Geostatistical and Geospatial Modelling of Landslide Susceptibility Mapping in Rangamati District, Chittagong Hill Tracts, Bangladesh

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ABSTRACT: This study aims to assess and map landslide susceptibility in the Rangamati District of the Chittagong Hill Tracts, a hilly and steeply sloping area undergoing rapid urbanization and extensive deforestation. The region also receives excessive monsoon rainfall, making it highly prone to frequent landslides. Using an integrated geostatistical and geospatial approach, the research incorporates 12 causative factors, including terrain attributes, rainfall variability, geological characteristics, soil properties, proximity to fault lines, proximity to roads and rivers, and land use changes, to identify high-risk zones. A total of 306 historical landslide events were analyzed, and key environmental factors were processed using geospatial simulation techniques. Kriging interpolation and weighted overlay analysis within a GIS framework were applied to generate susceptibility maps at a 30 m spatial resolution. Model validation was conducted through Union-level community consultations. The results indicate that 57% of the district area is moderately susceptible, 10.41% highly susceptible, and 0.29% very highly susceptible, representing 120 critical pinpoint locations. Baghai Chhari, Barkal, and Langadu were identified as the most vulnerable Upazilas. The key drivers of susceptibility include clay-loam soils, moderate slopes (10–30 degrees), weak sedimentary rock formations, extensive deforestation, heavy monsoon rainfall, and land alteration associated with road construction, 67% of historical landslides occurred within 500 meters of roads, highlighting their influence. The study recommends integrating susceptibility maps into local planning processes, early warning systems, and community-based disaster preparedness initiatives. Addressing landslide susceptibility and reducing associated risks will contribute to achieving SDG 11 (Sustainable Cities and Communities), while safeguarding human lives and biodiversity aligns with SDG 15 (Life on Land).

Keywords*:* Geospatial Modelling; Landslide Vulnerability; Susceptibility Mapping; Community-Based Preventive Measures

INTRODUCTION

Rangamati District, located in the Chittagong Hill Tracts (CHT) of Bangladesh, is distinguished by its rugged terrain, steep slopes, and dense forest cover, which together create a unique topographical landscape (Ahammad et al., 2023). The region's complex geology, shaped by long-term geological processes, has resulted in diverse soil types, rock formations, and landforms. While this landscape contributes to the area's ecological richness, it also makes the region highly susceptible to natural hazards, especially landslides (Abedin et al., 2020; Sarwar and Muhibullah, 2022).

Landslides in Rangamati and the broader CHT, driven by steep gradients and rugged terrain, cause significant loss of life and economic disruption. These hazards undermine community safety and efforts to achieve the SDGs, particularly those related to resilient infrastructure and sustainable land management. To address these challenges, this study employs advanced geospatial and geostatistical techniques to map landslide susceptibility, building on limited prior research in the region. In addition, the region's unique topography influences local weather patterns, hydrology, and ecological dynamics, affecting rainfall distribution (Hossain and Mohiuddin, 2020; Guzzetti et al., 2008; Satyanaga, 2014), water runoff, and soil erosion, all of which contribute to landslide vulnerability (Sarker and Rashid, 2013; Hossain et al., 2014; Costache et al., 2019).

A comprehensive understanding of landslide susceptibility is essential for disaster risk reduction, effective land use planning, and informed decision-making in the CHT region (Guzzetti et al., 1999; Lee, 2007). Geostatistical and geospatial modelling techniques are powerful tools for analyzing and

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mapping landslide susceptibility. These approaches integrate spatial data with statistical methodologies, considering factors such as topography, geology, land cover and precipitation to identify areas at risk (Ayalew and Yamagishi, 2005). By applying these techniques, areas vulnerable to landslides can be mapped with a higher degree of accuracy, offering valuable insights for disaster risk mitigation and management (Lee and Talib, 2005).

Landslide susceptibility mapping aligns with several United Nations SDGs, particularly Goal 11: Sustainable Cities and Communities and Goal 15: Life on Land. Effective identification and mitigation of landslide risks help build resilient infrastructure, promote sustainable land management practices, and safeguard the livelihoods of local communities (UNDP, 2015). Moreover, landslides pose severe risks to community safety, causing fatalities, damage to infrastructure, and disrupting local livelihoods (Malczewski et al., 1999; Rabby et al., 2022). Accurate susceptibility maps equip local authorities and communities with the knowledge necessary for disaster preparedness, risk reduction, and emergency response (Gariano and Guzzetti, 2016).

Despite the global adoption of geospatial and geostatistical methods for landslide susceptibility mapping, Rangamati District remains underexplored, with prior studies limited by small sample sizes, outdated datasets, or lack of Upazila-level analysis (Das and Raja, 2015; Chowdhury and Hafsa, 2021). This study addresses these gaps by employing medium-resolution datasets (e.g., SRTM DEM at 30 meters, Landsat 30-meter imagery) and advanced techniques (e.g., Kriging, weighted overlay) to comprehensively map landslide susceptibility. Additionally, the socio-economic context of Rangamati, characterized by high poverty rates and reliance on agriculture (BBS, 2022), exacerbates landslide impacts through displacement and loss of livelihoods, underscoring the need for community-based mitigation aligned with SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land). According to the historical landslide inventory, a total of 306 landslide incidents have occurred in the Rangamati District, indicating its severe vulnerability and highlighting the importance of modelling to identify landslide-prone localities. (Bangladesh Geological Survey [BGS], 2022). Notably, major events such as the devastating landslide on June 13, 2017, further highlight the severity of the issue (Rabbi et al., 2020; Abedin et al., 2020). Climate change, rapid urbanization, and unplanned land use changes continue to intensify the region's susceptibility to landslides (IPCC, 2014; Petley, 2012).

Recent technological advances, including remote sensing and Geographic Information Systems (GIS), offer opportunities to improve landslide hazard mapping and risk assessment (Van Westen et al., 2010).

This study seeks to address the existing knowledge gap by conducting a comprehensive analysis of landslide susceptibility in the Rangamati District using advanced geostatistical and geospatial modelling techniques. The novelty of this research lies in the incorporation of all major causative factors, validated through evidence from historical landslides using geospatial simulation. Through these simulations, the spatial influence of each factor was almost pinpointed with high precision.

Using high-resolution spatial analysis and integrated geospatial datasets, this study aims to identify and map areas at elevated risk of landslides, offering crucial insights for disaster risk reduction and land use planning in the region. By enhancing our understanding of landslide dynamics in the Chittagong Hill Tracts (CHT), this research aspires to contribute toward building resilient communities and promoting sustainable landscape management in the Rangamati District.

Accurate landslide susceptibility mapping is essential for effective land use planning, disaster risk management, and safeguarding the well-being of local communities in the CHT. This study will play a vital role in anticipating landslide-prone areas, supporting the implementation of mitigation strategies, and strengthening the resilience of the communities of Rangamati.

STUDY AREA

Rangamati District, located in southeastern Bangladesh (Fig. 1) within the Chittagong Hill Tracts (6,118 sq. km; 22°33'–23°34' N, 91°04'–92°05' E), is characterized by rugged terrain and dense forests, making it highly susceptible to landslides. The district's population grew from 301,753 in 1981 to 647,586 in 2022, with a declining growth rate (2.89% in 1981–1991 to 0.76% in 2011–2022) due to socio-economic shifts and migration (BBS, 2022). This population pressure has driven deforestation and land use changes, such as Jhum cultivation, exacerbating landslide risks. The region experiences a tropical monsoon climate, with annual rainfall averaging 2,500–3,000 mm, concentrated during June–September, which triggers landslides by saturating soils and destabilizing slopes (Hossain et al., 2014). The increasing population puts significant pressure on the natural environment, leading to various interventions. As a result, the district faces frequent landslides, especially during the rainy season.

