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GIS-based landslide susceptibility mapping using frequency ratio (FR) method - A case study of Murree Hills, Pakistan

Cartographie de la susceptibilité aux glissements de terrain basée sur un GIS utilisant la méth ode du rapport de fréquence (FR) - Une étude de cas de Murree Hills, Pakistan

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ABSTRACT: Murree hills, forming part of outer Himalayas, are located in the Galyat region of northern Punjab, Pakistan and constitute a high value tourist resort in the country. Landsliding is a common phenomenon in these hills mainly due to fragile geology, steep slopes, intense rainfall and high seismicity. The rampant development during the last decade led to deforestation, uncontrolled excavation, poor drainage, etc. and has further aggravated the landslide issue. Hence, landslide susceptibility mapping of 60 km^2 area of Murree hills was carried out; this would help the administrators for safer planning of new developments. A GIS-based landslide susceptibility mapping was carried out using bivariate statistical frequency ratio (FR) method. Firstly, a landslide inventory map was prepared by mapping reported landslides in the study area. Then, landslide causative factors, including slope gradient, slope curvature, slope aspect, geology, rainfall, distance to faults, distance to streams, roads and settlements, and vegetation cover were estimated. The relationship between landslide susceptibility and landslide causative factors was statistically evaluated using FR analysis. Landslide susceptibly index (LSI) for each pixel of the study area was then computed by summing up the FR values of all the factors, generating landslide susceptibility map.

RÉSUMÉ : Les collines de Murree, faisant partie de l'Himalaya extérieur, sont situées dans la région de Galyat au nord du Pendjab, au Pakistan et constituent une station touristique de grande valeur dans le pays. Les glissements de terrain sont un phénomène courant dans ces collines principalement en raison de la géologie fragile, des pentes abruptes, des précipitations intenses et de la sismicité élevée. Le développement effréné au cours de la dernière décennie a conduit à la déforestation, à des excavations incontrôlées, à un mauvais drainage, etc. Par conséquent, une cartographie de la susceptibilité aux glissements de terrain de la zone de 60 km² des collines Murree a été réalisée ; cela aiderait les administrateurs pour une planification plus sûre des nouveaux développements. Une cartographie de la susceptibilité aux glissements de terrain basée sur un GIS a été réalisée à l'aide de la méthode du rapport de fréquence statistique (FR) bivariée. Premièrement, une carte d'inventaire des glissements de terrain a été préparée en cartographiant les glissements de terrain signalés dans la zone d'étude. Ensuite, les facteurs causant les glissements de terrain, y compris le gradient de pente, la courbure de la pente, l'aspect de la pente, la géologie, les précipitations, la distance à la failles, la distance aux cours d'eau, aux routes et aux établissements humains, ainsi que la couverture végétale ont été estimées. La relation entre la susceptibilité aux glissements de terrain et les facteurs causant les glissements de terrain a été statistiquement évaluée à l'aide d'une analyse FR. L'indice de sensibilité aux glissements de terrain (LSI) pour chaque pixel de la zone d'étude a ensuite été calculé en additionnant les valeurs FR de tous les facteurs, générant une carte de sensibilité aux glissements de terrain.

KEYWORDS: landslide, landslide causative factors, landslide susceptibility mapping, frequency ratio, ArcGIS

1 INTRODUCTION

A landslide is a downslope movement of soil, rock or debris under the influence of gravity. It is one of the major natural disasters in a mountainous terrain that causes damage to infrastructure and casualties. Landslide susceptibility mapping depicts the relative spatial probability of landslide occurrence over an area and is vital to minimize losses and deaths caused by the landslides.

Landslide susceptibility assessment methods can be classified into qualitative and quantitative. Qualitative methods are subjective and use landslide inventories to identify sites with similar topographical, geological and geomorphological characteristics that are susceptible to landsliding. Quantitative methods determine the mathematical relationship between landslide occurrence and landslide causative factors. Quantitative methods can further be divided into deterministic and probabilistic. In a deterministic approach, a factor of safety (ratio of shear strength to shear stress) is estimated to determine landslide potential of the area. On the other hand, in a probabilistic approach such as frequency ratio (FR), weight of evidence (WOE), statistical index (SI), logistic regression (LR), etc., landslide susceptibility of an area is determined by evaluating the relationship between landslide inventory and landslide causative factors using different statistical algorithms. Deterministic approach is mainly adopted for small areas because of the effort required to measure factor of safety of each slope whereas probabilistic approach can be implemented for large areas, using spatial data gathered from remote sensing and secondary sources and analyzed in ArcGIS.

