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Geospatial Analysis of Landslide and Assessing its Risk Along the Swat Motorway, Pakistan

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Abstract
Landslides significantly threaten infrastructure and human lives, highlighting the need for effective landslide susceptibility mapping. This research focuses on creating a map showing landslide susceptibility along the Swat Motorway using Remote sensing (RS) and geographic information system (GIS) methods. The objective is to assess the spatial distribution of landslide-prone areas along the motorway corridor, aiding in informed decision-making for infrastructure development and risk mitigation measures. The study begins by collecting and analyzing relevant geological, geomorphological, and climatic data to identify factors contributing to landslide occurrences. This includes slope gradient, lithology, land cover, rainfall intensity, and land use patterns. Remote sensing data, such as satellite imagery and digital elevation models, are utilized to extract information on land surface characteristics and terrain attributes. GIS-based techniques are employed to integrate and analyze the collected data, employing various spatial analysis tools and algorithms to locate potential landslide locations. The Weighted Overlay Method is applied to assign weights and combine the different factors, generating a landslide susceptibility index. Based on the landslide susceptibility map, this research aims to identify and discuss the areas along the highway that are extremely vulnerable to landslides. After creating a map of the Swat Motorway's landslide susceptibility, numerous zones that are prone to landslides were found. Two of these zones are particularly prone to landslides. The creation of a susceptibility map of landslides provides valuable information for planning land use, management of infrastructure, and hazard mitigation along the Swat Motorway. It identifies high-risk zones prone to landslides, enabling policymakers and engineers to make informed decisions regarding the construction of new roads, slope stabilization, and implementation of early warning systems. The results of this research add knowledge to the already-existing knowledge on susceptibility mapping of landslides, specifically in the context of the Swat Motorway. By utilizing GIS and RS techniques, the study demonstrates an effective and efficient approach for assessing landslide hazards along transportation corridors.

Keywords
Geospatial analysis; Geographic Information System (GIS); Risk assessment; Landslide susceptibility mapping; Swat Motorway.

1 Introduction

Landslides are described as the downward motion of a rock mass, rubble, or material of earth caused by gravity. This is one of the main natural disasters that occurs every year and results in significant direct and indirect costs in terms of both lost property and deaths. Heavy rain, seismic shaking, low groundwater levels, steep slopes, rainfall, bedrock geology, and vegetation cover are only a few occurrences of internal and external elements that can cause landslides (Budetta, 2004; Bacha et al., 2018; Kakavas et al., 2021; Ullah et al., 2022). Landslides are predicted to cause S4 billion in annual direct and indirect losses and 600 to 1000 fatalities worldwide each year (Hungr et al., 2014; Shahabi & Hashim, 2015). Landslides that occur on the sides of a motorway may pose a major and long-lasting threat to infrastructure and people. Communities and socioeconomic activity in hilly areas are often severely impacted by landslides, making them one of the most catastrophic natural dangers. According to a recent analysis by (Toya & Skidmore, 2006; Mondal & Mandal 2018), landslides kill over 1018 people per year and cost businesses and individuals worldwide a total of $ 4.0 billion each year. Many natural and manmade factors combine to create unstable conditions on slopes that lead to landslides, including earthquakes, volcanic eruptions, heavy rain, deglaciation, a shifting water table, and removing vegetation and trees. The two most common causes of landslides are earthquakes and heavy rain (Basharat et al., 2016; Ali et al., 2018, 2021).

To determine the susceptibility of landslide using remote sensing and geographic information system analysis, highly hazardous areas were identified; a risk assessment was subsequently conducted on these sites (Bachri et al., 2020; Sharma et al., 2023). One of the main initiatives to assist highway authorities in preserving safe and hazard-free traffic is mapping landslide susceptibility (Cardinali et al., 2002; Akagunduz et al., 2008). Data related to geology and geomorphology were gathered and processed using GIS. Numerous factors related to landslide influencing and triggering were taken into account when creating the susceptibility map. Maps are created using lithology, faults, seismicity, rainfall amount and intensity, elevation, slope angle, aspect, curvature, water, and land cover. In this work, data from remote sensing, geology, and topography were gathered and processed using GIS software (Guzzetti et al., 2006; Hong et al., 2018; Bachri et al., 2020; Ullah et al., 2022; Ansar et al., 2023; Sharma et al., 2023). Landslides are considered disasters that result in major societal and economic harm in hilly places(Basharat et al., 2016; Ali et al., 2018, 2021).

In order to assess the likelihood of landslide hazards, the current study was conducted, beginning with the creation of a susceptibility map of the Swat Motorway site. The major landslides/landslide zones that could affect the proposed Swat Motorway site and their most likely failure modes were also identified in this study. The Swat Motorway site's landslide susceptibility map was initially generated in this research project using the methodology stated above. However, this research effort was done to assess things at the micro level for a more in-depth analysis.

2 Materials and Methods

2.1 Study Area

The Swat Motorway, commonly known as the M-16 or Swat Motorway, is a four-lane provincial controlled-access motorway in Pakistan's Khyber Pakhtunkhwa province that is 160 kilometers (99 mi) long. The project's first phase, which was finished in June, connects the M-1 highway at Nowshera to Chakdara, while the second phase, which is still under construction, will take the project to Fatehpur. The current research is on phase 1 of the Swat Motorway. Swabi, Mardan, Malakand, and Swat districts are traversed by the motorway's first phase, which runs from Nowshera to Chakdara in the Lower Dir District (Fig 1). The inauguration of the project's first phase took place in August 2016. and became operational on June 3, 2019. From Nowshera to Chakdara, phase 1 cut the travel time in half, from three hours to one (Swat Motorway: A Comprehensive Guide, n.d.; Swat Motorway - Swat Expressway - (M16) - Swat, n.d.).

