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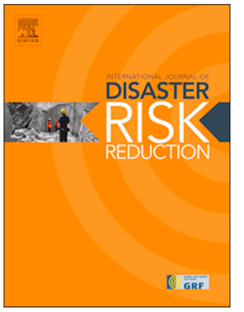

Assessing Community Vulnerability to Landslide and Flood in Northwestern Rwanda

Clémence Idukunda, Caroline Michellier, Florence De Longueville, Emmanuel Twarabamenye, Sabine Henry

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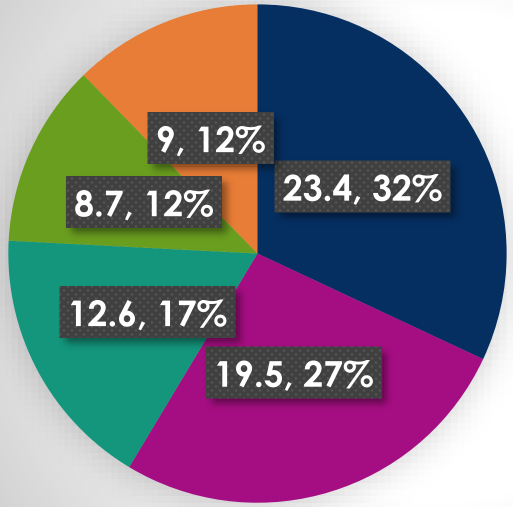
Assessing Community Vulnerability to Landslide and Flood in Northwestern Rwanda

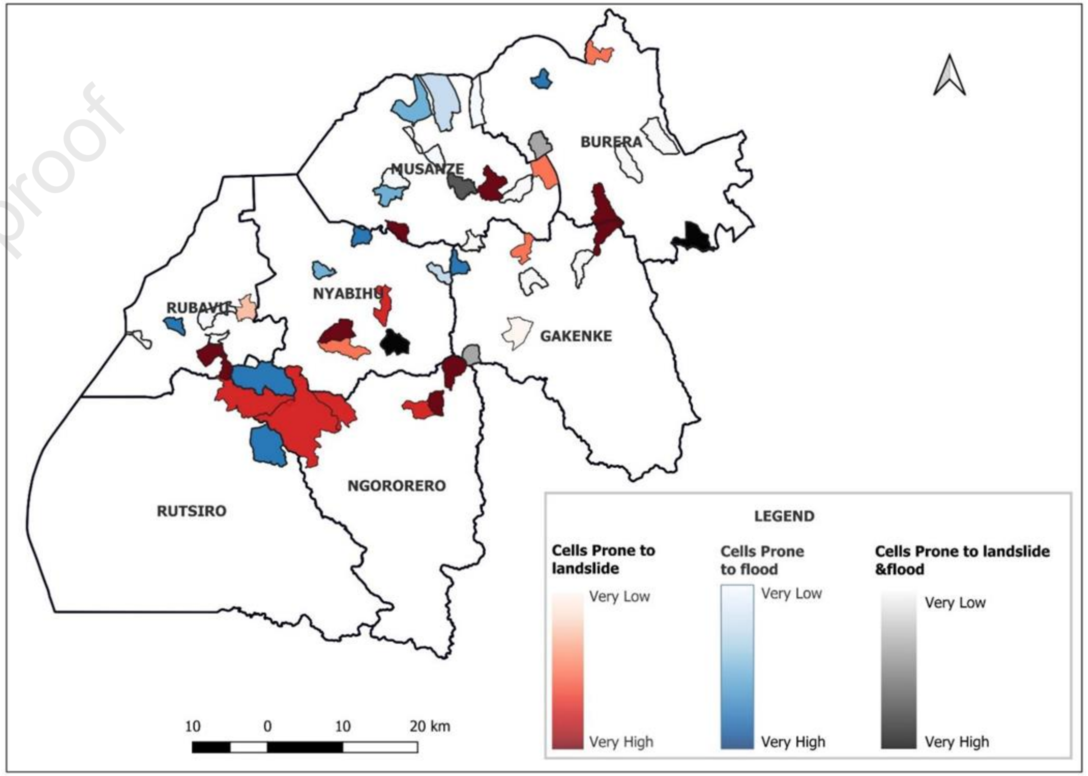
Northwestern Rwanda prone to Landslides and floods which affect the community

Household survey (904 households, 50 cells)

Vulnerability to Landslide and floods

Key Vulnerability Components





25 cells are highly vulnerable to landslide and flood

Landslide-prone areas show higher vulnerability

Idukunda et al,.2024

Assessing Community Vulnerability to Landslide and Flood in Northwestern Rwanda

Clémence Idukunda[a,c,*], Caroline Michellier[b], Florence De Longueville[a], Emmanuel Twarabamenye[d], Sabine Henry[a]

[a]Geography department and ILEE, University of Namur, P.O. Box: 5000, Namur, Belgium.
[b]Department of Earth Sciences, Royal Museum for Central Africa, P.O.Box: 3080 Tervuren, Belgium
Earth and Life Institute – Environmental Sciences, UCLouvain, P.O.Box: 1348 Louvain-la-Neuve, Belgium
[c]Department of Land Valuation and Management, INES-RUHENGERI, P.O. Box, 155, Musanze, Rwanda
[d]Department of Geography and Urban Planning, SABE, University of Rwanda, P.O. Box: 3900, Kigali-Rwanda

*: **Corresponding Author**. E-mail: clemence.idukunda@unamur.be

Abstract

Northwestern Rwanda's hilly terrain, frequent torrential rainfall, and dense population make it highly vulnerable to landslides and floods. A contextual understanding of community vulnerability is crucial for effective risk assessment and mitigation. To address data scarcity in the region, this study adopted an original approach based on household survey (from May to July 2023) encompassing 904 households across 50 cells (administrative level 4), sampled according to the hazard affecting them. The objective was to assess and compare the community vulnerability across landslide, flood, and both hazards combined. Using Principal Component Analysis (PCA), five key components were identified, accounting for 73.2% of the total variance in community vulnerability. These components included: (1) living conditions and location (23.4%), (2) demographic characteristics (19.5%), (3) education and economic status (12.6%), (4) household structure and past disaster experience (8.7%), and (5) land property ownership (9%). While the first four components were associated with increased vulnerability, land property ownership was found to reduce vulnerability. The analysis yielded a Contextualized Vulnerability Index (CoVI), revealing higher vulnerability in 25 cells, primarily in landslide-prone areas. Vulnerability is unevenly distributed, with the most vulnerable communities concentrated in the western part. Some communities displayed lower vulnerability despite hazard exposure, owing to higher adaptive capacity. The findings highlight the need for localized, hazard-specific mitigation strategies to address vulnerability in highly vulnerable areas. They offer actionable insights for authorities to prioritize interventions, allocate resources effectively, and strengthen community resilience. By analysing multiple hazards, the study provides a robust framework for policy-making and sustainable disaster risk reduction.

Keywords: Community vulnerability, CoVI, Field survey, Flood, Landslide, Northwestern Rwanda

1. Introduction

Natural hazards, particularly landslides and floods, represent persistent threats to communities worldwide, resulting in extensive damage, loss of life, and people displacement, particularly on low- and middle-income countries in tropical regions, where vulnerabilities like inadequate infrastructure and limited resources exacerbate the damage (Botzen et al., 2019; Dewitte et al., 2018; Molloy et al., 2017; Rewah, 2022). For instance, between 1998 and 2017, landslides affected an estimated 4.8 million people and killed more than 18,000 individuals (WHO, 2022). In the mountainous regions of northern Vietnam, landslides have been a major disaster, resulting in over 13,000 fatalities and causing average annual property damage of $6.4 billion, which represents 1.5% of the country's GDP over the past two decades (MONRE, 2017; World Bank, 2017). In 2012, landslides in the Philippines have had devastating impacts, particularly during typhoon events. The country experienced its worst typhoon-induced landslide in over a century, which affected more than six million people, claimed at least 1,000 lives, destroyed 200,000 buildings, and caused approximately US$1 billion in damages to crops, infrastructure, and private properties (Eugenio et al., 2016).

In addition, floods affect 56% of the global population and impact approximately 350 million people each year. Moreover, the devastation caused by floods is expected to double by 2050 (Merz et al., 2021). During 2010–2020, about 820,000 people in South and North America alone suffered from flood hazards (Abdullahi et al., 2022). In developing countries, floods have caused devastating impacts including loss of human lives, destruction of infrastructure, and severe economic damage (Glago, 2021). In Malaysia, it has been reported that floods are the most frequent disaster, particularly in low-lying areas, affecting approximately 22% of the population and accounting for nearly 9% of disaster occurrences nationwide (Yusoff et al, 2018). The 2018 monsoon floods in India (Kerala region), posed significant challenges for disaster response, with authorities struggling to coordinate emergency services and deliver timely relief due to the scale of the disaster's impact (Malik, 2011; Ntanganedzeni & Nobert, 2021).

The impacts of landslides and floods vary depending on their magnitude, frequency, and the level of exposure faced by vulnerable communities. Factors such as the concentration of assets in high-risk areas and the socio-economic conditions of the affected population collectively contribute to society's vulnerability to these hazards (Papathoma-Köhle et al. 2007). In Brazil, it has been reported that of the more than 8 million people most at risk, around 75% live in areas susceptible to combined landslides and floods (Assis Dias et al., 2020). Of the more than 8 million people most at risk, around 75% are in areas susceptible to combined landslides and floods. From January to July 2022 alone, landslides and floods triggered by heavy precipitation events have left hundreds of people dead and missing in this country (Marengo et al., 2023). In Uganda (Rwenzori subregion), landslides and floods caused significant damage between May 2019 and March 2021, with 71% of buildings in landslide-affected zones and 37% in flood-affected zones completely destroyed (Sekajugo et al., 2024).

