Integrating Machine Learning and Community-Based Approaches for Enhanced Early Warning Systems in Cascading Hazard Zones: A Case Study from Melamchi, Nepal

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Keywords: Machine learning, Citizen Science, Early warning, Cascading hazards

Summary

This study presents a comprehensive early warning system for cascading hazards in the Melamchi region of Nepal, integrating satellite data, machine learning, and community engagement. Ground-based surveys complement this by mapping risk zones, with local citizens actively marking flood entry points and landslide-risk areas. Utilizing Random Forest Regression, we assess flood and landslide susceptibility, enhancing predictive accuracy. This multi-faceted approach not only improves hazard prediction but also fosters community resilience and preparedness, offering a robust model for disaster risk reduction in vulnerable regions. This approach strengthens the technical aspect and also empowers local community by engaging them in disaster management process. By combining scientific data with local knowledge, it provides long-term preparedness in vulnerable regions. This model could be replicated in other areas exposed to similar risks.

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1. Introduction

Climate change is accelerating globally, and its impacts are increasingly, particularly in mountainous countries like Nepal. These regions are highly vulnerable to cascading hazards, where flood trigger landslides, and the combination of both significantly amplifies the risks (Talchabhadel et al., 2023). This results in substantial loss of infrastructure, live and livelihoods. Globally, Nepal is ranks as fourth most climate -vulnerable and its position among the top twenty countries exposed to multiple hazards (UNDRR, 2019).

Early warning system (EWS) are crucial for informing communities about impending hazards before they occur, enabling them to understand and mitigate risk effectively (Rogers David & Tsirkunov Vladimir, 2011). These systems utilize a variety of approach including satellite-based predictions of rainfall, flood forecasts, and radio public service announcements, to ensure timely and accurate dissemination of information. This process, often referred to as "last mile communication," is essential for reaching the most vulnerable populations and ensuring they receive and understand the warnings.

Globally, EWS has been widely adopted and integrated into disaster risk reduction strategies. For instance, satellite-based technologies provide real-time data on weather patterns, which can be used to predict and monitor potential hazards such as flood and landslide (Hong et al., 2007). In Nepal, the implementation of

EWS has been particularly impactful. The country has developed sophisticated flood early warning systems that combine hydro-meteorological data with community-based dissemination methods (Bajracharya et al., 2021). These systems not only provide accurate forecasts but also ensure that information is accessible and actionable for local communities.

Geospatial technology provide solution in disaster management, offering multiple approach to enhance early warning systems and risk assessment. Utilizing advanced tools such as remote sensing, GIS, and spatial analysis, it enables precise mapping and monitoring of hazard zones. Furthermore, machine learning algorithms further refine susceptibility analysis, providing accurate predictions of potential disaster impacts (Zennaro et al., 2021). A participatory approach exemplified by OpenStreetMap, involves communities in data collection and mapping, using satellite and drone imageries ensuring that the information is comprehensive and contextually relevant (Shrestha et al., 2023). This community engagement and advance technology not only improve data accuracy but also fosters a sense of ownership and preparedness among residents.

By integrating these advanced geospatial technologies with participatory methods, disaster management efforts become more effective, inclusive and resilient, addressing the limitations of traditional top-down approaches (Uddin & Matin, 2021). However, in the cascading hazard area these technologies lack the local community involvement. Thus, this study provides the community and satellite-based approach for early warning system.

2. Study Area:

The Melamchi municipality, located in the Sindhupalchowk district of Bagmati Province, Nepal. It is a mountainous region with elevations ranging from 2600ft to 2800ft. This municipality receives annual rainfall varying from 1500 to 3000 millimeters, with an average annual temperature of 16.3 °C (Data, 2020). The region is highly vulnerable to landslide, floods, and earthquakes. From 2000 to 2022, Sindhupalchowk district experienced a total 90 seismic events, with magnitudes ranging from 4.1 to 6.7, indicating a high risk of cascading hazards such as glacier lake outburst floods, earthquake-triggered landslide and result to debris flows in monsoon. Additionally, the district has experienced 32 flood events, further highlighted area's vulnerability (Thapa & Prasai, 2022).

