Probabilistic Evaluation of Landslide Vulnerability along the National Highways of Shimla Tehsil, Himachal Pradesh

C. Prakasam[1*], Aravinth. R[2] and B. Nagarajan[3]

Abstract

The research has been conducted to prioritize the landslide prone regions along the National Highways of the Shimla Tehsil, Himachal Pradesh. National Highway spanning 119.3 kms with a buffered radius of 1000 mts has been taken for the study. The research conducted provides an insight into the vulnerable zones of the National Highways (NH) of the study area through statistical modelling and landslide inventory datasets. The total geographical area of the study is 9351.45 ha. Landslide preparatory factors such as Landuse Landcover, Slope, Geology, Geomorphology, Normalized difference vegetative index (NDVI), aspect etc. have been used for the preparation of landslide vulnerability maps. The layers are integrated in the GIS environment using Weighted Overlay Model for the vulnerability mapping. Based on the results Landslide Vulnerability Mapping has been divided into 4 classes based on the rating ranging from low to very high. Based on the landslide inventory it has been estimated that 40.6% of the landslide occurs in the high category and 27.8% occurs in the very high category list. About 27.3% occurs in the moderate category. The research conducted reveals that out of the 44 landslide inventories 68% of the landslides occurred in the high and very high categories. 27% occurred in the moderately vulnerable category.

Keywords: *Weighted Overlay, National Highways, Shimla Tehsil, Landslide Vulnerability, Landslide Inventory*

[1] **C. Prakasam,** Department of Geography, School of Earth Sciences, Assam University, (A Central University), Diphu Campus, Karbi Anglong, Assam, India.
* Corresponding Author Email: cprakasam@gmail.com
[2] **Aravinth. R,** Department of Geography, School of Earth and Atmospheric Sciences, University of Madras, Chennai, India.
[3] **B. Nagarajan,** National Centre for Geodesy, Indian Institute of Technology Kanpur, Uttar Pradesh, India.

1. Introduction

Landslides are mass movements that are caused under influence of gravity, monsoon rainfall and Unstable Roadcut slopes, exposed barren land on rugged terrains, nature of soil, torrential rainfall, flash floods and earthquakes etc (John et al., 2020; Kaur et al., 2018; Kutlug et al 2020). These landslides are results of both natural disasters and manmade activities (Prasad & Siddique 2020; Singh & Meena, 2020; Youssef & Pourghasemi, 2020).. In India, landslides are one of the most frequent disasters occurred during the rainfall season compared to other natural hazards. Globally landslide causes more social and economic losses than other major disasters (Sekhri et al. 2020; Sridharan & Gopalan, 2020; Thakur et al. 2020). According to IAEG "International Association of Engineering Geology" 14% of the disaster causalities in the world are due to landslide events. Geological Survey of India has said that 0.42 million sq.km of country's surface are prone to landslides where most of it are situated in the Himalayan region and the Western Ghats (Saha & Saha, 2020). Himalaya being one of the youngest mountain constantly undergoes surficial and sub surficial movements due to tectonics and earthquake related activities. As such landslides pose a considerable threat to the various settlements, transportation corridors and barren lands of the Himalayan region where regional climatic condition are the main source of triggers for landslide initiation (Bera et al. 2020; Kutlug et al. 2020; Panahi et al. 2020). Even though monsoon rainfall and earthquake are the main causative factors, anthropogenic activities like slope excavation without proper toe support, forest plantation, building construction along unstable slopes also contribute to mass movements (Prakasam et al. 2020a). Data retrieved from the Regional Meteorological Centre, Shimla suggest that Shimla has been receiving 1250 to 1600 mm of rainfall in recent years. Highly jointed rocks and varying soil nature coupled with the high intensity rainfall made Shimla highly prone for landslide activities (Gobinath et al. 2020; Sridharan & Gopalan, 2020; Prakasam et al., 2020a; Prakasam et al., 2020b). Increased ground vibrations along the unstable road cut slopes due to heavy traffic movement is also of major contributing factor for the reduced slope strength (Ashutosh & Panthee, 2016; Martha, van Westen, Kerle, Jetten, & Vinod Kumar, 2013; Sarkar, Roy, & Raha, 2016). There is no one methodology or model to successfully predict or mitigate landslide scenario and events. Based on the literatures studied statistical methodology combined with field collection of landslide inventory provides best scenario in prediction of landslide vulnerable zones.

The current research is focused on evaluating the landslide prone areas along the National Highways of the Shimla Tehsil, Himachal Pradesh. The research has been carried out based on weighted overlay method coupled with frequency analysis using landslide inventories for the year (2002 to 2020).

2. Study Area

The study area chosen for the research work is the National Highways of the Shimla Tehsil, Himachal Pradesh (Figure 1). The total extend of the NH is 119.33 km. The geographical extent of the study area is 30˚59'3" to 31˚14'10" N and 76˚58'19" to 7˚19'21" E. The total geographical area of the study is 9351.45 ha. The National Highways connects the major locations along the upper reaches of Himachal Pradesh such as Kinnaur, Lahul & Spiti and Chamba to other parts of the country. The NH serves as an important transportation and tourism corridor across the Himachal Pradesh. For research purpose a buffer of 1000mts of the National Highway is taken for the study. Based on the geomorphology of the region retrieved from Soil and Landuse survey of India (SLUSI) maps is highly dissected with steep to moderate slopes in many areas. The study area has fine and coarse loamy soil types extending most of the region. The soil particles are poorly sorted and disintegrates during monsoon season. Slate and Schist are the most common types of rock material found in this part which are weak to moderately strong according to Geological Strength Index (GSI). Settlements, Forest, Shrub land and Barren land are the most dominant Landuse types found along the study area. In recent years Shimla received an annual rainfall of 1250 to 1600mm most of which are monsoon and winter rainfall.

