Journal of Institute of Science and Technology, 30(1), 89-99 (2025)
ISSN: 2467-9062 (print), e-ISSN: 2467-9240
https://doi.org/10.3126/jist.v30i1.76264

Research Article

LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN THE MARIN KHOLA WATERSHED OF THE SUB HIMALAYA, CENTRAL NEPAL

Subodh Dhakal[1]*, Niraj Bal Tamang[2]
[1]Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal
[2]River and Catchment Dynamics, WSP NZ, Christchurch, New Zealand
** Correspondence: dhakalsubodh@gmail.com*

(Received: *February 16, 2025;* **Final Revision:** *March 24, 2025;* **Accepted:** *March 25, 2025***)**

ABSTRACT

Nepal is facing the threat of landslides each year causing huge loss of lives and properties. Landslide prediction and susceptibility assessments help in identifying the potential zones of landslide occurrences and provide opportunities to treat them prior to their occurrence. Among different methods of landslide susceptibility mapping, the InfoVal method is one of the simple and useful methods. In this study, this method is used to study the landslide susceptibility in the Marin Khola Watershed within the Siwaliks of central Nepal as this area comprises of the weak geological formations that contribute to high potentialities of landslides, yet there are no studies for predicting landslides. A total of 217 landslides were taken for the study and they were divided into two groups: working landslides and validating landslides. 75% of these total landslides were selected as working landslides and the remaining 25% were selected for validating landslides. Spatial relationships of the landslide distribution with different causative factors including topographic factors, hydrologic factors, geological factors and landuse factors were employed and analyzed. The results depict that very high, high, moderate, low and very low susceptibility classes cover 1.15%, 49.93%, 30.17%, 11.48%, and 11.28% area, respectively. The Middle Siwaliks are most susceptible to landslides compared to the Upper Siwaliks and Lower Siwaliks. The accuracy values are found to be affected by the difference in the landslide characteristics and types occurring in the study area. The model accuracy remains at 66% and predictive accuracy at 75%.

Keywords: Landslide susceptibility, Marin Khola watershed, InfoVal method, Siwaliks

INTRODUCTION

Landslides refer to the downward movement of slope forming materials like rock, debris, or earth down a slope (Cruden, 1991). Landslides are the product of a complex interplay of various triggering and conditioning in situ factors. The Sub Himalaya or Siwaliks are formed by the very weak and young, sedimentary rocks that belong to the Middle Miocene to Upper Pleistocene in geological age. This zone occupies the area between the Terai in the south and the Lesser Himalaya in the North in between two major geological structures namely Main Frontal Thrust (MFT) in the south and the Main Boundary Thrust (MBT) in the north (Bhandari & Dhakal, 2021). As a consequence of mountain building process and related tectonics, these young sedimentary rocks in Siwaliks are highly weathered and deformed. The typical presence of interbedding of soft mudstone and hard sandstone beds causes differential weathering in this area providing options for slope instabilities and occurrence of different types of landslides (Dhakal, 2015; Bhandari & Dhakal, 2020). Marin Khola watershed also witnessed hundreds of landslides posing threats to many settlements. Landslide susceptibility assessment can help in identifying the areas most potential for landslides and will provide opportunities to the policy makers to reduce the risks to the communities from the future landslides. Many works have been done for landslide susceptibility mapping using different methods and perspectives. The methods vary from heuristic approach to advanced machine learning models. Heuristic methods rely on expert judgment but are subjective (Saaty, 1980; Varnes, 1984). Deterministic models, like Factor of Safety (FoS) analysis provide physics-based stability assessments but require high-resolution geotechnical data (Terzaghi, 1950). Statistical models quantify the relationships between landslides and causative factors but assume linearity (Lee & Pradhan, 2007). The choice of method depends on data availability, scale of study, and available technologies. In most of the methods, landslide susceptibility and hazard maps are prepared on the basis of the intrinsic factors such as bedrock geology, geomorphology, soil depth, soil type, slope gradient, slope aspect, slope curvature, elevation, landuse pattern, drainage pattern and so on along with extrinsic factors such as rainfall, earthquakes and volcanoes (Siddle *et al.*, 1991; Dai *et al.*, 2001; Cevik & Topal, 2003). A region is considered to be susceptible to landslides when the terrain conditions at that site are similar to those in the region where a slide has occurred (Van Westen, 2000).

Different studies tried to find the landslide susceptibility in different parts of Siwalik area using different methods (Paudyal *et al.*, 2021; Bhandari *et al.*, 2024), but it has not been applied precisely in Marin Khola watershed. Regarding the methods of susceptibility mapping, statistical methods, especially the Weight of Evidence (WoE), Frequency Ratio (FR) and InfoVal models have demonstrated high prediction accuracy for landslide susceptibility mapping (Bhandari *et al.*, 2024). This study implies the information value (InfoVal) method for the assessment of landslide susceptibility in the Marin Khola Watershed by considering the physical parameters contributing to the occurrence of landslides in that area. This area comprises of the weak geological formations that contribute to high potentialities of landslides, yet there are no studies in this area that focused on landslide zonation and prediction.

MATERIALS AND METHODS

Study Area

The study area (Fig. 1) is located in the Sindhuli District of the central Nepal (latitude 27º10'- 27°20'N, longitude 85°30'- 85º55'E). It covers an area of 442.97 km² and ranges in elevation from 140 m to 1540 m. The area mainly consists of the rocks of the Middle Siwaliks along with Lower Siwaliks, Upper Siwaliks and Pre Siwaliks rocks. The fragile sedimentary rocks of the Siwaliks in this area are prone to different forms of mass wasting. Most of the area is occupied by the forest and the slopes are mostly facing southwest. The study area is a wide river valley made by the Marin River flowing east to west within the area. A major thrust, namely, Marin Khola Thrust (Fig. 2) passes along the Marin River within the study area. The landslides within the study area are complex in type. They differ with the change of the terrain of different characteristics. The gravelly conglomerates of the Upper Siwaliks are prone to granular flow due to removal or washing away of the cementing materials while the massive sandstones of the Middle Siwaliks suffers rock slides due to differential weathering of the mudstones.

