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Geospatial mapping of terrain dynamics and rainfall patterns for hazard mitigation in Sikkim

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This paper presents a thorough examination of Sikkim's terrain characteristics, land usage, and geological aspects, focusing on its mountainous landscape in the Eastern Himalayas. The work employs an integrated approach that combines geospatial data and multidisciplinary methodologies, including slope analysis, aspect ratios, road buffer mapping, land use/land cover classification, and geological mapping, which aim to unravel the intricate dynamics that shape Sikkim's environment. The findings shed light on the considerable variation in terrain steepness, with the northern region characterized by steep to extremely steep slopes, contrasting with the more moderate slopes observed in the southern part, conducive to agriculture and settlements. Aspect ratios delineate a diverse array of slope orientations, influencing microclimates, vegetation distribution, and land use suitability. Road buffer mapping identifies areas susceptible to environmental disturbances from road infrastructure, emphasizing the need for conservation efforts. The land use/land cover analysis highlights the dominance of forested areas, indicating significant biodiversity and ecosystem services, alongside agricultural lands and urban settlements reflecting human activity. Geological mapping offers insights into the distribution of geological formations and rock types, crucial for assessing natural hazards and mineral resources. The integrated analysis underscores the importance of considering terrain features, land use patterns, and geological factors in environmental planning and sustainable development. By harnessing geospatial data and interdisciplinary methodologies, policymakers, planners, and stakeholders can make informed decisions to bolster resilience, mitigate hazards, and foster the well-being of communities and ecosystems in Sikkim amid the challenges posed by climate change and environmental degradation.

Keywords. Landscape analysis; geospatial data; geological mapping; climate change resilience.

1. Introduction

In the current era of rapid climate change, the vulnerability of mountainous regions to natural hazards, including landslides, has become increasingly pronounced. The Sikkim Himalayan region is prone to various geohazards, including landslides and earthquakes, which pose significant threats to human settlements, infrastructure, and ecosystems. Landslides are a recurring

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phenomenon in the region, often triggered by intense rainfall, seismic activity, and slope instability. Landslides pose a significant global threat and have caused $8 billion in losses, injured 4.8 million people, and resulted in 18,414 fatalities between 1998 and 2017 (Das *et al.* 2017). Developing nations are disproportionately affected, with 95% of reported landslides occurring in these countries (Chung and Fabbri 2005). In Asia alone, over 66 million people live in landslide-prone areas (Bui *et al.* 2019). India's Himalayan and north-eastern regions are particularly susceptible to landslides due to their topography (Sharma 2021). Factors influencing landslide distribution in the Lesser Himalayas include lithology, rainfall, local climate, and neotectonics activity (Gupta *et al.* 2023).

The complex geology, steep terrain, and climate change-induced alterations in precipitation patterns have exacerbated the landslide risk in Sikkim. Furthermore, the region's proximity to the active Himalayas fault system renders it susceptible to seismic hazards, with the potential for high-magnitude earthquakes. Recent seismic activities and landslides, like the 2011 earthquake and the severe flooding in 2015, have shown the urgency of understanding these risks. The 2011 earthquake has its epicentre near the Sikkim–Nepal border, caused extensive damage and highlighted the region's vulnerability to seismic hazards. Similarly, the 2015 floods, exacerbated by relaxed COVID-19 restrictions and an influx of migrants to the capital, exposed the fragility of Sikkim's infrastructure and the need for improved disaster preparedness and risk management strategies. The region is experiencing significant changes in precipitation patterns and accelerated melting of glaciers due to climate change, leading to increased instability in slopes and more frequent landslides. Sikkim, nestled amidst the towering peaks of the Eastern Himalayas, exemplifies this heightened susceptibility, where the interplay of geological fragility, intense precipitation, and evolving climatic patterns accentuates the risk of landslide occurrences (Mall *et al.* 2011). As climate change exacerbates environmental stressors, the importance of proactive measures, such as landslide zonation mapping, in assessing and mitigating landslide hazards in Sikkim has never been more critical (Dhungana *et al.* 2023). The impacts of climate change on Sikkim's landscape are multifaceted because rising temperatures lead to the accelerated melting of glaciers and permafrost, which alters the stability of slopes and triggers landslides (Ramya *et al.* 2023). Changes in precipitation patterns, characterized by more intense and erratic rainfall events, further destabilize the region's fragile terrain, increasing the frequency and magnitude of landslides (Dikshit *et al.* 2020). These dynamics not only pose immediate threats to human settlements, infrastructure, and livelihoods but also have cascading effects on ecosystems, water resources, and socioeconomic systems. In the face of these challenges, landslide zonation mapping emerges as a vital tool for understanding, predicting, and managing landslide risk in Sikkim. By integrating climatic data, geological surveys, remote sensing technologies, and spatial analysis techniques, landslide zonation mapping delineates areas of varying susceptibility to landslides, providing valuable insights for land use planning, disaster preparedness, and resilience-building efforts.

In recent years, the impact of climate change on vulnerable regions like Sikkim has become increasingly evident, with manifestations ranging from shifting weather patterns to the accelerated melting of glaciers and alterations in precipitation regimes (Das *et al.* 2009). Nestled in the heart of the Eastern Himalayas, Sikkim shares its borders with Bhutan to the east, Nepal to the west, and China's Tibet Autonomous Region to the north. The southern border of Sikkim adjoins the Indian state of West Bengal. The geographic extent of Sikkim covers an area of approximately 7,096 km^2, with a diverse and rugged terrain that ranges from subtropical foothills to alpine peaks. Sikkim is characterized by a mountainous terrain with significant variations in elevation and slope steepness. The northern part of the state, closer to the Himalayas, boasts extremely steep slopes, with elevations reaching up to 8,586 m at the summit of Mount Kangchenjunga, the third-highest peak in the world. The southern part of Sikkim, on the other hand, features more moderate slopes and is home to the Teesta River, which flows through the state and plays a crucial role in its hydrology. The central region exhibits a mix of steep and gentle slopes, creating a diverse topography that supports a variety of ecosystems and land uses.

Sikkim experiences a subtropical to temperate climate, with significant variations across its elevations. The climate is influenced by the South Asian monsoon season, which brings heavy rainfall from June to September. The average annual rainfall in Sikkim ranges from 1,500 to 3,000 mm, with the highest precipitation occurring in the southern and eastern parts of the state. Temperatures vary widely, with the northern high-altitude regions experiencing sub-zero temperatures in winter, while the southern foothills remain relatively warm. The region is also prone to erratic weather phenomena, such as landslides and flash floods, particularly during the monsoon season. Sikkim is home to a population of approximately 610,000 people, with a diverse ethnic composition that includes Nepalis, Bhutias, Lepchas, and other communities. The state's economy is primarily agrarian, with agriculture being a significant source of livelihood for the majority of the population. The cultivation of crops such as rice, maize, and potatoes is prevalent in the valleys and lower slopes and horticulture, particularly the cultivation of oranges, cardamom, and tea, is another important economic activity.

In Sikkim Himalaya, landslides are primarily caused by heavy rainfall, seismic activity, and human-made activities (Kuriakose 2009; Kumar *et al.* 2018). Ground penetrating radar has revealed subsurface conditions favourable for slope failure, exacerbated by road cuts in Sikkim's hilly areas (Kakkar *et al.* 2022). Rainfall thresholds for landslide early warning systems have been established for the region (Harilal *et al.* 2019). Seismic activity in the Eastern Himalayas is linked to collision tectonics and major thrust systems. The 2011 earthquake in Sikkim resulted in 360 new landslides (EERI Report, February 2012). Anthropogenic activities like road construction, mining, and deforestation also contribute to slope instability (Kumar and Gorai 2018; Nseka *et al.* 2019). A study on NH-10 in Sikkim revealed various types of slope failures due to road cuts (Dutta *et al.* 2023). Landslide Susceptibility Assessment Models (LSAM) have been developed to map highway routes for landslide risk. Various methods for assessing landslide susceptibility have been employed, including deterministic heuristic (Mondal *et al.* 2019), probabilistic (Saha *et al.* 2005; Kanungo *et al.* 2006), and machine learning techniques (Arora *et al.* 2004; Micheletti *et al.* 2014; Goetz *et al.* 2015; Kumar *et al.* 2017; Taalab *et al.* 2018; Luo *et al.* 2019). Satellite-based earth observation data has become crucial for data collection, monitoring, and damage assessment in landslide-prone areas.