Recently, a landslide susceptibility map was prepared for Murree hills located in the Galyat region of northern Punjab, Pakistan, based on secondary data and using frequency ratio (FR) method. This paper describes the methodology adopted for the preparation of landslide inventory, estimation of landslide causative factors, and development of a landslide susceptibility map using frequency ratio (FR) method in ArcGIS.

2 PROJECT AREA

The project area comprises Murree hills that form part of outer Himalayas and lies about 15 km northeast of Islamabad (Pakistan's Capital). It starts from Phulgran Toll Plaza and ends at Lower Topa covering an area of around 165 km^2, including Rawalpindi Murree Kohala Road and Islamabad Murree Expressway (see Figure 1).

Murree features a subtropical highland climate under the Koppean climate classification receiving more than 1700 mm of average annual precipitation in the form of rainfall and snow.

The terrain of the project area consists of terraces and mountains and the elevation of the area ranges between 595 m and 2269 m. The area is mostly covered by Pine forest, particularly at the upper regions of the ridges. The molasse deposits comprise Claystone, Shale, Siltstone and Sandstone of the Murree formation of the Miocene age constitutes most part of the project area. The Quaternary deposits include colluvium, alluvium and landslide deposits. Main Boundary Thrust (MBT), a system of thrust faults and Jhelum fault are amongst the most significant tectonic features of the area.

Landslides have always been a geohazard in the Murree hills owing to poor geology, high seismic environment and adverse weather conditions. Recently, increase in anthropogenic activities due to expansion of population such as deforestation, undercutting the bottom and loading the top of slopes for construction of roads and houses, irrigation, lawn watering, etc. has further aggravated the problem of landsliding.

3 DATA ACQUISITION AND PREPARATION

3.1 *Landslide Inventory*

A landslide inventory is a detailed record of the distribution and characteristics of past landslides. It is essential for susceptibility models that predict landslides on the basis of past conditions. A landslide inventory containing a total of 30 landslides was prepared based on the secondary data collected from various sources; the recorded landslides were also verified through field surveys and satellite imagery.

In order to develop an accurate and reliable landslide susceptibility map, the project area (165 km^2) was reduced to the extent of available secondary data (60 km^2) which will hereafter be called as study area. The study area had experienced various types of landslides, including fall, topple, slide and complex; however, majority of the landslides were rotational. A landslide inventory map was prepared in ArcGIS having 12.5 m resolution (see Figure 1).

3.2 *Landslide Causative Factors*

The spatial distribution of landslides is mainly governed by factors such as topography, geology, seismicity, weather conditions and land cover/use. Accordingly, a total of nine landslide causative factors, including slope gradient, slope curvature, slope aspect, geology, rainfall, distance to faults, distance to streams, roads and settlements, and vegetation cover were selected. The maps of all these parameters were developed in ArcGIS having same 12.5 m resolution.

3.2.1 *Slope Gradient*

Slope gradient controls the shear stresses acting on a slope; the steeper the slope, the larger the shear stresses and hence a higher probability of landslide occurrence. The gradient raster was derived from Advanced Land Observation Satellite (ALOS) Digital Elevation Model (DEM) in ArcGIS. The gradient raster was divided into three classes: 0º to 20º, 20º to 40º and 40º to 60º (see Figure 2A).

