Regional Rainfall-Induced Landslide Risk Assessment Using Susceptibility Mapping and Unexpected High-Intensity Rainfall

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Abstract. Landslides are one of the most common natural hazards in Malaysia, and besides geological conditions, rainfall intensity and duration are critical factors in assessing landslide risk. This study investigates the impact of daily rainfall variation on landslide susceptibility mapping and risk assessment. For this study, drainage, road, geological, and rainfall data were considered as key. The results show that rainfall significantly contributes to landslide risk increment by keeping geological and other triggering factors constant. Landslide vulnerability due to high-intensity rainfall was high on steep slopes causing high susceptibility compared to low-slope regions. The results also highlighted the relationship between triggering and geological factors in susceptibility assessment. Additionally, a comprehensive analysis through big data sets would help understand the spatio-temporal relationship between rainfall intensity and other landslide factors. Spatio-temporal data resolution will improve landslide susceptibility mapping and prediction accuracy to protect infrastructure and communities from potential landslide disasters in tropical climates.

1 Introduction

Landslides are one of the main natural hazards in Malaysia in which the main triggering factor is rainfall intensity. Rainfall intensity poses significant risks to properties and communities. There are several types of landslides in the world, which are classified based on motion and factors. Roadside human activities, passing through steep areas, often trigger landslides. These slopes are more prone to rainfall, which is common in Malaysia. Due to the increment in landslide events, several methodologies have been applied to assess the rainfall-induced landslide risk [1].

An increasing trend has been observed for landslide risk assessment and prediction. However, uncertainties and challenges are due to the lack of high-resolution data. Challenges include detailed soil information, geological variations, topographical changes, rainfall intensities and durations, and anthropogenic activities. Furthermore, data quality is important in accurate landslide risk assessment and prediction models [2].

Landslide susceptibility assessment involves likelihood evaluation using specific environmental factors. The assessment could be based on qualitative and quantitative approaches. Formerly include spatial distribution analysis, expert evaluations, and geomorphological analysis rely on the experience and knowledge of the evaluators [3].

In landslide susceptibility assessment, factors integration and weighting criteria are highly effective in risk-related studies using historical data through statistical methods. Susceptibility maps provide a spatial distribution of areas ranging from low to high risk based

on various factors which are helpful in planning and implementing mitigation measures to alert communities [4].

Anthropogenic activities such as urbanization, uncontrolled development, deforestation, and the lack of alert systems contribute to the increased frequency of landslides. In steep slope areas, deforestation for infrastructure projects like roads, housing, and farming commonly triggers landslides. In Malaysia, landslides are more common on human-made slopes compared to natural slopes, particularly during the northwest and southwest monsoon seasons [5].

In 2022, a tragic landslide occurred at Father's Organic Farm, along the Gohtong Jaya to Batang Kali highway. Twenty-seven (27) people, including children, lost their lives due to heavy rainfall. In another incident, the area experienced severe flash floods and landslides due to prolonged heavy rainfall, leading to significant loss of life, homes, and property. This disaster was one of the worst in the area's history and required a prolonged recovery period [6].

Various methods have been employed to predict landslides and create susceptibility maps, as described in the literature. Early efforts to mitigate landslide risks mainly involved managing landslide-prone areas, building protective structures, and using in-situ monitoring and warning systems. Landslides, while considered a natural process by Toshiyuki et al. [7], become a serious issue when they occur in populated areas.

Landslide analysis typically involves three steps: susceptibility, hazard, and risk [8]. Susceptibility assesses the likelihood of a landslide based on influencing factors, while hazard evaluates the potential threat to life and property, and risk estimates the financial costs. Various deterministic and heuristic methods for landslide susceptibility mapping have been summarized by Yilmaz [9] and VanWesten et al. [8]. These methods include approaches such as data mining with ANFIS, fuzzy logic, and artificial neural networks [10, 11, 12] as well as the original weights-of-evidence method [13]. The weights-of-evidence approach, combined with GIS, has proven especially effective in landslide susceptibility mapping.

Numerous studies have explored landslide susceptibility mapping. Probabilistic and statistical techniques such as frequency ratios, multivariate analysis, and logistic regression have also been applied to landslide susceptibility and hazard mapping [14]. In Malaysia, the limited research on landslide susceptibility and risk analysis, although some notable studies have been conducted in Penang and Kuala Lumpur.