This convergence of factors underscores the urgent need for comprehensive strategies to mitigate the heightened risks of landslides, which are exacerbated by the changing climate dynamics. Climate change-induced alterations in temperature and precipitation patterns have profound implications for the stability of Sikkim's slopes. With rising temperatures leading to the retreat of glaciers and thawing of permafrost, the structural integrity of mountainous landscapes is compromised, increasing the susceptibility to slope failures and landslides. Furthermore, the intensification of rainfall events, coupled with erratic weather phenomena, exacerbates soil erosion, slope instability, and landslide occurrences, amplifying the threats faced by communities, infrastructure, and ecosystems across the region.

The landslide-prone areas in India account for 12.6% of the total area, with the Darjeeling–Sikkim Himalaya region alone accounting for 43% (Martha *et al.* 2021). The northwest Himalaya covers about 33% of the region, followed by the western hill, Konkan Ghat, covering 22%, and the eastern hill, Aruku, covers 2%, as per data from the Geological Survey of India (https://www.gsi.gov.in). Landslides are a sort of mass movement that occurs when a huge volume of rocks and soils fall rapidly from upslope to downslope due to gravity. Effective disaster risk reduction strategies, including landslide and seismic hazard zonation mapping, are crucial for enhancing resilience and minimizing the adverse impacts of these geohazards on the region's communities and natural resources.

The unique features and challenges specific to the Sikkim region, including its mountainous terrain, complex geology, climate change impacts, proximity to active fault lines, high rainfall, and human activities, make it particularly susceptible to landslides. The role of landslide zonation mapping emerges as a crucial component of proactive risk management strategies tailored to the current climate change scenario in Sikkim. By harnessing advanced geospatial technologies, geological expertise, and interdisciplinary approaches, landslide zonation mapping offers a systematic framework for assessing, classifying, and prioritizing areas at risk of landslides (Xu *et al.* 2012). By integrating climatic data, terrain analysis, land cover assessments, and historical landslide records, this approach enables stakeholders to identify vulnerable zones, understand the underlying factors driving landslide susceptibility, and implement targeted mitigation measures (Dai *et al.* 2019). Moreover, landslide zonation mapping serves as a valuable decision support tool for informed land use planning, infrastructure development, and disaster preparedness initiatives in

Sikkim (Kavzoglu *et al.* 2014). By delineating areas of high, moderate, and low landslide susceptibility, policymakers, urban planners, and community stakeholders can allocate resources effectively, establish zoning regulations, and implement mitigation measures tailored to the specific needs and vulnerabilities of each region (Koley *et al.* 2023). This proactive approach not only enhances the resilience of Sikkim's communities and infrastructure but also fosters sustainable development practices that prioritize environmental conservation and risk reduction in the face of climate uncertainty. In light of the escalating challenges posed by climate change, this paper aims to explore the significance of landslide zonation mapping as a critical component of adaptive risk management strategies in Sikkim. Drawing upon empirical research, case studies, and best practices, this study seeks to elucidate the synergies between climate adaptation and landslide risk reduction efforts, with a focus on enhancing resilience, promoting sustainable development, and safeguarding the well-being of Sikkim's inhabitants amidst a rapidly changing climate. This paper aims to explore the significance of landslide zonation mapping in the context of climate change in Sikkim, drawing upon empirical evidence, case studies, and scholarly literature to underscore its relevance and efficacy in addressing the evolving landslide risk landscape. While previous studies have examined landslide susceptibility in Sikkim, this study employs a novel integrated approach that combines multiple geospatial datasets, rainfall datasets, and analytical techniques to provide a comprehensive assessment of terrain dynamics, land use patterns, and geological factors influencing landslide risk. By leveraging remote sensing data, GIS analysis, and interdisciplinary methodologies, this research offers a holistic understanding of the complex interaction between environmental factors and landslide occurrences in Sikkim. The primary objective of this research is to conduct an integrated geospatial analysis of Sikkim's terrain, land use, geology, and climate patterns to assess geohazard potential, particularly landslides and floods, to develop disaster risk reduction strategies.

2. Material and methods

The study focused on assessing the causative factors influencing landslides in the high-risk region of Sikkim, employing a multidisciplinary approach supported by various remote sensing datasets within the GIS platform. The analysis encompassed six key factors known to impact landslides: geology, topography, geomorphology, hydrology, land use/land cover, and ground conditions (streams and roads). The datasets used for this study and their sources are detailed in table 1. It is important to note that the geospatial resource layers and datasets used in this study, including satellite imagery, digital elevation models, geological maps, and land use/land cover data, were collected from various open-source platforms and repositories. These open-source data sources are widely used and accepted in the scientific community for research and analysis purposes. While the data itself has been presented and analysed in this study, the sources have been properly cited and acknowledged to ensure transparency and reproducibility. The study employed Arc-GIS platform to analyse various causative elements contributing to the heightened landslide risk in Sikkim. To facilitate mapping, all input data were transformed into a raster format. The research aimed to investigate the underlying causes of landslides in Sikkim using a multidisciplinary approach. Based on the literature review, causal elements such as geology, slope morphology, soil, moisture content, rainfall, and ground conditions were identified. Additionally, factors like stream buffer, road buffer, and land use/land cover were considered. Various datasets, including satellite imagery and geological maps, were collected from reputable sources such as the ESRI platform and remote sensing platforms like Landsat and Sentinel. Additionally, the India Meteorological Department (IMD) gridded dataset has been considered for yearly rainfall analysis of monsoon and post-monsoon seasons from 2012 to 2021. Sentinel-2 data was chosen for its high spatial resolution (10 m) and its open accessibility, which allows for comprehensive land use/land cover (LULC) mapping. This resolution is critical for accurately identifying and classifying different land cover types, such as forested areas, agricultural lands, and urban settlements, which are essential for understanding the environmental dynamics of Sikkim. The high-resolution imagery enables detailed analysis of land cover patterns, which is crucial for assessing the impact of human activities and natural processes on the landscape. The open accessibility of Sentinel-2 data ensures reproducibility and allows for integration with other datasets. Geological data from the US Geological Survey (USGS) World Geological Map was

Table 1. *Data used in the present study.*

Data	Availability of data and source	Parameter map	Resolution	Time-period	Pre-processing
Sentinel-2	The data supporting this study's findings are openly available in the European Space Agency (ESA) at https://www.esa.int.	(Land use/land cover) LULC map	10 m	2015–2021	Data was processed to remove cloud cover, and a supervised classification method was used to categorize land cover types.
Geological data	The data supporting this study was openly available in the USGS WorldGeological Map http://www.usgs.gov/	Geology map	1:250,000	N/A	Data was digitized and georeferenced to align with other datasets.
DEM (Digital Elevation Model) Sentinal-2	Data available openly	Slope, aspect, hill shade	10 m	2015–2021	Data was processed to generate slope and aspect maps
Road (Digital Chart of the World)	Data is available openly at https://www.diva-gis.org/	Road buffer map	1:1,000,000	2015–2021	Buffer zones were created around road networks to assess potential environmental disturbances
Streams	Data are available openly at https://www.hydrosheds.org/	Stream buffer map	30 m	2015–2021	Buffer zones were created around water bodies to assess potential flooding and erosion

selected for study on geological formations and rock types in Sikkim. This dataset is essential for understanding the geological structure and assessing the potential for geohazards, such as landslides and earthquakes. The detailed geological mapping provides a foundation for analysing the distribution of different rock types and geological formations, which are critical factors in determining landslide susceptibility. The DEM data derived from Sentinel-2 imagery was chosen for its high resolution (10 m) and its ability to provide detailed terrain information. This includes slope and aspect analysis, which are key factors in assessing landslide risks. The high-resolution DEM enables precise calculation of slope steepness and aspect ratios, critical for understanding terrain characteristics and their impact on landslide susceptibility. The integration of DEM data with other datasets allows for a comprehensive analysis of terrain dynamics. The road data from the Digital Chart of the World is crucial for assessing the impact of road infrastructure on the environment and for planning conservation efforts. This is essential for understanding the indirect effects of road networks on both human communities and natural ecosystems. The stream data from the HydroSHEDS platform is utilised for understanding hydrological dynamics and assessing the potential for flooding and erosion. The dataset's high resolution (30 m) allows for the creation of stream buffer zones and the analysis of hydrological processes. This is essential for assessing the impact of water bodies on the landscape and for implementing flood control measures.

