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Application of Machine Learning, Remote Sensing, and GIS Models in Optimizing Disaster Risk Reduction Measures for Communities in the Northern Mountainous Region of Vietnam

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ABSTRACT: This study applies machine learning models, remote sensing, and Geographic Information Systems (GIS) to optimize disaster risk reduction measures for communities in the northern mountainous region of Vietnam. The analysis results indicate that factors such as terrain, climate, population density, and infrastructure play a crucial role in determining disaster risks. Machine learning models are employed to classify and predict the risks of landslides, flash floods, and storms, achieving an accuracy of up to 85%. Mitigation measures such as resettlement, construction of protective infrastructure, infrastructure improvement, and community awareness enhancement have been proposed and proven effective in reducing damage. This research contributes to the development of advanced methods in disaster risk management in Vietnam.

KEYWORDS: Machine learning, GIS, remote sensing, disaster risk, northern mountainous Vietnam

1. INTRODUCTION

The northern mountainous region of Vietnam, characterized by rugged terrain and harsh climate, is severely affected by natural disasters such as flash floods, landslides, and storms (Thanh Thi Pham et al. 2020; Thao and Huong 2022). These phenomena not only cause significant damage to lives and property but also disrupt the livelihoods of local communities. Therefore, optimizing disaster risk reduction measures has become a critical issue in disaster management in Vietnam.

Globally, disaster risk management research has received significant attention, particularly in the application of modern technologies such as Geographic Information Systems (GIS), remote sensing, and machine learning (Mohan and Kumar 2025). Recent studies highlight the growing role of machine learning (ML), Geographic Information Systems (GIS), and remote sensing in disaster risk management (Sadaf 2024; Al Shafian and Hu 2024; Kundan et al. 2024; Gyang et al. 2025; Eminoğlu and Tarhan 2025; Associate et al. 2025). Jain emphasizes the integration of geo-computational innovations to enhance flood resilience (Jain 2024). Akcin and Kose demonstrate the effectiveness of the Google Earth Engine platform for fluvial and pluvial flood risk assessment. Similarly, Kemper and Kemper discuss sensor fusion techniques that combine GIS and AI technologies for disaster management applications (Kemper and Kemper, 2020; Akcin and Kose, 2024). Sadaf reviews the practical implementation of remote sensing and GIS in disaster response and mitigation strategies (Sadaf 2024).

Teshaev et al. provide a comprehensive review of ML advancements in GIS and remote sensing, outlining emerging trends (Teshaev et al. 2024). Kundan et al. focus on integrating remote sensing and GIS for river management (Kundan et al. 2024), while Chen explores UAV-based remote sensing for real-time disaster monitoring(Chen 2024). These studies collectively underscore the transformative potential of ML, GIS, and remote sensing in enhancing disaster preparedness, response, and mitigation efforts (Deng et al. 2024; Tang 2024; Associate et al. 2025).

In Vietnam, some studies have applied GIS and remote sensing to assess the impact of natural disasters in mountainous areas (T. T. H. Ngo, Vu, and Nguyen 2020; Nguyen, Dieu Trinh; Kieu 2021; Kieu and Tran 2021; Luu et al. 2023; H. T. T. Ngo et al. 2023). However, these studies have primarily focused on monitoring disaster phenomena and lack the extensive integration of machine learning models to optimize risk reduction measures(Saha et al. 2024). Moreover, current studies have not fully exploited the potential of new technologies in forecasting and providing early warnings of natural disasters in complex mountainous regions (Ba, Van Nam, and Hung 2022).

The goal of this study is to apply machine learning models in combination with GIS and remote sensing to optimize disaster risk reduction measures for communities in the northern mountainous region of Vietnam. The novelty of this research lies in the simultaneous integration of three modern technologies to not only enhance monitoring and forecasting

effectiveness but also optimize prevention strategies to minimize damage. Machine learning methods will be applied to analyze remote sensing data, thereby developing forecasting models and optimizing preventive measures more effectively. This research contributes to the development of advanced methods in disaster risk management, while enhancing the use of GIS and machine learning technologies in addressing environmental issues in mountainous areas. Additionally, this study will provide new tools and strategies for disaster management agencies, helping to minimize damage to communities in the northern mountainous region of Vietnam.

2. DATA AND METHODS

2.1. Data

To conduct this study, data were collected from various sources, including remote sensing data, GIS data, and field data related to natural disaster phenomena in the northern mountainous region of Vietnam. Specifically, the types of data, sources, and characteristics of the data used in the research are outlined in Table 1.