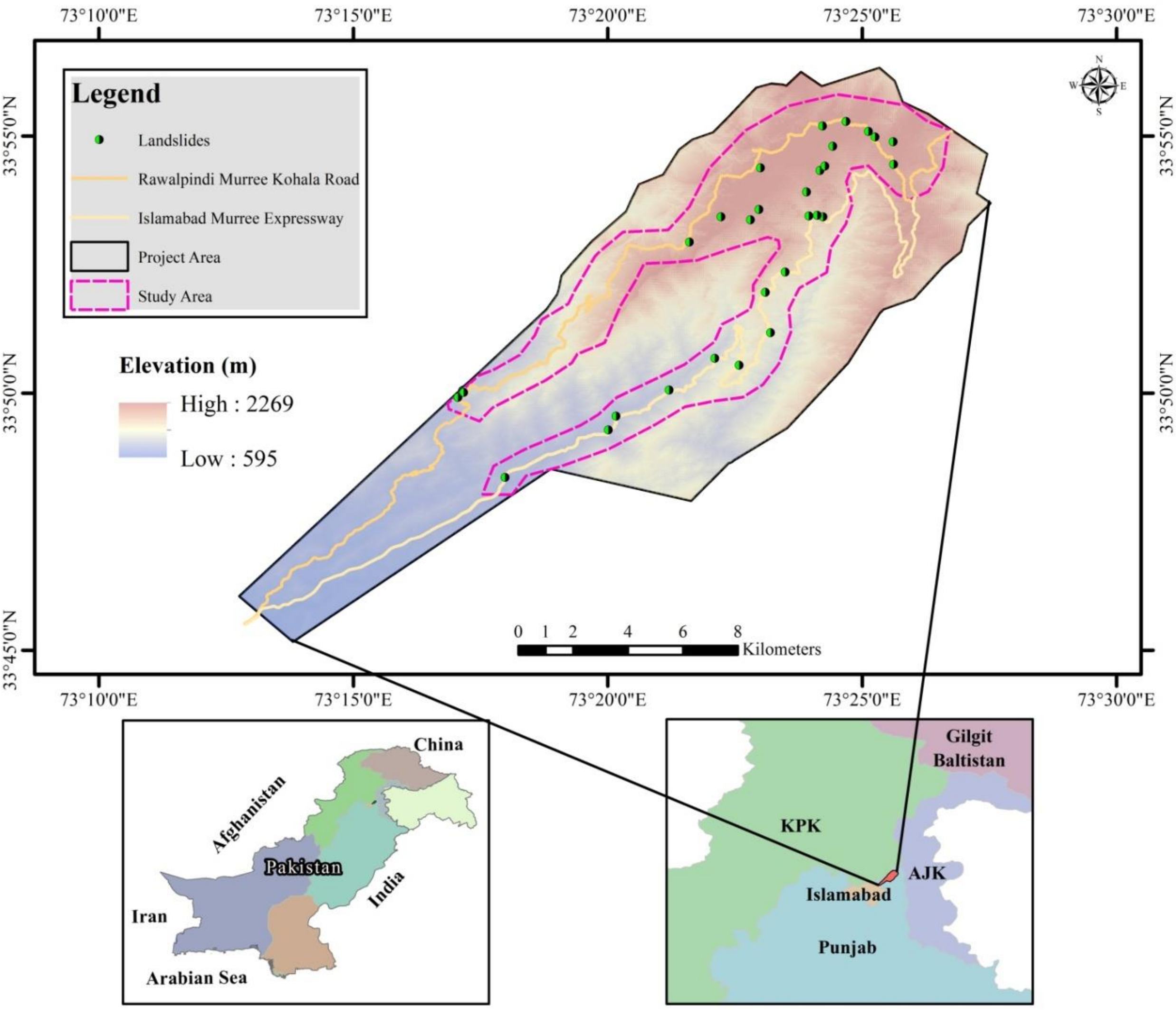

Figure 1. Project Location and Landslide Inventory Map

3.2.2 *Slope Curvature*

Slope curvature can have a significant effect on safe slope angles as it influences the convergence and divergence of water flow. A positive curvature indicates that the surface is upwardly convex at that cell. A negative curvature indicates that the surface is upwardly concave at that cell. A value of zero indicates that the surface is flat. The curvature raster was derived from ALOS DEM in ArcGIS and was divided into three classes: -15 to -1, -1 to 1 (flat slope) and 1 to 15 (see Figure 2B).

3.2.3 *Slope Aspect*

Slope aspect is the orientation of the slope face, measured clockwise from the north. It determines slope exposure to sunlight, wind and rainfall. In addition, structurally controlled failures in rock slopes depend upon the orientation of slope face with respect to the orientation of discontinuities. The aspect raster was derived from ALOS DEM in ArcGIS and was divided into nine classes: -1º to 0º (flat slope), 0º to 45º, 45º to 90º, 90º to 135º, 135º to 180º, 180º to 225º, 225º to 270º, 270º to 315º and 315º to 360º (see Figure 2C).

3.2.4 *Geology*

Geology is one of the most important landslide causative factors as each type of material has distinct shear strength and permeability characteristics and hence a different likelihood of landsliding. The geological map of the study area was prepared by digitizing the regional geological map available at 1:50,000 scale, published by Geological Survey of Pakistan.