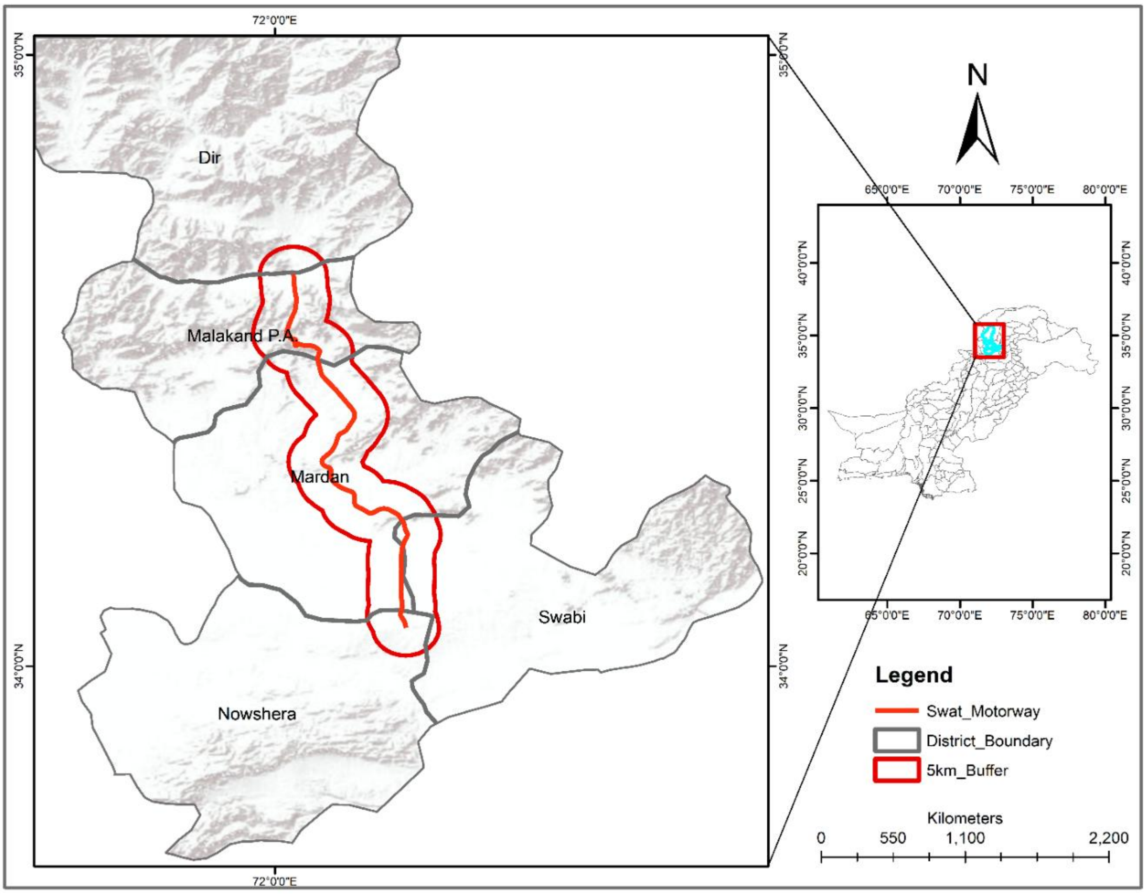

Fig. 1. Showing study area map of the Swat motorway with a 5 km buffer

2.2 METHODOLOGY

2.2.1 Data preparation

Data collecting for susceptibility maps is the initial step in the assessment of the risk of landslides.

2.2.2 Digital Elevation Model

Digital elevation models (DEMs) are the most relevant and valuable data currently accessible in remote sensing. The spatial resolution of a DEM is determined by the size of its cells along the X and Y horizontal dimensions (Taud et al., 1999; Fujisada et al., 2012; Saleem et al., 2019). PALSAR DEM with 12.5 m resolution was downloaded from the Alaska Satellite Facility's (ASF) website. The Japan Aerospace Agency (JAXA) released PALSAR, one of the most effective radar systems. This radar system is capable of producing high-quality digital elevation models with a resolution of 12.5m. PALSAR stands for Phased Array L-band Synthetic Aperture Radar (Kumar & Anbalagan, 2016; Dibs et al., 2018; Saleem et al., 2019).

A. Susceptibility Mapping data

The likelihood of slope failure is quantitatively calculated using statistical analytic methods based on the characteristics that lead to slope instability. Such methods could be utilized to create susceptibility maps by utilizing GIS-based multi-criteria analysis (Tsangaratos et al., 2017; Bacha et al., 2018; Biswakarma et al., 2020). Gathering indicator map units is the most important step in conducting suitability research. The next step is to weigh and rank each indicator unit according to how significant or important it is to slope instability. Landslide susceptibility is the probability that a future landslip will occur. A number of statistical techniques can be applied to produce a highly accurate map of landslide susceptibility. Important landslide zones can be easily and affordably identified using a landslide susceptibility map. The outcomes' quality is influenced by the data's quality. The more precise the data, the more precise the results. Data is available for purchase, digitalization, or free download. The variables that normally control slope instability are the main focus of landslide susceptibility mapping. Slopes, geology, precipitation, vegetation, seismicity, and many other factors can cause landslides (Ahmed et al., 2014; Spinetti et al., 2019; Wang et al., 2020). In this research, Weighted overlay models are utilized for susceptibility mapping. The indicator map elements (data) which were used to map the risk of landslides are listed below.

i. Elevation

ii. Slop

iii. Slop Aspect

iv. Curvature

v. Structure (geological Fault line)

vi. Geology (Lithology)

vii. TWI

viii. Seismicity

ix. Rainfall

x. Normalized Difference Vegetation Index

i. Elevation

Rise or elevation has a critical role in slope instability. When the height is higher, there are more landslides. A USGS explorer elevation map (DEM) with a 12.5 m resolution was obtained from the open-source site asf.alaska.edu (Fujisada et al., 2012; Saleem et al., 2019).

ii. Slope

Slope angle is another element that contributes to slope instability. The slope angle is the shape between a region of the ground and the even datum. ArcGIS 10.5 generates a slope (Moradi et al., 2019).

iii. Slope Aspect

The aspect of the slope is its direction. The amount of sunlight and the amount of precipitation depend on this angle (Tarolli et al., 2011).

iv. Curvature

Curvature, which is the second geomorphic component after aspect, is essential for categorizing topographic features(Akagunduz et al., 2008). Regardless of the geometry of a surface, its convexity and concavity can be seen through its curvature (Kayastha et al., 2013). Values of curvature can be used to characterize topographic morphology.

v. Structure Map

The structure map includes Faults or Suture zones. The tectonic map was freely downloaded from open source (https://www.researchgate.net/figure/Tectonic-Map-of-PakistanCourtesy-Geological-Survey-of-Pakistan_fig1_261363284), and then it was processed (multi-ring) buffer in ArcGIS 10.5 (Bopche, & Rege, 2022).