This study adopts an innovative multidisciplinary approach by integrating diverse geospatial datasets and analytical techniques within a GIS framework. The combination of remote sensing data, geological surveys, terrain analysis, land use/land cover classification, hydrological mapping, and rainfall data visualization of the recent decade provides a comprehensive understanding of the factors influencing landslide susceptibility in Sikkim. The integration of these datasets and analytical methods represents a unique contribution to the field of landslide risk assessment and environmental planning in mountainous regions and addresses the geohazard risks in Sikkim, especially landslides and earthquakes. The geological map (figure 1) and terrain analysis, including slope, aspect, and stream buffer maps (figure 2), provide insights into the vulnerability of different areas to landslides, hence enabling the identification of high-risk zones. For seismic hazard

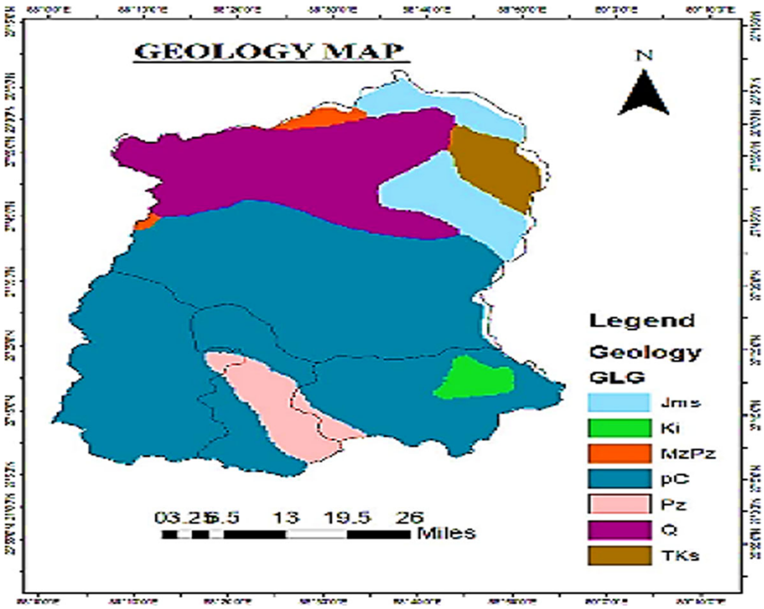

Figure 1. Geology map showing the mineral distribution over the Sikkim region. The map uses colour-coding to indicate various geological units: Possibly Jurassic to Mississippian sedimentary rocks (Jms, green), Possibly Cretaceous intrusive rocks (Ki, red), Possibly Mesozoic to Paleozoic undifferentiated rocks (MzPz, orange), Possibly Precambrian rocks (pC, purple), Possibly Paleozoic rocks (Pz, blue), Quaternary deposits (Q, yellow), and Possibly Tertiary to Cretaceous sedimentary rocks (TKs, brown).

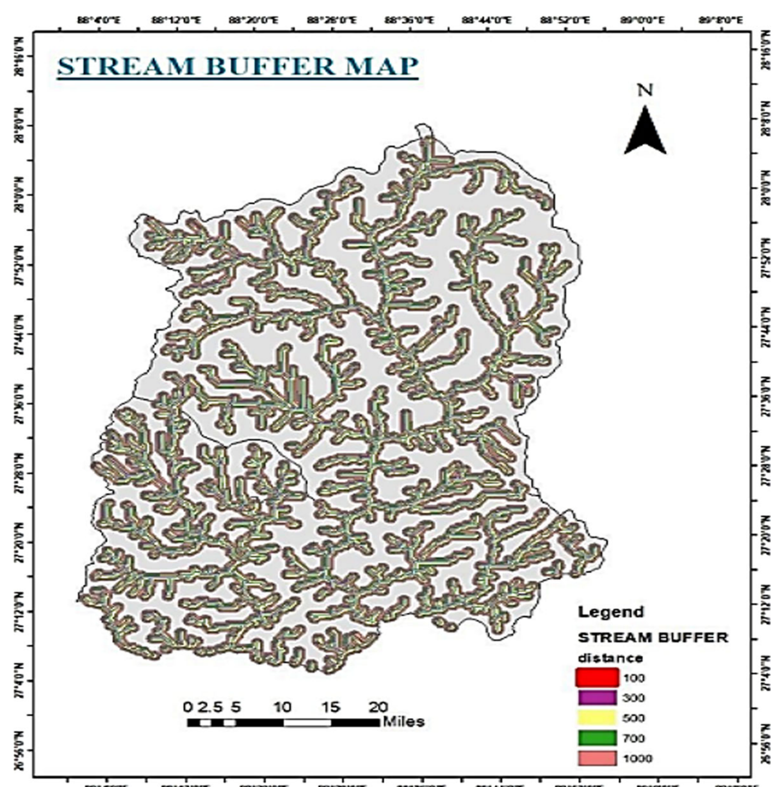

Figure 2. Stream buffer map of the study area. The map shows the main water bodies and streams in Sikkim, with buffer zones extending outwards from the centreline of each water body.

assessment purposes, fault lines' data, historical earthquake records as well as ground motion parameters are examined within a GIS framework to delineate different levels of seismic risk across the region. However, the land use/land cover classification relies on supervised methods, which may have errors due to the quality of training data and the complexity of land cover types. Those datasets which are related to geological formations and historical landslide events, may have limitations in terms of completeness and accuracy but efforts have been made to compile and validate comprehensive datasets through remote sensing techniques.

3. Result and discussion

Figure 3 shows the colour-coded representation of different slope values, which are measured in degrees and indicate the steepness of the terrain. Slopes which are less than or equal to 0 degrees indicate flat terrain, and 0–15°, 15°–25°, 25°–35°, 35°–45°, and 45°–55° represent gentle, moderate, steep, very steep, and extremely steep slopes respectively (USGS, 2020). The map exhibits a significant variation in terrain steepness across Sikkim. The northern part of Sikkim, which is closer to the Himalayas, has a higher concentration of brown and yellow areas, indicating extremely steep and very steep slopes. This suggests a mountainous and rugged terrain, which is typical for regions close to the Great Himalayan Mountain range. The southern part of Sikkim, in contrast, has more areas indicating more moderate and gentle slopes. This could imply that the southern region has more accessible terrain, which might be more suitable for agriculture, settlements, and infrastructure development. The central region shows a mix of all colours, suggesting a diverse topography with a range of slope steepness. Quantitative analysis (table 2) of the slope maps reveals that approximately 32.3% of Sikkim's terrain falls under the category of steep slopes, primarily concentrated in the northern region. The southern part, with about 47.8% of the land classified as moderate to gentle slopes, is more conducive to agriculture and human settlements, although it still requires careful land management to prevent soil erosion and landslides. The remaining 20% presents a mix of challenges for development and challenges for infrastructure planning due to the varying extreme steepness of the slope. This could present challenges for development and transportation but also opportunities for various ecosystems and biodiversity. The steepness of slopes is a critical factor in land use planning, as it affects soil erosion rates, suitability for construction, agricultural potential, and risk of natural disasters like landslides. The map indicates that careful planning is needed to manage the natural resources and mitigate potential hazards, especially in the northern mountainous regions.