Tropical Africa has also experienced a dramatic rise in landslides and floods in recent decades, with severe consequences (Deijns et al, 2022). Between 2011 and 2020, Nigeria recorded more than 1,000 deaths from floods and landslides, representing 15% of all disaster-related fatalities in Africa (Echendu, 2022; Olanrewaju et al., 2019). The total property damage amounted to over $900 million, accounting for 21% of Africa's disaster-related property losses during that period (Umar et al., 2023). Landslides in Uganda, particularly in the Kigezi Highlands, have had significant impacts. Between June 2018 and May 2020, landslide caused extensive damage and put many properties at risk (Nseka et al. 2021). On May 2nd –3rd, 2023, Rwanda experienced severe floods and landslides, causing 135 fatalities, 110 injuries, the destruction of nearly 5,500 houses, and affecting over 51,900 people (MINEMA, 2023; IFRC, 2023).

Assessing the level of landslide or flood risk faced by a population is influenced by its vulnerability, *i.e.* the physical, social, economic and environmental factors that contribute increasing its susceptibility to the impacts of hazards (UNDRR, 2020; Agliata et al., 2021). Thus, a deep understanding of vulnerability to hazards is crucial for developing and implementing effective mitigation strategies (Hejazi et al., 2022; Lee et al., 2022; Michellier et al., 2016; Tran et al., 2017). While numerous studies have explored community vulnerability to hazards, achieving an unified analysis framework remains a significant limitation in the field, particularly in terms of scale of analysis, hazard specificity and indicators selection (De Silva & Kawasaki, 2018; Samir, 2013; Mugisha et al., 2020; Munyai, 2017). The complexity is further increased when dealing with multiple hazards simultaneously (De Ruiter & Van Loon, 2022).

Cutter et al. (2003) have developed an indicator-based approach that aims at quantifying the social vulnerability of a population through a complex index built on a wide range of socio-economic data (*e.g.*, household composition and income levels, education levels within the population, access to healthcare services, unemployment rates, poverty levels, transportation infrastructure). The Social Vulnerability Index (SoVI) was defined as a metric used to assess the vulnerability of communities to natural hazards (Adger, 2006; Cutter et al., 2003). Such index associates several vulnerability indicators, each defined, according to Birkmann (p.57, 2006), as “a variable which is an operational representation of a characteristic or quality of a system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of an albeit ill-defined event linked with a hazard of natural origin”.

Several studies on assessing social vulnerability to natural hazards rely on the data-driven methodology proposed by Cutter et al. (2003). Some have been conducted in data-rich contexts (Birkmann et al., 2014; Eidsvig et al., 2014; Fatemi et al., 2017; Ignacio et al., 2016; Rossignol et al., 2015), while other have derived contextualized approaches to address data scarcity at a country, district or city scale (Mavhura et al., 2017; Birkmann et al., 2013; Michellier et al., 2020; Mustafa et al., 2011, 2019). Although assessing social vulnerability at a regional level in rural areas and considering the occurrence of all hazards in the region can significantly enhance risk understanding, only few studies have focused on this approach (Hinkel, 2011; Papathoma-Köhle, 2016; Spielman et al., 2020). De Ruiter & Van Loon (2022) and Terti et al. (2015) emphasize that assessing dynamic vulnerability is particularly crucial in multi-hazard settings, where one hazard can increase vulnerability to subsequent hazards. Most research conducted in Africa have concentrated on the analysis of a single hazard rather than addressing multiple hazards simultaneously, as done on floods in Nigeria (Ajibade et al., 2013), in Botswana (Dintwa et al., 2019), and in Mozambique (Kienberger, 2012). In Rwanda, such approach have been conducted towards landslides (Habimana, 2016; Mugisha et al., 2020). However, northwestern part of Rwanda is highly prone to both landslide and flood. A comprehensive approach considering the vulnerability in this context of multi-hazards setting is critically needed.

The present study addresses this gap by assessing community vulnerability to both landslide and flood in the rural northwestern region of Rwanda. Specifically, it aims to (a) identify components of community vulnerability to landslide and flood, (b) develop a Contextualized Vulnerability

Index (CoVI) and (c) compare the community vulnerability levels across areas prone to landslides, to floods, and to both landslides and floods. Through these objectives, the study aims to provide an understanding of vulnerability dynamics in areas grappling with multiple hazards, contributing valuable insights to the existing body of knowledge. The study's findings will contribute to the scientific literature on social vulnerability to hazards and provide policymakers and disaster risk management authorities with practical insights for developing tailored strategies to reduce community vulnerability to landslide and flood in the Northwestern Rwanda, and other similar contexts worldwide.

2. Understanding Community Vulnerability in Rural Northwestern Rwanda

The assessment of **social vulnerability** to hazards has been extensively studied across various contexts, often relying on secondary data collected at the national level (De Silva & Kawasaki, 2018; Ignacio, 2015; Terti et al., 2015). However, this approach may overlook the intricacies of hazard-prone areas alone. Assessing vulnerability in only hazard-prone areas can significantly enhance the effectiveness of vulnerability reduction efforts (Hejazi et al., 2022; Mugisha et al., 2020; Osuret et al., 2016). It is imperative to differentiate factors directly linked to pre-existing socio-economic conditions, such as poverty and education, which are present among individuals both inside and outside hazard-prone areas, from the adaptive capacities specific to those living in hazard-prone regions (Birkmann et al., 2013; Cardona et al., 2012; Koks et al., 2015). In this regard, the term "**community**" is defined in our study as people inhabiting a common geographical space characterized by its susceptibility to landslide and/or flood (adapted from Aksha et al. (2020)). By delineating the community at a local level accordingly, it becomes feasible to conduct vulnerability assessment tailored to specific contexts (Michellier et al., 2020; Munyai, 2017; Sabri & Ash'aari, 2023).

Several studies undertaken in African contexts have adopted such an approach. Michellier et al. (2020) emphasized the importance of tailored vulnerability assessments of the population of Goma (DRC) facing the Nyiragongo volcano, by developing both a Social Vulnerability Index (SoVI) and an Operational Vulnerability Index (OVI) to improve volcanic risk understanding and inform urban planning effectively. Munyai (2017) identified key determinants of flood vulnerability in South Africa's Limpopo lowveld and highlighted local coping strategies, recommending integrated resilience programs and early warning systems. The study of Mavhura & Manyangadze (2021) using 24 social vulnerability indicators, found poor rural districts of western and southern Zimbabwe have moderate to high social vulnerability. Using data from census records, government reports, and household interviews, the study of Letsie & Grab (2015) revealed that the most vulnerable communities in Lesotho are concentrated in the rural highlands, primarily due to underdevelopment, poverty, and inaccessibility. Going one step further, the study of Sabri & Ash'aari (2023) undertaken in East Malaysia utilized SoVI to pinpoint high-risk areas, demonstrating that increased adaptive capacity can mitigate vulnerability, thereby guiding targeted disaster prevention and mitigation efforts.

Adaptive capacity refers to the ability of individuals, communities, and systems to adjust to potential hazards, take advantage of opportunities, and cope with the consequences (Carmen et al., 2022; Gaillard et al., 2019). Strengthening adaptive capacity involves fostering social cohesion, enhancing access to resources and information, supporting livelihood diversification, and promoting inclusive governance structures (Dapilah et al., 2020; UNDRR, 2019). For instance, research by Dapilah et al. (2020) emphasized the importance of adaptive capacity in resilience-building efforts. Figure 1 illustrates three important issues. First, **social vulnerability and adaptive capacity** are ultimately interrelated and determined by the combination of socio-economic conditions of the community, as well as its location and experience of past disasters. In other words, these factors, including community demographics, such as household size and structure, educational attainment and economic status of the community members, play a pivotal role in assessing community vulnerability and shaping its adaptive capacity to withstand the impacts of hazards (Figure 1).

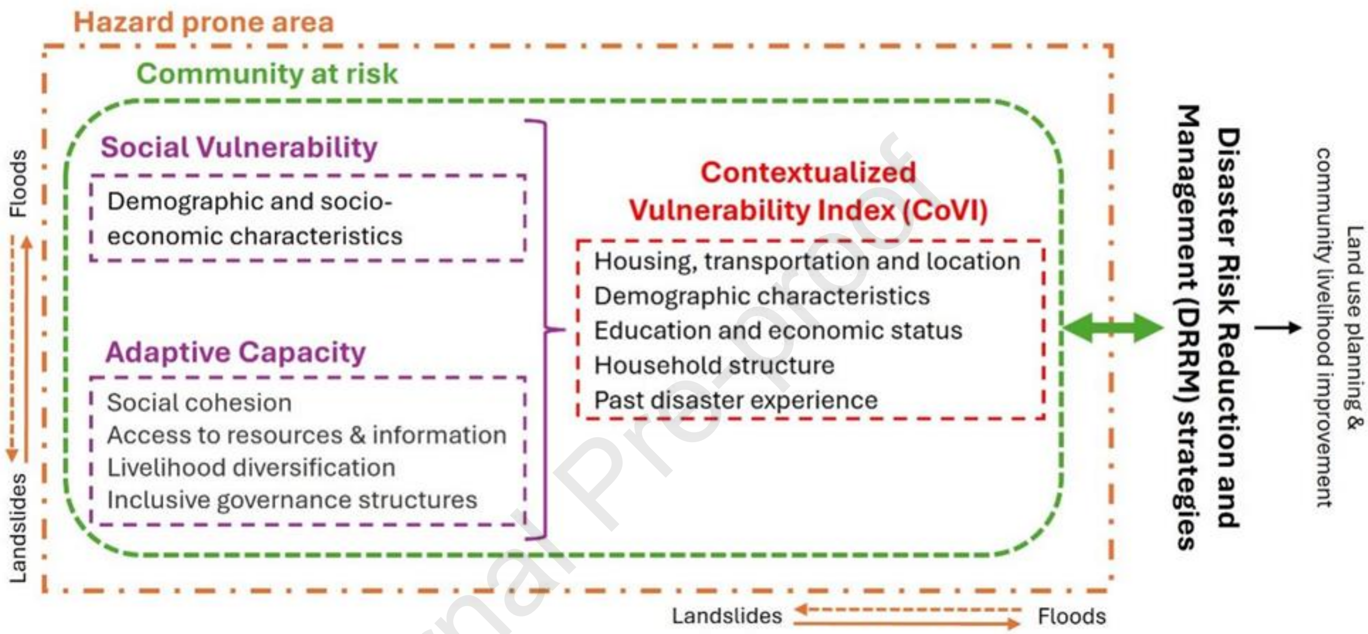


Fig. 1. Conceptual framework for Contextualized Vulnerability Index (CoVI) assessment: The community in landslide and flood-prone areas (orange border) faces increased risk due to social vulnerability and limited adaptive capacity (purple border). These factors, used to calculate the Contextualized Vulnerability Index (CoVI) (red border), highlight the need for tailored DRRM strategies to mitigate hazard impacts (green border). (Source: Authors' illustration).