vi. Geology

One of the main causes of landslides is lithology (geology) (Kayastha et al., 2013). Due to differences in their physical and chemical properties, all rocks behave differently. Hard compacted rocks are often more stable than loss-connected rocks or soil formations.

vii. TWI

The TWI (topographic wetness index) displays the moisture of soil and surface saturation. It shows how local topography is impacted by hydrology (Beven & Kirkby, 1979). It is calculable by:

$$TWI = ln\frac{a}{tan\,\beta} \tag{1}$$

Where a = specific area of upslope,

$tan\,\beta$ = local angle of slope grid.

viii. Seismic Hazard Map

Seismic hazard map was freely downloaded from open source (http://a.2002-acuratl-radio.info/page-a/diagram-of-2005-kashmir-earthquake-76047.html) and then processed (digitized) in ArcGIS 10.5 (Moradi et al., 2019).

ix. Rainfall Map

The rainfall map was freely downloaded from open source (https://www.mdpi.com/2073-4441/10/7/918/html) and then processed (digitized) in ArcGIS 10.5 (Ullah et al., 2022).

x. Vegetation Cover

NDVI (Normalized Vegetation Difference Index) was processed in Google Earth Engine (GEE) and then the NDVI map was downloaded for further processing (Ullah et al., 2022).

B. Data processing

The study processes the data using a computer program called a geographic information system (GIS). GIS is useful for storing, confirming, interpreting, and gathering data about positions on the earth's surface. GIS shows a variety of data types, such as forests, routes, and architectural structures. GIS is used in this research work to create a susceptibility map of landslides and to process other thematic layers. The weighted overlay tool of ArcGIS is used to prepare the susceptibility map of the research area. The thematic layers include slope, aspect, rainfall, curvature, fault buffer, geology, seismicity, and topographic wetness index.

C. Data Reclassification

All layers, including slope, fault buffer, slope aspect, elevation, curvature, TWI, and geology of the area, were reclassified into different new classes and assigned new values using the reclassify tool of ArcMap 10.5 software. They were then used to create landslide susceptibility maps.

D. Weighted overlay method

In a weighted overlay, various map layers are layered on top of one another(Galli et al., 2008; Bachri & Shresta, 2010). In cases like landslides, this method obtains results by using the relative roles of each parameter(Ayalew et al., 2005). Several raster layers are used in the weighted overlay approach, and composites are created by assigning each class a specific weight percentage based on its significance (Saaty, 1990; Guzzetti, 2000; Biswakarma et al., 2020). The strategy of weighted overlay was applied in this research to create the map of landslide susceptibility because it is an effective technique for the task. Using professional judgements, this approach assigns each raster layer a weight based on its relative value.

The collection of raster data must also be reclassified as part of the weighted overlay process. Utilizing the "Weighted Overlay" tool comes after the process of reclassification. According to its proportional contribution, each dataset is given a percentage effect in a weighted overlay (Pachauri & Pant, 1992). Numbers for % influence and categorization are given based on expert knowledge. Figure 2 shows the methodology flow chart used in this research.

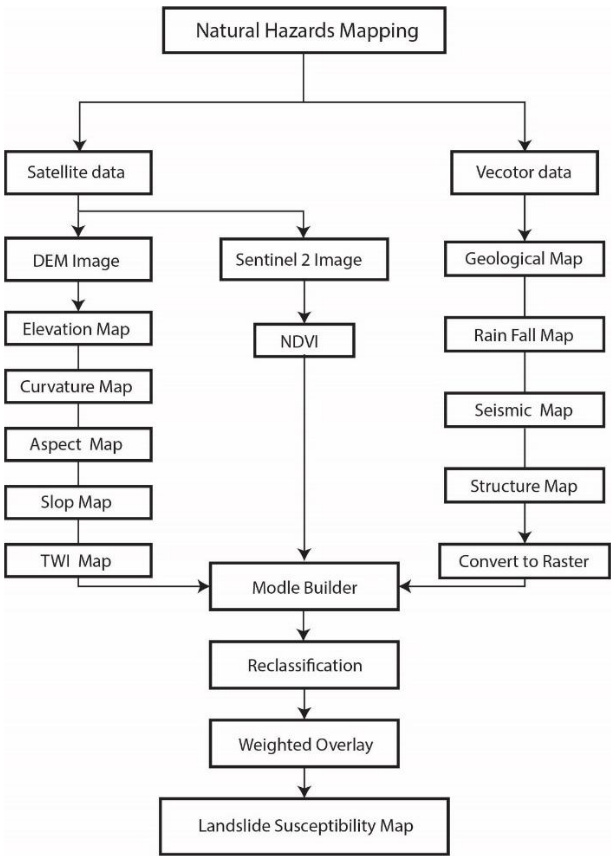

Fig. 2. Showing methodology flow chart

3. Results and Discussion

3.1 Susceptibility Map for Landslide

The weighted overlay approach was used to create a map of the Swat Motorway, which shows the susceptibility of landslides. To do this, the ArcGIS 10.5 program's primary triggering variables for landslides were processed before running the weighted overlay technique on them.

3.2 Triggering Factors of Landslide

Elevation, curvature, slope, slope aspect, geology, TWI, Seismicity of area, tectonic structures, average rainfall, and NDVI were the influencing factors that were processed to create the maps.

a. Elevation (m)

The most common cause of landslides is elevation. Landslides occur more frequently at higher elevations(Ercanoglu & Gokceoglu, 2004). Elevation data, commonly known as a DEM, can be acquired for free from online sources. In the research area, elevation differences range from a minimum of 300 meters to a high of 1500 meters. As indicated in Figure 3g, the elevation map was divided into five categories with intervals of 300 meters each: 300, 300-600, 600-900, 900-1200, and 1500 meters.

b. Slope Angle (°)

The angle of slope is widely utilized in the production of landslide maps of susceptibility since the angle of slope is directly related to the hazards of landslides. Historical data show that the likelihood of failure increases with slope steepness(Ayalew et al., 2005). If the material friction angle is small in comparison to the angle of the slope, the likelihood of a slope or blocks falling will be highest(Cevik & Topal, 2003). In the research region, the slope angles range from 0 to 76. It was divided into nine categories: 0–3, 3–7, 13–20, 27–34, 34–41, 49–76. Fig 3c depicts the area's slope angle.

