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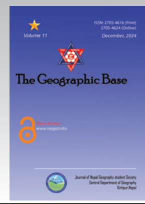

Rainfall-Induced Landslide Susceptibility Hazard in Budhiganga Municipality and Chhededaha Rural Municipality, Bajura District, Sudurpashchim Province, Nepal

Tek Bahadur Thami [1,*], Dhiraj Pradhananga [2], Nistha Niraula [1]

[1]Central Department of Hydrology and Meteorology Tribhuvan University, Nepal.

[2]Department of Meteorology, Trichandra Multiple Campus, Nepal.

***Corresponding Author**: tek.805508@cdhm.tu.edu.np, ORCID iD: https://orcid.org/0009-0001-3856-0973

Article info

Keywords:
rainfall-induced landslides, landslide susceptibility mapping, GIS, Far-western Nepal

Received: 25th May 2024

Accepted: 15th Sept. 2024

DOI: https://doi.org/10.3126/tgb.v11i01.88574

Abstract

Landslides triggered by heavy rainfall pose a significant threat to communities and the infrastructure in the hilly region. Most of the landslides occur during the monsoon season. Since the risks associated with rainfall-induced landslides are unknown, in the study area a detailed examination of these risks is necessary for sustainable planning and disaster risk management. This study relied on a Geographic Information System (GIS) to integrate SRTM data with additional datasets to estimate and map landslide susceptibility in Budhiganga Municipality and Chhededaha Rural Municipality. Six parameters- slope, LULC, geology, rainfall, drainage density, and elevation were analyzed using three Digital Elevation Model (DEM), Climatic Research Unit (CRU), hydrostatics SRTM data, geology data, and landslide data. A landslide susceptibility map was generated by categorizing the terrain into five major groups: very low, low, moderate, high, and very high. Then the obtained results were compared with existing landslide maps, providing valuable insights for planning and development, while also identifying areas with a higher likelihood of future

landslides, ultimately reducing the risk of potential damage in the Budhigana Municipality and Chhededaha Rural Municipality.

Introduction

Natural catastrophes often impact lives and cause significant economic losses globally, standing out as one of the most prevalent hazards in mountainous regions, frequently resulting in human fatalities and significant economic and structural losses (Confuorto et al., 2019; Pourghasemi & Rahmati, 2018). Over the past century, many studies (Bozzano et al., 2011; Notti et al., 2015; Sammarco, 2004) have demonstrated that several landslides have been triggered by human negligence, which has altered natural landscapes without proper interventions, often increasing the risk of slope failure.

However, in Nepal, landslides cause a serious social and economic threat because of the unique combination of Nepal's dynamic geological surroundings, quick weathering, and abundant rainfall (Dhungana et al., 2023). Furthermore, even though landslides are thought of as natural phenomena, human activity frequently causes them (Lima et al., 2017). Rain leads to the development of pore water pressure within rocks and soils, leading to a decrease in the shear strength of rocks and soils and potentially triggering landslides (Dhungana et al., 2023). The amount of rainfall directly influences landslide occurrences in Nepal, across the Nepal Himalayas, which have consistently resulted in colossal loss of life, property, infrastructure, and the environment during the monsoon (Dahal & Hasegawa, 2008). 10% of all landslide incidents caused by rainfall and 93% of all those caused by seasonal monsoons occur in Nepal, according to a worldwide landslide dataset (Froude & Petley, 2018).

In mountainous regions, particularly in Nepal, where steep topography, delicate geology, and intense monsoon rains make locations like Benighat-Rorang Rural Municipality extremely vulnerable to landslides, these events are frequent and destructive (Dhungana et al., 2023). However, Nepal experiences a large number of landslides, primarily due to heavy monsoon precipitation (DHM, 2014; DHM, 2017). Landslides commonly occur during a long period of heavy rainfall and occur in many parts of the world, especially in environments that provide a prolonged and intense rainfall, steep slopes, sparse vegetation and abundant sources of incoherent fine-grained soils, including colluvium and residual soil (Tohari, 2018). Additionally, in Nepal, intense rainfall is regarded as the main triggering factor of landslides because most landslide disasters in the region occur during the monsoon every year resulting in heavy losses in large and small-scale landslides throughout the country (Dahal, 2012).