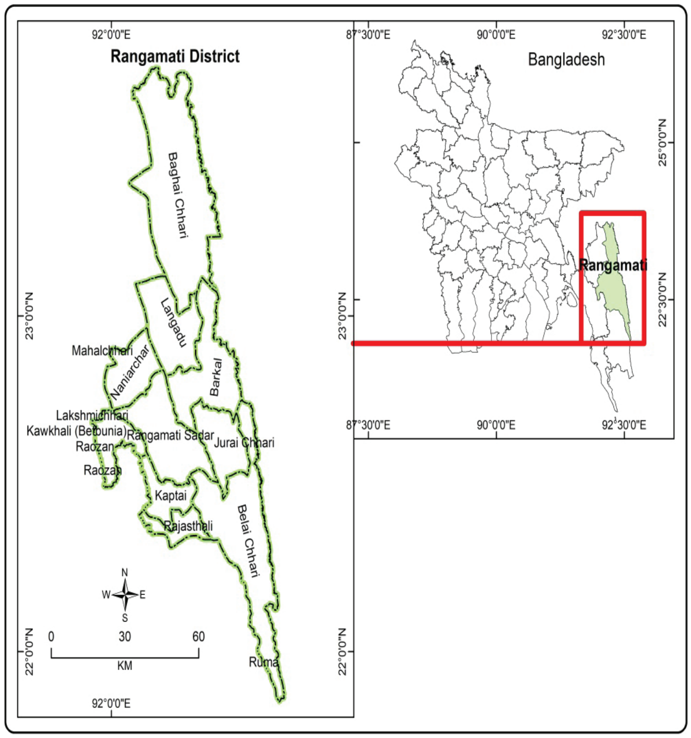

Figure 1: Study Area- Rangamati District

Aim and Objectives of the Study

This study aims to assess landslide susceptibility in Rangamati District using advanced geostatistical and geospatial techniques to support disaster risk reduction. The objectives are:

1. To map landslide susceptibility zones by integrating environmental factors (e.g., slope, elevation, rainfall, geology) using geospatial tools.

2. To analyze spatial variability of landslide susceptibility across Upazilas, correlating environmental variables with historical landslide occurrences using statistical methods.

3. To predict landslide susceptibility in areas lacking historical data using geostatistical models like Kriging, enhancing spatial risk assessment.

4. To propose actionable mitigation strategies, including early warning systems and community-based measures, to reduce landslide risks.

MATERIALS AND METHODS

Materials

The landslide susceptibility modelling study in Rangamati District utilized a comprehensive set of datasets to ensure robust and accurate assessment of terrain vulnerabilities. The datasets included:

Landslide Inventory: A detailed inventory of 306 landslide locations in Rangamati District was compiled in 2022 using Participatory Rural Appraisal (PRA) methods. This inventory provided historical data on landslide events, enabling the identification of spatial patterns, trends, and contributing factors for model validation.

SRTM DEM 30 m: This medium-resolution elevation dataset was used to derive critical topographic parameters, including slope, aspect, and elevation, which are essential for identifying landslide-prone areas.

Geological Dataset: Geological data from the Government of Bangladesh (GoB) detailed the region's rock formations, structures, and potential geological hazards affecting slope stability.

Soil Dataset: Soil properties and characteristics, key influencers of landslide susceptibility, were sourced from the Soil Resource Development Institute (SRDI). This dataset offered insights into soil types, textures, and cohesion, enhancing the assessment of ground stability.

Topographic Map Dataset: The Survey of Bangladesh (SoB) topographic maps provided detailed information on slope, land cover, and drainage patterns, fundamental for terrain analysis and susceptibility mapping.

Land Use Data: Land use changes were analyzed using 30-meter resolution imagery from GloVis, including datasets from Landsat 5, Landsat 8, and Landsat 9, to assess their impact on landslide susceptibility.

By integrating these datasets—encompassing elevation, landslide inventories, soil properties, topographic maps, geological data, and land use—the study achieved a comprehensive understanding of terrain vulnerabilities and landslide risks. This multi-faceted approach ensures the accuracy, reliability, and robustness of the landslide susceptibility models, supporting informed decision-making, strategic land use planning, and effective disaster risk reduction in landslide-prone areas.

Methods

Rangamati District, located in the Chittagong Hill Tracts of Bangladesh, is characterized by complex geological formations, varied topography, and significant climatic influences, making it highly susceptible to landslides. The methodology for assessing landslide susceptibility integrated multiple datasets and analytical steps, as illustrated in a flowchart (Fig. 2). Figure 2 outlines the workflow, including data acquisition, preprocessing, modelling, and validation phases. The key steps are detailed below in the data processing section:

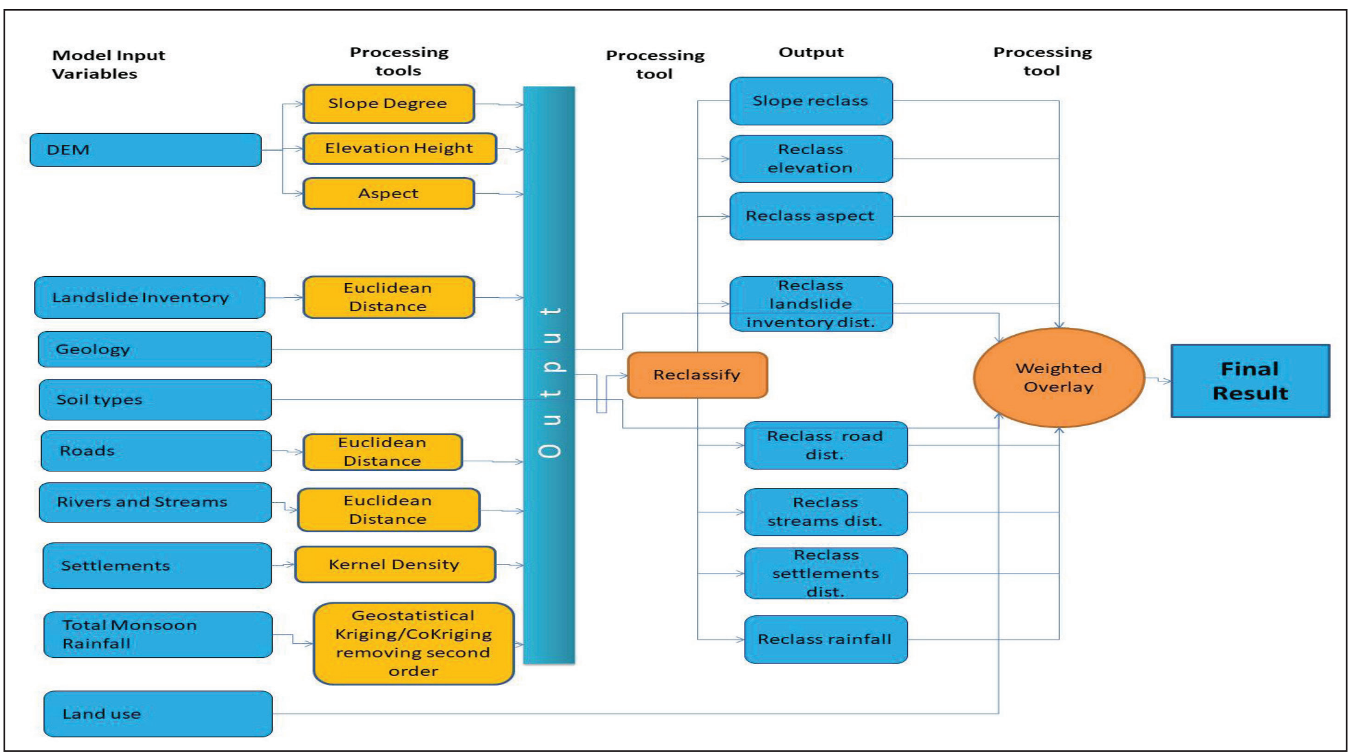

Figure 2: Landslide Susceptibility Model - A Methodological Framework

Data Preprocessing

To conduct landslide susceptibility modelling, a total of 12 causative factors were considered. These include elevation, slope, and aspect derived from the SRTM DEM; geological formation; soil texture; land use/land cover (LULC) 2023; NDVI 2023; annual monsoon rainfall (interpolated for 1973–2023); proximity to rivers; proximity to roads; proximity to fault lines; and the kernel density of past landslides. In the next step, all data layers were resampled to a common spatial resolution of 30 m, ensuring that all datasets were projected to the WGS84/UTM Zone 46N coordinate system.

