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Limitations of existing landslide mitigation, detection and early warning approaches in Bududa District, Uganda

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Abstract
Landslides in Bududa District, Uganda, pose a persistent threat, with existing mitigation and early warning systems proving largely ineffective. This paper investigates the limitations of these approaches, focusing on the critical gaps in risk communication, underutilization of local indigenous knowledge, and lack of community trust that undermine current systems. Using a mixed-methods approach, qualitative data were collected through Focus Group Discussions, interviews, documentary reviews, and observations, which informed quantitative data gathered via survey questionnaires. The study had sample size of 199 participants, generated using Slovin's formula (1960), including 12 key informants. The findings revealed that current technology-based solutions are unreliable, while traditional methods are inefficient and lack comprehensive coverage. A central finding is the threatening disconnect between formal, top-down disaster management and the community's valuable local knowledge. The paper argues that current systems, which often focus narrowly on rainfall, fail to account for the complex, multi-causal nature of landslides and do not integrate with trusted community communication channels. Therefore, to genuinely enhance landslide risk reduction, Bududa District should adopt a customized, integrated, and holistic early warning system that seamlessly combines the precision of modern technology with the proven strength of local wisdom. By creating a system that is maintained, trusted, and co-managed by the community, it becomes possible to bridge the existing gaps, providing timely, accurate, and actionable alerts to save lives and mitigate the devastating impact of future landslides

Keywords Landslide early warning, Community risk knowledge, Participatory monitoring, Bududa district, Uganda

1 Introduction

Bududa District, located in the mountainous region of eastern Uganda, has endured a series of devastating landslides over the past decades. These disasters have caused significant loss of life, widespread displacement, and long-term disruption of livelihoods [6, 7, 21]. Despite the frequency and severity of these events, efforts to mitigate landslide risks have yielded limited success. Community-level responses remain weak, and government-led resettlement programs designed to relocate residents from high-risk zones have struggled to gain traction. These initiatives have faced logistical challenges and resistance from affected populations, resulting in poor implementation and limited sustainability [9, 10]. Over time, the understanding of landslide risks in Bududa has evolved, shaped by both lived experience and external interventions. Local communities often rely on traditional knowledge, such as interpreting weather patterns, vegetation changes, and soil behavior, to anticipate potential hazards. While this indigenous knowledge is valuable, it is insufficient for comprehensive risk assessment or timely action, especially in the face of increasingly unpredictable environmental conditions. Meanwhile, humanitarian organizations, notably the Uganda Red Cross Society (URCS), have played a critical role in emergency response. Their support includes search and rescue operations, first aid, and psychosocial care [4]. However, these interventions are largely reactive and do not address the underlying weaknesses in early preparedness and long-term risk reduction.

In recent years, Early Warning Systems (EWS) have emerged as essential tools for minimizing the impact of landslides. These systems rely on technical instrumentation and data analysis to detect potential landslide events and issue alerts [24]. However, their effectiveness in Bududa is undermined by several limitations. Technological reliability remains inconsistent, and more critically, the community's ability to interpret warnings, recognize landslide triggers, and trust official messages is often lacking. Recent events have shown that technical alerts alone do not prompt protective action when residents lack clear risk heuristics or perceive warnings as unreliable or irrelevant [9, 10].

To improve landslide risk reduction in Bududa District, it is imperative to integrate local knowledge with scientific approaches and strengthen communication pathways between warning systems and communities [22]. Participatory methods that enable residents to identify high-risk zones and recognize early signs of landslides can significantly enhance preparedness and response. This paper investigates the limitations of existing landslide mitigation, detection, and early warning approaches in Bududa District. It focuses on how gaps in risk communication, local knowledge integration, and community trust impair the effectiveness of current systems. By evaluating detection methods and exploring the socio-cultural dimensions of risk perception, the study recommends a more holistic and context-sensitive framework for landslide risk management.

2 Methodology

According to the government agency responsible for the collection, analysis, and dissemination of statistical data in Uganda, Uganda Bureau of Statistics (UBOS) projections of 2019–2023, Bududa district has a population of 282,900, 98 parishes, 955 villages, 38,100 households as operational in mid-2019. The participants were recruited from four randomly selected landslide prone sub counties, two of which had landslide early warning systems installed. These sub counties were Bududa, Bushika, Bududa Town Council and Bukalasi, with a study population of 70,300. According to UNICEF [20], close to 60% Uganda's population are below 18 years of age and since the study does not include children, the researcher reduced the study population by 60% of 70,300 leaving the target population of 28,120. This target population is the group of individuals the researcher generalized the findings to, to ensure that the study's results are applicable to the intended group. Using 1960 Slovin's formular, written as: n = N/(1 + Ne2), where: n = the number of samples, e is the margin of error (5%), N = the target population, the sample size in the 4 sub counties were 199.