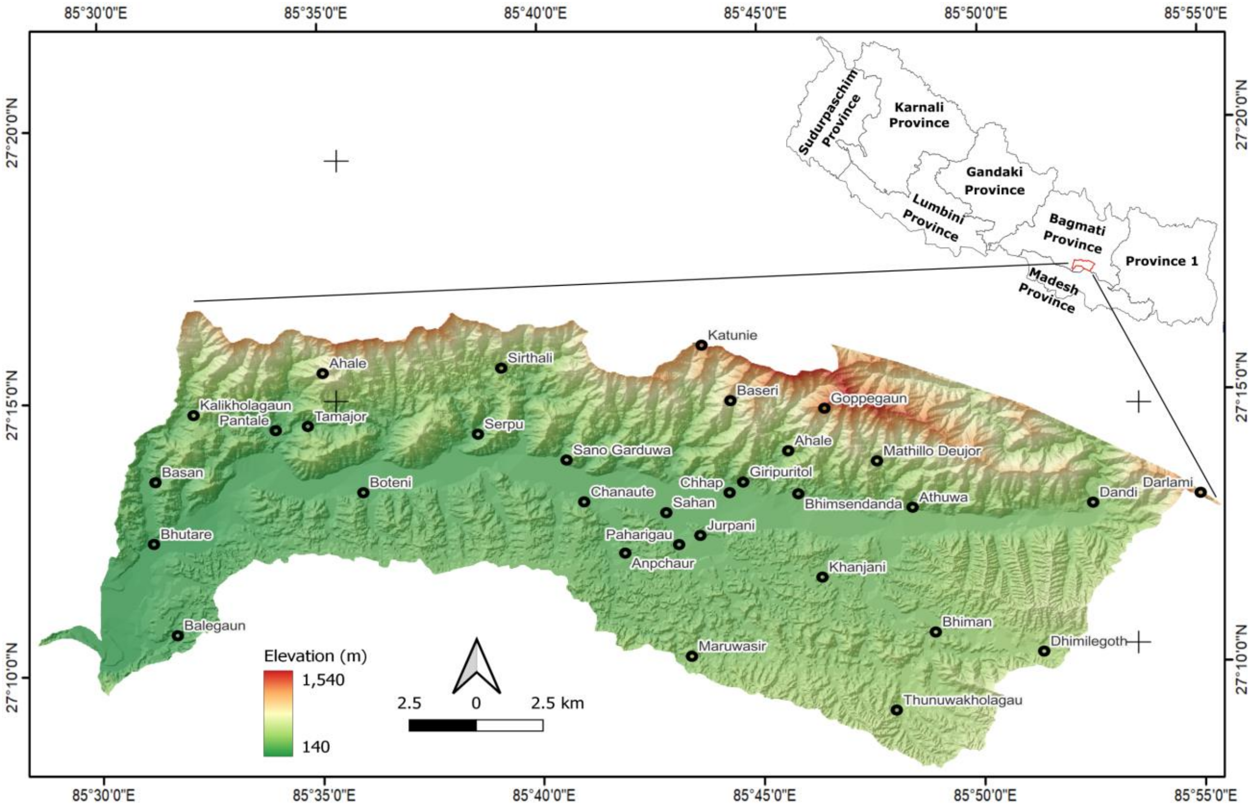

Figure 1. Location Map of the Marin Khola watershed

Geology and Geomorphology

The Marin Khola watershed primarily comprises of the Siwalik Group, which consists of Neogene molassic sedimentary rocks. These are predominantly made up of fluvial deposits that accumulated on the southern front of the Himalayas. In addition to the presence of lower, middle, and upper Siwalik, the area also consists of Pre-Siwalik rocks in some parts (Fig. 2). The area is largely characterized by an upward-coarsening sequence of mudstone, siltstone, sandstone, and conglomerate rocks. The area exhibits diverse geomorphological features with a rugged topography and deeply dissected gullies and steep slopes. The area also includes wide valleys, low to high terraces adjacent to rivers, alluvial fans, and badlands. To study the geology of the area, geological map was updated on the basis of the geological map of petroleum exploration produced by Department of Mines and Geology (DMG), GoN based on authors' field observations. It can be divided into 5 geological units: recent deposits (Q), Upper Siwaliks (US), Middle Siwaliks (MS), Lower Siwaliks (LS) and Pre Siwaliks (PreS) (Fig. 2). The impact of geology can also be observed on the landslides through their origin and mechanism. Differential weathering can be observed within the massive sandstones of the Middle Siwaliks while effect of water can be observed on the soft mudstones of the Lower Siwaliks.

Landslide Inventory Mapping

The landslide inventory map of the study area was prepared at first using Google Earth images. Among them, 75% landslides were used as working landslides while the remaining 25% landslides were used as validating landslides. The map was verified through field investigations and consulting the local government authorities. The landslides verified from site investigation as the active ones were taken for the susceptibility mapping. The total landslides were divided into two groups as the working landslides and validation landslides (Fig. 3).