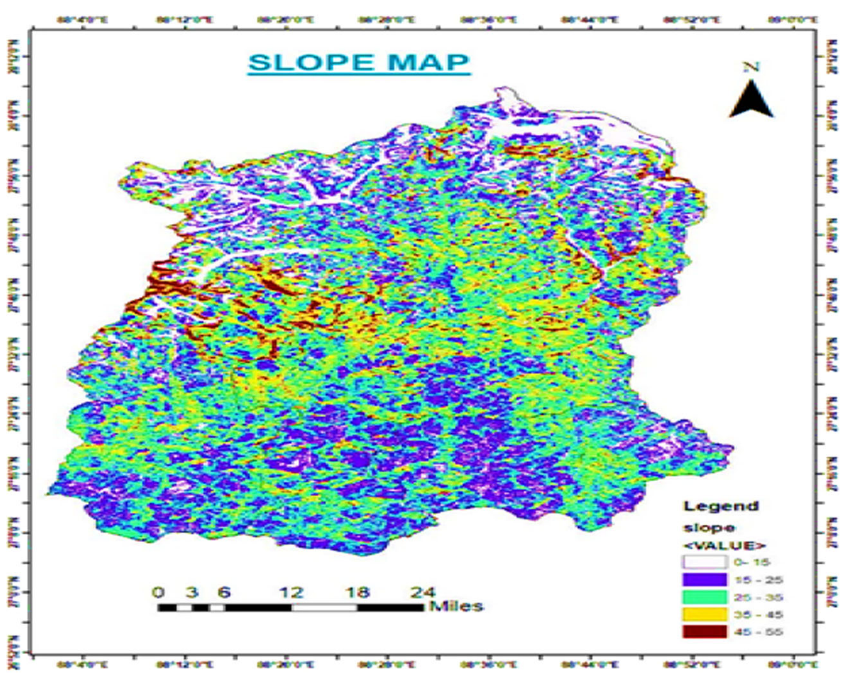

Figure 3. Slope map of Sikkim which represents the lowest slope value in white colour and brown colour with extremely steep slopes in degree. The slope map of Sikkim illustrates the variation in terrain steepness across the region. The map employs a colour-coded scheme to represent different slope categories: flat terrain (white), gentle slopes (0–15°, green), moderate slopes (15°–25°, yellow), steep slopes (25°–35°, orange), very steep slopes (35°–45°, red), and extremely steep slopes (45°–55°, brown).

Climate change can lead to more intense and frequent rainfall events. In areas with steep slopes, there is an increased risk of landslides and soil erosion, as the water may not be absorbed quickly enough by the soil, leading to runoff that destabilizes slopes. Sikkim is in the Himalayan region, where glaciers are sensitive to rising temperatures. Accelerated glacial melt can lead to the formation of glacial lakes, which can burst and cause flash floods (glacial lake outburst floods or GLOFs) downstream, affecting steep slopes. As temperatures rise, vegetation zones may shift, which can affect the stability of slopes. Vegetation typically helps to anchor soil and reduce erosion, so changes in vegetation can alter the risk of landslides. The slope map can be used to identify areas that are at higher risk of landslides and erosion. This information is crucial for disaster risk reduction strategies, including where to focus mitigation efforts like slope stabilization, drainage improvements, and reforestation. Understanding the topography is essential for the safe design and construction of infrastructure. Roads, buildings, and other structures need to be designed with consideration for the slope to ensure stability and reduce the risk of collapse or damage.

Aspects significantly influence microclimates within a region, affecting factors such as sunlight exposure, wind patterns, and moisture retention, which in turn can impact vegetation, wildlife habitats, and the potential for certain types of land use. The map shows a diverse distribution of aspects throughout Sikkim. There is no dominant aspect, which suggests a complex terrain with a variety of slope orientations. The area-wise percentage cover of the aspect is almost similar which is depicted in table 3. The central and northern regions show a varied aspect and, thus, a potential diversity in microclimates and ecosystems. North-facing slopes (red) in the Northern Hemisphere tend to be cooler and moist than south-facing slopes because they receive less direct solar radiation (Holland and Steyn 1975; Finney *et al.* 2004). However, this aspect–moisture relationship can also be influenced by other factors such as precipitation patterns, vegetation cover, soil characteristics, and local topographic effects (Pardos *et al.* 2003; Rocha *et al.* 2022). They may have different vegetation and are more likely to retain snow in the winter. South-facing slopes (green) receive more sunlight, making them warmer and drier, which can influence the types of vegetation that grow there and can be more prone to soil dryness and erosion. East-facing slopes (yellow) receive sunlight in the morning and are cooler in the afternoon, while west-facing slopes (blue) are shaded in the morning and receive sunlight in the afternoon. This can affect daily temperature fluctuations and moisture conditions. Aspect is an important factor in agriculture, as it determines the amount of sunlight and moisture crops receive. Farmers may choose different crops for different aspects to optimize growth conditions. South-facing slopes might be preferred for certain types of agriculture that require more sunlight, while north-facing slopes might be better for crops that require cooler conditions. The variety of aspects indicated on the map suggests that Sikkim likely has a rich diversity of habitats and ecosystems, supporting a wide range of flora and fauna. South-facing slopes have a higher potential for solar energy generation due to greater sunlight exposure. This aspect map helps identify suitable locations for solar panels.

A road buffer map is used to visualize the impact zones around roads, which can be important for environmental planning, urban development, and assessing the influence of road networks on surrounding areas. The map shows the main roads in Sikkim, with buffer zones extending outwards from the centreline of each road. The buffers indicate areas that may be affected by the road, such as noise pollution, visual impact, and ecological disturbances. The buffer zones can help identify areas where environmental protection measures are needed to mitigate the impact of roads on wildlife and natural habitats. The buffers can be used to plan wildlife corridors that allow animals to safely cross roads, reducing roadkill and habitat fragmentation. By understanding the extent of road influence, measures can be taken to preserve ecosystem services like water purification and pollination. The road buffer map of Sikkim is a strategic tool for assessing the impact of roads on the environment and for guiding development and conservation efforts. It highlights the need for careful planning to balance infrastructure needs with environmental protection and safety considerations. The map also underscores the importance of considering the indirect effects of road networks on both human communities and natural ecosystems.

This LULC map is crucial for understanding how land is being utilized and the distribution of various natural and man-made features within a region. Table 4 shows the vegetation cover details. The map shows a larger portion of green areas,

Table 2. *Showing the area-wise percentage cover of the slope.*

Sl. no.	Degree of slope	Represented colour	Area (km^2)	Percentage
1	0–15	White	1277	17.9
2	15–25	Blue	2105	29.7
3	25–35	Green	2290	32.3
4	35–45	Yellow	1098	15.5
5	45–55	Brown	249	3.5
6	>55	Not categorised	77	1.09

Table 3. *Showing the area-wise percentage cover of the aspect.*

Sl. no.	Value	Colour	Area (km^2)	Percentage
1	North	Red	1620	22.9
2	East	Yellow	1948	27.5
3	South	Green	1915	26.9
4	West	Blue	1613	22.7

indicating that a large portion of Sikkim is covered by forested areas or trees. There are patches of pink, particularly in the southern regions, which represent agricultural lands where crops are grown. Black-coloured areas represent built-up areas and are scattered throughout the map but are more concentrated in certain locations, likely indicating towns or cities. The presence of white areas, especially in the northern part of the map, suggests snow or ice cover, which is consistent with the higher elevations of the Himalayan region. Light grey areas could be clouds, which means that some land cover information might be missing or obscured in these regions. The dominance of forested areas suggests that Sikkim has a rich natural environment with potentially high biodiversity. The agricultural lands indicate areas of human activity and land cultivation, which are important for the local economy and food production. The built-up areas show human settlements and urbanization, which could be associated with infrastructure, services, and economic centres. Planners can use the map to identify areas suitable for development while minimizing environmental impact. The distribution of crops can guide agricultural policies and the implementation of sustainable farming practices. Understanding the distribution of snow and ice cover is important for monitoring the effects of climate change, as these areas are sensitive to temperature changes. The map can help in assessing vulnerability to natural disasters, such as floods, landslides, and soil erosion, by showing the distribution of different land cover types.