2.1 Sampling methods

Based on the study, the researcher adopted both non-probability sampling for qualitative method and simple random sampling for quantitative method. Non-probability sampling method does not provide every member of the target population with an equal chance of being selected. Instead, participants are selected based on judgment criteria since it is difficult or impractical to obtain a representative sample from the target population. The researcher relied on practical considerations rather than statistical calculations to determine the sample size. Therefore, non-probability sampling techniques used was purposive sampling to select the key informants since the researcher was interested in the sample purely on the basis of her knowledge and credibility, and Snowball sampling where the chosen key informants at the village level identified FGD participants until the exhaustion list from which the sample size was drown. Whereas, simple random sampling method allowed every member of the target population an equal chance of being selected. These steps ensured that the researcher obtain a representative sample and can make valid inferences about the target population. The sample size was determined based on factors such as available budget, and the desired depth of analysis.

The participants In the first stage, the 4 sub-counties of Bududa district were randomly selected. Two sub counties from high landslides risk areas, and two sub counties had landslide early warning systems installed. In the second phase, the LC 3s listed a number of parishes prone to landslide and one was randomly selected from each subcounty. From the 4 parishes selected, the LC 2's listed a number of villages prone to landslides and two villages were identified through snowballing from each parish making a total of eight villages. From the eight selected villages, each LC 1s, selected two FGD groups each consisting of 8–12 participants who were knowledgeable and willing to participate in this study through snowballing making a total of 187 participants. In addition, 12 participants were selected though purposive sampling: the eight LC 1s, two from the centralized facility established by the Office of the Prime Minister's Department for Disaster Preparedness and Management in Uganda, the National Emergency Coordination and Operations Centre (NECOC), two from the local governance structure established to coordinate disaster risk management efforts at the district level, the District Disaster Risk Management Committee (DDRMC). This totaled to a sample size of 199 participants.

2.2 Data collection methods and instruments

This study employed a mixed-methods approach, utilizing both primary and secondary data to inform the design process. Primary data was gathered directly from the field through key informant interviews (KIIs), focus group discussions (FGDs), structured observations, and surveys. To complement these, secondary data was systematically harvested from existing sources using the 5Cs framework (cite, compare, contrast, critique, and connect). This multi-tool approach ensured a holistic understanding of landslide early warning systems within the study area.

The qualitative phase involved structured and semi-structured interviews with 16 purposively selected stakeholders, supported by detailed note-taking to capture nuances and direct quotes. Additionally, FGDs comprising 8–12 participants each were conducted in Lumasaba to ensure cultural context and comfort, using open-ended questions to facilitate deep discussion. These were supplemented by direct field observations of landslide-prone areas, guided by a standardized checklist and photographic documentation. For the quantitative phase, a structured questionnaire was administered to a representative sample through both paper forms and face-to-face interactions to gather statistical insights into community perceptions.

2.3 Validity and reliability of instruments

To ensure the rigor of the research instruments, a two-stage validation process was implemented. First, cognitive pre-testing was conducted with a small surrogate group to identify and correct any linguistic ambiguities. Second, content validity was assessed by a panel of four experts, including senior researchers and subject matter specialists. These experts evaluated the relevance of each item against the research objectives to calculate the Content Validity Index (CVI). The resulting CVI ranged from 0.818 to 1.0, comfortably exceeding the standard 0.7 threshold for academic research. Reliability was established through pilot testing in the Manafwa district with participants outside the main study sample, focusing on the usability and clarity of the administration process. The internal consistency of the quantitative questionnaire was further verified using Cronbach's alpha. The analysis yielded a coefficient of alpha (α) = 0.899, indicating high internal reliability and ensuring that the instrument consistently measured the intended constructs.

2.4 Data processing and analysis

Following collection, data underwent a systematic cleaning and transformation process. Qualitative recordings and notes were transcribed, formatted for readability, and stripped of irrelevant "noise." These texts were then subjected to thematic analysis, where data was coded, categorized, and synthesized into overarching themes that captured shared experiences and contextual risks. Quantitative data from the questionnaires were digitized using SPSS (Version 20). The dataset was then cleaned for outliers and missing values to ensure the integrity of the final output, and descriptively analysed, visualized using excel.

2.5 Data convergence

The final analysis utilized a triangulation multilevel model to merge the findings. By integrating the thematic insights from the qualitative data with the statistical trends from the quantitative analysis, the study achieved a triangulated conclusion that addressed the research objective from multiple analytical perspectives.

2.6 Ethical considerations

In line with the Ethical Principles of the international and independent confederation of national medical associations representing physicians worldwide, the World Medical Association (WMA), Declaration of Helsinki (1964) guidelines, Ethical approvals were obtained from: School of Postgraduate Studies and Research, Nkumba University, Research Ethics Committee of Mildmay, Uganda, Uganda National Council of Science and Technology (UNCST), Written permissions from Bududa District Local Government, Office of Disaster Risk Management Committee, endorsement by Sub County Chiefs (Local Council Authorities III), Parish chiefs (Local Council Authorities II), Local Council Authorities I, and written consents from the research respondents.