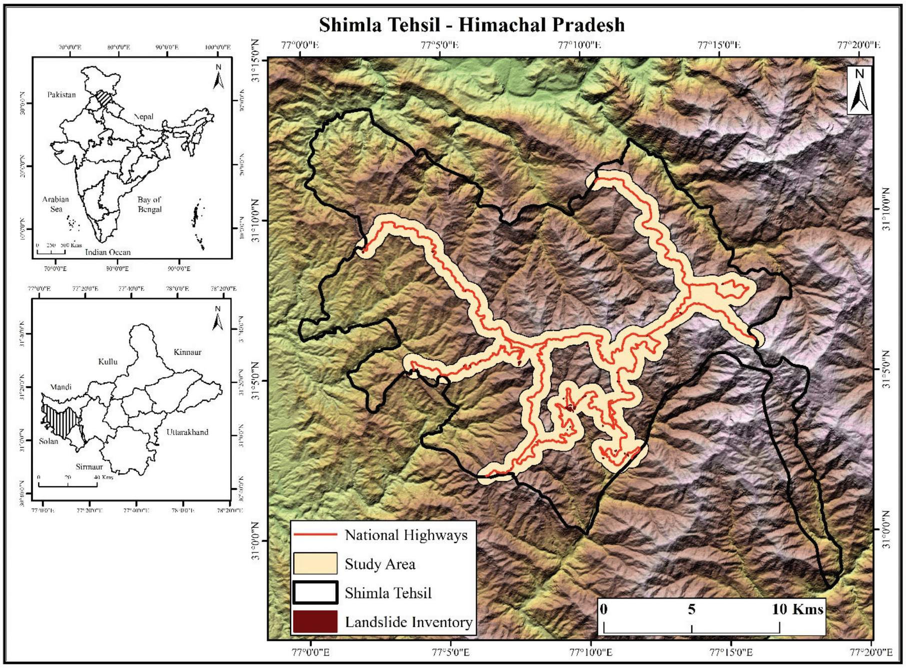

Figure 1: Study Area

3. Materials and Method

The research is focused on evaluating the vulnerability of the Shimla Tehsil and to assess the risk posed by the different vulnerability zones on various landslide factors. Topographic sheets from the Survey of India, Sentinel 2B satellite imageries, Soil, Geology and Geomorphological data retrieved from the "Soil and Landuse Survey of India (SLUSI)" and PALSAR DEM have been used as a data source for studying various causative factors. Various data source used are given in (Tab 1).

Table 1: Datasets

Sl. No	Data Type	Source	Date	Resolution
1	Sentinel – 2B	European Space Agency	2020	10 mts
2	PALSAR DEM	Alaska Satellite Facility	2008	12 mts

3	Topographical maps	Survey of India (53E/04)	1974	1:50,000
4	Landslide Inventory	Google Earth, Sentinel – 2B	2002 to 2020	0.4 mts to 10 mts
5	Geology	Soil and Landuse Survey of India (SLUSI)		1:50,000
6	Soil	Soil and Landuse Survey of India (SLUSI)		1:50,000
7	Geomorphology	Soil and Landuse Survey of India (SLUSI)		1:50,000

The present study uses Weight of evidence model (WOM) to categorize the landslide vulnerable areas of the region. The WOM is a bivariate statistical method that uses various training such as landslide inventory data to predict landslide occurrences (Kaur et al. 2018; Rana et al., 2016; Reichenbach, Rossi, Malamud, Mihir, & Guzzetti, 2018). The WOM model is most suited for regional scale studies of landslide hazards to develop hazard and vulnerability maps with higher accuracy for mitigation strategies. The WOM model used in the current research includes both data driven (statistical method) and knowledge based method for developing accurate Landslide vulnerability and risk maps. Landslide causative factors such as Landuse Landcover, Slope, Soil, Geology, Geomorphology, Aspect, Elevation and Drainage density where differentiated into five types ranging from very low to very high on a numerical scale of 1 to 5 vulnerability and risk assessment. Vulnerability assessment are derived based on the fusion of landslide risk zones and landslide inventory data collected from field work. The causative factors are integrated into the GIS environment to produce Landslide Vulnerability maps. The landslide inventory is then used to evaluated the percent of various class that falls under different scale of vulnerability. The final vulnerability maps are then integrated with the LULC maps to produce risk Assessment map (Fig. 2) of various Landuse features that falls under different vulnerable categories (Nandy, Singh, Das, Kingma, & Kushwaha, 2015; Rautela & Lakhera, 2000; Torkashvand, 2014).

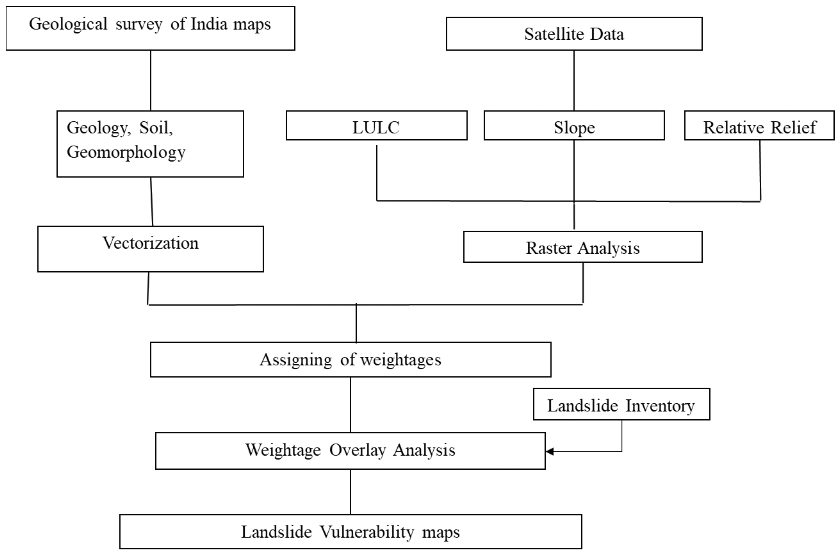

Figure 2: Research Methodology

4. Results and Discussion

4.1 Landslide Inventory

Landslide Inventory data was collected from Google Earth and Sentinel – 2B imageries using Visual Image Interpretation techniques. A total of 44 landslides were demarcated between (2002 to 2020) within 1000 mts of the National Highways and Metalled Roads (Fig 3). Most of the landslides demarcated were debri slides and rock slides were found at few locations. The landslides occurred along the hill cut slopes and along the downside of the slopes where there is bare or no vegetation cover.