These events have increased awareness among researchers and government agencies about the critical nature of landslide risks. However, there is still limited research on landslide susceptibility in the surrounding of Gohtong Jaya. Therefore, this study aims to develop a landslide susceptibility model, with a focus on understanding the role of rainfall as a triggering factor in landslide events. The research involves data preparation, model development, and analysis, which are essential for implementing effective disaster management strategies.

2 Materials and Methods

2.1 Study area

Gohtong Jaya is a small township located in the state of Selangor, Malaysia (Figure 1). It is a tourist place especially for those who want to go Genting Highlands. Elevation in Gohtong Jaya is highly variable from 380m to 1870m which shows dynamic surface topography (hilly and rugged). Rainfall in Gohtong Jaya also high especially during monsoon season. The area receives abundant rainfall throughout the year, with the wettest months occurring during the northeast monsoon season, usually between November and March. Slope in the area vary from 0 to approximately 40 degrees with temperatures ranges from 18°C to 25°C. The combination of elevation, frequent rainfall, and steep slopes makes Gohtong Jaya an important area for geological and environmental monitoring, especially for the prevention of landslides and other slope-related hazards
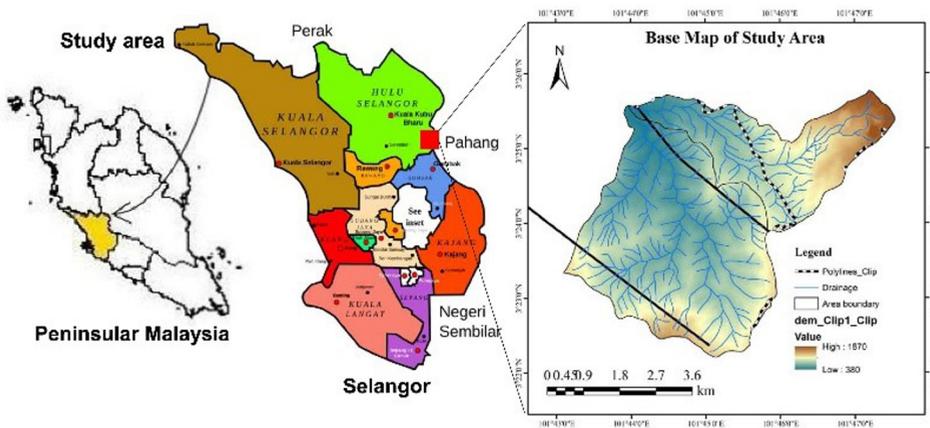

Fig. 1. Study area location.

2.2 Methodology

The methodology for generating the landslide susceptibility map began with acquiring and preparing various thematic maps essential for assessing potential hazards (Figure 2). Initially, a topographic map was used to generate both the drainage map and the road map, critical components in understanding surface water flow and anthropogenic influences, respectively. These elements are essential in assessing how water runoff and human activities may contribute to slope instability in the region.
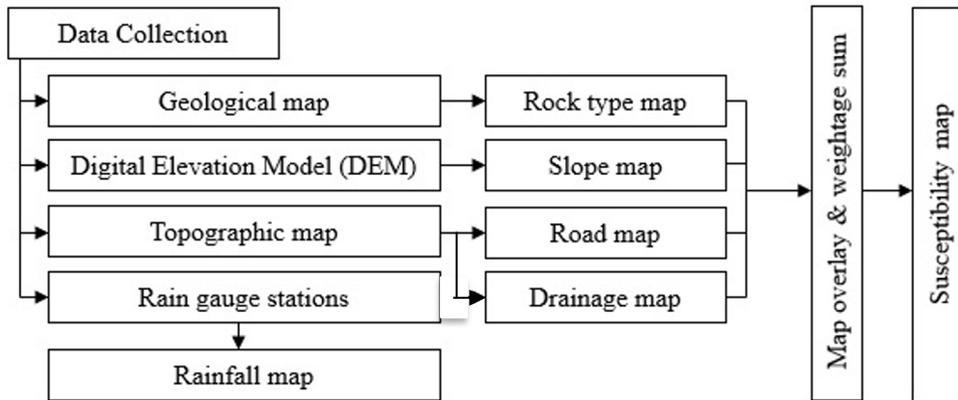
Fig. 2. Flow chart of the methodology.

