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Geo-Spatial Analysis to Access Land Slide Susceptibility in Tehsil Balakot, District Mansehra, Pakistan

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Land slides are one of the recurrent natural problems that are widespread throughout the world, especially in mountainous areas, which cause significant injuries and loss of human lives, damage to properties and infrastructures. The term "landslide" is the movement of a mass of rock, debris, or earth down a slope under the influence of gravity. Landslide hazard mapping is a fundamental tool for disaster management activities in fragile mountainous terrains. The main purpose of this study was to find out landslide hazard assessment by bivariate statistical modelling and prepare an optimized mitigation map of the tehsil Balakot. The modelling was performed using a geographical information system (GIS) to derive a landslide hazard map of the tehsil Balakot. To achieve the objectives of the study, two types of variables, that is, dependent variables and independent variables, were used. The dependent variable that was selected for study was landslide occurrences. As a mandatory part of the study, the sites of previous landslides were collected from Google Earth Pro software, and a consecutive field visit was also conducted to validate the landslide sites on the ground. The Independent variables were the landslide causal factors. The causal factors that were used to achieve the objectives are Slope, Aspect, Curvature, NDWI, NDVI, Geological map, Elevation, and River distance network. The DEM data, Sentinel-2 data, and regional geologic map were used to process the landslide causal factors. The information value model was used for assessing the landslide susceptibility. The landslide susceptibility map was evaluated using the ROC curve. The result of the AUC curve was 78.71% which indicated good accuracy in the identification of the landslide susceptibility zone in a region.

Keywords: GIS, LSM, Balakot, Hazard

Introduction:

Landslides rank among the most dangerous natural hazards in mountainous regions worldwide, often resulting in loss of life, property damage, and disruption of livelihoods [1] Landslides are triggered by various natural and human-induced factors, including heavy or prolonged rainfall, earthquakes, snowmelt, changes in land use and land cover, and deforestation, posing a significant challenge to the sustainable development of hazard-prone regions [2]. Overall, landslides are complex systems occurring repetitively in time as hazards, and landslide susceptibility mapping (LSM) has established itself as a useful tool in disaster risk reduction, sustainable development, and land use planning [3].

Balakot Tehsil, situated in Mansehra District of Khyber Pakhtunkhwa (KPK), Pakistan, is highly vulnerable to landslides due to its mountainous terrain with steep slopes, underlying geology, dense forest cover, remoteness, and seismic activity [4]. The Kashmir earthquake of October 2005, which destroyed 80–90% of Balakot's buildings and resulted in significant loss of life, has left the area vulnerable to a range of interacting hazards [5]. Balakot Tehsil, covering an estimated area of approximately 2,300 km², is situated in the western lower Himalayas, with elevations ranging from under 737 meters to over 5,100 meters [6]. Located along the Kunhar River and at the gateway to the Kaghan Valley, Balakot benefits from tourism; however, this location also exposes the region to multiple hazards, including earthquakes, flash floods, avalanches, and landslides [7].

Although Balakot is important for agriculture and tourism, comprehensive studies on landslide susceptibility remain limited. Research in the surrounding mountainous regions most recently by the USGS in 2020 has demonstrated the effectiveness of statistical and GIS-based models in mapping landslide-prone areas, such as those in the Himalayas where Balakot is located [8], However, the lack of localized susceptibility models limits planning and risk mitigation efforts, which are crucial for balancing tourism development with the protection of local resources [9]. As the district depends heavily on natural resources, agriculture, and tourism, developing an accurate susceptibility map is crucial for ensuring safe access, conserving ecological habitats, and effectively protecting communities at risk from landslides or floods.

This study employs a bivariate statistical method called the Information Value (IV) model to assess landslide occurrences in Balakot Tehsil in relation to geo-environmental factors. By integrating layers of geology, slope, aspect, elevation, land use/land cover, drainage, and soil properties within a GIS (Geographic Information System), a susceptibility map can be generated to identify areas at high risk of future landslides. The outcomes of this project are intended to provide scientific evidence for use by local jurisdictions, planners, and policymakers in the management of land use practices and development strategies to reduce future losses. The goals of this research are to: Evaluate the variables of conditioning that affect landslides in Balakot Tehsil. Assess and map landslide susceptibility zones by using the Information value model.

Novelty:

This research presents one of the first regional assessments of landslide susceptibility in Balakot Tehsil using GIS-based statistics. Unlike other studies that are limited to a regional scale, this one Integrates PALSAR DEM, Sentinel-2 derived indices (NDVI, NDWI), and geological data with a detailed landslide inventory. Includes vegetation and water indices to reflect the conditions of a post-earthquake setting. Uses the Information Value (IV) model and validates results from the study through sources (Success Rate Curve (SRC) & ROC curve (AUC=78.71%). The inclusion of vegetation and hydrology indicators in conjunction with terrain and geological variables creates a noteworthy difference from previous studies taking place in northern Pakistan. The findings also produce outputs that are relevant to tourism and agricultural corridors in Balakot, enabling future decisions regarding infrastructure safety and hazard mitigation.