Landslide susceptibility is defined as the spatially varying and time-independent likelihood of landslides occurring in the area of interest (Paudyal et al., 2021)

Landslide Susceptibility Mapping (LSM) can be categorized into three basic methods: knowledge-driven (expert opinion-based), data-driven (statistical analysis of historical landslide data) and physically-based (numerical modelling of slope stability) (Corominas et al., 2014). In the knowledge-driven method, the landslide conditioning factors are identified by experts, and each factor is ranked or scored qualitatively to identify the importance of each factor on the occurrence of a landslide (Kaur et al., 2018). Thus, the success of this method is dependent on the expert knowledge (Van Westen et al., 2003).

Currently, remote sensing (RS) techniques and Geographic Information System (GIS) have been widely applied to analyzed process and manage landslide hazard (Dhungana et al., 2023). The obtained map for landslide susceptibility can be used for assisting the proper planning of land use land cover (LULC) and reducing and mitigating landslide hazards (Intarawichian & Dasananda, 2011).

Bajura District of Sudurpashchim Province of Nepal is also of grave concern due to its rugged terrain, fragile geology and intense monsoon rainfall. Therefore, this study aims to develop a landslide susceptibility map using the weighted mean considering the related conditioning factor. Furthermore, providing a sophisticated understanding of the dynamic interaction between rainfall patterns, terrain features, and geological elements sheds light on the mechanisms through which heavy rainfall produces landslides.

Methods and Materials

Study area

The study area is situated in Budhiganga Municipality (29.41°N 81.22°E) and Chhededaha Rural Municipality (29.42°N 81.25°E) of Bajura District, Sudurpashchim Province, Nepal, along the elevation range of 300 m to 6400 m with Budhiganga Municipality covering the area of 56.41 sq km, and Chhededaha Rural Municipality with 135.08 sq km area. This region had landslides for decades. Many people are migrating to a safer place, but there are still people living in the risk region due to a lack of proper knowledge and government support. As a result, people are forced to live in these areas. Additionally, these places are characterized by extremely rugged topography in the lesser Himalayan sequence (Cieslik et al., 2019). This region has a temperate highland tropical climate with dry winters and a yearly average temperature of 31.24 °C and 178.11 mm of precipitation (Weather and Climate).

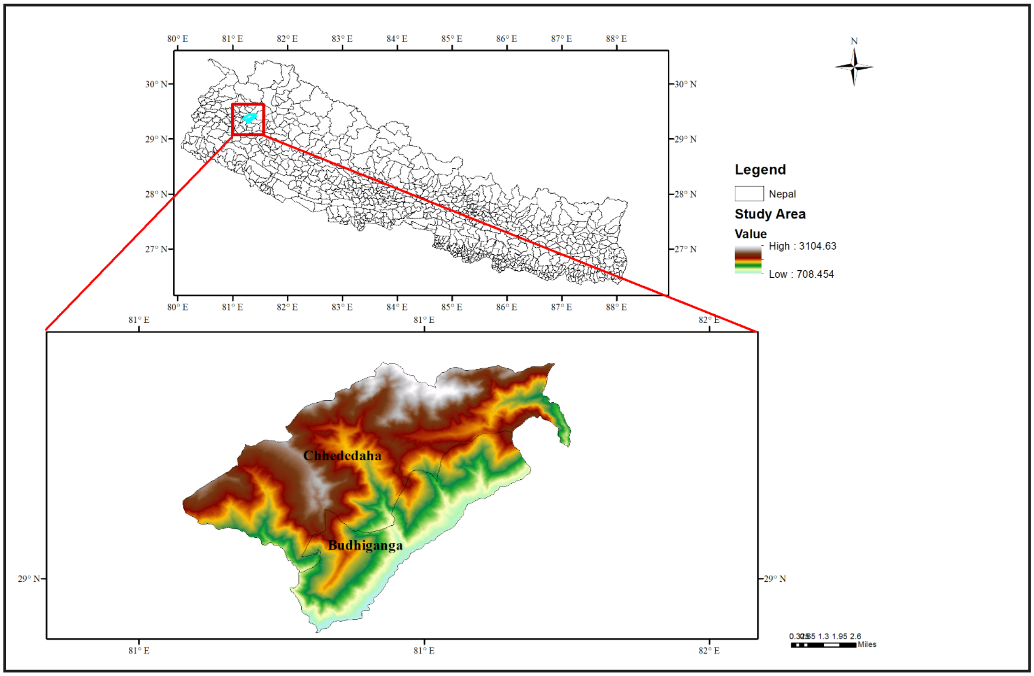

Figure 1. Location map of the study area (Budhiganga municipality and Chhededaha rural municipality)