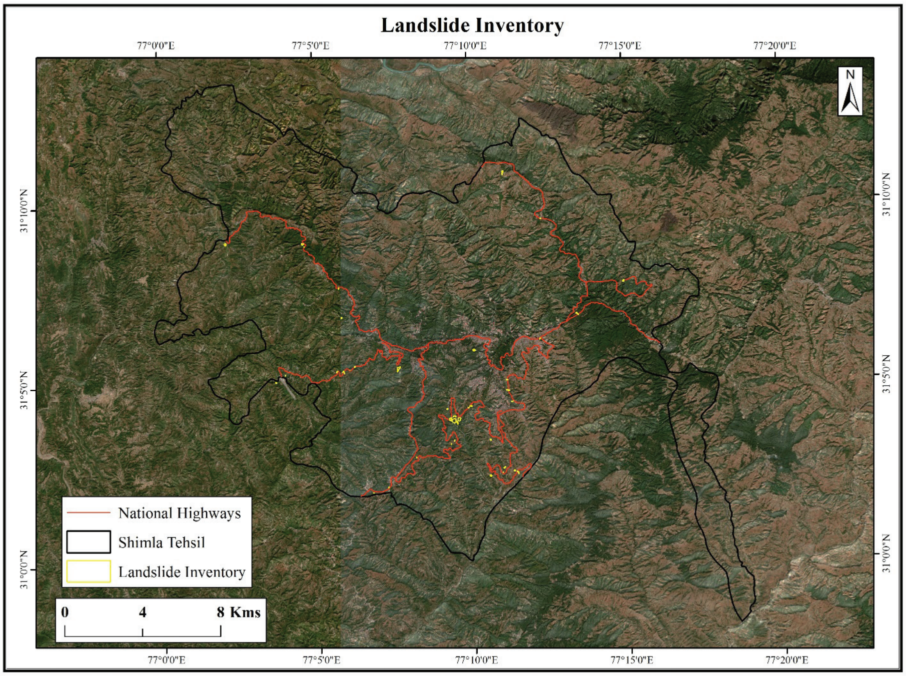

Figure 3: Landslide Inventory

4.2 Landuse Landcover

LULC was interpreted using the Sentinel - 2B satellite Imagery through supervised classification (Fig 4). The LULC was classified based on the NRSC level 1 classification. Four major types were identified in the region namely Built-Up land. Barren land, Forest and Shrub Land (Tab 2). 51% of the area is covered under forest. Shrub Land and Barren land covers about 21% and 17% of the study area. Built-Up land covers only 10%. The landslides are predominantly found in the shrub and barren land where there is less or no vegetation coverage. Bare soil exposed to monsoon rainfall gets dislodged due to gravity and soil overburden leading to slope failure.

Table 2: LULC

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	Built-up Land	941.9	10.07%
2	Barren Land	1625.5	17.38%
3	Forest	4775.4	51.07%
4	Shrub Land	2008.3	21.48%
	Total	**9351.2**	**100.00%**

4.3 NDVI

NDVI stands for Normalized Difference Vegetative Index. NDVI is calculated based on the spectral output of the various features present in the earth surface ranging from -1 to +1. NDVI is calculated using the Infra-Red and Red band of the Sentinel – 2B satellite imagery based on the formula

$$\mathbf{NDVI = (NIR - R) / (NIR + R)}$$

Where, NIR = Near Infra-Red
R = Red

Table 3: NDVI

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	- 0.2 to 0.25	534.1	5.59%
2	0.26 to 0.44	1201.8	12.58%
3	0.45 to 0.59	1662.7	17.41%
4	0.6 to 0.71	2724.7	28.53%
5	0.71 to 1	3427.0	35.88%
	Total	**9351.2**	**100.00%**

NDVI has been classified into five different classes ranging from -0.2 to 1 (Tab 3). NDVI values between 0.6 to 1 accounts for about 64% of the study area which includes moderate to dense vegetation. Sparse vegetation and Barren land accounts for 30% of the study area (Fig 5). Landslides are predominantly located in the Barren land and Shrub land areas which has no vegetation.

4.4 Drainage Density

Drainage Density (DD) estimates the frequency of drainages within a particular area. Drainage Density is an important parameter as water percolation and rainfall runoff are discharged in huge amount through the drainage channels. Drainages are interpreted from the Survey of India Toposheets. The results reveal that DD of 1.7 to 3.8 per sq.km makes around 63.6% of the total study area. The rest makes for only about 12%, 16% and 8% (Tab 4 & Fig 6).

Table 4: Drainage Density

Sl. No.	Class (Density/km2)	Area (ha)	Area in Percent (%)
1	0 to 1.6	1129.3	12.08%
2	1.7 to 2.7	2953.2	31.58%
3	2.8 to 3.8	3007.2	32.16%
4	3.9 to 5.2	1506.0	16.10%
5	5.3 to 7.5	755.5	8.08%
	Total	**9351.2**	**100.00%**

4.5 Soil

Soil plays important role in landslide initiation based on the particle size and sorting. Soil data was extracted from the data retrieved from Soil and Landuse Survey of India (SLUSI). Four major types namely Fine & Coarse loamy, Habitation and loamy skeletal were found along the region (Fig 7). Fine loamy covers about 94% of the study area while the rest of the types covers a total of 6% combined (Tab 5). The soils are poorly sorted and arranged in this region causing landslide initiation.