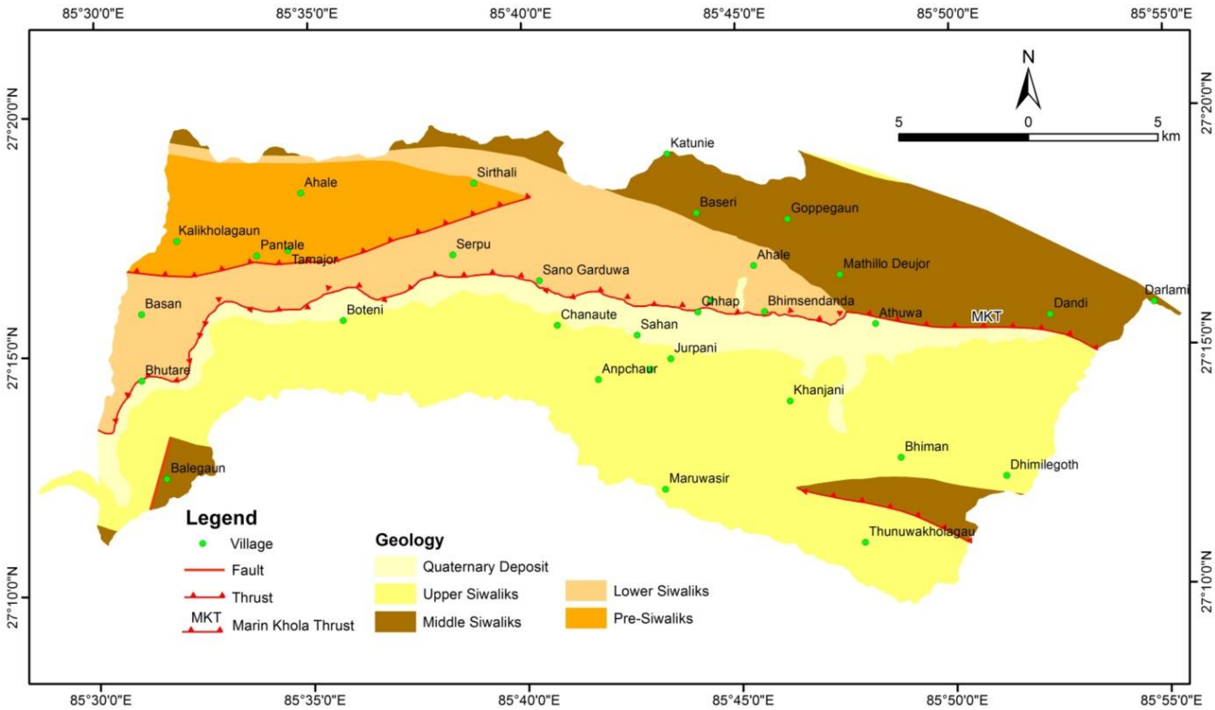

Figure 2. Geological Map of the Marin Khola watershed (adopted from TU-CDES, 2016)

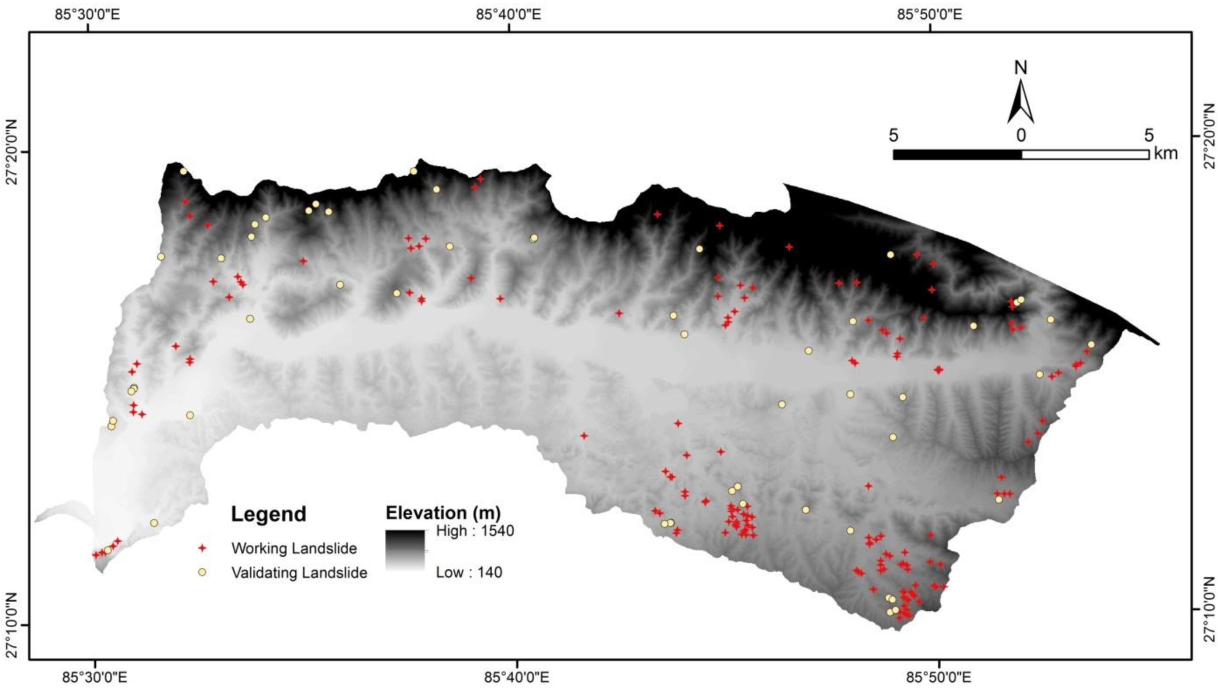

Figure 3. Landslide inventory map of the study area

Preparation of the Landslide Causative Factor Maps

Different factor maps were prepared in Arc GIS 9.3 and QGIS 2.16 for the susceptibility analysis. As gravity plays a vital role with increase in height, elevation map was prepared using the Digital Elevation Model (DEM) of 20m × 20m of the Department of Survey, Government of Nepal. The elevation was divided into 8 different categories: 140-200, 200-400, 400-600, 600-800, 800-1000, 1000-1200, 1200-1400 and 1400-1600m. Slope also controls the gravity and speed of sliding material, so slope maps were prepared using the DEM. It was divided into 6 categories: 0-5, 5-10, 10-20, 20-30, 30-40 and >40º. Aspect gives the direction which the slopes are facing and it was divided into 9 categories as flat (0º), north N (337.5-360º and 0-22.5º), northeast NE (22.5-67.5º), east E (67.5-112.5º), southeast SE(112.5-157.5º), south S(157.5-202.5º), southwest SW (202.5-247.5º), west W (247.5-292.5º) and northwest NW (292.5-337.5º).

Drainage proximity, Compound Topographic Wetness Index (CTI) and Stream power Index (SPI) are some of the major hydrologic factors which play a vital role in triggering landslides. Drainage proximity map was prepared in GIS using the Multiple Ring buffer tool and classified into 5 categories: 0-25, 25-50, 50-75, 75-100 and >100m. The SPI measures the erosive power of the water (Moore and Burch, 1986). It was classified into 5 categories based on natural breaks: -13 - -8, -8 - -4, -4 - -1, -1 – 1 and 1 – 12. The CTI describes the effect of topography on the locations and sizes of saturated source areas of runoff generation (Pradhan and Kim, 2016). It was classified into 4 categories based on natural breaks: < -2, -2 – 3, 3 – 8 and >8. Landuse map was prepared in GIS by modifying the digital layer of landuse prepared by the Department of Survey, GoN. It was classified into 7 categories as built up, barren land, cultivation, forest, bush and grass, river and pond or lake. The geology of the study area is divided into five major geological zones as shown in Fig. 2 and the representative landslides within the predominant rock types in the area are shown in Fig. 4.