The geology map is used to represent the distribution of different geological formations and rock types in a region. It is a critical tool for understanding the geological history, mineral resources, and potential geohazards of an area. The colour schemes define Jms, Ki, MzPz, pC, Pz, Q, and TKs as possibly Jurassic to Mississippian sedimentary rocks, possibly Cretaceous intrusive rocks, possibly Mesozoic to Palaeozoic undifferentiated rocks, possibly Precambrian rocks, possibly Palaeozoic rocks, Quaternary deposits, and possibly Tertiary to Cretaceous sedimentary rocks, respectively. The map shows a variety of geological units, indicating a complex geological history for Sikkim. The presence of Precambrian rocks (pC) suggests that some of the oldest rocks on Earth are found in this region, which could be important for understanding the early history of the continent. Geological analysis (table 5) reveals that approximately 57% of Sikkim's area is underlain by Precambrian rocks, which are known for their stability and resistance to weathering. However, the presence of Quaternary deposits (Q), which account for about 17% of the geological units, indicates areas more prone to landslides due to their looser and less consolidated nature. These deposits are particularly susceptible to slope failures, especially in the context of increased rainfall and seismic activity. The geological map indicates that the northern and central regions of Sikkim have a higher concentration of Quaternary deposits, which coincide with the areas that have experienced the most frequent landslides in the past decade. Different geological formations can be associated with

Table 4. *Showing the area-wise percentage cover of the vegetation cover.*

Sl. no.	Value	Colour	Area (km^2)	Percentage
1	Water	Blue	39.8	0.56
2	Tree	Green	3227	45.6
3	Crop	Pink	0.07	0.01
4	Build-up area	Black	1.2	0.02
5	Snow/ice	White	22.58	0.31
7	Grassland	Lime	1027	14.5
8	Barren land	Purple	60.9	0.86
9	Valley	Brown	1747.3	24.7

Table 5. *Showing the area-wise percentage cover of the Geological Classification.*

Sl. no.	Value	Colour	Area (km^2)	Percentage
1	Jms (Jurassic metamorphic and sedimentary rocks)	Light blue	514	7
2	Tks (tertiary and cretaceous igneous and metamorphic rocks)	Brown	226	3
3	Q (quaternary sediments)	Purple	1213	17
4	Pz (undivided Palaeozoic rocks	Pink	326	5
5	Pc (undivided Precambrian rocks)	Dark blue	4078	57
6	Ki (cretaceous igneous rocks)	Green	107	2
7	MzPz (Mesozoic and Palaeozoic rocks	Orange	65	1

specific mineral resources. For example, intrusive rocks (Ki) might host valuable minerals such as precious metals or rare earth elements.

Understanding the geology is essential for assessing natural hazards such as earthquakes, landslides, and soil erosion. For instance, Quaternary deposits (Q) might be more prone to landslides due to their typically looser and less consolidated nature. The geology of an area affects groundwater flow and storage. For example, sedimentary rocks (TKs) may contain aquifers that are important for water supply. The geology map of Sikkim provides valuable insights into the region's geological composition and history. It is a fundamental tool for mineral exploration, assessing geohazards, land use planning, and managing water resources. The diversity of geological units depicted on the map reflects the complex tectonic processes that have shaped the region over millions of years. Understanding the geology is crucial for sustainable development and risk management in Sikkim.

Figure 3, illustrating the slope distribution across Sikkim, reveals a landscape characterized by significant variation in steepness. The northern region, closer to the Himalayas, exhibits predominantly steep to extremely steep slopes, typical of mountainous terrain. Conversely, the southern part displays more moderate slopes, suggesting areas suitable for agriculture and human settlements. This variability underscores the importance of slope considerations in land use planning and disaster risk management, particularly in mitigating landslide risks and soil erosion. A total of 60% of the landslide events recorded in the past decade occurred in areas with slopes greater than 35 degrees. This data highlights the critical role of slope steepness in landslide susceptibility and the need for targeted interventions in steep terrain areas to reduce the risk of landslides. Figure 4, depicting aspect ratios, highlights the diverse slope orientations throughout Sikkim. The varied aspect distribution influences microclimates, vegetation patterns, and agricultural practices. North-facing slopes tend to be cooler and moist, while south-facing slopes receive more sunlight and are warmer, impacting vegetation growth and land use suitability. Understanding aspect ratios is essential for optimizing land use practices and renewable energy planning, considering factors such as solar exposure and moisture retention. Figure 5, presenting road buffer zones, delineates areas potentially affected by road infrastructure, emphasizing the need for environmental planning and conservation measures. Buffer zones (figure 2) help identify areas vulnerable to ecological disturbances and habitat fragmentation, guiding efforts to minimize the environmental impact of roads and

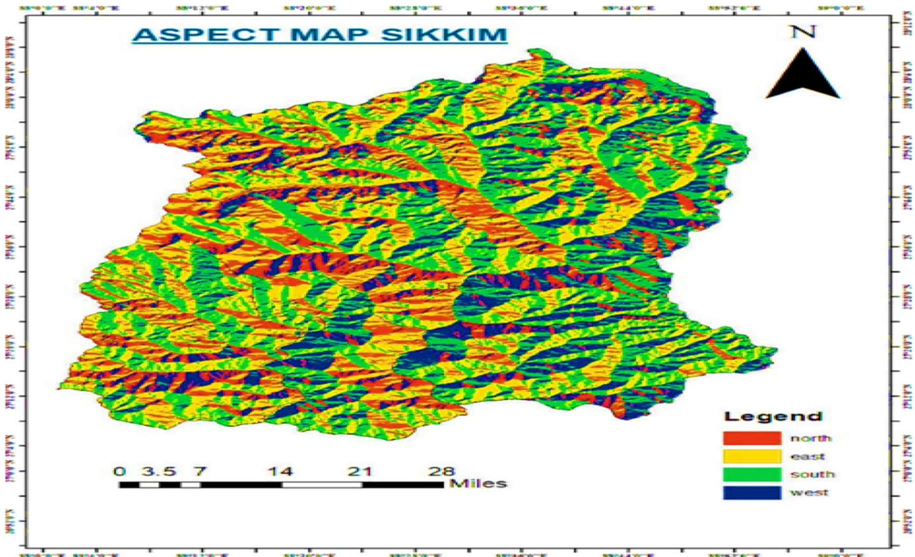

Figure 4. Aspect ratio of Sikkim in which red colour shows north, yellow shows east, and green and blue represent westward orientation of terrain surfaces. The aspect ratio map of Sikkim depicts the diverse orientations of slopes across the region. The map uses colour-coding to represent different aspects: north-facing slopes (red), east-facing slopes (yellow), south-facing slopes (green), and west-facing slopes (blue).

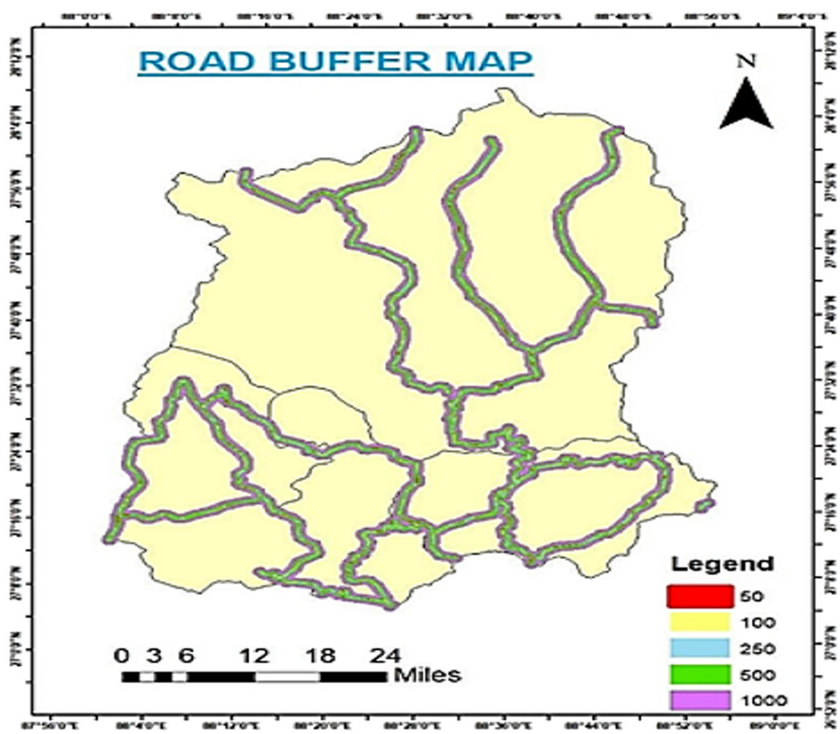

Figure 5. Showing road buffer map. The map shows the main roads in Sikkim, with buffer zones extending outwards from the centreline of each road.

infrastructure development. Figure 6, the land use/land cover map, provides valuable insights into the distribution of natural and anthropogenic features across Sikkim. Forested areas dominate the landscape, indicating rich biodiversity and ecosystem services. Agricultural lands and urban settlements reflect human activity and development patterns, necessitating sustainable land use planning to balance economic growth with environmental conservation. Figure 1, the geology map, offers critical information on the distribution of geological formations and rock types, influencing natural hazards and mineral resources. Understanding the geological composition is essential for