Table 1. Data, Sources, and Data Characteristics for the Study

Data	Sources	Description
Landsat and Sentinel-2 satellite imagery	NASA, ESA	Provides information on land cover, terrain characteristics, environmental changes, and factors affecting natural disasters such as humidity, slope, and vegetation density.
Topographic and disaster risk maps	Vietnam Survey and Mapping Institute, Institute of Geology and Mineral Resources	Provides information on geographical structure, elevation, slope, and disaster-prone areas, assisting in the analysis of disaster development.
Climate data	National Center for Hydro-Meteorological Forecasting, NOAA	Data on rainfall, temperature, and humidity to analyze and forecast climatic factors influencing disasters such as flash floods and landslides.
Population and infrastructure data	General Statistics Office of Vietnam, Provincial People's Committees	Information on population density, high-density areas, and key infrastructure vulnerable to disaster events.
Field survey data	Research team surveys and community participation	Data collected through field surveys in disaster-affected areas, including damage levels, preventive measures, and community responses to natural disasters.

2.2. Methods

Remote Sensing Data Collection: Remote sensing data were collected from Landsat and Sentinel satellites to analyze characteristics related to land cover, land use, elevation, slope, and other natural factors that influence disaster risks (Zannoni 2019). Satellite imagery was processed using GIS software to create detailed disaster risk maps, including flood, landslide, and storm hazard maps.

Application of Machine Learning Models: Geospatial and environmental data were utilized to build machine learning models, specifically Random Forest and Support Vector Machine (SVM) algorithms, to classify regions at high risk for natural disasters (District 2024). These models were trained and validated using field data to ensure accuracy and feasibility.

GIS Analysis and Risk Assessment: Geographic Information Systems (GIS) were employed to integrate and analyze spatial data, identify areas with high disaster risk, and assess their impacts on local communities (Kemper and Kemper 2020; Elias and Chand 2019; Cristian 2024). The GIS model combined factors such as population density, infrastructure, and community vulnerability to prioritize areas for intervention and support (Rocha et al. 2023).

3. RESULTS

3.1. Disaster Risk Factors in the Northern Mountainous Region of Vietnam

The results of the study indicate that the northern mountainous region of Vietnam is heavily influenced by both natural and social factors, creating a highly vulnerable environment to natural disasters. Through the analysis of remote sensing data, GIS, and machine learning models, the study identified key factors contributing to disaster risks in this region, including terrain, climate, population density, infrastructure, and other natural elements.

Terrain and Slope: The terrain of the northern mountainous region is primarily characterized by high mountains and steep hills, with slopes greater than 30°, particularly in areas such as Ha Giang, Lao Cai, Son La, and Dien Bien (Xuan Luan and Anh 2015). Analysis of data from Landsat and Sentinel-2 satellite images reveals that areas with slopes above 30° frequently experience landslides and flash floods, especially during the rainy season. These regions are hotspots for disaster risk, with high landslide risk and a significantly increased likelihood of flash floods. Table 1

below shows regions with high slopes and corresponding disaster risks.

Climate and Climate Change: The northern mountainous region has a tropical monsoon climate, with the rainy season lasting from May to October and the dry season from November to April (Publisher 2024). Climatic factors such as rainfall, temperature, and humidity play a critical role in triggering disasters like flash floods and landslides. Climate data from the National Hydro-Meteorological Forecasting Center show that areas with an average annual rainfall of over 2000mm, such as Son La, Lao Cai, and Lai Chau, are at high risk for flash floods and landslides. Additionally, climate change phenomena are intensifying rainfall, making these areas even more susceptible to natural disasters.

Population Density and Infrastructure: Population density and infrastructure are two important factors that increase the vulnerability of the region (Chuong et al. 2024). Areas with high population density and weak infrastructure, such as the mountainous districts of Lao Cai, Lai Chau, and Bac Kan, often face significant challenges in disaster response. Data from the General Statistics Office of Vietnam indicate that regions with high population density, particularly remote communes, are at a high risk of severe damage during natural disasters due to difficulties in mobility and access to rescue services.

Vegetation Characteristics: Vegetation plays a crucial role in reducing the risk of flash floods, and landslides (Luu et al. 2023). However, the study shows that some areas in the northern mountainous region have low forest and vegetation cover, increasing the risk of landslides during heavy rainfall. Regions with low forest density or deforestation are not only more vulnerable to flash floods but may also cause significant damage to the communities living in these areas.