3 Results

This section shows the qualitative and quantitative analysis regarding various current understanding of landslide risks in Bududa District, and presents a matrix that evaluates the effectiveness of existing mitigation measures in terms of detection and early warning.

3.1 Participants demographic findings

Sixteen Focus group discussions of 8–12 participants were held with a gender representation of 55.8% male and 44.2% female, of which 85.3% were married. 75% of them live in mud houses with an average household size of 6–10 persons. In terms of education, 51.3% attained tertiary/vocational education while 11.5% had no education, and the majority of the participants (76.9%) were peasants. The detailed demographic findings have been presented in Fig. 1 below.

Respondents' demographic presentation provided a basis for understanding landslide risks in Bududa District, and the effectiveness of existing mitigation measures in terms of detection and warning as it was quite informative of the respondents' characteristics.

3.2 Understanding of landslide risks in Bududa District

The theme of landslide risk knowledge had three sub-themes of: landslide common causes, signs for potential landslides and landslide community awareness. These were analyses both qualitatively and quantitatively as hereby presented.

Quantitative data presentation had the analysis of findings added-up percentages of strongly agree with those of agree since they were both positively inclined while those of strongly disagree and disagree were also added up together since they were both

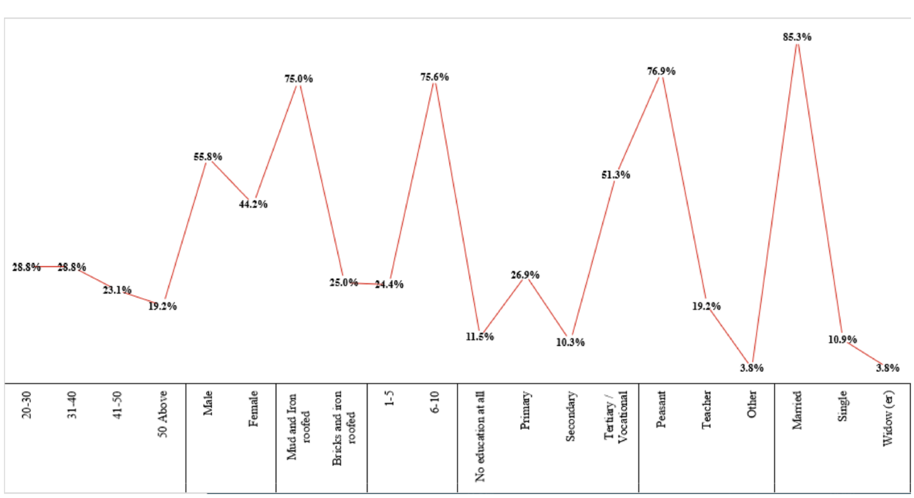

Fig. 1 Demographic data of the participants

negatively inclined. Meanwhile, findings indicated as neutral were presented separately since they were neither positive nor negative.

3.2.1 Causes of landslides

Qualitative findings from Key Informants at the district, Local Councils and FGD identified the major causes of landslides verbatim as stated below.

A District Disaster Risk Management Committee member stated that:

> *The most common causes of landslides in the district that were on record are heavy rainfall, over-farming, deforestation, burning vegetation, terrain and soil type. Existence of these causes may however, vary from village to village depending on the human activities taking place in that particular area, (Interview with the District Disaster Risk Management Committee member, Bududa Town Sub-County on 15th August, 2023).*

However, interviews with all the Local Council officials and findings from the FGD were in agreement that:

> *The most popular causes of landslides in their areas were heavy rainfall and poor farming methods, (LC I and FGD from all the four sub-counties, August, 2023).*

Qualitatively identified causes of landslides were ranked quantitatively whereby respondents agreed (100%) that heavy rainfall was the major cause of landslides in the area. This implies that all the respondents were knowledgeable about their response on this issue since only 11.5% were not educated. followed by over farming/Poor farming practices with 82.7%, deforestation with 80.8%, terrain (70.5%), soil type with 66.1%, and the least factor was burning vegetation (52.6%) as shown in Fig. 2 below.

Additionally, the terrain identified as another cause of landslides (70.5%), though 18% disagreed while 11.5% were neutral, was supported by the observation findings as shown in the Figs. 3 and 4 below, implying that this cause of landslides was beyond the community's ability to control.