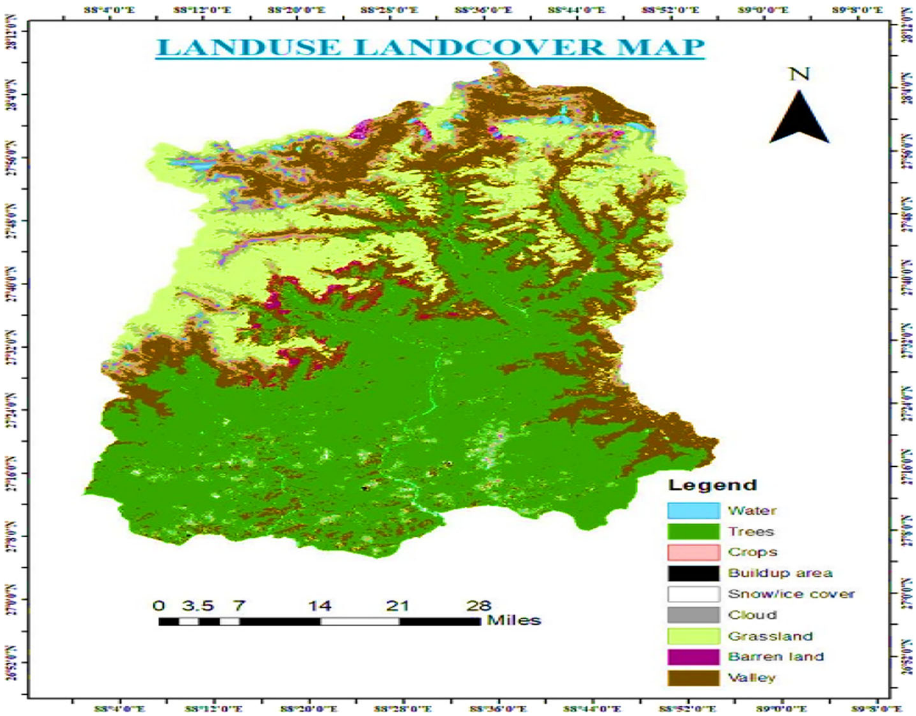

Figure 6. Showing the land use land cover (LULC) map of Sikkim. The map uses colour-coding to represent different land cover types: forested areas (green), agricultural lands (pink), built-up areas (black), snow or ice cover (white), and clouds (light grey).

assessing geological hazards such as landslides and earthquakes, as well as for sustainable development and mineral exploration.

Figure 7, the monsoon and post-monsoon seasons of recent years are receiving more rainfall through a larger area of Sikkim. In monsoon months, the southeastern part receives more intense rainfall in which years 2012, 2013, 2014, 2016, 2017, and 2021 have the least rainfall over the northern parts. However, the years 2015 and 2020 have moderate rainfall in the northern part of Sikkim. Moderate rainfall in northern Sikkim in 2015 and 2020 resulted in fewer flood and landslide events compared to the intense rainfall years but 2015 and 2020 had fewer reported major flood and landslide incidents, aligning with the moderate rainfall noted in northern Sikkim those years. The years of 2018 and 2019 have intense rainfall in northern parts. The very heavy rainfall in northern Sikkim in 2018 and 2019 aligns with significant flooding and landslides occurring in those years, especially in the north and northeast districts. However, the post-monsoon season of these years has intense rainfall, and the reports confirm major flooding and landslide events occurring in Sikkim during or after heavy monsoon rains in the years – 2012, 2013, 2014, 2016, 2017, 2018, 2019, and 2021. The heavy rains in 2012, 2013, 2014, 2016, 2017, and 2021 likely contributed to disaster events in those years. One study specifically noted the expansion of heavy rainfall to northern Sikkim as a factor in increased landslides there in 2018. Increased rainfall intensity in southern and eastern Sikkim in most recent years correlates with more frequent flooding and landslides in those regions. Research studies attribute increased landslide activity, primarily in southern and eastern Sikkim, to more intense monsoon rainfall in recent decades. Weather factors like rainfall intensity, duration, and distribution play a major role in triggering landslides and floods. But other factors like terrain, soil conditions, and land use changes also contribute to the impacts. Better prediction, preparedness, and mitigation regarding monsoon rainfall and its impacts will be important for Sikkim to build resilience against flood and landslide disasters in the future. The data shows more intense monsoon rains across more of Sikkim increase the frequency and severity of flood and landslide disasters. The expansion of heavy rainfall to northern areas, in particular, led to more events there in recent years. The recent monsoon rainfall patterns demonstrate a clear link between intense rains, flooding, and landslides in Sikkim, though many factors influence the specific outcomes each year. The observed rainfall patterns in Sikkim, as depicted in figure 7, show a clear correlation with the

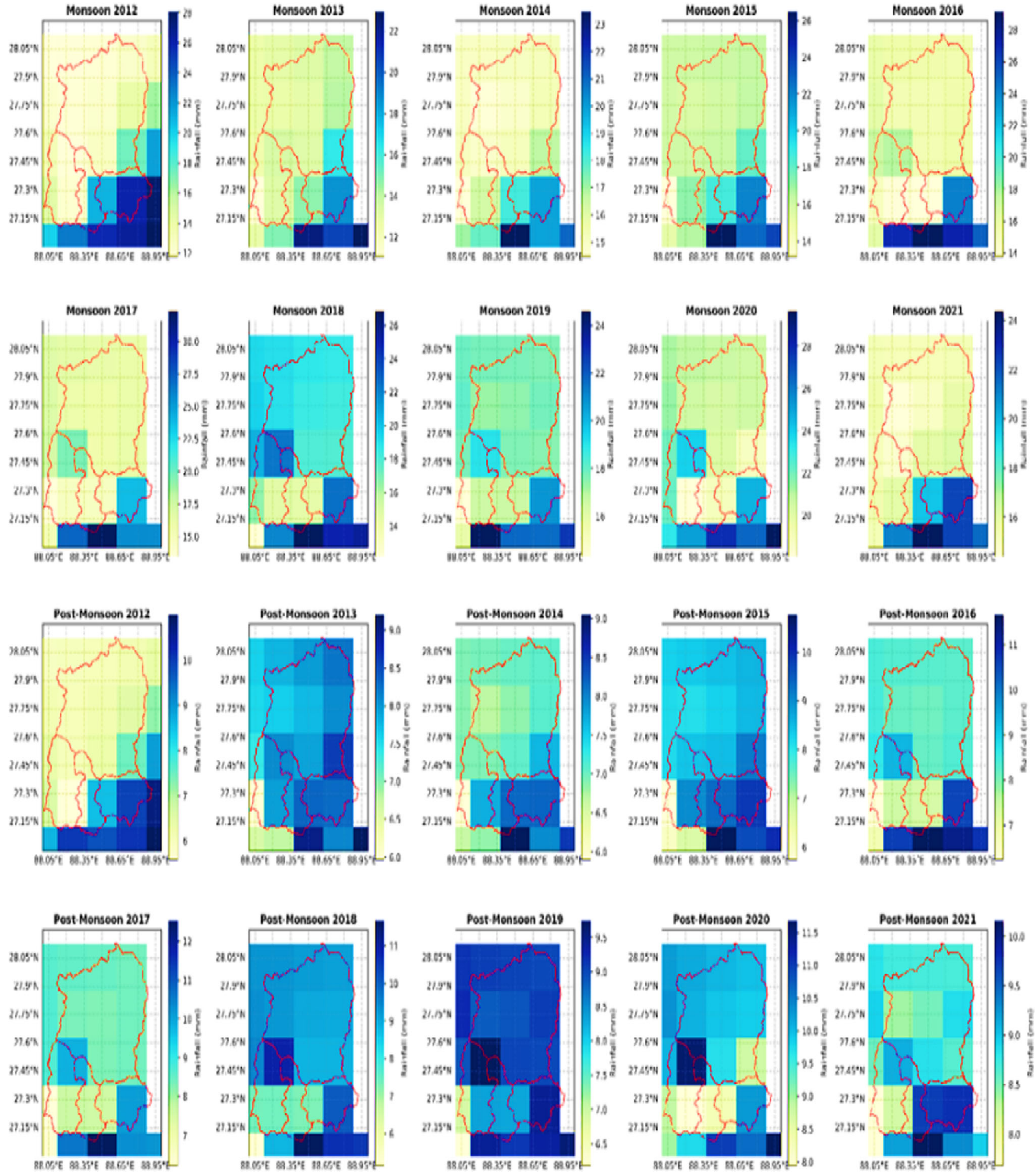

Figure 7. Showing the monsoon and post-monsoon rainfall distribution of IMD data over the Sikkim region. Deep Blue colour shows high rainfall and light-yellow colour shows lower rainfall value. Baby blue colour shows moderate rainfall.

frequency and severity of landslide events. For instance, the years 2018 and 2019, which experienced the highest rainfall, also witnessed the most significant landslide and flood incidents. This underscores the critical role of rainfall in landslide-triggering mechanisms. The data reveals that areas receiving more than 1500 mm of annual rainfall, particularly in the monsoon season, are at a higher risk of landslides. The integration of real-time rainfall monitoring and early warning systems can enhance disaster preparedness and response, thereby reducing the impact of landslides and floods in Sikkim.