Table 5: Soil

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	Coarse Loamy	77.7	0.83%
2	Fine Loamy	8824.8	94.37%
3	Habitation	342.8	3.66%
4	Loamy Skeletal	106	1.13%
	Total	**9351.2**	**100.00%**

4.6 Geology

Geology refers to the rock types formation. The study area two major dominant rock formations Schist and Slate. Slate accounts for 93% of the study area and Habitation accounts for only about 5.33%. Schist covers a mere 1.43% (Fig 8). The rock types found along these area ranges from weak to moderately strong. The rocks are heavily jointed along the rock cut slopes and pose threatening to landslide during monsoon seasons. Most of the landslides noted occurred along the slate rock types (Tab 6). Some of the landslides occurred near the settlements are structurally controlled rock slides involving wedge failure.

Table 6: Geology

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	Habitation	498.9	5.33%
2	Schist	139.1	1.49%
3	Slate	8713.3	93.18%
	Total	**9351.2**	**100.00%**

4.7 Geomorphology

Only a single geomorphological type is found in the area. Undifferentiated Mountainside Slope with a total coverage of 94.6% has been found (Fig. 9). The hillside has rugged terrain and highly dissected regions in the valleys and peaks. Drainage system are more dendritic and parallel in nature in Shimla tehsil (Tab 7).

Table 7: Geomorphology

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	Habitation	498.9	5.33%
2	Undifferentiated Mountainside Slope	8852.3	94.67%
	Total	**9351.2**	**100.00%**

4.8 Elevation

Elevation is being considered as parameter to determine the landslide frequencies occurring at particular elevation. PALSAR DEM has used to classify elevation and estimate other elevation based ranges. The ranges were classified into five types based on the equal interval method. Elevation range more than 2200 covers only 9.9% of the study area (Fig. 10). The other classification covers a total area of 16.1%, 29.7%, 23.2%, 20.9% etc. (Tab 8).

Table 8: DEM

Sl. No.	Elevation (mts)	Area (ha)	Area in Percent (%)
1	< 1500	1513.2	16.18%
2	1,501 to 1,800	2781.3	29.74%
3	1,801 to 2000	2170.7	23.21%
4	2,001 to 2200	1959.5	20.95%
5	> 2200	926.5	9.91%
	Total	**9351.2**	**100.00%**

4.9 Slope

Slope indicates the dip of a rock bed with respect to the horizontal earth surface. Slope is a major landslide causative factor as such landslide and mass movements tend to occur along the steeper slopes compared to the flat regions. The slope is classified using the PALSAR DEM data into five classification ranging from very gentle to very steep (Fig. 11). The results reveals that moderate and steep slopes have a combined area of 51% and gentle slopes covers about 29.2% of the study area (Tab 9).

Tab 9: Slope

Sl. No.	Class (Degrees)	Area (ha)	Area in Percent (%)
1	< 17	1344.6	14.38%
2	18 to 25	2735.8	29.26%
3	26 to 32	2876.7	30.76%
4	33 to 42	1916.3	20.49%
5	> 42	477.9	5.11%
	Total	**9351.2**	**100.00%**

4.10 Aspect

Aspect estimates the direction of slopes. Aspect is a governing factor because landslides occurs along regions that are receiving high water percolation, soil burden and steep slopes etc. Aspect helps predicting the direction of landslide occurrence based on the landslide frequencies. Most of the slopes are equally distributed between various direction ranging from north east to north west (Fig. 12 & Tab 10).

Table 10: Aspect

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	Flat	1.4	0.01%
2	North	572.8	6.12%
3	Northeast	1117.0	11.95%
4	East	1139.2	12.18%
5	South East	1109.6	11.87%
6	South	1149.6	12.29%
7	South West	1538.8	16.45%
8	West	1111.8	11.89%
9	North West	1077.2	11.52%
10	North	533.0	5.71%
	Total	**9351.2**	**100.00%**

4.11 Curvature

Curvature indicates the relief nature of the mountain region. Curvature is divided into five types ranging from -28 to 26 indicating the surface is extremely relief in nature (Fig. 13). Class III and IV type of curvature contributes a total of 82.8% of the study area indicating the surface is extremely rough (Tab 11).

Table 11: Curvature

Sl. No.	Class	Area (ha)	Area in Percent (%)
1	-28 to -3.9	135.7	1.45%
2	-3.8 to -1.4	1213.9	12.98%
3	-1.3 to 0.59	4069.1	43.51%
4	0.6 to 3.1	3587.0	38.37%
5	3.2 to 26	344.5	3.68%
	Total	**9351.2**	**100.00%**

