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Assessing the Relationship Between Landslide Occurrence and Causative Factors in the Upper Satluj River Basin, Kinnaur District, Western Himalaya

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ABSTRACT

In the Himalayan region, landslides are among the most frequently occurring geomorphic hazards, resulting in significant loss of life, degradation of natural resources, and damage to infrastructure. A spatial relationship between landslide occurrence and conditioning factors is fundamental for effective hazard assessment and risk mitigation. This study aims to explore the relationship between the thirteen causative factors and landslides in the Upper Satluj River Basin in Kinnaur district of Himachal Pradesh, by employing Chi-square (χ^2) statistics and standardized residual analysis in a Geographic Information System (GIS) environment. For this, a landslide inventory consisting of 1543 landslide locations was prepared based on the data available in the Geological Survey of India (GSI) Bhookosh portal and field surveys. The results show that all the selected factors have statistically significant relationship with landslide distribution. Among them slope, relative relief, land use/land cover, and lithology emerged as the most influential controls. Standardized residual analysis suggests that landslides tend to be concentrated on steep slopes, on south facing slopes, moderate to high relief, structurally disturbed areas, shrub dominated landscape, fine-loamy soils and areas with low to moderate vegetation cover. The landslide occurrence is comparatively low in the areas with dense vegetation, sandy skeletal soil, and high TWI. The results show that the spatial pattern of landslides in the basin is controlled by the interplay of terrain morphology, geological conditions, and land-surface properties. The results of the study give insight into the environmental controls of landslide occurrence and serve as a scientific foundation for the landslide susceptibility assessment, landslide hazard zonation, and disaster risk reduction planning in the Himalayan region for the future.

INTRODUCTION

Landslides are geomorphic processes characterized by the downslope movement of rock, soil, and debris under the action of gravitational forces (Cruden & Varnes, 1996). These mass movements cause serious damage to human lives, infrastructure, economic assets and ecosystems, especially in mountainous areas, where steep slopes and complex geology are common (Ghimire, 2011). The distribution of landslides is not random but it is influenced by a complex interaction of intrinsic and extrinsic environmental factors that are related to topography, lithology, geological structures, hydrological conditions, land use, vegetation cover and climatic influences (Dai &

Lee, 2002; Guzzetti et al., 2005). The spatial relations are key to understanding the causative processes of slope failures, and to the enhancement of hazard prediction.

The natural factors that lead to landslide instability include several factors; each has a different degree of importance depending on the geology, geomorphology and climate of the area. It is well known that topographic parameters, such as slope angle, slope aspect, and relative relief, are direct controls of gravitational stress, surface runoff and weathering intensity, and microclimatic conditions, which play a key role in landslide occurrence (Dai & Lee, 2002; Guzzetti et al., 2005). The gravitational potential is generally higher on steeper slopes and thus increases the risk of failure, while on the contrary, the aspect influences the amount of solar radiation, the moisture conditions of the soil, the distribution of the vegetation and the weathering processes, which affect the stability of the slopes indirectly (Guzzetti et al., 2005, Zhao et al., 2023).

Lithological characteristics influence the mechanical qualities of slope materials, such as shear strength, permeability, and susceptibility to erosion. The geological structures such as fault and bedding planes create weaknesses which are utilized in the slope failure (Kumar et al., 2021). Precipitation, drainage density, and groundwater conditions are important hydrological factors which influence slope instability by increasing pore-water pressure and/or soil moisture content and, thus, decreasing effective stress and shear strength in the slope materials (Sidle & Ochiai, 2006). The vegetational cover may play a stabilizing role by reinforcing the soil with roots, intercepting rainfall, and reducing soil moisture with transpiration, while deforestation and land use changes may have a significant impact on the susceptibility of landslides (Sidle & Ochiai, 2006; Glade, 2003). Landslide frequency and spatial distribution have been correlated with land use and land cover (LULC), which can be related to anthropogenic changes in slope geometry, hydrological pathways and loading on the surface (Glade, 2003; Reichenbach et al., 2018).