Data

Open-source data like Shuttle Radar Topography Mission (SRTM) DEM data, LULC data, drainage data, geology data, and precipitation data were accessed from different sources and modified by using the GIS programming to analyze the different parameters (Slope, Geology, Precipitation, LULC, Drainage Density, and Elevation) of landslide formation (Table 1). Thus, Table 1 depicts the types of open-source data that have been used for the study, along with their scale/spatial references:

Table 1. Types of open-sources spatial data used in this study

S.N.	Data	Sources	Scale/ Spatial References
1.	DEM	SRTM DEM (earthexplorer.usgs.gov)	30 m
2.	Drainage	Open Street Map	https://github.com/nickbond/hydrostats
3.	Land Use and Land Cover	ESRI Sentinel-2	10 m
4.	Geology	ICIMOD (2007)	1:1,000,000
4.	Precipitation	CRU Data (2001-2020)	https://crudata.uea.ac.uk/cru/data/hrg/

Conceptual framework

Landslides, being one of the destructive geological processes, occur due to the complex interaction of geological, geomorphological, and various meteorological factors (McColl, 2015; Rawat et al., 2015). Therefore, landslide susceptibility mapping is essential for identifying the potential landslide areas (Dhungana et al., 2023c; Pal et al., 2022). The conceptual framework portrayed in Figure 1 presents the methodology employed in this study.

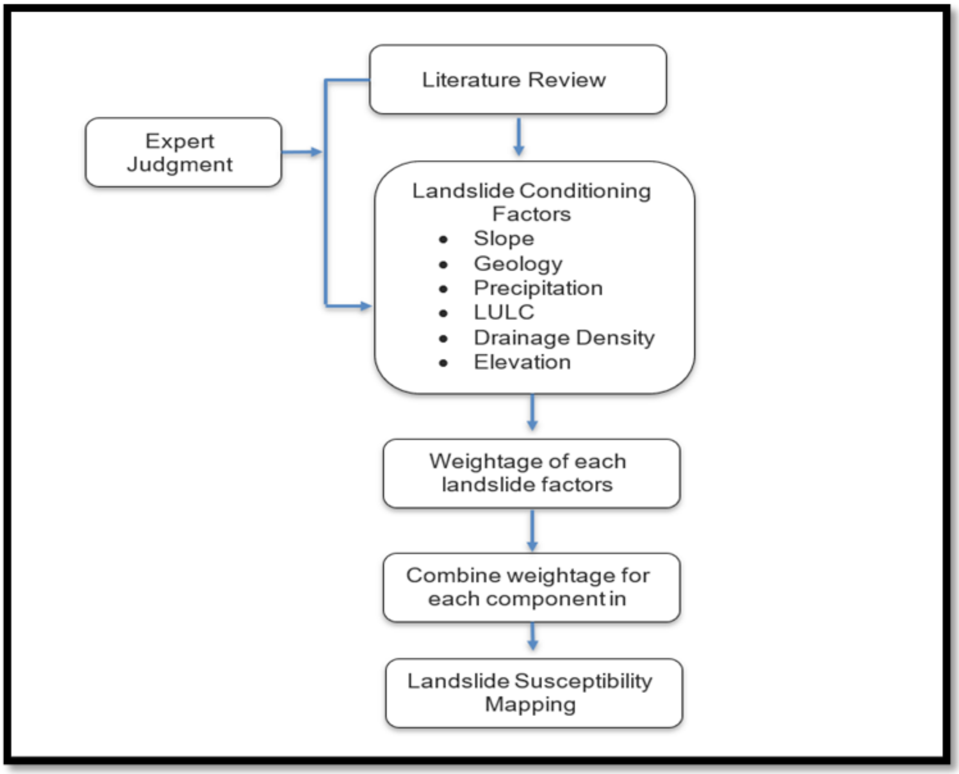

Figure 2. Methodological framework of the study.

Landslides parameters

The basic conditioning parameters used in this study for mapping landslide susceptibility were slope, geology, rainfall, LULC, drainage density and Elevation. SRTM data, a freely available digital elevation model (DEM) with a high resolution (~30m), is further processed in GIS to yield additional landslide conditioning parameters like slope, LULC, geology, rainfall, drainage density and Elevation.