Information Value (InfoVal) Method

The Information Value method is considered as a powerful data-driven technique for landslide susceptibility mapping. It is a bivariate statistical method, and it determines the relationship between landslides and their contributing factors by assigning weights based on the occurrence probability of landslides. The benefit of InfoVal method is due to its simplicity in handling large datasets for landslide susceptibility assessment (Yin & Yan, 1988; Lee *et al.*, 2004). Moreover, this method is more effective in data scarce regions (Regmi *et al.*, 2014). In this method, the weight value for a parameter class is defined as a natural logarithm of the landslide density in the class divided by landslide density of each parameter class; and the weight for each factor maps is calculated using Equation 1:

$$W_{ij} = \ln\left(\frac{f_{ij}}{f}\right) = \ln\left[\left(\frac{A^*_{ij}}{A_{ij}}\right) \times \left(\frac{A}{A^*}\right)\right] \qquad (1)$$

Where,

W_{ij} = weight given to a certain class I of parameter j

f_{ij} = dense class or landslide density within the class I of parameter j

f = dense map or landslide density within the entire map

A^*_{ij}= area of landslide in certain class I of parameter j

A_{ij}= area of certain class I of parameter j

A^* = total area of landslide in the entire map,

A = total area of the entire map.

In the case of no landslide occurrence in a certain class of parameter, the weight is assigned as 0 (van Westen, 1997; Yalcin, 2008). All the factor maps were correlated with the landslide map to find the landslide density in each class. In this process, a higher positive weightage value implies the higher landslide susceptibility, and a negative weightage value implies a lower landslide susceptibility (Yin & Yan, 1988).

RESULTS AND DISCUSSION

For this study, 217 landslides were taken from the study area, out of which 75% were used as working landslides while the remaining 25% were used as validating landslides. The results of the spatial relationships between topographic factors and landslide distribution (Table 1) show that most of the landslides occur in the slopes facing southeast direction. Similarly, landslide distribution is high in the altitude between 600-800m. The slope range of 30-40º consists of the highest number of landslides. For both the plan and profile curvature, the concave category consists of the majority of the landslides. The concave nature indicates the water convergence path on the hill slope. In this way, 5 topographic factor maps (Fig. 5) were used for analysis of the study area.

The spatial relationships between the hydrologic factors and the landslide distribution (Table 2) show that most of the landslides in the study area are situated at a distance range of 50-75m. The landslides are also triggered by the river toe cutting which removes the bearing force at the bottom making the upslope materials unstable. Similarly, the SPI value is very high (>1) majorly in the landslide area which indicates water contributions from upslope areas and high flow velocity. For the TWI values, the majority is in the lowest and lower categories (<-2 and -2 – 3) which coincide with the lower order drainages (Pradhan & Kim, 2016). These 3 hydrologic factor maps (Fig. 6a, b, c) show their effects in the study area. The relationship between the landuse and landslides is given in Table 3 and Fig. 6d, which shows that the barren land class has the highest landslides. Field observations also showed that the top soil of most of the areas has been washed away because of the weak rock types and fragility of the area. Less settlement in the areas is also one of the causes of the barren land. The spatial relationship between geology and the landslide distribution shows that the Lower Siwaliks rocks are more prone to landslides (Table 4, Fig. 6e). This is due to the presence of relatively soft sedimentary rocks such as mudstone in comparison to massive sandstones of the Middle Siwaliks and conglomerates of the Upper Siwaliks.

Figure 4. Representative landslides within the Siwaliks occurring in the a) and b) Mudstones, c) and d) Sandstones.

Table 1: Landslide distribution in different topographic factors

	Class	Dense Class	Dense Map	Weight
Aspect	Flat	0.0013	0.0023	-0.553
	N	0.0020	0.0023	-0.158
	NE	0.0020	0.0023	-0.153
	E	0.0021	0.0023	-0.093
	SE	0.0029	0.0023	0.231
	$	0.0027	0.0023	0.152
	SW	0.0028	0.0023	0.189
	W	0.0024	0.0023	0.042
	NW	0.0028	0.0023	0.209
Elevation (m)	< 200	0.0026	0.0023	0.114
	200-400	0.0015	0.0023	-0.436
	400-600	0.0034	0.0023	0.392
	600-800	0.0041	0.0023	0.574
	800-1000	0.0014	0.0023	-0.473
	1000-1200	0.0001	0.0023	-3.491
	1200-1400	0.0009	0.0023	-0.990
	>1400	0	0.0023	0

Slope (º)	0-5	0.0015	0.0023	-0.4498
	5-10	0.0025	0.0023	0.0959
	10-20	0.0021	0.0023	-0.0845
	20-30	0.0026	0.0023	0.1256
	30-40	0.0038	0.0023	0.4940
	> 40	0.0029	0.0023	0.2201
Plan Curvature	Concave	0.0030	0.0023	-0.258
	Planar	0.0022	0.0023	0.053
	Convex	0.0026	0.0023	-0.124
Profile Curvature	Concave	0.0026	0.0023	0.105
	Planar	0.0022	0.0023	-0.045
	Convex	0.0025	0.0023	0.088