Furthermore, the region steep topography and high precipitation levels, which increase with altitude. The 2021 Melamchi flood disaster, triggered by intense upstream precipitation, with cascading impact of earthquake triggered landslide, flood and debris flow caused significant loss of infrastructure and life (Bikash et al., 2021). Thus, combining scientific data with local knowledge and participatory approach, and early warning studies is required in this area.

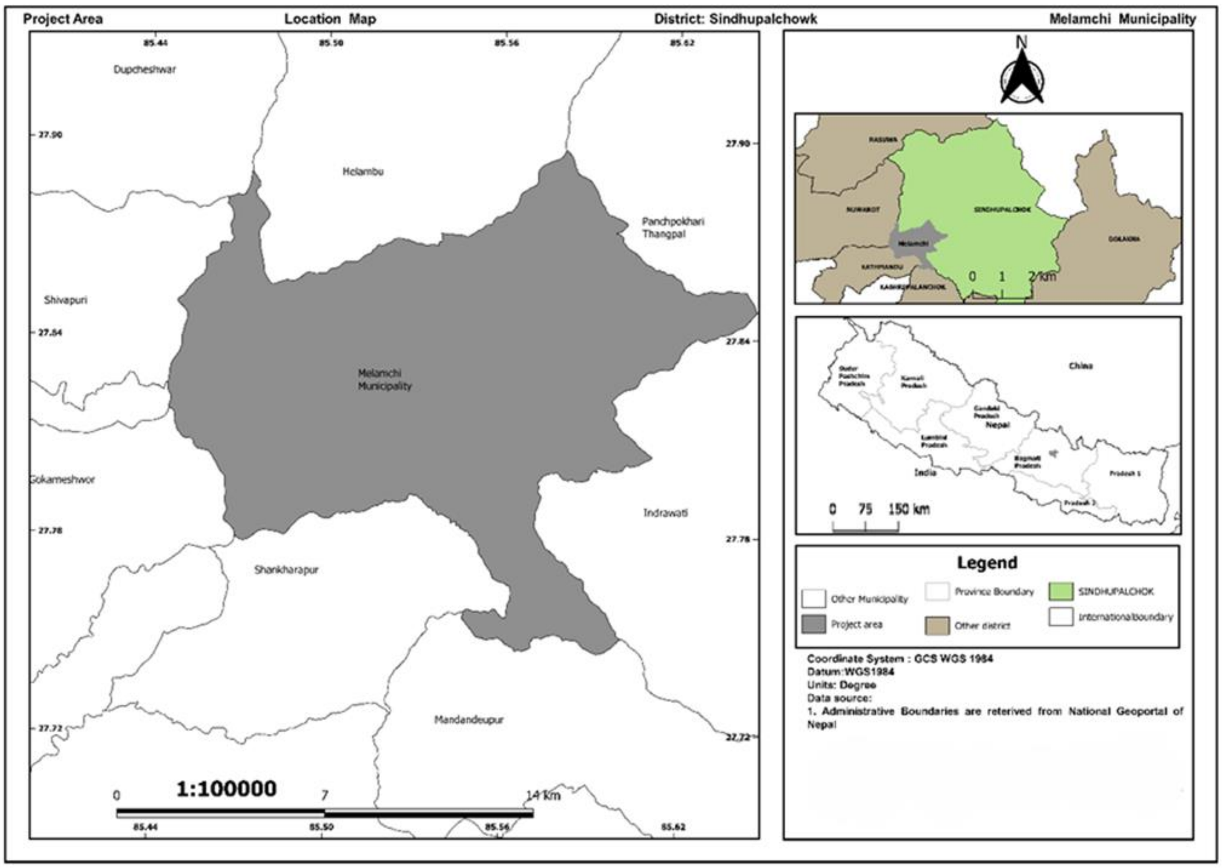


Figure 1:Study Area showing administrative division

3. Methodology

3.1 Community approach

For community-based hazard zonation, enumerators collected data on local capacities, resources, and vulnerability. The local community with diverse group of local people representatives, disable people, teachers, farmers, women, disable people then validated and map risk zones based on past experiences.

