Landslide Susceptibility Mapping of District Ghizer, Gilgit Baltistan

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FINAL APPROVAL

It is certificate that we have read the thesis titled as "**Landslide susceptibility mapping of district Ghizer, Gilgit Baltistan**" submitted by Ms. Irum Rahim and it is our judgment that this project is of sufficient standard to warrant its acceptance by the International Islamic University, Islamabad for the M.S Degree in Environmental Sciences.

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DEDICATION

This thesis is dedicated to my parents, whose words of encouragement and pushes for tenacity holds me up. I will always appreciate all they have done.

DECLARATION

I hereby declare that the work present in the following thesis is my own effort, except where otherwise acknowledged and that the report is my own composition. No part of this thesis has been previously presented for any other degree.

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CONTENT

ACKNOWLEDGMENT

In the name of Allah, the most Merciful, the most Gracious. All praise is due to Allah; we praise him, seek His help, and ask for His forgiveness. I am thankful to Allah, who supplied me with the courage, the guidance, and the love to complete this research.

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Many thanks, to my friends and family for supporting and helping me throughout my studies and thesis.

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LIST OF ABBREVIATIONS

Acronym	**Abbreviations**
AHP	Analytical Hierarchy Process
CI	Consistency Index
CKNP	Central Karakoram National Park
CR	Consistency Ratio
DEM	Digital Elevation Model
GB	Gilgit Baltistan
GIS	Geographic Information System
GLOF	Glacial Lake Outburst Flood
GPS	Global Positioning System
ICIMOD	International Centre for Integrated Mountain Development
IDW	Inverse Distance Weighted
LSI	Landslide Susceptibility Index
LULC	Land Cover Land Change
PFRV	Prioritized Factor Rating Value
RI	Random Consistency Index
RS	Remote Sensing
SPI	Stream Power Index
TWI	Topographic wetness Index
WLC	Weighted Linear Combination

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Abstract

District Ghizer as a rugged mountainous territory experiences several landslide each year, there are sixteen major landsliding areas and thirteen small villages prone to rock fall, consequently as a whole 53 villages are considered to be at high risk to hazards in district Ghizer. Therefore, this study focuses on the susceptibility mapping of landslides based on twelve causative factors, to identify major landslide prone areas of the district Ghizer, using Analytical Hierarchy Process (AHP) and GIS. Soil sampling of the study area was carried to determine soil texture, and data for other factors were acquired from freely available sources. Further a temporal assessment of land cover change was studied for the years 1999 and 2015, to assess the impact of land cover change on landslides. 74.38% of the total area in district Ghizer lies in moderate to very high susceptible zones. The temporal assessment of land cover change indicated that the land cover classes barren soil/ exposed rocks and glaciers have reduced while the vegetation and water classes have shown increment. In this study, observed landslide sites were used to validate the susceptibility map, which showed 88.1% of the landslides have occurred in the moderate to very high susceptible zones.

Abstract

The Gilgit Baltistan region located within the highest mountains of the world is predominantly susceptible to landslides. In this regard, Landslide susceptibility mapping helps in identifying the landslide prone areas. Therefore, this study focuses on generating a landslide susceptibility map for the district Ghizer, using Analytical Hierarchy Process (AHP) and GIS. In this research, twelve factors were considered for the susceptibility mapping: slope, aspect, elevation, drainage, SPI, TWI, lithology, distance from fault lines, rainfall, distance from roads, land cover and soil texture. Soil sampling of the study area was carried to determine soil texture, and data for other factors were acquired from freely available sources. Further a temporal assessment of land cover change was studied for the years 2002 and 2015, to assess the impact of land cover change on landslides. The results showed that moderate and high susceptible zones comprised of 28.14% and 28.22% area. While the very high susceptible zones covers an area of 18.02%. Additionally, the low susceptible zone covers 16.96% and the very low zone covers 8.66% of the area in district Ghizer. The temporal assessment of land cover change indicated that the land cover class "barren soil/ exposed rocks" has largely increased from 41.34% in 2002 to 78.46% in 2015, which is the highest landslide susceptibility class. In this study, 34 observed landslide sites were used to validate the susceptibility map, and the validation result showed that the highest landslide frequency in the very high landslide susceptibility zone that was 38.2%.

1.0. INTRODUCTION

Landslides are the major natural destructive disasters in the mountainous or hilly regions (Ayala *et al.*, 2006). Landslides are described as "the rock, debris, or mass movements of earth downward a slope" (Cruden, 1991). Different types of slope movement are described as landslides such as falls, topples, slides, spreads, and flows. Based on geological material these are more subdivided into (bedrock, debris, or earth). Debris flows and rock falls are considered frequent slope movements (Cruden and Varnes, 1996). Landslides are described by Varnes (1958) as "downhill and outer movement of natural rock, soils, artificial fills or combinations of these materials". While Terzzghi (1950) expresses; "landslides is rapid dislocation of rock, residual soil or sediments adjacent to a slope and center of gravity of moving the mass advances in a downward and out ward direction". Furthermore, Hutchinson (1995) puts in plain word landslides as "relatives swift down slopes movement of soils and rock, which take place typically on or more, distinct bounding slip surfaces which define the moving mass".