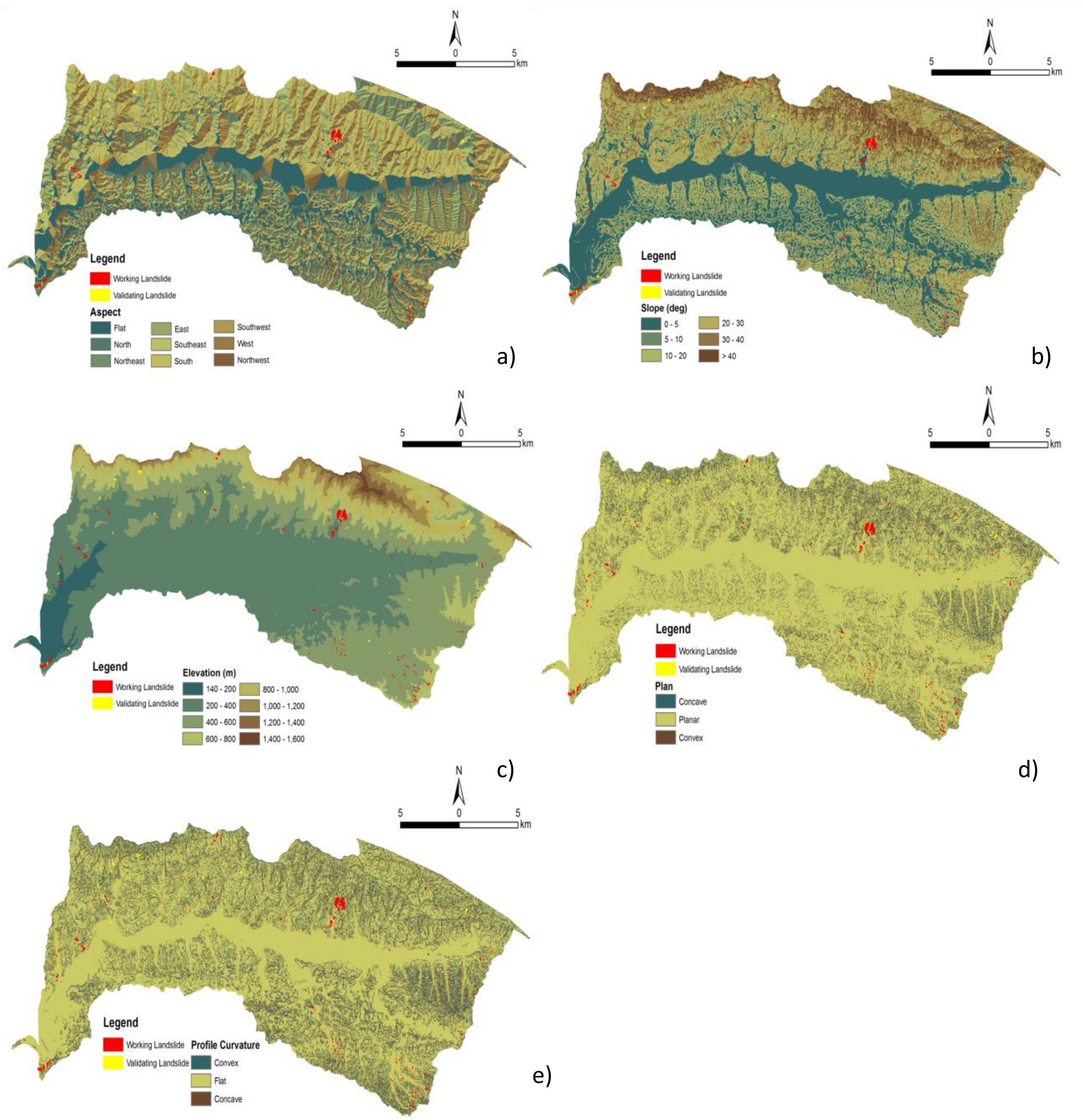

Figure 5. Topographic factors: a) aspect, b) slope, c) elevation, d) plan curvature and e) profile curvature

But the field observations showed that the Middle Siwaliks are also equally prone to landslides due to the differential weathering between the sandstone and softer mudstone beds. The Upper Siwaliks also have significant number of landslides mainly at the sources of the streams. The streams in this are generally ephemeral and wash a huge amount of sediments during monsoon.

Table 2. Landslide distribution in different hydrologic factors

Factor	Class	Dense Class	Dense Map	Weight
TWI	<-2	0.0023	0.0023	0.025
	-2-3	0.0025	0.0023	0.085
	3-8	0.0022	0.0023	-0.019
	>8	0.0016	0.0023	-0.388
Proximity	0 25m	0.0023	0.0023	-0.017
	25 50m	0.0030	0.0023	0.254
	50 75m	0.0032	0.0023	0.328
	75 100m	0.0024	0.0023	0.027
	>100m	0.0022	0.0023	-0.053
SPI	<-8	0.0021	0.0023	-0.105
	-8--4	0.0019	0.0023	-0.188
	-4--1	0.0017	0.0023	-0.321
	-1-1	0.0028	0.0023	0.202
	>1	0.0030	0.0023	0.261

Table 3. Landslide distribution in different landuse classes

Factor	Class	Dense Class	Dense Map	Weight
Landuse	Built-Up	0	0.0023	0
	Barren Land	0.0040	0.0023	0.541
	Cultivation	0.0015	0.0023	-0.404
	Forest	0.0025	0.0023	0.101
	Bush and Grassland	0.0004	0.0023	-1.876
	River Body	0.0020	0.0023	-0.139
	Ponds and Lake	0	0.0023	0

Table 4. Landside distribution in different geological formations

Factor	Class	Dense Class	Dense Map	Weight
Geology	Q	0.0013	0.0023	-0.605
	US	0.0016	0.0023	-0.373
	MS	0.0013	0.0023	-0.592
	LS	0.0061	0.0023	0.976
	PreS	0.0009	0.0023	-0.944

