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# Spatial Delineation of Zones Vulnerable to Landslides in the Upper Beas Basin

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**ABSTRACT**
The Himalayas have long been prone to various disasters due to their active tectonic activity. Landslide is closely increasing in relation with changing physical as well as anthropogenic environment. In this series the Upper Beas Basin (UBB) is facing escalation in landslide incidents with changing man-nature action. The presented paper focuses at delineation of probable landslide zones using geoinformatics and statistical methods. Spatial landslide data and 12 factors were used, and with the help of geospatial and statistical methods, a weightage value for each factor was calculated. Then overlay analysis delineated the risky zones. Landslide prone areas were divided into five class, varying from very low to very high susceptibility. The Results were supported using the Receiver Operating Characteristic (ROC) curve, ensuring model dependency and predictive accuracy. Mitigation strategies are propounded through land use planning, physical and policy interventions and it also includes community-based approaches. The research focuses on combining scientific analysis with collaborative planning to support disaster risk reduction in mountainous regions.
**Keywords**: Landslide Susceptibility, Upper Beas Basin, Geoinformatics, Statistical Modelling, Disaster Risk Reduction.

## INTRODUCTION

Landslides refer to the declension movement of rocks, debris, earth, and soil, driven primarily by gravity (1). They occur when the gravitational and other tangential stress are more than the tangential resistance of slope materials (2). Landslides are very dangerous natural hazards that can cause people to lose their lives and can destroy homes, roads, and other property in many parts of the world (3). The risk is not equally distributed; it is higher in densely populated regions near margins of plates, mountainous corridors, and transition zones between plains and mountains (4). The Himalayan rim, Central and South America, Iran, and Italy are more vulnerable, with developing countries bearing the highest risk of death due to their expansive mountainous terrains and limited mitigation capacities (5).India records the largest number of tragic landslides. As per Geological Survey of India (GSI), around 1.4 lakh km² area in the north-western Himalayas, comes under landslide susceptible zones (6). In recent decades, the Indian Himalayan region (IHR) has seen an increase in landslide events, due to unpredictable monsoon patterns (7). Flash floods due to the melting of glaciers and heavy monsoon rainfall are primary reasons. Other reasons leading to increase in landslide events include lithological diversity, steep slopes, soil type, geological disturbances, and anthropogenic activities (8). Overflowing of the Beas River is also one of the reasons, slope failures are occurring in higher numbers (9). The Indian Himalayan region being affected by landslides, impact the major economic sectors, including agriculture and transportation, also leading to loss of people (10). With around 4.2 lakh km² of vulnerable area, high population density, and heavy monsoon rainfall, managing and mitigating landslides in a developing country like India becomes crucial (11). Community-based disaster management (CBDM) helps engage local people for mitigation, preparedness, and response (12).Himachal Pradesh often experiences natural hazards like flash floods, cloudbursts, landslides, forest fires, etc (13). Among all the disasters, landslide is a more frequent natural hazard in Himachal Pradesh and causes extensive disruption of natural resources, assets, and mankind (14). The UBB, situated in the ecologically weaker region of Himachal Pradesh, has faced severe landslides in recent years with high frequency and intensity (15). The speedy expansion of tourism infrastructure, rapid construction of hotels and roads, deforestation, and an increase in traffic on roads have resulted in disturbance of the natural slope stability and drainage basin of the region, increasing region's



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vulnerability to landslides (16).Therefore, the study emphasizes on landslide susceptibility of the UBB and deeply analyzes the factors affecting and triggering the landslides in the region. This study also focuses on frequency of events, distribution patterns, mitigation strategies and policy options to address the negative impacts and plan for future landslides.

## MATERIALS AND METHODS

**Study area:** The study area is located along Beas River which joins Sutlej River in Punjab. The Beas River rises at Beas Kund glacial lake in the Kullu region, at an elevation of 4085 m above mean sea level (17). The Beas River basin stretches between 75°84'E and 77°88'E longitudes and 31°41' N and 32°46' N latitudes in Himachal Pradesh (18,19). The Upper Beas Basin lies in northern India's Himachal Pradesh, stretching from 76°56'30.12"E to 77°52'20.65"E and 31°20'25"N up to 32°25'01"N (20). Rugged slopes, narrow valleys, along a fast-moving river network define this area, while seasonal rains combined with melting glaciers feed its waters (21).