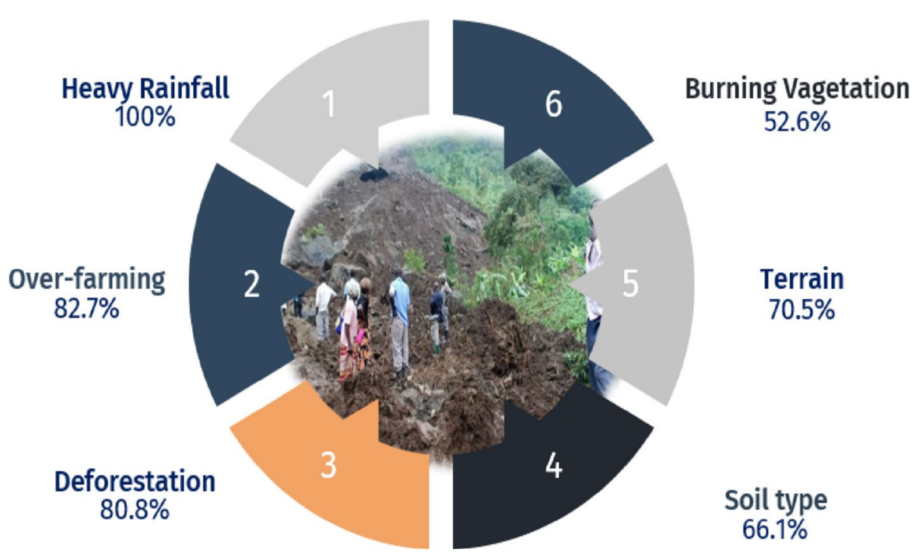

Fig. 2 Causes of landslides. *Source*: Primary data, 2023

Fig. 3 Bududa sub-county. *Source*: Primary data, 2023

Fig. 4 Bududa town council sub-county. *Source*: Primary data, 2023

3.2.2 Signs of potential landslides

Concerning signs of potential landslides, qualitative and quantitative findings from respondents were as stated below:

A member from the District Disaster Risk Management Committee stated that:

> *The indigenous signs are identified by the communities and they alert the district. The most common has been the soil cracks, unusual water pruning from under-*

ground, dark soils rolling down/mudslides from the direction of the forest, the rivers increasing in volume and goes beyond its banks, soil smelling, (Interview with the District Disaster Risk Management Committee member, Bududa Town Sub-County on 15th August, 2023).

Furthermore, interviews with the Local Council officials and findings from the FGD in Bududa sub-county were in agreement that:

The most signs of potential landslide were soil cracks, soil smelling, unusual water pruning from underground and soil rolling from the hill (LC I and FGD from Bududa sub-county, August, 2023).

In addition, interviews with the Local Council officials and findings from the FGD in Bukalasi sub-county were in agreement that:

The common signs of potential landslide were soil cracks, soil smelling, unusual water pruning from underground and mudslides from the direction of the forest and rivers increasing in amount of water flows, (LC I and FGD from Bukalasi sub-county, August, 2023).

The above expressions indicate that the views of the District Disaster Risk Management Committee on the signs of potential landslides were not specific to sub-counties as responses from individual Local Councils and FGD indicated some slight variations in depending on their location.

Nevertheless, the qualitatively identified signs of potential landslides above were quantitatively ranked as in Fig. 5 below and the findings established that respondents were able to identify potential landslides when there is appearance of soil cracks (94.8%), soil softening (89.8%), dark soils rolling down the hills/mudslides from the direction of the forest (81.4%), water volume increase in rivers (81.4%), unusual water flow from underground (78.8%); while soil smells (69.9%) comparatively scored the lowest.

3.2.3 Mechanisms of raising awareness of potential landslides

Qualitatively, key informants expressed the following views for raising awareness of potential landslides in the district.

A member from the District Disaster Risk Management Committee stated that:

Numerous approaches have been employed to raising awareness among community of potential landslides; they include public awareness campaigns, community meet-

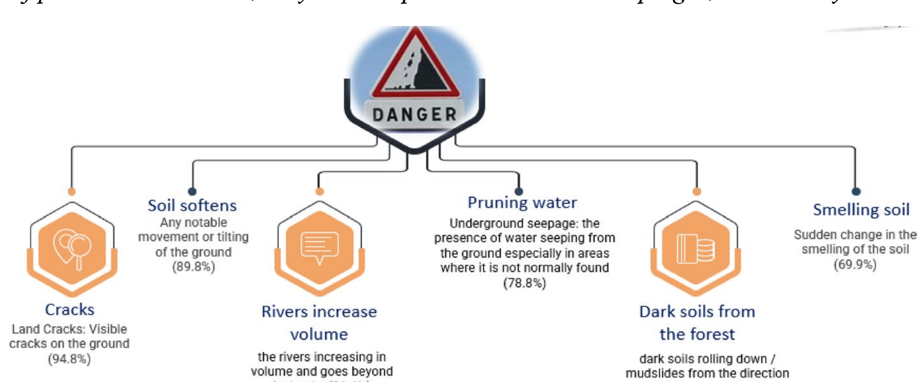

Fig. 5 Signs of potential landslides. *Source*: Primary data, 2023

ings, use of early warning systems, community radios, a Hazard map and weather information on local community radios. However, he expressed disappointment over the Hazard map being outdated (2013) given new sub-counties have been created by government, (Interview with the District Disaster Risk Management Committee member, Bududa Town Sub-County on 15th August, 2023).