To map landslide susceptibility zones by integrating environmental factors, spatial statistics from the 306 historical landslide points for all data layers were simulated using the *Simulate* tool from the Geostatistical Analyst Tools. This procedure helped to understand the spatial influence of each variable on landslide susceptibility. The simulation results provided insights into the raster datasets, allowing interpretation of the spatial behavior and relative contribution of each individual variable. Based on these insights, all data layers were classified.

As all variables were continuous, they were reclassified into 10 classes using the natural breaks method. Each variable was then assigned an influence value, and the weights for the classes were determined accordingly. Finally, the weighted overlay model was executed, and the most susceptible locations for landslides were identified.

All raster datasets were then combined using a weighted overlay approach to generate a landslide susceptibility map for Rangamati. Weights were assigned based on the statistical analysis of historical landslide data and supported by relevant literature (van Westen et al., 2003; Ayalew and Yamagishi, 2005; Pradhan and Lee, 2010; Ashwath et al., 2023). The normalized weights, reflecting the relative influence of each factor, were determined as follows: Soil Texture (14.1%), Slope Gradient (12.7%), Rainfall (12.7%), Elevation (10.6%), Geological Formation (9.9%), Proximity to Roads (8.5%), Land Use/Land Cover (8.5%), Proximity to Fault Lines (7.0%), NDVI (7.0%), Slope Aspect (5.6%), Proximity to Rivers (5.6%), and Kernel Density of Landslides (4.9%), summing to a total influence of 100%. This weighted overlay approach integrated the contributions of each factor to produce a comprehensive landslide susceptibility assessment, ensuring transparency, robustness, and consistency with observed spatial patterns.

To obtain spatial variability in landslide susceptibility at the upazila level, upazila-wise statistics were extracted, and corresponding maps and tabular reports were generated using ArcGIS.

Validation: The outcomes of the landslide susceptibility assessment were validated at the field level through consultation workshops conducted at the union level. The union-specific results were printed on A0-sized sheets and presented to local community members. Their responses reflected strong agreement with the findings, with many expressing appreciation by saying, wow, what an excellent result-this area is indeed highly vulnerable. This field-based validation reinforced the reliability and practical relevance of the modeled susceptibility zones.

RESULTS AND DISCUSSION

Results

Mapping Environmental Factors Using Spatial Statistics

Rangamati Historical Landslides and Elevation: Analysis of historical landslide data in Rangamati reveals a strong correlation with elevation (Fig. 3). The majority of landslides (58.82%) occurred at elevations between 50–150 meters, indicating that mid-elevation hills are highly susceptible. About 26.80% took place in the 0–50 meter zone, often in foothill areas affected by human activity and colluvial deposits. Higher elevations saw fewer events—150–300 meters (11.44%), 300–500 meters (2.29%), and above 500 meters (1.63%)—likely due to reduced human disturbance. Overall, landslides are most frequent in low to mid-elevation zones (0–150 meters), driven by slope vulnerability, geological factors, and anthropogenic impacts.

Rangamati Historical Landslides and Slope Gradient: Historical landslide analysis in Rangamati shows a clear link with slope gradient (Fig. 4). Most landslides (51.63%) occurred on slopes between 10–20 degrees, indicating high vulnerability in moderately steep terrain, especially during heavy rainfall. Slopes of 5–10 degrees contributed 20.92%, while gentle slopes (0–5 degrees) saw 10.46% of events, likely in disturbed or low-stability areas. Steeper slopes (20–50 degrees) accounted for 16.67%, where natural and human factors such as weathering and deforestation increase risk. Slopes above 50 degrees saw only 0.33% of events, reflecting their limited presence. Overall, slopes between 10–20 degrees are most landslide-prone due to combined geomorphic and anthropogenic factors.

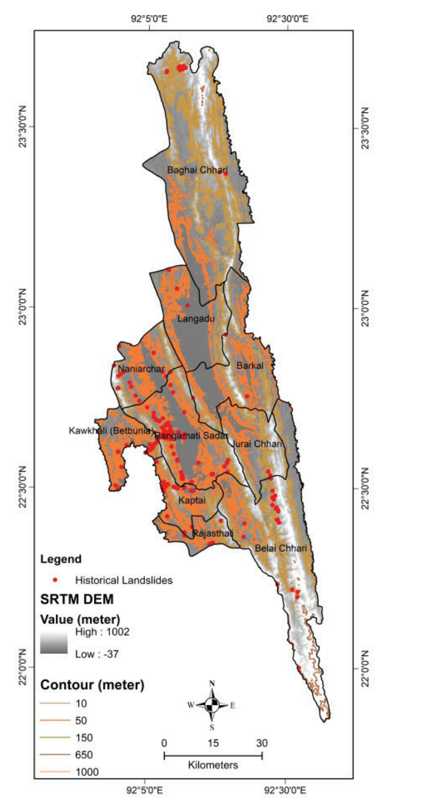

Figure 3: Elevation and Historical Landslides of Rangamati District

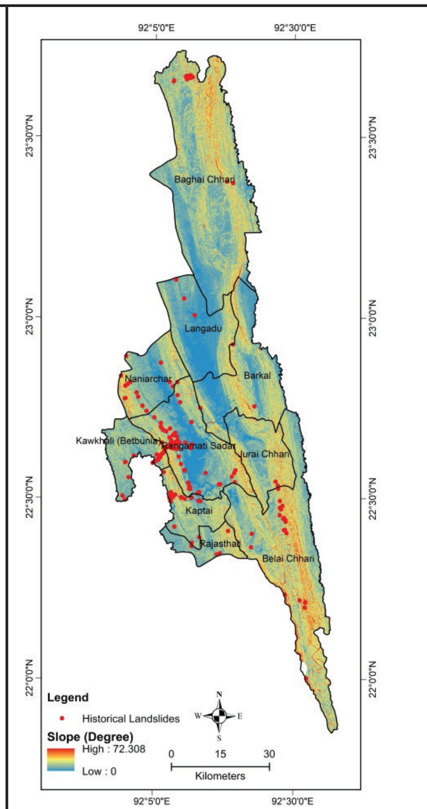

Figure 4: Slope and Historical Landslides of Rangamati District

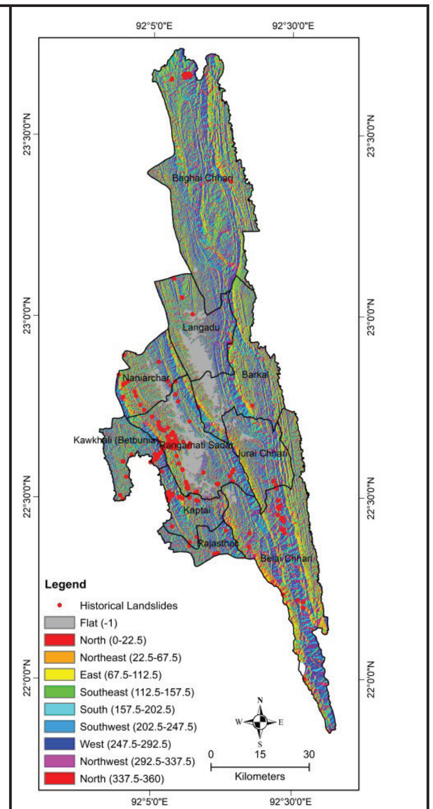

Figure 5: Aspects and Historical Landslides of Rangamati District

Rangamati Historical Landslides and Slope Aspect: Slope aspect analysis in Rangamati shows a strong influence on landslide distribution (Fig. 5). South-facing slopes (143°–213°) recorded the highest landslide frequency (24.51%), followed by southwest-facing slopes (214°–284°) at 23.53%, likely due to greater exposure to monsoon rainfall and solar radiation. East-facing (72°–142°) and north to northeast-facing slopes (0°–71°) experienced moderate landslide activity, with 21.57% and 19.61%, respectively. The lowest occurrence (10.78%) was observed on northwest to north-facing slopes (285°–356°), likely due to lower rainfall and sunlight exposure. These patterns underscore the role of slope orientation in landslide susceptibility across Rangamati.