There have been several developments in Geographic Information Systems (GIS), remote sensing and spatial analysis methods in recent years that have greatly enhanced the evaluation of landslide conditioning factors. GIS allows the incorporation of multiple geospatial data types, such as digital elevation models (DEMs), geological data, soil properties, climatic data, and satellite imagery, and can be used to conduct in-depth analyses of the relationships between landslides and the environment (Carrara et al., 1999; Reichenbach et al., 2018). In this study, Chi-square (χ^2) analysis was employed to investigate the relationship between landslide occurrence and the selected causative factors.This method determines whether the distribution of landslides among the classes of a factor is significantly different, than the distribution they would have had if the landslides were random. Contingency tables were made for each causative factor to display the observed frequency of landslides for each of the classes. The expected frequency was derived from the relative area of each of the classes in the study area.

Several studies have shown that the topographic, geological, hydrological and land-cover parameters play a crucial role in the control of landslide occurrence. For instance, Ghimire (2011) has found that the slope gradient and relief are the most significant controls on the occurrence of landslides in Lesser Himalaya, Nepal, and Reichenbach et al. (2018) have referenced the variations of terrain, lithology, hydrology and land use on landslide susceptibility under different physiographic settings.

Although significant advances have been made in landslide studies, the relative importance of causal factors is different in various geomorphological and geological environments, and it is hard to draw general conclusions for landslide behaviour from one area to another. Therefore, region-specific investigations are necessary to understand the environmental controls governing landslide occurrence (Reichenbach et al., 2018; Merghadi et al., 2020). In the present context, Chi-square statistics and standardized residual analysis has been used to explore the spatial association between landslide occurrence and causative factors in the Upper Satluj River Basin, Western Himalaya. The distribution of landslides across the different factor classes are compared between observed and expected to highlight significant associations between the environment and landslide occurrence. The results offer useful information on the major controls on the landslide activity that occurred in the basin and will help in understanding the problems of slope instability in the Himalayas.

STUDY AREA

This study was conducted in Upper Satluj River Basin in eastern part of the state of Himachal Pradesh in Kinnaur district. The basin constitutes an extensive part of district and a major part of the northwest Himalayan mountain ranges. The region is one of the most landslide prone areas of Indian Himalaya with rugged topography and significant altitudinal gradients, with an area of about 6245 km^2 (fig.1), and characterized by the presence of active geomorphic processes.

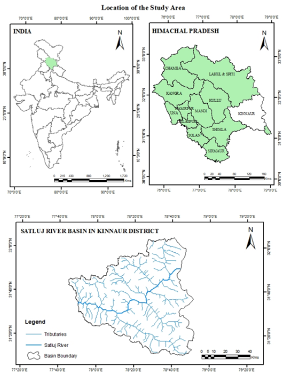

Figure 1. Location map of the Upper Satluj River Basin, Kinnaur District, Western Himalaya, showing the spatial extent of the study area within Himachal Pradesh, India.

Satluj river and its major tributaries such as Spiti, Baspa, Tidong and Ropa river traverse the basin which has produced highly incised valleys and has resulted in a highly dissected landscape (Kuniyal et al., 2019). The relief is very steep, from 1200 m in the valley bottoms to over 6700 m along the mountain ridges, giving a very wide variation in local relief and slopes. Topographic contrasts are important factors that influence hillslope processes and landscape evolution.

Geologically, the region is part of the tectonically active Himalayan mountain belt, and is a complex amalgamation of metamorphic, sedimentary and crystalline rock types. The Haimanta Group, Vaikrita Group, Kanwar Group and associated granitoid bodies are prominent lithological formations (Jamir et al., 2020). Major regional tectonic features such as the Main Central Thrust (MCT) and the South Tibetan Detachment System (STDS) have contributed to strong deformation, faulting and fracturing of the rock masses (Kumar et al., 2021). These structures have markedly affected the mechanics of the slopes and influenced the general instability in the basin.

Elevational variation in climatic conditions is significant. Climate conditions are relatively moderate in the lower and middle basin while the higher parts are cold-arid (Jamwal et al., 2020). Precipitation is in the form of rainwater and snow and depends on the altitude. Spatial variation in precipitation combined with steep terrain and active geomorphic processes has a significant impact on weathering, erosion, and slope processes. There is also significant inter-regional variation across the basin in land-cover patterns. Forests are found on a large proportion of lower and middle elevation slopes, whilst higher elevations are covered by shrublands, alpine pastures, barren rocky areas, snow fields and glaciers. Crops are mostly located around the valley bottoms and on occupied slopes.