Furthermore, key informants from the selected eight villages were specific about raising awareness on this matter by stating that:

There are several methods which they use to raise awareness of potential landslides in the villages including: community meetings, community radios, word of mouth and weather information on local community radios, (Interview with the Local council members, all Sub-Counties, August, 2023)

Additionally, various FGD were in agreement with how potential landslides awareness was raised among community. These stated that:

According to us, community meetings, word of mouth, phones/SMS and weather information on local community radios were the most common methods that we use, (FGD members, all Sub-Counties, August, 2023)

The qualitative views from key informants above established that several mechanisms were applied in Bududa district to raise community awareness of potential landslides. The study, therefore, sought to analyse them further by ranking so as to establish the most commonly used mechanisms to raise community awareness. Accordingly, findings do indicate that raising awareness among the community about potential landslides ranked word of mouth (94.9%) as the most common, followed by public awareness campaigns (79.4%), then use of phones/SMS (71.8%), community meetings (69.9%), community radios (65.5%), with the least being early warning systems installed by the government and humanitarian organizations (50.6%). This ranking has been shown in Fig. 6 below.

Other findings in Table 1 below supported those in Fig. 6 above, whereby FGDs responses indicated that information on weather by local community radios (84.6%) was the most accessible resource that help them assess the landslide risk knowledge, followed by landslide verbal history from the elderly (37.2%). Only 9% of the respondents indicated that hazard maps were available resources. These findings can be explained by

Fig. 6 Mechanisms of raising awareness of potential landslides. *Source*: Primary data, 2023

Table 1 Available resources for landslide risk knowledge. *Source*: Primary data, 2023

Variables	Yes	Not sure	Total
Hazard Maps	09% (14)	91% (142)	100% (156)
Information on weather by local community radios	84.6% (132)	15.4% (24)	100% (156)
Landslide verbal history	37.2% (58)	62.8% (98)	100% (156)

the fact that whoever hears a message about landslide risk on the community radio easily spreads it further by word of mouth.

3.3 Existing landslide detection and early warning system in Bududa district

During the key informant interviews, the respondents from the district disaster risk management committee stated that several approaches have been employed to detect landslides and warn people. It included satellite imagery, weather stations (measures both temperature & rainfall), landslide hazard map, drone, community radios, mega phones, river pegging on river banks, Committees are formed along the river to make alarms when landslides signs occur, and smart phones that were donated for easy and fast hand communication.

Each of these approaches has its own design thinking, methods, tools/technologies, challenges, weaknesses, and strengths. This section analyzes these approaches:

3.3.1 Weather stations

In 2018, the Office of the Prime Minister in partnership with the University of Maryland in the United States and Strasbourg University in France, installed five automated early weather warning equipment for monitoring landslides in the Elgon region, specifically in three sub-counties in Bududa district. These gauges employ a funnel-shaped collector that channels rainwater into a graduated plastic measuring container for precise measurement. Built-in sensors detect the water level and convert it into an electronic signal processed by a microcontroller. Additionally, the equipment is equipped with a wind cup, humidity sensor, leaf wetness sensor, radiation shield, solar panel, and sensor recalibration for signals. The rain gauges utilize highly sensitive wireless communication technology to collect weather data from up to 15 kilometers apart and send it to the Bududa district headquarters, serving as the gateway monitoring center. This data is transmitted in real-time to a server via satellite, facilitating continuous monitoring of rainfall patterns and enabling professionals to access the data through web-based platforms. Despite the system's accuracy and effectiveness, challenges such as powering the devices and potential vandalism by community members pose significant obstacles to the program's success.

3.3.2 Landslide hazard map

In 2013, the Office of the Prime Minister developed a landslide hazard map that utilized human expertise and field observations to identify areas at risk for landslides. This approach is grounded in understanding geological and environmental factors contributing to landslides, including slope stability, rainfall patterns, and land use changes. The methodology operates on the premise that historical landslide occurrences can inform predictions of future events by highlighting regions with similar characteristics. The process involves a combination of field surveys, remote sensing techniques, and data analysis. Field surveys include visiting potential sites to observe terrain features, collect soil samples, and document signs of instability. Remote sensing methods such as aerial photography, satellite imagery, and radar provide critical information regarding slope morphology, vegetation cover, surface displacement, and other indicators that may signal potential landslides. The main advantage is its powerful visualization, helping stakeholders understand risk areas effectively; however, it relies heavily on the quality and resolution of input data and requires specialized knowledge and training. The map is now outdated, with new sub-counties created since its inception, highlighting the need for updates.

3.3.3 Ground-based surveys

The manual ground-based survey approach to landslide detection and warning involves systematic monitoring of landslide-prone areas by trained professionals, such as geologists and engineers, who collect data through visual inspections, field measurements, and soil sampling. This method allows for the identification of early warning signs of potential landslides, such as ground cracks or changes in drainage patterns, which is analyzed to develop predictive models assessing future risks. The advantages of this approach include the provision of detailed geological and topographical information, customization of monitoring strategies based on local conditions, integration with other early warning systems for comprehensive risk assessment, community engagement in preparedness efforts, and expert analysis ensuring reliable data interpretation. However, it is time-consuming, labor-intensive, difficult to access remote areas, and limited in coverage due to resource constraints. Besides, data collection and analysis can be inaccurate and subjective, relying heavily on human expertise.