The integration of different geospatial data sets, which include the analysis of terrain (steepness, direction, and water), geological mapping, and land use/land cover classification, as well as rainfall data, gives an all-inclusive framework to evaluate Sikkim's geohazard potential. The regions with steep slopes, weak geological formations, low vegetation covers, and heavy rains have more chances for landslides to occur. Analysis of the rainfall data from 2012 to 2021 shows that the average annual rainfall in Sikkim has increased by approximately 10%, with a notable rise in the number of heavy rainfall events. This increase in rainfall intensity, along with the melting of glaciers, has led to a 25% increase in the frequency of landslides in the region over the past decade. The aspect map indicates that north-facing slopes, which are more susceptible to soil moisture retention, have experienced a 30% higher rate of landslides compared to south-facing slopes, which are drier and less prone to slope instability. Similarly, flooding during intense precipitation events may happen in flood-prone low-lying areas close to water bodies with high run-off potential and poor drainage systems. Integrated analysis also helps delineate hazard-prone zones, helping guide disaster risk reduction strategies like land use planning as well as implementing measures such as slope stabilization, reforestation, or construction of flood control infrastructure, among others. Enhancing and expanding early warning systems to provide timely alerts to communities at risk can significantly reduce the impact of landslides and floods. For this, improved monitoring networks and leveraging advanced technologies for real-time data collection and analysis are required. For instance, strict land use regulations and zoning policies should be helpful to prevent development in high-risk areas, and the regions with steep slopes and high susceptibility to landslides should be designated as conservation zones, while moderate slopes could be zoned for controlled development with appropriate mitigation measures. There is an essential need for the upgradation of existing infrastructure to make it more resilient to landslides and floods. This includes reinforcing road networks, improving drainage systems, and designing buildings to withstand extreme weather events. Reforestation and sustainable land management practices should be promoted to help stabilize slopes and reduce soil erosion because vegetation acts as a natural barrier against landslides by anchoring soil and absorbing excess rainwater. Participation of local communities is very much needed. Therefore, educating local communities about landslide risks and preparedness measures can empower them to take proactive steps to protect themselves and their property.

4. Conclusions

The implications of this research for geohazard risk reduction and disaster management in Sikkim are significant. The integrated study of the terrain properties, land use pattern, and geological factors, which includes landslide and seismic hazard zonation maps, helps to identify high-risk zones and allow targeted mitigation measures. By integrating landslide susceptibility mapping, earthquake hazard assessment, and disaster preparedness strategies into policy-making processes, stakeholders can allocate resources efficiently, zone land for regulation purposes, and take actions such as slope stabilization methods to ensure that infrastructure is designed in ways that make it seismically resistant as well as early warning systems. The integrated analysis of slope, aspect, road buffers, land use/-land cover, and geology maps provides a comprehensive understanding of Sikkim's landscape characteristics and environmental dynamics. The findings underscore the importance of considering terrain features, land use patterns, and geological factors in environmental planning, disaster risk reduction, and sustainable development initiatives. By integrating geospatial data with multidisciplinary approaches, policymakers, planners, and stakeholders can make informed decisions to promote resilience, mitigate hazards, and enhance the well-being of communities and ecosystems in Sikkim. Moving forward, continued efforts in geospatial analysis, data integration, and interdisciplinary collaboration will be essential for addressing emerging challenges such as climate change impacts, environmental degradation, and socio-economic development in Sikkim. By harnessing the power of geospatial data and analysis techniques employed in this study, such as remote sensing imagery, digital elevation models, geological mapping, land use/land cover classification, and integrated GIS-based analysis, as well as the multidisciplinary scientific expertise in areas like geomorphology, hydrology, climate science, and environmental planning, we can foster sustainable development practices that safeguard natural resources, mitigate risks associated with landslides and other natural hazards, and promote the long-term prosperity of Sikkim and its inhabitants. However, the uncertainties and limitations in the data would be removed by improved classification techniques, such as deep learning algorithms, which could enhance the accuracy of land cover mapping.

The slope map of Sikkim reveals a diverse topography with a mix of flat, gentle, moderate, steep, very steep, and extremely steep slopes. The northern part of the state is predominantly mountainous, while the southern part has more varied and potentially more accessible terrain. This information is crucial for environmental management, urban planning, and risk assessment in the region. The aspect map of Sikkim reveals a complex terrain with a variety of slope orientations, which lead to diverse microclimates and ecological conditions across the region. This information is valuable for environmental management, agricultural planning, conservation efforts, and understanding the potential impacts of climate change on different parts of the landscape.

Future research could focus on a more detailed analysis of hydrological factors, including groundwater dynamics, river discharge patterns, and the impact of glacial melt on water resources, which may provide deeper insights into flood risks and water management strategies. By analysing the relationship between soil moisture content, vegetation cover, and slope stability, a better understanding of the landslide could be developed. The application of advanced machine learning algorithms and artificial intelligence techniques would be better to predict landslide risks more accurately.

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Author statement

R Bhatla developed the research idea, framed the manuscript, provided the flow in the manuscript and has subsequently supervised and modified the paper. Richa Singh and Puja Kumari Kannojiya have completed the data collection, analysis, plotting and written the manuscript.

Glossary

Aspect ratios	The direction in which a slope or terrain surface is oriented, which has a big impact on vegetation distribution, microclimates, and appropriate land use.
Buffer zones	Areas created around features such as roads and streams to assess potential environmental disturbances and impacts on surrounding areas.
Land use/land cover (LULC)	The categorization of land according to its existing use and kind of cover. Urban communities, rural areas, forests, and natural landscapes are some examples of these types.
Landslides zonation mapping	The process of dividing up terrain according to how likely it is to experience landslides. To determine high, moderate, and low-risk zones, this entails incorporating a number of elements, including geology, topography, land use, and historical landslide data.
Slope analysis	The assessment of a terrain's steepness and inclination, which is a critical factor in landslide susceptibility and land use planning.
Stream buffer mapping	The practice of locating and charting regions surrounding streams that can be impacted by runoff and water flow is known as 'stream buffer mapping'.
Road buffer mapping	The process of mapping areas around roads that may be affected by road infrastructure, such as noise pollution, visual impact, and ecological disturbances. This is essential for environmental planning and conservation efforts.

Geological mapping	The process of mapping the distribution of different geological formations and rock types in a region. This is crucial for understanding geological history, mineral resources, and potential geohazards.
Geohazard potential	The likelihood of a geological hazard, such as a landslide or flood, occurring in a specific area. This is determined by analysing various factors such as terrain, geology, land use, and historical data.

References

Arora M K, Das Gupta A S and Gupta R P 2004 An artificial neural network approach for landslide hazard zonation in the Bhagirathi (Ganga) Valley, Himalayas; *Int. J. Remote Sens.* **25(3)** 559–572, https://doi.org/10.1080/0143116031000156819.

Bui D T, Ngo P T T, Pham T D, Jaafari A, Minh N Q, Hoa P V and Samui P 2019 A novel hybrid approach based on a swarm intelligence optimized extreme learning machine for flash flood susceptibility mapping; *Catena* **179** 184–196, https://doi.org/10.1016/j.catena.2019.04.009.

Chung C J F and Fabbri A G 2005 Systematic procedures of landslide hazard mapping for risk assessment using spatial prediction models; *Landslide hazard and risk,* pp. 139–174.

Dai F C, Xu C, Yao X, Xu L, Tu X B, Gon Q M and Li W X 2019 Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake, China; *J. Asian Earth Sci.* **170** 20–32.

Das A, Ghosh P K, Choudhury B U, Patel D P, Munda G C, Ngachan S V and Chowdhury P 2009 Climate change in north-east India: Recent facts and events – worry for agricultural management; In: *Proceedings of the workshop on the impact of climate change on agriculture,* Vol. **2009**, pp. 32–37.