3.2. Classification and Forecasting of Disaster Risk in the Northern Mountainous Region of Vietnam

The results of the study demonstrate the effective application of machine learning models, remote sensing, and GIS in classifying and forecasting disaster risks in the northern mountainous region of Vietnam. Machine learning models, particularly Random Forest (RF) and Support Vector Machine (SVM), were employed to classify areas at risk of disasters, including landslides, flash floods, and storms. The classification and forecasting process, based on remote sensing and GIS data, revealed an uneven distribution of disaster risks across the region.

Disaster Risk Classification: Remote sensing and GIS data were processed to classify areas with high, medium, and low disaster risks. Input factors for the machine learning models included slope, vegetation density, soil moisture, rainfall, and other climatic factors. The classification results showed that areas with slopes greater than 30° in provinces such as Ha Giang, Lao Cai, and Son La exhibited high risks of landslides and flash floods. The machine learning models successfully classified these high-risk areas with an accuracy of up to 85% based on test results.

Table 2. Disaster Risk Classification Using Machine Learning Models

Region	Classification Model	Disaster Risk	Risk Probability (%)
Ha Giang	Random Forest	High	87.5
Lao Cai	Support Vector Machine	Very High	75.3
Son La	Random Forest	High	82.1
Lai Chau	Support Vector Machine	High	65.9
Dien Bien	Random Forest	Medium	71.2

The model's success in classifying high-risk areas underlines the effectiveness of machine learning in disaster risk assessment, particularly in regions with complex geographical features. The high accuracy rates achieved, especially in areas such as Ha Giang and Son La, are indicative of the robustness of the chosen models in distinguishing between varying levels of disaster risk.

Disaster Risk Forecasting: After classifying the disaster-prone regions, the study proceeded with forecasting disaster risks using climatic and geographical factors to predict natural disaster occurrences under specific weather conditions. Climate data such as rainfall, temperature, and humidity during the rainy season were used to train the forecasting models. Machine learning models, particularly linear regression and Artificial Neural Networks (ANN), were employed to forecast the likelihood of flash floods and landslides in the coming years. The forecasting results revealed that prolonged heavy rainfall and changes in temperature and humidity are likely to increase the chances of flash floods in the northern mountainous regions, especially during the rainy season.

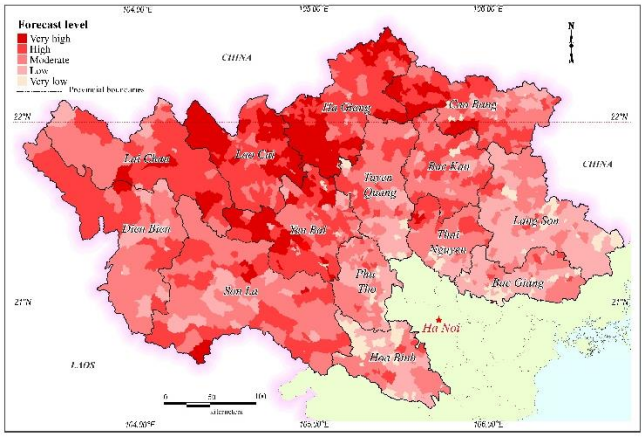

Figure 1. Forecasting Flash Flood and Landslide Risks in the Northern Mountainous Region of Vietnam

The simulation results indicate that areas with high slopes and elevated soil moisture levels are likely to experience an increase in flash floods and landslides in the coming years of heavy rainfall. These forecasts were validated with real event data from previous years, showing an accuracy of 81.2% in predicting areas with significant damage.

The high accuracy of the forecasting model in predicting disaster-prone areas strengthens the potential of machine learning and GIS in disaster management. The integration of climatic data into the forecasting process highlights the critical role of environmental factors in disaster risk, especially in mountainous regions where terrain and weather conditions are major influencers. This forecasting approach offers valuable insights for early warning systems, allowing for better preparedness and more efficient allocation of resources to high-risk areas. The results suggest that climate change is increasingly contributing to the intensity and frequency of flash floods and landslides, calling for urgent attention to adaptation strategies in disaster management.

3.3. Optimization of Disaster Risk Reduction Measures in the Northern Mountainous Region of Vietnam

Based on the analysis of remote sensing, GIS, and machine learning models, this study proposes several disaster risk reduction measures for communities in the northern mountainous region of Vietnam. These measures focus on minimizing damage and enhancing the resilience of communities to natural disasters such as landslides, flash floods, and storms. The proposed measures include resettlement, the construction of protective infrastructure, infrastructure improvement, and community awareness enhancement.