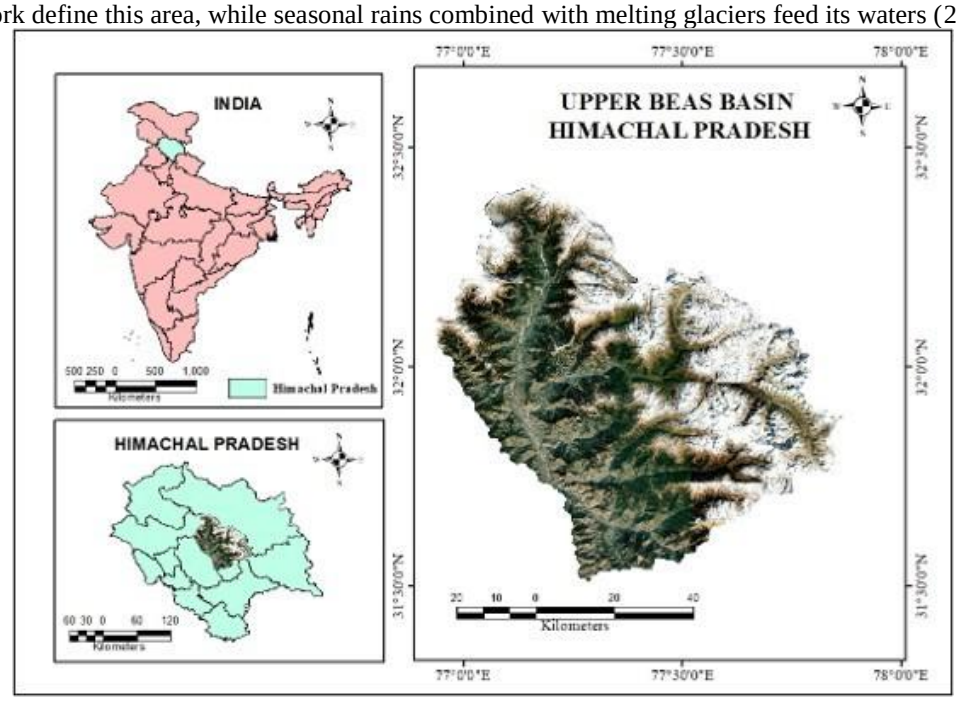


**Figure 1:** Study Area

**MapSource:** Google Maps
**Methodology**: We collect geospatial data from several data sources to conduct this investigation, as shown in

**Table 1: Factors and their data sources**

| Source | Factor |
|---|---|
| USGS (Landsat 8) | Normalized Difference Vegetation Index (NDVI) |
| NASA Earth Data (ALOS PALSAR DEM) | Slope |
| | Altitude |
| | Topographic Ruggedness |
| ESRI Living Atlas | Land Use Land Cover (LULC-10m) |
| Bhukosh – GSI | Geomorphology |
| OpenStreetMap (OSM) | Distance to rivers (DTR) |
| | Distance to road (DTR) |
| Food and Agriculture Organization (FAO) | Soil |
| USGS | Earthquake Magnitude |
| NASA Power | Rainfall |
| Himachal Pradesh State Disaster Management Authority | Landslide point |



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Datasets of different factors were clipped to the area of interest and classified into 5 classes as per risk level, from very low risk to very high risk. Then the historical landslide points were overlaid on each map to assess risk class and the number of landslide events in each class.
Landslide risk zones are specified areas likely to be affected. To delineate the risk zone, a simple statistical and bivariate approach is applied in this paper, that is Frequency ratio method.
This method assesses how landslide events are connected with different factors. In this method, we compute the frequency ratio (FR) for each factor class by,

$$FR = \frac{(\mathrm{N}si \ / \ \mathrm{N}s)}{(\mathrm{Nti}/\mathrm{Nt})}$$

Here, N*si* stands for landslide spots in the category; N*s* means all landslide locations overall; Nti refers to pixels inside that class; otherwise, Nt shows the entire pixel number across the region. Alternatively, once we figure out the frequency ratio, here's how to get the adjusted value called normalized frequency ratio (FRn) for every group: take that number, then tweak it based on its category using this method:

$$\mathrm{FR}n = \frac{\mathrm{FRi} - \mathrm{FRmin}}{\mathrm{FRmax} - \mathrm{FRmin}}$$

Where, FR*i* = FR of class, FRmin = *minimum FR of the factor*, *FR*max = maximum FR of the factor.