c. Aspect

Slope direction is known as aspect. According to Tarolli et al. (2011), this angle controls the amount of sunlight and precipitation. Although it does influence transpiration, which in turn affects plant activities, root growth, and weathering, the relationship between slope and its impact on hazards of landslides is still up for question. After running the tool, the aspect of the research area classified into ten classes, i.e., Flat (-1), North (0-22.5), Northeast (22.5-67.5), East (67.5-112.5), Southeast (112.5-157.5), South (157.5-202.5), Southwest (202.5-247.5), West (247.5-292.5), Northwest (292.5-337.5), and North (337.5-360). Aspects are rated from 0 to 360 in a clockwise fashion. The numbers 0 and 90 and 180 and 270, respectively, stand in for the North, East, South, and West. The Southwest and West are the regions most severely impacted by rain (Rashid, 2004). Fig. 3a displays the area's aspect map.

d. Curvature

Curvature is the division of a territory into concave, and convex shapes to identify the places that are susceptible to landslides. The curvature map has three possible values: positive, negative, and zero. Flat areas have zero values. Positive values are found for convex surfaces, whereas negative values are found for concave surfaces. Landslides mostly occur in specific regions where the surface is concave, according to the currently available literature. Landslides and rockfalls are extremely unlikely to occur on flat terrain. A surface's curvature and a mass's motion are strongly correlated. A landslide is more likely to occur when concave surfaces have negative values because they tend to hold mostly more water during heavy downpours(Drzewiecki et al., 2014; Kakavas et al., 2021). According to Fig 3b, the study area's curvature is separated into two classes.

e. Geology

Landslides and geology are connected in a number of ways. Rock type controls slope tensile strength as well as the variety of materials that are prone to landslides. Due to differences in each rock's physical and chemical properties, each one responds differently. One of the factors that is most likely to cause and control landslides is geology. The region's geology is composed of three main lithologies, as indicated in Fig 3i.

f. TWI

The TWI (topographic wetness index) displays the moisture of soil and surface saturation. It shows how local topography is impacted by hydrology (Beven & Kirkby, 1979; Kakavas et al., 2021). It is calculable by:

$$TWI = ln \frac{a}{tan\,\beta} \tag{2}$$

Where a = specific area of upslope,

$tan\,\beta$ = local angle of slope grid.

As shown in Fig 3f, the topographic wetness index in our research area is separated into five classes: 1-4, 4-6, 6-8, 8-10, and 10-18.

g. Structure Map

Seismicity is produced in many ways, one of them is movement along faults. Due to tectonic forces, many small to regional-size faults are created in a region. Some may be inactive today, but most of them are active and produce earthquakes. Major suture zones in northern Pakistan are Main Boundary Thrust, Main Mantle Thrust, and Main Karakorum thrust (DIPIETRO & LAWRENCE, 1991; Dewey & Lamb, 1992; DiPietro & Pogue, 2004; Lewandowski, 2009). No minor faults were reported in the study area, only one major fault. Multiple zones (multi-ring buffer) were classified along the fault line, as shown in Fig. 3j.

h. Rainfall Map

In the instability of slopes, rainfall in the area plays the most important role and is one of the major reasons for global landslides. Pakistan is known for the summer monsoon season. From the Bay of Bengal, monsoon rainfall originates and enters Pakistan (Hassan Arsalan & Fatima, 2014; Anjum et al., 2021). According to data published by the Pakistan Metrological Department in 1993, annual rainfall varies between 500 and 800 mm. Water infiltrates rapidly into fractures or pores and increases the degree of saturation, hence triggering landslides. Water reduces friction between blocks and acts as a slippage material. In soil or highly fractured rocks, water easily gets in, increasing pore water pressure and the chances of mass movement. That is why drainage measurements should be taken along the slopes of roads and other infrastructures (Hassan Arsalan & Fatima, 2014; Anjum et al., 2021). The rainfall map of the Swat motorway is classified into four different zones with different intensities of rainfall, as shown in Fig 3e.

i. Vegetation Cover

The role of Vegetation in landslides is also important, but in the opposite manner. Mass movement and Vegetation cover are inversely proportional. If the area is densely vegetated, there are fewer chances of mass movement. In mountainous regions, the role of the forest is very important. It protects the lives and properties of people against events like avalanches, rockfalls, and landslides. A thick, dense forest provides the best protection against events like landslides or snow avalanches (Carlson & Ripley, 1997; Pettorelli et al., 2005). The NDVI (Normalized Vegetation Difference Index) is used to measure the vegetation density of an area. Vegetation index values range from -0.0729162 to 0.463774 in Fig. 3h. Literature shows that areas with high vegetation are less prone to erosion and landslides, while areas with less vegetation like Soil/Rock are highly prone to erosion and landslides (Carlson & Ripley, 1997; Pettorelli et al., 2005; Huang et al., 2021). Rankings for each class were given based on their contribution to slope instability. Areas with dense vegetation are ranked less than those with only rock/soil.

j. Seismic Hazard Map

When dealing with landslide susceptibility, you cannot ignore Seismicity. Earthquakes are the major global trigger factor for major landslides (Khurshid et al., 1984; Yadav et al., 2012; Ali et al., 2018). Earthquakes have produced many landslide dams throughout the globe at different times. The seismic Map of Swat Motorway shows that the study area lies in a high seismic zone where seismicity occurs above VI on the MM scale (Fig. 3d).