Sentinel InSAR L-band data of 12.5 m resolution was downloaded from the Copernicus website to derive accurate slope information, a Digital Elevation Model (DEM). Slope map was generated in the geographic information system (GIS) environment. Geological map was obtained from Department of Geology, Faculty of Science, Universiti Malaya. Different rock types were digitized in the GIS environment. Similarly, topographic map was used to generate a road map for further analysis.

A total of 4 rain gauge stations data located nearest possible sites was collected and interpolated to create a rainfall map for the region. For this study, daily rainfall data was assess on 6th, 7th, 8th, and 10th December, focusing on these particular events to evaluate the impact of heavy rainfall on slope stability.

All generated factor maps were re-classified, ranked, and overlayed with their assigned weightage based on their contribution in landslide occurrence.

Finally, four susceptibility maps were generated for selected four rainfall dates allowing for a temporal analysis of how different rainfall events affected the likelihood of landslides in the area.

3 Results and Discussion

3.1 Factors analysis and ranking

The slope analysis revealed a diverse range of terrain categories in the study area. The majority of the area (36.06%) is characterized by slopes ranging from 15 to 25 degrees, followed by 25 to 35 degrees covering 26.80% of the area. Slopes greater than 35 degrees account for 11.49%, indicating steep terrain that is particularly susceptible to landslides under certain conditions. Slopes between 5 to 15 degrees cover 22.54%, while gentle slopes of 0 to 5 degrees represent 3.06% of the area. Flat terrain, with zero slope, covers only 0.05% of the total study area, suggesting minimal regions of absolute flatness.

From a geomorphological perspective, these slope categories are critical for landslide susceptibility analysis. Steeper slopes, particularly those above 15 degrees, which together account for more than 74% of the total area, are more prone to failure, especially under the influence of external triggers such as heavy rainfall. The large proportion of 15 to 25-degree slopes combined with the dendritic drainage pattern, which indicates a dense and highly connected drainage network, significantly increases the risk of landslides during periods of heavy precipitation.

The drainage density in the study area was divided into five classes, reflecting varying degrees of surface water runoff potential. Class 1 represents areas with the lowest drainage density (0 - 1.674 km/km²), where surface runoff is minimal, reducing the likelihood of water accumulation contributing to landslides. As the drainage density increases through Class 2 (1.674 - 2.986 km/km²) and Class 3 (2.986 - 4.046 km/km²), the risk of concentrated water flow and potential slope saturation also rises. Areas in Class 4 (4.046 - 5.050 km/km²) and Class 5 (5.050 - 7.115 km/km²) exhibit the highest drainage density, with dense networks of water channels that can lead to rapid runoff and accumulation during rainfall events, significantly increasing the risk of landslides. In these high-density areas, steep slopes combined with heavy rainfall would pose the greatest risk of slope failure.

The geological setting of the area consists primarily of two rock types: granite and schist. Relatively, granite is a hard and resistant rock. It is more stable under normal conditions due to less prone to weathering and erosion. Whereas, schist is foliated, and more susceptible to weathering when exposed to water infiltration. Schist on steep slopes increases the area's overall vulnerability due to its failure under saturated conditions, contributing to landslides. Furthermore, the presence of a primary road in the study area further enhances landslide risk due to slope cuts during construction.

Rainfall data from the four stations provide a critical insight into the temporal variability of precipitation and its role in triggering landslides. According to the USGS, rainfall greater than 10 mm per hour is considered a heavy shower, while anything above 50 mm per hour qualifies as a violent shower, both of which can initiate landslides in susceptible areas. On 6th December, Station 1 recorded 41.8 mm, Station 2 recorded 25 mm, Station 3 recorded 23.4 mm, and Station 4 recorded 18 mm of rainfall. This represents a significant precipitation event, with Station 1 particularly close to the violent rainfall threshold. On 7th December, Station 3 recorded 40.4 mm, which also approaches the violent shower threshold, suggesting a heightened risk of landslides during this period. Rainfall on the 8th and 10th December remained moderate but above 10 mm at all stations, indicating sustained wet conditions that would have saturated the ground.

The rainfall data shows that on 6th and 7th December, the study area experienced heavy showers, with potential slope failures most likely occurring on these days due to the high cumulative rainfall. The slope categories (particularly those above 25 degrees), coupled with the rock type and drainage characteristics, imply that these rainfall events would have likely triggered landslides in areas of schist, steep slopes, or near drainage lines. The highway crossing through the region would have been at significant risk during these events, particularly in areas where road cuts intersected steep slopes.