Geological Formation and Landslides: Historical landslide data in Rangamati show a strong correlation with geological formations (Fig. 6). The Boka Bil Formation, consisting of alternating sandstone, siltstone, and shale layers, accounts for the highest number of events (44.77%) due to its structural weaknesses and susceptibility to weathering. Tipam Sandstone follows with 29.08%, likely influenced by jointed rock layers and steep slopes. The Bhuban Formation, contributing 12.42%, may be affected by tectonic disturbances and weathered strata that reduce slope stability. Other formations such as Dupi Tila (2.29%), Girujan Clay (4.25%), and valley alluvium/colluvium (1.31%) show lower frequencies but may still contribute to localized failures under certain conditions. The combined Dihing and Dupi Tila formations represent 5.88%, indicating moderate risk. Overall, sedimentary and structurally weak formations significantly contribute to landslide susceptibility in the region.

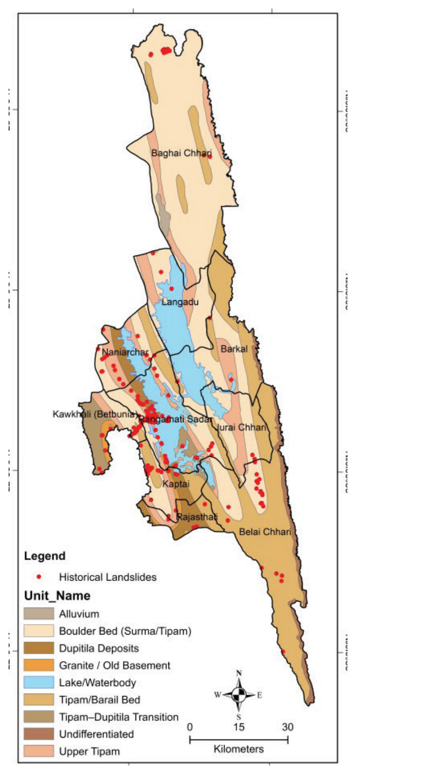

Figure 6: Geology and Historical Landslides of Rangamati District

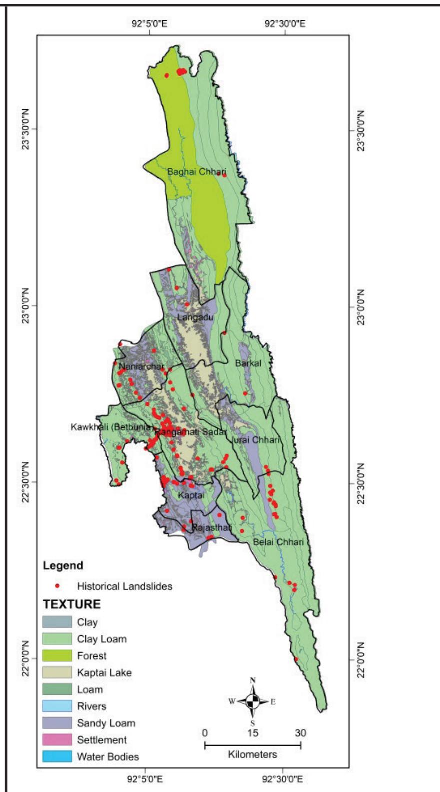

Figure 7: Soils and Historical Landslides of Rangamati District

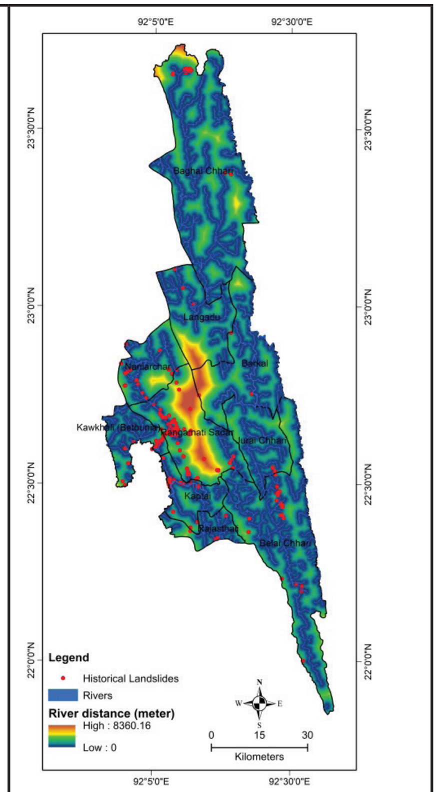

Figure 8: River Distance and Historical Landslides of Rangamati District

Soil Texture and Landslides: Soil texture also plays a key role in slope failure (Fig. 7). Clay Loam, which dominates 70.92% of landslide sites, is fine-textured with poor drainage, increasing pore water pressure during rainfall and triggering landslides. Sandy Loam accounts for 20.59%, and though better draining, it is prone to erosion and runoff on steep slopes. Loam soils (1.31%) and settlement areas (7.19%) also report minor landslide activity, often linked to human disturbances like deforestation and construction. These findings suggest that fine-grained soils, particularly clay loam, are highly vulnerable to landslides, especially when combined with rainfall and anthropogenic pressures.

Rangamati Historical Landslides and Proximity to Rivers: Approximately 30% of historical landslides occurred within 0–500 meters of rivers (Fig. 8), suggesting high risk near riverbanks due to erosion and slope weakening. Events within 500–1000 meters and 1000–5000 meters made up 22.04% and 29.28%, respectively. Only 5.59% occurred between 5000–10000 meters and 11.84% beyond 10,000 meters. The data highlight river proximity as a contributing factor to historical landslide distribution.

Rangamati Historical Landslides and Proximity to Roads: Historical landslide data in Rangamati reveal a strong association with road proximity (Fig. 9). About 45.07% of events occurred within 0–50 meters of roads, reflecting the impact of road construction and slope disturbance. Another 22.37% were within 50–500 meters. Fewer events were recorded 500–5000 meters (10.53%) and beyond 5000 meters (15.13%). These patterns indicate roads are a key anthropogenic factor in historical landslide occurrences.

Rangamati Historical Landslides Kernel Density: Kernel density analysis of historical landslides in Rangamati reveals clear clustering patterns (Fig. 10). The highest concentration (44.74%) occurred in areas with a kernel density of 0.1–0.2, followed by 35.53% in the 0.2–0.5 range. Low-density zones (0–0.1) accounted for 13.48%, while high-density areas (0.5–1.05) saw the fewest events (6.25%). This indicates that historical landslides tend to cluster in moderately dense zones rather than highly dense or sparse areas.