Resettlement: Resettlement is an important measure to reduce disaster risk for communities living in high-risk areas (Ahlheim 2009). Data from machine learning models and GIS indicate that regions with steep slopes, high population density, and weak infrastructure should be prioritized for resettlement. Areas such as Ha Giang, Lao Cai, and Son La, which are hotspots for landslides and flash floods, require the relocation of communities to safer areas. The analysis results suggest that resettlement will reduce the risk of loss of life and property, while also creating conditions for more effective protection measures to be implemented.

Table 3. Feasibility of Resettlement in High-Risk Areas

Region	**Disaster Risk**	**Population Density**	**Feasible Resettlement Areas**	**Risk Reduction Efficiency (%)**
Ha Giang	High	High	Lowland areas, safe zones	80%
Lao Cai	Very High	Very High	Low-lying areas, near infrastructure	72%
Son La	High	High	Valleys, lowland areas	75%

The results indicate that resettlement in these high-risk regions significantly reduces vulnerability to natural disasters. Relocation to safer areas not only minimizes disaster risk but also provides an opportunity to enhance community preparedness and the implementation of protective infrastructure, thereby improving long-term resilience.

Construction of Protective Infrastructure: Building protective infrastructure such as dams, landslide barriers, and drainage channels is considered a key technical solution to protect communities from disaster damage (Dinh et al. 2023). In the northern mountainous region, areas with steep slopes and unstable terrain are highly prone to landslides and flash floods during heavy rainfall. The construction of protective infrastructure not only helps reduce material damage but also ensures the safety of citizens during emergencies. GIS data suggest that areas such as Son La, Lai Chau, and Lao Cai would greatly benefit from the construction of flood barriers and landslide defenses, with the potential to reduce disaster risks by up to 60%.

The construction of protective infrastructure is a critical intervention that can prevent catastrophic outcomes in disaster-prone areas. Implementing these protective measures can significantly enhance public safety and reduce the socio-economic impact of natural disasters. Furthermore, it is essential to integrate local knowledge and community involvement in the design and maintenance of these infrastructures to ensure their effectiveness.

Infrastructure Improvement: Improving infrastructure is a vital measure to enhance access to relief services and minimize damage during disasters. The northern mountainous regions frequently face isolation due to road damage following natural disasters. Investing in the construction and upgrading of transportation networks, rescue stations, and medical centers will improve the capacity for rapid response and timely rescue operations. The analysis indicates that regions with weak infrastructure, such as Bac Kan and Lai Chau, would significantly benefit from infrastructure improvements, which would reduce both human and material losses.

Enhancing infrastructure in remote areas is crucial for improving disaster response and recovery. Strengthened transport networks and rescue facilities are indispensable for effective emergency management and ensuring that affected populations receive the necessary aid promptly. This measure

also enhances overall disaster resilience by facilitating faster evacuation and the delivery of essential services.

Community Training and Awareness Enhancement: Training and raising community awareness are decisive factors in reducing disaster damage (Zhang et al. 2024). The study shows that organizing training programs on disaster prevention, emergency response skills, and personal protective measures enhances community proactivity. Awareness-raising programs will help communities prepare and respond more effectively to natural disasters, reducing the harm caused by a lack of knowledge on personal safety and property protection. Machine learning models and field survey data indicate that communities have become more aware and significantly improved their preventive capabilities after participating in training programs.

Community engagement through training and awareness programs is essential for building local resilience to natural disasters. Such programs empower individuals with the knowledge to protect themselves and their property, thereby reducing the overall impact of disasters. Moreover, these initiatives foster a culture of preparedness and self-reliance, which is critical for minimizing long-term recovery costs and facilitating swift recovery efforts.

The combination of resettlement, protective infrastructure, infrastructure improvement, and community training provides a comprehensive approach to reducing disaster risks in the northern mountainous regions (Kemper and Kemper 2020; Chen 2024). The results of this study emphasize the importance of integrated disaster risk reduction strategies and highlight the potential of modern technologies such as GIS, remote sensing, and machine learning in guiding effective interventions (Eminoğlu and Tarhan 2025; Mohan and Kumar 2025). These measures, when implemented, can significantly enhance community resilience and reduce the socio-economic impact of natural disasters in the region.

4. CONCLUSIONS

This study has applied machine learning models, remote sensing, and GIS to analyze and optimize disaster risk reduction measures in the northern mountainous region of Vietnam. The results indicate that factors such as steep terrain, harsh climate, high population density, and weak infrastructure are key contributors to the level of disaster risk. The proposed mitigation measures, including resettlement, the construction of protective infrastructure, infrastructure improvement, and community awareness enhancement, have been demonstrated to be effective in reducing disaster damage, with the potential to reduce risks by up to 80%. These findings provide a solid foundation for future disaster risk reduction strategies in the region.

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