The study area contains four lithological units, namely Alluvium, Chorgali formation, Kuldana formation and Murree formation (see Figure 2D). The rocks present in all the units are intensely folded, faulted and sheared mainly due to the close proximity of Main Boundary Thrust (MBT) and Jhelum fault.

The alluvium is loose, moderately sorted stream deposits of gravel, sand, silt and clay. The Chorgali formation of Eocene age consists of shale and limestone. It is divisible into two distinct units. The lower unit comprises dolomitic limestone and shale. The dolomitic limestone is white to light grey and yellowish grey and medium-bedded while the shale is grey to greenish grey, calcareous and occurs as interbeds in the upper part of the unit. The upper part of the formation is composed predominantly of shale with one thick bed of dark grey limestone and a bed of nodular argillaceous limestone near the top. The shale is greenish grey, red, occasionally variegated and calcareous. Some grit beds are also intercalated. The Chorgali formation is conformably overlain by Kuldana formation.

The Kuldana formation of Eocene age consists dominantly of vari-coloured gypsiferous and arenaceous shale and brown to grey, gypsiferous marl, interbedded with red sandstone and calcareous conglomerate. It is disconformably overlain by Murree formation. The Murree formation of Miocene age is a monotonous sequence of dark red and purple shale and purple grey and greenish grey sandstone. The shale is characterized by a splintery nature, presence of fracture cleavage and tension gashes. The sandstone, though very abundant, is nevertheless subordinate to shale. It is fine to medium grained, thickly-bedded, cross-bedded, jointed and calcareous. Throughout its extent the Murree formation unconformably overlies various formations of Eocene age.

3.2.5 *Rainfall*

Intense and prolonged rainfall can trigger landslides as it increases pore water pressure within the slope and thereby reduces effective stress and hence shear strength of the slope material. The Murree features a subtropical highland climate receiving more than 1700 mm of average annual precipitation. The rainfall data in the form of mean annual rainfall (MAR) of various stations that surround the study area was collected from Pakistan Meteorological Department (PMD). The data showed that spatial distribution of rainfall within the study area had a clear correlation with the elevation (the higher the elevation of the area, the higher the MAR) mainly owing to the orographic lifting phenomenon. Accordingly, rainfall zonation map of the study area was developed having three elevation classes: < 1000 m having MAR = 1500 mm, 1000 m to 1500 m having MAR = 1700 mm and > 1500 m having MAR = 1800 mm (see Figure 2E).

3.2.6 *Distance to Faults*

The proximity of a slope to a fault or fault zone increases the likelihood of instability as the rocks near the fault zones are weaker due to tectonic deformation. Main Boundary Thrust (MBT), one of the major Himalayan thrusts and Jhelum fault are amongst the most significant tectonic features of the area. The fault map was prepared from the regional geological map of the area. The distance from faults was divided into five classes: 0 m to 1500 m, 1500 m to 3000 m, 3000 m to 4500 m, 4500 m to 6000 m and > 6000 m (see Figure 2F).

3.2.7 *Distance to Streams*

Streams can cause slope instabilities due to various reasons, including slope erosion and saturation. The Korang River is a major stream in the study area that originates from Murree hills and flows towards Islamabad. It crosses Islamabad Murree Expressway from between Korang Town and Judicial Colony. In addition, there are many small streams in the study area that flow downhill and end up in the Korang River. The stream network map was derived from ALOS DEM in ArcGIS software. The distance from streams was divided into four classes: 0 m to 100 m, 100 m to 200 m, 200 m to 300 m and > 300 m (see Figure 2G).

3.2.8 *Roads and Settlements*

In hilly terrain, human activities such as construction of roads and settlements which lead to deforestation, undercutting the bottom and loading the top of a slope, etc. can initiate slope instability. The map showing roads and settlements built within the study area was prepared by digitizing high resolution Google Earth Image of November, 2016 and was categorized into three classes: roads, settlements and others (see Figure 2H).

3.2.9 *Vegetation Cover*

Vegetation cover has a significant influence on slope stability. The slopes covered with thick vegetation are often more stable compared to the barren slopes because vegetation cover with strong root system reduces erosion and holds the slope together. The vegetation cover map of the study area was prepared by digitizing high resolution Google Earth Image of November, 2016. The vegetation cover was divided into two classes: non-vegetative areas (areas having sparse or no vegetation, including barren land, roads and settlements) and vegetative areas (areas having thick vegetation) (see Figure 2I).