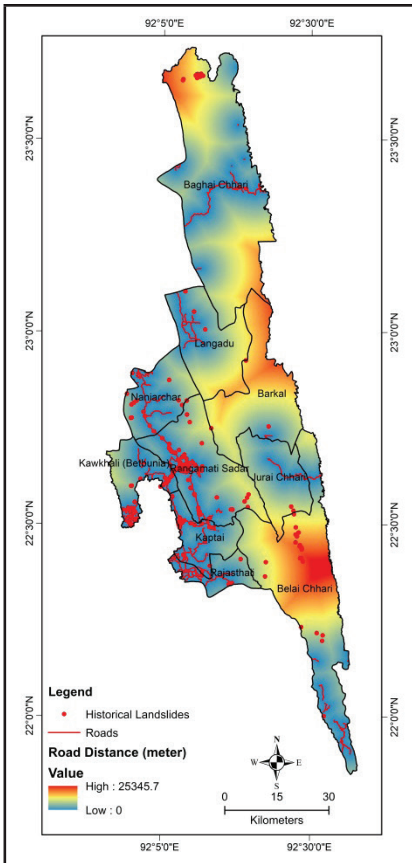

Figure 9: Road Distance and Historical Landslides in the Rangamati District

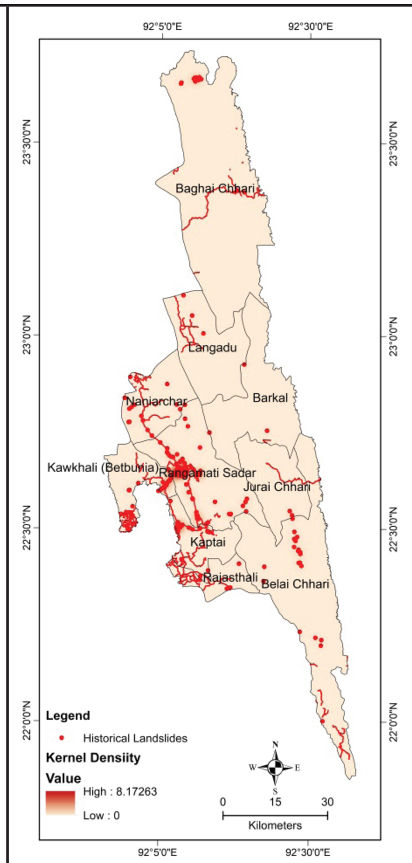

Figure 10: Kernel Density of Historical Landslides in the Rangamati District

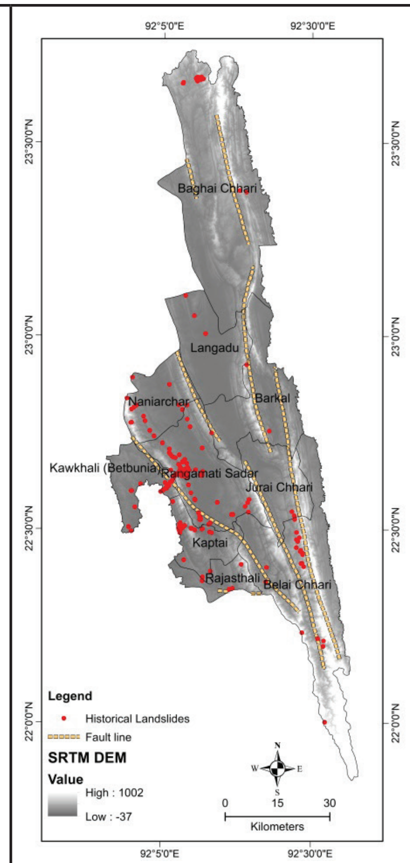

Figure 11: Fault Line and Historical Landslides in the Rangamati District

Rangamati Historical Landslides and Seismic Risk (Proximity to Fault Lines): Historical landslides in Rangamati show a strong link to seismic zones (Fig. 11). A majority (58.17%) occurred within 1000–5000 meters of fault lines, suggesting increased landslide susceptibility in these moderately proximal areas due to past seismic stress and slope weakening. Another 32.03% occurred within 5000–10000 meters. Very close proximity (0–1000 meters) had a low share (4.57%), possibly due to limited steep terrain near fault traces. Only 5.23% of events were found beyond 10,000 meters. These patterns highlight that historical landslides are more frequent in areas 1–5 km from active fault lines.

Historical Landslides and Land Use/Land Cover (LULC) Changes in Rangamati District: A Comparison Between 2016 and 2023 : Between 2016 and 2023, LULC changes in landslide-affected areas of Rangamati show a sharp decline in forest cover and a rise in human activity (Fig. 12 and Fig. 13). In 2016, 93.79% of historical landslides occurred in dense vegetation zones. By 2023, this dropped to 27.45%, while sparse vegetation areas rose from 4.90% to 64.05%, indicating widespread deforestation. Settlements increased from 0% to 3.27%, and bushland from 1.31% to 5.23%. These shifts highlight how forest loss and land conversion have increased slope vulnerability over time.

Normalized Difference Vegetation Index (NDVI) is a satellite-derived index used to assess plant and vegetation health using satellite imagery. Here NDVI analysis shows a significant decline in vegetation health at historical landslide sites. In 2016, 72.22% of events occurred in areas with high NDVI (>0.60), but by 2023, none were found in this range. Most 2023 events occurred in moderately vegetated areas (46.08% in NDVI 0.40–0.60 and 43.46% in 0.25–0.40). Low NDVI zones (0–0.25) increased from 1.63% to 10.46% (Fig. 14 and Fig. 15). This trend reflects growing vegetation loss, which contributes to increased landslide susceptibility.

