GIS Based Spatial Analysis of Landslide Hazard in Tehsil Balakot, KP, Pakistan

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Abstract

The Himalayan region is highly susceptible to landslides due to intense rainfall and seismic activity, posing significant risks to slope stability. Due to landslides, Tehsil Balakot valley has suffered substantial damage to infrastructure, roads, and the tourism sector. This research aims to develop a landslide susceptibility map and identify hazard-prone areas to support sustainable development and mitigate risks in Balakot valley. The study employs a weighted overlay analysis using primary and secondary data raster layers, including slope, aspect, precipitation, and seismic raster maps. The slope and aspect maps are derived from a 30-meter ASTER digital elevation model, while precipitation maps are generated using Inverse Distance Weighted (IDW) interpolating data from the Pakistan Meteorological Department. Seismic data is acquired from the Geological Survey of Pakistan (GSP). The resulting landslide susceptibility map classifies the region into five hazard classes: very high, high, medium, low, and very low. The landslide susceptibility maps provide valuable insights for identifying areas at varying levels of landslide risk.

Keywords: Landslide Susceptibility, GIS, Seismic Activity, Weighted Overlay Analysis.

Introduction

Landslides represent one of the most significant and destructive natural hazards, particularly in mountainous regions worldwide (Bathrellos et al., 2021). These geological phenomena involve the downward and outward movement of slope-forming materials—such as rocks, soil, and debris—primarily driven by gravity (Ibrahim, 2022). The consequences of landslides are profound, often resulting in considerable economic losses, extensive damage to infrastructure, and, tragically, the loss of human lives (Thapa, 2023). The threat posed by landslides is especially acute in areas characterized by steep terrain, high precipitation, and seismic activity, where these factors collectively contribute to a heightened susceptibility to slope failures (Tyagi et al., 2022).

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The occurrence of landslides is typically triggered by a combination of factors, including the steepness of slopes, geological conditions, weathering processes, and external stimuli such as heavy rainfall or seismic events (McColl, 2022). In vulnerable regions, the sudden and often unpredictable nature of landslides makes them particularly hazardous, with the potential to cause widespread devastation in densely populated areas (Pollock & Wartman, 2020). Historical events, such as the 1999 Vargas tragedy in Venezuela, highlight the catastrophic potential of large-scale landslides, which can claim thousands of lives and cause irreparable damage (Glade et al., 2005).

Globally, landslides and related geological hazards—such as debris flows, rockfalls, and mudslides—are among the most catastrophic natural hazards, responsible for significant destruction of infrastructure and the economy, as well as posing a continual threat to human safety (Dou, 2019; Gan, 2019). On average, landslides result in approximately 1,016 deaths and cause economic losses of around 4 billion US dollars each year (Kanungo et al., 2008). While individual landslide risk assessments have advanced considerably, the evaluation of landslide risk on a regional scale remains relatively underexplored in the literature (Wang, 2021). Creating a landslide susceptibility map (LSM) is one approach to predicting the likelihood of landslides occurring under various causative factors. Landslide risk assessment (LRA) also focuses on identifying the elements—such as infrastructure, populations, and critical facilities—that are most at risk in hazard-prone areas (Jaiswal et al., 2010). To effectively mitigate and prevent risks, it is crucial to evaluate the hazard and the exposure and vulnerability of at-risk elements (Haq et al., 2020).

Landslide hazard assessment, mainly through Geographic Information Systems (GIS) application, has garnered significant attention recently (Neamat & Karimi, 2020). Integrating GIS with various geospatial data sources, such as remote sensing data and Digital Elevation Models (DEMs), has proven to be a robust method for identifying and analyzing landslide-prone areas (Psomiadis et al., 2020). Johnson and Smith (2010) demonstrated the utility of GIS in integrating geospatial data for landslide hazard assessment, emphasizing the importance of terrain analysis and geomorphometric indices in understanding slope stability. Their work laid the foundation for using GIS as a critical landslide hazard mapping and analysis tool.

Building on this, Brown et al. (2015) highlighted the importance of statistical models within a GIS framework for landslide susceptibility mapping. Their study effectively showcased the ability of GIS-based statistical models to identify areas with varying degrees of landslide susceptibility. Such models are crucial in mountainous regions where the terrain's complexity requires detailed analysis to predict potential landslide occurrences accurately.

In addition to susceptibility mapping, assessing landslide vulnerability is critical to risk management. Johnson and Williams (2019) integrated exposure data with landslide susceptibility maps to conduct a GIS-based vulnerability and risk assessment. Their study identified high-risk areas and provided valuable insights for disaster preparedness planning, demonstrating the importance of considering hazards and vulnerability in landslide risk assessments.

The development of early warning systems (EWS) for landslides is another area where GIS has played a pivotal role. Smith et al. (2021) developed a GIS-based EWS that combined real-time monitoring data with hazard zonation maps. Their system effectively provided timely alerts and facilitated proactive risk mitigation strategies, underscoring the critical role of GIS in enhancing disaster response capabilities.

Remote sensing technologies, particularly satellite imagery and LiDAR, have also been instrumental in landslide monitoring. Wu et al. (2018) utilized high-resolution satellite imagery to detect and monitor real-time landslide occurrences. Integrating remote sensing data with GIS enables efficient and cost-effective landslide monitoring, aiding in the early identification of potential hazards. This combination of technologies is essential for regions prone to frequent landslides, where timely detection and monitoring can significantly reduce the risk of catastrophic events.

Assessing landslide risk involves evaluating an area's susceptibility to landslides and considering the potential consequences on communities, infrastructure, and the environment. Huang and Yang (2019) conducted a GIS-based landslide risk mapping study that quantified risk levels by considering physical and societal vulnerability factors. Their work highlights the importance of a comprehensive approach to landslide risk assessment, which can aid in prioritizing mitigation efforts and emergency response planning.

Various studies have also explored the adaptation of GIS-based techniques to different geographical settings. González and López (2017) emphasized the need for context-specific approaches in landslide hazard assessment, as the physical and environmental characteristics of each region can significantly influence the accuracy and applicability of the models used. Their study underscores the importance of tailoring GIS methodologies to the unique conditions of each study area.