Slope is one of the critical factors that often influence landslide occurrence, as steeper slopes tend to have higher shear stress, making them more prone to failure (Dai et al., 2001; Saha et al., 2010; Acharya et al., 2016). Here, in this study, slope is categorized into five classes (Table 2). Moreover, the region receives moderate to extremely high rainfall, often increasing landslide susceptibility. Thus, to assess rainfall patterns, CRU data from 2001–2020 were used to generate an annual rainfall map in GIS, which was also classified into five categories (Table 2).

Land Use and Land Cover (LULC) significantly affects the hydrological cycle and slope stability by altering runoff, infiltration, and vegetation cover. Here, LULC is divided into seven classes: Water, trees, flooded vegetation, crops, built-up area, and bare ground (Table 2). Furthermore, Geological data, sourced from ICIMOD, along with Drainage density, another important factor in landslide susceptibility, representing the total stream length per unit area (Zzaman et al., 2021), was also classified into five categories. Additionally, Elevation, which influences slope stability, was grouped into five classes ranging from 0 to 4000 m, as most of the study area lies within moderately to highly elevated terrain. However, the weightage of each subclass of landslide conditioning factor, as determined here in Table 2, was obtained from expert judgement based on site scenario and literature review.

Table 2. Weightage of each parameter of the landslide triggering factor using expert opinion

Factors	Classification	Landslide Susceptibility	Weight
Slope (in Degree)	0 - 15.4 15.5 - 22.8 22.9 - 29.9 30 – 38.4 38.5 – 70	Very low Low Moderate High Very high	1 2 3 4 5
Geology	Basic Rocks Bu Lakharpata Formation Ranimatta Formation Suntar Formation	Very low Very Low Low Very high Moderate	1 1 2 5 3
Rainfall (mm)	785.5 – 835.4 835.5 – 878 878.1 – 924.8 924.9 – 987.2 987.3 – 1, 050.7	Very low Low Moderate High Very high	1 2 3 4 5

LULC	Water Forest Crops Built Area Bare Ground Rangeland	Moderate Very Low Moderate High Very High High	3 1 3 4 5 4
Drainage Density (m^{-1})	0 – 91.3 91.4 – 239.9 240 – 374.6 374.7 – 559.8 559.9 – 971.1	Very low Low Moderate High Very high	1 2 3 4 5
Elevation(meters)	0 – 705 706 – 999 1,000 – 1,999 2,000 – 2,999 3,000 – 4,000	Very low Low Moderate High Very high	1 2 3 4 5

Results and Discussion

Examination of landslide susceptibility

In this study, Landslide Susceptibility Mapping (LSM) from a knowledge-driven approach is applied and compared by calculating the mean weightage of the six parameters individually, and is further processed in GIS. The parameters are reclassified into five classes based on very low, low, moderate, high, and very high. Based on the class's susceptibility index, expert advice, personal judgment and field observations are given. Thus, after the total mean of all six parameters, a landslide susceptibility map is prepared by using GIS, showing the very low, low, moderate, high and very high landslide susceptibility zones.

Table 3. The percentage of susceptibility index of the area

S.N.	Landslide susceptibility	Area in sq. km.
1.	Very Low (1)	0.05
2.	Low (2)	14.46
3.	Moderate (3)	117.92
4.	High (4)	47.43
5.	Very High (5)	0.44