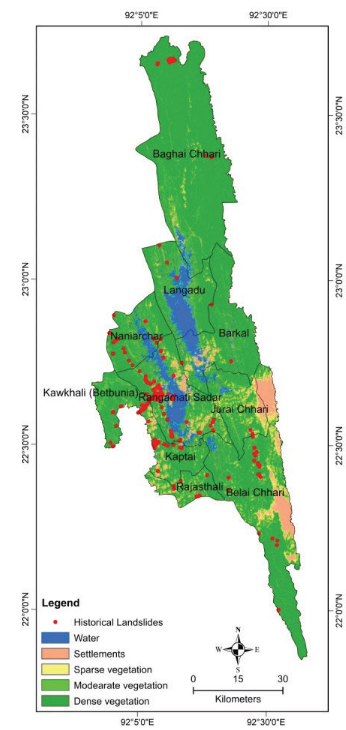

Figure 12: Land use and Historical Landslides in the Rangamati District, 2016

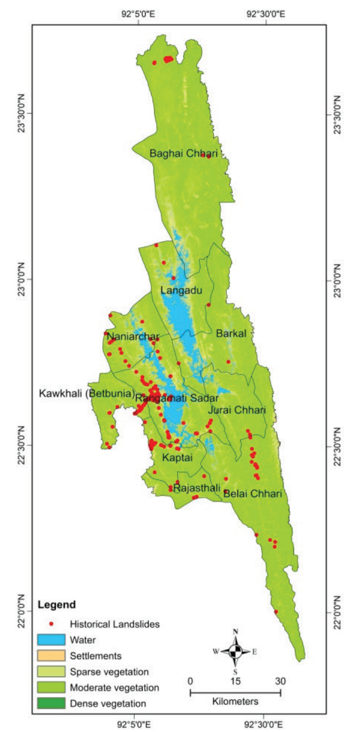

Figure 13: Land use and Historical Landslides in the Rangamati District, 2023

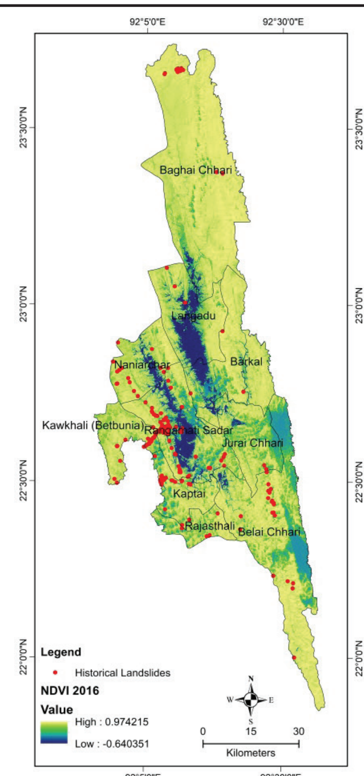

Figure 14: NDVI Values and Historical Landslides in the Rangamati District, 2016

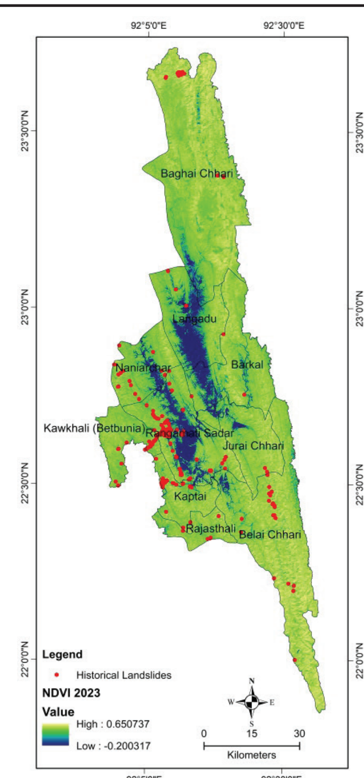

Figure 15: NDVI Values and Historical Landslides in the Rangamati District, 2023

Land use policy and governance mechanisms in the CHT are pivotal for addressing environmental degradation driven by Jhum cultivation, a traditional slash-and-burn practice that accelerates deforestation due to shortened fallow periods of 2–5 years, spurred by population growth and land scarcity (Nath et al., 2005). The CHT Regulation, 1900 (CHT Manual), governs land administration and recognizes customary rights but is outdated, with weak enforcement enabling illegal logging and land grabbing (Jashimuddin & Inoue, 2012). Similarly, the CHT Land Dispute Settlement Commission Act, 2001, aims to resolve land disputes but has limited progress, restricting secure land access for Jhum cultivators (Khan et al., 2007). The Forest Act, 1927, prohibits Jhum in reserved forests but fails to regulate unclassified state forests, where most Jhum occurs, due to inadequate monitoring (Jashimuddin & Inoue, 2012). The CHT Development Board promotes agroforestry as an alternative to Jhum, yet inconsistent implementation and poor community engagement limit its impact (Ahammad, R., et al., 2023). Key gaps include the lack of an integrated land use policy, unclear zoning, and exclusion of indigenous knowledge, such as Village Common Forests (VCFs) (Nath et al., 2005). To enhance sustainability, a CHT-specific policy should integrate sustainable Jhum and agroforestry, leveraging deforestation susceptibility maps to target high-risk zones. Clear land zoning based on soil and biodiversity data, strengthened enforcement via satellite monitoring and community patrols, and scaled-up alternatives like ecotourism can reduce reliance on Jhum. Incorporating indigenous knowledge and supporting VCFs will ensure culturally relevant solutions (Jashimuddin & Inoue, 2012). By aligning susceptibility maps with robust policies and collaborative governance, the CHT can balance ecological conservation with indigenous livelihoods.

Historical Landslides and Rainfall Distribution in the Rangamati District (1987–2017): Rainfall trends over three decades reveal a growing link between precipitation intensity and historical landslides in Rangamati (Fig. 16). From 1987–1997, 88.24% of landslides occurred in areas receiving 1751–1900 mm of rainfall. In 1997–2007, this shifted, with 92.16% of events in zones with 1901–2050 mm, indicating a rise in rainfall-triggered slope failures. Between 2007–2017, landslides became more dispersed: 50.65% in 1901–2050 mm, 36.60% in 1751–1900 mm, and 6.21% in 2051–2200 mm zones. These changes reflect increasing rainfall intensity and variability—likely driven by climate change—contributing to expanded landslide risk in moderately to highly wet regions (Fig. 16).

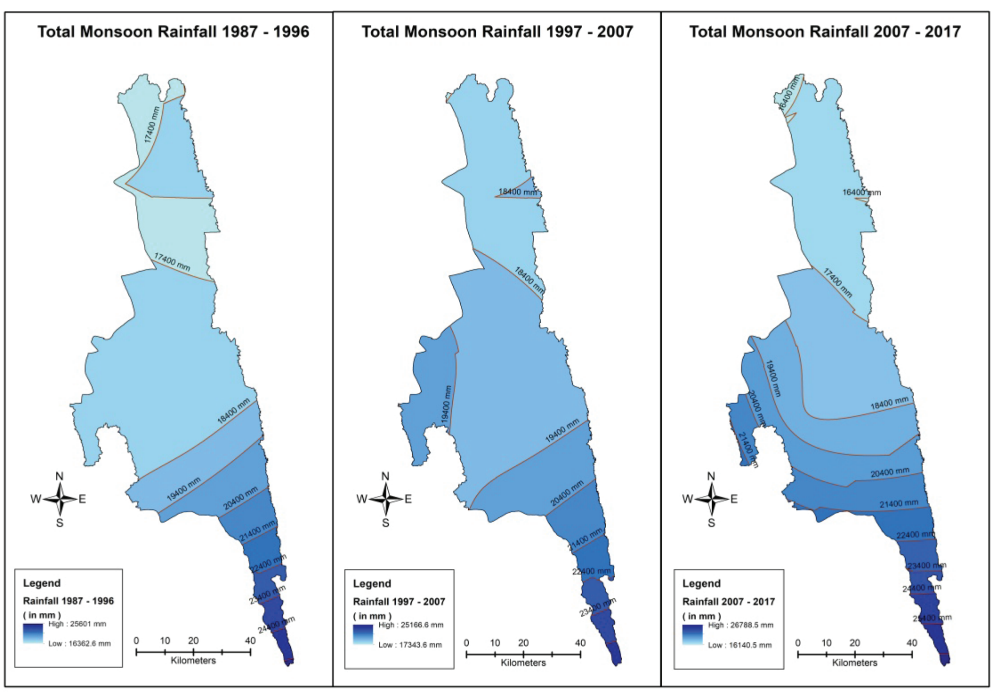

Figure 16: Rainfall Variability in Rangamati District

Potential Landslide Susceptibility in Rangamati District

The results of Rangamati district's potential landslide susceptibility are detailed in the following sections, classified on a scale ranging from 1 to 5, representing the Susceptibility Classes: No Susceptibility, Low Susceptibility, Medium Susceptibility, High Susceptibility, and Very-High Susceptibility (Table 1 and Fig. 17)

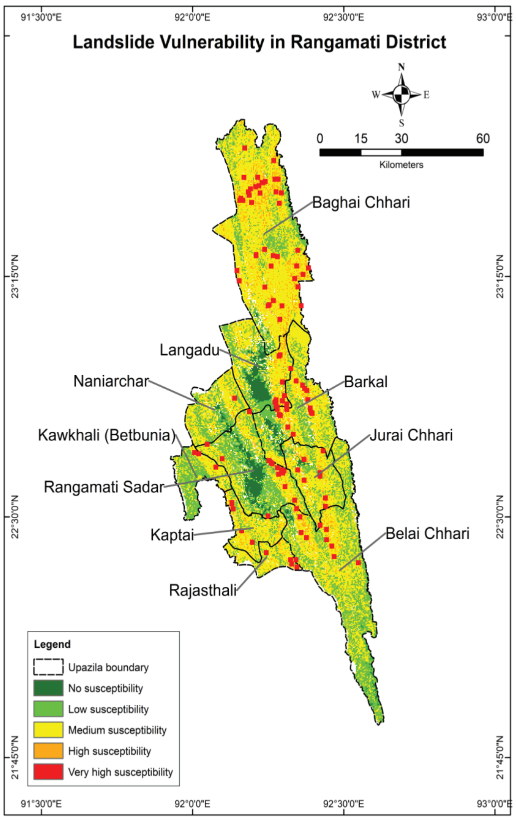

Figure 17: Landslide Susceptibility in Rangamati district of Chittagong Hill Tract, Bangladesh

In Rangamati District, the susceptibility assessment reveals a concerning landscape of landslide susceptibility across the region. A notable 4.51% of the district, equivalent to 24,081.67 hectares, is identified as having No Susceptibility to landslides. However, the largest portion of the district, 28%, encompassing 148,436.34 hectares, falls under the Low Susceptibility category. Even more alarming is the fact that a significant 57% of the district, amounting to 304,439.72 hectares, is classified as Medium Susceptibility, making it the most prevalent risk level. Additionally, 10.41% of the district, or 55,600.14 hectares, is at High Susceptibility to landslides, and a small but critical 0.29% of the district, totalling 1,562.90 hectares, is categorized as Very-High Susceptibility with 120 specific locations identified (Table 1). This data underscores the urgent need for targeted landslide risk assessments and mitigation strategies, particularly in the medium to high susceptibility areas, to enhance the safety and resilience of the district's communities and infrastructure.