Second, given the central role that vulnerability to hazards plays in determining their potential impacts, **context-specific vulnerability assessments** are crucial for improving Disaster Risk Reduction and Management (DRRM) strategies, as well as community resilience. In other words, through targeted interventions, such as land use planning and community livelihood improvement aimed at reducing vulnerability, DRRM strategies have the potential to not only minimize the immediate impacts of hazards, but also build long-term adaptive capacity within communities (Abenir et al., 2022; Amri et al., 2017; Michellier et al.,2020; Pigeon, et al., 2020; Osuret et al., 2016).

Lastly, in the northwestern region of Rwanda, communities face the **dual threat of landslides and floods**, where the occurrence of one hazard can exacerbate the impacts of the other. This interconnectedness of hazards necessitates a comprehensive assessment of vulnerability by considering the combined effects of both hazards (Asare-Kyei et al., 2017; Bronfman et al., 2019; Cardona et al., 2012). While significant researches have explored landslide and flood in Rwanda, much of these exhibit some limitations. For instance, the emphasis on susceptibility mapping often overshadows a comprehensive community vulnerability assessment, leaving critical questions unanswered about the differential impacts on various populations (Few & Tran, 2020; Kellenberger & Mobarak, 2008 Nor Diana et al., 2021). This limitation undermines effective DRR strategies, leading to poorly targeted interventions, wasted resources, and continued lack of protection for the most vulnerable populations (Birkmann et al., 2013; Cardona et al., 2012; Koks et al., 2015). The need for a contextualized approach, focusing on locally defined communities within hazard-prone zones is clear (Aksha et al., 2020). By adopting a contextualized approach that accounts for the interplay between social vulnerability and adaptive capacity, we foster the holistic understanding of the vulnerability of communities in Northwestern Rwanda (Figure 1).

3. Study area and methodology

3.1 Study area

The study focuses on Northwestern Rwanda, encompassing seven districts (Figure 2), namely Musanze, Gakenke, and Burera of the Northern Province, and Nyabihu, Rutsiro, Rubavu, and Ngororero of the Western Province. The study area is predominantly rural, with most inhabitants living on hillsides or on the foothills of mountains. The majority reside in grouped settlements, while others live in scattered settlements that are relatively close to one another. The population density in the study area is notably high, ranging from 520 to 1,614 inhabitants per square kilometer, exceeding the national average of 503 inhabitants per square kilometer. The average population density in the study area stands at 818 inhabitants per square kilometer, with Musanze and Rubavu districts surpassing 1,000 inhabitants per square kilometer (NISR, 2022). Most households in the region rely on subsistence farming, primarily cultivating crops like maize, beans, and potatoes.

The study area is characterized by steep mountainous terrain, with elevations ranging from 1,300 to 4,500 meters above sea level and slopes of 24 to 50 degrees. It also experiences heavy rainfall patterns, receiving between 1,500 and 3,000 mm annually, marked by two rainy seasons (March to May and September to December). The lithology of the region consists primarily of igneous rocks made from intrusive rocks in the south of the region (granites, pegmative gabbro) and extrusive (volcanic) in the north of the region (basalts, etc.), and a bit of metamorphic rocks (micashistes, quartzite), making it highly susceptible to landslide, particularly during periods of intense rainfall (Depicker et al, 2020). The dense population in this rural area contributes to increased vulnerability, as the interaction between landslides and floods often affects the same communities, exacerbating the impacts on livelihoods, infrastructure, and safety.

According to reports from the Ministry in charge of Emergency Management (MINEMA), between 2016 and 2020, 485 people died and more than 200 were injured due to landslides and floods in the country, with over 8,600 houses damaged and 18,300 hectares of crops destroyed, the majority of which were recorded in the northwestern region. Flood occurs due to river overflows primarily from the Mukungwa and Sebeya rivers, whose catchments are included in the study area or in the form of devastating flash floods that cause significant property and infrastructure damage. Landslide predominantly occurs on steep slopes characterised by weathered lithology and the presence of mobile regolith (Depicker et al., 2020, 2021, Dewitte et al., 2021). The interaction between flooding and landslides is significant, as intense rainfall can lead to both hazards simultaneously, further complicating the disaster response and recovery efforts. Communities affected by these hazards often experience overlapping impacts, such as loss of property, agricultural land, and access to essential services.

Despite mitigation efforts such as bench terraces, tree plantations, trenches, contour farming, and dikes, these multi-hazard interactions continue to pose significant challenges to the community. Recent events, such as the May 2023 disaster, underscore the severity of this issue, as both landslides and floods caused widespread destruction across multiple districts, resulting in 135 fatalities, 110 injuries, and the displacement of around 8,000 people (IFRC, 2023; MINEMA, 2023). The fact that the same communities are regularly impacted by both hazards underscores the importance of studying these interconnected risks and finding sustainable solutions.

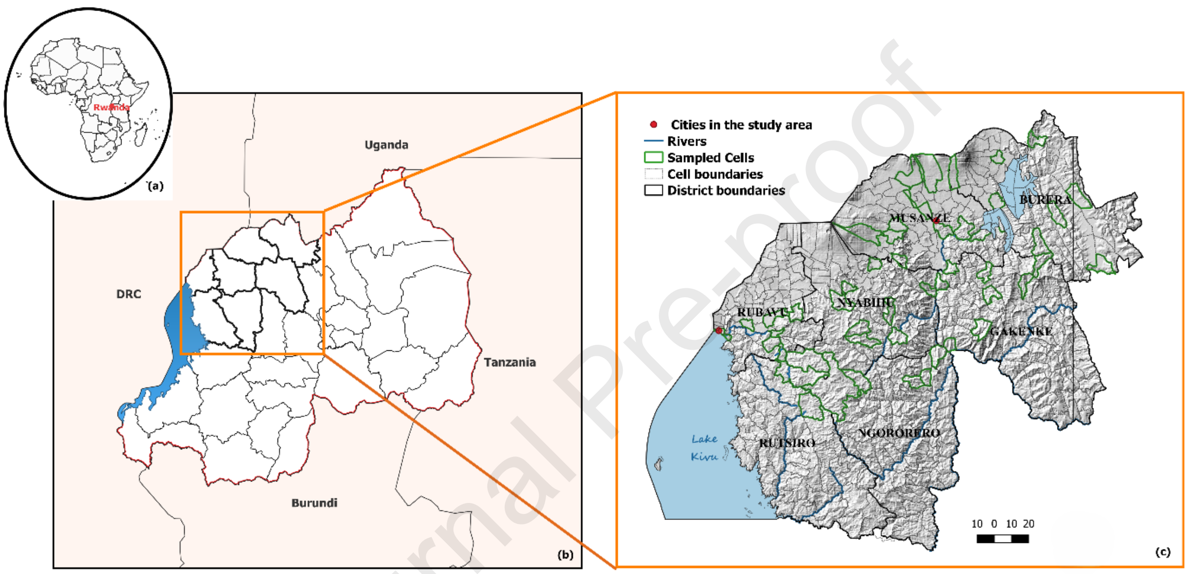


Fig.2. Geographical location of the study area. (a) The location of Rwanda in Africa (*Source: DIVA-GIS: https://diva-gis.org/)*. (b) The location of the study area at national level along with administrative district boundaries. (c) Detailed view of the study area, presenting the districts of Rubavu, Nyabihu, Musanze, Burera, Gakenke, Ngororero, and Rutsiro and their elevation (*Source: Copernicus data, accessed on 5 January 2025*)

3.2 Methodology

Data used for this study was collected from household survey and validated through various published documents and key informants interviews. This section presents the household survey design and the description of the sample. It also details the primary data collection process, a questionnaire used, and a summary of the analysis steps, which are illustrated in Figure 3. The study was conducted at the cell level, the smallest administrative unit, which serves as the primary point of implementation for the country's DRRM policies.

3.2.1 Survey implementation and sample description

A stratified sampling at administrative cell level was adopted: cells were selected and grouped according to their susceptibility to landslide and/or flood .This approach was adopted to ensure a representative sample that captures the variability across different cells. On the one hand, landslide-prone cells were identified by overlaying the shapefile of the study area onto the landslide susceptibility map produced by Depicker et al. (2020). This map, originally generated through an analysis of topographic, lithological, and land cover characteristics, provides a detailed representation of landslide-prone areas. By clipping the relevant portion of the map corresponding to the study area, landslide-prone cells were accurately extracted. On the other hand, flood-prone cells were identified by overlaying the study area's shapefile onto a flood-prone area map provided by the Rwandan Ministry of Disaster Management and Refugee Affairs (MIDIMAR, 2015). This map, based on hydrological modeling and historical flood data, highlights areas frequently affected by floods in Rwanda. The same process was used to clip the flood-prone sections within the study area boundaries. Finally, the combined landslide and flood-prone cells were determined by intersecting the two datasets, ensuring precise identification of areas exposed to both hazards. Using the Cochran formula, adjusted for accessibility, time constraints, and financial costs, a representative sample of 50 cells was determined: 22 landslide-prone cells, 17 flood-prone cells, and 11 cells prone to both hazards. Households to be surveyed were randomly sampled by selecting nth household from the list of households in respective cells, ensuring that each household had an equal chance of being included in the study within these cells.