Open spaces that could be used during disaster periods were also mapped with the help of Google Earth pro. This collaborative effort result in a holistic map of risk, hazard, and vulnerability providing a detailed view of area at risk.

The communication framework was developed through a participatory approach involving local representatives, radio partners, security forces, downstream and upstream residents, and NGOs representative. This framework includes contact protocols, social media, and WhatsApp groups to ensure effective communication during the events. By involving diverse community members, the framework ensures that communication is timely and reaches all necessary parties, enhancing the overall disaster response and management.

3.2 Community based capacity resource, hazard and vulnerability mapping

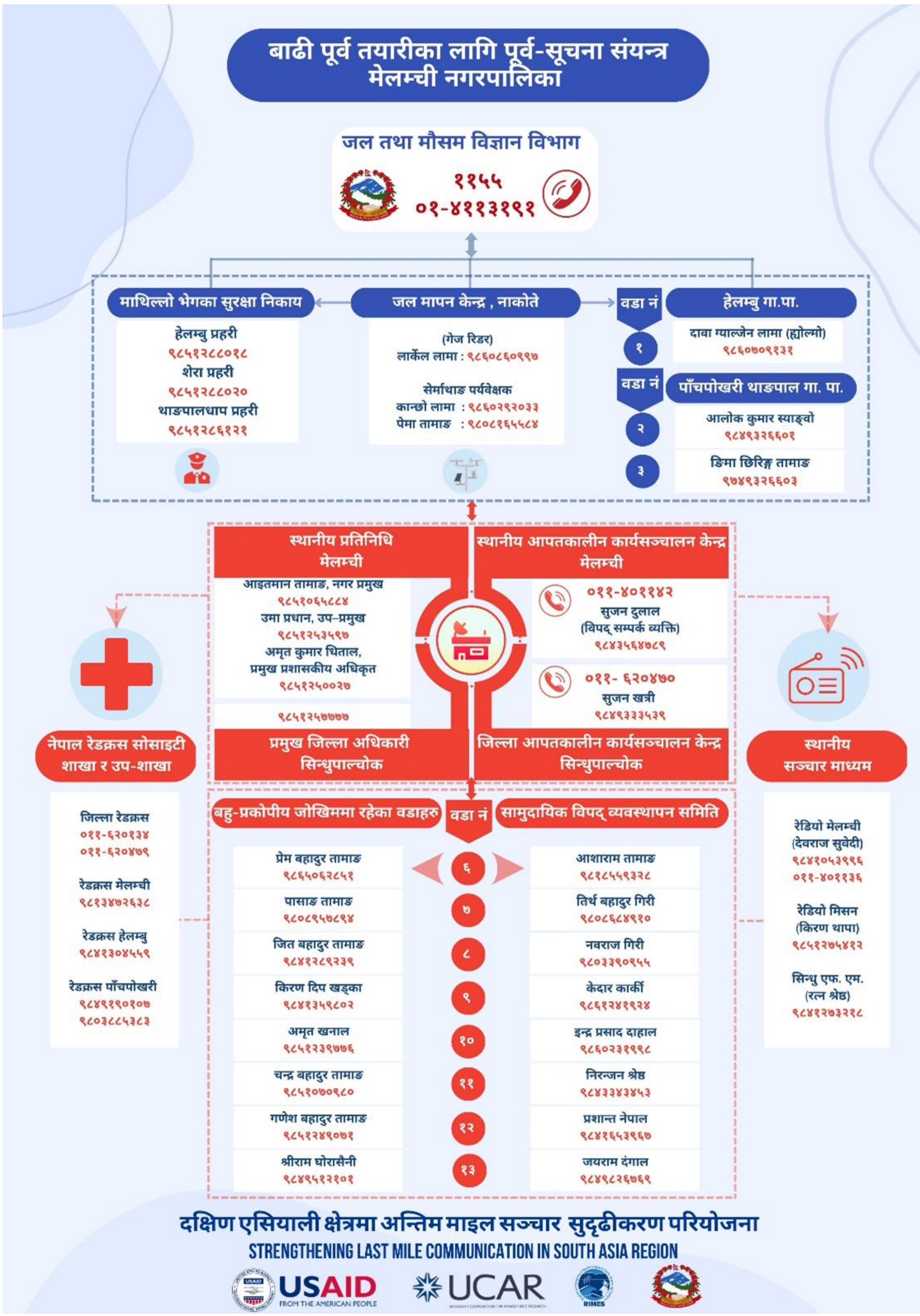
The data collection process utilized as structured questionnaire was designed with the help of framework of disaster management (Government for Nepal Ministry of Home Affairs, 2019). The dataset was focused on capacity, resources, vulnerability and hazards. These areas were categorized into 17 sectors, such as agro-farms, security agencies, education institution, water resources, open spaces, governance bodies, and so on. Vulnerability data include details about individuals and housing material which were obtained from municipality and ground survey was carried by enumerators. Those data were validated by diverse groups of citizens which includes teachers, local government representatives, senior citizens, women's, farmers, and individuals with disabilities. The collected data was visualized in Google Earth Pro, allowing citizens to verify the location of critical infrastructure. The risk map was conducted using criteria like proximity to open spaces, hospitals, vulnerabilities, frequency of occurrences. The flood entry point was mapped based on there past experiences and risk zones for both flood and landslide were identified based on multiple prospective of citizen and their experiences.