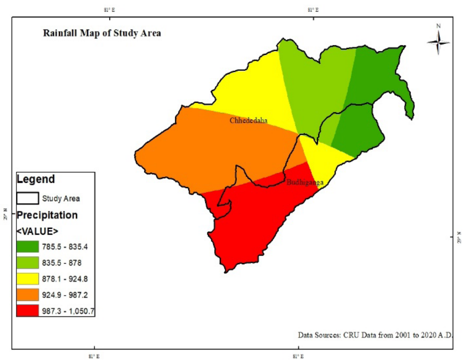

Figure 3. Slope map of the study area

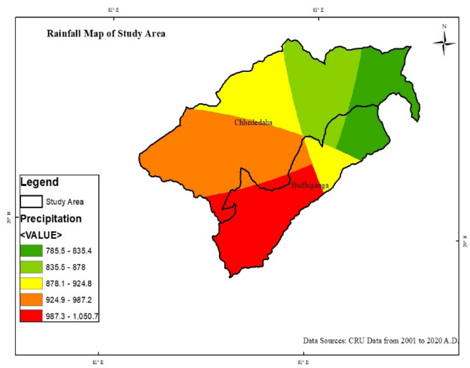

Figure 4. Rainfall map of the study area

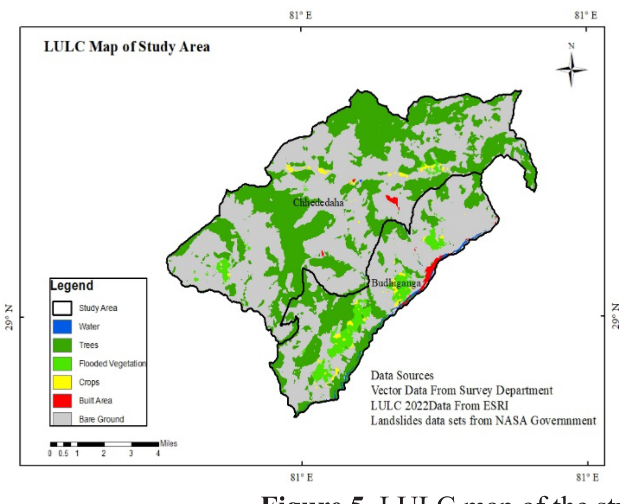

Figure 5. LULC map of the study area

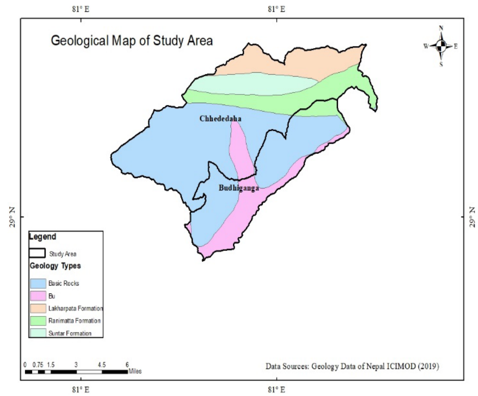

Figure 6. Geological map of the study area

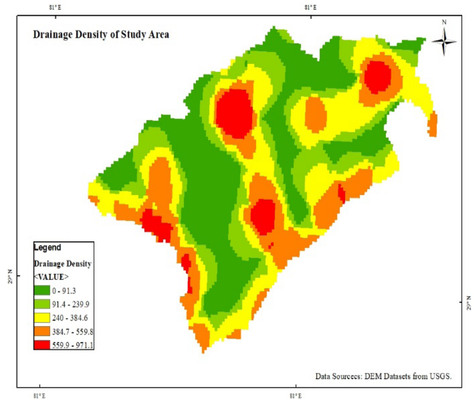

Figure 7. Drainage density of the study area

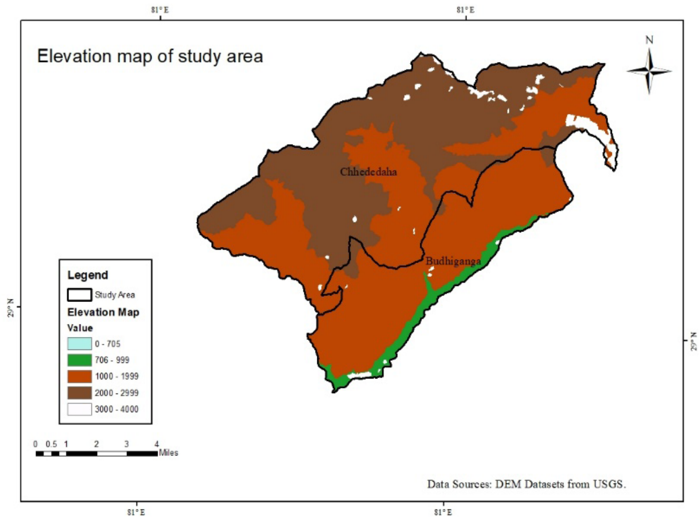

Figure 8. Elevation map of the study area

Figure 3 (Slope Map) illustrates the wide range of slopes, ranging from gentle (0-15°) to very steep slopes (38.5°-70°). The gentle slopes are located in the lower valley, which are stable and are less prone to landslides. However, the very steep slopes (represented by red) are in the ridgelines and scraps, where landslide susceptibility is high due to gravitational instability. Heavy rainfall along with slope plays a crucial role in landslide initiation. The summer monsoon mostly dominates this region while the effect of the western disturbances can also be seen. Figure 4 shows that the lower part receives above average rainfall, while the higher altitude receives less due to the orographic effect. Areas receiving higher annual precipitation, corresponding with the steep topography, enhance susceptibility. High rainfall promotes pore water pressure buildup, which causes slope failure, indicating that rainfall intensity is a direct contributor to landslides.

The LULC distinguishes the land into Water, trees, flooded vegetation, crops, built area, and bare ground. Trees are dominant in the central and upper Catchments, which enhances the infiltration capacity and makes the area more stable. However, agricultural and built-up areas are located on moderate to steep slopes, which are more vulnerable due to less vegetation and improper land management, which intensifies the landslides.

Figure 6 reveals that the area consists of weak metamorphic rock along with the fractured and faulted zones. The higher regions consist of Lakharpata, Ranimatta, and Suntar Formation, which exacerbate the landslide. In contrast, the lower regions, which are based on Bu rocks, are more stable and less vulnerable. The drainage density in Figure 7 reflects the compactness and the erosive capability of the surface water. Most of the area is characterized by low drainage density, and the landslide-prone areas have high drainage density capacity, which shows the steep, slow, and intense rainfall. Figure 8 shows that the terrain ranges from low-lying valleys to high ridges. Both the slope and the rainfall are affected by the Elevation, and higher Elevation receive more rainfall. Further, this enhances the rainfall, which induces landslides.

Planning and decision making for the landslide-prone zones depend heavily on the Landslide Susceptibility Map, which aids in identifying or predicting the high-risk zone or the area that is susceptible to landslides. Results obtained from the map can be fruitful in sustainable planning and implementation of development works (Corominas et al., 2014). Here, the final evaluation score was estimated using the weightage shown in Table 2, and then it was classified into five sub-classes: very low, low, moderate, high, and very high. The high and very high susceptibility zones combined comprise 47.87 sq km, a sizable fraction of the area under consideration, emphasizing the importance of immediate risk assessment and prioritizing solutions such as early warnings, slope stabilization, and settlement relocation.