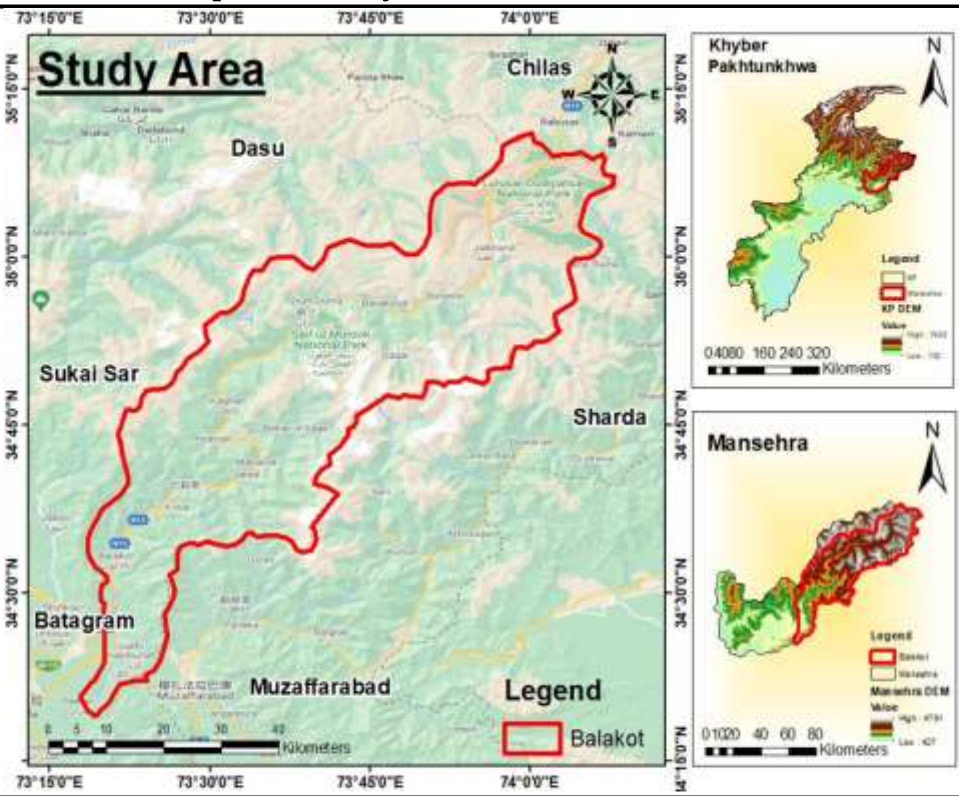
In the context of landslide impacts on settlements, Priyono et al. (2020) applied a bivariate statistical approach in a GIS environment to analyze the risk of landslides on settlements in Central Java, Indonesia. Their study demonstrated the effectiveness of integrating statistical methods with spatial analysis to generate landslide risk maps, which are crucial for mitigation. Furthermore, Dikshit et al. (2020) explored spatial landslide risk assessment in the Phuentsholing region of Bhutan. Their study combined GIS to develop hazard and vulnerability maps to create a comprehensive landslide risk map. This approach is precious in areas with limited data availability, where GIS-based methods can provide essential insights for risk management. Various studies have also explored landslide susceptibility assessment at a local spatial scale. Vojteková and Vojtek (2020) used multi-criteria evaluation and GIS to assess landslide susceptibility in Slovakia. Their study highlighted the importance of considering local terrain predispositions and the effectiveness of GIS-based analysis in identifying areas with high landslide susceptibility.

Finally, recent studies have focused on integrating vulnerability and hazard factors in landslide risk assessment. Arrogante-Funes et al. (2021) developed a heuristic risk model that integrated susceptibility and vulnerability maps to assess landslide risk in Mexico. Their study demonstrated the adaptability of GIS-based risk assessment tools to different regions, emphasizing the importance of considering ecological and socio-economic vulnerabilities in landslide risk management.

Study Area

The Balakot valley, located between latitudes 34° 30' 0'' to 35° 15' 0'' North and longitudes 73° 15' 0'' to 74° 0' 0'' East (Figure 1), is a region of striking natural beauty and significant historical and cultural importance in northern Pakistan. Positioned north of Mansehra city within the Khyber Pakhtunkhwa province, the valley is dominated by towering mountains, with elevations ranging from 2,000 meters in the south to over 4,500 meters above sea level in the north. The northern part of the valley, along its boundary with the Kohistan district, is home to the majestic Himalaya Range, including the renowned Babusar Pass on the northeastern edge of the valley. Notably, the peak of Nanga Parbat, one of the world's highest mountains, lies approximately 40 kilometers from the northeast boundary of Balakot valley. Nestled in the scenic Kaghan Valley, Balakot's breathtaking landscapes have drawn local and international attention.

Figure 1: Location map of the study area



Methods and Materials

Data Sources

Data for this study was obtained from multiple sources, including the Pakistan Meteorological Department, the Soil Survey of Pakistan, and the USGS Earth Explorer.

Elevation Data

Digital Elevation Models (DEMs) represent the topographic surface and provide essential information on slope and slope aspect, both of which are critical factors influencing slope stability (Kakavas & Nikolakopoulos, 2021). For this study, ASTER 30-meter elevation data was acquired from the USGS website and extracted to the area of interest to facilitate landslide susceptibility mapping. The DEMs were utilized to generate slope, aspect, and contour layers, which were subsequently used in the development of landslide hazard zonation (Blaschke et al., 2013).

Precipitation Data

Annual precipitation data was obtained from the Pakistan Meteorological Department. A precipitation map was created using the Inverse Distance Weighted (IDW) interpolation method to visualize spatial variations in rainfall across the study area.

Seismic Data

Seismic data, crucial for understanding the potential triggers of landslides, was acquired from the Soil Survey of Pakistan. A seismic hazard map was developed using the IDW interpolation method, incorporating earthquake points to illustrate seismic activity within the study area.

Figure 2: Flowchart showing methodology of the study

Methodology Approach for Weighted Overlay Analysis (WOA)

To assess landslide susceptibility in Tehsil Balakot, a Weighted Overlay Analysis (WOA) was employed. The process began with the acquisition and preprocessing of key input datasets, including a DEM for generating slope and aspect layers, as well as seismic hazard maps and precipitation data. All input layers were standardized to ensure consistency in spatial resolution and coordinate systems.

The next step involved reclassifying each data layer. The slope layer was categorized based on steepness, with steeper slopes assigned higher values. The aspect layer was reclassified according to directional orientation, reflecting its impact on moisture retention and sunlight exposure. Seismic data was reclassified into risk levels, while precipitation data was categorized by rainfall intensity, with higher values assigned to areas with greater precipitation. Fault lines, if included, were reclassified based on proximity, with higher values given to areas closer to faults. To determine the relative importance of each layer in influencing landslide susceptibility, weights were assigned based on expert knowledge or the Analytic Hierarchy Process (AHP).

The reclassified layers were then combined using the Weighted Overlay tool in ArcGIS's Spatial Analyst extension (figure 2). This process involved mathematical operations that produced a composite raster representing overall landslide susceptibility across Tehsil Balakot. The resulting susceptibility map was analyzed to identify areas with varying levels of landslide risk, providing critical insights for disaster management, land-use planning, and infrastructure development.

Result and Discussion

The Weighted Overlay Analysis (WOA) conducted for Tehsil Balakot revealed a spatial distribution of landslide susceptibility, highlighting areas at varying levels of risk. The composite susceptibility map clearly delineates zones with very high, high, moderate, low and very low landslide potential. Very high-risk areas are predominantly located on steep slopes with unfavorable aspects, where seismic activity and high precipitation further exacerbate the instability. These findings align with historical landslide occurrences, validating the accuracy of the model.