Table 1*:* Distribution of Landslide Susceptibility Classes across Rangamati District

Susceptibility class	Risk area (in hectares)	Percentage
No susceptibility	24081.67	4.51
Low susceptibility	148436.34	27.79
Medium susceptibility	304439.72	57.00
High susceptibility	55600.14	10.41
Very-high susceptibility	1562.90	0.29

Given the high susceptibility to landslides in various areas of Rangamati District, particularly those identified as having Very-High Susceptibility (0.29%), it is crucial to implement immediate and effective measures to mitigate the risks and protect community safety. Landslides in these regions are primarily triggered by heavy rainfall, emphasizing the need for proactive actions such as the installation of rain gauges for early warning systems, continuous monitoring by local communities, and evacuation plans during rainfall events. These preventive measures are essential for reducing the impact of landslides and safeguarding both lives and property in the most vulnerable areas.

Table 2 illustrates the distribution of areas with very high landslide susceptibility in Rangamati District, showing substantial differences in vulnerability across various upazilas. Baghai Chhari stands out as the most vulnerable, with 35.83% (43 out of 120) of its land highly susceptible to landslides, underscoring the urgent need for focused mitigation strategies in this area. Barkal and Langadu follow, each contributing 12.50% (15 cases each), indicating significant landslide risks in these regions. Belai Chhari and Jurai Chhari exhibit moderate susceptibility, each accounting for 8.33% (10 cases), suggesting a relatively lower but still notable risk. Rangamati Sadar, the district's central region, also has a significant portion of land (11.67%, 14 cases) identified as highly susceptible, indicating that even urbanized areas face considerable landslide risks. On the other hand, upazilas such as Kaptai (4.17%), Rajasthali (3.33%), and Kawkhali (2.50%) show fewer areas of high susceptibility. Naniarchar is the least affected, with just 0.83% (1 case) of its area deemed highly vulnerable. These results highlight the uneven distribution of landslide risks across the district, with the highest risks concentrated in Baghai Chhari, Barkal, and Langadu, which require targeted disaster management and mitigation strategies.

Further analysis of the landslide susceptibility along with the causative factors shows that the gradual change in land use is a very important factor for landslides. Another strong correlation was found with settlements, meaning that areas near settlements experience higher levels of intervention, which increases vulnerability. In addition, excessive rainfall is a major contributing factor. Roads are also directly correlated with landslides, mainly due to land alteration and slope disturbance along road corridors.

The landslide model further indicates that most of the identified susceptible areas fall within livelihood zones characterized by low elevation and low slope gradients. Almost all landslides are likely to occur at elevations below 150 meters and on slopes up to 30 degrees. This suggests that areas under human intervention in the hilly region are particularly vulnerable to landslides.

Table 2: Very High Landslide Susceptibility in Rangamati District

Upazila Name	No of very high susceptibility	Percentage
Baghai Chhari	43	35.83
Barkal	15	12.50
Belai Chhari	10	8.33
Jurai Chhari	10	8.33
Kaptai	5	4.17
Kawkhali (Bet-bunia)	3	2.50
Langadu	15	12.50
Naniarchar	1	0.83
Rajasthali	4	3.33
Rangamati Sadar	14	11.67
Total	120	100.00

Upazila Level Landslide Susceptibility in Rangamati District

Rangamati District exhibits significant variation in landslide susceptibility across its Upazilas due to its unique geographical characteristics (Table 3 and Fig. 17). In Rangamati Sadar, 39.57% of the area shows low susceptibility, while 38.17% is moderately susceptible, 5.85% highly susceptible, and 0.33% very highly susceptible. Rajasthali has the highest proportion of medium susceptibility at 74.48%, followed by low susceptibility at 14.47%, high susceptibility at 10.69%, and very high at 0.36%. In Naniarchar, 53.72% is moderately susceptible, with 34.76% low, 7.82% high, and a minimal 0.04% very-high susceptibility. Langadu shows 45.40% medium susceptibility and 23.89% low, with 12.10% high and 0.40% very high. Kawkhali has the largest proportion of low susceptibility (51.64%), with 44.54% medium, 3.64% high, and 0.18% very-high susceptibility. Kaptai displays 66.10% medium susceptibility, 18.90% low, 14.29% high, and 0.27% very-high susceptibility. Jurai Chhari has 62.38% medium susceptibility, while Belai Chhari shows 52.69% medium susceptibility and 39.42% low. Barkal displays 57.64% medium susceptibility and 27.15% low, with 10.52% high and 0.33% very high. Baghai Chhari also shows a significant portion (57.64%) of medium susceptibility, with 14.49% low, 10.52% high, and 0.33% very-high susceptibility. Rajasthali exhibits the highest percentage of medium susceptibility, while Kawkhali and Kaptai also show considerable medium susceptibility levels. The most vulnerable areas are relatively few, with Rajasthali having the highest high susceptibility at 10.69%. Very-high susceptibility is minimal across all Upazilas, with Rajasthali and Kaptai having the highest at 0.36% and 0.27%, respectively. These variations emphasize the need for focused mitigation efforts, particularly in areas like Rajasthali and Kaptai, which are more prone to landslides.

Table 3: Upazila-wise Potential Landslide Susceptibility in the Rangamati District (in Percent)

Potential Landslide susceptibility	Upazila Name									
	Rangamati Sadar	Rajasthali	Naniarchar	Langadu	Kawkhali	Kaptai	Jurai Chhari	Belai Chhari	Barkal	Baghai Chhari
No susceptibility	16.07	0.00	3.66	18.22	0.00	0.44	2.06	1.62	4.36	0.37
Low susceptibility	39.57	14.47	34.76	23.89	51.64	18.90	23.52	39.42	27.15	14.49
Medium susceptibility	38.17	74.48	53.72	45.40	44.54	66.10	62.38	52.69	57.64	69.23
High susceptibility	5.85	10.69	7.82	12.10	3.64	14.29	11.67	6.15	10.52	15.52
Very-high susceptibility	0.33	0.36	0.04	0.40	0.18	0.27	0.38	0.13	0.33	0.40

DISCUSSION

The results of the study provide an explicit insight into landslide susceptibility in the Rangamati District of the Chittagong Hill Tracts. According to the results, a large portion of the landscape, about 67.7% is facing moderate to extreme risk (medium, high, and very high classes). At the areal level, 57% of the district falls under the moderate-risk class, 10.41% falls under the high-risk class, and only a small area (0.29%), but with 120 locations identified in the model has been classified as a very critical area that needs to be addressed immediately.

The spatial pattern of very high–risk areas varies across the Upazilas; all Upazilas are not equally vulnerable. A very high concentration is observed in Baghai Chhari Upazila, which covers about 35.83%. This Upazila is very critical because of high human intervention, soil texture, and slope gradient. The next Upazilas, Barkal and Langadu are facing high concentrations due to the high-weighted causative factors of steep slopes (about 10° to 30°), dominance of clay soil, a high rate of deforestation between 2016 and 2023, and other anthropogenic factors such as proximity to roads, rivers, and settlements, which have increased human intervention and contributed to the high concentration of landslide susceptibility. A strong association with road corridors was found in the analysis: about 45% of historical landslides occurred within 50 m of roads, and 67% were associated within a distance of 500 m.

The dominant influence of soil texture is very important in this regard; the factor was weighted 14.1 based on its influence, and slope gradient was assigned a 12.7% weight due to its historical impact. Another important factor is geology or sedimentary formations, such as the Boka Bil, Tipam, and Bhuban formations.