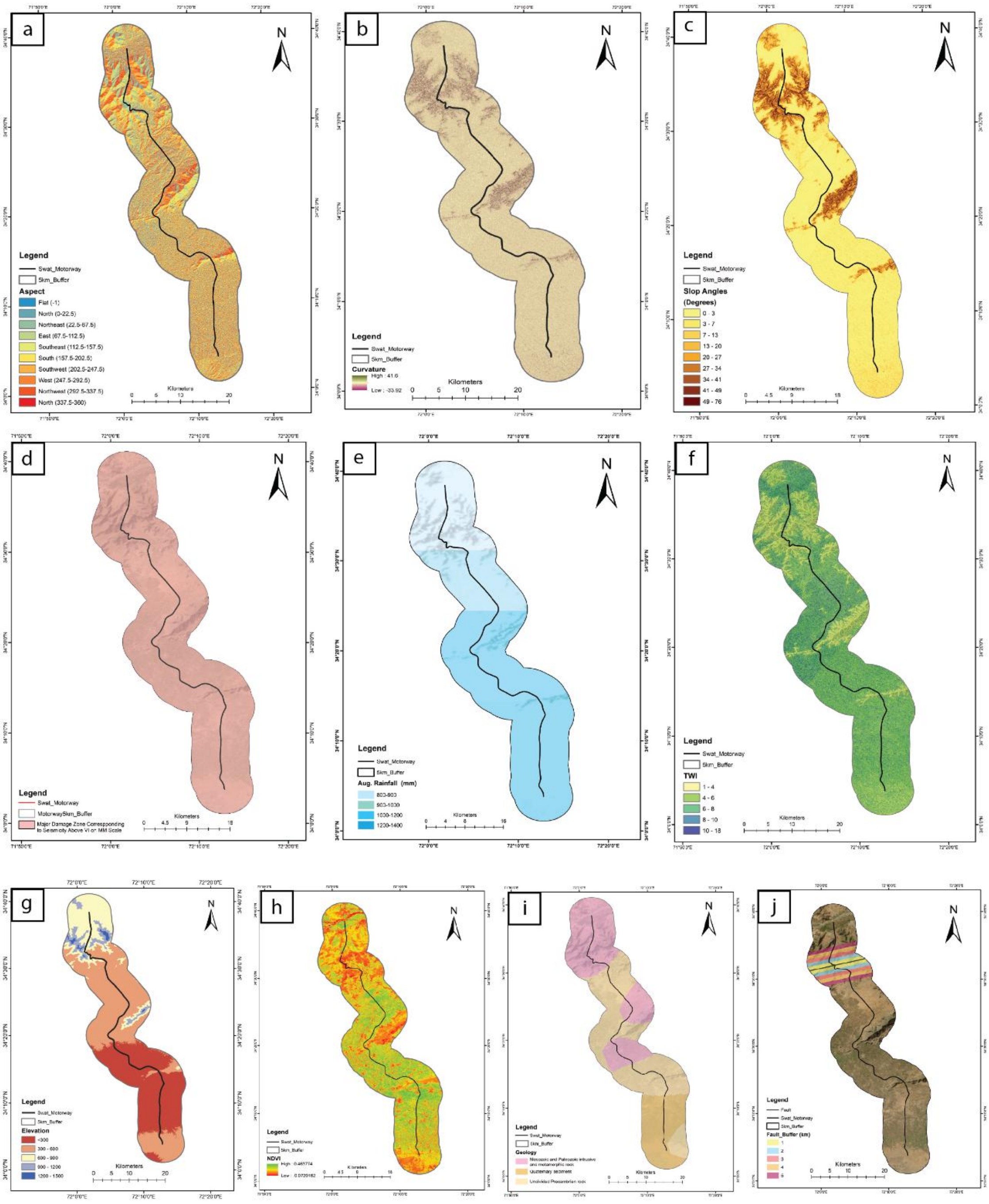

Fig. 3. Showing various parameter maps that control landslides. (a) Aspect Map, (b) Curvature Map, (c) Slop Angles Map, (d) Seismic Map, (e) Average Rainfall Map, (f) TWI Map, (g) Elevation Map, (h) NDVI Map, (i) Lithological Map, (j) Structure Map.

3.3 Weighted Overlay Method

The approach of weighted overlay, provided by ArcGIS, is a very straightforward and fundamental tool for suitability evaluation. This method used a number of input map layers that may have contributed to the slope failure (Basharat et al., 2016). It is a strategy or procedure in which multiple factors that affect landslides are used, including aspect, elevation, geology, slope, etc. (Bachri & Shresta, 2010). Each and every raster map unit is reclassified, with each class receiving a certain ranking. Following reclassification, the "weighted overlay" tool of ArcGIS is implied to assign rate and influence to each unit of the map, as illustrated in Table 5.1. An equal percentage of influence is given in the first run, whereas the remaining five runs are based on a blend of various influences from all the input raster data layers. The fault, slope steepness, elevation, and hydrology were given higher percentages of the rate because these were the most important triggering elements for landslides. Other elements have less of an impact on these kinds of areas. (Guzzetti et al., 2006; Bachri & Shresta, 2010; Basharat et al., 2016; Bacha et al., 2018). Four classes, i.e., low susceptible area, moderate susceptible area, high susceptible area, and very high susceptible area, are subsequently generated from the results of the weighted overlay technique.

A map of the Swat Motorway's landslide susceptibility is shown in Fig 4. According to interpretations, the low susceptible area comprises 0.79% of the land, the moderate risk area is 36.808%, the high landslide susceptible area is 55.009%, and the extremely high hazard area is 7.388, as illustrated in Fig 5.

Tab. 1. Showing classification of raster data and weighted used for weighted overlay technique.

Factors	Influence	Field	Rate	Factors	Influence	Field	Rate
Slope (º)	**10**			**Structure Faults (km)**	**15**		
0-13		1	5	1		1	9
13-27		2	7	2		2	8
27-39		3	8	3		3	6
39-55		4	8	4		4	4
55-76		5	9	5		5	3
Geology	**15**			**Elevation (m)**	**10**		
Intrusive and Metamorphic rock		1	9	>300		1	5
Quaternary Sediment		2	6	300-600		2	6
Undivided Precambrian rock		3	8	600-900		3	7
Aug. Rainfall (mm)	**10**			900-1200		4	8
800-900		1	7	1200-1500		5	9
900-1000		2	8	**Slope Aspect**	**5**		
1000-1200		3	9	Flat		1	1
1200-1400		4	9	North		2	9
NDVI	**10**			Northeast		3	7
High 0.463774		1	5	East		4	5
Low -0.0729162		2	9	Southeast		5	5
Seismicity	**10**			Southeast		6	6
Major damage zone corresponding to seismicity above VI on the MM scale		1	9	Southwest		7	7
Curvature	**10**			West		8	5
High 41.6		1	5	Northwest		9	9
Low -33.92		2	9	North		10	7
TWI	**5**						
1-4		1	3				
4-6		2	5				
6-8		3	7				
8-10		4	8				
10-18		5	9				