Each factor was assigned a rank from 1 to 5, with Rank 1 representing the lowest susceptibility and Rank 5 indicating the highest for factors slope (Figure 3), geology (Figure 4), road distance (Figure 5), drainage density (Figure 6), and rainfall map (Figure 7).
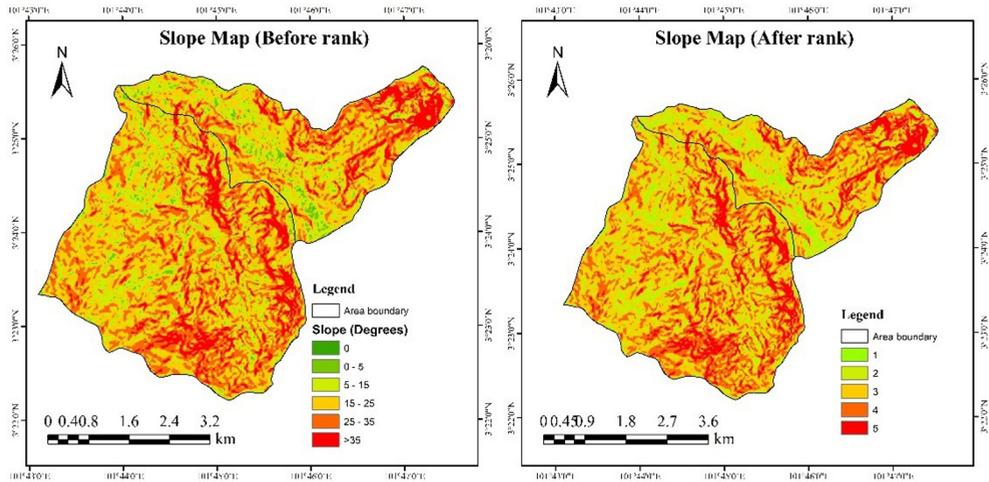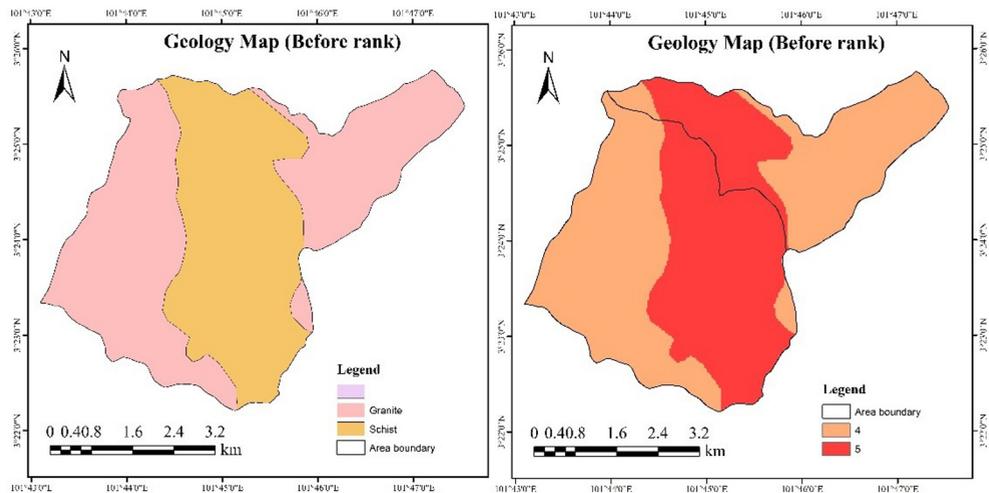

Fig. 3. Slope map before and after ranking.