The household survey was conducted from May to July 2023, and on the assumption that livelihoods are similar within the same cell but differ from those of cells located in geographically distinct areas; similar livelihoods mean that households within a given cell engage in comparable economic activities and face similar environmental and socio-economic conditions. Approximately 18 households per cell were surveyed, resulting in a total of 904 households (Table 1).

Table1 Sampled cells and distribution of households per cell

Hazard type	Number of sampled cells	Number of sampled households
Landslide	22	398
Flood	17	307
Landslide & flood	11	199
Total	**50**	**904**

3.2.2 Data collection and questionnaire

Data were collected from each household through face-to-face interviews with either the head of the household, their spouse, or another permanent adult resident. Interviews were conducted using a structured questionnaire designed with Kobotoolbox to gather information on social vulnerability and adaptive capacity indicators. To address language barriers, the questionnaire was translated into Kinyarwanda, the national language of Rwanda. A field test ensured clarity and comprehensibility before actual data collection began. The questionnaire, which was developed based on Michellier et al. (2020), included questions on demographic characteristics, socioeconomic conditions, livelihoods, hazard experiences, and included questions to understand the adaptive capacity to landslide and flood (See Supplementary material 2). Each household's location was recorded first, followed by a photograph of the house to gather all necessary information for assessing vulnerability in the study area. Data reliability was further strengthened through triangulation, by cross-referencing information from household surveys, validated by secondary data including government reports and published articles, and key informant interviews. However, the study acknowledges certain limitations, such as potential recall bias in self-reported data, the focus on households near hazardous sites which may not be representative of those further away, and the reliance on the validation of the key informant interviews that may highlight official perspectives while potentially overlooking informal community practices.

3.2.3 Data analysis

The data collected was processed into Stata (SE, 15) for descriptive statistics and Principal Components Analysis (PCA)**.** The choice of descriptive statistics was guided by their ability to provide a comprehensive summary of the data, including measures of central tendency, dispersion, and variability, while the PCA was employed to reduce the dimensionality of the dataset and identify the most significant factors contributing to household vulnerability.

In the initial phase, data from all 904 households were weighted by dividing the number of sampled households by the total number of households at the cell level. Weighting was instrumental in ensuring that the sampled households made proportional contributions to the total number of households within their respective cells.

Following the second step outlined in Figure 3, seventeen vulnerability indicators were derived from the survey data using our contextualized approach. In this step, descriptive statistics were applied to the sampled vulnerability indicators. These indicators include variables of demographic and socio-economic characteristics (Cutter et al., 2003), as well as variables associated with adaptive capacity, which are further detailed in Table 2. In this step, descriptive statistics were used to summarize the vulnerability indicators within the cells.

Pursuing the descriptive analysis, variables were normalized in order to be standardized into z-scores before conducting further statistical analysis.

To calculate the Contextualized Vulnerability Index (CoVI), the PCA method was adopted. The PCA facilitates reducing the dimensionality of a dataset while retaining as much relevant information as possible for all cells. Varimax rotation was used in order to maximize the loading of each variable on a single component, thus facilitating the interpretation of the components (Schmidtlein et al,. 2008) and Kaiser criterion was then applied to select the principal components (factors) having eigenvalue larger than 1 (Zwick and Velicer, 1986). The PCA produced a set of uncorrelated components that represented a linear weighted combination of the initial set of variables. The resulting components were used to calculate CoVI for each cell.

Components that increased vulnerability were considered positive, and those that reduced vulnerability were viewed as negative (Cutter et al., 2003; Solangaarachchi et al., 2012). No variable loaded both positively and negatively on a component. Then, a composite CoVI score was developed by adding all five component scores (factor loadings) for each cell. The selection of an additive model was deliberate, as it avoids any prior assumptions regarding the significance of individual factors within the overall sum (Cutter et al., 2003). This approach ensures that each component is regarded as equally influential towards the overall vulnerability assessment, with emphasis placed on capturing spatial variability. Ultimately, this methodology contributes to a deeper understanding of the interconnected explanations underlying vulnerability complexity.

The final CoVI scores were then divided into five groups (quintiles) to indicate the degree to which each cell's score deviated from the average. This classification categorized cells into five levels of vulnerability: very low, low, medium, high, and very high. Using ArcMap 10, the CoVI levels were mapped to show their spatial variability.

This enabled comparison of the level of social vulnerability across the 50 cells in the region. Figure 3 shows the process steps.

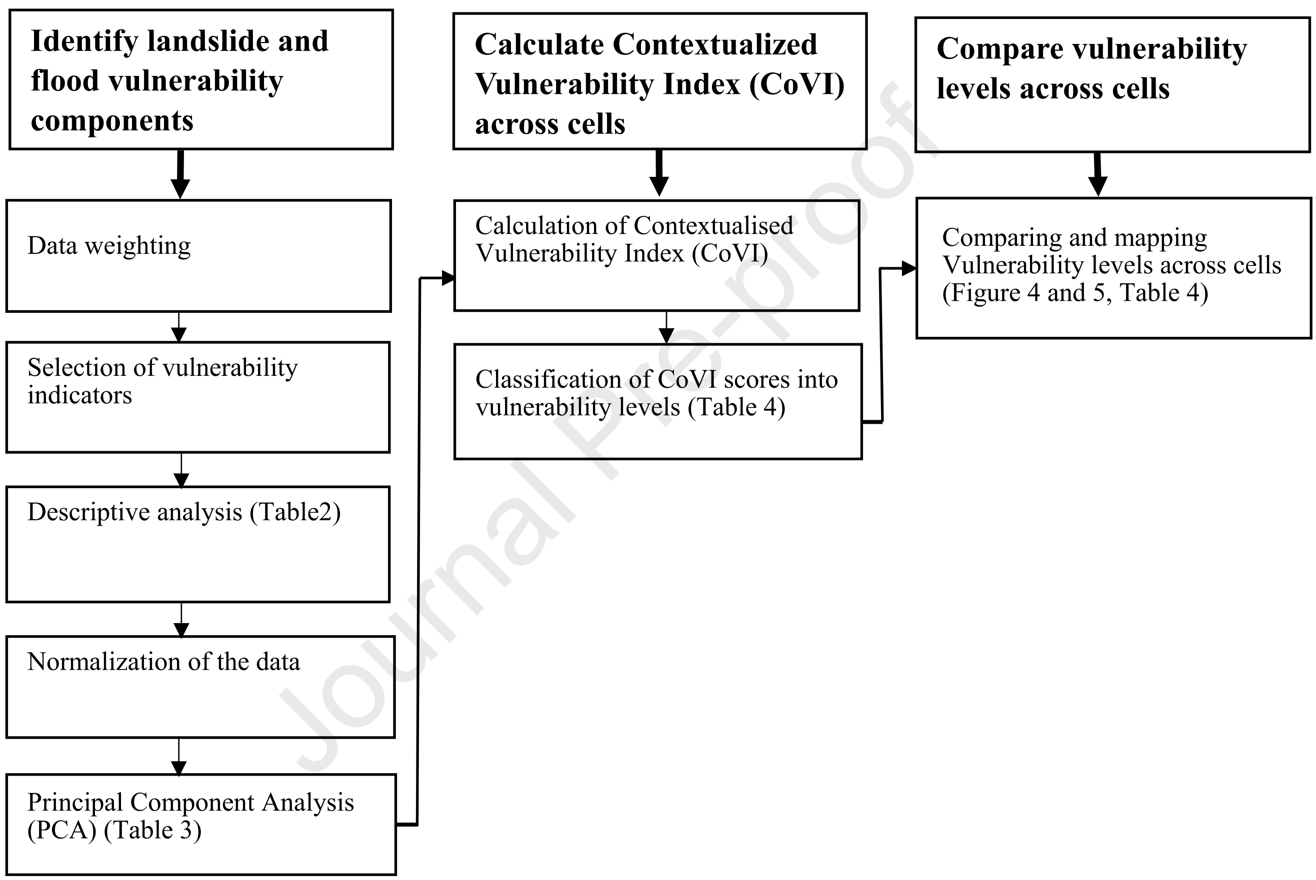


Fig. 3. Summary of steps used for vulnerability analysis

4. Results

The results presented in this section include the identification and descriptive analysis of the variables used to calculate the Contextualized Vulnerability Index (CoVI), along with a comparison of CoVI levels across cells and the spatial distribution of these levels within the study area. Additionally, the CoVI for each cell is provided (Annex1).

4.1 Variables used to calculate CoVI

Table 2 presents the descriptive statistics of the PCA-selected variables used to calculate the CoVI. These variables, expressed as percentages across 50 cells, offer insights into various demographic, socio-economic, and adaptive capacity factors contributing to community vulnerability. Each variable's minimum, maximum, range, mean, and standard deviation values provide a comprehensive overview of the data distribution and pattern.