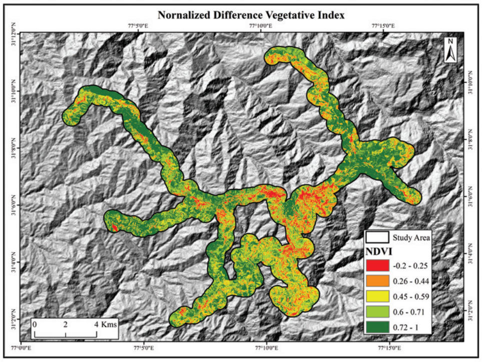

Figure 4: Landuse Landcover

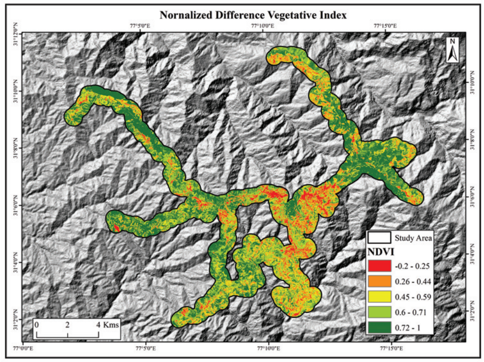

Figure 5: NDVI

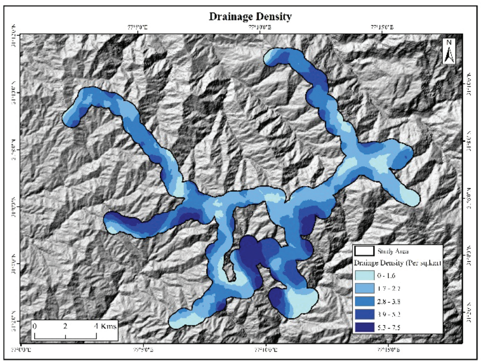

Figure 6: Drainage Density

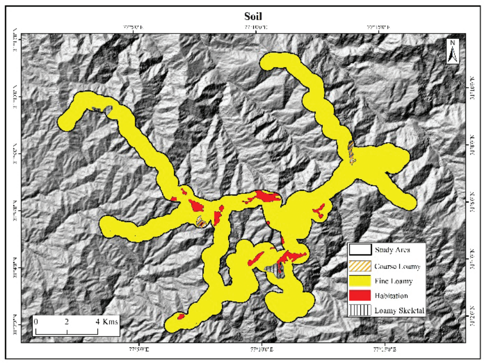

Figure 7: Soil

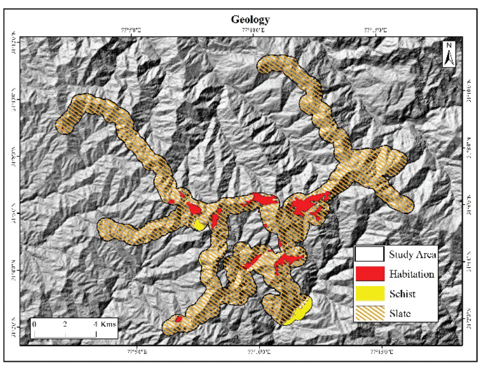

Figure 8: Geology

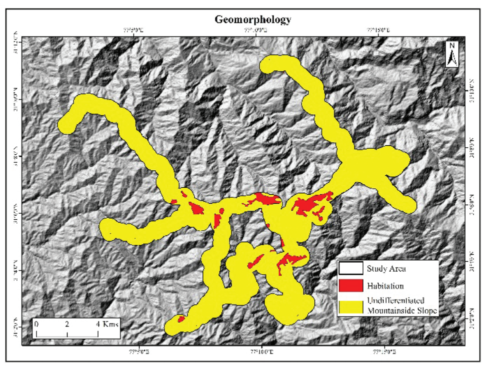

Figure 9: Geomorphology

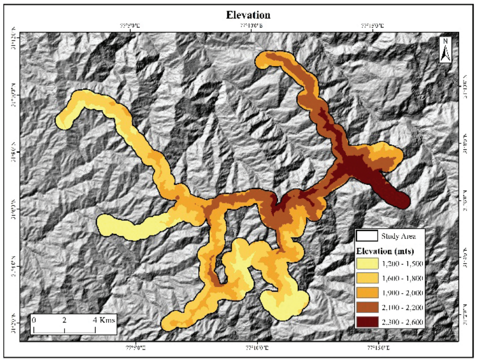

Figure 10: DEM

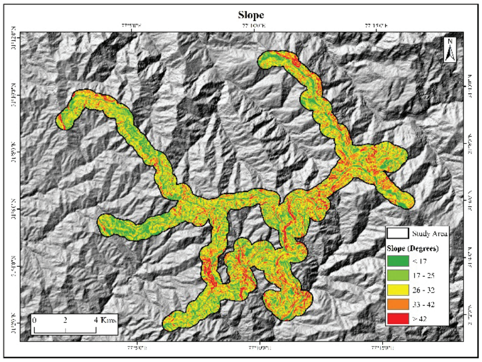

Figure 11: Slope

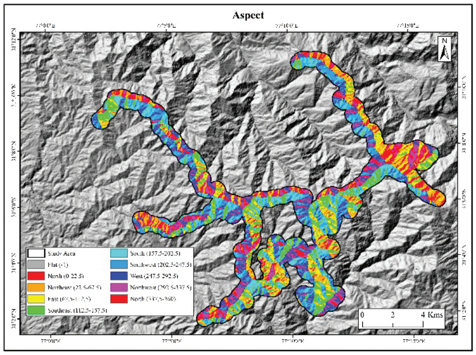

Figure 12: Aspect

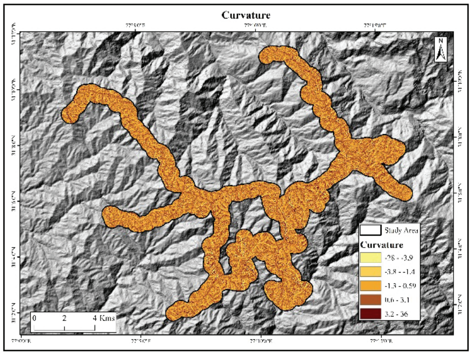

Figure 13: Curvature

5. Landslide Vulnerability Assessment

Vulnerability assessment was calculated using the Weighted Overlay method. Causative factors such as LULC, Soil, Geology, Geomorphology, Aspect, Slope have been taken into account for the vulnerability mapping. The weightage has been assigned based on the statistical model and experts knowledge. The final Landslide vulnerability map was prepared by integrating the all the raster layers in the GIS environment using the Weighted Overlay Sum model.

