastern half of Goma seemingly bears the greatest hazard burden, experiencing the largest levels of destruction from each of the three recent volcanic eruptions, landslide risks from several hotspots (particularly South of the Western airport), and recent seismic activity. Given the context of this area's elevated vulnerability, this region should be targeted for stronger hazard mitigation measures. Landslide risk is also higher in several areas along the Western third of Goma, as is the prevalence of Mazuku vents, also coinciding with areas of increased vulnerability.

4.2. Mitigation Strategy

Any hazard mitigation strategy for Goma must address the complex interrelation between the multihazard environment and vulnerability in the city. It is difficult to directly mitigate many of this region's hazards, so this report recommends that a hazard mitigation strategy should instead focus on vulnerability reduction and building community resilience.

This report's first recommendation is the implementation of education schemes to inform the population about the varied dangers posed by the area's varied hazards. Information campaigns focusing on, for example, the locations of areas previously

affected by lava flows and the dangers posed by Mazuku vents, could provide a powerful tool for Goma's population to make more informed decisions about where to live. Existing education campaigns in schools were found to be effective at increasing students' awareness of the risks of recent volcanic eruptions, but failed to improve hazard awareness for other volcanic hazards which were not seen in the 2002 or 2021 eruptions (Mafuko-Nyandwi et al., 2024). Mafuko-Nyandwi et al. (2024) argue that sustained educational engagement, particularly in relation to hazards not seen in recent eruptions, is essential for these campaigns to have long-term effects.

However, providing information is insufficient if residents do not have the means to act upon it. Thus, this report's second recommendation is to strengthen the region's governance and support community mobility. This is impossible until the widespread disruption, damage and loss of life resulting from rebel activity is curtailed - once this has been achieved, targeted poverty reduction schemes focusing on the most at-risk areas identified (areas of both high vulnerability and hazard prevalence) should be implemented, to reduce the vulnerability disparities in the city.

Whilst strengthening the region's governance and curtailing conflict in the area directly improves two of the key issues outlined in the PAR framework utilised here, mitigating the impacts of the region's hazards must not be ignored. Effective early warning systems can drastically reduce the impact of hazard events, particularly in a complex multihazard environment such as Goma's (Otuogha, 2024). Restoring funding for the Nyiragongo Observatory is an essential part of this strategy. Furthermore, the installation of additional monitoring equipment, particularly for Lake Kivu, the source of the most devastating potential hazard in the area, could greatly reduce the risk posed not only to Goma, but also the millions of others who live in the lake's catchment area. Jolie (2019) suggest an integrated mapping approach for the monitoring of potentially dangerous lakes such as Lake Kivu. Whilst specifically tailored towards Ngozi Crater Lake, its methodology is still useful for application to other lakes. In particular, gas monitoring stations and thermal mapping, for example, are realistic, and should offer early-warning capabilities before an eruption (Jolie, 2019). Moreover, given Goma's complex multihazard environment, the integration of each hazard's monitoring network into a wider whole is critical for an effective overview of the broad spectrum of threats posed by hazards in the area.

Early warning capabilities are inconsequential without an effective way of alerting the local populace: therefore, this report's fourth recommendation is the implementation of widespread announcement systems. One solution could be a tannoy system, much like those found in Illinois to provide early warnings for

various emergencies (Kolios et al., 2016; Ready Illinois, 2023). Other simple and cost-effective strategies could include the distribution of radios to local community leaders, who would then have a responsibility to relay evacuation orders (for example) to the rest of that area's population.

Finally, this report recommends a strengthening of infrastructure around key access routes to the city. The vulnerability of the highways and airports to landslides and lava flows, and the port to tsunamis or flooding would seriously impact both the ability of the population to evacuate, and the capacity for aid to enter the city following an event. There are many examples of mitigation for these hazards around the world: Iceland has successfully implemented lava barriers to redirect lava away from key infrastructure (Henley, 2024). Japan has successfully trialled self-powering sea gates to protect from tsunamis, and slope stabilisation nets are common worldwide to reduce landslide risk (Takagi, 2024; Rock Con, 2025). Whilst the fixed costs of this infrastructure is high, investment in infrastructure is widely recognised to be a strong catalyst for economic growth, providing long-term jobs and increasing the flow of money in the local economy (Alpert, 2023). Funding could be secured through international development loans, offered by many organisations such as the World Bank Group (2025) or the International Monetary Fund (2025). Seismic hazards can be effectively mitigated by introducing stricter building codes and strengthening existing infrastructure (Jackson, Copley and Priestley, 2021). In an economic climate such as that of Goma, however, the majority of the population lacks the resources needed to adhere to building codes, despite the necessity for mandating earthquake-resistant buildings. This presents a so-called 'wicked' problem - it is important to mitigate against hazards, but (particularly in low-income regions such as Goma) resources are limited - expending resources to improve building standards (including the retrofitting of existing buildings) prevents those resources from being used to, for example, create additional food banks or implement new vaccination programs (Steckler et al., 2018).

It is clear that - whilst there are no clear-cut solutions - by combining targeted education & poverty reduction schemes, improving local governance, strengthening infrastructure, and creating a comprehensive monitoring and alert network for the region's complex hazards, Goma's vulnerability can be reduced and its residents better prepared. Much like the region's hazards, however, the impact of each of these recommendations is compounded when they are implemented together. In response to a complex multi-hazard environment, this report proposes a similarly interconnected multi-response plan, within which each of these recommendations, at least in part, is reliant upon the others to realise its full potential - education campaigns, for example, will be ineffective if Goma's population still lives under the shadow of rebel violence.

5. Conclusions

This report has demonstrated that Goma is situated in a complex multihazard environment, threatened by volcanic eruptions, landslides, limnic eruptions, mazuku vents, earthquakes, tsunamis and flooding. The risks posed by these interrelated hazards are further compounded by the region's endemic socioeconomic and political vulnerability, primarily driven by political instability and violence.

In the context of this complex web of hazard and vulnerability, this report underscores the recommendations of the Sendai Framework: the need for an integrated approach to hazard mitigation, focusing not only on mediating hazards, but also on reducing vulnerability and building resilience. Whilst this report was constrained by data availability and modelling limitations, future research - applying quantitative modelling and using more detailed data - could add further clarity to understandings of Goma's complex and interconnected multihazard environment and how to mitigate against it.

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