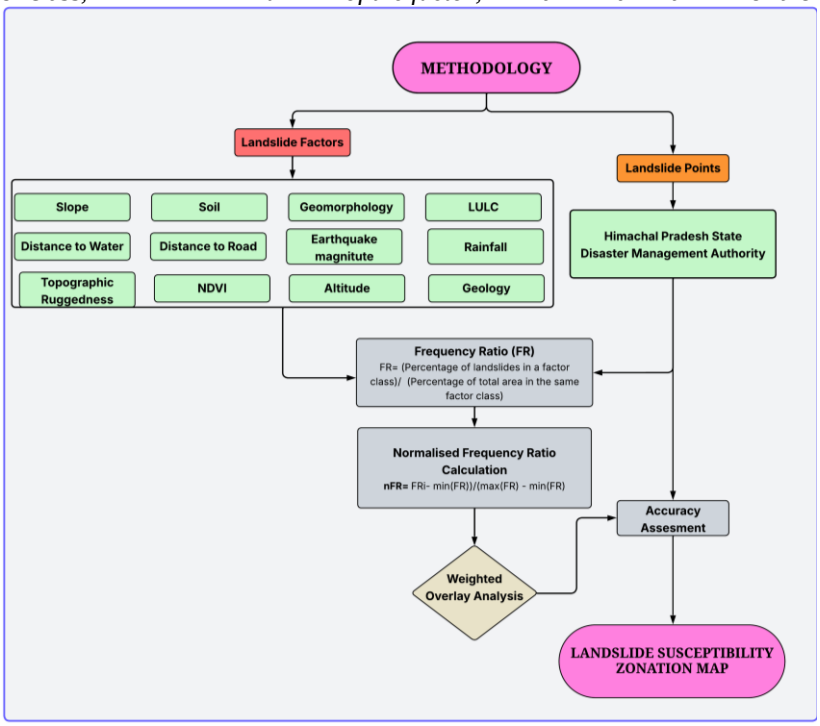


**Figure 2: Research Methodology**

We have calculated the FRn value for each class. The sum of FRn of each factor is used for the weightage value of the respective factor of the weighted overlay analysis (WOA). During this process, one of the most important things is to rank classes of factors as per their importance in landslide occurrence.
12 most important factors influencing landslides were identified namely slope angle (degrees), altitude, NDVI, geology, LULC, soil types, rainfall, Topographic Ruggedness Index (TRI), and others (shown in Figure 3). All factors and historical landslide points were collected from various sources, which were processed in ArcGIS 10.8 software to prepare our map. The process of mapping landslide susceptibility zones is shown in Figure 2.
Later, the ROC and Area Under Curve (AUC) are calculated for the prepared map and historical landslide points to validate our method. Validation means comparing the susceptibility map with locations where landslides have happened and where not occurred.