Tab 13: Landslide Vulnerability Class

Sl. No.	Class	Pixels (Causative Factor)	Pixels (Landslide)	Landslide (%)
1	Low	2290	45	4.27%
2	Moderate	266397	288	27.32%
3	High	219394	428	40.61%
4	Very High	110397	293	27.80%
	Total Pixel Count	**598478**	**1054**	**100.00%**

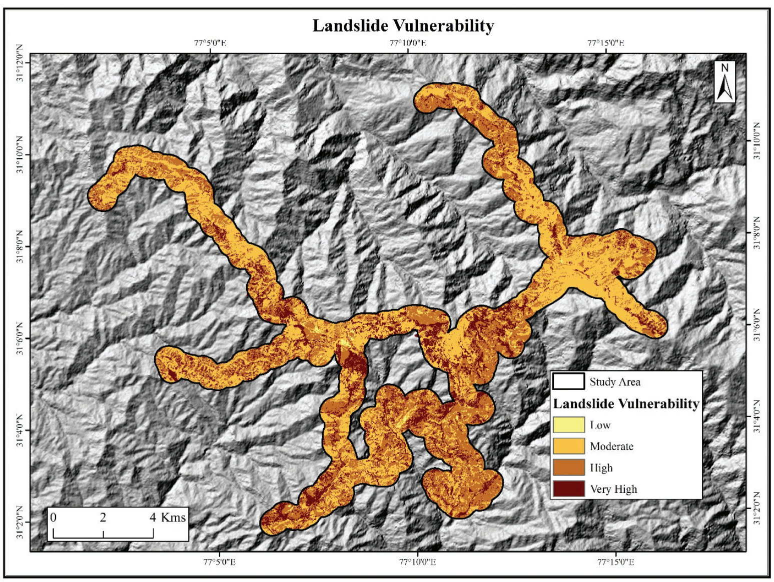

Figure 14: Landslide Vulnerability (Shimla NH)

Figure 15: Indicates landslides along major national highways of the Shimla town

Figure 16: Settlements located along highly jointed rock surface; Soil slipping along the NH

The Landslide Vulnerability Mapping has been divided into 4 classes based on the rating ranging from low to very high. Based on the landslide Inventory it has estimated that 40.6% of the landslide occurs in the high category and 27.8% occurs in the very category list (Fig. 14). About 27.3% occurs in the moderate category. Most of the soil and lithology is composed of Debri and mud particles leading to such type of landslides (Fig. 15 and Fig. 16). Most of the high and very high vulnerable regions are located along the central part and as well as southern part of the study area. The landslide vulnerability map reveals that 67% of the total study area are composed of high and very high vulnerable regions located within 1000 mts of the NH (Tab 13). These areas predominantly include Built-Up lands, Shrub lands and Barren lands adjoining the national highways.

6. Conclusion

National Highways of Shimla Tehsil are highly prone to landslide and mass movements especially during the monsoon and winter rainfall time. The research conducted reveals that out of the 44 landslide inventories collected from various source of satellite imageries 68% of the landslides occurred in the high and very high category. 27% occurred in the moderately vulnerable category. The research reveals that 96% of the study area which is less than 1000 mts from the National Highways are prone to landslide initiation. The research provides a quick and accurate estimation of landslide vulnerable areas using both statistical and expert based knowledge system. The research provides a quick and accurate estimation of landslide vulnerable areas using both statistical and expert based knowledge system. Landslide investigation should promote disaster preparedness and need to establish detailed network of communication that include Governmental, Non-governmental and local NGO's to provide effective disaster related activities during pre-disaster, actual disaster situations and post-disaster times.

Regions such as Shimla are highly prone to landslides. Careful consideration must be taken before any constructions. Due to the highly rugged nature of the terrain high-resolution 3D modeling and site-specific detailed investigations will provide more insight into the developmental activities along these landslide-prone areas. To help control the slides planting of different species of grass can be done. Planting fast-growing, deep-rooted trees along the crown and main scarp can be done and also in the lower reaches of slide zones help in stabilizing the slope.

Acknowledgement

We would like to thank DST and CSIR, New Delhi, government of India for funding the research work.

We extend our thanks to Dr. Naresh Kochhar, Retd. Professor, Department of Geology, Panjab University, Chandigarh, India and Dr. Tejpal Singh, Sr. Scientist, Central Scientific Instruments Organization (CSIO-CSIR), Chandigarh, India for their valuable suggestions and guidelines.