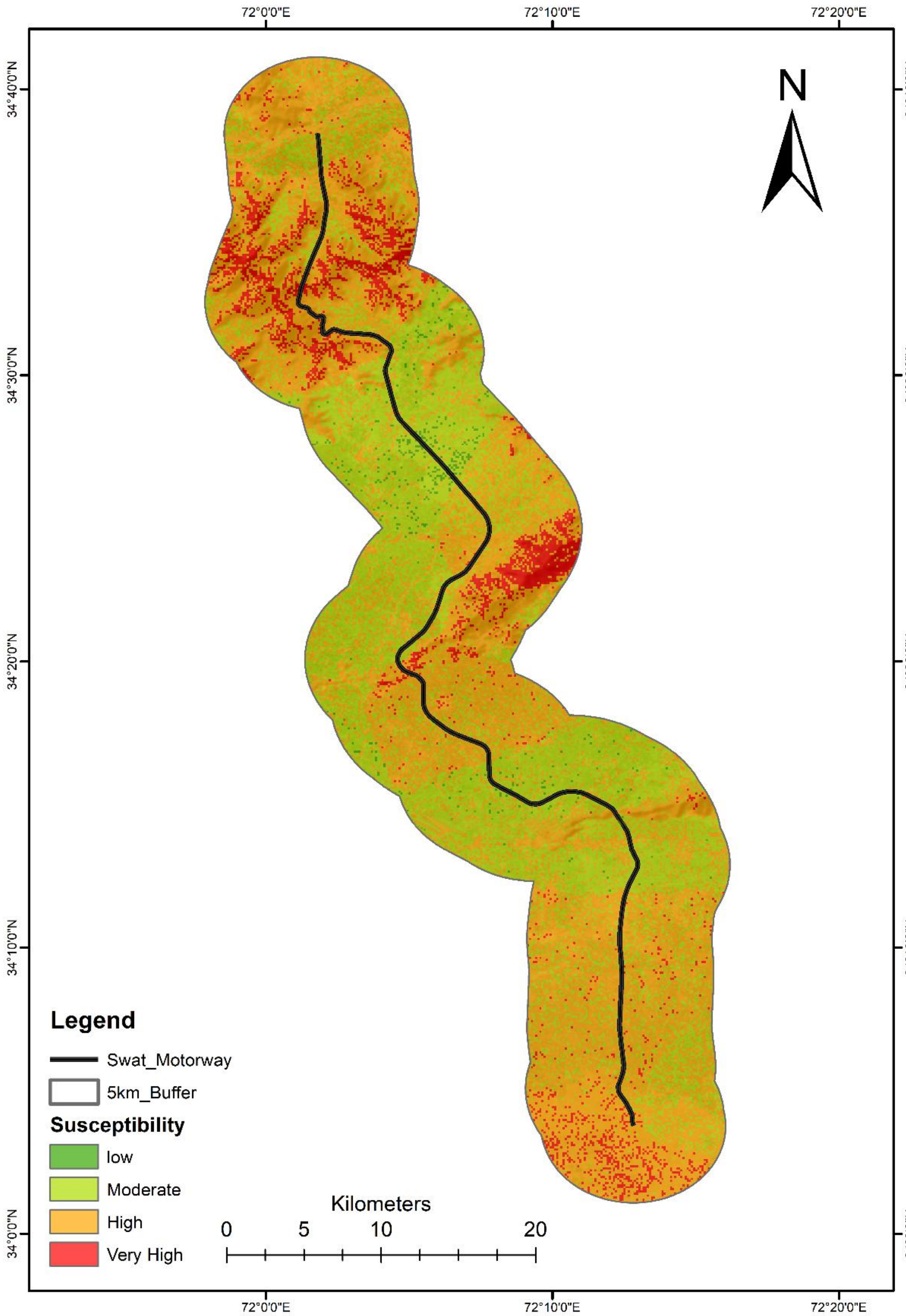

Fig. 4. Map showing hazards map of the Swat motorway

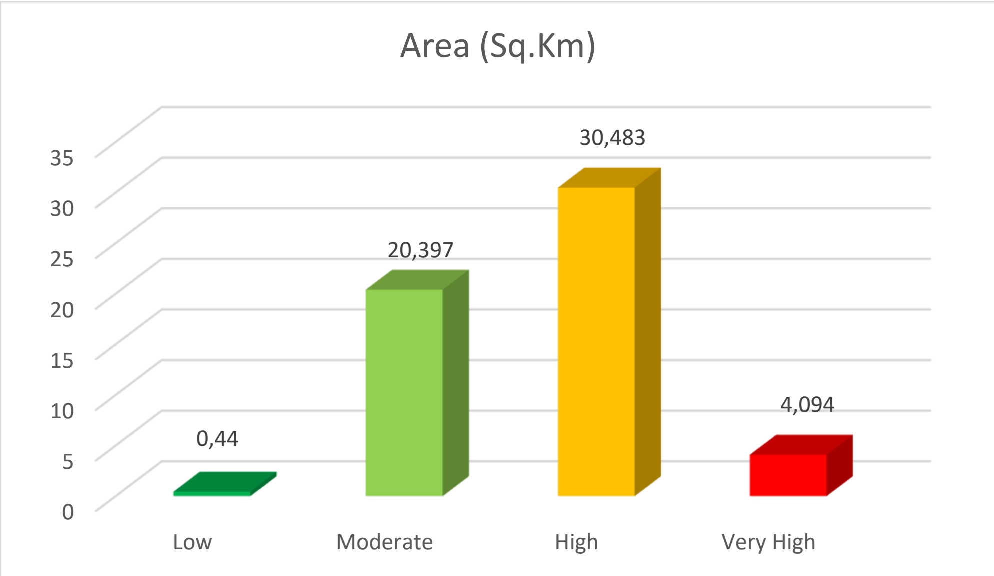

Fig. 5. Showing areas along the Swat motorway that are susceptible to landslide

3.4 Highly Susceptible Zones for Landslides along the Swat Motorway

After creating a map of the Swat Motorway's landslide susceptibility, numerous zones that are prone to landslides were found. Two of these zones are particularly prone to landslides. Based on the landslide susceptibility map, this research aims to identify and discuss the areas along the highway that are extremely vulnerable to landslides. The map includes different metrics and landslide-causing elements, such as topographical features, land cover, geology, rainfall patterns, etc.