3.3 Susceptibility mapping

This study uses remotely sensed dataset along with data collected from community approach to assess flood and landslide susceptibility. The key parameter includes Digital Elevation Model (DEM), slope, aspect, hydrological conductivity, landcover, proximity to roads and rivers, Height Above Nearest Drainage (HAND), Terrain Roughness Index (TRI), Terrain Wetness Index (TWI), and Normalized Difference Vegetation Index (NDVI), landslide and non-landslide dataset, flood and non-flooded areas. The random forest regression model was employed using 200 training samples and 50 testing samples. The model constructs multiple decision trees from bootstrap samples, selecting a random subset of features at each node to reduce correlation and variance (Breiman, 2001). The model's accuracy was assessed by area under curve resulting in a comprehensive susceptibility mapping (Biau & Scornet, 2016).

4. Result:

The communication framework developed by a diverse team is designed to ensure the effective communication to reduce the impact of disaster ***Figure 2***. It includes contact number for key entities such as the Department of Hydrology and Meteorology, security forces in upstream (Helambu), rain gauge readers, and local representatives from Helambu and Pachpokhari municipalities which is adjoining municipalities of Melamchi Municipality ***Figure 1***. The framework facilitates seamless communication between upstream and downstream contacts, including Red Cross representatives, local representatives and local radio stations. Upon receiving information from any source, it is validated within 3-10 minutes. If deemed valid, radio stations disseminate the information for rapid response. Hospitals, and municipal administrations will start the process to manage the event. Additionally, updates about river flow conditions are provided on social media every 10-15 minutes, which helps in understand the lead time. Thus, this framework is essential for early warning, preparation and mitigation of risk.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जित बहादुर तामाङ ९८४१२८९२३९
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STRENGTHENING LAST MILE COMMUNICATION IN SOUTH ASIA REGION
USAID
FROM THE AMERICAN PEOPLE
UCAR
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Figure 2: Communication frame work with detail contact number