References

1. Ashutosh, P. K. S., & Panthee, K. S. 2016. Rockfall analysis along transportation corridors in high hill slopes. Environmental Earth Sciences, 1–11. https://doi.org/10.1007/s12665-016-5489-5
2. Bera, S., Guru, B., Chatterjee, R., & Shaw, R. 2020. International Journal of Disaster Risk Reduction Geographic variation of resilience to landslide hazard : A household-based comparative studies in Kalimpong hilly region , India. International Journal of Disaster Risk Reduction, 46(September 2019), 101456. https://doi.org/10.1016/j.ijdrr.2019.101456
3. Gobinath, R., Ganapathy, G. P., & Akinwumi, I. I. 2020. Stabilisation of natural slopes using natural plant root as reinforcing agent. Materials Today: Proceedings, (xxxx). https://doi.org/10.1016/j.matpr.2020.08.227
4. Jamwal, A., Kanwar, N., & Kuniyal, J. C. 2020. Use of geographic information system for the vulnerability assessment of landscape in upper Satluj basin of district Kinnaur , Himachal Pradesh , India. Geology, Ecology, and Landscapes, 4(3), 171–186. https://doi.org/10.1080/24749508.2019.1608410
5. John, J., Bindu, G., Srimuruganandam, B., & Wadhwa, A. 2020. Annals of GIS Land use / land cover and land surface temperature analysis in Wayanad district , India , using satellite imagery. Annals of GIS, 00(00), 1–18. https://doi.org/10.1080/19475683.2020.1733662
6. Kaur, H., Gupta, S., Parkash, S., & Thapa, R. (2018). Knowledge-driven method : a tool for landslide susceptibility zonation (LSZ). Geology, Ecology, and Landscapes, 00(00), 1–15. https://doi.org/10.1080/24749508.2018.1558024
7. Kutlug, E., Colkesen, I., Semih, S., & Akgun, A. 2020. Computers and Geosciences Developing comprehensive geocomputation tools for landslide susceptibility mapping : LSM tool pack. Computers and Geosciences, 144(March), 104592. https://doi.org/10.1016/j.cageo.2020.104592
8. Martha, T. R., van Westen, C. J., Kerle, N., Jetten, V., & Vinod Kumar, K. 2013. Landslide hazard and risk assessment using semi-automatically created landslide inventories. Geomorphology, 184, 139–150. https://doi.org/10.1016/j.geomorph.2012.12.001
9. Nandy, S., Singh, C., Das, K. K., Kingma, N. C., & Kushwaha, S. P. S. 2015. Environmental vulnerability assessment of eco-development zone of Great Himalayan National Park , Himachal Pradesh , India. Ecological Indicators, 57, 182–195. https://doi.org/10.1016/j.ecolind.2015.04.024
10. Panahi, M., Gayen, A., Reza, H., Rezaie, F., & Lee, S. 2020. Science of the Total Environment Spatial prediction of landslide susceptibility using hybrid support vector regression (SVR) and the adaptive neuro-fuzzy inference system (ANFIS) with various metaheuristic algorithms. Science of the Total Environment, 741, 139937. https://doi.org/10.1016/j.scitotenv.2020.139937
11. Prakasam, C., Aravinth, R., Kanwar, S, Varinder., Nagarajan, B., (2021). Mitigation and Management of Rainfall Induced Rockslides along the National Highways of Himalayan region, India. Geomatics, Natural Hazards and Risk, 12(1), Pp 1401-1424. https://doi.org/10.1080/19475705.2021.1928772
12. Prakasam, C., Aravinth, R., Kanwar, S, Varinder., Nagarajan, B. (2020a). Comparative Evaluation of Various Statistical Models and Its Accuracy for Landslide Risk Mapping: A Case Study on Part of Himalayan Region, India. In; Kanlı, Ali Ismet . (eds) Slope Engineering, IntechOpen, London, 1-18, DOI: 10.5772/intechopen.94347.
13. Prakasam, C., Aravinth, R., Kanwar, Varinder, S and Nagarajan, B (2020b). Comparative study between the weighted overlay and fuzzy logic models for landslide vulnerability mapping – a case study of Rampur tehsil, Himachal Pradesh. In: Kanwar V., Shukla S. (eds) Sustainable Civil Engineering Practices. Lecture Notes in Civil Engineering, vol 72. Springer, Singapore. Pp 155-171. https://doi.org/10.1007/978-981-15-3677-9_16
14. Prakasam, C., Aravinth, R., Nagarajan, B., & Kanwar, V. S. (2020c). Site-specific geological and geotechnical investigation of a debris landslide along unstable road cut slopes in the Himalayan region , India. Geomatics, Natural Hazards and Risk, 11(1), 1827–1848. https://doi.org/10.1080/19475705.2020.1813812