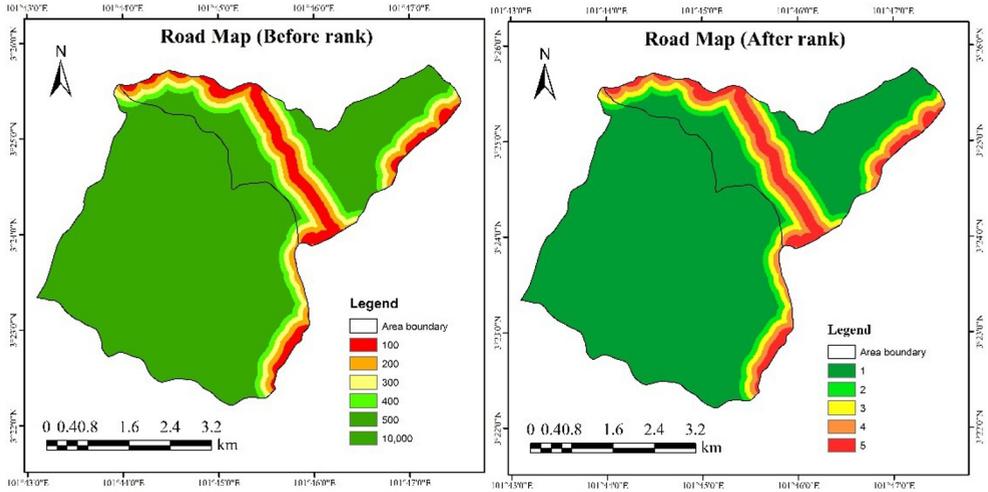**Fig. 4.** Geology map before and after ranking.

Fig. 5. Road map before and after ranking.

This ranking framework facilitates the integration of multiple variables into the landslide susceptibility analysis, allowing for a comprehensive evaluation of the interplay between different factors. By using this systematic ranking, decision-makers can better understand the relative risks and implement appropriate measures to mitigate landslide hazards in vulnerable regions.
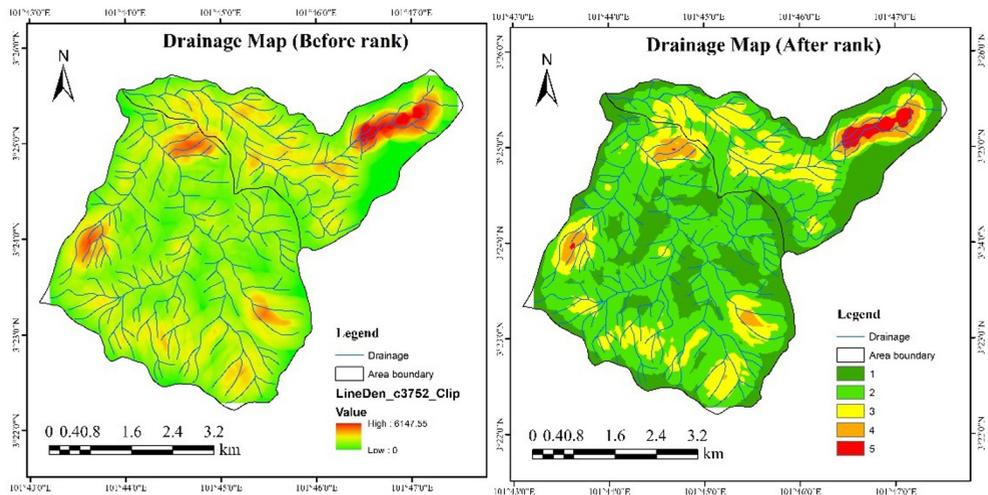

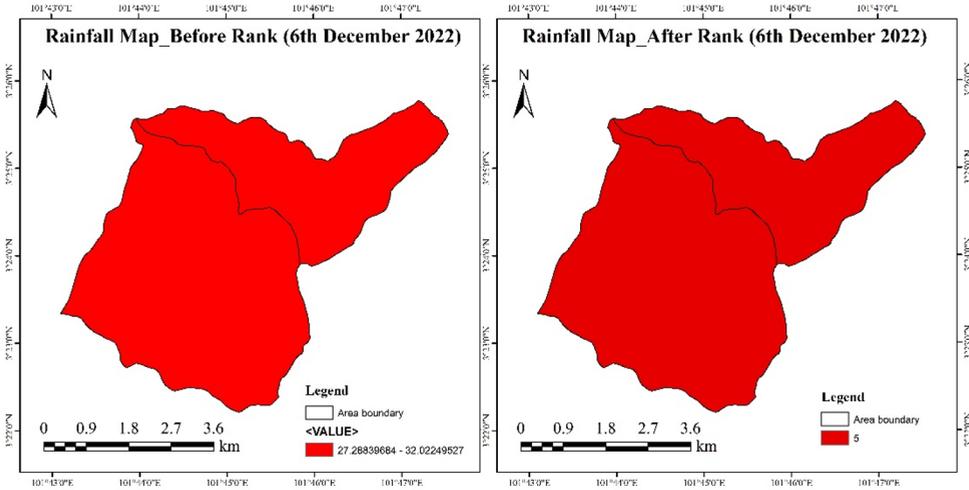**Fig. 6.** Drainage map before and after ranking.