Rainfall- induced landslides in Nepal Himalaya are assessed from three different angles: hydrology and slope stability modeling, rainfall threshold of landslides and landslide hazards analysis to comprehend landslide process, mechanism, and related hazard (Dahal, 2012), since these landslides are more likely to occurring temperate regions where residual soil predominates with environment providing prolonged and intense rainfall, and an abundance of incoherent fine-grained soils, including colluvium (Tohari, 2018). Therefore, catastrophe risk reduction and mitigation measures can be prioritized in these landslide-prone areas, and thorough site investigations for key sites, assisting development planners and policymakers in accurately assessing the situation in the region and allocating resources to address the issue (Corominas et al., 2014; Paudyal et al., 2021).

Despite the inadequate open-source data, this research effectively utilized available geo-spatial information to determine the susceptibility of the area, providing a baseline for analyzing the viability of development activities. Open-source data can help comprehend disasters in data-scarce regions and evaluate progress towards the Sendai Framework for Disaster Risk Reduction targets (Li et al., 2019). In order to understand the accessibility of open-source data in the context of Nepal, the landslide susceptibility of remote regions of Nepal, with a primary focus on Budhiganga Municipality and Chhededaha Rural Municipality, was analyzed. Since this study used a small number of landslide conditioning factors such as slope, rainfall, geology, drainage density, LULC, additional parameters including soil thickness and soil type, with reasonably coarse resolution, can be included in future analysis to improve landslide prediction. A similar study of landslide distribution in the Sindhupalchowk district of central Nepal, utilizing satellite-based remote sensing data such as rainfall, soil depth, and soil type, discovered that the frequency of landslides is twice as high along poorly designed roadways as it is on unpaved terrain(McAdoo et al., 2018). Moreover, weight values for each parameter were assigned based on expert advice, and the weighted sum function in GIS (Figure 9) was utilized to generate the Landslide Susceptibility Index (LSI) map using all relevant factors. To aid in the assessment of landslide hazard, the LSI value was manually divided into five groups. These categories were then categorized to create the landslide susceptibility map. LSI values less than 2.2070 were classified as very low susceptibility zones, 2.2070-2.6713 as low value zones, 2.6713-3.0892 as moderate zones, 3.0893-3.4838 as high, and 3.4838-4.25 as very high susceptibility zones. Apart from this, the positive weight value, as seen in Table 2, has a significant relationship to landslide occurrence. The slope angles found between 29.8 and 38.2, and 38.3 and 70.0, were most vulnerable to cause a landslide (Figure 3). Slope instability and landslides are also significantly impacted by land use and land cover, as a large portion of the area was covered by forest land and flooded vegetation (Figure 5).