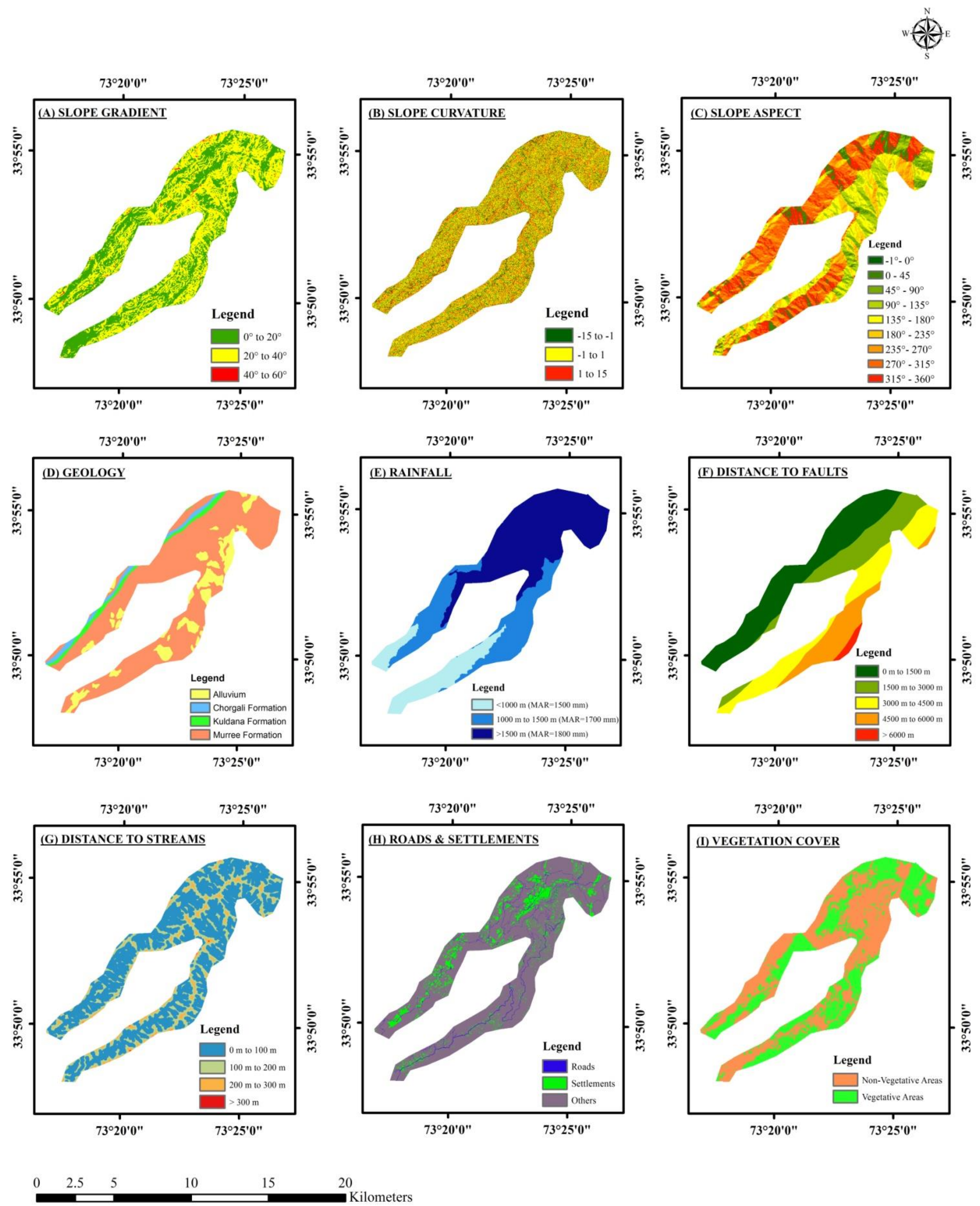

Figure 2. Landslide Causative Factors Map

4 LANDSLIDE SUSCEPTIBILITY MAPPING USING FREQUENCY RATIO METHOD

Landslide susceptibility mapping was carried out by one of the simplest and widely used bivariate statistical frequency ratio (FR) method in ArcGIS (Reis et al., 2012; Chen et al., 2016; Wang and Li, 2017). The FR quantifies the relation between landslide occurrence and each landslide causative factor.