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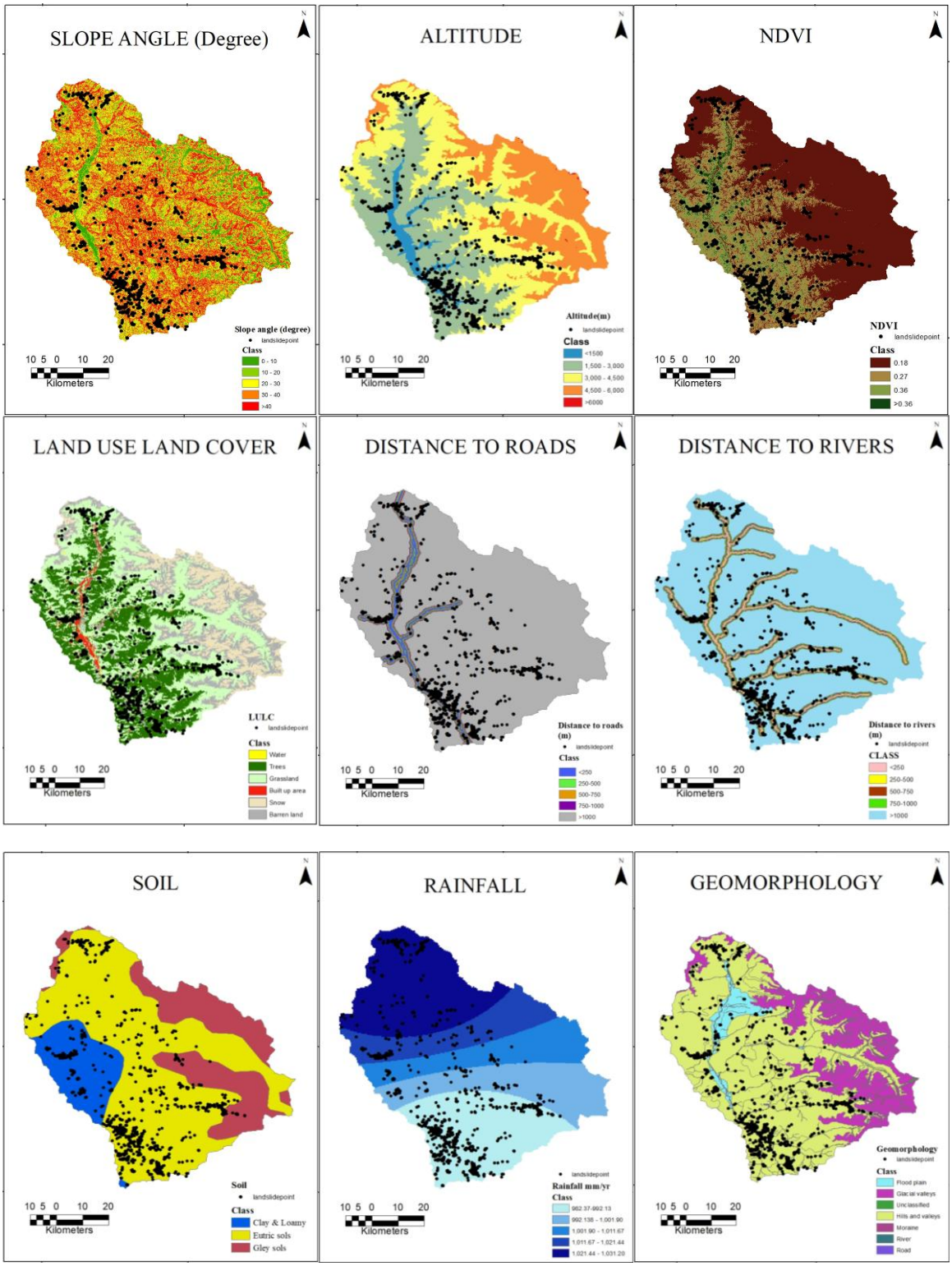




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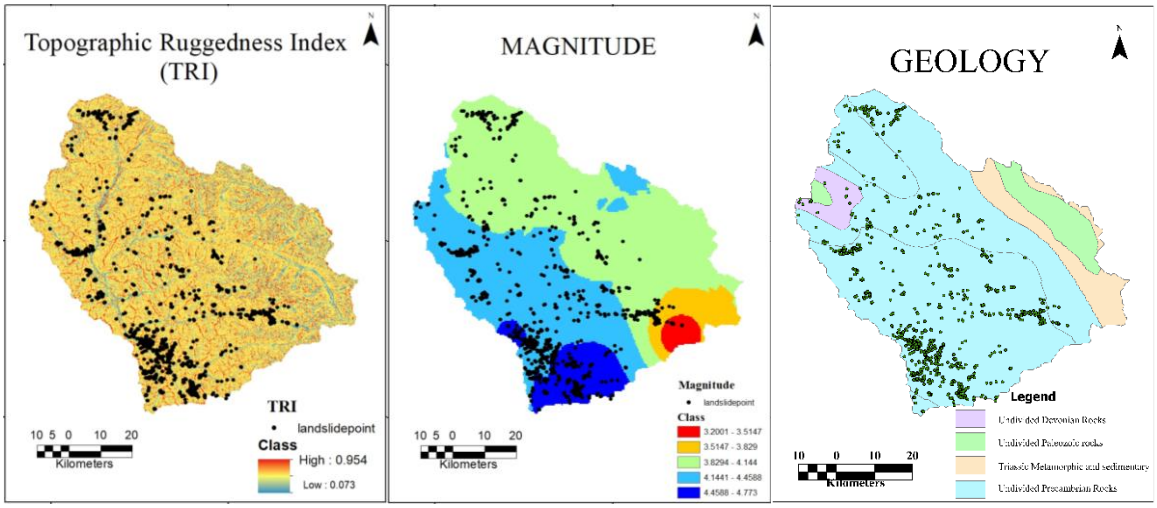