The upper Satluj river basin is a suitable basin to study the spatial association between the landslides and their controlling factors due to the combined influence of topographic complexity, tectonic activity, lithological heterogeneity, climatic variability and anthropogenic activities.

METHODOLOGY

Landslide inventory and data preparation

The first step in comprehending the relationship between the occurrence of landslides and their conditioning factors is a landslide inventory (Fell et al., 2008). In the present study, landslide inventory was prepared using the landslide records from the Geological Survey of India (GSI) Bhookosh portal and supplemented by field surveys along the roads of study area. The inventory was well checked for duplicate inventory and positional discrepancies. 1543 locations of landslides were identified and mapped (fig.2). For understanding the spatial association between landslides and geo-environmental factors, thirteen causative factors were chosen which are relevant to slope failure in the Himalayan terrain. These factors comprised slope, aspect, relative relief, lithology, land use/land cover (LULC), normalized difference vegetation index (NDVI), rainfall, drainage density, lineament density, distance from thrust line, soil, SPI and TWI. The thematic layers were created using remotely sensed data, topographic data, geological maps and other ancillary data (table.1). All data were projected to a common datum and coordinate system, the Universal Transverse Mercator (UTM) coordinate system (Zone 43N) and datum, the World Geodetic System (WGS 1984), to ensure consistency and compatibility of all data sets. This standardised framework allowed spatial analysis and integration of all thematic layers, necessary for further modelling. The landslide inventory and thematic layers were then used in a Chi-Square analysis to assess the correlation between the occurrences and the selected causative factors.

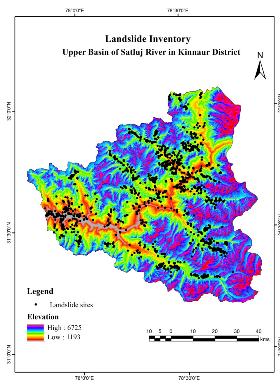

Figure 2. Landslide inventory map of the study area showing the spatial distribution of landslide occurrences.

Chi-Square (χ^2) Analysis

A statistical relationship between the occurrence of landslides and the selected causative factors was assessed using the Chi-Square (χ^2) analysis. The method compares the actual landslide distribution for each factor class to a random distribution of landslides and determines if there is a significant positive or negative correlation between the two. The method tests if the observed distribution of landslides in each factor class is significantly different from a random distribution, which identifies factor classes that are positively and negatively correlated with landslide occurrence (Agresti, 2013). Standardized residuals from the Chi-square analysis give further information about the contribution of each factor class since they are used to identify whether the observed frequencies are significantly higher or lower than the expected frequencies. Residual-based interpretations can help identify environmental conditions that tend to be associated with landslide occurrence and can provide an indirect comparison of the importance of different conditioning factors (Agresti, 2013).

The Chi-Square statistic was computed using the following equation (McHugh, 2013).

$\chi^2 = \Sigma [(O_i - E_i)^2 / E_i]$

where:

χ^2 = Chi-Square statistic,

O_i = Observed number of landslides in class *i*,

E_i = Expected number of landslides in class *i*,

i = class of a conditioning factor.

The expected frequency for each class was calculated as:

Expected frequency for class i: $E_i = (A_i / A_t) \times N$

Where:

E_i = Expected number of landslides in class $_i$

A_i = Area of class $_i$

A_t = Total area of the study area

N = Total number of landslides in the inventory

To identify the specific classes contributing to the Chi-Square value, standardized residuals were calculated for each class using the following equation (Sharpe, 2015).