Firstly, each landslide causative factor map was divided into different classes as defined in section 3.2 and numbers of pixels of each class were calculated. Secondly, landslide inventory map was combined with each landslide causative factor map separately and then numbers of landslide pixels in each factor's class were calculated. Then, frequency ratio of each factor's class was calculated using Eq. 1 (Mondal and Maiti, 2013):

$$FR_j = \frac{N_{ij}/N_{total}}{A_{ij}/A_{total}} \quad (1)$$

where:
- FR = the frequency ratio of each factor's class
- N_{ij} = the number of landslide pixels in jth class of factor i
- N_{total} = the total number of landslide pixels in the study area
- A_{ij} = the number of pixels of jth class of factor i
- A_{total} = the total number of pixels in the study area

The FR value indicates the degree of relation between the landslide and a certain class of the landslide causative factor; FR = 1 is an average value, FR > 1 indicates a stronger relation and hence high probability of landslide occurrence and FR < 1 represents a weaker relation and hence a low probability of landslide occurrence (Akgun et al., 2007); see Table 1.

The frequency ratio (FR) map of each landslide causative factor was prepared in ArcGIS by assigning the calculated FR values. Then the FR maps were overlaid and numerically added using the raster calculator of the spatial analyst tool in ArcGIS to compute landslide susceptibility index using Eq. 2 (Lee and Talib, 2005) and generate landslide susceptibility map; the map is shown in Figure 3:

$$LSI = FR_1 + FR_2 + FR_3 + \cdots + FR_n \quad (2)$$

where:
- LSI = the landslide susceptibility index at each pixel of the study area
- FR = the frequency ratio of a certain class of each factor at the pixel
- n = the total number of factors

The resulting landslide susceptibility map was then reclassified into three landslide susceptibility classes: low, moderate and high.

5 RESULTS AND DISCUSSION

Table 1 shows frequency ratio (FR) values for each class of all landslide causative factors. More than 99 % of the slopes present in the study area fall within two gradient classes, i.e. 0º to 20º and 20º to 40º; the computed FR values indicate that steeper slopes with slope gradient ranging from 20º to 40º have higher probability of landsliding compared to relatively gentle slopes with slope gradient between 0º and 20º. The concave slopes are more susceptible to instability having FR of 1.09 because soils on concave slopes preserve more rain water compared to convex or flat slopes. In case of slope aspect, aspect classes 135º to 180º and 180º to 225º have higher FR values of 1.81 and 1.65, respectively in comparison to other aspect classes indicating that south-east, south and south-west slopes have higher probability of landsliding; this is owing to the fact that in Murree, southern slopes are mostly bare or have sparse vegetation while northern slopes have dense vegetation (forest).

Table 1 shows that Murree formation which is a series of predominant shale with subordinate sandstone is more susceptible to slope instability as compared to other geological units; the shale is very weak to weak and gets further weaken on wetting and unloading. The high rainfall zone that lies above 1500 m elevation with MAR = 1800 mm has highest FR value of 1.73; 90 % of the recorded landslides occurred in high rainfall zone which shows that rainfall is one of the major landslide triggering factors in Murree hills. The area in the vicinity of streams, i.e. 0 m to 100 m is vulnerable to slope instability having FR value of 1.27 and containing about 90 % of the recorded landslides; this can be attributed to slope erosion and saturation caused by stream flow. The landslide susceptibility is higher at a distance to faults ranging between 1500 m and 3000 m as indicated by FR value of 2.95 and then decreases as the distance increases.

A higher FR value of 1.67 is observed in case of settlements indicating that populated areas are prone to instabilities. In case of vegetation cover, non-vegetative areas have higher FR value of 1.31, while vegetative areas have lower FR value of 0.59 because vegetation binds soil together with their root system and hence impart stability to the slope.

The computed FR values were added in ArcGIS to compute landslide susceptibility index (LSI) at each pixel of the study area (see Eq. 2). The LSI values range between 4.56 and 14.29.

These values were classified into three landslide susceptibility classes to generate landslide susceptibility map: low, moderate and high (see Figure 3). The results show that 43.6 % of the study area falls in low susceptibility class, whereas moderate and high susceptibility classes cover 48.2 % and 8.2 % of the study area, respectively.