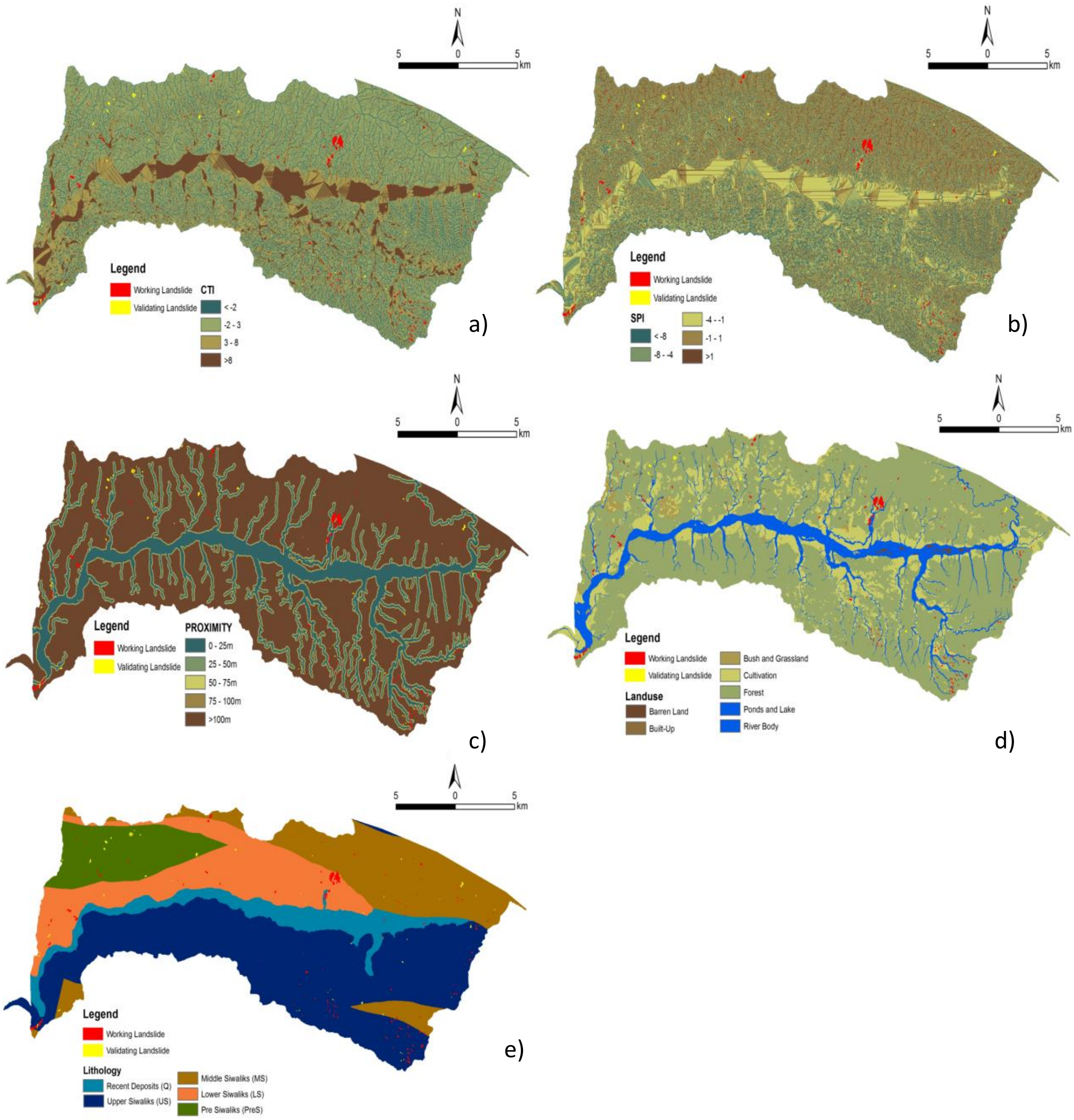

Figure 6. Other landslide causative factor maps: a) CTI b) SPI c) drainage proximity d) land use, and e) geology

Landslide Susceptibility Map

All of these factor maps are analyzed in GIS and MS-Excel to assign weight values for each class. Then, these weight values were used during overlaying of the factor maps in QGIS to produce a landslide susceptibility map (Fig. 7) of the study area. The susceptibility map is divided into 5 classes on the basis of natural breaks: very low, low, moderate, high and very high.

The landslide susceptibility map shows that the coverage of very high, high, moderate, low, and very low susceptibility classes is 1.15%, 49.93%, 30.17%, 11.48% and 11.28% area, respectively (Table 5). With respect to geological formations, Middle Siwalik comprises of most of the high susceptibility class followed by Lower Siwaliks (Table 6). Northern portion of the watershed falls under very high susceptible class. The central north and northeastern parts are even more susceptible to landslides. Particularly, the village named Ahale is entirely under very highly susceptible zone. The rocks of those areas primarily belong to the Middle Siwaliks along with the Lower Siwaliks in some portions. The area also consists of high elevation along with steep slopes which make it more favorable for the landslide occurrence. The differential weathering found in the Middle Siwaliks that is comprised of the stronger sandstone beds and weaker mudstone beds should have provided favorable conditions for the landslide occurrences in this area. The area around Baseri, Goppegaun and Mathilo Deujor are also under very high landslide susceptibility zones. Most of the northernmost parts of the area and southeastern part of the areas fall under the high susceptible zone. Other than that, the southern and southwestern parts of the area are found under the moderate landslide susceptibility zone, which are mostly comprised of the Upper Siwaliks. The area near to the recent river terraces and older terraces are under the low landslide susceptibility zone (Fig. 7).

Table 5. Area percentage of different landslide susceptibility classes in the study area

Landslide susceptibility class				
Very Low	Low	Moderate	High	Very high
11.28	11.48	30.17	45.93	1.15