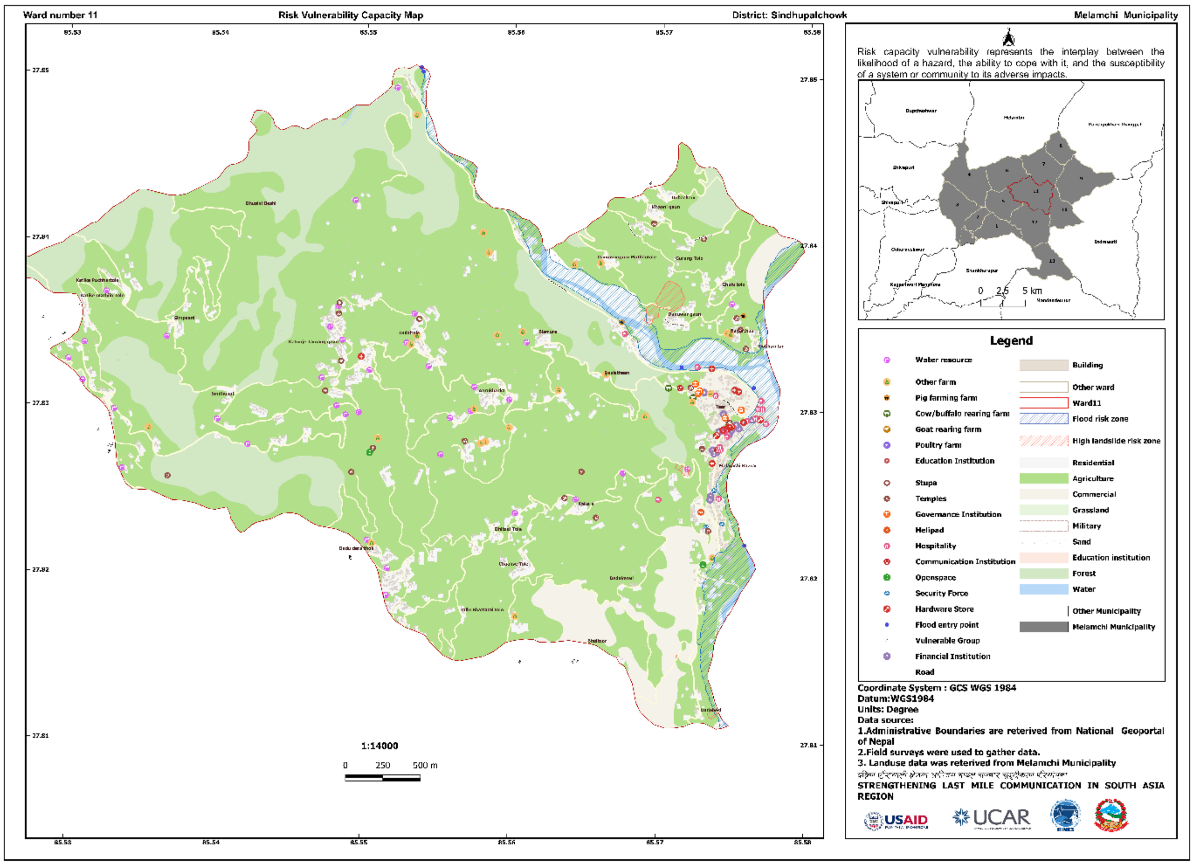

Figure 3: showing hazard capacity and risk zone of ward number 11

The **Figure 3** illustrates the hazard capacity and risk zones that the local citizen map with the assistance of GIS technicians. This map includes all the information with current land use type residential area, agricultural area, commercial, grassland, military area, sand, education institution, forest, and water bodies area, and also capacity resources that are useful in disaster management like open spaces, water resources, agricultural farm and so on. The flood risk zones along with the flood entry point was mapped which is the point in the past from where the flood enter to the urban area. Similarly, the landslide risk zone was mapped using the parameter which includes probable impact on roads, settlement, cropland area, proximity to vulnerable group which include old age, disable poor individuals, pregnant women, single women and other individual, proximity to open space which was taken average distance from all open space, how close it is from the risk point to hospital, cause of landslide, area at risk zone, and past frequency of landslide event. In this region different landslides are very close to the river bank area which shows cascading impact and need effort.