6 CONCLUSIONS

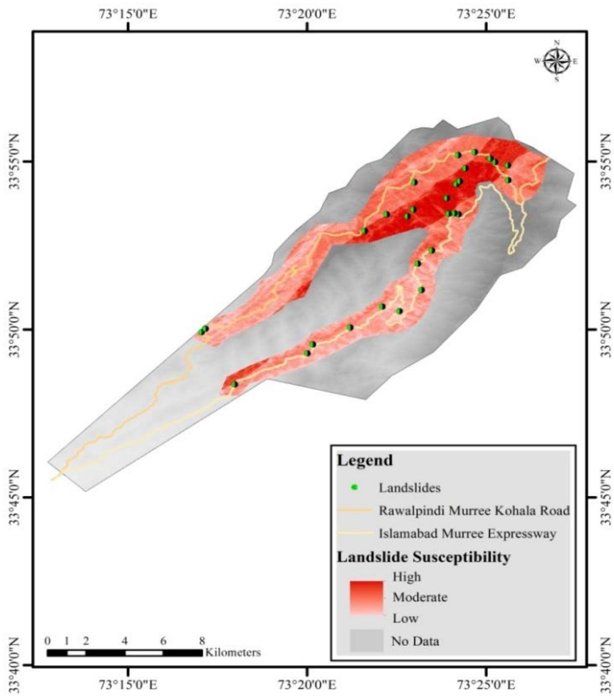

Figure 3. Landslide Susceptibility Map

In this study, the relationship between landslide inventory and landslide causative factors, including slope gradient, slope curvature, slope aspect, geology, rainfall, distance to faults, distance to streams, roads and settlements, and vegetation cover was evaluated using bivariate statistical frequency ratio (FR) method in ArcGIS to prepare landslide susceptibility map. The

Table 1. Frequency Ratio for Each Class of all Landslide Causative Factors

Landslide Causative Factors	Classes	Number of landslide pixels in a class (Nij)	Total number of landslide pixels in the study area (Ntotal)	Number of pixels of a class (Aij)	Total number of pixels in the study area (Atotal)	Frequency ratio (FR) of a class FR = (Nij/Ntotal) / (Aij/Atotal)
Slope Gradient	0º to 20º	2059	5615	182252	390847	0.79
	20º to 40º	3512		205351		1.19
	40º to 60º	44		3244		0.94
Slope Curvature	-15 to -1	1341	5615	85352	390847	1.09
	-1 to 1	3205		219450		1.02
	1 to 15	1069		86045		0.86
Slope Aspect	-1º to 0º	15	5615	2501	390847	0.42
	0º to 45º	249		26001		0.67
	45º to 90º	218		28022		0.54
	90º to 135º	834		53208		1.09
	135º to 180º	1529		58928		1.81
	180º to 225º	829		34877		1.65
	225º to 270º	197		48705		0.28
	270º to 315º	938		80841		0.81
	315º to 360º	806		57764		0.97
Geology	Alluvium	225	5615	58666	390847	0.27
	Chorgali Formation	0		14271		0.00
	Kuldana Formation	0		17821		0.00
	Murree Formation	5390		300089		1.25
Rainfall	< 1000 m (MAR = 1500 mm)	313	5615	68853	390847	0.32
	1000 m to 1500 m (MAR = 1700 mm)	265		118879		0.16
	> 1500 m (MAR = 1800 mm)	5037		203115		1.73
Distance to Faults	0 m to 1500 m	1421	5615	148505	390847	0.67
	1500 m to 3000 m	3550		83754		2.95
	3000 m to 4500 m	416		94431		0.31
	4500 m to 6000 m	228		57651		0.28
	> 6000 m	0		6506		0.00
Distance to Streams	0 m to 100 m	4957	5615	272078	390847	1.27
	100 m to 200 m	658		100275		0.46
	200 m to 300 m	0		18216		0.00
	> 300 m	0		278		0.00
Roads and Settlements	Roads	345	5615	49169	390847	0.49
	Settlements	249		10353		1.67
	Others	5021		331325		1.05
Vegetation Cover	Non-Vegetative Areas	4191	5615	222041	390847	1.31
	Vegetative Areas	1424		168806		0.59

computed FR values indicate that rainfall, geology and distance to streams are one of the most influential factors, controlling the spatial distribution of landslides in the study area. The non-vegetative and urbanized areas are also susceptible to slope instabilities.

The landslide susceptibility map indicates that northern part of the study area is more susceptible to landslides mainly because of higher mean annual rainfall and settlement density. The landslide susceptibility map would help the administrators for safer planning of new developments.

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