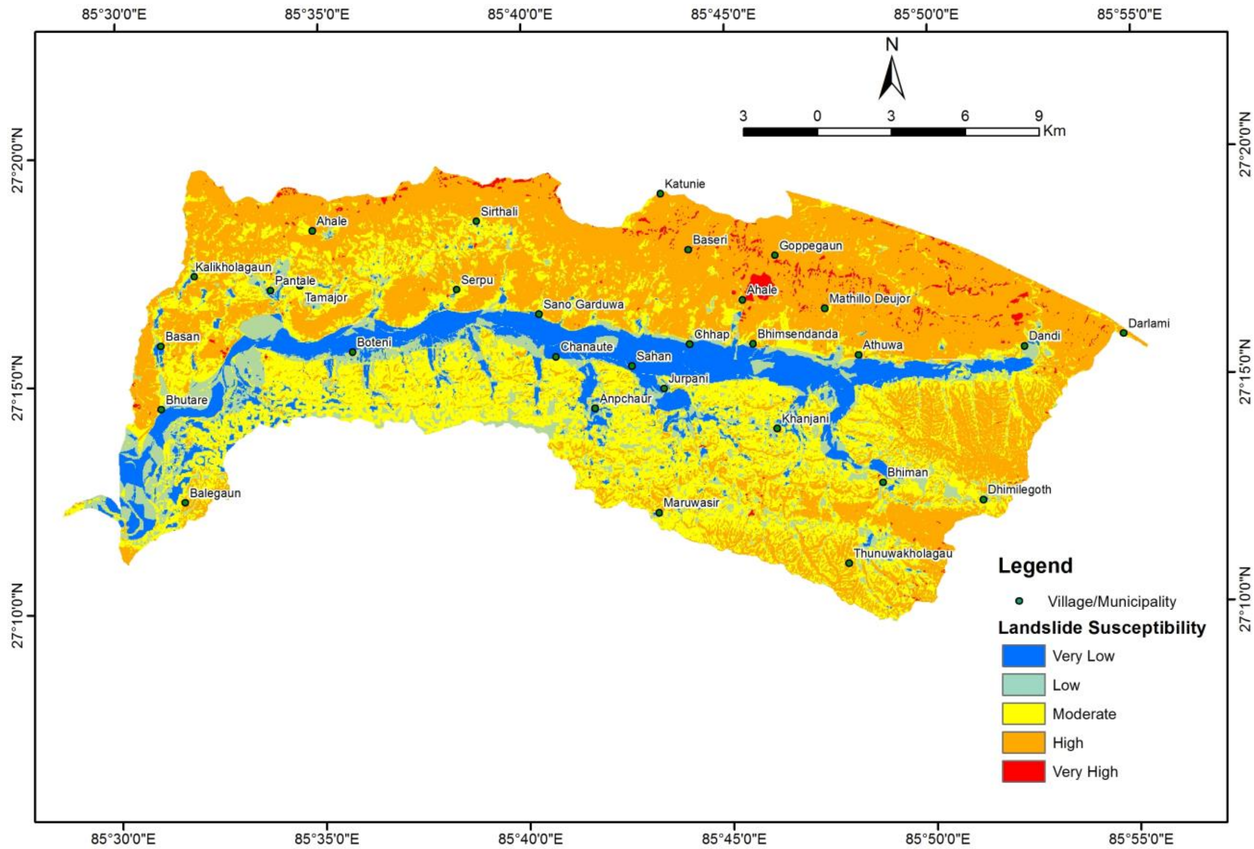

Figure 7. Landslide susceptibility map of the study area

Table 6. Percentage of area of landslide susceptibility classes in different geological formations

		Landslide susceptibility class				
Geological formation	Short ID	Very Low	Low	Moderate	High	Very High
Lower Siwaliks	LS	0.58	1.44	3.97	12.46	0.71
Upper Siwaliks	US	3.89	7.61	20.58	9.71	0.12
Pre Siwaliks	PreS	0.14	0.58	3.40	5.70	0.08
Middle Siwaliks	MS	0.09	0.36	1.55	16.63	1.44
Recent Deposits	Q	6.58	1.48	0.57	0.31	0.01

Validation of Results

The performance of the model was verified and validated using the success rate and prediction rate curves. The total landslide data was divided into working data (75% of total landslides) and validating data (25% of total landslides). The success rate curve was obtained by plotting the percentage of the working landslides against the percentage of the susceptibility class. Similarly, the prediction rate curve (Fig. 8) was obtained by plotting the percentage of the validating landslides against the percentage of the susceptibility class. The prediction rate (75%) was higher than the success rate (66%) for this InfoVal method. The accuracy values are somewhat affected by the difference in the landslide characteristics and types occurring in the study area.

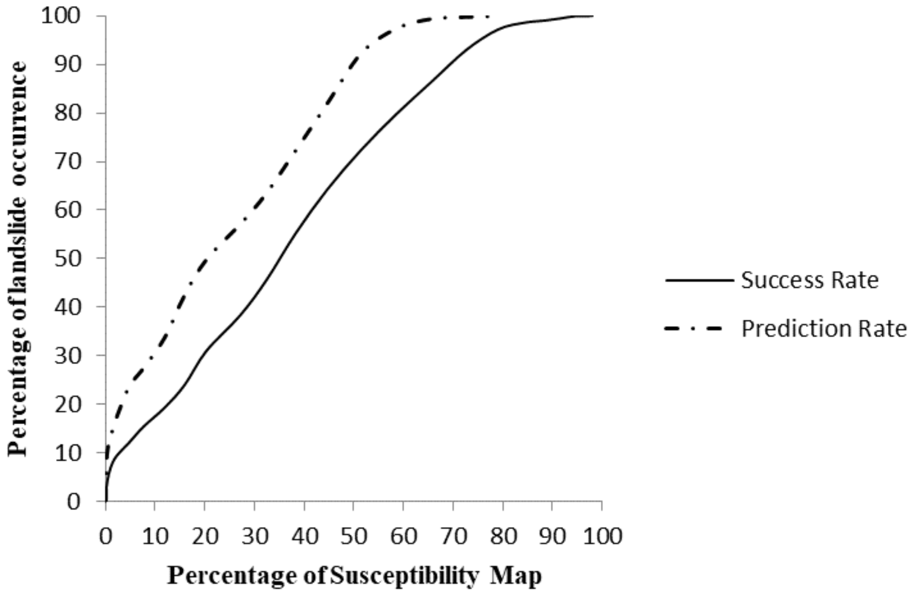

Figure 8. Success rate and prediction rate curves for the validation of landslide susceptibility

The use of the InfoVal method in this study is consistent with previous applications by Regmi *et al.* (2014) and Bhandari *et al.* (2024), demonstrating similar accuracy levels (66% success rate and 75% predictive accuracy). However, studies utilizing hybrid models have reported higher predictive performance, suggesting that integrating additional statistical techniques could further improve model reliability (Chen *et al.*, 2018).

While comparing with the past studies, the result of this study aligns with previous studies conducted in the Siwalik region of Nepal, in terms of landslide-prone zones, geotechnical factors, and landslide susceptibility distribution. Similar to findings by Bhandari *et al.* (2024) in the Siwalik Hills, this study also identified that the Middle Siwaliks and Lower Siwaliks are the most landslide-prone zones. This result is consistent with Dhakal (2015) and Paudyal *et al.* (2021), which identified weak sedimentary rocks, steep slopes, and high elevations as primary contributors to slope instability in Nepal's Siwalik Belt. Moreover, the low susceptibility in the river terraces aligns with Siddle *et al.* (1991) and Van Westen (2000), who found that alluvial and older terrace deposits exhibit relatively lower landslide distribution.