i. Zone 1

Zone 1, a highly sensitive zone for landslip hazards, starts at about 34.5 km from the Kernel Sher Khan junction. Zone 1 extends a distance of roughly 13.5 kilometers. This area is particularly vulnerable to natural disasters due to a number of variables. High slope gradients are present in the zone, exceeding the stability cutoff for slope stability. This zone's geological units are made up primarily of weak or severely worn materials that are prone to mass movement. There have been several recorded landslides in this area, indicating a higher danger. The area has heavy rainfall, especially during the monsoon season, which increases pore pressure and causes slope instability. An average rainfall of 1000 to 1200 mm is noted in this location. Limited vegetation cover and loose or unconsolidated soil further increase landslide susceptibility. Zone 1 of the Swat Motorway's landslide susceptibility map is shown in Figure 6. As shown in Figure 7, interpretations indicate that low susceptible area for landslides covers 0.79% of the total area, while moderate susceptibility is present in 35.166% of the area, high susceptibility is present in 51.737% of the area, and very high susceptibility is present in 13.144% of the area.

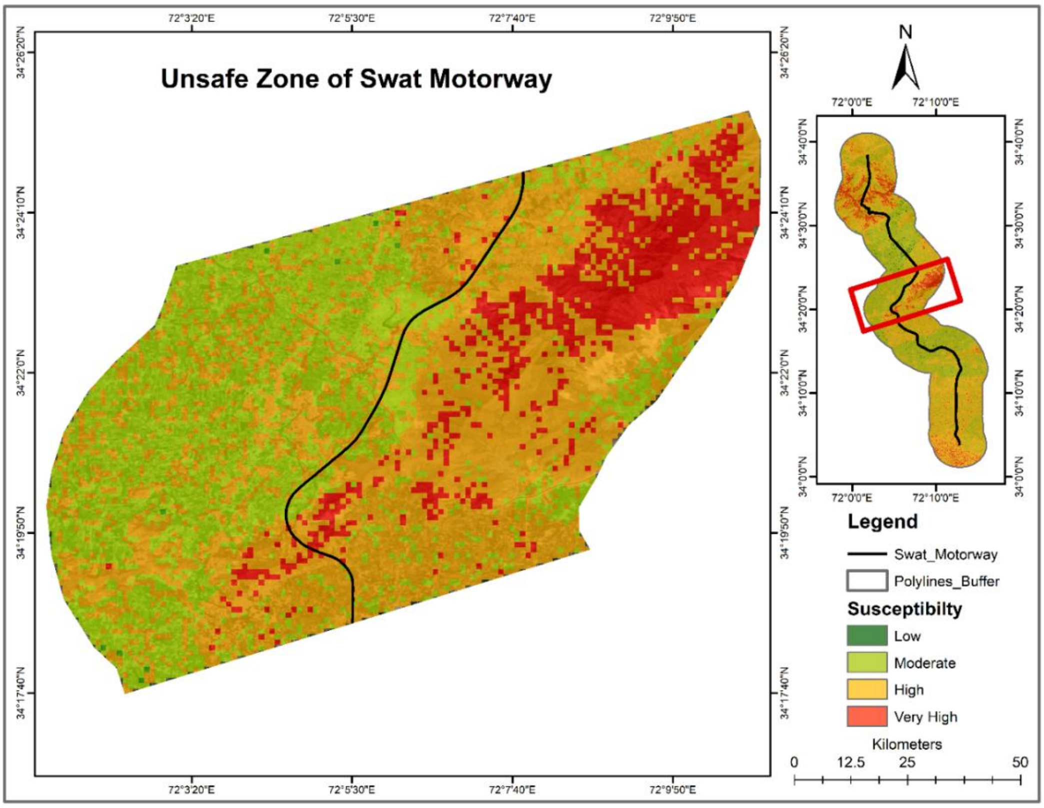

Fig. 6. Map showing zone 1 of the Swat motorway, which is highly susceptible to landslide

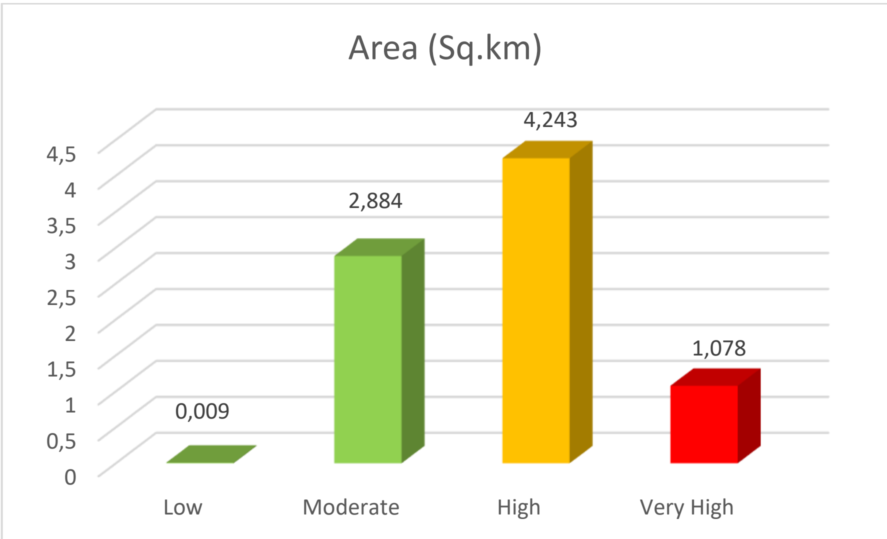

Fig. 7. Showing areas of zone 1, which are susceptible to landslide

ii. Zone 2

Zone 2 of the Swat Motorway's which is located around 14 km from Zone 1 is highly susceptible place landsliding. About 17.5 miles make up zone 2's whole length. Geological fault lines cross this area, which could weaken the rock bulk, resulting in landslides. The region in this zone is characterized by a combination of rocky terrain, sharp elevation changes, and steep slopes, all of which contribute to instability. The zone is located in a seismically active area, which raises the risk of earthquake-induced slope failures. Materials having a high vulnerability to landslides, such as clay-rich or heavily worn formations, are present in this zone, geology and soil composition. Zone 1 map of the Swat Motorway's which show landslide susceptibility is shown in Fig 8. According to interpretations, 0.096% of the total area is show low susceptibility to landslides, 16.820% is moderately susceptible, 67.814% is highly susceptible, and 15.268% is extremely susceptible, as shown in Fig 9.