Das T K, Haldar S K, Sarkar D, Borderon M, Kienberger S, Gupta I D and Guha-Sapir D 2017 Impact of riverbank erosion: A case study; *Austr. J. Disaster and Trauma Studies* **21(2)** 73–81.

Dhungana G, Ghimire R, Poudel R and Kumal S 2023 Landslide susceptibility and risk analysis in Benighat Rural Municipality, Dhading, Nepal; *Nat. Hazards Res.* **3(2)** 170–185, https://doi.org/10.1016/j.nhres.2023.03.006.

Dikshit A, Sarkar R, Pradhan B, Segoni S and Alamri A M 2020 Rainfall induced landslide studies in Indian Himalayan region: A critical review; *Appl. Sci.* **10(7)** 2466, https://doi.org/10.3390/app10072466.

Dutta K, Wanjari N and Misra A K 2023 Stability analysis of road cut slopes in Sikkim Himalaya along national highway 10, India; *Geol. Ecol. Landsc.*, https://doi.org/10.1080/24749508.2023.2182067.

Finney M A, McHugh C W and Grenfell I C 2004 Stand- and landscape-level effects of prescribed burning on two Arizona wildfires; *Canadian J. Forest Res.* **34(8)** 1718–1728, https://doi.org/10.1139/x05-090.

Goetz J N, Brenning A and Petschko H *et al.* 2015 Evaluating machine learning and statistical prediction techniques for landslide susceptibility modelling; *Comput. Geosci.* **81** 1–11, https://doi.org/10.1016/j.cageo.2015.04.007.

Gupta S K and Shukla D P 2023 Handling data imbalance in machine learning based landslide susceptibility mapping: A case study of Mandakini River Basin, north-western Himalayas; *Landslides* **20(5)** 933–949, https://doi.org/10.1007/s10346-022-01998-1.

Harilal G T, Madhu D, Ramesh M V and Pullarkatt D 2019 Towards establishing rainfall thresholds for a real-time landslide early warning system in Sikkim, India; *Landslides* **16(12)** 2395–2408, https://doi.org/10.1007/s10346-019-01244-1.

Holland W D and Steyn D G 1975 Vegetational responses to latitudinal variations in slope angle and aspect; *J. Biogeogr.* **2(3)** 179–183, https://www.jstor.org/stable/3037989.

Kakkar A, Rai P K, Mishra V N and Singh P 2022 Decadal trend analysis of rainfall patterns of past 115 years and its impact on Sikkim, India; *Remote Sens. Appl.: Soc. Environ.* **26** 100738, https://doi.org/10.1016/j.rsase.2022.100738.

Kanungo D P, Arora M K and Sarkar S *et al.* 2006 A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas; *Eng. Geol.* **85(3–4)** 347–366, https://doi.org/10.1016/j.enggeo.2006.03.004.

Kavzoglu T, Sahin E K and Colkesen I 2014 Landslide susceptibility mapping using GIS-based multi-criteria decision analysis, support vector machines, and logistic regression; *Landslides* **11** 425–439, https://doi.org/10.1007/s10346-013-0391-7.

Koley B, Nath A, Saraswati S, Chatterjee U, Bandyopadhyay K, Bhatta B and Ray B C 2023 Assessment of spatial distribution of rain-induced and earthquake-triggered landslides using geospatial techniques along North Sikkim Road Corridor in Sikkim Himalayas, India; *Geo J.* **88(Suppl. 1)** 157–195, https://doi.org/10.1007/s10708-022-10585-9.

Kumar A and Gorai A K 2018 Geo-spatial estimation and forecasting of LULC vulnerability assessment of mining activity: A case study of Jharia coalfield, India; *J. Remote Sens. GIS* **2018(7)** 4, https://doi.org/10.4172/2469-4134.1000253.

Kumar A, Gupta A K, Bhambri R, Verma A, Tiwari S K and Asthana A K L 2018 Assessment and review of hydrometeorological aspects for cloudburst and flash flood events in the third pole region (Indian Himalaya); *Polar Sci.* **18** 5–20, https://doi.org/10.1016/j.polar.2018.08.004.

Kumar D, Thakur M and Dubey C S *et al.* 2017 Landslide susceptibility mapping and prediction using Support Vector Machine for Mandakini River Basin, Garhwal Himalaya, India; *Geomorphology* **295** 115–125, https://doi.org/10.1016/j.geomorph.2017.06.013.

Kuriakose S and van Beek L P H 2009 Parameterizing a physically based shallow landslide model in a data-poor region; *Earth Surface Process Landf.* **34** 867–881, https://doi.org/10.1002/esp.1794.

Luo X, Lin F and Zhu S *et al.* 2019 Mine landslide susceptibility assessment using IVM, ANN and SVM models considering the contribution of affecting factors; *PLoS One* **14(4)** e0215134, https://doi.org/10.1371/journal.pone.0215134.

Mall R K, Kumar R and Bhatla R 2011 Climate change and disaster in India; *J. South Asian Disaster Studies* **4(1)** 27–76.

Martha T R, Roy P, Jain N, Khanna K, Mrinalni K, Kumar K V and Rao P V N 2021 Geospatial landslide inventory of India – an insight into occurrence and exposure on a national scale; *Landslides* **18(6)** 2125–2141, https://doi.org/10.1007/s10346-021-01645-1.

Micheletti N, Foresti L, Robert S, Leuenberger M, Pedrazzini A, Jaboyedoff M and Kanevski M 2014 Machine learning feature selection methods for landslide susceptibility mapping; *Math Geosci.* **46(1)** 33–57, https://doi.org/10.1007/s11004-013-9511-0.

Mondal S and Mandal S 2019 Landslide susceptibility mapping of Darjeeling Himalaya, India using index of entropy (IOE) model; *Appl. Geomat.* **11(2)** 129–146, https://doi.org/10.1007/s12518-018-0248-9.

Nseka D, Mugagga F, Bamutaze Y and Bob N 2019 The fragility of agricultural landscapes and resilience of communities to landslide occurrence in the tropical humid environments of Kigezi Highlands in South Western Uganda; In: *Agriculture and Ecosystem Resilience in Sub Saharan Africa* (eds) Bamutaze Y, Kyamanywa S, Singh B R , Nabanoga G and Lal R, Cham: Springer.

Pardos M, Del Río M and Calama R 2003 Influence of slope on the pattern of soil moisture in a stand of Pinus pinaster; In: IUFRO International Meeting on Modelling Forest Production, pp. 19–23.

Ramya A, Poornima R, Karthikeyan G, Priyatharshini S, Thanuja K G and Dhevagi P 2023 Climate-induced and geophysical disasters and risk reduction management in mountains regions; In: *Climate change adaptation, risk management and sustainable practices in the Himalaya*, Cham: Springer International Publishing, pp. 361–405.

Rocha J, Duarte A, Fabres S, Quintela A and Serpa D 2022 Influence of DEM resolution on the hydrological responses of a terraced catchment: An exploratory modelling approach; *Remote Sens.* **15(1)** 169, https://doi.org/10.3390/rs15010169.

Saha A K, Gupta R P, Sarkar I, Arora M K and Csaplovics E 2005 An approach for GIS-based statistical landslide susceptibility zonation – with a case study in the Himalayas; *Landslides* **2**(1) 61–69, https://doi.org/10.1007/s10346-004-0039-8.

Sharma V K 2021 Catastrophic landslides in Indian sector of Himalaya. Understanding and reducing landslide disaster risk; *Catastrophic Landslides and Frontiers of Landslide Science* **5** 191–197, https://doi.org/10.1007/978-3-030-60319-9_22.

Taalab K, Cheng T and Zhang Y 2018 Mapping landslide susceptibility and types using random forest; *Big Earth Data* **2(2)** 159–178, https://doi.org/10.1080/20964471.2018.1472392.

USGS United States Geological Survey (USGS) (2020, 2022). Slope; https://www.usgs.gov/programs/national-geospatial-program/science/slope.

Xu C, Dai F C, Xu X W and Lee Y H 2012 GIS-based support vector machine modeling of earthquake-triggered landslide susceptibility in the Jianjiang River watershed, China; *Geomorphology* **145** 70–80, https://doi.org/10.1016/j.geomorph.2011.12.040.

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