Fig. 7. Rainfall map (6th December 2022) before and after ranking.
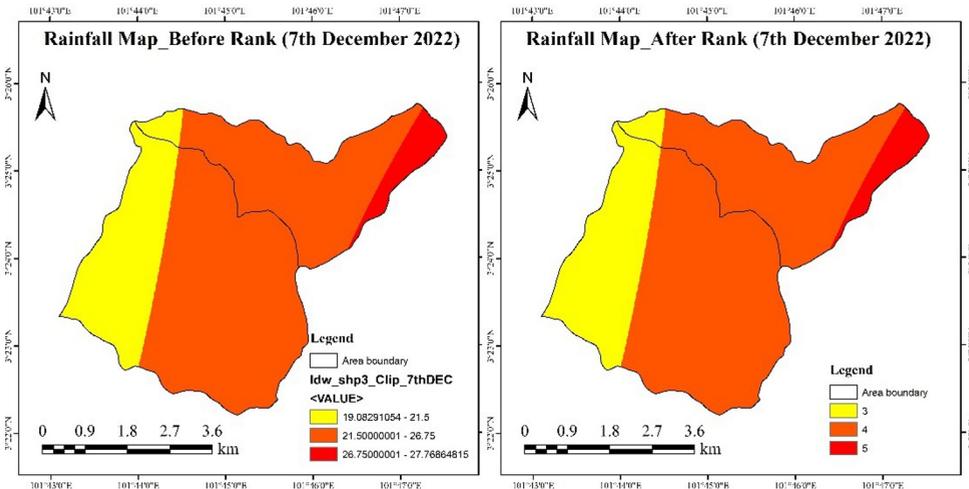

Fig. 8. Rainfall map (7th December 2022) before and after ranking.
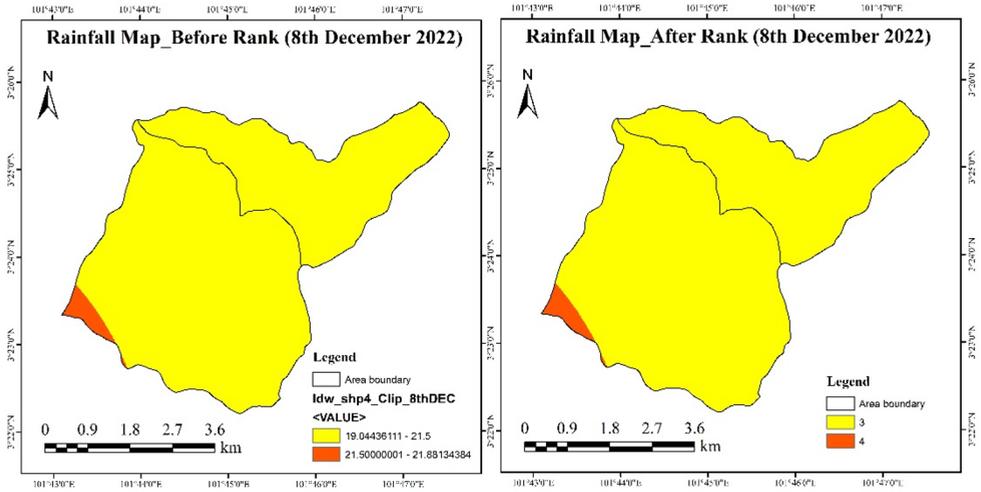
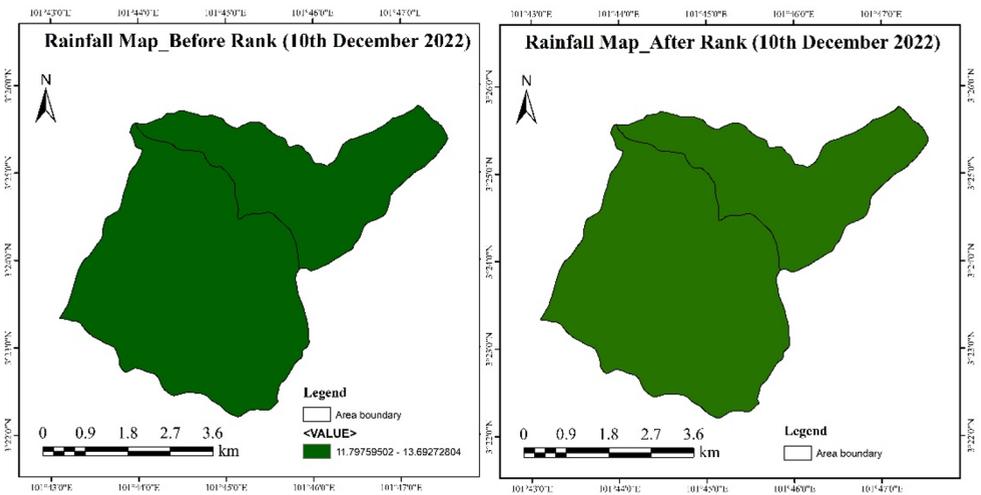**Fig. 9.** Rainfall map (8th December 2022) before and after ranking.