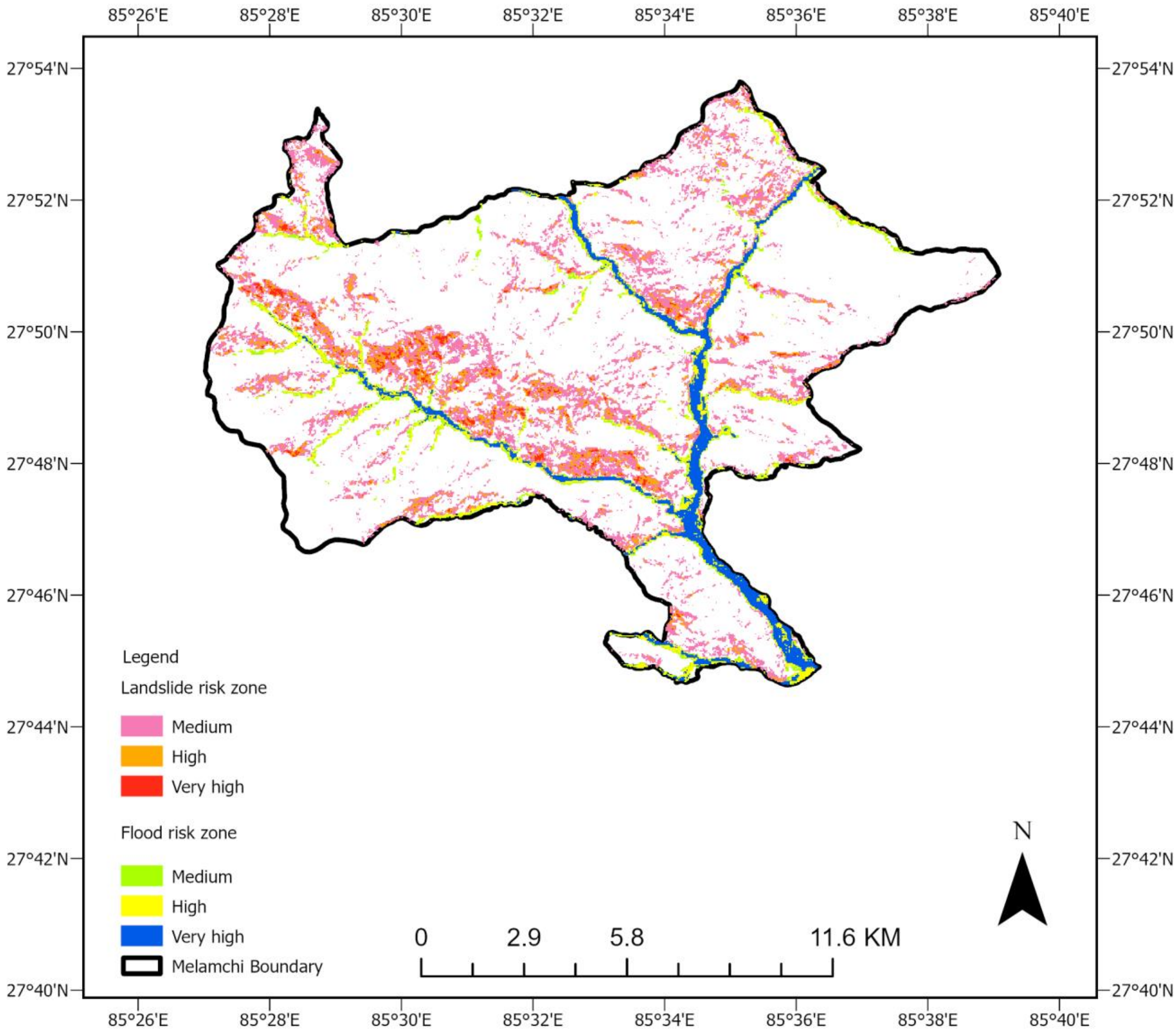

Figure 4:Landslide and flood risk zone using machine learning

The **Figure 4** illustrates the results from a random forest regression model, predicting flood and landslide risk. The analysis achieved an accuracy of 82% for probability of occurrences of flood and 83% for landslide as indicated by the area under the curve (AUC) metrics. This map has been utilized for early warning long term planning. In the map the risk of flood predominately located along river banks and landslide risk lies in the cutting edge of river. These zones represent during the monsoon the impact of landslide is magnifying the impact of flood.

5. Discussion

This study incorporates the both grounds based, citizen based and satellite-based data to understand the risk. The involvement of this types of datasets fosters a sense of ownership and responsibility among residents making them more likely to engage in risk mitigation efforts (Baudoin et al., 2016). Several studies show that these types of mixed approaches are useful for disaster management and early warning actions (Fritz et al., 2017; Le Cozannet et al., 2020; Marchezini et al., 2017). This study presents three frameworks that validate the use of a citizen science approach for communication frameworks, capacity and resources, hazard and vulnerability mapping, as well as a satellite-based approach enhanced with advanced machine learning for identifying susceptibility areas.