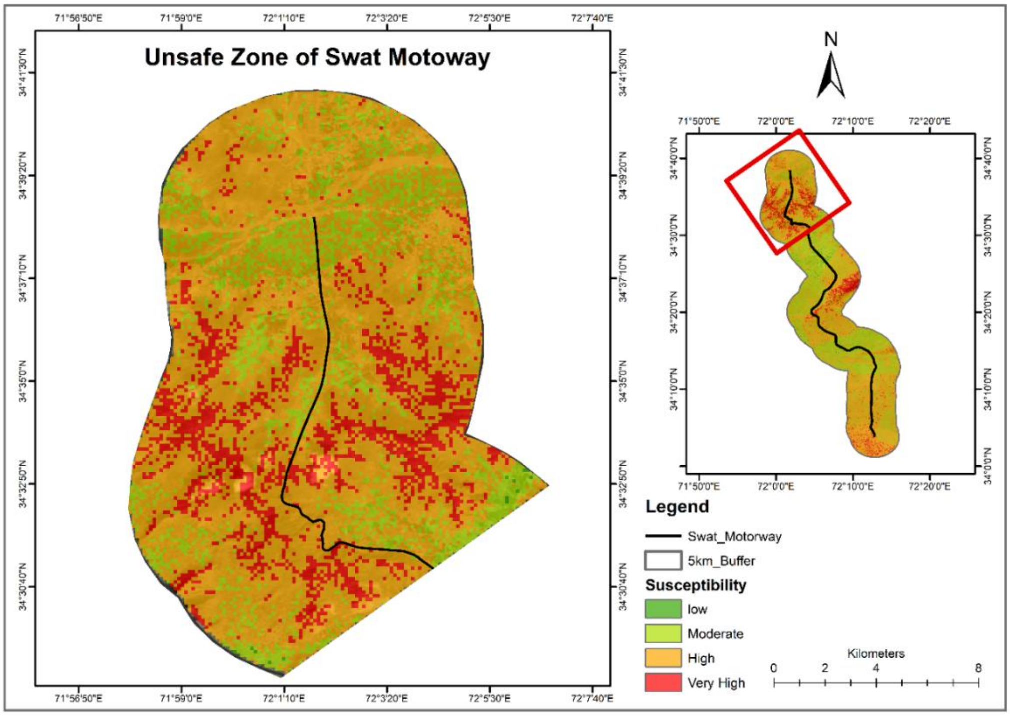

Fig. 8. Map showing Zone 2 of the Swat motorway, which is highly susceptible to landslide

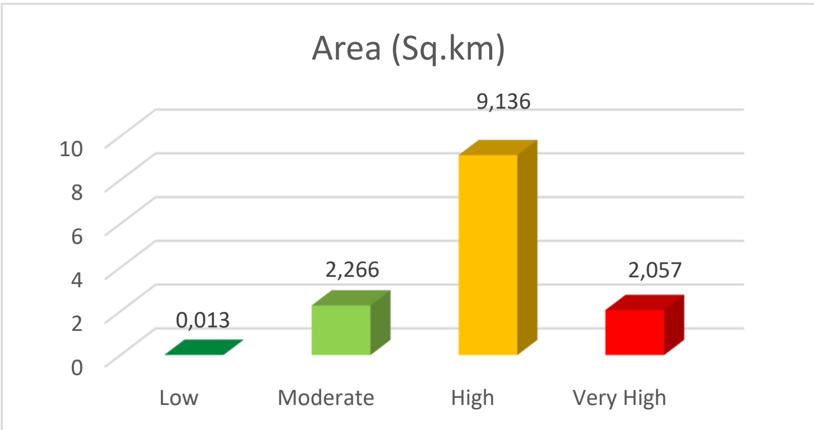

Fig. 9. Showing areas of zone 2, which are susceptible to landslide

4 Conclusion

The main topic of this research was the application of GIS and remote sensing for susceptibility mapping for a landslide of the Swat Motorway. The goal was to evaluate these techniques' potential for locating landslide-prone regions along the motorway corridor. A thorough understanding of the triggers contributing to landslip vulnerability was attained through the study of multiple data layers and characteristics. The study's findings showed how well GIS and remote sensing work to map landslide vulnerability. In order to analyze the spatial distribution of places that are prone to landslides, a comprehensive strategy was employed that included terrain analysis, land cover classification, geological analysis, and rainfall patterns. The combination of these methods created a solid basis for precise and trustworthy estimates of landslip vulnerability.

The Swat Motorway's landslide susceptibility map indicated two separate regions that showed a high propensity to landslides. Zone 1, which was characterized by steep slopes, flimsy geological formations, a history of landslides, and intense rainfall, posed a serious threat to the road system. Zone 2, which has crossing geological faults, complicated topography, and significant seismicity, also showed higher susceptibility to landslides, indicating possible safety risks to road users. The results of this study have a number of implications for the Swat Motorway's efficient control of landslide risk. In order to reduce the potential effects of landslides, it is possible to apply suitable mitigation measures by identifying particularly sensitive zones. Techniques for stabilizing slopes, better drainage, early warning systems, plant regeneration, and routine inspections are some examples of these efforts.

The study also contributes to the existing knowledge on landslide susceptibility mapping by showcasing the potential of GIS and remote sensing techniques in assessing landslide-prone areas. The integration of multiple data sources and parameters allowed for a comprehensive analysis, enhancing the accuracy of the results. Future research on landslide susceptibility mapping in related geographical contexts can use the methods used in this study as a guide. It is crucial to recognize that landslide susceptibility mapping is a continuous process and that the model still has to be improved and validated. The accuracy of the model's predictions can be improved by including other data sources, such as ground truthing and high-resolution imaging. Ongoing landslip monitoring and updates will enhance the susceptibility map's dependability and effectiveness.

In conclusion, this study successfully illustrated the use of GIS and remote sensing methods for mapping landslide susceptibility along the Swat Motorway. For land use planning, infrastructure development, and disaster management in the research region, the created landslip susceptibility map and identified high-risk zones offer useful information. The study's findings advance our understanding of landslides and provide a solid basis for future research as well as preventative actions to reduce the risk of landslides along the highway corridor.

Declaration of Competing Interest

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

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