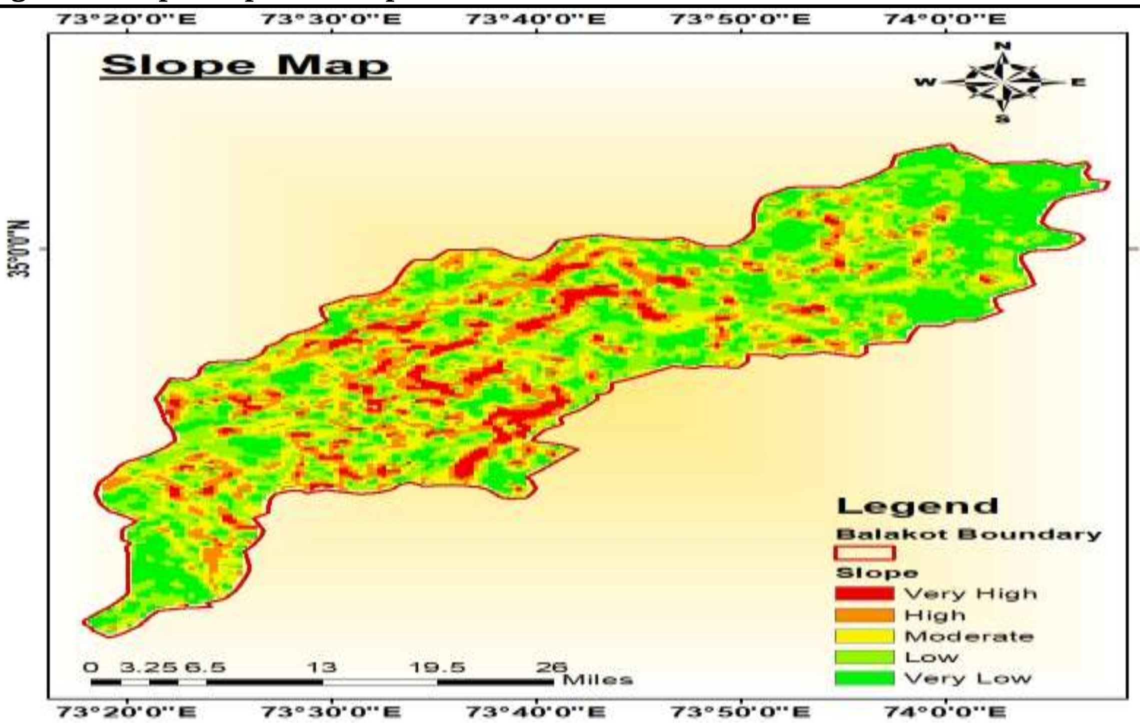
The results emphasize the critical role of slope and seismic activity in driving landslide susceptibility, with precipitation acting as a significant contributing factor. The integration of multiple layers, each weighted according to its influence, provided a nuanced understanding of how these factors interact spatially. This analysis not only identifies vulnerable areas but also serves as a valuable tool for land-use planning and disaster risk management in the region, guiding targeted interventions and mitigation strategies.

Slope

Figure 3 provides a visual representation of the slope orientation for Balakot Tehsil, Khyber Pakhtunkhwa, Pakistan, which is a critical factor in assessing landslide hazards. The map classifies the slope into two main categories: "high" (marked in red) and "low" (marked in green), indicating areas with varying degrees of slope inclination. The classification helps to identify regions that are more susceptible to landslides based on their slope characteristics. The slope model divides the terrain into categories based on slope angles, with low slopes (0-10 degrees and 10-20 degrees) representing gentler slopes. While these areas may seem less prone to landslides, they are actually vulnerable due to high-velocity water discharge and flow accumulation during heavy rainfall, which can trigger landslides. Conversely, areas with steeper slopes (20-30 degrees, 30-40 degrees, and 40-76 degrees) are identified as highly prone to landslide hazards, particularly during intense rainfall periods. These steeper slopes pose a significant risk for landslides, making them critical areas for monitoring and implementing mitigation measures.

In the Balakot region, slope steepness is a primary determinant of landslide susceptibility. The analysis revealed that areas with steeper slopes are at a significantly higher risk of landslides. This is due to the increased gravitational forces acting on the soil and rock materials, which are more likely to slide downhill as the slope angle increases. The mountainous terrain of Balakot, particularly in areas near the Kaghan Valley, features numerous steep slopes where past landslide events have been documented. The results indicate that these steep areas are consistently categorized as high-risk zones in the susceptibility map, underscoring the need for careful monitoring and mitigation in these regions.