The mean percentage of female-headed households is 18.1%, with a large standard deviation of 10.9%. Single-parent households have a slightly higher mean at 19.8% (SD = 10.6%). Notably, households where more than 50% of the members are children under the age of 16 constitute 42.1% on average, while those headed by individuals with no formal education show a mean of 65.9% (SD = 15.7%). Additionally, the sample highlights that 96.8% of households have a low monthly income (<$50), with a very narrow standard deviation of 4.5%, indicating consistent financial vulnerability across the sample (Table 2). These variables guide targeted interventions, such as subsidized health insurance or educational programs in vulnerable communities, addressing socio-economic disparities that exacerbate vulnerability.

Table 2 Variables used to calculate the CoVI in the 50 cells

Selected variables calculated by cell (in %)	Min	Max	Range	Mean	Std. Dev.
Demographic and socio-economic characteristics					
Female headed households	0.0	43.8	43.8	18.1	10.9
Single parent- households	0.0	43.8	43.8	19.8	10.6
Households in which more than 50% of the members are children under the age of 16	31.1	58.5	27.5	42.1	6.7
Households in which more than 50% of the members are adults aged 65 and older	0.0	12.2	12.2	5.1	3.1
Households headed by individuals with no formal education	16.7	94.1	77.5	65.9	15.7
Households headed by people attained primary education as highest	40.0	100.0	60.0	67.5	12.2
Households with at least two unemployed adults	0.0	35.3	35.3	3.7	6.1
Households with low monthly income (<50usd/month)	84.2	100.0	15.8	96.8	4.5
Households with no health insurance (MUSA)*	0.0	17.6	17.6	1.7	3.9
Poor households**	6.7	95.0	88.3	53.1	23.1
Households located in close proximity to hazard-prone areas***	0.0	100.0	100.0	70.7	28.0
Households in scattered/unplanned habitat	33.3	100.0	66.7	87.1	16.5
Adaptive capacity					
Households without land property	0.0	20.0	20.0	1.8	4.3
Households without any transport means	73.3	100.0	26.7	93.8	7.5
Rain-fed agriculture-dependent households	20.0	100.0	80.0	75.2	20.0
Households receiving post-hazard recovery support	0.0	100.0	100.0	53.8	37.4
Households affected by flood/ landslide	66.7	100.0	33.3	96.7	7.6

*MUSA (*Mutuelle de Santé* in French or *Community Health Insurance* in English) is the public health insurance used by the communities in Rwanda **Poor households: Poverty level was calculated using wealth assets index (indicators of wealth include ownership of durable goods (like TVs, refrigerators, cars), housing quality (materials used for walls, roof), access to basic services (water, electricity, sanitation), together with educational attainment or employment status,*** proximity to hazard-prone areas: settlement within less than 50m near the rivers/water bodies, or zones previously affected by floods or landslides.

4.2 Landslide and flood vulnerability components

Table 3 highlights the factors that contribute to the community's vulnerability to landslides and floods. The PCA results pinpoint a total of five significant components collectively explaining 73.2% of the variability in a dataset comprising 17 variables across 50 cells. The results indicate an increased vulnerability attributed to the living conditions and location (PC1) with 23.4% of the total variance. Demographic characteristics (PC2), education and economic status (PC3), and household structure and past disaster experience (PC5) are three additional components raising vulnerability with 19.5% and 12.6%, and 8.7% of the total variance respectively. On the other hand, the component associated with landownership (PC4: 9% of the variance) lowers vulnerability. Policymakers can use these components to design hazard-specific action plans, such as stricter regulations on construction in landslide-prone areas and investment in flood defense systems.

Table 3 Factors contributing to community vulnerability in Northwestern Rwanda

Components	Component Interpretation	Eig.	Var (%)	Cum. Var (%)	Variables	Factor loadings	Impact on Vulnerability
PC1	Living conditions and location	4.6	23.4	23.4	Households in scattered/unplanned habitat	0.8333	+ increase
					Households without any means of transportation	0.7932	
					Poor households	0.7833	
					Households located in close proximity to hazard-prone areas	0.7495	
					Households receiving post-hazard recovery support	0.5459	
					Households headed by people attained primary education as highest	0.4961	
PC2	Demographic characteristics	3.3	19.5	42.9	Female-headed households	0.9024	+ increase
					Single parent households	0.9087	
					Households with at least two unemployed adults	0.7967	
					Households with no health insurance	0.654	
PC3	Education and economic status	1.6	12.6	44.5	Households headed by individuals with no formal education	0.8732	+ increase
					Rain-fed agriculture-dependent households	0.5704	
					Households with low monthly income (<50usd/month)	0.5019	
PC4	Land property ownership	1.2	9	64.5	Households with no land property	-0.8072	- decrease
PC5	Household structure and past disaster experience	1.0	8.7	73.2	Households in which more than 50% of the members are children under the age of 16	0.6344	+ increase

	Households in which more than 50% of the members are adults aged 65 and older	0.852
	Affected by landslide/flood	0.898

4.3 Contextualized Vulnerability Index (CoVI)

The PCA results indicate the CoVI of each cell (see supplementary 1). Using the equal interval width classification method, CoVI score were classified into five categories, from “very low” to “very high” vulnerability levels, revealing a gradient across the study area (Table 4).

Table 4 Distribution of cells within the study area according to their CoVI score and corresponding vulnerability level

CoVI levels	CoVI Score range	Number of cells per CoVI level
5 : Very high vulnerable	2.44 to 4.44	8
4 : High vulnerable	0.44 to 2.44	17
3 : Moderately vulnerable	−1.56 to 0.44	14
2 : Low vulnerable	−3.56 to −1.56	9
1 : Very low Vulnerable	−5.56 to −3.56	2
		N=50

Respectively 8 and 17 cells fall into the “very highly vulnerable” and “highly vulnerable” categories to the adverse impacts from landslide, flood or both landslide and flood. Fourteen cells were classified as “moderately vulnerable”. Finally, the presence of nine and two cells respectively in the “low vulnerable” and “very low vulnerable” categories identifies communities that are comparatively better able to cope with the hazard impact. The CoVI provides a spatially nuanced understanding of vulnerability, enabling urban planners to prioritize interventions in the most affected areas.

4.4 Comparison of vulnerability levels across hazard-prone cells

The results indicate that vulnerability levels differ according to the hazard type that may affect the cell. “Very high vulnerability” is predominantly observed in cells prone to landslides and “high vulnerability” in those susceptible to both landslides and floods. In contrast, “low vulnerability” is highly observed in cells prone to floods (Figure 4).

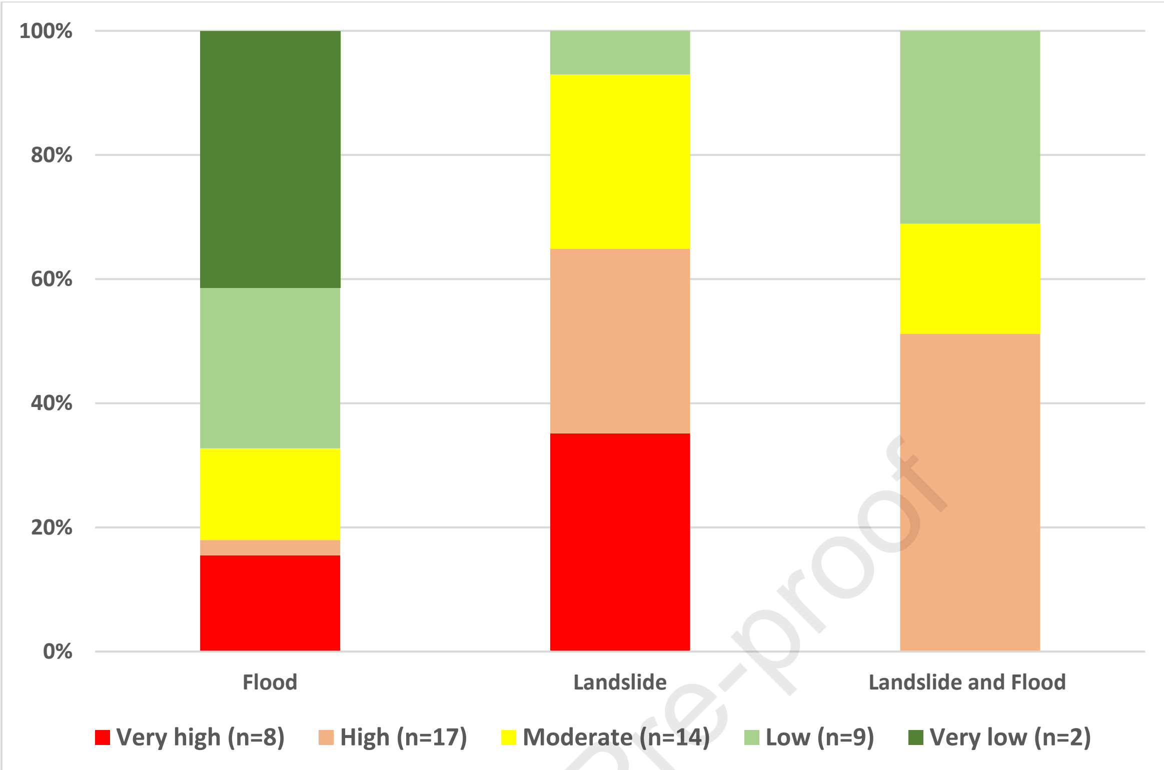


Fig.4. Distribution of Vulnerable levels across hazard-prone cells (Source: Idukunda, 2023)

This variability is also shown by comparing the average CoVI and its standard deviation across three categories of hazard-prone cells (Table 5). Landslide-prone cells have a relatively high average CoVI of 1.10, indicating higher vulnerability, with a substantial standard deviation of 1.76, suggesting a considerable variability of vulnerability within the cells. In contrast, flood-prone cells exhibit a lower average CoVI of -1.14, indicating lower vulnerability on average, but with a higher standard deviation of 2.65, pointing to a wide range of vulnerability levels within the cells. Finally, cells prone to both landslides and floods have an average CoVI of 0.25, with a relatively low standard deviation of 0.44; this suggests that these areas experience moderate vulnerability with less variability compared to the other two categories.