CONCLUSIONS

The landslides in Chure area of Nepal are mostly caused by the natural factors like weak rock types, intense weathering and differential weathering together with the human intervention. The InfoVal method used in this study is one of the simple and popular bivariate statistical methods to analyze the landslide susceptibility of an area and prepare a landslide susceptibility map. The landslide susceptibility map of Marin Khola watershed prepared in this study shows that the northern part of the watershed in general, and the central north and northeastern part in particular, falls under the very high to high susceptible zones. These areas comprise of higher elevation and steeper slopes. Among the settlement areas, the village named Ahale within Marin Khola watershed is particularly under the very high landslide susceptible zone. Geologically, the Middle Siwaliks are the most susceptible units in the study area in terms of landslides. The massive beds of the sandstones with steeper slope and seeping groundwater are some of the major causes for this high susceptibility in Middle Siwaliks. The accuracy of the model is affected by the landslide types and characteristics. This generally occurs due to the combined effects of the different factor maps used during the preparation of the landslide susceptibility map. This research can be used as a reference for the planning and policy making of the development as well as the conservational works in the research area.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Tribhuvan University and President Chure-Tarai Madesh Conservation Development Board, Government of Nepal for their support during this study.

AUTHOR CONTRIBUTIONS

SD conceptualize the research, set methodology, made manuscript frame, finalized the manuscript; NBT generated the data, analyses in GIS and wrote the first draft of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest while publishing this paper.

DATA AVAILABILITY STATEMENT

The data that supports the findings of the present work are available from the corresponding author upon reasonable request.

REFERENCES

Bhandari, B.P., Dhakal, S., & Tsou, C.-Y. (2024). Assessing the prediction accuracy of frequency ratio, weight of evidence, Shannon entropy, and information value methods for landslide susceptibility in the Siwalik Hills of Nepal. *Sustainability, 16*(5), 2092.

Bhandari, B.P., & Dhakal, S. (2021). Decadal evolution of landslides in the Siwalik Zone: a Case Study of Babai Watershed, Nepal. *Journal of Institute of Science and Technology, 26*(1), 57–62. https://doi.org/10.3126/jist.v26i1.37864.

Bhandari, B.P., & Dhakal, S. (2020). Spatio-temporal dynamics of landslide in the sedimentary terrain: A case of Siwalik zone of Babai watershed, Nepal. *SN Applied Sciences, 2,* 854, https://doi.org/10.1007/s42452-020-2628-0.

Cevik, E., & Topal, T. (2003). GIS-based landslide susceptibility mapping for a problematic segment of the natural gas pipeline, Hendek (Turkey). *Environmental Geology*, 44, 949-962.

Chen, W., Li, W., Xie, X., *et al.* (2018). Landslide susceptibility modeling using hybrid machine learning techniques based on GIS. *Sustainability, 10*(5), 1452.

Cruden, D.M. (1991). A simple definition of a landslide. *Bulletin of the International Association of Engineering Geology, 43*, 27–29.

Dai, F.C., Lee, C.F, Li, J., & Xu, Z.W. (2001). Assessment of landslide susceptibility on the natural terrain of Lantau Island, Hongkong, *Environmental Geology, 40*, 381-391.

Dhakal, S. (2015). Evolution of geomorphologic hazards in Hindu Kush Himalaya, In: Shaw, R., & Nibanupudi, H.K. (Eds.), *Mountain hazards and disaster risk reduction* (pp. 53-72), Springer Japan, doi: 10.1007/978-4-431-55242-0_4.

Lee, S., & Pradhan, B. (2007). Landslide susceptibility mapping using frequency ratio, logistic regression, and artificial neural network models: A case study of Korea. *Environmental Earth Sciences, 53*(1), 117-131.

Paudyal, K.R., Devkota, K.C., Parajuli, B.P., Shakya, P., & Baskota, P. (2021). Landslide susceptibility assessment using open-source data in the Far Western Nepal Himalaya: Case studies from selected local level units. *Journal of Institute of Science and Technology, 26*(2), 31–42. https://doi.org/10.3126/jist.v26i2.41327.

Pradhan, A.M.S., & Kim, Y. (2016). Spatial data analysis and application of evidential belief functions to shallow landslide susceptibility mapping at Mt. Umyeon, Seoul, Korea. *Bulletin of Engineering Geology and Environment*, 76, 1263-1279.

Pradhan, A.M.S., Duwadi, A., & Kim, Y. (2012). Use of different statistical landslide susceptibility methods: A case study of Kulekhani watershed, Nepal. *Journal of Nepal Geological Society, 44*, 1-12.

Regmi, A.D., Devkota, K.C., Yoshida, K., *et al.* (2014). Application of statistical index and weights-of-evidence models in landslide susceptibility mapping. *Arabian Journal of Geosciences, 7*(2), 725-742.

Saaty, T.L. (1980). *The analytical hierarchy process*. McGraw-Hill, New York.

Siddle, H.J., Jones, D.B., & Payne, H.R. (1991). Development of a methodology for landslip potential mapping in the Rhondda Valley (pp. 137-142). In: Chandler, R.J. (Ed.), *Slope stability engineering*. Thomas Telford, London.

Terzaghi, K. (1950). Mechanism of landslides. *Engineering Geology, 1*, 83-123.

TU-CDES. (2016). *Landslide inventory characterization and engineering design for mitigation works of Chure area in ten districts*. Central Department of Environmental Science, Tribhuvan University and Government of Nepal, Chure-Tarai Madhesh Conservation Development Board, Kathmandu.

Van Westen, C.J. (1994). GIS in landslide susceptibility zonation: A review, with examples from the Andes of Colombia (pp. 135-165). In: Price, M.F., & Heywood, D.I. (Eds.), *Mountain environments and geographic information systems*. Taylor and Francis Publishers.

Van Westen, C.J. (1997). *Statistical landslide susceptibility analysis, ILWIS 2.1 for Windows application guide*. ITC Publication, Enschede: pp. 73-84.

Van Westen, C.J. (2000). The modelling of landslide hazards using GIS. *Surveys in Geophysics*, *21*(2-3), 241-255.

Varnes, D.J. (1984). *Landslide hazard zonation: a review of principles and practice*. UNESCO, Paris.

Yalcin, A. (2008). GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey): Comparisons of results and confirmations. *CATENA*, *72*, 1-12.

Yin, K.L., & Yan, T.Z. (1988). *Statistical prediction model for slope instability of metamorphosed rocks*. Proceedings of 5th International Symposium on Landslides, Lausanne, Switzerland (2), pp. 1269–1272.