3.3.4 Drone

In 2018, the Prime Minister's Office introduced a drone-based approach for landslide detection that utilizes remote sensing technology. Drone is equipped with high-resolution cameras deployed to capture detailed imagery and collect data from areas that are difficult to access. This data is then analyzed by experts to identify indicators of slope instability, such as cracks, bulges, or changes in vegetation patterns that may signal potential landslides. The primary advantage of this method is the ability to quickly gather information from hazardous locations without endangering human lives, real-time data transmission via Wi-Fi, 4G/5G, and detailed, accurate data collection. However, challenges include limited battery life, which restricts flight time and coverage, and weather conditions like strong winds or heavy rainfall that can hinder operations and compromise data quality.

3.3.5 Megaphones

In 2020, the Red Cross introduced a manually operated landslide warning system in Bududa District, leveraging megaphones for community-based monitoring and alarms. The cone-shaped megaphones amplify voices to alert residents to potential landslides. A communication network is established to connect the observers with local authorities and communities. This is via the alarm systems installed in communities i.e., community radios, drums, telephones, mouth to mouth communication channels. The alarm is triggered by the observers when they detect a potential landslide. Observations and alarms are recorded and analyzed to improve the system's performance and accuracy.

This low-cost approach harnesses local knowledge and is adaptable to specific community needs, enhancing resilience. However, it relies heavily on human observation and traditional communication methods, lacking real-time data analysis and modern technology integration.

3.3.6 Water level poles/river pegging

In 2020, the Red Cross introduced water level poles for disaster detection and warning in Bududa district. These poles, placed on the river banks, provide visible indicators of rising water levels using marks made of durable materials to alert local communities of potential landslide. The height of the marks is based on historical flood levels, and trained personnel manually monitor and drum alerts when necessary. Data collected from monitoring systems is analyzed manually to identify trends, patterns, and potential risk. The straightforward concept is easily understood by locals, thereby promoting active participation in disaster preparedness. However, the manual process is time-consuming, and drum alerts may not reach all community members, necessitating modern technological integration for enhanced efficiency (Table 2).

4 Discussion and interpretation of findings

4.1 Landslide risk knowledge

The study confirms that the local communities in Bududa District possess a deep and valuable understanding of landslide risks. This knowledge, passed down through generations, encompasses the causes, the early warning signs, and the most effective communication strategies. However, this crucial indigenous knowledge is largely underutilized by the formal, top-down disaster management systems.

4.1.1 Causes of landslides

The findings consistently identify heavy rainfall as the primary trigger for landslides in the region, a conclusion supported by a wide range of scholarly work [1, 9, 11, 12]. The text highlights a particularly important nuance: it is not just the intensity of rain, but its prolonged duration that is a significant factor. This prolonged wetting of the soil increases pore water pressure, compromising slope stability and leading to landslides [5, 15, 19].

While rainfall is a key trigger, the study also notes that local communities and scholars recognize other critical contributing factors, including over-farming, deforestation, vegetation burning, and specific soil types [7, 9]. The current EWS, however, has a critical flaw: its singular focus on heavy rainfall. By ignoring the interconnectedness of these other factors—which can make slopes vulnerable even during low-intensity rainfall events—the systems provide incomplete and potentially unreliable warnings. The fragmentation of data, with information from weather stations, hazard maps, and drones existing in isolated silos, prevents a holistic risk assessment. This one-dimensional approach to a multi-causal problem leads to fragmented and ineffective decision-making.

4.1.2 Signs of potential landslides

The local population's ability to identify early signs of a potential landslide is one of the most powerful and underutilized assets in the district's disaster management strategy.

Table 2 Summary of the existing approaches for landslide detection and early warning in Bududa district. *Source*: Primary data, 2023