Objectives:

This study aimed to examine and assess the geo-environmental conditioning factors, namely, slope, aspect, curvature, NDVI, NDWI, geology, elevation, and distance from the river, related to landslide inducing sustainability within Balakot Tehsil. A landslide inventory was developed through the use of satellite imagery and ground-truthing to be employed to train and test the models in this study. In a GIS environment, the Information Value (IV) model was utilized to evaluate and map landslide susceptibility zones. The susceptibility model was validated through both the Success Rate Curve (SRC) and the Receiver Operating Characteristic (ROC) curve methodologies. Ultimately, the overall objective of this study was to develop a reliable Landslide Susceptibility Map (LSM), which is useful in land-use planning, disaster risk reduction, and infrastructure development of Balakot Tehsil.

Study Area:

The largest administrative unit in the Mansehra District is Balakot Tehsil, which embraces an area of about 2,300 km². It is located in the lower Himalayas from an elevation of 737 m to 5,101 m above sea level. The area is mountainous, featuring steep slopes, dense black pine forests, and the fast-flowing Kunhar River, which originates from Lulusar Lake and joins the Jhelum River at Muzaffarabad. Balakot is known as a gateway town into the Kaghan Valley and is one of the prominent tourism areas. As a result of the active tectonic zone it is located in, as well as weak lithological formations, Balakot is really prone to natural hazards like earthquakes, floods, avalanches, and landslides. Balakot is positioned within the Hazara–Kashmir Syntax and is bounded by the Main Boundary Thrust (MBT), which causes geological instability.

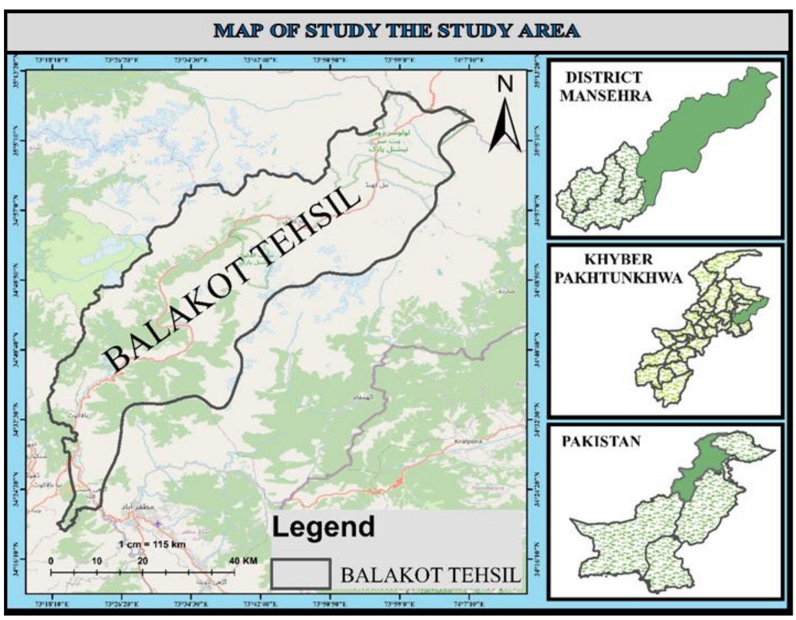

Figure 1. Location Map of the study area.

Materials and Methodology:

Data Sources and Preparation:

The research methods for this study were based on a combination of remote sensing data, field surveys, and GIS-based spatial analysis. Topographic parameters such as slope, aspect, curvature, and elevation were sourced from a Phased Array L-band Synthetic Aperture Radar (PALSAR) DEM at 12.5 m resolution. Sentinel 2 multispectral imagery was processed using remote sensing techniques to produce vegetation and water indices, including NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index) as indicators for vegetation cover and soil moisture, respectively. Geology data was acquired from the Dayar-A and B regional geological map of the Mansehra District of the Geological Survey of Pakistan. The work also allowed for the compilation of a landslide inventory via visual interpretation of Google Earth Pro, which was further field checked. We identified a total of 1,155 landslide polygons covering an area of 165 km². To maintain spatial consistency, all datasets were projected to UTM Zone 43N and resampled to a 30 m grid resolution, with the study area boundary obtained from the official administrative shapefile.

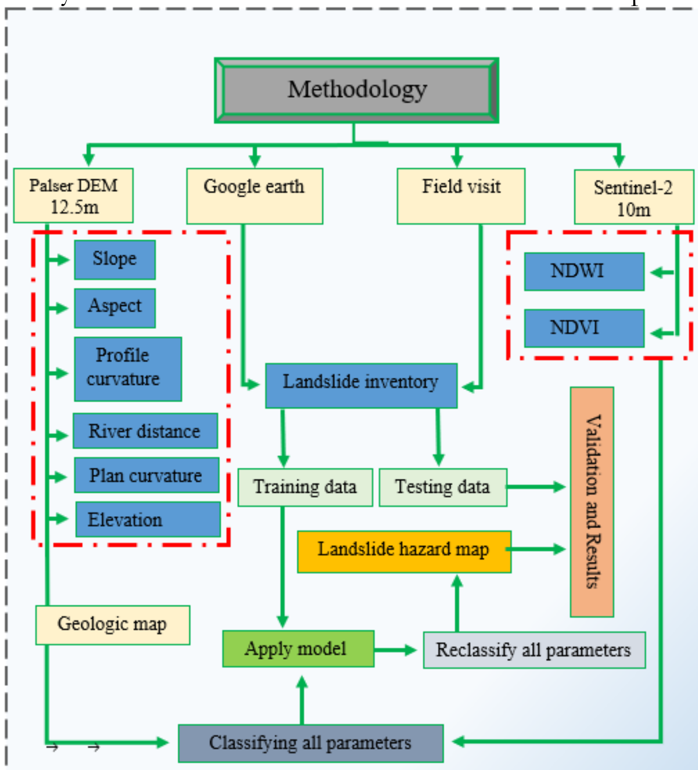

Figure 2. Methodology flowchart for depicting the landslide susceptibility analysis.