Fig. 10. Rainfall map (10th December 2022) before and after ranking.

3.2 Weightage criteria

The weightage assigned to each factor reflects its relative importance in influencing slope stability and the likelihood of landslides in the study area. The weightage allocation is based on the understanding of the key factors that contribute to landslide occurrences, with more critical factors receiving higher percentages. Slope gradient is one of the most significant factors in landslide susceptibility. Steeper slopes are inherently more prone to failure due to gravity, making this factor highly influential in the analysis. A higher weightage of 40% is assigned to slope, indicating its primary role in determining landslide risk. The rock type and structural geology of an area also play a crucial role in slope stability. Some rock types and geological formations are more prone to weathering, erosion, and failure under certain conditions. By assigning a 20% weightage to geology, the analysis acknowledges its significant but secondary role compared to slope. Proximity to roads can influence landslide risk due to human activities such as construction, excavation, and deforestation, which can

destabilize slopes. While important, this factor is given a lower weightage of 10%, as its impact is more localized and less direct than natural factors like slope and geology. Areas with higher drainage density may have a higher concentration of water flow, which can contribute to slope erosion and instability. Drainage patterns influence how water moves through the terrain, and poor drainage can exacerbate landslide risk. Like distance to road, drainage density is assigned a 10% weightage to reflect its moderate influence. Rainfall intensity is a critical trigger for landslides, particularly in regions with steep slopes and weak geology. Intense or prolonged rainfall can saturate soils, reduce shear strength, and increase pore water pressure, leading to slope failure. A 20% weightage is assigned to rainfall, highlighting its important role as an external triggering factor (Table 1).

Table 1. Susceptibility results based on rainfall (values in percentages).

Susceptibility	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5
6thDEC	0	0.00	10.30	72.72	16.98
7thDEC	0	0.00	26.53	63.40	10.07
8thDEC	0	0.00	36.43	60.65	2.93
10thDEC	0	1.80	67.58	30.60	0.03

3.3 Susceptibility map analysis

The susceptibility map analysis illustrates the relationship between rainfall and landslide susceptibility, highlighting how variations in rainfall impact the area percentages across different susceptibility ranges. Rainfall data is showing in Table 2. Each range categorizes areas based on their likelihood of experiencing landslides, with higher values indicating greater susceptibility. As rainfall increases, the distribution of area percentages shifts, demonstrating that higher rainfall correlates with increased susceptibility. For instance, on December 6th, a significant portion of the area (72.72%) falls within the susceptibility range of 2 to 3, reflecting a notable risk of landslides during rainfall events. This trend continues on December 7th, with 63.40% in the same range, suggesting sustained risk due to ongoing rainfall (Figure 11). However, on December 8th, the percentage of area in the 2 to 3 range rises to 36.43%, indicating continued susceptibility but with a slight decrease. By December 10th, there is a notable drop in the 3 to 4 range (30.60%), while a significant portion (67.58%) remains in the 2 to 3 range, suggesting lingering risks from prior saturation (Figure 12). This relationship underscores the critical role of soil saturation in landslide stability, emphasizing the need for continuous monitoring and effective warning systems. Understanding this dynamic can inform land-use planning and risk management strategies, ensuring safety for communities and infrastructure in landslide-prone areas.