	Approach	Purpose	Design theory	Tools and technologies	Strengths	Limitations
1.	Ground-based surveys	Gather specific, localized data to identify early warning signs and provide timely alerts	A user-centered approach to ensure the survey is effective and efficient	Human expertise • Visual inspections • Field measurements • Cameras	• Localized data • Detailed information on the geological and topographical factors that contribute to landslides • Customization of monitoring strategies based on local conditions	• Time-consuming • Labor-intensive process • Limited coverage • Inaccuracies in data collection and analysis • Reliance on human expertise • Weather conditions such as rain hinder survey activities or affect equipment performance. • Some locations are difficult to access due to terrain, limiting the scope of surveys
2.	Landslide hazard map (by OPM in 2013)	Understanding the landslide risk areas	Mark potential landslide-prone areas	• Field surveys (Human expertise) • Remote sensing techniques • Data analysts	• Powerful visualization capabilities that help stakeholders understand risk areas effectively • Can adapt to local conditions • Incorporate site-specific factors that may not be captured by automated methods	• Hazard map is very old • Image resolution (outputs heavily relies on the quality and resolution of input data) • Requires specialized knowledge and training
3.	Weather stations (by OPM in 2018)	Measure precipitation, specifically rainfall, temperature over a set period	User-centered Understanding the specific requirements of the users and the environment	• Funnel-shaped collector • Plastic measuring container • Built-in water sensors • Microcontroller • Web-based platforms	• Ability to monitor precipitation and temperature • Provide real-time data • Measures rainfall intensity and total accumulation accurately	• Powering the devices • Vandalization of the equipment • Maintenance requirements • Manual reading
4.	Drone (by OPM in 2018)	Monitor and capture images	Blending creativity, engineering, and problem-solving	• High resolution cameras • LiDAR (Light Detection and Ranging • Zoom Cameras	• Collect data from inaccessible areas • Advanced sensors they capture high-resolution imagery • Create detailed topographical maps by measuring the time it takes for the light to reflect back from surfaces	• Data analyzed by human experts • Limited battery life which restricts their flight time and coverage area • Strong winds or heavy rainfall can hinder drone operations and compromise data quality

Table 2 (continued)

	Approach	Purpose	Design theory	Tools and technologies	Strengths	Limitations
5.	Megaphones (by RedCross in 2020)	Provide timely and accurate landslide warnings to communities at risk	Based on its cone shape	• Amplifier • Microphone • Loudspeaker	• Relatively low-cost • Residents have valuable knowledge about their environment • Can be easily adapted to local conditions • Involves locals in the monitoring and warning • Suitable for areas with limited access to technology and communication infrastructure	• Relies on human observation
6.	Water level Poles/River pegging (by RedCross in 2020)	Measuring the height of water in rivers,	Visual reference for water levels	• Vertical marked pole • Large stones or boulders	• Resistant to weathering and can withstand strong currents. • Provides instant protection against erosion upon installation.	• Manual observation • May not blend well with natural landscapes • Transportation and placement of heavy stones can be expensive.
7.	LEWaM- proposed model [10]	Provide timely alerts to at-risk populations about potential landslide	Integrating observatory data, historical data and sensor data and utilizing predictive models that assess the likelihood of landslides based on collected data	• Sensors • Remote sensors • Coordinates • USSD (unstructured supplementary service data) • Machine learning (large datasets • LoRa (Long Range) technology • SMS alerts for disseminating warnings	• Real-time Monitoring • Improved Accuracy • Community Engagement	• Insufficient historical data available for accurate modeling • Implementation can be expensive

The study lists a number of these signs, including soil cracks, soil softening, mudslides, and unusual river volume [12, 14]. These subtle, on-the-ground observations often provide the earliest possible indicators of a developing event, a point emphasized by Murphy [8] who notes that such knowledge can be used to facilitate timely evacuation.

However, a significant disconnect exists. The current EWS is a fragmented system that lacks a formal mechanism for community members to transmit these vital signs to officials in real-time. This means that the most immediate and localized warnings are unutilized, creating a critical gap in the overall response capability. The technology deployed, such as automated weather stations and drones, is not equipped to detect these sensory or subtle physical changes. A weather station cannot smell a change in the soil, nor can a drone detect the subtle sound of continuous whistling birds. This reliance on manual and inefficient communication methods prevents a cohesive data flow between the community and officials. Ultimately, the failure to integrate indigenous knowledge into the formal warning system renders the entire mitigation effort ineffective, jeopardizing the timely action needed to save lives.

4.1.3 Mechanisms of raising awareness of potential landslides

The study reveals that traditional communication methods, such as word of mouth, community meetings, and community radios, are far more effective at raising awareness than the formal EWS installed by the government and NGOs. This finding contradicts the assertion by Onek [13] that the official EWS is the primary method of warning dissemination. The low score of the official EWS highlights a critical lack of community trust and awareness, a problem underscored by Namono et al. [9].

The ineffectiveness of the EWS is due to a "disjointed mix" of technological and traditional methods. The advanced systems are unreliable due to power issues, vandalism, and sensor malfunctions, while manual approaches like megaphones are inefficient and subjective. This fragmentation is a critical weakness; different warning methods operate in isolated silos rather than as a cohesive, centralized system. This prevents warnings from being verified or amplified effectively. The danger of this gap is that even if a technological warning is successfully generated, it may not be received, understood, or acted upon by the residents it is meant to protect. This highlights the urgent need for a unified, well-maintained system that genuinely serves the community by integrating modern technology with local, trusted communication methods.