Figure 3: Slope Map of Balakpt Tehsil

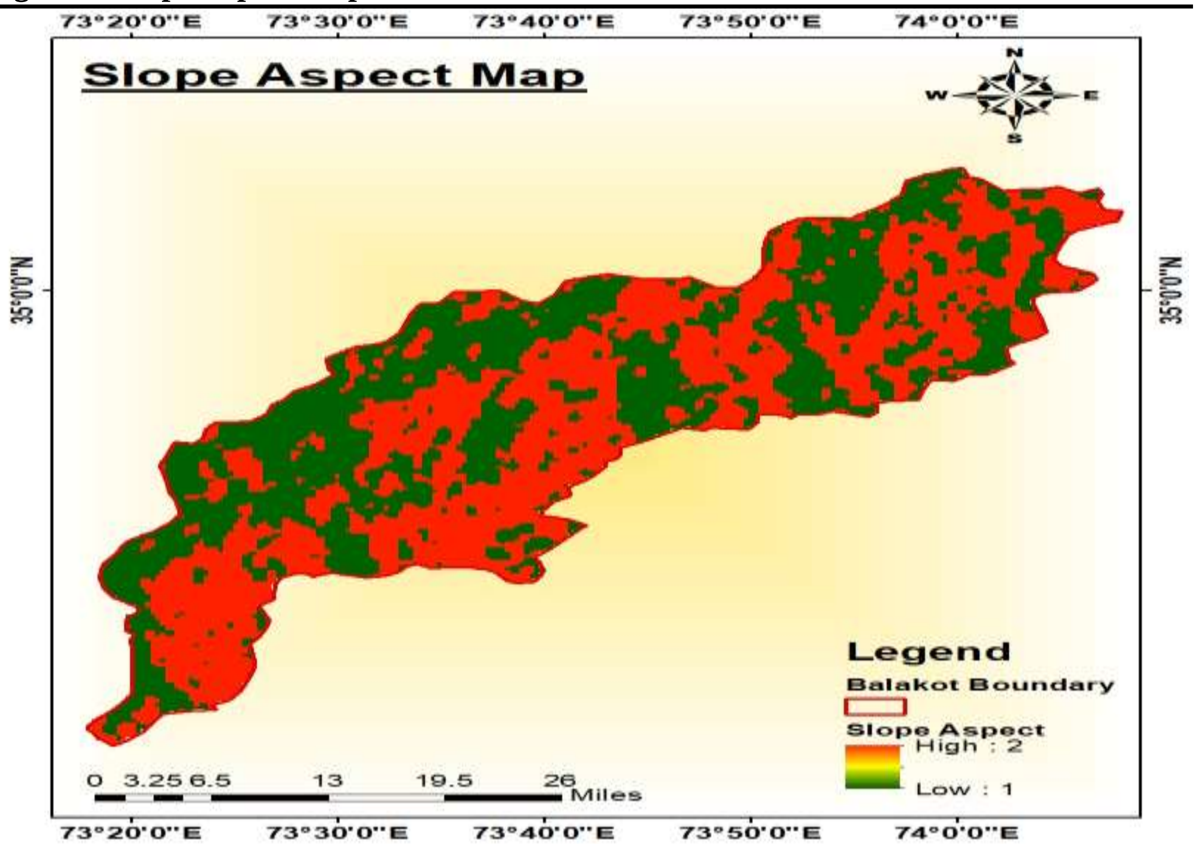


Aspect

Figure 4 illustrates the orientation and inclination of slopes across the region, which are key factors in assessing landslide risks. The map categorizes the terrain into two main slope aspects: areas with a "high" aspect (marked in red) and areas with a "low" aspect (marked in green). These classifications indicate regions with different slope angles, with the "high" aspect likely representing steeper slopes and the "low" aspect representing more gentle inclinations. The map serves as an essential tool for understanding the potential susceptibility of various areas within Balakot Tehsil to landslides, as the slope aspect can significantly influence the direction of water flow, sunlight exposure, and overall stability of the land. Steeper slopes, often marked as "high," are typically more prone to landslide occurrences, especially during heavy rainfall, making this map critical for disaster risk assessment and land-use planning in the area.

Slope aspect, which refers to the direction a slope faces, also plays a crucial role in landslide susceptibility in Balakot. The aspect influences microclimatic conditions such as sunlight exposure, moisture retention, and wind patterns, all of which can affect the stability of a slope. In the Balakot region, north-facing slopes tend to retain more moisture due to reduced sunlight exposure, making them more prone to landslides, especially during and after heavy rainfall. Conversely, south-facing slopes, which receive more direct sunlight, are often drier but may still be vulnerable if they have steep inclines. The analysis shows that slopes with unfavorable aspects, particularly those facing north or northwest, are more susceptible to landslides, aligning with observed landslide patterns in the area.

Figure 4: Slope Aspect Map of Balakot Tehsil



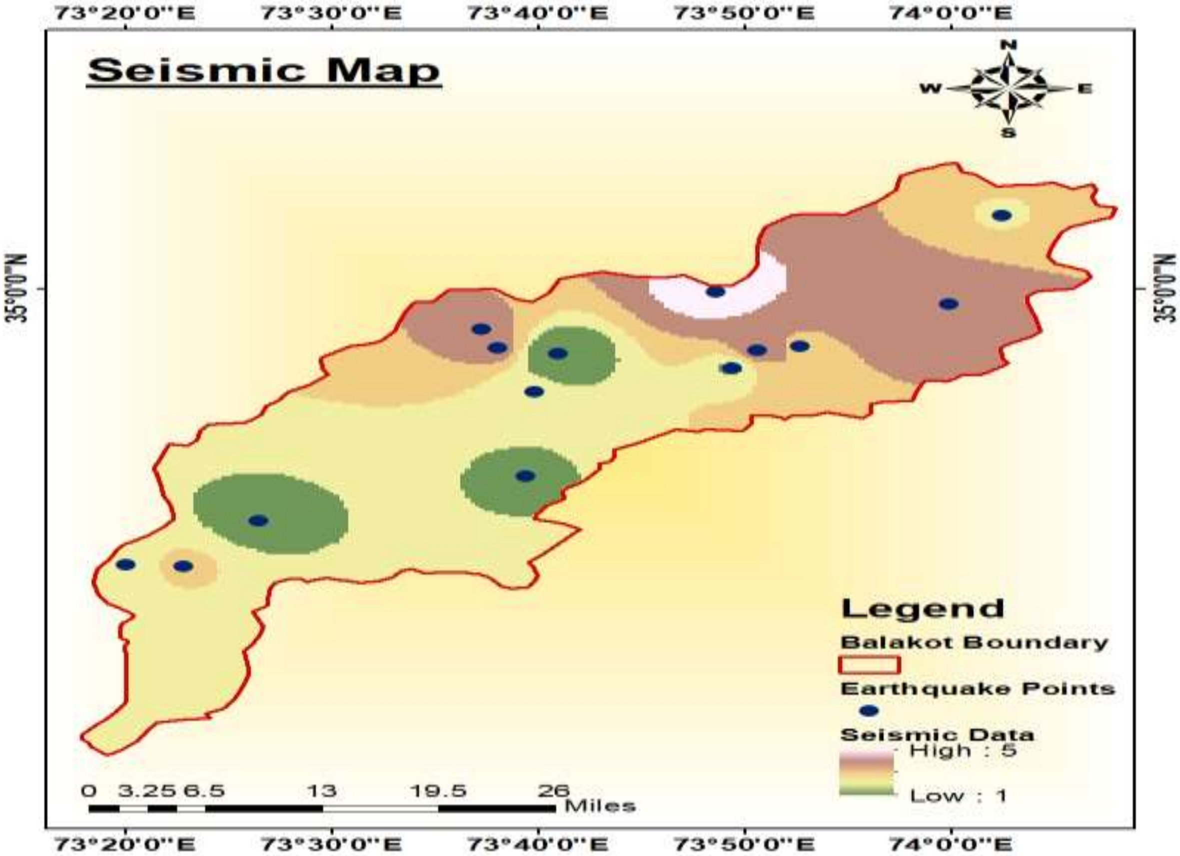
Seismic Map

Figure 5 highlights the seismic activity and potential earthquake hazards within the region. The map is color-coded to indicate varying levels of seismic risk, ranging from "low" (marked in green) to "high" (marked in brown and dark brown). The presence of multiple "earthquake

Points" (represented by blue dots) across the map indicates areas where seismic events have been recorded. These points are crucial for understanding the distribution and intensity of past earthquakes, which in turn help in assessing the likelihood of future seismic activity. The regions marked with higher seismic data values, particularly in the northern and central parts of Balakot Tehsil, are more susceptible to seismic hazards, making them critical areas for monitoring and disaster preparedness. This map is essential for guiding infrastructure development, land-use planning, and implementing seismic-resistant construction practices in the region to mitigate the risks associated with earthquakes.

The seismic map provides an in-depth look at the seismic activity across the Balakot region. It illustrates the intensity and distribution of seismic waves, highlighting areas that are most prone to earthquakes. The map uses color gradients to indicate zones of varying seismic intensity, with darker shades representing regions that experience stronger ground shaking. This information is critical because seismic activity is one of the primary triggers for landslides. In areas where the seismic intensity is high, the stability of slopes is significantly compromised, making these regions more vulnerable to landslides. By identifying these high-risk zones, the seismic map is an essential tool for disaster risk management and for planning mitigation strategies in the Balakot region (figure 5).