15. Prakasam, C., Aravinth, R., Kanwar, S, Varinder., Nagarajan, B. (2019) Kinematic Analysis of Rainfall Induced Rock Slide Along Roadcut Slopes – A Case Study on Dhalli Landslide, Himalayan Region, Disaster & Development (NIDM, Govt of India), Vol 8(1), Pp 97-109. 1- D&D Management- NIDM - v8-N1- Dec 14 to Jan 19- 10-02-21.indd
16. Prasad, S., & Siddique, T. (2020). Journal of Rock Mechanics and Geotechnical Engineering Stability assessment of landslide-prone road cut rock slopes in Himalayan terrain : A fi nite element method based approach. Journal of Rock Mechanics and Geotechnical Engineering, 12(1), 59–73. https://doi.org/10.1016/j.jrmge.2018.12.018
17. Rana, N., Kumar, P., Bisht, P., Bagri, D. S., Wasson, R. J., & Sundriyal, Y. (2016). Abstract the Weights of Evidence method. Geomorphology. https://doi.org/10.1016/j.geomorph.2016.11.008
18. Rautela, P., & Lakhera, R. C. (2000). Landslide risk analysis between Giri and Tons Rivers in Himachal Himalaya (India). ITC Journal, 2(3–4), 153–160. https://doi.org/10.1016/S0303-2434(00)85009-6
19. Reichenbach, P., Rossi, M., Malamud, B. D., Mihir, M., & Guzzetti, F. (2018). Earth-Science Reviews A review of statistically-based landslide susceptibility models. Earth-Science Reviews, 180(March), 60–91. https://doi.org/10.1016/j.earscirev.2018.03.001
20. Saha, A., & Saha, S. (2020). Comparing the efficiency of weight of evidence, support vector machine and their ensemble approaches in landslide susceptibility modelling: A study on Kurseong region of Darjeeling Himalaya, India. Remote Sensing Applications: Society and Environment, 100323. https://doi.org/10.1016/j.rsase.2020.100323
21. Sarkar, S., Roy, A. K., & Raha, P. (2016). Deterministic approach for susceptibility assessment of shallow debris slide in the Darjeeling Himalayas, India. Catena, 142, 36–46. https://doi.org/10.1016/j.catena.2016.02.009
22. Sekhri, S., Kumar, P., Fürst, C., & Pandey, R. (2020). Mountain speci fi c multi-hazard risk management framework (MSMRMF): Assessment and mitigation of multi-hazard and climate change risk in the Indian Himalayan Region. Ecological Indicators, 118(April), 106700. https://doi.org/10.1016/j.ecolind.2020.106700
23. Sema, H.V., Guru, B. & Veerappan, R. (2017). Fuzzy gamma operator model for preparing landslide susceptibility zonation mapping in parts of Kohima Town, Nagaland, India. Model. Earth Syst. Environ. 3, 499–514 https://doi.org/10.1007/s40808-017-0317-9
24. Shit, P.K., Bhunia, G.S. & Maiti, R. (2016). Potential landslide susceptibility mapping using weighted overlay model (WOM). Model. Earth Syst. Environ. 2, 21 https://doi.org/10.1007/s40808-016-0078-x
25. Sridharan, A., & Gopalan, S. (2020). Materials Today : Proceedings Correlations among properties of lithological units that contribute to earthquake induced landslides. Materials Today: Proceedings, (xxxx). https://doi.org/10.1016/j.matpr.2020.07.265
26. Sur, U., Singh, P., & Meena, S. R. (2020). Landslide susceptibility assessment in a lesser Himalayan road corridor (India) applying fuzzy AHP technique and earth-observation data Landslide susceptibility assessment in a lesser Himalayan road corridor (India) applying fuzzy AHP technique and. Geomatics, Natural Hazards and Risk, 11(1), 2176–2209. https://doi.org/10.1080/19475705.2020.1836038
27. Thakur, M., Singh, G., & Malik, J. N. (2020). Geological and geomorphic evidences of neotectonic activity along the Himalayan Frontal Thrust , Nahan Salient , NW Himalaya , India. Quaternary International, (July). https://doi.org/10.1016/j.quaint.2020.07.014
28. Torkashvand, A. M. (2014). The preparation of landslide map by Landslide Numerical Risk Factor (LNRF) model and Geographic Information System (GIS). The Egyptian Journal of Remote Sensing and Space Sciences, 17(2), 159–170. https://doi.org/10.1016/j.ejrs.2014.08.001
29. Youssef, A. M., & Pourghasemi, H. R. (2020). Landslide susceptibility mapping using machine learning algorithms and comparison of their performance at Abha Basin, Asir Region, Saudi Arabia. Geoscience Frontiers. https://doi.org/10.1016/j.gsf.2020.05.010
30. Prasad, S., & Siddique, T. 2020. Journal of Rock Mechanics and Geotechnical Engineering Stability assessment of landslide-prone road cut rock slopes in Himalayan terrain : A fi nite element method based approach. Journal of Rock Mechanics and Geotechnical Engineering, 12(1), 59–73. https://doi.org/10.1016/j.jrmge.2018.12.018
31. Rana, N., Kumar, P., Bisht, P., Bagri, D. S., Wasson, R. J., & Sundriyal, Y. 2016. Abstract the Weights of Evidence method. Geomorphology. https://doi.org/10.1016/j.geomorph.2016.11.008
32. Rautela, P., & Lakhera, R. C. 2000. Landslide risk analysis between Giri and Tons Rivers in Himachal Himalaya (India). ITC Journal, 2(3–4), 153–160. https://doi.org/10.1016/S0303-2434(00)85009-6
33. Reichenbach, P., Rossi, M., Malamud, B. D., Mihir, M., & Guzzetti, F. 2018. Earth-Science Reviews A review of statistically-based landslide susceptibility models. Earth-Science Reviews, 180(March), 60–91. https://doi.org/10.1016/j.earscirev.2018.03.001
34. Saha, A., & Saha, S. 2020. Comparing the efficiency of weight of evidence, support vector machine and their ensemble approaches in landslide susceptibility modelling: A study on Kurseong region of Darjeeling Himalaya, India. Remote Sensing Applications: Society and Environment, 100323. https://doi.org/10.1016/j.rsase.2020.100323
35. Sarkar, S., Roy, A. K., & Raha, P. 2016. Deterministic approach for susceptibility assessment of shallow debris slide in the Darjeeling Himalayas, India. Catena, 142, 36–46. https://doi.org/10.1016/j.catena.2016.02.009
36. Sekhri, S., Kumar, P., Fürst, C., & Pandey, R. 2020. Mountain speci fi c multi-hazard risk management framework

(MSMRMF): Assessment and mitigation of multi-hazard and climate change risk in the Indian Himalayan Region. Ecological Indicators, 118(April), 106700. https://doi.org/10.1016/j.ecolind.2020.106700

37. Sridharan, A., & Gopalan, S. 2020. Materials Today : Proceedings Correlations among properties of lithological units that contribute to earthquake induced landslides. Materials Today: Proceedings, (xxxx). https://doi.org/10.1016/j.matpr.2020.07.265
38. Sur, U., Singh, P., & Meena, S. R. 2020. Landslide susceptibility assessment in a lesser Himalayan road corridor (India) applying fuzzy AHP technique and earth-observation data Landslide susceptibility assessment in a lesser Himalayan road corridor (India) applying fuzzy AHP technique and. Geomatics, Natural Hazards and Risk, 11(1), 2176–2209. https://doi.org/10.1080/19475705.2020.1836038
39. Thakur, M., Singh, G., & Malik, J. N. 2020. Geological and geomorphic evidences of neotectonic activity along the Himalayan Frontal Thrust , Nahan Salient , NW Himalaya , India. Quaternary International, (July). https://doi.org/10.1016/j.quaint.2020.07.014
40. Torkashvand, A. M. 2014. The preparation of landslide map by Landslide Numerical Risk Factor (LNRF) model and Geographic Information System (GIS). The Egyptian Journal of Remote Sensing and Space Sciences, 17(2), 159–170. https://doi.org/10.1016/j.ejrs.2014.08.001
41. Youssef, A. M., & Pourghasemi, H. R. 2020. Landslide susceptibility mapping using machine learning algorithms and comparison of their performance at Abha Basin, Asir Region, Saudi Arabia. Geoscience Frontiers. 12(2). 639-655. https://doi.org/10.1016/j.gsf.2020.05.010