$SR_i = (O_i - E_i) / \sqrt{E_i}$

where:

SR_i = Standardized residual for class i

O_i = Observed number of landslides in class i

E_i = Expected number of landslides in class i

$\sqrt{E_i}$ = Square root of the expected frequency for class i

Table 1. Data sources of landslide causative factors

Parameter	Source	Scale / Resolution
Slope, aspect, relative relief, TWI, SPI, drainage density	ALOS PALSAR DEM https://search.asf.alaska.edu	12.5 m
Lithology, lineament, thrust	Geological Survey of India https://bhukosh.gsi.gov.in/Bhukosh/Public	1:50,000
Soil	National Bureau of Soil Survey and Land Use Planning (NBSS&LUP)	1:50,000
Rainfall	IMD Gridded Data https://imdpune.gov.in/	0.25° x 0.25°
LULC, NDVI	Sentinel-2 https://dataspace.copernicus.eu/data-collections	10 m

The standardized residual is the difference between the observed and the expected frequency for a class, where the assumption of independence is made. Positive standardized residual values indicate that landslides occur more frequently than expected, whereas negative values indicate fewer landslides than expected. Classes with larger absolute values of the residual are making a bigger contribution to the overall Chi-square statistic and indicate either over-representation or under-representation of that class in relation to the distribution of landslides (Agresti, 2013; Sharpe, 2015). Positive residuals mean that there is a positive association between a factor class and landslide occurrence, meaning that landslides are grouped together in a specific class. In contrast, negative residual values suggest that the landslide occurrence was below average and, thus, the relatively weaker association with slope failure processes (Agresti, 2013).

RESULTS AND DISCUSSION

The obtained Chi-Square values of the selected causative factors were compared to each other and the relationships between these factors and landslide occurrence were determined. Likewise, standardized residuals with high positive values were used to define landslide prone zones. The findings were then analyzed for understanding the spatial distribution of the relationships between the landslides and geohazard features in the study area and selection of the most important landslide factors affecting landslide instability.

All thirteen causative factors showed statistically significant associations with landslide occurrence ($p < 0.0001$) in the Upper Satluj River Basin indicating that in the basin landslides are controlled by various topographic, geological, hydrological, environmental and anthropogenic processes and not by random spatial processes. The magnitude of the Chi-square values and standardized residuals, however, suggest that the relative influence of individual factors varies considerably.

Relationship Between Landslides and Topographic Causative Factors

The topographic factors exhibit the strongest control on landslide occurrence in the Upper Satluj River Basin. In the present study, three topographic factors, namely slope, aspect, and relative relief were used. The slope layer used in the present study was obtained from the ALOS PALSAR DEM (12.5 m resolution) and reclassified into five classes (fig. 3a), namely: <15°, 15–25°, 25–35°, 35–45°, and >45°.

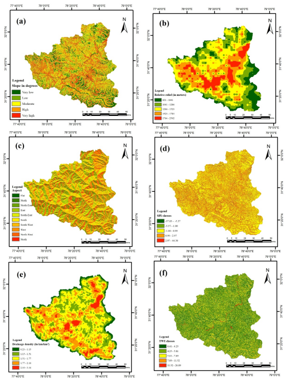

Figure 3. Causative factors used in the study: (a) Slope, (b) Relative relief, (c) Aspect, (d) SPI, (e) Drainage density, (f) TWI

Topographic factors have the greatest influence on the distribution of landslides in the Upper Satluj River Basin. The results indicate that among all the variables investigated, slope has the highest Chi-square value ($\chi^2 = 12{,}904.15$) (table .2). The standardized residual analysis showed strong positive residual for the high (35° to 45°) and very high (>45°) slopes classes (69.32 and 28.51 respectively) (fig. 4a), which means that the number of landslides is significantly higher than the expected number of the statistical model, while the low and very low slopes category had strong negative residuals. The pattern shows that steep terrain offers the best conditions for slope failure because the gravitational stress and slope stability is greater.