Table 2. Rainfall in mm at different stations.

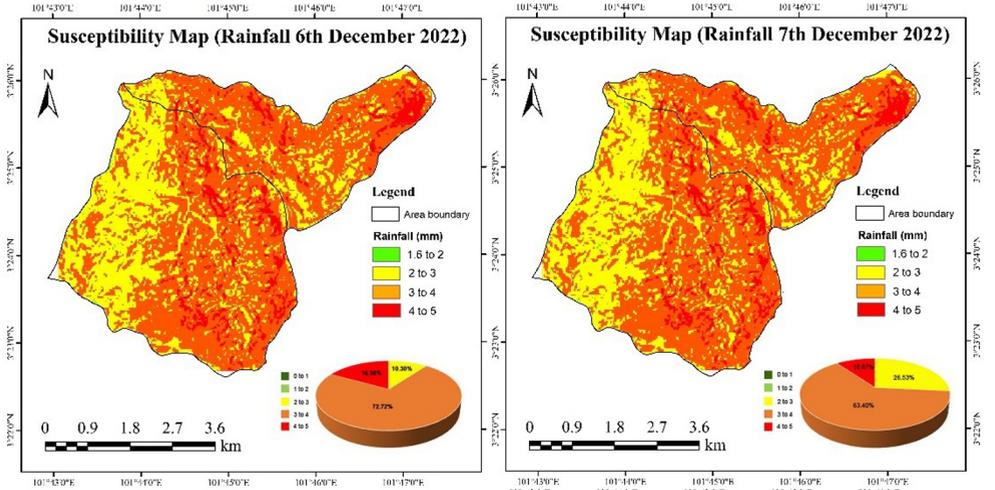| Rainfall Station No.	12/6/2022	12/7/2022	12/8/2022	12/10/2022
1	41.8	7.5	33.1	12.3
2	25	23.5	9.5	15.5
3	23.4	40.4	18.5	7.9
4	18	17.5	14	29.4

Fig. 11. Susceptibility map (Rainfall 6th and 7th December 2022).
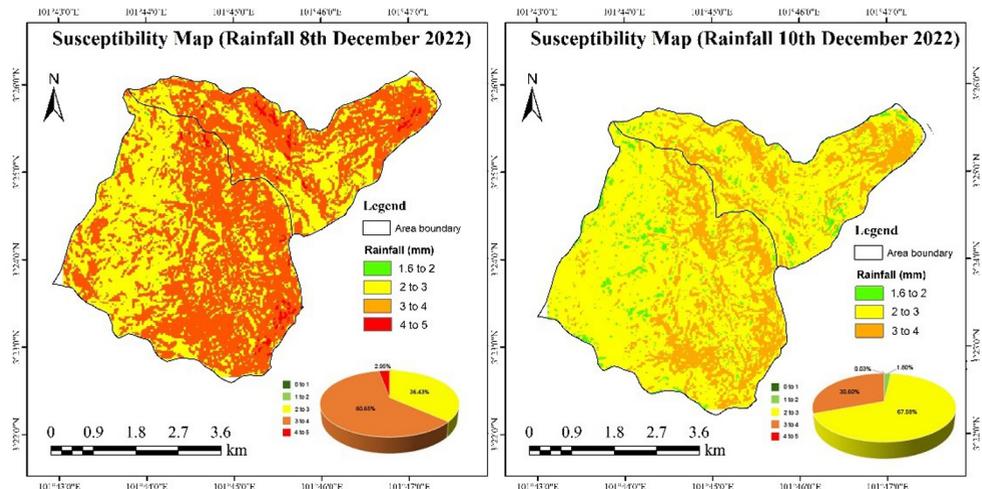

Fig. 12. Susceptibility map (Rainfall 8th and 10th December 2022).

4   Conclusions

This study examined daily rainfall intensities interpolated from four rain gauge stations. The slope map indicates that over 50% of the area is at high elevation, suggesting a significant landslide risk. Additionally, the dense drainage network plays a crucial role in assessing landslide risk. The observed daily rainfall intensities range from heavy to violent showers, underscoring their importance in evaluating landslide risk and susceptibility. Overall, these

factors collectively enhance our understanding of the potential for landslides in the region and highlight the need for effective risk management strategies.

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