Table 5 Vulnerability levels per hazard-prone cells

Cell Category	Average CoVI	Standard Deviation	N=50
Landslide-prone cells	1.10	1.76	22
Flood prone cells	-1.14	2.65	17
Landslide and flood prone cells	0.25	0.44	11

Moreover, as shown in Table 6, the components contributing significantly to the various levels of vulnerability among the different hazard-prone cell categories have been identified.

Table 6 Principal Components contributing to different vulnerability levels per hazard-prone cells

Principal Component (PC)	Contribution to variance	Landslide-prone cells	Flood prone cells	Landslide & flood prone cells
PC1: Living conditions and location	23.4	High	Low	High
PC2: Demographic characteristics	19.5	Low	High	Low
PC3: Education and economic status	12.6	High	Low	Low
PC4: Land property ownership	9	Medium	Medium	High
PC5: Household structure and past disaster experience	8.7	Low	High	Medium

In landslide-prone cells, PC1 (living conditions and location) and PC3 (education and economic status) highly contribute to the CoVI. This suggests that living conditions and location, associated with education and economic status, are critical determinants of vulnerability in landslide-prone regions. PC4 contributes moderately to the CoVI value, while PC2 (demographic characteristics) and PC5 (household structure and past disaster experience) contribute less to the overall vulnerability in these cells.

On the contrary, PC1 and PC3 are weakly contributing to the CoVI values in flood-prone cells, while PC2 and PC5 contribute strongly to the CoVI. It means that key demographic factors, such as female-headed households, single parenting, households with at least two unemployed adults, and households without health insurance, are significant regarding the level of vulnerability in these cells. PC4 shows a moderate contribution to CoVI value.

For landslide and flood-prone cells, PC1 and PC4 contribute significantly to CoVI, highlighting that living conditions and location and land property ownership play a key role in the vulnerability level. Additionally, PC5 shows a medium value in these cells, depicting the moderate role of household composition, as the proportion of dependents, in determining communities' vulnerability in landslide and flood-prone areas. This comparison supports evidence-based policymaking by highlighting disparities in vulnerability that require tailored approaches, such as housing subsidies or community preparedness programs.

4.5 Spatial Distribution of Vulnerability

The CoVI distribution shows regional variations in vulnerability levels across different districts. Cells in Nyabihu, Rubavu, and Ngororero districts display high levels of vulnerability, particularly in cells prone to landslides and floods. In contrast, cells of Musanze and Burera districts show high vulnerability to floods. This distribution indicates that vulnerability is not uniformly spread across the region but is concentrated in specific zones, particularly in the western part (Nyabihu, Rubavu, Rutsiro and Ngororero districts) of the study area. Additionally, some cells in the Nyabihu district show low community vulnerability to floods (Figure 5). These spatial insights enable cross-sectoral collaboration, such as involving environmental agencies and urban planners in crafting integrated disaster risk reduction strategies.

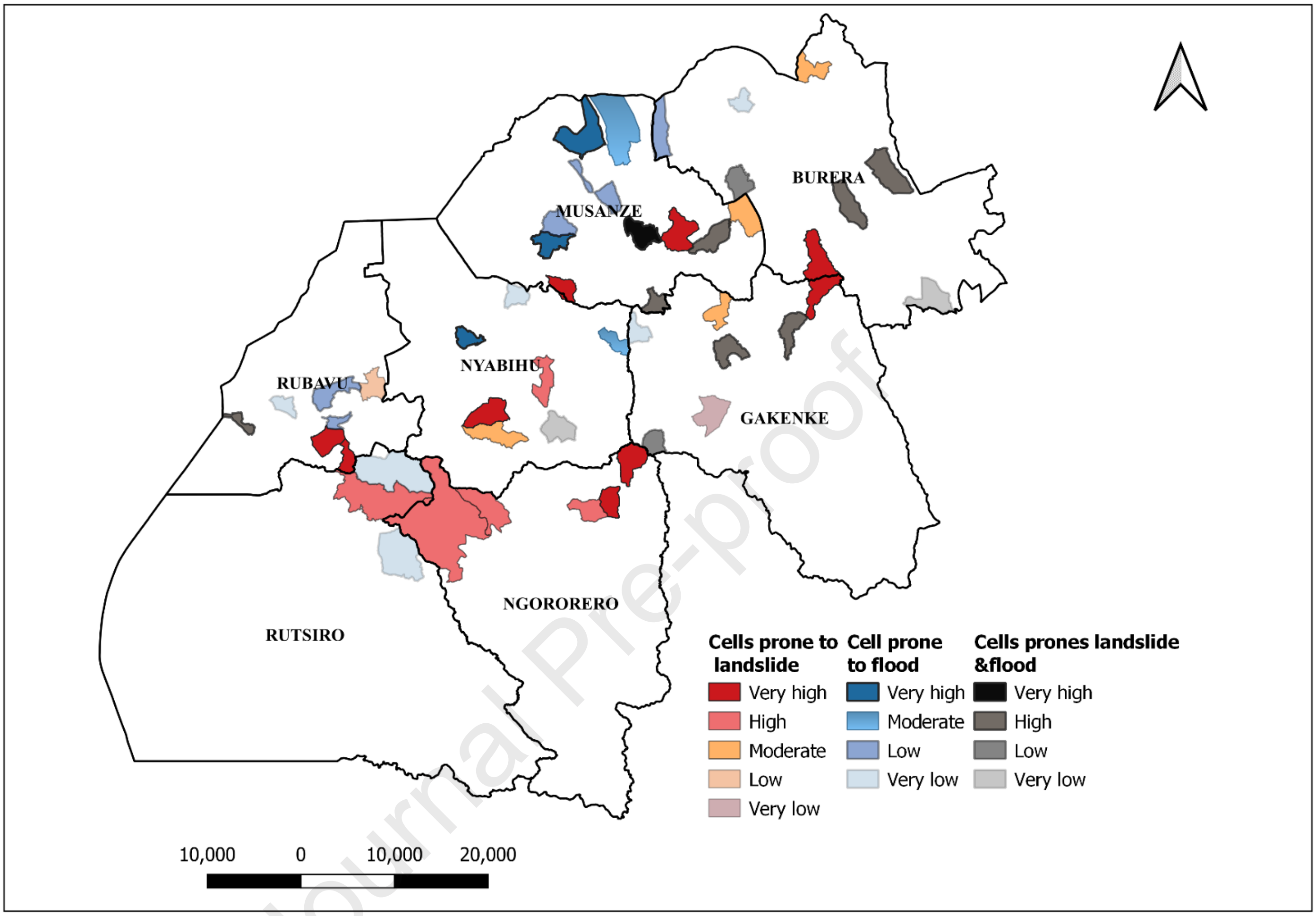


Fig. 5. Vulnerability distribution in the study area

5. Discussion

The present study assesses contextualized vulnerability of the communities living in landslide and flood-prone cells in Northwestern Rwanda. This approach enabled us to **capture localized vulnerability** by considering both the demographic and socio-economic characteristics and the adaptive capacities of households residing within each of the studied cells. As such, it aligns with assertions from other scholars advocating for vulnerability assessments to be tailored to contextual nuances (De Ruiter & Van Loon, 2022; Mavhura et al., 2017; Michellier et al., 2016). Specific variables providing insights into various socio-economic and adaptive capacity factors contributing to vulnerability were selected to calculate the Contextualized Vulnerability Index (CoVI), showing the extent and variability of vulnerability within the cells (Bang, 2022; Ibok et al., 2021; Mendes et al., 2019). By focusing on these cells as communities, we were able to identify those with higher vulnerability and understand their spatial distribution. This method helps to emphasize the importance of community-level interventions and planning to mitigate natural hazard risks effectively through DRRM strategies (UNDRR, 2020).

Community vulnerability within the study area stems mainly from **living conditions and location**. Indeed, these communities are settled in zones typically situated in valleys, adjacent to rivers, on hillsides, or at the base of mountains. Although used as such, these zones are not categorized as residential areas in land use plans regulations of Rwanda (NLA, 2022), which means that the land use policy are not very well implemented. It is also important to note that the land use master plan was developed after the population had already settled in high-risk areas, many decades prior. Until the 2000s, there were no clear guidelines for identifying areas suitable for settlement in rural regions, and people settled according to their own preferences. However, the first scientific discussions on rural settlement patterns and their reorganization took place in the early 1980s (MINITRAPE, 1983). Moreover, as documented by previous research, the vulnerability is also raised by the **demographic characteristics**, such as female-headed households, single parenting, unemployment among the household members, as well as the absence of health insurance (Dumenu & Takam, 2020; Flanagan et al., 2011; Kapuka & Hlásny, 2020). Such households lack physical strength to evade dangers during landslides and flood events, consequently increasing the risk of injury or fatality. Moreover, these vulnerable groups encounter challenges in recovering from the landslide or flood impacts, particularly relocation to safe places, or rebuilding and repairing their houses, as well as regaining their property damaged by hazardous events, due to their weak resources.

Furthermore, **education and economic status**, as well as **household structure and past disaster experience**, were also identified as factors increasing community vulnerability in landslide-prone and flood-prone cells respectively. These findings align with the previous studies (Chauhan et al., 2020; De Silva & Kawasaki, 2018; Samir, 2013; Michellier, et al., 2020) which underscored the role of education and economic status in vulnerability assessment. Communities in the study area present low education and low economic status. Moreover, these communities predominantly rely on rainfed agriculture for surviving. Not only does the dependence on rainfed agriculture exacerbates vulnerability by subjecting crops to damage from the frequent heavy rainfall characteristic of the region, but also crops are likely to be damaged or completely lost in the event of landslides or floods, thereby depriving the household from its main resource. In additional, in rural Rwandan settings, households often consist of extended family members, and there is a high dependency ratio. Households with more dependents, such as children or elderly members, often struggle to respond effectively during disasters. Moreover, past disaster experience increases vulnerability. Communities that have suffered significant losses face increased economic strain, limiting their capacity to recover from future events. This is particularly true for low-income households with fewer resources to invest in recovery and disaster mitigation strategies (Blake et al., 2017; Martins et al., 2019; Paton et al., 2015).