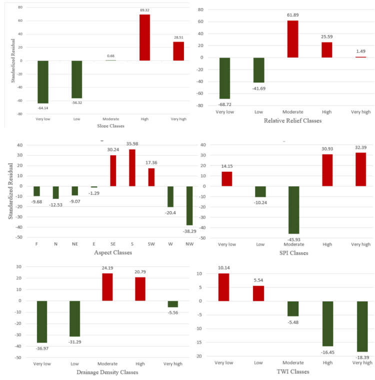

Figure 4. Standardized residuals for landslide occurrence across classes of the causative factors. (a) Slope, (b) Relative relief, (c) Aspect, (d) SPI, (e) Drainage density, (f) TWI

Relative relief also demonstrated a strong relationship with landslide occurrence ($\chi^2 = 10{,}959.20$) (table .2). The DEM of the study area was used to derive relative relief which was then placed into five classes using the Natural Breaks technique (fig. 3b). Both the moderate and the high relief classes had the greatest positive residuals of all relief classes, and the high relief class had a significant positive residual (fig. 4b). The extremely low relief class had the most negative residual, reflecting a considerable lack of landslides. The same has been noted in some of the Himalayan regions where slope angle and local relief have been found to be the most significant landslide conditioning factors (Anbalagan,1992; Merghadi et al., 2020).

The aspect map was extracted from the same ALOS PALSAR DEM and classified into nine directional classes according to the common practice (Bisht et al., 2024) (fig. 3c). The results of aspect analysis ($\chi^2 = 4{,}730.69$) showed that the occurrence of landslides was strongly controlled by direction. Strong positive residuals were found on south and southeast facing slopes, suggesting a significant number of landslides exists there that are more than expected by chance; north facing slopes and especially northwest facing slopes had strong negative residuals. Greater solar radiation, more weathering, seasonal freeze and thaw processes and differences in soil moisture conditions can explain the concentration of landslides on south-facing slopes. This aspect related landslide pattern has been reported elsewhere in the north-western Himalaya (Sarkar & Kanungo, 2004).

Relationship Between Landslides and Hydrological Causative Factors

Parameters related to hydrology are important in controlling surface runoff and infiltration, soil moisture, and erosion rates, and thus slope instability (Rahardjo et al., 2007). Four hydrological variables: Stream Power Index (SPI), drainage density (DD), topographic wetness index (TWI) and rainfall were taken in consideration to investigate their correlation with the occurrence of landslides in the present study. The ALOS PALSAR DEM was used to calculate the density of drainage, SPI and TWI. Indian Meteorological Department (IMD) gridded rainfall data were used to get rainfall information. The results of all factors were classified into five categories and analyzed statistically by Chi-square statistics and standardized residual analysis, to investigate their influence on the occurrence of the landslide.

Stream Power Index (SPI) showed strong positive residuals within the high and very high classes, while the moderate SPI class displayed the strongest negative deviation, indicating fewer landslides than expected.

Another significant relation with landslide occurrence was drainage density ($\chi^2 = 3{,}397.43$). The moderate and high drainage density classes had relatively high positive residuals of 24.19 and 20.79, respectively, while very low and low drainage density classes had high negative residuals of −36.97 and −31.29, respectively (fig. 4e). The high degree of drainage dissection observed in this pattern encourages the instability of slopes by undercutting of the slopes and channel incision. Topographic Wetness Index (TWI) showed negative correlation to landslide occurrence. The very low TWI class had a positive residual of 10.14, the low TWI class had a residual of 5.54, while the high and very high TWI classes had strong negative residual of −16.45 and −18.39, respectively (fig. 4f). This indicates that landslides tend to be localized on steep hillslopes, with moderate moisture availability, and not found in saturated valley-bottom environments.

The relationship of rainfall and landslide occurrence was more complex. The strong positive residual (25.36) was obtained for the very low rainfall class, whereas moderate rainfall class had obtained a positive residual of 21.40. Low, high and very high rainfall classes had negative residuals in comparison. This is an unusual pattern but may be due to the variability in the distribution of rainfall over the basin, lithology, and slope morphology.

Relationship Between Landslides and Geological and Structural Causative Factors

Geological and structural conditions have a significant impact on the mechanical behaviour of slopes as they affect rock strength, weathering features, fracturing, and groundwater movement (Anbalagan, 1992). To evaluate their role in landslide occurrence, lithology, lineament density, and distance from thrusts were analysed which were obtained from the Geological Survey of India at 1:50,000 scale.

lithology was divided into 12 lithological units that were analysed as a dataset (fig. 5b). Lithology was one of the most significant factors influencing the occurrence of landslides with a value of $\chi^2 = 6{,}350.76$. The Haimanta Group (33.67) and Jeori–Wangtu Banded Gneissic Complex (49.71) had significant positive residuals (fig. 6b), which are much higher than the number of landslides observed compared to their area. The Lilang Group, Vaikrita Group, Rakcham Granite, Nako Granite and Kuling Group showed negative residual values indicating their comparatively stable geological character. The results indicate that the rock strength, weathering state and structural discontinuities are important factors to consider in determining the instability of a slope.