Landslide Inventory:

The landslide inventory was used as the dependent variable for model training and validation. The identified landslide polygons were randomly divided into two subsets, with 70% allocated for training and 30% reserved for validation. The training dataset was used to develop statistical relationships between landslide occurrence and the selected causative factors, while the validation dataset was used for independent testing to measure the effectiveness and predictive power of the model.

Selection of Causative Factors:

This study evaluated the intrinsic factors of terrain and environmental conditions using eight factors of intrinsic nature: slope, aspect, plan curvature, profile curvature, elevation, geology, distance to rivers, NDVI or normalized difference vegetation index, and NDWI or normalized difference water index. Slope demonstrates the steepness of the terrain, which can be classified as gentle (less than 15°), moderate (15 to 30°), or steep (greater than 30°). Aspect defines the orientation of slopes and can impact sunlight exposure, vegetative processes, and retained moisture. Curvature consists of plan curvature, which can control surface flow convergence or divergence, and profile curvature, which can determine the flow acceleration or deceleration across the slope. The NDVI, or normalized difference vegetation index, was used to assess the aerial extent of vegetated cover. NDWI, or normalized difference water index, was used to inform evaluations of aquatic and soil moisture conditions. Geology, or lithological units, was classified with the Murree Formation and Panjal Volcanics considered.

Distance to rivers was evaluated through Euclidean distance from the drainage network, which offers metrics related to hydrology.

Statistical Modeling: Information Value (IV) Method:

A bivariate statistical model, the Information Value (IV) model, was used to quantify the relationship between landslide events and classes representing different causative factors. Using this approach, we calculated the IV for each class based on the proportion of landslide pixels in that class to total landslide pixels in the study area.

$$IV_j = \ln\left(\frac{N_{si}/N_s}{N_i/N}\right)$$

Where: Nsi = number of landslide pixels in factor class i, Ns = total number of landslide pixels in the study area, Ni = total number of pixels in factor class i, and N is the total number of pixels in the study area. A positive IV value suggests a higher probability of landslide occurrence, and a negative value suggests a lower probability of occurrence. The Landslide Susceptibility Index (LSI) was created by summing the IV values of all classes of contributing factors for each cell in the grid, resulting in a spatially distributed landslide susceptibility value.

$$LSI = \sum IV_j$$

Landslide susceptibility mapping and Model validation:

The Landslide Susceptibility Index (LSI) values were classified into five susceptibility zones - very low, low, moderate, high, and very high - using a quantile classification system to balance the number of classes across the area of interest. This classification scheme shows areas that are more susceptible to landslides in a clear spatial representation, as opposed to the LSI values themselves. The final landslide susceptibility map for this study was produced using ArcGIS 10.7 and establishes a method for representing and visualizing possible hazard zones.

To assess the reliability and predictive performance of the model, two validation techniques were employed. The first technique was the Success Rate Curve (SRC), which was developed using the training data set to show the cumulative percentage of lost area that fell within various susceptibility classes and thus demonstrated the ability of the model to explain past landslide episodes. The second technique included the Receiver Operating Characteristic (ROC) curve, which produced an Area Under the Curve (AUC) value using the validation data set to estimate predictive accuracy. The model achieved an AUC value of 78.71%, indicating a reasonable ability to discriminate between areas prone to landslides and those that are not. The validation results and processes demonstrate that the model established a dependable representation of landslide susceptibility that can be appropriately used for hazard assessment and risk management purposes in the area of interest.

Results and Discussion:

Slope:

Slope is a critical indicator of landslide activity. The analyses continued to show that slopes greater than 30° experienced a higher density of landslides. In these slopes, the magnitude of the gravitational force, even upon unconsolidated or weaker materials, made it unstable. There was little and no landslide activity on gently sloped (<15°) slopes, indicating that it had stable conditions. Moderately sloped (15–30°) slopes were moderately prone to failures. They had generally stable conditions, but with the introduction of a trigger, such as highly intense rainfall or seismic shocks, they would have been prone to failure. In Balakot, it was observed that steep mountainous terrain in the Kaghan Valley showed the greatest slope-related susceptibility, particularly where there had been persistent rain for the past year.