Conversely, the study underscores the reduced vulnerability observed among **households lacking land ownership**. While relatively few households in Northwestern Rwanda do not own land, those without land tend to experience lower vulnerability compared to those who do own land. This is primarily because landless households enjoy greater mobility and possess fewer belongings, enabling them to adapt more easily in the face of hazards. Previous studies have corroborated that temporary residents experience lower vulnerability to hazards (Hamideh & Sen, 2022; McConnell & Bertolin, 2019; Phillips, 2023). These individuals typically inhabit the area temporarily due to, for instance, part-time employment. When a hazard strikes, these people escape its impact by losing only their limited possessions and relocating relatively easily, enabling them to pursue their current activity or look for alternative employment close to their new place of residence. However, as shown in the study of Tran et al. (2017), we could have expected that households with temporary residency would be highly vulnerable because they face low livelihood diversity and income, and low educational level. Yet, unlike in the Mekong Delta in Vietnam, these factors do not seem to hinder households from investing to enhance their on-farm earnings or looking for better off-farm jobs to improve their own living conditions. These contrasting results highlight the importance of considering context-specific factors in vulnerability assessments. While low livelihood diversity, income, and education levels are associated with vulnerability in the Mekong Delta, other factors may mitigate these effects in the Rwandan context. These differences could be related to factors such as social safety nets, access to credit, community support structures, different cultural norms regarding migration, land tenure systems, government policies among others.

Moreover, in the study area, communities residing in planned settlements engage in agricultural activities combined with other small businesses or part-time employment; thus, their vulnerability tends to be lower. As found in other contexts, **house structure, health and other income** can help to reduce the hazards' impact (Asare-Kyei et al., 2017; Kais & Islam, 2016; Kapuka & Hlásny, 2020; Lee et al., 2022; Letsie & Grab, 2015). Communities exhibit resilience by building robust housing structures capable of withstanding landslides and floods and relying on diversified income sources for post-disaster recovery, including income from business ventures. These factors characterize the adaptive capacity of the northwestern communities of Rwanda, underscoring the need for communities' livelihood diversification.

Looking closely at the vulnerability spatial variation within susceptible areas, communities in landslide-prone cells experience more elevated vulnerability relative to other cells. Most of these cells are characterized by mountainous and hilly terrain, compounded by high population density, and consequent alterations in land use patterns. Previous studies have underscored the influence of landscape characteristics on landslide occurrences (Broeckx et al., 2018; Depicker et al., 2021; Maki Mateso et al., 2024; Monsieurs et al., 2018). Additionally, communities generally appear to be less vulnerable to flooding in the susceptible cells. However, flooding in the mid flat, as observed in Northwestern Rwanda, is sometimes induced by landslides that occur on the hillsides around (Dewitte et al., 2018; Mugaruka Bibentyo et al., 2024). In this context, communities seem to be unable to adapt to the compound landslide and flood impacts, hence exacerbating their limited capacity for post-event recovery. This finding highlights the importance of targeted interventions based on landslide and flood profiles, as social vulnerability varies widely depending on the type of hazard to which the community is exposed.

In addition, this study shows that high-vulnerability cells can be found throughout the study area. This is mainly attributed to the fact that the community lacks the capacity to adapt to the hazards' threat, associated with the high frequency of hazards (MIDIMAR, 2015). This observation is consistent with the scientific literature, which stresses that vulnerability is intricately influenced by a multifaceted interplay of environmental and socio-economic factors (Cutter et al., 2003; Eidsvig et al., 2014; Rossignol et al., 2015). Moreover, some studies have demonstrated that increased risk of climate change will accelerate the adverse impacts of landslide and flood hazards on communities (Dewan, 2015; Huang & Zhao, 2018; Zahmatkesh & Karamouz, 2017).

Moreover, the CoVI framework emerges as a valuable tool for assessing community vulnerability and identifying vulnerable hotspots, offering insights for informed decision-making and efficient resource allocation. The CoVI enables the tracking of community dynamics over time, reinforcing its usefulness in vulnerability assessment and resilience planning (Flanagan et al., 2011; Ignacio et al., 2016; Spielman et al., 2020). Comparing CoVI levels across cells prone to landslides, floods, and both hazards is essential for prioritizing mitigation and adaptation measures and then to reduce community vulnerability.

Addressing these findings necessitates targeted interventions aimed at reducing community vulnerability to landslides and floods. Such strategies could encompass the enforcement of zoning regulations to curtail settlements in areas highly susceptible to landslides and floods, with the designation of these areas as green spaces. Furthermore, the establishment of buffer zones along riverbanks, steep slopes, and other vulnerable terrains would serve to attenuate the repercussions of floods and landslides on communities. Moreover, future initiatives should be guided by a more detailed vulnerability assessment of both land and infrastructure (Habimana, 2016). Although the recommendations offer potential risk reduction strategies, their feasibility and effectiveness require further investigation within the study area. Future research should address the study's limitations, notably the lack of detailed land and infrastructure vulnerability assessments, by integrating environmental, socioeconomic, and physical factors into comprehensive vulnerability and resilience assessments to guide more effective interventions. Besides enhancing community livelihoods and promoting resilience is critical to address vulnerability to landslides and floods. This involves the establishment of social safety nets, such as crop insurance or savings groups, in order to provide financial support to communities during disasters and aid in recovery. Likewise, imparting skills training and education empowers community members to adapt to hazards' threat and pursue new livelihood opportunities. Furthermore, promoting livelihood diversification beyond agriculture, through endeavors such as small-scale businesses or eco-tourism, not only enhances community resilience but also ensures economic stability, particularly in the face of hazards' occurrence. Moreover, fostering public awareness and education regarding the hazards associated with inhabiting high-risk areas, using contextualized tools (Mafuko Nyandwi et al., 2023; Mossoux et al., 2016), is pivotal in promoting informed decision-making (Supplementary 3).

Despite efforts to comprehensively assess vulnerability, some aspects, such as cultural factors or psychological resilience, have not been fully captured in the study. The dynamic nature of vulnerability and socio-economic conditions underscore the need for continued research and an integrated approach to vulnerability assessment and disaster risk reduction efforts.

6. Conclusion

The study assessed community landslide and flood vulnerability in Northwestern Rwanda. Using a contextualized approach based on demographic and socioeconomic conditions together with adaptive capacity of the communities, the Contextualized Vulnerability Index was analyzed, and community vulnerability was compared between cells prone to landslide, flood, or both landslide and flood. Results indicate that communities in the study area are vulnerable to landslides due to factors such as living conditions and settlement in hazard-prone areas, demographic characteristics, low education level and economic status, as well as past disaster experience, characterize their inadequate adaptive capacity to hazards' threat. The study highlighted the high vulnerability among cells prone to landslides and those prone to both landslides and floods and indicated that the high vulnerability is predominant in the western part of the country.

The differentiated contributions of various principal components across landslide-prone, flood-prone, and dual hazard areas highlight the complex interplay of socio-economic and environmental factors influencing community vulnerability. This nuanced understanding demonstrates that tailored interventions and risk management strategies must consider the specific characteristics and vulnerabilities of each hazard-prone community. By identifying which factors are most significant in each context, the study provides a foundation for developing more effective disaster risk reduction and management policies that address the unique challenges faced by these communities.

The study findings indicate that interrelationship of hazards necessitates a comprehensive assessment of vulnerability that considers the compounded risks posed by multiple hazards. Incorporating a comparative approach between landslides and floods prone areas is already one step towards a better understanding of the holistic vulnerability of communities in multi-hazard prone areas. Despite these contributions, the study has limitations that warrant further investigation. The reliance on data from a specific time frame may not capture the dynamic nature of vulnerability and adaptive capacity over time. Longitudinal studies are recommended to monitor changes and evaluate the effectiveness of interventions.

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<u>Declaration</u>

During the preparation of this work the author(s) used ChapGPT-4o in order to improve language and readability, with caution. After using this tool/service, the author(s) reviewed and edited the content as needed and took(s) full responsibility for the content of the publication.