**Figure 3: Factors of Susceptibility Zonation**

## RESULTS AND DISCUSSION

Frequency ratio method decides the weights for each factor by using statistical analysis of landslide occurrence patterns across different factor classes, which gives the importance of one factor compared to others as shown in

**Table 2: Frequency Ratio and Normalised Frequency Ratio Calculation**

| Factor/Thematic layers | Classes | % of Landslide pixels in class | Percentage of class pixels | FR | FRn |
|---|---|---|---|---|---|
| Slope Angle (Degree) | (0 - 10) | 0.648 | 7.139445908 | 0.09073159 | 0 |
| | (10-20) | 5.911 | 15.31646195 | 0.385920142 | 0.2293 |
| | (20 - 30) | 21.538 | 25.45294192 | 0.846207154 | 0.5667 |
| | (30 - 40) | 36.923 | 27.39646996 | 1.347731185 | 0.9423 |
| | >40 | 34.980 | 24.69468027 | 17.49364622 | 1 |
| | | | | | 2.7383 |
| | | | | | |
| Altitude (m) | <1500 | 4.603 | 4.602919317 | 4.380251299 | 1 |
| | 1500 - 3000 | 35.791 | 35.7909259 | 1.59948261 | 0.3653 |
| | 3000 - 4500 | 36.156 | 36.1557136 | 0.624827748 | 0.1427 |
| | 4500 - 6000 | 23.362 | 23.36202813 | 0 | 0 |
| | >6000 | 0.088 | 0.088413048 | 0 | 0 |
| | | | | | 1.508 |
| | | | | | |
| NDVI | No Vegetation | 42.510 | 60.7012675 | 0.700316867 | 0.3378 |
| | Low Vegetation | 45.830 | 24.39241366 | 1.878861196 | 1 |
| | Moderate Vegetation | 11.336 | 12.60751851 | 0.899148582 | 0.4485 |
| | Dense Vegetation | 0.324 | 2.298800334 | 0.140893767 | 0 |
| | | | | | 1.7863 |
| | | | | | |
| LULC | Water | 0.162 | 0.258684418 | 0.626 | 0.3537 |
| | Trees | 17.895 | 29.04975417 | 0.616 | 0.3481 |
| | Crops/ Grass | 75.547 | 42.70589016 | 1.769 | 1 |
| | Builtup | 0.972 | 1.430082479 | 0.679 | 0.3826 |
| | Bare | 5.425 | 10.45688641 | 0.519 | 0.2933 |
| | Snow | 0.000 | 16.09870235 | 0.000 | 0 |
| | | | | | 2.3777 |
| | | | | | |
| DTR | 0 - 250 m | 9.960 | 2.31812383 | 4.296368486 | 1 |



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| | | | | | |
|---|---|---|---|---|---|
| | 250 - 500 m | 3.401 | 1.922438133 | 1.769008666 | 0.2765 |
| | 500 - 750 m | 3.968 | 1.780304596 | 2.228613769 | 0.4019 |
| | 750 - 1000 m | 6.559 | 1.637409532 | 4.005536992 | 0.9124 |
| | > 1000 m | 75.951 | 92.34172391 | 0.82250378 | 0 |
| | | | | | 2.5908 |
| | | | | | |
| DTR | 0 - 250 m | 15.951 | 4.678825422 | 3.409278091 | 1 |
| | 250 - 500 m | 17.409 | 8.693260536 | 2.002575076 | 0.4962 |
| | 500 - 750 m | 7.045 | 4.431644588 | 1.589598235 | 0.3844 |
| | 750 - 1000 m | 59.352 | 81.8162033 | 0.725433647 | 0.0477 |
| | > 1000 m | 0.243 | 0.380066151 | 0.639138685 | 0 |
| | | | | | 1.9283 |
| | | | | | |
| Soil | Clay and Loamy | 75.789 | 63.36785951 | 1.196023888 | 0.7372 |
| | Eutric Sols | 3.401 | 22.86518655 | 0.148733084 | 0 |
| | Gley Sols | 20.648 | 13.76695394 | 1.499806955 | 1 |
| | | | | | 1.7372 |
| | | | | | |
| Rainfall (mm/yr) | 982.37 – 992.13 | 61.700 | 25.42512899 | 2.426748941 | 1 |
| | 992.138 – 1,001.90 | 9.474 | 18.63006416 | 0.50851592 | 0.0822 |
| | 1,001.90 – 1,011.67 | 4.858 | 14.8803851 | 0.326490179 | 0 |
| | 1,011.67 – 1,021.44 | 12.308 | 14.22260107 | 0.865361564 | 0.2235 |
| | 1,021.44 – 1,031.20 | 11.660 | 26.84182068 | 0.434393746 | 0.0506 |
| | | | | | 1.3563 |
| | | | | | |
| Geomorphology | Flood plain | 2.348 | 25.8342526 | 0.09 | 0.0176 |
| | Glacial valleys | 3.968 | 4.889709162 | 0.81 | 0.1575 |
| | Unclassified | 91.012 | 68.22164999 | 1.33 | 0.2573 |
| | Hills and valleys | 0.000 | 0.212719818 | 0.00 | 0 |
| | Moraine | 0.324 | 0.062862224 | 5.15 | 1 |
| | River | 0.000 | 0.018603012 | 0.00 | 0 |
| | Road | 2.348 | 0.76020319 | 3.09 | 0.6001 |
| | | | | | 2.0325 |
| | | | | | |
| TRI | 0.954 – 0.777 | 0.405 | 1.004597429 | 0.403005511 | 0.2713 |
| | 0.777 – 0.601 | 29.069 | 19.57339931 | 1.485118934 | 1 |
| | 0.601 – 0.425 | 67.126 | 71.10920621 | 0.943977716 | 0.636 |
| | 0.425 – 0.249 | 3.401 | 8.252558096 | 0.412091581 | 0.2776 |
| | 0.249 – 0.073 | 0.000 | 0.060238957 | 0 | 0 |
| | | | | | 2.1849 |
| | | | | | |
| Earthquake's Magnitude | 3.2001 – 3.5147 | 0.972 | 1.826490892 | 0.531981804 | 0.0633 |
| | 3.5147 – 3.829 | 4.049 | 5.229816283 | 0.774134841 | 0.1352 |
| | 3.8294 – 4.144 | 17.814 | 49.8396504 | 0.357421552 | 0 |
| | 4.1441 – 4.4588 | 53.927 | 34.74424412 | 1.552116815 | 0.4498 |
| | 4.4588 – 4.773 | 23.239 | 8.359798302 | 2.779835776 | 1 |
| | | 100.000 | | | 1.6483 |
| | | | | | |
| Geology | Undivided Devonian Rocks | 98.866 | 82.02106704 | 1.205378085 | 1 |
| | Undivided Paleozoic Rocks | 0.000 | 8.286095205 | 0 | 0 |
| | Triassic Metamorphic and Sedimentary Rocks | 0.081 | 6.474690187 | 0.012505874 | 0.0104 |



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| | | | | | |
|---|---|---|---|---|---|
| | Undivided Precambrian Rocks | 1.053 | 3.218147567 | 0.32709239 | 0.2714 |
| | | 100.000 | 100 | | **1.2818** |

**Table 3: Landslide Susceptibility Factors: Normalized Frequency Ratio and Weightage**

| **Factor** | **FRn** | **Weightage Value** |
|---|---|---|
| Slope Angle (Degree) | 3.3008 | 14.18 |
| Altitude (m) | 1.7895 | 7.69 |
| NDVI | 1.86442 | 8.01 |
| LULC | 1.819 | 7.81 |
| Distance to Road | 2.135 | 9.17 |
| Distance to River | 2.1093 | 9.06 |
| Soil | 2.5415 | 10.92 |
| Rainfall (mm/yr) | 1.656 | 7.11 |
| Geomorphology | 1.7936 | 7.71 |
| TRI | 1.3994 | 6.01 |
| Earthquake's Magnitude | 1.5856 | 6.81 |
| Geology | 1.2818 | 5.51 |
| **Total** | **21.8886** | **100** |

**Landslide Susceptibility Index (LSI) Mapping**

The landslide vulnerability map (Figure 4) is created by adding the weighted averages of all the twelve factors (Table 3). The weights for each factor were calculated by the frequency ratio method and then weighted overlay analysis was applied to prepare the final map. This map demonstrates the various pixels for landslide vulnerability, with ranking from very low to very high. Areas with high pixels are indicative of expressing higher susceptibility to landslide while areas with low pixels are safer.

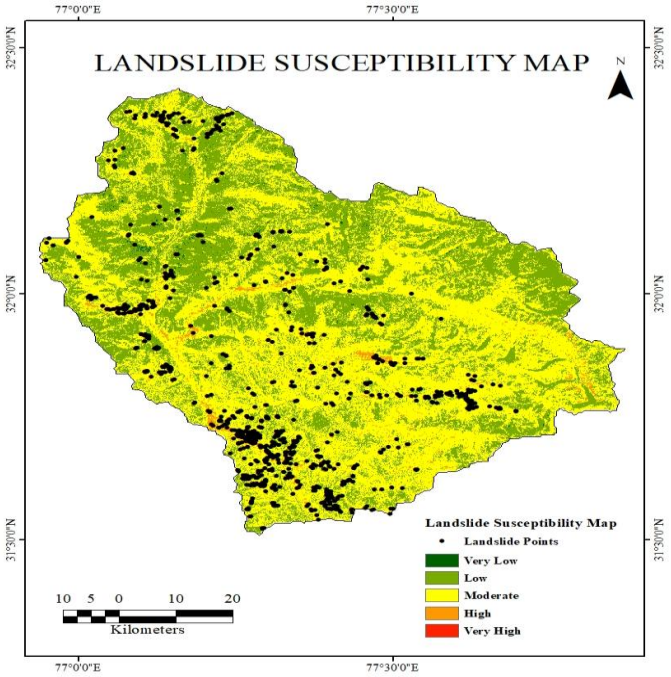


**Figure 4: Landslide Susceptibility Map**



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The layout of spots with greater risk helps when deciding how to use land or reduce dangers. Places with medium risk - covering nearly 58% of the region - should be carefully considered during growth plans and where buildings go. On the flip side, the rare high-risk zones (under 2%) ought to get urgent focus through detailed checks and ongoing monitoring setups.

**Table 4: Landslide Susceptibility**

| Landslide Susceptibility Class | Area($km^2$) | Area in % |
|---|---|---|
| Very Low | 16.20 | 0.33 |
| Low | 1987.63 | 40.04 |
| Moderate | 2870.07 | 57.82 |
| High | 89.76 | 1.81 |

Findings from the above process classify risk zones into 4 classes, i.e., very low, low, moderate, and high (Table 4). Here major portion of the area lies under the moderate risk zone, which is 2870.07 $km^2$ or 57.82%. The area having very low and high risk criteria is around 2% and the very high risk zone is negligible so we didn't show that. Area classified as low risk accounted for 1987.63 $km^2$ (40.04%), showing major portion lies under low and moderate risk zones.

Although high susceptibility area was confined spatially, to 89.76 $km^2$ (1.81% surface area) its importance for risk assessment and planning is a critical aspect to consider. This observation of distribution documented in the landslide vulnerability map indicates a clear spatial clustering of higher susceptible areas, grouping heavily in the south and southwest region of the study area. This study gives a solid starting point for checking local risks which helps guide choices on building projects, crisis preparation, or how lands used around here.

**Validation**

The ROC curve is a type of graph that demonstrates the effectiveness of a prediction model. The AUC value and ROC curve show how the model determined zones susceptible to landslides (22). This investigation was being tested using real data and plotted on the ROC curve (23,24,25). The ROC analysis included here is an essential measure of model performance for assessing prediction ability of landslide susceptibility models. The model achieved an AUC value of 0.873, which indicates very good predictive performance. The shape of the ROC curve indicates excellent model performance. The steep initial slope shows that the model was able to predict a good percentage of true landslide prone locations with low false positive rates. The curve stays well above the diagonal reference line (random guess line) and indicates that the model performs much better than random classification for all threshold values (shown in Figure 5).