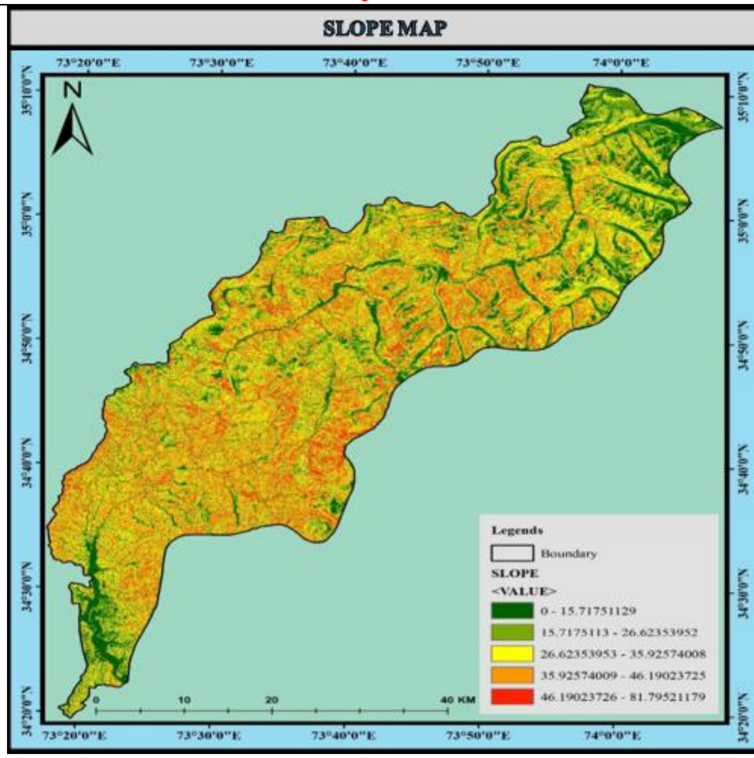

Figure 3. Slope map illustrating the spatial distribution of slope classes across the study area.

Aspect:

Aspect affects slope orientation, which influences solar radiation, vegetation establishment, and the retention of moisture. South-facing slopes had more frequent landslides in Balakot, which could be attributed, in part, to low vegetation density and higher levels of weathering. North-facing slopes could also fail; that failure usually resulted from soil saturation levels after snowmelt. East and west-facing slopes had moderate failure. It shows evidence that the aspect affected slope stability in conjunction with local climate and vegetation.

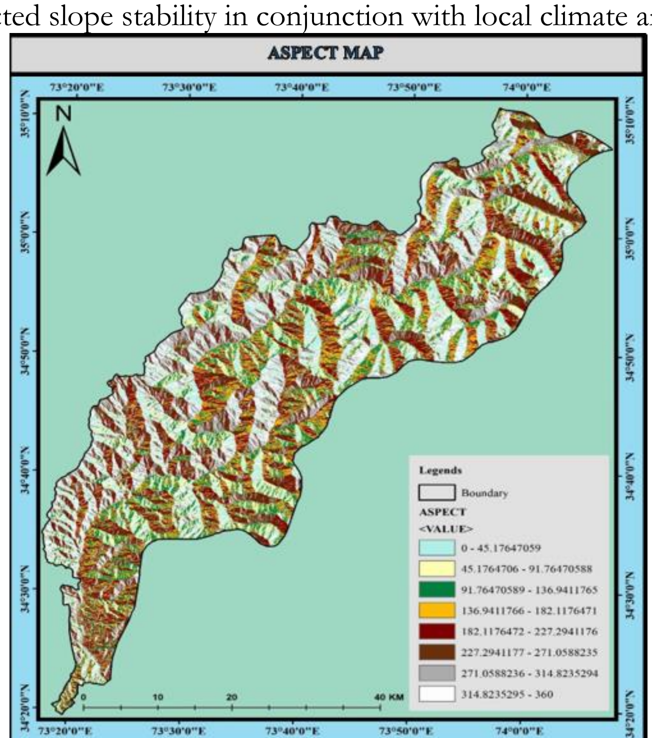

Figure 4. Aspect map showing the directional orientation of slopes across the study area.

Curvature:

Terrain curvature is a critical factor in water flow and slope stability. Concave (negative) slopes had the greatest density of landslides. These slopes served as natural water collectors, increasing pore-water pressure and weakening soil strength. Convex (positive) slopes were relatively stable because water quickly drained through the soil, reducing saturation. The planar slopes experienced movement and moderate instability. Plan curvature controlled the convergence and divergence of flow across the slope. Profile curvature dictated the acceleration or deceleration of water flow downward, influencing soil erosion and overall stability. These aspects of terrain curvature illustrate the difference in landslide density between concave valleys and areas with drainage alignments in Balakot.

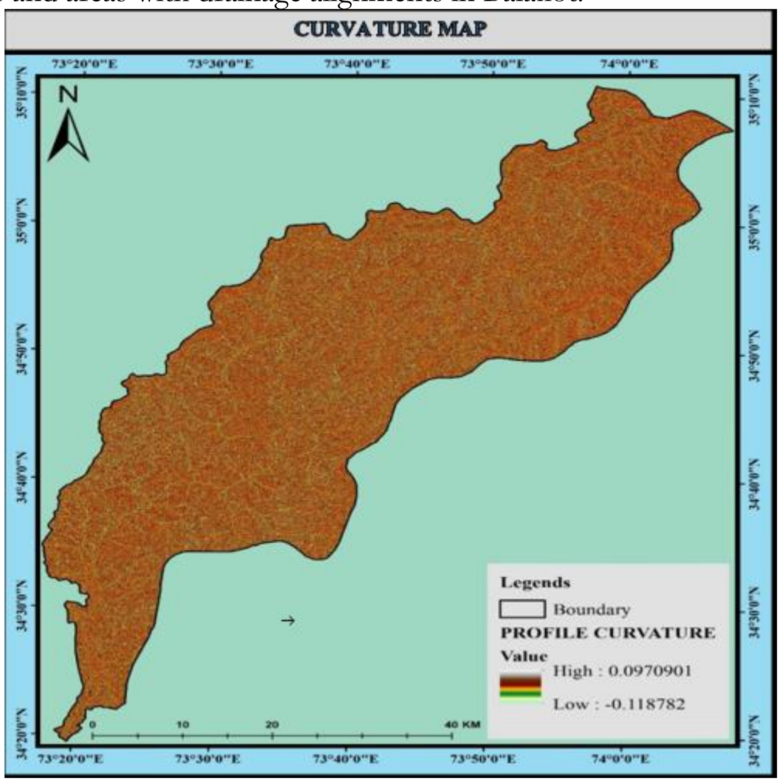

Figure 5. Curvature map representing the variation in concave and convex landform features across the study area.

Geology:

Geological formations are key contributors to slope stability. The Murree Formation was composed of weakly cemented sandstones, siltstones, and shales, which made this formation particularly prone to landslides due to weak cohesion and weathering susceptibility. Similarly, the Panjal Volcanics featured fractured lava flows and altered rocks and exhibited a significant amount of landslide activity. Conversely, rock types with stronger lithologies, such as granitic rock or metamorphic rock, exhibited fewer landslides. The location of major fault lines and thrust zones (like the Main Boundary Thrust or MBT) added to this susceptibility by providing a fractured and weakened rock mass and thus, compound slope failure susceptibility.

River Distance:

Another major factor was the proximity of the river and its streams. Landslides were more likely to occur 0–500 m from the Kunhar River and its tributaries. Continuous undercutting and riverbank erosion destabilized valley walls, and slope failure occurred. The lower valley areas with weak lithologies and continuous fluvial activity had the greatest susceptibility.

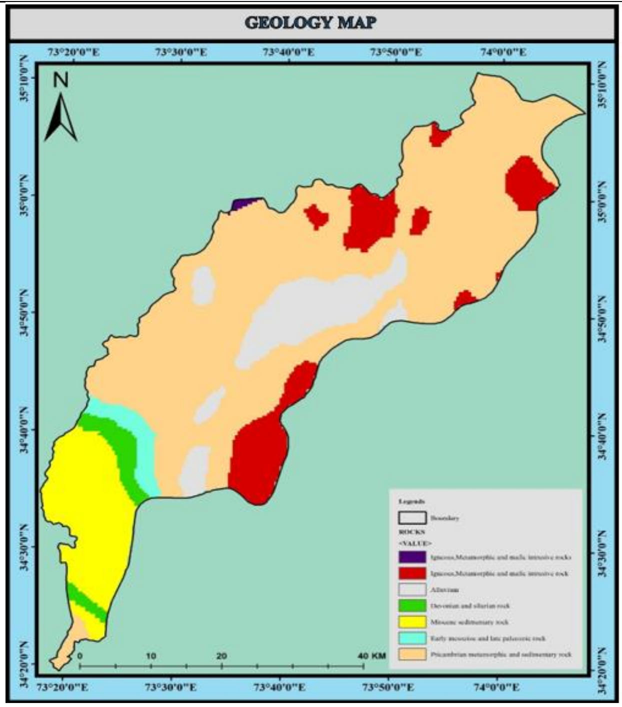

Figure 6. A geology map illustrating the spatial distribution of different rock types and formations within the study area.

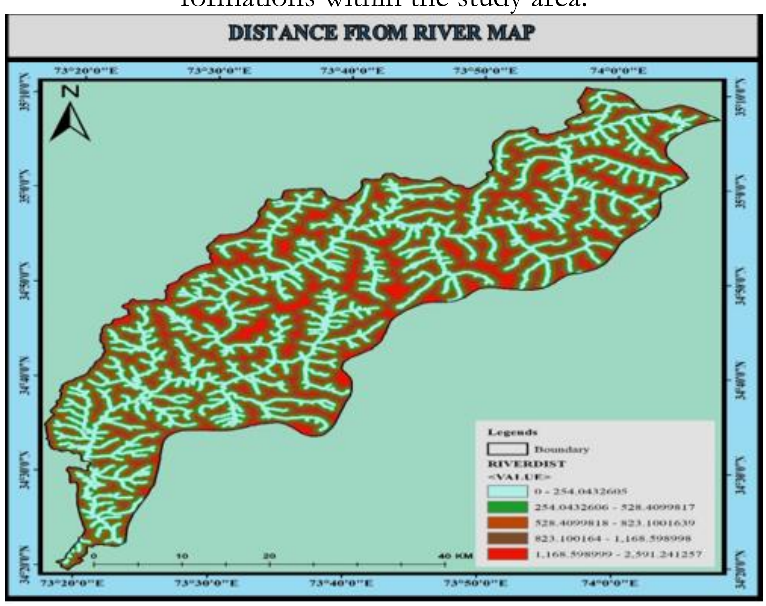

Figure 7. River distance map depicting the spatial variation in proximity to river networks across the study area.