The communication framework ensures effective disaster communication by providing early warnings. This framework is not only effective in the disaster cycle but also serves as a strategic approach for health-related issues communication. It supports frameworks developed by WHO strategic communication framework (WHO, 2017), the Health Emergency and Disaster Risk Management Framework (WHO, 2019), the Sendai Framework for Disaster Risk Reduction (United Nation, 2015) and the Public Health Emergency Preparedness (Lee et al., 2023). This framework discusses the principles of effective communication, including accessibility, actionability, credibility, relevance, timeliness and understandability. As communication framework is developed by the engagement of community with other stakeholders, it provides the sense of ownership, encourage them to utilize this framework to minimize the loss and damage. It incorporates one-way dissemination through social media and radio public service announcements, two-way dialogues for validation and sharing information to stakeholders, and three-way participation initiatives. This multiple approach highlights the effectiveness of risk communication between communities and decision-makers, motivating action and enhancing overall disaster preparedness and response.

The integration of citizen science in hazard, vulnerability, capacity, and resource mapping is a transformative approach is disaster management. The involvement of active non-professional scientists in data collection and analysis enhance the data collection as they have better knowledge of the area, can provide-detailed and accurate information on capacity, resources, historical disaster events and vulnerable population. This community engagement also fosters a sense of ownership (Schismenos et al., 2021) and responsibility towards disaster preparedness and response. When community are involved in mapping hazards and vulnerabilities, they gain a better understanding of the risk they face and might face in future(Ramesh et al., 2023). The knowledge of local people on capacity and resources like open space, water resources will be vital for early warning actions, planning and resource allocation. Furthermore, citizens can provide exact locations of flood entry points and also landslide risk area based on there past experiences. This knowledge is invaluable for creating accurate risk maps. This process makes the local community aware where to go when they get alert from communication framework. Furthermore, this data can be use by land use planning and zoning decision, ensuring that development is carried out in safer areas. This data can be use by local government in creating disaster management strategies like prioritizing the open space for multipurpose use, improving the development plans.

The risk map provides significant insights in early warnings, such as identifying medium to high risk of both flood and landslide. As, it provides empirical data which can be used to develop evidence-based policies for disaster risk reduction and management. This map can be used by government to enforce zoning regulations that prevent construction activities in high-risk area which is supported by land use policy. It can also guide the development of infrastructure projects, ensuring that new constructions are resilient to floods and landslides. The joint research by government, INGO and NGOs can prioritize funding for mitigation project in the most vulnerable areas, ensuring that resources are used where they are needed most. It can also be used in different land use suitability analysis (Bathrellos et al., 2012; Thapa et al., 2023; Uddin & Matin, 2021). Although these studies have several advantages, there should be joint research on how it can be used for country level analysis or regional level analysis.

6. Conclusion

The study demonstrates the effectiveness of integrating machine learning, satellite data, and community-based approaches to enhance early warning systems in cascading hazard zones. The development of communication framework in collaboration with local community ensures timely dissemination of information, improving preparedness, and risk mitigation. Additionally, the involvement of local knowledge in capacity resources mapping, hazard and vulnerability assessment empowers communities for understanding risk and better planning for the future. Finally, use of machine learning to develop risk maps supports long-term vision for disaster management and early warning in this region.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Author contributions

Narayan Thapa conceived of the study and compiled and analyzed the database with Sushant Sharma. Narayan Thapa wrote the first manuscript. All authors contributed to the final version of the paper.

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While all authors were affiliated with the project during its implementation, we acknowledge that their current affiliations may have changed. We extend our gratitude to all those who have made this research possible. Your support has been pivotal in the success of this study.

Data Availability Statement (DAS)

Upon the publication of this paper, all authors agree to share the processed data, questionnaire forms used in this paper

Biographical Note

Mr. Narayan Thapa is Geomatics Engineer who graduated from Kathmandu University. He provides geospatial solution in the field of disaster risk reduction, early warning, sustaining mountain settlements, and clean air simulations. Utilizing a citizen science approach, and advance machine learning techniques for assessment and downscale global product to the higher resolution image. Mr. Thapa has worked with different regional organizations and currently work as Geospatial Associate at ICIMOD.

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