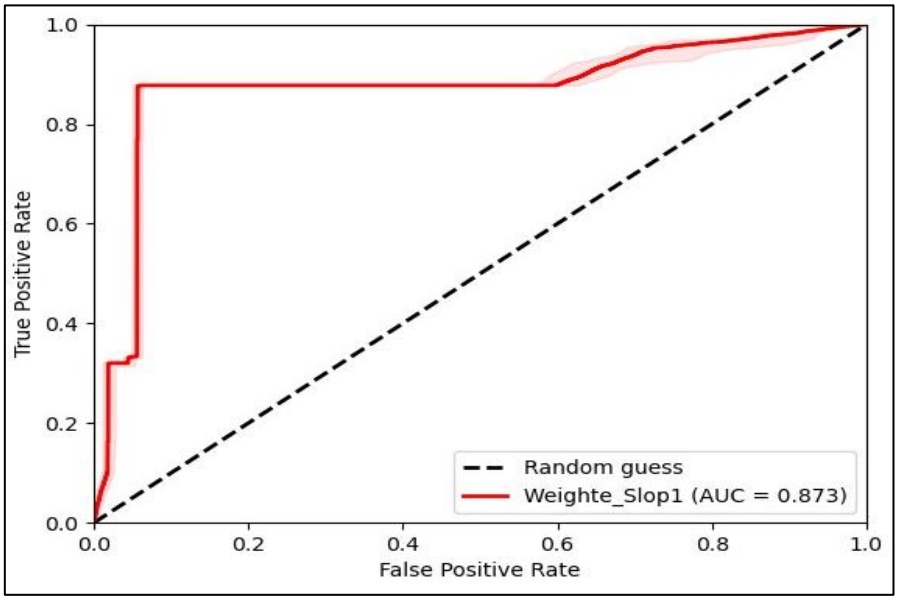


**Figure 5: Validation Through AUC value and ROC curve**



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There are many methods of overlay analysis where we use various factors to create zonation or susceptibility maps. Like the Analytical Hierarchy Process (AHP) and related to AHP, in which we compare different factors with each other to calculate factor weightage for WOA. This method is based on different factors and finds a relation with landslide events. Factors were classified on the basis of how they accelerate landslides or we can say how different class of factors and their role in landslide events. On observing slopes, we found that the major portion of the area lay in Class 4, having the greatest risk (FR = 1.42), meaning that most area has steeper slopes leads to landslides. Like slopes, other factors were also classified and related to landslide events. The weightage method will be more reliable when we use landslide event data in vector-polygon format, having the actual area of the landslide event, making this type of investigation stronger. Spatial data of the population is also an important factor, but we have outdated data on that, so we didn't use that and relied on the LULC map. Landslide area and population data will enhance this study.

## CONCLUSION

The landslide susceptibility map shows major area under low and moderate landslide risk zones and an AUC value of 0.873, meaning an 87.3% chance that this method is correct. This type of study is very helpful for the administration as well as the population residing there. But as we know, natural disasters are not so certain. Thus, landslide would happen in the lower risk zones. Each landslide event would strengthen this type of zonation map. With all the above limitations, this map is very helpful for designing development schemes in the Upper Beas Basin.

## ABBREVIATIONS

AHP- Analytical Hierarchy Process, AUC- Area Under Curve, DTR- Distance to Road, DTR- Distance to River, FAO- Food and Agriculture Organization, FR- Frequency Ratio, FRn- Normalized Frequency Ratio, GSI- Geological Survey of India, LULC- Land Use Land Cover, NDVI- Normalized Difference Vegetation Index, OSM- OpenStreetMap, ROC- Receiver Operating Characteristics, TRI- Topographic Ruggedness Index, UBB- Upper Beas Basin, WOA- Weighted Overlay Analysis

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## AUTHOR'S CONTRIBUTIONS

All author contributes equally to the research, design the study, analyzed data and approved the final manuscript.

## CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

## DATA AVAILABILITY

Secondary data has been used in this research and the data source has been mentioned in the manuscript in Table 1.

## DECLARATION OF ARTIFICIAL INTELLIGENCE (AI) ASSISTANCE

The authors declare that no generative AI was used in the writing process.

## ETHICS APPROVAL

The researchers obtained ethical approval from the University Ethics Committee.

## FUNDING

None.

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