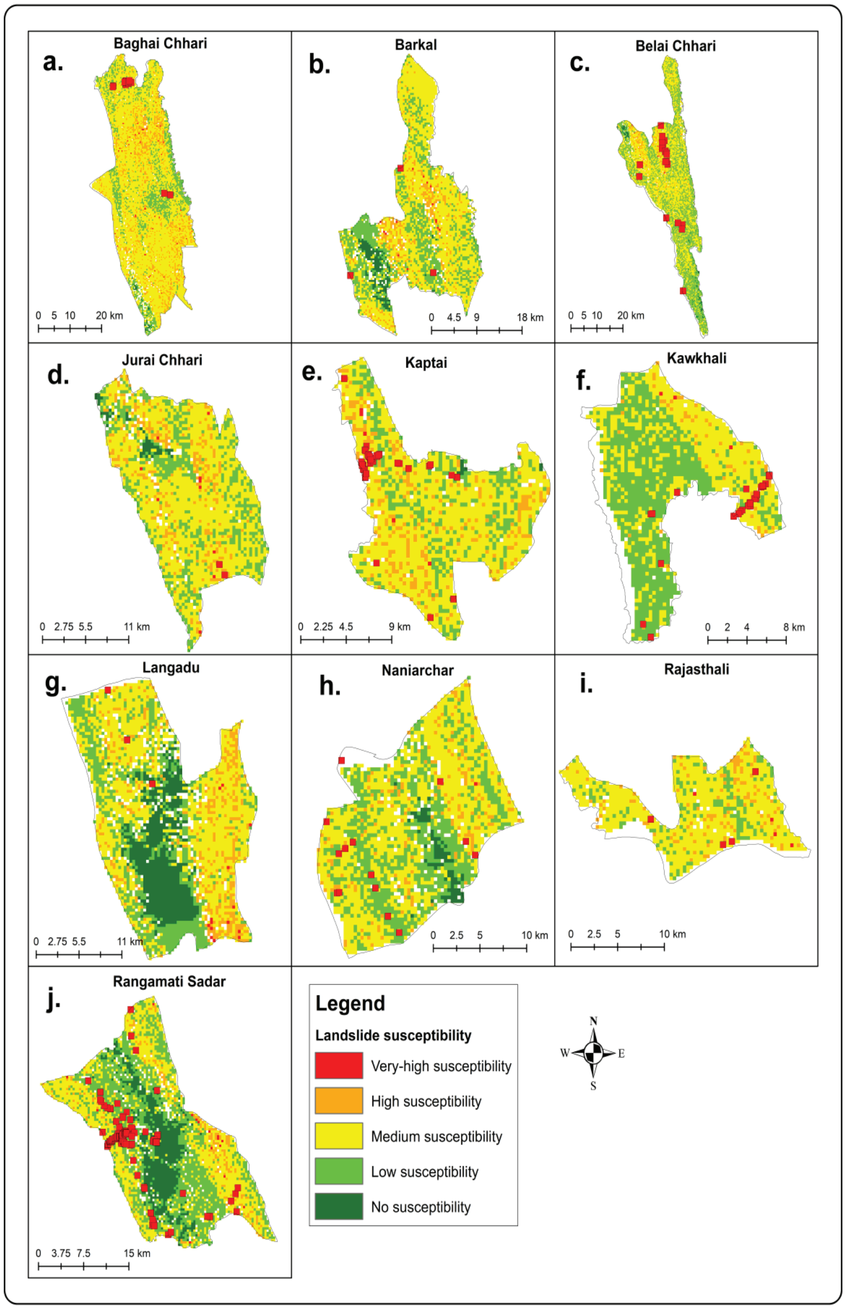

Figure 18: Upazila-wise Landslide Susceptibility a. Baghai Chhari b. Barkal c. Belai Chhari d. Jurai Chhari e. Kaptai f. Kawkhali g. Langadu h. Naniarchar i. Rajasthali j. Rangamati Sadar

Slope aspect is also significant, south and southwest-facing slopes account for about 48% of historical landslides.

Finally, the triggering factor rainfall is crucial because most disasters occur during the monsoon. Historical landslides occurred when total decadal rainfall was very high: about 1751–1900 mm during 1987–1997, and around 1901–2200 mm during the 2007–2017 decade, which increases pore pressure in clay-rich soils and contributes to slope failure.

From the methodological viewpoint, the combination of geospatial simulation, classification processes, and assigning the influence of factors is very rare. Based on the simulation results, a relative weight was assigned for the weighted overlay model, which is a relatively precise exercise. Furthermore, union-level validation provides another high level of precision. On the other hand, a total of 306 historical landslides is a relatively standard and reliable number to simulate factor influence and derive the final outcomes.

Overall, the results shift the narrative of landslides from being purely natural hazards to socioeconomically driven, human-modified, and almost human-induced hazards. Human interventions such as slope cutting, deforestation, and other landscape disturbances strongly establish this narrative. Without strict enforcement against slope cutting, proper regulatory measures, and strong penalties, along with large-scale afforestation and land use zoning, it will be difficult to protect landscape sustainability. Such measures are essential to achieving SDG 11 (resilient settlements) and SDG 15 (sustainable terrestrial ecosystems), as well as saving lives. Naturally, landscapes change every year. Some causative factors related to landslides remain constant, while others vary over time. Therefore, annual pre-monsoon modelling should be conducted to incorporate these dynamic factors into the assessment.

Implications for Mitigation and Risk Management

To mitigate landslide risks effectively, it is essential to adopt strategies that address both environmental and human factors. Reforestation and sustainable land-use practices should be prioritized to restore dense vegetation, stabilize slopes, and reduce soil erosion. Regulatory measures, such as zoning laws that restrict development in high-risk areas, especially those with slopes greater than 18°, are also vital to minimizing exposure to landslide hazards.

In addition, establishing early warning systems is crucial. These systems should integrate rainfall intensity, soil moisture levels, and seismic activity to forecast potential landslides. Such systems can provide early alerts, allowing for timely evacuations and preparedness actions. Community-based disaster preparedness programs are also essential, as they can educate local populations on best practices for landslide risk reduction and ensure that residents are well-equipped to respond to warnings.

SUMMARY AND CONCLUSIONS

Summary

The study's landslide susceptibility mapping, produced using medium-resolution (30 m) datasets, delivers highly relevant and policy-ready insights for Rangamati District in the Chittagong Hill Tracts. By detecting susceptibility at both macro (district) and micro (upazila) levels, and identifying 120 of the most high-risk locations, the study directly supports the government's key disaster management frameworks, including the Disaster Management Act 2012, the Standing Orders on Disaster (SOD) 2019, and the National Plan for Disaster Management (NPDM) 2021–2025. The susceptibility maps, ranging from Low to Extreme categories, provide District and Upazila Disaster Management Committees with essential evidence-based tools for preparing disaster management plans, enforcing land-use planning and zoning, regulating hill cutting, and strengthening early-warning systems.

The study also generates actionable insights from its modelling and geostatistical simulations that align with the institutional responsibilities of the Roads and Highways Department (RHD), Forest Department, Ministry of Disaster Management and Relief (MoDMR), Bangladesh Meteorological Department (BMD), Soil Research Development Institute (SRDI), Bangladesh Geological Survey (BGS), and others. Key findings, such as 10.7% of the district area being in High and Very High susceptibility zones, 67% of historical landslides occurring within 500 m of roads, and a 60% vegetation loss during the study period, clearly highlight the accountability of relevant authorities. These data-driven results provide a strong mandate for enforcing stricter regulations on slope modification, vegetation management, and coordinated actions to improve landslide early-warning systems.

Overall, this study fills long-standing policy gaps and offers a clear pathway for authorities to develop actionable plans. The upazila-specific susceptibility information can actively involve local communities in risk reduction. By bridging scientific evidence with community-level disaster management, the model provides a practical foundation for significantly reducing landslide risk on the ground.

CONCLUSIONS

This study successfully maps landslide susceptibility in Rangamati District at a fine spatial scale, offering critical insights for disaster risk management. With 0.29% of land classified as very-high risk and 120 critical locations identified, the findings highlight the compounded threats of geological fragility, monsoon rainfall, deforestation, and unplanned development. Baghai Chhari, Barkal, and Langadu stand out as the most vulnerable Upazilas. The dominance of clay loam soils, presence of weak rock formations, and moderate slopes significantly elevate susceptibility. The model's predictive performance (AUC 0.85) affirms its reliability for guiding interventions. To mitigate future risks, the study advocates for immediate integration of susceptibility data into building codes and land use decisions, reforestation efforts, and enhanced early warning systems. Incorporating indigenous knowledge and promoting agroforestry as a sustainable alternative to Jhum are also essential. These actions will strengthen local resilience in alignment with national disaster policies and global sustainable development targets.

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