Figure 5: Seismic Map of Tehsil Balakot

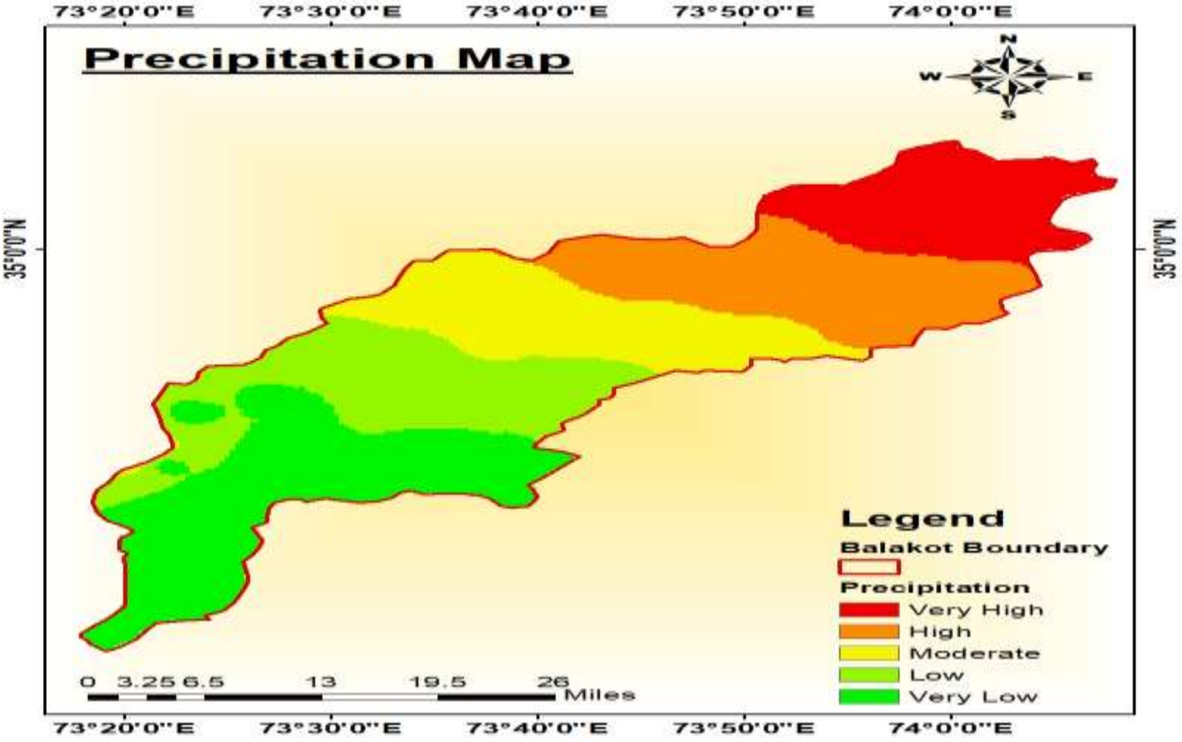


Precipitation

Figure 6 illustrates the precipitation levels across the region of Balakot, represented in varying shades of color to denote different precipitation intensities. The map is categorized into five distinct zones: "very high," "high," "moderate," "low," and "very low" precipitation areas, which are indicated by red, orange, yellow, light green, and dark green, respectively. The areas in the northern part of Balakot are marked in red, indicating very high precipitation, while the southern regions show much lower precipitation, transitioning from orange and yellow to light green and dark green as one moves further south. The geographical extent is outlined with coordinates, and the Balakot boundary is clearly delineated with a red border. The map provides a clear visual representation of how precipitation varies across Balakot, which could be useful for understanding local climate patterns, planning, and resource management in the region.

The precipitation map offers a detailed overview of the rainfall distribution across the Balakot region. It shows the average annual precipitation levels, highlighting areas that receive the most rainfall. The map is color-coded to indicate different levels of rainfall intensity, with the highest precipitation zones clearly marked. Heavy rainfall is a well-known trigger for landslides, as it increases the water content in the soil, reducing its cohesion and making slopes more likely to fail. The map helps in identifying regions where intense and frequent rainfall could lead to the saturation of soil and subsequent landslides. By understanding these precipitation patterns, researchers and planners can better predict where landslides are likely to occur and take preventive measures to protect these vulnerable areas (figure 6).

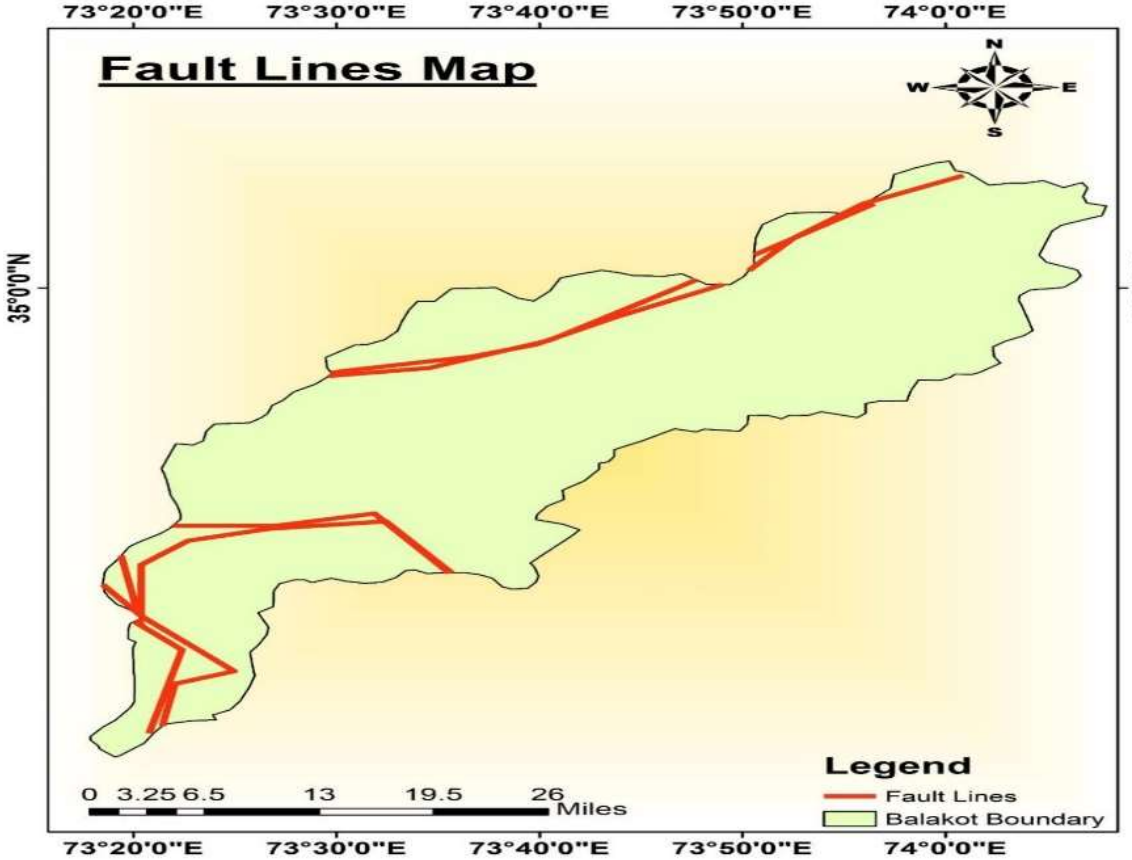
Figure 6: Precipitation Map of Balakot Tehsil



Fault Line

The fault line map is a critical component of the landslide risk assessment for the Balakot region. This map delineates the major fault lines that traverse the area, showing the points where the Earth's tectonic plates meet and move. These fault lines are of great significance because they are often the sites of earthquakes, which can trigger landslides. The map clearly marks the locations of these fault lines and provides insights into the regions that are most likely to experience seismic disturbances. Areas located near these fault lines are at a higher risk of landslides, especially when seismic activity is combined with other factors like heavy rainfall. By mapping these fault lines, researchers can better understand the seismic behavior of the region and its impact on landslide occurrences, making the fault line map an invaluable tool in disaster preparedness and response planning (figure 7).

Figure7: Fault Line Map of Balakot Tehsil



Landslide Hazard Mapping and Risk Classification

Figure 8 visualizes the varying levels of landslide risk across the region. The map is color-coded to reflect different levels of landslide risk, ranging from "very high" to "very low."

Very High Hazard Class

The areas with the highest landslide risk are depicted in red, indicating "very high" risk zones. These high-risk zones are primarily located in the central and southern parts of Tehsil Balakot. The very high hazard class, which indicates the greatest risk of landslides, covers the smallest area in the region. Although this class represents a limited portion of the land, the areas within this category are extremely vulnerable to landslides. Any development or habitation in these zones poses a significant threat due to the high likelihood of landslide occurrences.

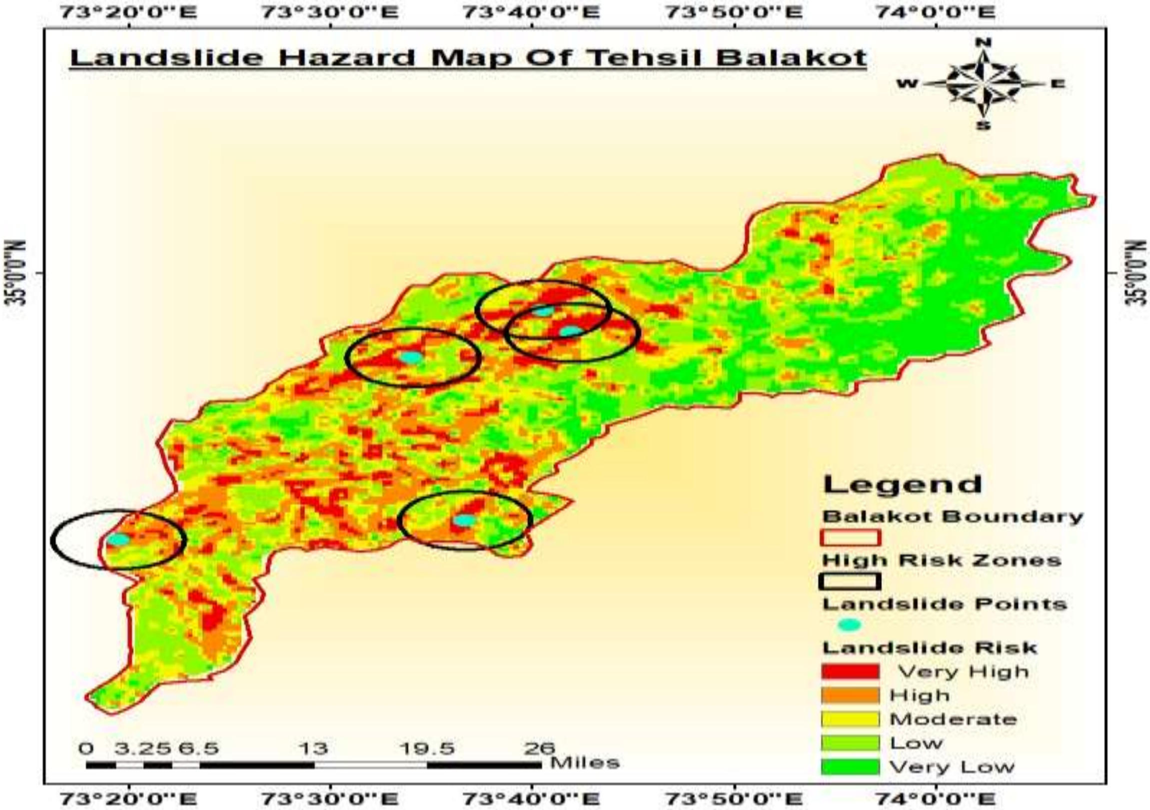
High and Medium Hazard Classes

The orange areas represent "high" risk zones, while yellow, light green, and dark green areas signify "moderate," "low," and "very low" landslide risk, respectively. Figure 8 also highlights specific "high risk zones" with black circles, indicating areas that are particularly vulnerable to landslides. These high-risk zones are mostly clustered in the central part of the region, with a few located in the southern section. The high and medium hazard classes occupy a larger portion of the region compared to the very high hazard class. These classes represent areas with a considerable risk of landslides. The larger coverage of these classes means that more extensive regions are prone to landslides, which increases the overall risk to the population, infrastructure, and the environment. The high and medium hazard areas are critical to monitor and manage, as they are more likely to experience landslide events.

Low and Very Low Hazard Classes

The low and very low hazard classes cover the largest areas in the Balakot region. These areas have the lowest risk of landslides, making them relatively safer for development and habitation. However, while the risk is lower in these zones, they are not entirely free from the possibility of landslides, especially under extreme conditions like heavy rainfall or seismic activity.

Figure 8: Landslide Hazard Map of Tehsil Balakot



Landslide Impact Balakot

The map also marks "landslide points" with blue dots, showing the exact locations where landslides have occurred or are likely to occur. These points are primarily concentrated within the high-risk zones, emphasizing the vulnerability of these areas. This detailed landslide hazard map is crucial for disaster management, urban planning, and risk mitigation strategies in Tehsil Balakot. It provides valuable insights for authorities and residents to identify high-risk areas, implement necessary safety measures, and plan infrastructure development to minimize the impact of potential landslides in this geologically sensitive region. These classes are based on the susceptibility of different areas to landslides, and their distribution across the region provides crucial insights into the potential risks.

Tehsil Balakot has suffered considerable impacts from landslides, which have affected tourism, local residents, their homes and belongings, and critical infrastructure such as roads and communication systems. The damage from slope failures has been substantial and appears to be increasing, especially during the monsoon season when the already fragile mountains face additional rainfall.

Over recent decades, the rapid increase in tourist activities in Northern Pakistan has intensified the effects of landslides. These landslides have caused extensive damage to both human life

and the natural environment. However, accurately assessing and evaluating these impacts remains difficult.
The Balakot valley's steep slopes, delicate land cover, and frequent strong earthquakes, coupled with heavy rainfall, create conditions that are highly favorable for landslide hazards. The socioeconomic effects of these landslides are significant, impacting tourism, damaging homes, possessions, and communication systems, and compromising seasonal tourism facilities. Disruptions in communication systems due to roadblocks, particularly during peak tourist seasons, are a growing issue. The Balakot-Kaghan road, being the sole route to Naran Kaghan, is especially vulnerable to blockages during the high tourist season.

Discussion

The study of landslide hazards in Balakot Tehsil, Khyber Pakhtunkhwa, Pakistan, using GIS-based techniques provides crucial insights into the region's vulnerability to landslides. The slope aspect, elevation, precipitation, and seismic data were all key factors in determining areas most susceptible to landslides. These findings align with previous research and highlight the need for a comprehensive, context-specific approach to landslide risk assessment.
The slope aspect map of Balakot Tehsil, which categorizes the terrain into high and low slope aspects, is indicative of the area's vulnerability to landslides. The regions identified with steep slopes (high slope aspect) are particularly prone to landslides, especially during periods of heavy rainfall or seismic activity. This observation is consistent with the findings of Huang and Yang (2019), who emphasized the importance of considering both physical and societal factors in landslide risk mapping. The steep slopes identified in the study area suggest a high potential for slope failure, particularly in areas with poor vegetation cover or where human activities have further destabilized the terrain.
The elevation and slope model maps further support these findings by classifying the terrain into different slope categories. The study identified areas with slopes ranging from 20 to 76 degrees as highly susceptible to landslides. This is in line with the work of González and López (2017), who highlighted the need for context-specific approaches in landslide hazard assessment. In Balakot Tehsil, the steep and rugged terrain exacerbates the risk of landslides, making it essential to tailor GIS methodologies to the region's unique topographical characteristics.
The seismic map of the study area reveals the spatial distribution of earthquake points and their potential impact on landslide occurrence. The areas with higher seismic activity, as shown on the map, correlate with regions of steep slopes, further increasing the risk of landslides. This finding is supported by the research of Dikshit et al. (2020), who demonstrated the effectiveness of combining seismic and topographical data in GIS to assess landslide risk. In Balakot Tehsil, the integration of seismic data into the landslide hazard model provides a more comprehensive understanding of the region's vulnerability, particularly in the context of the 2005 Kashmir earthquake, which significantly impacted the area.
The precipitation map developed through Inverse Distance Weighted (IDW) interpolation highlights the role of rainfall in triggering landslides. The map shows that areas with higher annual precipitation are more susceptible to landslides, particularly in regions with steep slopes. This is consistent with the findings of Priyono et al. (2020), who emphasized the importance of integrating precipitation data into landslide risk models. In Balakot Tehsil, the combination of high precipitation and steep slopes creates a hazardous environment, particularly during the monsoon season when the risk of landslides is highest.
The weighted overlay analysis (WOA) used in this study to assess landslide susceptibility combines the slope, seismic, and precipitation data to generate a comprehensive landslide hazard map. The process of reclassifying each data layer and assigning weights based on expert knowledge is crucial in producing an accurate landslide risk map. This approach is similar to

the multi-criteria evaluation method used by Vojteková and Vojtek (2020) in Slovakia, which also demonstrated the effectiveness of GIS-based analysis in identifying areas with high landslide susceptibility. The resulting landslide susceptibility map for Balakot Tehsil identifies high-risk areas, providing valuable information for disaster management and land-use planning. Furthermore, the study's findings emphasize the importance of integrating both physical and socio-economic vulnerabilities into landslide risk assessments. As Arrogante-Funes et al. (2021) demonstrated in their study in Mexico, the inclusion of ecological and socio-economic factors in risk models can provide a more comprehensive understanding of landslide risks. In Balakot Tehsil, the integration of topographical, seismic, and precipitation data into the landslide hazard model is a crucial step towards developing effective mitigation strategies. However, future studies should also consider incorporating socio-economic data to better understand the impact of landslides on local communities and to prioritize areas for intervention.

In conclusion, the GIS-based approach used in this study has proven effective in identifying areas of high landslide susceptibility in Balakot Tehsil. The integration of slope, seismic, and precipitation data into a comprehensive landslide hazard model provides valuable insights into the region's vulnerability. These findings are consistent with previous research and highlight the importance of a context-specific, multi-criteria approach to landslide risk assessment. The resulting landslide susceptibility map can serve as a vital tool for local authorities in disaster management, land-use planning, and the development of targeted mitigation strategies to reduce the impact of landslides on the region. Future research should focus on incorporating socio-economic factors into the model to provide a more holistic understanding of landslide risks in Balakot Tehsil.

Recommendations

Based on the findings from the spatial analysis of landslide hazards in Balakot Tehsil, Khyber Pakhtunkhwa, the following area-specific recommendations are proposed to mitigate the risk and enhance the resilience of the local communities:

1. The landslide susceptibility map highlights several high-risk zones within Balakot Tehsil, particularly areas with steep slopes, high precipitation, and significant seismic activity. These zones should be prioritized for immediate intervention, including the implementation of slope stabilization measures, such as retaining walls, terracing, and reforestation. Engineering solutions like slope reinforcement and the construction of drainage systems can help reduce the likelihood of landslides in these areas.
2. Given the region's susceptibility to landslides triggered by heavy rainfall and seismic events, establishing a robust early warning system is crucial. This system should integrate real-time data from weather stations, rainfall monitoring, and seismic sensors to provide timely alerts to communities at risk. The early warning system should be complemented by public awareness campaigns to ensure that residents understand the risks and know how to respond in the event of a landslide warning.
3. Local authorities should revise land-use plans and zoning regulations to restrict development in areas identified as high-risk on the landslide susceptibility map. Construction activities should be carefully monitored and regulated, particularly in steep slope areas where any form of land disturbance could exacerbate landslide risk. Encouraging the relocation of settlements away from high-risk zones and promoting the use of safer areas for future development is essential.
4. Involving local communities in disaster risk reduction efforts is critical for building resilience. Community-based programs should be developed to educate residents about the risks of landslides and the importance of maintaining natural vegetation, which plays a vital role in slope stabilization. Training programs on emergency preparedness, including evacuation drills and first aid, should be conducted regularly in high-risk areas.

5. Reforestation and afforestation projects should be undertaken in areas with degraded vegetation cover, particularly on steep slopes. Trees and vegetation help to stabilize soil and reduce surface runoff, thereby decreasing the likelihood of landslides. Sustainable land management practices, such as contour plowing and agroforestry, should be promoted among local farmers to prevent soil erosion and enhance the overall stability of the landscape.
6. Critical infrastructure, including roads, bridges, and communication networks, should be assessed for vulnerability to landslides. In high-risk areas, infrastructure should be reinforced or relocated to safer zones. Designing infrastructure with landslide risk in mind—such as elevated roads or tunnels—can significantly reduce the impact of landslides on transportation and communication networks.
7. Since seismic activity is a significant factor in landslide occurrence in Balakot Tehsil, efforts should be made to improve the seismic resilience of buildings and infrastructure. Retrofitting existing structures to withstand earthquakes and enforcing stricter building codes for new constructions can help mitigate the risk of earthquake-triggered landslides. Public education on earthquake preparedness should also be integrated into broader disaster risk reduction initiatives.
8. Continuous monitoring of landslide-prone areas is essential for updating risk assessments and refining hazard maps. Local universities and research institutions should be encouraged to collaborate on research projects focused on landslide dynamics, risk reduction strategies, and the impact of climate change on landslide frequency and intensity. Data collected from these efforts can inform future risk management and policy decisions.
9. The development of an integrated disaster management strategy for Balakot Tehsil is recommended. This strategy should include a multi-hazard approach, addressing not only landslides but also other natural hazards like floods and earthquakes that may compound the impacts of landslides. Coordination between local government, disaster management authorities, and community organizations is key to the successful implementation of this strategy.
10. Strengthening the capacity of local government officials and disaster management teams to respond effectively to landslides is vital. Training programs on landslide risk assessment, emergency response, and disaster management should be provided regularly. Additionally, ensuring that local authorities have access to the necessary resources, such as GIS tools and landslide monitoring equipment, will enhance their ability to manage landslide risks effectively.

These recommendations aim to reduce the risk of landslides in Balakot Tehsil, protect lives and property, and enhance the overall resilience of the region to natural hazards. By implementing these strategies, local authorities and communities can work together to mitigate the impacts of landslides and ensure sustainable development in the area.

Conclusion

Research on landslide susceptibility in Tehsil Balakot has shown that the combination of rainfall data, digital elevation models (DEMs), and seismic data plays a significant role in determining landslide occurrence and distribution in the area. The high and medium hazard areas pose a greater risk due to their larger coverage. Increased landslide activity in Tehsil Balakot is linked to heavy rainfall, seismic activity, and the region's steep slopes. Rainfall is a major trigger for landslides in Tehsil Balakot. Historical rainfall data analysis indicates that intense or extended rainfall events heighten the likelihood of landslides. The combination of steep slopes and heavy rainfall leads to soil saturation, which weakens soil stability and promotes landslides. The study found a clear correlation between the amount and intensity of rainfall and the frequency of landslides. DEMs provided essential information on the topography and slope characteristics of Tehsil Balakot. Areas with steep slopes were found to be more prone to landslides, especially when combined with loose soil and heavy rainfall. The DEM analysis helped identify these high-risk areas by highlighting regions with significant slope gradients. Seismic data also had a substantial impact on understanding landslide susceptibility in Tehsil Balakot. The region's geological structure and seismic activity affect terrain stability. Faults and tectonic movements can weaken rock formations, making them more vulnerable to landslides, particularly during seismic events. Including seismic data in the analysis allowed for a thorough understanding of the geological factors contributing to landslides.

The integration of rainfall data, DEMs, and seismic data in the spatial analysis of landslide susceptibility in Tehsil Balakot has provided valuable insights into the factors influencing landslide occurrences. The research highlights the significant roles of heavy rainfall, steep slopes, and geological conditions in triggering landslides. To better manage and reduce landslide impacts on communities and infrastructure, disaster management strategies should consider these factors. Using Geographic Information Systems (GIS) and Remote Sensing (RS) for landslide hazard mapping is crucial in mountainous areas like Balakot. Further research using techniques such as ground-penetrating radar (GPR) and soil testing could provide deeper insights into landslide hazards in Tehsil Balakot.

This study has provided a detailed spatial analysis of landslide hazards in Balakot Tehsil, Khyber Pakhtunkhwa, Pakistan, using a combination of GIS-based techniques and multi-criteria evaluation methods. The findings reveal that the region is highly susceptible to landslides due to its complex terrain, high levels of precipitation, and significant seismic activity. The susceptibility maps generated in this study highlight specific zones within Balakot Tehsil that are at heightened risk, emphasizing the urgent need for targeted mitigation measures. The comprehensive assessment underscores the critical role of GIS in identifying and prioritizing high-risk areas for landslides. The integration of slope aspect, seismic data, and land use patterns has enabled a nuanced understanding of the factors contributing to landslide risk in the region. This spatial analysis is not only essential for disaster risk reduction but also for informing land use planning and infrastructure development in the area.

The results of this study have significant policy implications for disaster management and urban planning in Balakot Tehsil and similar mountainous regions in Pakistan. Firstly, there is a pressing need for the implementation of strict zoning regulations that prevent construction in identified high-risk areas. Policymakers should consider revising existing land use policies to incorporate landslide risk assessments as a mandatory component in development planning.

Secondly, the findings advocate for the integration of disaster risk reduction strategies into local and regional development plans. This includes the establishment of early warning systems, community-based disaster risk reduction (CBDRR) programs, and infrastructure resilience enhancement measures. These strategies should be supported by adequate funding and resources from both governmental and non-governmental organizations to ensure their effective implementation.

Furthermore, the study highlights the importance of building local capacity for disaster management. Policymakers should prioritize training and equipping local authorities with the necessary tools and knowledge to monitor, assess, and respond to landslide hazards. This capacity-building effort should be complemented by public education campaigns to raise awareness about landslide risks and promote community participation in disaster preparedness initiatives.

While this study provides valuable insights into the landslide hazards of Balakot Tehsil, several areas warrant further research to enhance the robustness of landslide risk management in the region. Future studies could explore the impact of climate change on the frequency and intensity of landslides in Balakot Tehsil, as changing precipitation patterns and temperature extremes may exacerbate the existing risks. Additionally, there is a need for longitudinal studies that monitor the effectiveness of implemented mitigation measures over time. Such research would provide empirical evidence on the success of various interventions, allowing for adjustments and improvements in disaster risk reduction strategies. The development of more sophisticated models that incorporate additional variables such as soil type, vegetation cover, and anthropogenic activities could further refine the landslide susceptibility maps. These models could be used to simulate various scenarios, providing policymakers with a range of possible outcomes to inform decision-making. Finally, expanding the study to include a broader geographic area could offer a comparative analysis of landslide hazards across different regions, providing insights that could be applied to other vulnerable areas in Pakistan and beyond. Collaborative efforts with international researchers and institutions could also bring in new perspectives and methodologies, enhancing the overall understanding and management of landslide hazards.

In conclusion, this study not only highlights the significant landslide risks in Balakot Tehsil but also sets the stage for informed policy decisions and future research that can collectively contribute to a safer and more resilient environment for the local communities. By adopting the recommended policies and continuing to explore new research avenues, stakeholders can mitigate the impacts of landslides and promote sustainable development in this hazard-prone region.

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