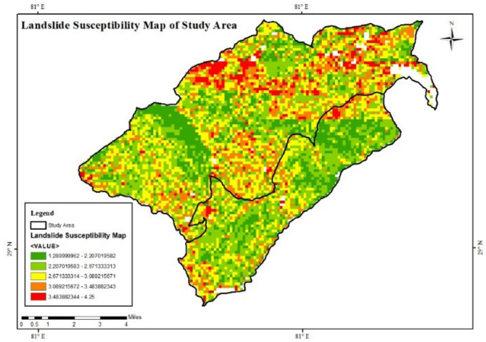

Figure 9. Landslide Susceptibility Map of Budhiganga Municipality and Chhededaha Rural Municipality

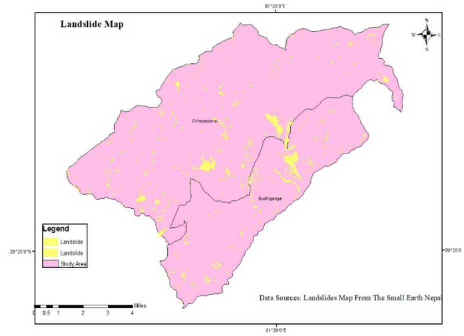

Figure 10. Landslides of Budhiganga Municipality and Chhededaha Rural Municipality

Furthermore, the distance from drainage is a significant aspect in susceptibility mapping since drainage density also plays a crucial role in triggering landslides along with the data of rainfall and geological maps. The summer monsoon season (June-September) brings 70-80% of yearly rainfall and is crucial for agriculture; however, it also causes the majority of floods and landslides (Nayava et al., 2022). So, it has become necessary to incorporate rainfall as a variable in the landslide susceptibility simulation, as most parts of our study area lie under the moderate to very high rainfall zones. Apart from this, Table 3 shows that most of the study area falls under moderate susceptibility, followed by high, very low, very high, and extremely low zones, implying that only a small section is less prone to landslides, while the rest is highly sensitive.

Validation of landslide susceptibility

There are numerous approaches for validating the landslide susceptibility maps. In this work, landslide susceptibility maps were validated against a landslide map collected from SEN (The Small Earth Nepal). Figure 10 verifies that landslides occur in the majority of the study area's high susceptibility zones, but none occur in the low susceptibility zones, and others occur periodically.

Additionally, the majority of the landslides observed during the field visit occurred in high-susceptibility zones, whereas no landslides occurred in low-susceptibility zones. According to FGD, landslides become active during the monsoon season when sediment flows constantly with a high threshold, causing a brief earthquake. Many decades have passed since the landslides began, yet their effects are still causing concern and fear among the inhabitants.

Conclusion

In a mountain region like Nepal, where landslides cause a significant annual loss of life and property, landslide studies are crucial. Thus, an attempt is made to assess landslide susceptibility utilizing open-source analytical tools and techniques as a preliminary step for landslide hazard assessment. The present paper assesses the landslide susceptibility of the Budhiganga Municipality and Chhededaha Rural Municipality as a case study. Here, we evaluated landslide susceptibility using expert knowledge based on site scenarios and literature review and sparse data in a free and open-source framework as remote parts of Nepal frequently lack data regarding previous landslide occurrences. Following the expert's recommendations on landslide susceptibility, the causative actor was further divided into five subclasses: very low, low, moderate, high, and very high. As a result, this map is helpful for both planning and development of this study area. Thus, mapping landslide susceptibility provides information about the relative likelihood of future landslide areas, which can help make recommendations to reduce future damage. Furthermore, the local representatives and stakeholders can also use this map to organize and develop policies

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