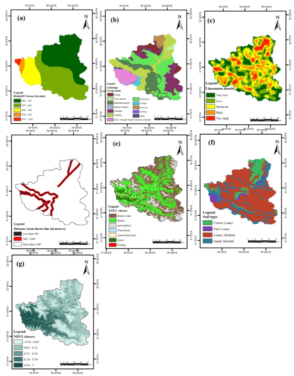

Figure 5. Causative factors used in the study: (a)Rainfall, (b)Lithology, (c) Lineament density, (d) Distance from thrust line, (e) LULC, (f) Soil, (g) NDVI

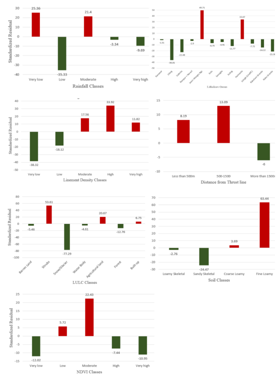

Figure 6. Standardized residuals for landslide occurrence across classes of the causative factors: (a)Rainfall, (b)Lithology, (c) Lineament density, (d) Distance from thrust line, (e) LULC, (f) Soil, (g) NDVI

Significant relationships between landslide occurrence and structural factors were also found. The data of lineament density were classified by natural breaks method with classes ranging from very low to very high (fig. 5c). Lineament density ($\chi^2 = 3{,}399.40$) showed greater concentration of landslides from low density landslide zones to high density landslide zones. Positive residuals were found for moderate, high, and very high lineament density classes (fig. 6c), suggesting a tendency for the most intensely fractured and faulted areas to have a higher density of landslides, while the very low and low-density classes exhibited negative residuals. Rock-mass integrity is reduced when fractures, joints and fault zones are present,

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which increase the permeability and provide favourable slope failure conditions (Anbalagan, 1992; Dai & Lee, 2002; Kanungo et al., 2009).

Distance from thrusts was also statistically significant related to landslide occurrence (χ^2 = 193.84). To account for the effects of the thrust proximity the 3 buffer areas shown in fig. 5d were added to the current study; 0–500 m, 500–1500 m and > 1500 m. The distance classes <500 m and 500-1500 m had strong positive residuals of 8.19 and 13.09 respectively, whereas distance classes >1500 m had a negative residual of −6.00 (fig. 6d). The results suggest that the areas of the slopes that are in tectonic state of disturbance are more prone to slope failures than other areas further away from major thrust systems.

Relationship Between Landslides and Land Surface

Causative Factors

Land surface characteristics influence landslide occurrence in terms of the effects they can have on vegetation cover, soil characteristics, infiltration capacity and surface runoff dynamics (Reichenbach et al., 2018). In the present study, to assess their contribution in controlling the slope instability, three land surface factors such as LULC, NDVI and soil texture were analyzed. LULC map and NDVI layer were derived from Sentinel-2 satellite data (fig.5e, 5g), soil layer was taken from the NBSS&LUP database at 1:50,000 scale and reclassified by soil texture classes (fig. 5f). Selected factors were classified into respective categories and evaluated by Chi-square statistics and standardized residual analysis to check the relationship between the selected factors and landslide occurrence.

Table 2. Chi-square test results

Causative factor	χ^2 Value
Slope	12,904.15
Relative relief	10,959.20
Aspect	4,730.69
SPI	4,424.88
Drainage density	3,397.43
TWI	772.94
Rainfall	2,456.95
Lithology	6,350.76
Lineament density	3,399.40
Distance from thrust line	193.84
LULC	10,347.90
Soil	4648.85
NDVI	856.56

LULC (χ^2 = 10,347.90) ranked third among all investigated factors. The residual value for shrub-dominated land was the highest positive value (53.61) of all the LULC categories. The residuals for agricultural land (20.67) and built-up areas (6.75) were also marked with strong positive (fig. 6e). Conversely, snow/glacier cover had an extremely high negative residual of −77.29 and other forest and barren land classes had negative residuals. The results here show that anthropogenically modified and less vegetated environments are much more prone to slope failure than highly vegetated areas (Glade 2003; Sidle & Ochiai 2006). Other soil properties like soil texture (χ^2 = 4,648.85) also had a good correlation with landslide occurrence. The positive residual for fine-loamy soils was abnormally high at 63.44, meaning that a landslide concentration was observed far higher than what is expected statistically. The coarse-loamy soils had a small positive residual of 3.69, while the sandy skeletal soils had a strong negative residual of −24.47. Loamy skeletal soils had a near neutral residual of −2.76, which was close to what is statistically expected (fig. 6f). The results demonstrate the significance of soil texture influence on moisture content, pore-water pressure build-up and shear strength. Landslide occurrence was also significantly related to vegetation conditions (represented by NDVI) (χ^2 = 856.56). The moderate NDVI class had a strong positive residual (22.43) and the low NDVI class had a positive residual (5.72). In contrast, negative residuals of −12.02, −7.44 and −10.95 were observed for very low, high and very high NDVI classes, respectively (fig. 6g). This pattern points to the fact that poorly vegetated or moderately vegetated landscapes are more likely to contain landslides while landscapes with dense vegetation tend to have more stable slopes.

CONCLUSION

In the present study, the relationship between landslides and 13 causative factors in the Upper Satluj River Basin has been investigated and analyzed with the help of Chi-square (χ^2) statistics and standardized residual analysis. The results show that landslides do not occur randomly on the landscape and are heavily influenced by the various topographic, geological, structural, hydrological and land-surface characteristics. Of the factors investigated, slope, relative relief, land use/land cover and lithology were the most important controls on the occurrence of landslides. The landslides are located on steep slopes, rugged terrain, and on the south aspects indicating the important control of terrain morphology on slope instability. Likewise, within the Haimanta Group and Jeori–Wangtu Banded Gneissic Complex, a high susceptibility was observed, which shows that the geological conditions and rock-mass characteristics play an important role in landslide distribution. The effects of the tectonic disturbances on slope failure processes are further illustrated by structural features such as the density of lineament and the distance from thrust zones. It was also found that landslides tend to be primarily linked to the moderately to highly drained sections, high stream power zones, fine-loamy soils, shrub-dominated landscapes, agricultural lands, and low to moderate vegetation cover zones. The results of this study showed that hydrological processes, soil properties, vegetation characteristics and land-use modification have a significant effect on slope stability, and have a combined effect with terrain and geology to increase landslide susceptibility. Conversely, high vegetational density, snow/glacier covers, sandy skeletal soils, and high TWI values typically showed low landslide frequency with relatively stable conditions. From the ranks of the conditioning factors it is deducted that terrain morphology is the main control on landslide occurrence followed by land-surface characteristics and geological conditions. This shows, as a group, that the landslide susceptibility in the Upper Satluj River Basin is controlled by the interaction of steep topography, high local relief, structurally weak lithological units, geomorphic processes and anthropogenic alterations of the landscape. All of these factors contribute to the potential for slope failure and account for the spatial clustering of landslides in certain environmental contexts. The results of this work give useful information on the environment during the occurrence of landslides in the northwestern part of the Himalaya and also to the understanding of the process of slope instability in a tectonically active mountain environment. The identified relationships can contribute to the future modelling of landslide susceptibility, Hazard zonation, Infrastructure planning and Disaster Risk reduction strategies in the Upper Satluj River Basin and other Himalayas with similar geo-environmental conditions.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CONFLICTS OF INTEREST

There is no conflict of interest among the authors.

ETHICS APPROVAL

No animal or human being is involved in this study

CONSENT TO PARTICIPATE

Authors have given their consent to participate

CONSENT TO PUBLISH

Authors have given their consent for publication

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