4.2 Existing landslide detection and early warning approaches in Bududa district

The existing landslide detection and early warning approaches in Bududa District are limited due to a combination of technological, financial, and social challenges. While a variety of methods have been implemented, their fragmentation, resource dependency, and lack of community trust hinder their overall effectiveness:

Limitations of technology-based systems The more advanced approaches, such as automated rain gauges and drones, face significant technical and operational limitations. The study findings, supported by Namono et al. [9] and Kizito [6], highlight that these systems suffer from power supply issues, vandalism, and sensor malfunctions. This makes them unreliable, particularly in a crisis. Drones are also restricted by battery life and adverse weather conditions, which often coincide with the periods of highest landslide risk. Furthermore, there is a lack of financial and technical resources for the proper maintenance and operation of these systems, as noted by [23], leading to their eventual failure. The core issue is that while these technologies can provide accurate data, they are not robustly maintained or integrated into the local context.

Inefficiency of manual and traditional methods Traditional, ground-based methods, while leveraging local knowledge, are plagued by inefficiencies and a lack of comprehensive coverage. Manual ground-based surveys are time-consuming and labor-intensive, making them unsuitable for large-scale or urgent assessments. The reliance on human observation makes them subjective and prone to error, as pointed out by Ramesh et al. [16] and Han and Yoo 2. Similarly, the megaphone approach, while promoting community involvement, is limited by sound range, background noise, and environmental factors, making it ineffective for reaching all community members, especially in remote areas or during heavy rainfall, as noted by [3]. The water level poles, while simple, are also limited by their manual nature and localized coverage. They can also give inaccurate readings due to debris and require regular, resource-intensive maintenance, as detailed in the UNECE [18] report.

Lack of integration and community engagement Perhaps the most critical limitation is the fragmented nature of the systems and the low level of community trust. The study shows that different detection methods from automated gauges to manual surveys are not integrated into a cohesive, centralized system. This is a major gap, as highlighted by Strząbała et al. [17] and Ramesh et al. [16], who emphasize the need for an integrated approach. This fragmentation means that a warning from one system may not be corroborated or amplified by another. Additionally, the findings from Namwano et al. [10] and Kizito [6] indicate a significant lack of community awareness and engagement, with only a small percentage of residents being aware of the EWS and rating its effectiveness as low. This low trust and reliance on formal systems lead to a dangerous reliance on informal methods like word-of-mouth. This critical gap in community engagement and education means that even if a warning is successfully generated by a technological system, it may not be received, understood, or acted upon by the people it's meant to protect, rendering the entire effort moot.

5 Conclusion

Despite persistent efforts to implement landslide mitigation strategies, the rising frequency of landslides in Uganda, particularly in the Bududa District, highlights a profound and dangerous disconnect between modern technology and local knowledge. While the government has invested in advanced systems, the community's invaluable indigenous knowledge remains largely excluded from the formal warning framework. These systems operate in fragmented silos, failing to create a cohesive structure for effective detection and response. Consequently, even when a warning is generated, it often does not reach the community effectively or fails to prompt appropriate action. The conclusion is clear: to genuinely enhance landslide risk reduction, Bududa District must abandon its current fragmented approach. The path forward involves adopt a customized, integrated, and holistic early warning system that seamlessly combines the precision of modern technology with the proven strength of local wisdom. By creating a system that is maintained, trusted, and co-managed by the community, it becomes possible to bridge the existing gaps, providing timely, accurate, and actionable alerts to save lives and mitigate the devastating impact of future landslides

6 Recommendations

Based on the analysis of the existing landslide mitigation and early warning systems in Bududa District, here are recommendations:

Upgrading equipment The Office of the Prime Minister should enhance monitoring by upgrading equipment, integrating satellite data, remote sensing technologies and involving local communities in monitoring efforts. By involving local residents in the monitoring process, the government can gather real-time updates and observations from those who are on the ground. This will ensure continuous and comprehensive monitoring of landslide-prone areas.

Develop customized landslide system NECOC should collaborate with relevant organization to adopt customized landslide detection and early warning systems tailored to the specific needs of Bududa District.

Enhance data management The Office of Prime Minister should adopt a centralized landslide data management system to handle multi-scale datasets and ensure real-time data analysis. This system should be accessible to both local authorities and researchers to facilitate timely decision-making and collaboration.

Author contributions
N.S. wrote the main manuscript J.T.L, D.P.M, D.A. are supervisors who reviewed the manuscript

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Data availability
The data supporting the findings of this study can be accessed from the authors upon a reasonable request.

Declarations

Ethics approval and consent to participate
All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board (IRB) and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards: Nkumba University School of Postgraduate Studies and Research (Ref: NU/DPSR/REC/2023), Mildmay Uganda Research Ethics Committee (MUREC, Ref: MUREC-2023-207), Uganda National Council for Science and Technology (UNCST, Ref: SIR243ES), and informed consent was obtained from all individual participants included in the study. Informed consent was obtained from all individual participants included in the study. [NOTE: all participants were above 18].

Consent for publication
The authors affirm that human research participants provided informed consent for publication of the images in Figs. 3, and 4. The participants were informed that their images would be published in an online and/or print journal.

Competing interests
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