NDVI and NDWI:

Slopes with low vegetation cover (NDVI <0.2) experienced high landslide activity. Areas classified as having moderate vegetation (0.2–0.4 NDVI) showed moderate susceptibility, while slopes with considerable density of forests (NDVI >0.4) tended to be securely stable. Landslides did occur in steeply sloped forested areas, suggesting that slope angle and lithology are likely more influential than just vegetation. High NDWI values, which indicate wet saturated soils, were associated with landslide-prone areas, especially when close to rivers, streams, and areas that facilitate meltwater. Saturated soils have lower shear strength and higher pore-water pressures that can contribute to slope failures. Whereas drier slopes with low NDWI values show lower landslide density.

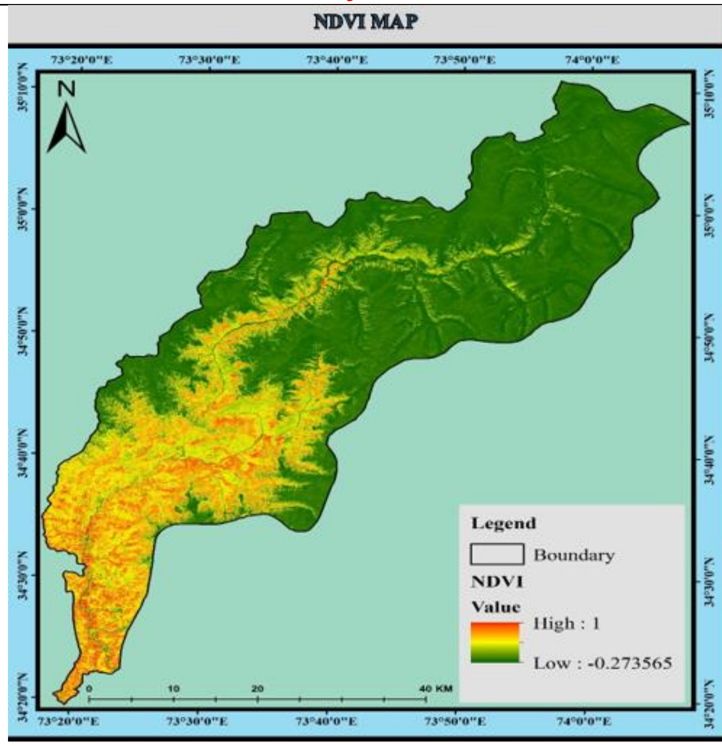

Figure 8. NDVI map showing the spatial distribution of vegetation density and health across the study area.

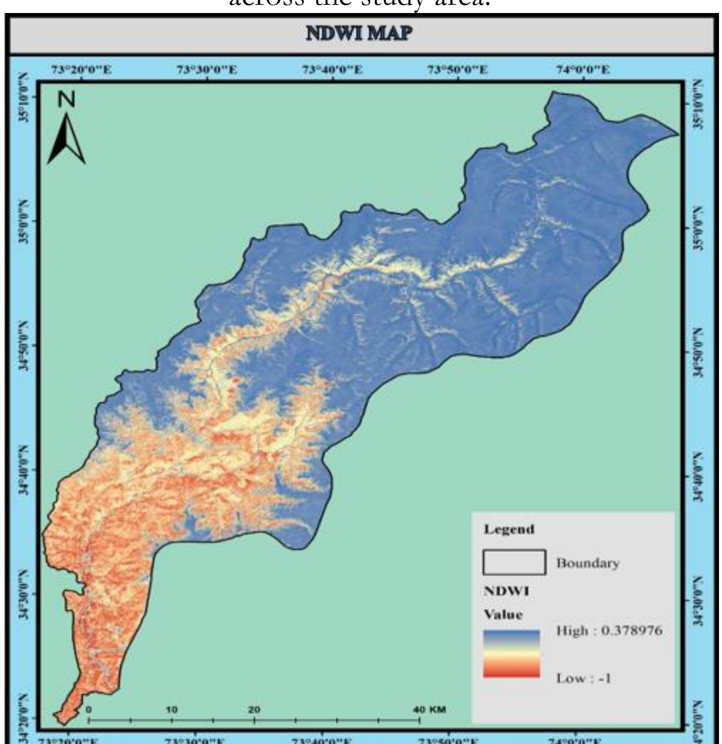

Figure 9. NDWI map illustrating the spatial distribution of surface water presence and moisture content in the study area.

Landslide Susceptibility Analysis:

The Landslide Susceptibility Map (LSM) for Balakot Tehsil was developed using the Information Value (IV) model. After classification, the final map delineated five susceptibility zones: very low, low, moderate, high, and very high. The results indicate that the high and very high susceptibility zones are primarily concentrated in the northern and northeastern parts of the study area, corresponding to steep slopes, weak lithologies, and areas of intense river erosion, including the Kaghan Valley and other mountainous regions prone to frequent landslides. Moderate susceptibility zones were found in the central part of the tehsil. Although the slopes there were gentler, these areas were still influenced by structural discontinuities and land-use pressures. Low susceptibility zones were observed in the flatter southern regions of the tehsil.

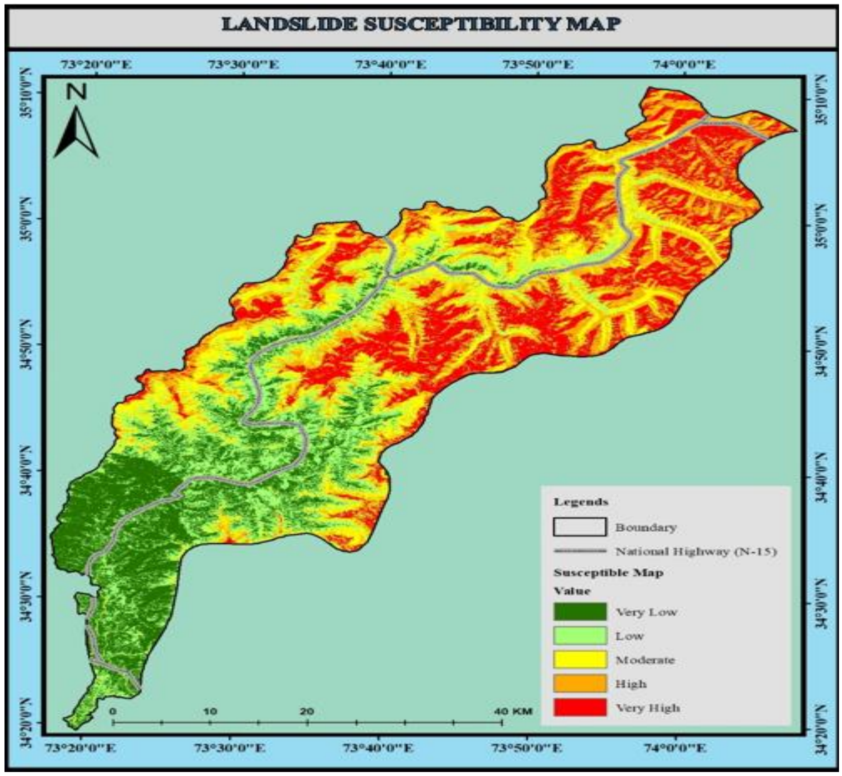

Figure 10. Landslide Susceptibility Map (LSM) indicating spatial zones of varying landslide risk across the study area.

Model Validation:

The Success Rate Curve (SRC) and Receiver Operating Characteristic (ROC) curves were used to assess model performance. The SRC showed that over 80% of the inventoried landslides fell within the high and very high susceptibility zones, demonstrating the model's strong predictive capability. The ROC analysis yielded an AUC of 78.71%, which indicates good predictive power and reliability of the IV model for regional-scale susceptibility mapping.

The findings indicate that landslide occurrence in Balakot is largely influenced by steep topography, weak geological formations, and proximity to drainage networks. Additionally, other studies from northern Pakistan's mountainous areas and the Himalayas also primary conditioning factors of slope and lithology. The introduction of vegetation and water indices (NDVI and NDWI) in this study revealed the additional component of land cover and moisture influence on slope stability.

The calculated LSM is relevant, especially in the case of the Kaghan Valley corridor, which is a tourism and agriculture hub but prone to slope failures. Outlining the high-risk areas provides scientific information used for land-use planning, engineering activities, and disaster risk mitigation planning. The significant validation also shows that the Information Value model is appropriate for regional-scale assessments of landslide susceptibility.