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Supplementary 1: Composite CoVI scores for the 50 cells in the Northwestern Rwanda

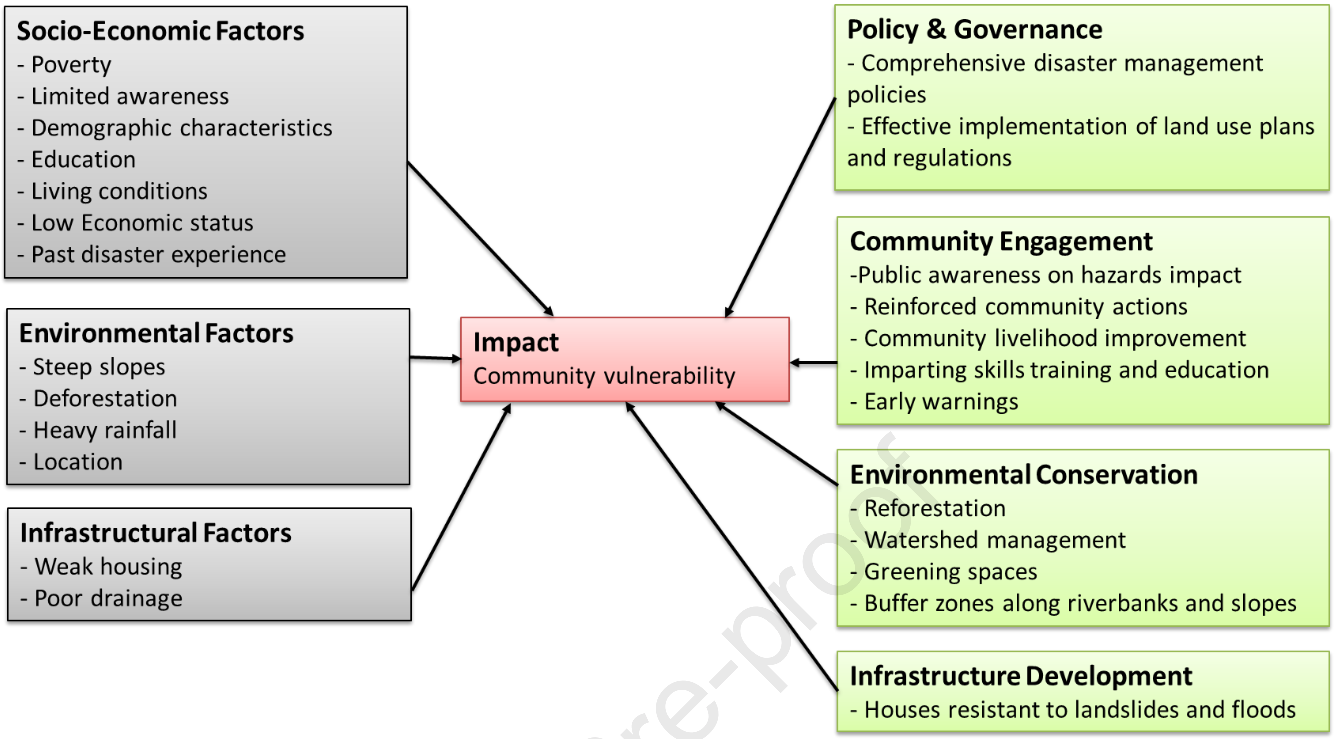
Province	District	Sector	Cell	Hazard Type	PC1	PC2	PC3	PC4	PC5	CoVI Score
West	Ngororero	Matyazo	Binana	Landslide	1.05	-0.28	0.29	-0.13	-0.26	0.67
West	Rubavu	Nyakiriba	Bisizi	Flood	-0.39	-0.02	-0.96	0.29	-0.58	-1.65

West	Ngororero	Muhanda	Bugarura	Landslide	0.44	-0.99	1.85	0.21	-0.52	0.99
North	Musanze	Rwaza	Bumara	Landslide &Flood	0.60	-0.81	0.52	0.35	0.85	1.51
West	Nyabihu	Karago	Busoro	Landslide	0.74	-0.62	0.30	0.26	-0.82	-0.14
West	Rutsiro	Nyabirasi	Busuku	Flood	0.53	-0.82	-0.57	0.58	3.19	2.91
North	Musanze	Musanze	Cyabagarura	Flood	-0.67	2.03	-1.12	-0.98	-0.46	-1.20
North	Burera	Rwerere	Gacundura	Landslide &Flood	0.79	0.77	-0.14	-0.02	-0.22	1.18
North	Musanze	Shingiro	Gakingo	Flood	-0.74	0.79	0.27	-2.01	0.65	-1.04
West	Nyabihu	Rugera	Gakoro	Flood	-1.68	-0.23	-1.42	0.97	-0.39	-2.74
North	Gakenke	Rusasa	Gataba	Flood	-1.19	-0.41	0.60	-1.69	0.51	-2.19
North	Musanze	Gataraga	Gataraga	Flood	-1.38	3.68	2.25	0.73	-1.36	3.72
West	Ngororero	Hindiro	Gatega	Landslide	0.35	1.52	0.27	0.90	-0.60	2.44
West	Rutsiro	Ruhango	Gihira	Flood	0.64	-0.37	-0.24	0.04	0.76	0.83
North	Burera	Gahunga	Gisizi	Flood	0.89	0.17	-1.06	-0.18	-1.00	-1.18
North	Burera	Cyanika	Gisovu	Flood	-1.99	0.12	0.10	-1.12	0.67	-2.22
North	Burera	Ruhunde	Gitovu	Landslide &Flood	-0.63	-0.57	-0.18	-1.05	-0.10	-2.53
North	Musanze	Gacaca	Kabirizi	Landslide	1.25	0.54	-0.82	0.57	0.36	1.90
North	Gakenke	Busengo	Kamina	Landslide &Flood	0.36	-0.36	0.73	1.19	-0.73	1.19
North	Musanze	Busogo	Kavumu	Landslide	0.60	0.25	-0.04	1.06	-0.16	1.72
West	Nyabihu	Rambura	Kibisabo	Landslide	0.80	1.91	-0.37	0.63	1.17	4.13
North	Gakenke	Kamubuga	Kidomo	Landslide	-0.81	0.53	2.05	0.48	2.19	4.44
North	Musanze	Gashaki	Kigabiro	Landslide	0.79	-0.84	0.34	0.33	-0.67	-0.05
West	Rubavu	Nyundo	Kigarama	Landslide	0.82	-0.94	0.38	-0.42	0.70	0.55
North	Musanze	Muhoza	Kigombe	Landslide &Flood	0.18	0.49	-0.41	0.71	1.06	2.03
West	Nyabihu	Rurembo	Kirimbogo	Landslide	0.41	0.10	-0.24	0.34	1.04	1.65
West	Rubavu	Kanama	Mahoko	Flood	-1.45	0.01	-2.16	1.04	1.41	-1.15
West	Ngororero	Muhanda	Mashya	Landslide	0.97	-0.60	-1.27	0.15	-0.43	-1.18
North	Gakenke	Nemba	Mucaca	Landslide &Flood	1.13	0.53	-0.13	-1.47	1.56	1.61
West	Rubavu	Nyundo	Mukondo	Landslide	-0.34	0.11	-0.16	1.29	1.34	2.24
West	Rubavu	Nyundo	Muramba	Landslide	-1.58	3.68	2.25	0.73	-1.36	3.72
North	Burera	Kivuye	Murwa	Landslide &Flood	0.68	0.53	0.41	-0.79	0.07	0.90
North	Musanze	Remera	Murwa	Landslide	1.16	-0.48	0.20	-0.28	-1.11	-0.51
North	Burera	Kinyababa	Musasa	Landslide	-0.04	-1.30	0.76	0.80	-0.55	-0.34
North	Gakenke	Mugunga	Mutego	Landslide &Flood	0.66	-0.13	0.01	-0.45	-0.61	-0.51
West	Rubavu	Gisenyi	Nengo	Landslide &Flood	-0.15	1.23	-1.20	1.30	0.18	1.37

West	Rutsiro	Nyabirasi	Ngoma	Landslide	-0.71	-0.49	0.44	-0.01	0.29	-0.49
North	Musanze	Nyange	Ninda	Flood	0.69	1.33	-0.29	-0.38	-1.77	-0.43
North	Burera	Kinoni	Ntaruka	Landslide &Flood	0.80	-0.68	0.31	-0.12	-1.31	-1.00
West	Nyabihu	Jomba	Nyamitanzi	Landslide &Flood	-1.54	-1.87	-0.17	1.50	-0.90	-2.97
North	Burera	Rugengabari	Nyanamo	Landslide	-0.06	0.86	2.21	0.21	-0.76	2.45
West	Nyabihu	Jenda	Nyirakigugu	Flood	-2.43	-0.35	-0.23	-2.79	0.23	-5.56
North	Musanze	Kinigi	Nyonirima	Flood	-1.05	-1.63	-0.76	-0.48	-1.65	-5.56
North	Musanze	Gataraga	Rubindi	Flood	-1.48	3.58	2.15	0.63	-1.26	3.62
West	Rubavu	Rugerero	Rugerero	Flood	-1.60	-0.06	-1.10	1.22	-0.87	-2.41
North	Gakenke	Kivuruga	Rugimbu	Landslide	-0.74	-1.42	2.74	-0.15	0.30	0.73
West	Ngororero	Hindiro	Runyinya	Landslide	0.58	-0.11	0.29	0.78	0.11	1.64
West	Nyabihu	Mukamira	Rurengeri	Flood	-0.93	-0.48	-1.15	0.20	-0.90	-3.27
North	Gakenke	Muzo	Rwa	Landslide	1.67	0.25	-1.29	-2.89	-0.54	-2.81
West	Nyabihu	Muringa	Rwantobo	Landslide	1.02	-0.76	0.25	-0.64	0.54	0.41

Supplementary 2: Household Questionnaire for Assessing community vulnerability to landslide and flood hazards in North-western Rwanda (N.B: This questionnaire is added in a separate file).

Supplementary 3: Community Vulnerability and disaster management policy improvements


Socio-Economic Factors
- Poverty
- Limited awareness
- Demographic characteristics
- Education
- Living conditions
- Low Economic status
- Past disaster experience
Environmental Factors
- Steep slopes
- Deforestation
- Heavy rainfall
- Location
Infrastructural Factors
- Weak housing
- Poor drainage
Impact
Community vulnerability
Policy & Governance
- Comprehensive disaster management policies
- Effective implementation of land use plans and regulations
Community Engagement
-Public awareness on hazards impact
- Reinforced community actions
- Community livelihood improvement
- Imparting skills training and education
- Early warnings
Environmental Conservation
- Reforestation
- Watershed management
- Greening spaces
- Buffer zones along riverbanks and slopes
Infrastructure Development
- Houses resistant to landslides and floods

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Highlights

- Social vulnerability and adaptive capacity are ultimately interrelated
- A contextual vulnerability assessment promotes a comprehensive understanding
- Northwestern Rwanda faces dual threats: landslides worsen flooding impacts

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: