Iranian Journal of Geophysics, Vol 16 No 4, 2023, Page 69 – 84 (Research Article)
DOI: 10.30499/ijg.2022.329722.1399

Landslide susceptibility mapping of Chilas area along Karakorum highway, Gilgit Baltistan, Pakistan

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(Received: 25 Feruary 2022, Accepted: 8 March 2022)

Abstract

The use of a Geographic Information System (GIS) for assessing landslide susceptibility in the steeply rugged mountainous terrain of Chilas Basin, Pakistan, is covered in this research. Chilas is the part of Karakorum mountain ranges that lie north of Gilgit. Northern Pakistan is the region in which all the catastrophic events like earthquakes, mass wasting, and flash floods are routine marvels. Among them, catastrophic landslide events in this highly elevated and steeply mountainous region are a severe threat to human as well as economic property. To assess these catastrophic landslide events, a detailed landslide inventory map was constructed based on Google Earth images. Followed by field observation in which the selected spots of a landslide triggered locations were confirmed in the field. Four main controlling parameter groups were collaborated to generate landslide susceptibility maps: (1) Human-induced parameters like road distance, (2) Topographical parameters in terms of slope, and land cover, (3) Hydrological parameters, like rainfall, distance to stream, and temperature (4) Geological parameters in term of lithology and distance from major faults. These thematic layers were developed in a GIS environment to construct the landslide hazard map of the Chilas Basin. Among all the controlling parameters slope is regarded as the highest-ranked factor as followed by geology and landcover. Analytical Hierarchy Process (AHP) basis weighted overlay technique was used to assess the final susceptibility map followed by Area under Curve (AUC) model. Based on these analyses, four distinct susceptible regions were detected in the area, with severe mass wasting activities. The AUC model gives an 81% result, which is satisfactory.

Keywords: GIS, Landslide, susceptibility, land cover, analytical hierarchy process, slope

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1 Introduction

The destruction of a certain location's natural ecosystem has resulted in natural hazards, such as slope failure and soil erosion. Natural disasters are catastrophic events that occur due to hydrological, geological, or atmospheric factors. Sources are capable of killing people, destroying infrastructure, and interfering with societal functioning (Maqsoom et al., 2021).

Landslide susceptibility is defined as the spatial distribution of landslide occurrences subjected to internal and external causal factors—several factors triggering mass movements like precipitation, seismicity, temperature change, lithology, and geological structures. Lithological heterogeneity affects the hydrological and mechanical qualities of rock masses. The magnitude and kind of mass movement vary as lithology and structure change. Some lithology is more permeable than others, enabling water to pass through and increasing pore pressure. During rainy events, the shear strength of the rock mass and slope stability are both impacted by the increase in pore water pressure Ali et al. (2019).

Due to the complex topography and seismically active location on the earth, the Karakoram landscape is vulnerable to natural disasters such as landslides, earthquakes, and glacial lake outburst events. Rock falls, debris flows, mudslides, and flash floods have been a constant hazard to Gilgit-Baltistan (M. Hussain et al., 2021). In mountainous areas, landslides are one of the most dangerous natural dangers. Hundred of people die every year in landslides across the world, and these catastrophes have significant economic consequences on both the local and global economies. Many governments and international research institutes worldwide have spent significant resources over the last 25 years studying landslide susceptibilities and attempting to generate maps depicting their spatial distribution(Yalcin et al., 2011).

Landslides have become a severe hazard to agricultural fields, towns, highways, transit, and the tourism sector in Pakistan's Western Himalayan. People have lost their lives, homes, and property due to the valley's periodic landslides. Landslides kill roughly 1,000 people per year, according to global damage data, and property loss is estimated to be over $4 billion (Akbar & Ha, 2011). To minimize human losses and economic losses, detailed mapping and susceptibility zonation is needed for hazardous areas.

There are two types of qualitative and quantitative approaches used for producing landslide susceptibility maps (Cardozo et al., 2021). GIS-assisted landslide susceptibility mapping now employs several methodologies, like qualitative approaches that rely on expert opinions and are frequently used for regional evaluations (Ayalew et al., 2004). Various approcahes of the landslide numerical risk factor (LNRF) bivariate model was used in collaboration with linear multivariate regression (LMR) and boosted regression tree (BRT) models, coupled with radar remote sensing data and geographic information system (GIS), for landslide susceptibility mapping (LSM) in the Gorganroud watershed, Iran (Arabameri et al., 2019). Based on over 110 years of landslides inventory and professionals' findings, a semi-quantitative analytical hierarchy process (AHP) method has been applied to evaluate the role of nine landslide conditioning factors, which include both natural and anthropogenic elements (Roccati et al., 2021).

Chilas area has not been properly studied using AHP in terms of Landslide susceptibility. Therefore to know the triggering factors of landslides and to construct the susceptibility map of the Chilas area, AHP techniques were used.

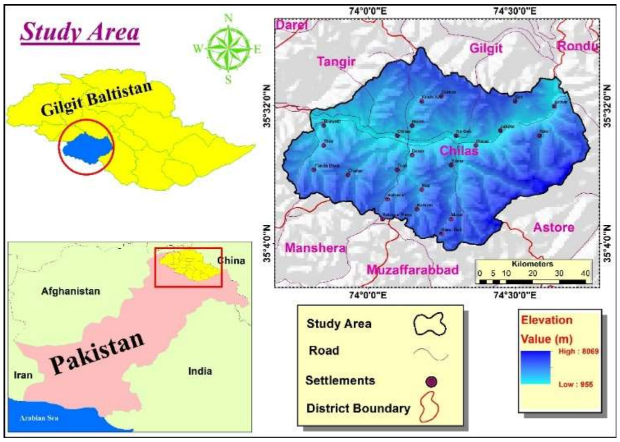

Figure 1. Location map of Study area.

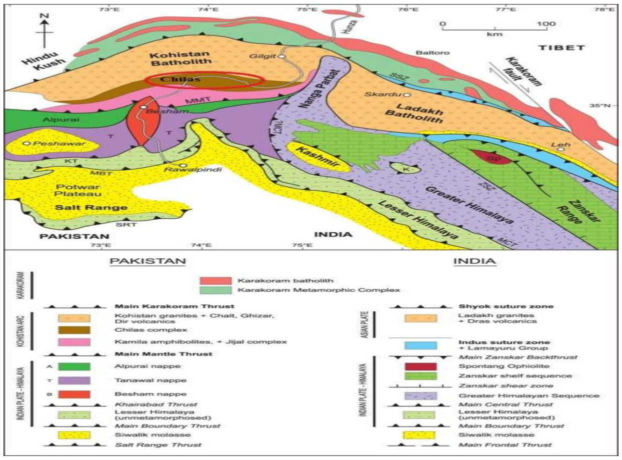

Figure 2. Geological map of study area (Northern Pakistan).

2 Study area

The study area is part of Chilas town in the vicinity of the Indus River Gilgit Baltistan. Chilas is accessible through Silk Road, which includes the Karakoram Highway and the N-90 National Highway, with a direct connection to the capital Islamabad. This road ie extended to Tashkurgan and Kashgar in Xinjiang, China, through Khunjerab Pass in the north. The study area lies under Latitude 35˚ 25′13″N and Longitude 74˚06′11″E. Area has a complex physical relief and climatic variation, has a semi-arid climate zone with an average annual rainfall of 125 mm rainfall and glacial erosion, which make the study area more prone to landslides. The terrain is thought to be 1265 meters above sea level, with a dry to semi-arid habitat. (Figure 1) illustrates the geographical location of the study area.

3 General geology of Study area

Geological study area lies in the complex tectonic regime of northern Pakistan, which is bounded by the Main Karakoram Thrust in the north and the Main Mantle Thrust in the south. To the east research, area is bordered by the Nanga Parbat syntaxes. The southern half of the Kohistan Island Arc is located in the northern section of the Karakoram plat,e as shown in (Figure 2. Geological). This area displays a diverse spectrum of lithology, tectonic settings, and active seismic nature. It passes through cliffs, generating granitic gneisses from the Karakoram plate, as well as mafic and ultramafic rocks from the KIA (Z. Hussain et al., 2021). Their lithological environment and geological history provide insights into the mechanisms that cause shear strain localization, as well as the parameters that affect deformation stabilization in shear zones and flow characteristics at the mantle-crust transition (M. A. Hussain et al., 2021). The area comprises the hard rocks,

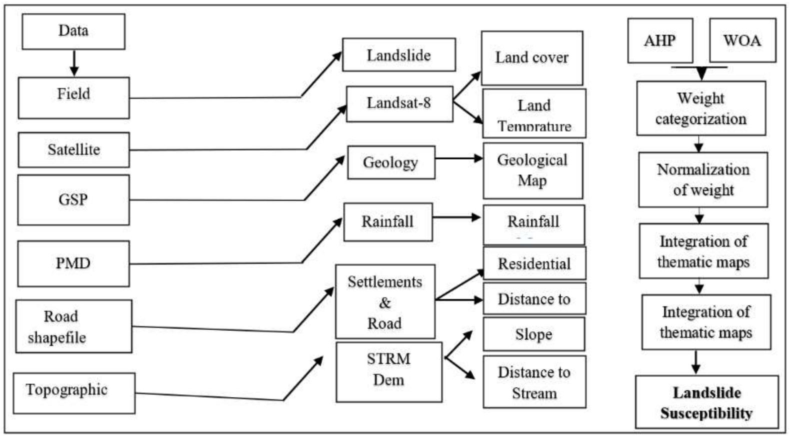

Figure 3. Data sets used in the current study. GSP (Geological Survey of Pakistan), PMD (Pakistan meteorological department).

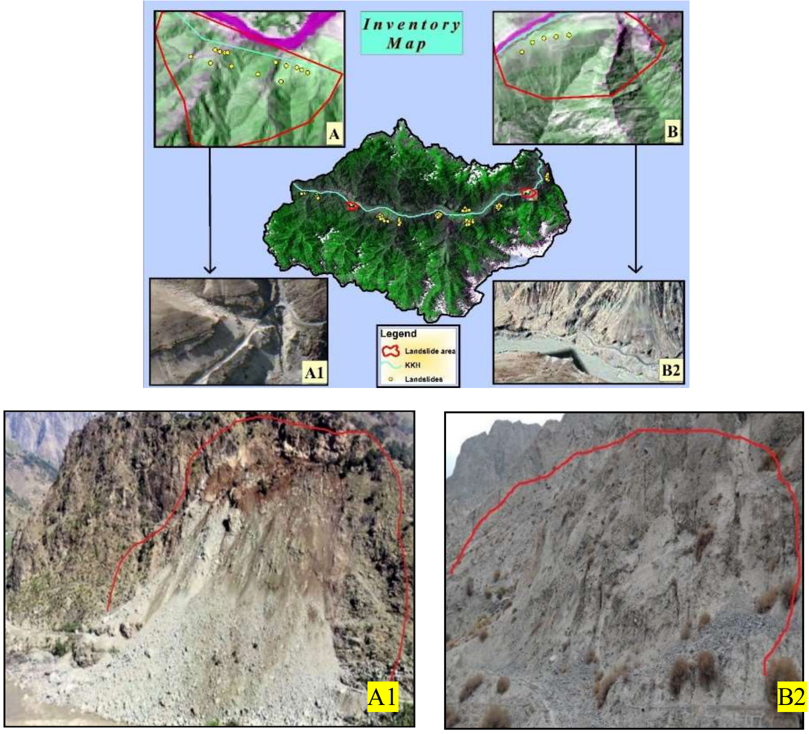

Figure 3. Inventory map of the study areaPictures acquired during the field visit show (A), (B) enlarged areas of the research region, whereas A1 shows active rock fall in Lichargah, and B2 a complicated landslide above suspension bridge Chilas.

thickly overlain by recent sediments in some places. The closeness of cracked slopes to rivers, faults, and highways is a crucial element in causing landslides and slope failure.

3 Materials and methods

For the current research, data sets were gathered from various source,s as shown in (Figure. 3). Google earth images were used to mark the landslide-affected region and were also used for landslide inventory map. DEM images were downloaded from the USGS website to extract the topographic maps. Landsat 8 images were used to make the land cover map. A geological map is modified from the GSP (Geological Survey of Pakistan) map of northern Pakistan. Rainfall data is acquired from the Pakistan Meteorological department of Pakistan to construct the precipitation map of the study area. Finally, all these thematic layers were processed in a GIS environment to construct the landslide susceptibility map.

Table 1:Pairwise comparison of landslide susceptibility factors

Pairwise comparison of Landslide Susceptibility Factors

Factors	Slope	Geology	Land use	Distace to road	Distance to fault	Reseidential density	Temprature	Rainfall	Weigh total (%)
Slope (SL)	1	2	3	5	5	6	7	8	32.1721
Geology (G)	0.5	1	2	4	3	5	6	7	21.7699
Land use/Cover	0.333333333	0.5	1	4	5	6	7	8	20.1825
Distance to Road	0.2	0.25	0.25	1	2	4	6	8	10.1752
Distance to Stream	0.2	0.333333	0.2	0.5	1	2	4	6	6.8744
Residential Density	0.166666667	0.2	0.166666667	0.25	0.5	1	2	5	4.3431
Land surface Temperature	0.142857143	0.166667	0.142857143	0.166666667	0.25	0.5	1	2	2.6377
Rainfall	0.125	0.142857	0.125	0.125	0.166666667	0.2	0.5	1	1.8452

Consistency Ratio = 0.074

3.1 Landslide inventory map

The location and characteristics of landslides are defined via landslide inventory mapping. It requires determining the origin of previous landslides as well as the sort of landslide that happened, as well as identifying the causative variables that prompted the landslide mechanism. These factors, which have contributed to and resulted in landslides in the past, can provide useful evidence of areas where landslides are likely to occur in the future(Miao et al., 2012). Prone landslide areas were marked on google earth, and detailed field were carried out to selected landslide spots for confirmation of sites, as shown in (Figure. 4).

3.2. AHP techniques

Analytical hierarchy process (AHP) is a decision-based procedure in which each criterion from a collection of options or alternatives must be compared with each other. AHP is utilized in landslide susceptibility mapping to examine causal elements that influence slope failure movements more precisely and correctly (Rahim et al., 2018). It specifies the most reliable process for determining the weight of a criterion and estimating the relative size of components using pairwise comparisons and human expertise and experience. It demonstrates the significance of a particular element in determining slope stability by comparing it to other factors statistically (Yalcin et al., 2008), like Analytical Hierarchy Process (AHP) (Hasekioğulları, G. D. and Ercanoglu 2012), and a variety of machine learning methods. In the case of AHP, many applications have been reported from around much of the world, such as Spain (Barredo et al., 2000), (Saadatkhah et al., 2014), Japan (Ayalew et al., 2000), Slovenia (Komac 2006), Taiwan (Wu et al., 2009), USA (Gorsevski, P. V. and Jankowski, P. (2010), India (Ghosh et al., 2011), Turkey (Hasekioğulları, G. D. and Ercanoglu 2012), Nepal (Kayastha et al., 2013).

For the landslide susceptibility analysis, this technique is performed in several steps, including structurting the problem as a hierarchy by defining the objective and classifying criteria and sub-criteria based on their comparative analysis (Thanh et al., 2012). Many researchers used the AHP technique to assign weight to criteria and sub-criteria (Yalcin et al., 2011). All of these variables were compared using a pair-wise comparison matrix (PCM) (Table 1), which agrees to a dependent assessment of separately aspect's influence and termination, eliminating the extent of fault and generating a measure of judgment consistency (Komac et al., 2006). The following steps were considered for the weight calculation of all landslide conditioning factors. ,The first stage aims to identify any irregularities in the rank comparison of each couple of criteria. The CR is almost the mathematical sign of the result re garding randomly made decisions, and is determined by using equation 1 and (Table 2).

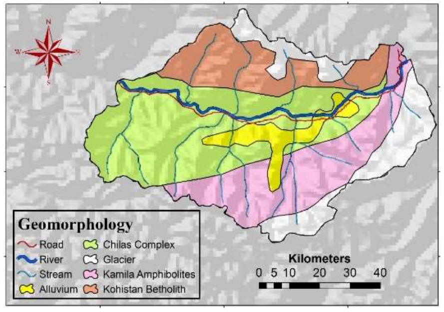

Figure 4. Geomorphology of Chilas district Pakistan.

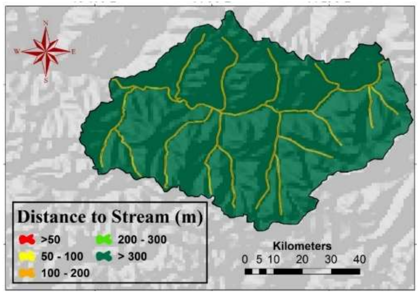

Figure 5. Distance to stream map.

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \quad (1)$$

In equation 1, RI defines the random consistency index, whereas CI defines the consistency index that is shown in Eq. (2).

$$CI = \lambda\mathrm{Max} - 1/(\mathrm{n} - 1) \quad (2)$$

Where λ max is the Principal Eigen calculation of the matrix, which is determined from matrix and small n is equal to matrix order. CR must be less than or equal to 10% or a roughness <10% (Saaty, 1977). The principle involves relating the finding with a random weighting of features. Lastly, acquired weights were related to numerous causal classes in each hazard susceptibility index using equation 3 below.

$$\mathrm{LSI} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{Ri} * \mathrm{Wi}) \quad (3)$$

To express the relative rank values for all the factors, Saaty’s 1-9 standard scale (Table. 3) was used, where 1 designates the ‘equal importance,’ and ‘9’ shows the extreme importance of one factor relevant to the other.

4 Results

The various factors control the landslide hazards, which include geology, slope, seismicity, rainfall, streams, and anthropogenic activities. The following thematic layers were constructed in a GIS environment.

4.1.1 Geomorphology

Geomorphology is one of the most conclusive factors regarding the landslide index. For the study area, the classes of geomorphology have arisen from its geological setting based on literature (Rozos et al., 2006) and fieldwork. The distinctive geomorphological formations are digitized and unified according to their engineering geological behavior, about landslide index. Thus, geomorphology includes eight classes as follows: (a) Road, (b) river, (c) stream, (d) alluvium, (e) chilas complex, (f) Glacier, (g) Kamila amphibolite and Kohistan batholith. Thus this chilas complex class has a higher rate. (Figure. 5).

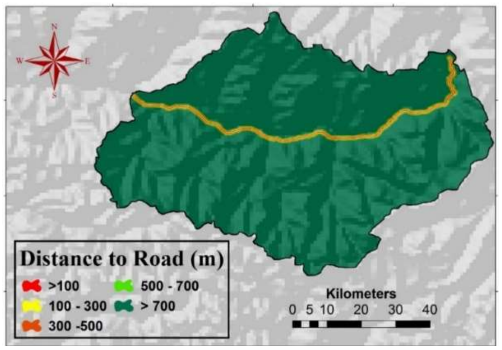

Figure 6. Distance to the road map of the study area

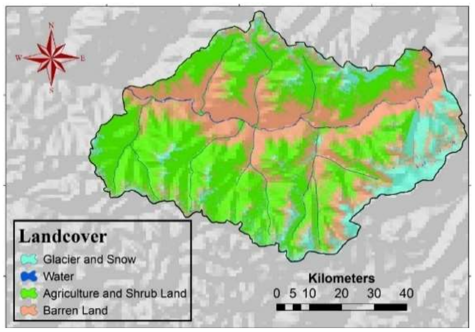

Figure 7. Land cover classification

Table 2. Landslide factors weight for classes subclasses and Consistency ratio.

Landslide Casual Factors weight for classes, obtained through AHP in the study area

Factor	**Classes**	**Final Weight**	**Consistency Ratio**
Slope	<10°	0.035	0.017
	10°-20°	0.048	
	20°-30°	0.088	
	30°-40°	0.154	
	40°-50°	0.307	
	>50°	0.367	
Residential Density	Low	0.068	0.0254
	Moderate	0.137	
	High	0.303	
	Very High	0.492	
Rainfall	>81	0.061	0.017
	81-82	0.097	
	82-83	0.159	
	83-84	0.262	
	>84	0.418	
Land Cover	Bare Land	0.48	0.031
	Vegetation	0.3	
	Glacier	0.14	
	Water	0.07	
Land Surface Temperature	Very Low	0.08	0.0667
	Low	0.2	
	Moderate	0.27	
	High	0.45	
Geology	CC	0.08	0.098
	Ka	0.13	
	KB	0.044	
	PZ	0.047	
	Sg	0.025	
	Gm	0.205	
	Hig	0.125	
	CV	0.256	
	GL	0.027	
	Q	0.061	
Distance to Stream	<50	0.468	0.0103
	50-100	0.268	
	100-200	0.144	
	200-300	0.076	
	>300	0.044	
Distance to Road	<100	0.454	0.0209
	100-300	0.285	
	300-500	0.139	
	500-700	0.092	
	>700	0.038	

Table 3. Saaty (2001) Scale for pairwise comparisons.

Intensity	Explanation
1	Equal Importance
2	Weak or Slight
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very strong
8	Very extreme strong
9	Extreme Importance

4.1.2 Distance to Stream

The stream's influence also plays an active role in disrupting the slope geometry. It involves material erosion from the slope's toe and sliding material saturation. Using Arc-Hydro tools, a stream map is created on an Aster DEM. The effectiveness of streams on landslide activities was determined by buffering at twenty-meter intervals >50, 50-100, 100-200, 200-300, and >300 (Figure. 6).

4.1.3 Distance to Road

The road network in steep places decreases the slope's stability. Landslides are caused by the destabilization of rock masses caused by road cuts and other human activity. Poor blasting for road construction procedures hasexacerbated the condition on the Karakorum Highway, one of the world's marvels. The road network of the region is extracted in a GIS environment to determine the impact of roads in the research area. This map is further classified into five groups based on 100 m intervals, i.e.,>100, 100-300, 300-500, 500-700, and >700 (Fig. 7).

4.1.4 Land Cover

The land cover depicts what is covering the land or how the land is used in the area. In the research region, six land cover classes are defined and digitized on a Landsat-8 picture. These classes comprise barren land, irrigated land, alpine pastures, forest, and shrubland, as well as snow and glaciers, which are among the land-cover classifications (Figure 8). Mostly, the barren land experiences mass movement as compared to the grassy land. **4.1.5 Slope**

Slope gradient determines the spatial distribution of landscape. The slope is considered the main landslide controlling factor for the mass movement. Steep to very steep slopes along the KKH is the dominant reason to slope failures. Slope map is generated on ASTER DEM and classified into seven classes, i.e., <10°, 10°-20°, 20°-30°, 30°-40°, 40°-50°, >50° (Figure 9).

4.1.6 Temperature variation

Climate change is becoming increasingly visible in many areas, indicated by an increase in mean, minimum, and maximum temperatures, as well as more violent rainstorms. Landslides in high mountains may become more common due to these changes (Huggel et al., 2012). Climatic change may be to blame for unpredictable climate variability since various environmental changes are occurring

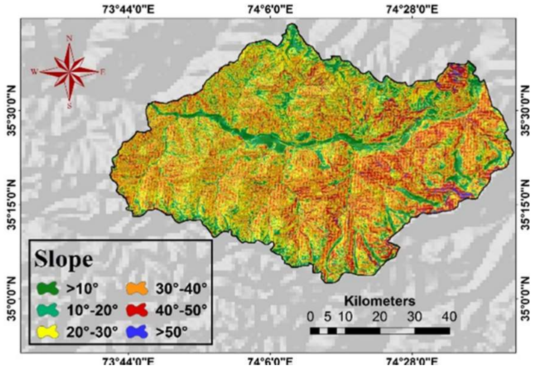

Figure 9: Slope

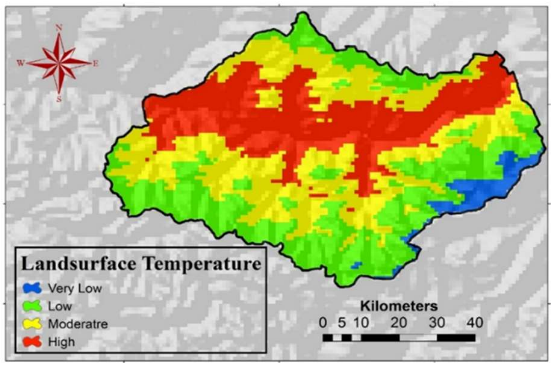

Figure 10: Land surface Temperature map of the study area

throughout the world as a result of climate change or global warming (Rathnaweera et al., 2012). Thermal infrared bands collected from the natural frequencies of Landsat 8 were used to compute the Land Surface Temperature of the Chilas area (Figure 10).

4.1.7 Rainfall

Precipitation is one of the most common triggering causes for landslides, as it is widely documented (Giraldo et al., 2022). Various rainfall stations are hypsometrically and territorially well dispersed throughout the research region, yielding excellent findings in terms of precipitation distribution. The area's yearly precipitation averages between 550.7 and 700.1 millimeters. The precipitation map was created for this study utilizing data from the area primary meteorological stations and processed in a GIS environment using Inverse distance weighted (IDW) interpolation techniques. The precipitation map was further divided into five categories, including 81 mm, 82 mm, 82-83 mm, 83 mm, and 84 mm (Figure 11). As precipitation increases, the proportion of landslides increases, hence the more the precipitation, the higher the rating of mass movement. (Rozos et al., 2011).

4.2 Landslide Susceptibility Index

The landslide susceptibility index map depicts the high and low-risk areas for landslides. It is created by adopting AHP techniques in a GIS environment to calculate the weightage of causative variables and the frequency of each class, then integrating and analyzing the data in ArcGIS software. Equation 2 is used to create the index map.

Figure 8: Precipitation map of the study area.

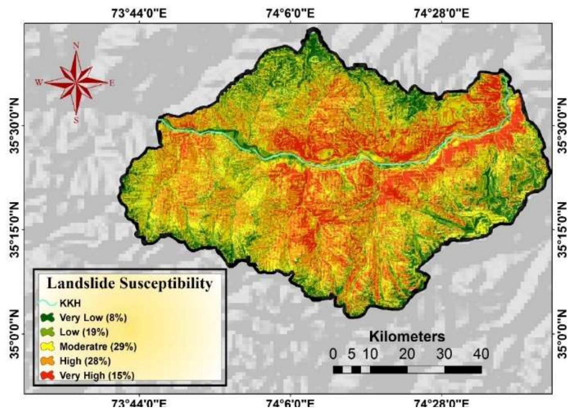

Figure 12. Landslide susceptibility index map of the study area.

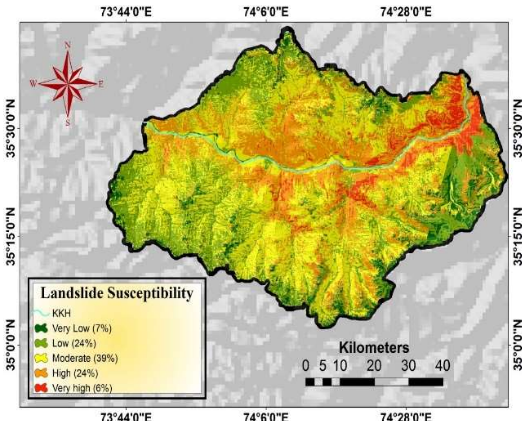

Figure 13. Final Land susceptibility map

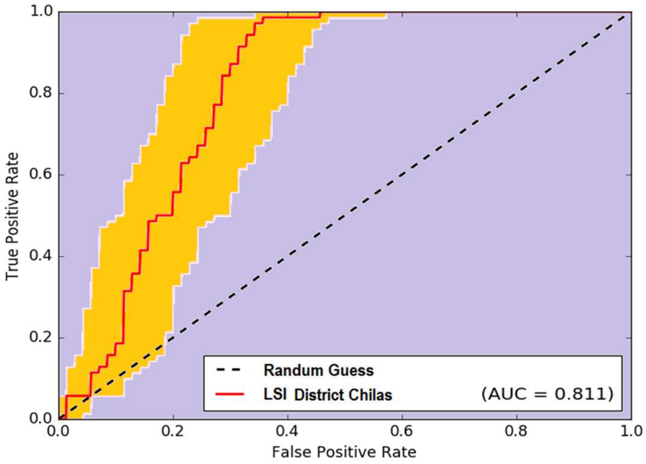

Figure 94. Key settlements superimposed on the LSI map of the study area after integration of all casual factors layers.

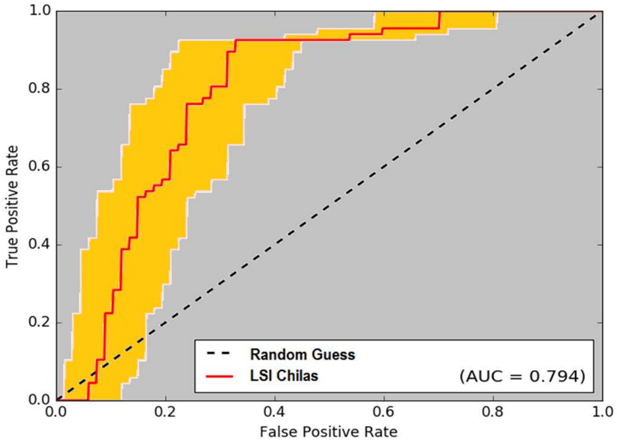

Figure 105. AUC model for current research.

$$\mathrm{LSI}=\sum_{i}^{n} Ri * Wi \qquad (5)$$

The research area's landslide susceptibility index map spans from 8% to 15% in (Figure 12), with the lower number indicating places that are less vulnerable to landslides and the greater value indicating areas that are very sensitive to landslides. These LSI values are further categorized into four groups; low, moderate, high, and extremely high Figure13.

Landslide susceptibility is measured using maps and charts to describe the likelihood of a terrain resulting in slope failure. It is required to establish the geographical distribution of terrain area and the causative variables that rule the landslide in the past and will affect this mechanism in the future for landslide susceptibility mapping (Lee & Talib, 2005). Analytical hierarchy process built on a rating system carried by competent decision is used to determine the weightage of each factor responsible for the slope failures.

4.3 Area Under curve map

The area under the curve (AUC) is a graphical depiction of binary operational classes (true positive rate (TPR) and false-positive rate (FPR), which indicates project accuracy (Prasannakumar & Vijith, 2012). These values are used to calculate the true positive rate (TPR), then compared to the false positive rate (FPR) calculated by the AHP tool in ArcGIS software. The accuracy of mapping is explained through a graphical depiction of AUC (Pourghasemi et al., 2012). The area under the curve result is 0.811, which is higher than the threshold value of 0.5 and is regarded as accurate for landslide susceptibility mapping (Figure 14 and 15).

5 Discussion:

Understanding the mechanism that causes landslides, as well as the effort to map susceptibility, provides crucial information on the evolution of landscapes, as well as establishing the framework for hazard management and the development of safety measures. This research covers a comprehensive examination of slope stability assessment for the construction of susceptibility mapping for a mass movement in a portion of the Chilas area in northern Pakistan. The region under investigation is tectonically active, causing the material to disintegrate and collapse due to the active seismicity of the northern region. The studied region is particularly vulnerable to slope collapse due to the occurrence of dynamic responsibilities and seismic areas, most notably MKT (Main Karakoram Thrust), and the closeness to the upper Kohistan fault. Aside from that, frost action plays an important function in thinning the slope material. The results of all the factors, like the slope map, are classified into 7 classes in which greater slope triggered high mass movement, and gentle slope triggered slightly landslide. Because 60^o slope instability is by far the most critical factor, more emphasis has been placed on landslide triggering owing to slope instability in this study (Table 2). Slope was regarded as the highest rank factor, followed by geology and landuse/landcover (Table 1). The study area received 84mm rainfall by this weathered factors to an increase in the unit weight of weathered material, which eventually overcomes resistant forces and begins to move downhill under gravity's influence; in the current study, rainfall has less impact on mass movement. After the rainfall effect, Closeness to road area mostly unsettled to slope eroding, which can result in slope instability and landslides. Distance to road rank four in this study. Others remaining factors like temperature and distance to stream are considered as less affecting variables in land sliding (Table 1,2).

6 Conclusion:

This study investigates the landslide hazard analysis along the Chilas basin close to Karakoram Highway in northern Pakistan. Remote sensing images were interpreted in a GIS environment for the construction of thematic maps, followed by field observations. Seven triggering factor maps were investigated to indicate landslide-prone locations. AHP analysis were carried out to rank all the factors and to determine the impact of these factors on landslides. The key factors identified by the results and thematic maps were slope gradient and lithology, followed by other factors. To record landslide vulnerability in the training region, researchers utilized a qualitative index-based heuristic technique. The slope, geology, and land cover were the most relevant and heavily weighted components, according to the empirical findings. Finally, the susceptibility map was categorized into three susceptibility classes: v. low, low, medium, high, and very high classes. Percentage for these classes, 8 % showing the very low class, 19 % for low, 29% for high, and 15 % is regarded as the highest susceptibility class. The findings of the landslide susceptibility map were validated using the data from some landslide occurrences, revealed that they primarily happened in the intermediate vulnerability region, which coincided with the zone anywhere the majority of people in this area resided. In the rest of the area, no information on landslide events was available.

7 Recommendation

The procedure applied in this learning gives rapid outcomes and is so unassuming that the results may be reorganized on response. These initial findings of landslide susceptibility mapping provided us with a clue for a detailed and comprehensive analysis of this landslide prone region. This work might serve as a starting point for further research into landslide hazards in other basins in northern Pakistan, particularly.

Acknowledgments:

Author of this paper is highly thankfull to the National natural science foundation of China for providing financial aid for this research.

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