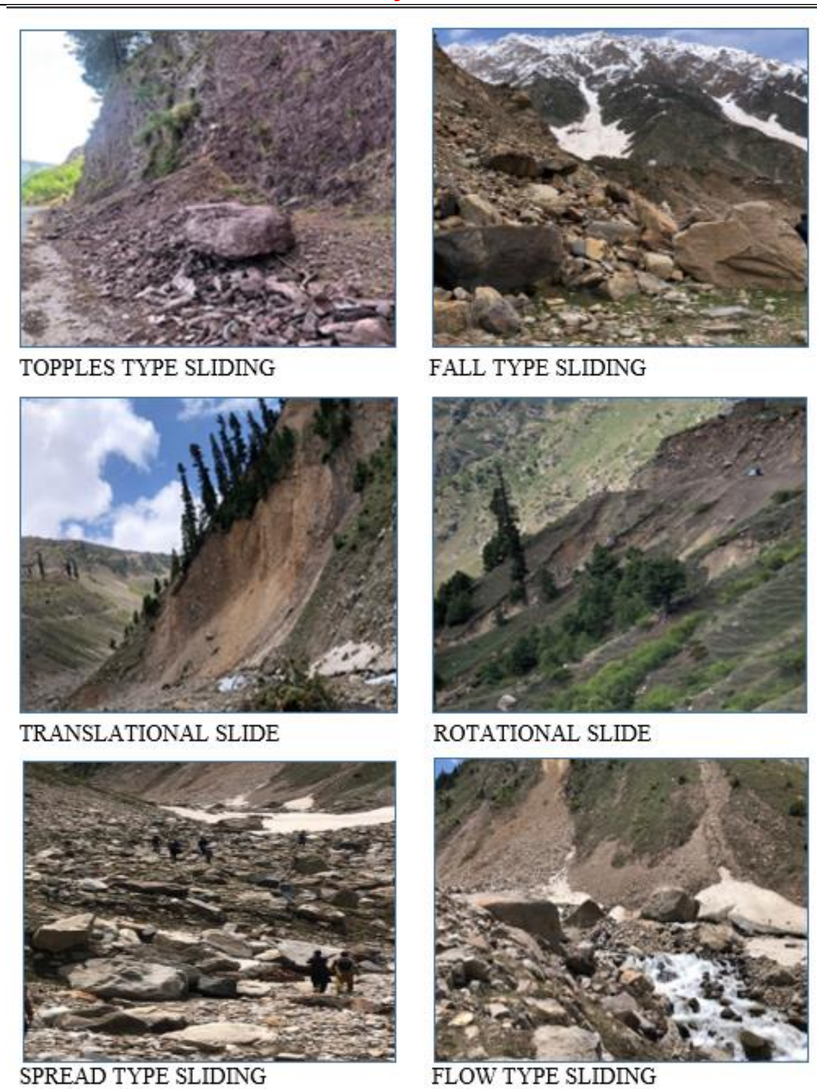

Figure 11. Field survey photographs documenting on-site observations and ground validation within the study area.

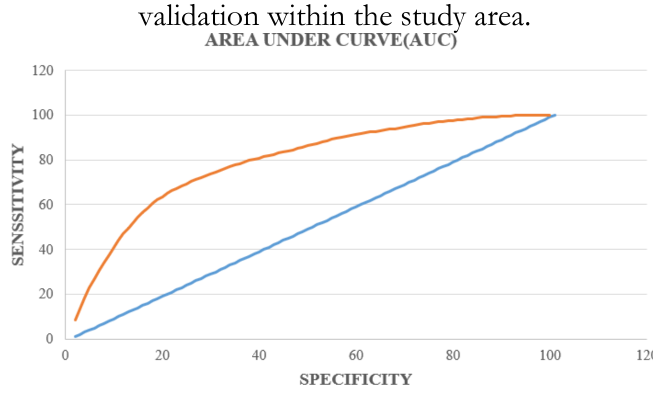

Figure 12. AUC Graph

The results of this study underscore the important role of slope, lithology, and distance from rivers in controlling landslide occurrences in Balakot Tehsil. Steep slope (>30°) and weak geological formations, especially the Murree Formation and Panjal Volcanics, were identified as the most significant conditioning factors, which agrees with previous work in the Himalayas and northern Pakistan [10]. Vegetation (NDVI) and moisture (NDWI) indices were also imbued with relevance to slope stability in areas where lower NDVI and higher NDWI corresponded with higher landslide densities. This supports the argument that land cover and soil moisture dynamics act as additional layers of influence beyond topography and geology [11]. In a comparison of GIS-based susceptibility assessments conducted in mountainous settings, this study's predictive performance (AUC = 78.71%) provides an indication of a strong model performance. For instance, [5][1] reported relatively similar AUC values between 75-80% using statistical approaches, giving confidence that the Information Value (IV) model is credible for regionally-scaled susceptibility mapping. Additionally, the place-based approach employed here allows for a more localized understanding of hazards in Balakot Tehsil, especially where slope instability is present due to earthquake-induced landslides (e.g., 2005 Kashmir earthquake) and frequent monsoonal rainfall events. The spatial distribution of susceptibility zones provides indications for planners, policy makers, and disaster management entities. High and very high susceptibility zones, focused along the Kaghan Valley corridor, need to be prioritized for slope stabilization, hazardous monitoring, and land-use adaptations. In summary, the study enhances existing literature by examining both terrain and environmental variables, validating model outputs with different methods, and creating a usable susceptibility map that can directly assist with tourism management, infrastructure safety, and disaster risk reduction in one of the most landslide-prone regions of Pakistan.

Conclusion:

This study used a GIS-based Information Value (IV) model to evaluate landslide susceptibility in Balakot Tehsil, one of the most landslide-prone areas in Mansehra District, Pakistan. Using multi-source data, including topographic variables derived from a DEM, Sentinel-2 indices, geological maps, and a detailed landslide inventory, the analysis determined that the most important conditioning factors were slope, elevation, geology, and distance to river. The susceptibility map identified five zones in the tehsil with high & very high susceptibility, mostly confined to the northern and northeastern sectors, particularly in the Kaghan Valley corridor. Model validation using Success Rate Curves and ROC analysis (AUC = 78.71%) showed reasonably good predictive ability. These findings provide a reliable basis to better inform land-use planning, infrastructure development, and disaster risk reduction in the extremely vulnerable mountain environment of Pakistan. Future studies should incorporate variables such as rainfall intensity, seismic triggers, and human dimensions in a more integrated analysis focused on improving susceptibility and developing more comprehensive risk assessment.

Authors Contribution:

Ummer Iqbal: Conceptualization, Methodology, Formal analysis, Writing- original draft. Mazhar Hussain Shah: Supervision, Conceptualization. Abdullah Riaz: Writing- review & editing.

Declaration of Competing Interest:

The authors declare that there is no conflict of interest either financially or as personal relationships that could have inappropriately influenced the work presented in this paper.

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