Landslides be capable of travel unhurriedly, or be able to travel rapidly and dreadfully, like debris flows. The slope gradient, water quantity, debris amount, and form of soil and debris in the run affect the speed of debris flow movement (Cruden and Varnes, 1996). In spite of the fact that, it is still hard to anticipate a landslide occasion in space and time, a range might be positioned by level of potential risk from landslide keeping in mind the end goal to conceivably minimize harm (Saha *et al.*, 2005).

With particular reference to high seismicity, the mountainous regions are predominantly prone to natural hazards (Billington *et al.*, 1977). In these regions, earthquakes, landslides, snow avalanches and flash floods are the most frequent types of geological hazards, therefore only small portions of the area are appropriate for life and the local people are in turn, forced to live in dangerous zones.

Landslides are caused as a result of numerous factors such as rain, earthquake, volcanic actions, erosion, and instability of slope. Sidle and Ochiai (2006) analyzed and separated likely landslide factors into five categories i.e. seismicity strength, chemistry, mineralogy of soil, geology, geomorphology and hydrology. The Landslide is consequence of multifarious interaction within various factors such as meteorological, geomorphological and geological. The spatial information associated with mentioned factors be able to extract from remote sensing facts, land based information, along with quite a lot of other data resources (Sarkar and Kanungo, 2002). Dai and Lee (2002) recommended assembling landslide triggering factors into preliminary factors and triggering factors.

Landsliding is a phenomenon associated to slopes. If the slope angle is steep there could be more chances of landsliding. For that reason it is considered as a major factor in susceptibility mapping (Ayalew *et al.*, 2005). As indicated by Lee and Min (2001) the major factor in the slope instability is its degree or extent. In landslide susceptibility mapping the highest rank is usually set to slope (Pradhan, 2011). The direct association of slope with landslides is supported by many studies (Saha *et al.*, 2005).

The aspect is the expression of solar insolation (Calligaris *et al.*, 2013), wind direction, intensity of rainfall (Liu and Shih, 2013), and favors erosion of the slopes facing the sun. The different amount of solar radiation received by different slopes may result in differences in soil temperature, moisture and soil thickness. The slopes can develop unique gradients and soil cover characteristics, because of weathering and erosion that differentiate the exposed north-facing slopes from the more shaded south-facing slopes.

The altitude of a region is associated with slope, lithology, precipitation, soil type, tectonics and land use. The strong relationship between landslide events and elevation is mentioned in various researches (Dai and Lee, 2002; Long, 2008). These studies illustrate that, high elevated hilly regions frequently experience slope failure more than the low elevated regions (Kayastha, 2007). Weather and climate conditions differ to a great extent at different elevations, which cause differences in the soil types and vegetation cover (Aniya, 1985). The freeze–thaw processes cause weathering of rocks at high altitudes, whereas lower altitudes tend to facilitate thicker unconsolidated sediments to be formed (Dai and Lee, 2001).

In general, if the distance to river or drainage network is less, water level will increase which may cause landslides, because streams may have negative effect on slop stability, which can cause erosion of the slopes and saturation (Ercanoglu *et al.*, 2004). Stream networks drastically impact fluvial processes and bedrock openings in high seismic mountain ranges. The distance from main perennial channel too plays a vigorous task in assessing landslide susceptibility hazards. Drainage networks can cause erosion because of torrential activities which results in landslide susceptibility. The drainage networks close to the slope is also a significant factor in terms of stability.

Topographic Wetness Index (TWI) is used to study the effects of topography of an area on hydrological processes and associated to soil moisture and surface flow. Moore *et al.*, (1991) expresses TWI as:

$$\text{TWI} = Ln\left(\frac{\alpha}{\tan\beta}\right) \qquad (1.1)$$

Where 'α' is the catchment area and β is slope.

The stream power index (SPI) is a force of a stream to cause erosion. Moore *et al.*, (1991) express SPI as:

$$\text{SPI} = As \times tan\beta \qquad (1.2)$$

Where A_s is the catchment area and β is the slope. SPI increases if the slope and catchment area increases which apparently causes erosion. In this way, SPI and TWI are considered to be causative factors in landsliding (Akgun and Turk, 2010).

Geology plays an essential part in slope stability. Geomorphology can be determined through physical characteristics of rocks in that area (Dai *et al.*, 2001). The type and weathering properties of the rocks of an area can affect the cause of landslides. Landslides may significantly command by means of the lithological characteristics of the particular area. Each rock unit possess dissimilar landslide susceptibility rate, therefore these rock units are essential in landslide susceptibility mapping. This predicts, to categorize the rock units accordingly (Mejia-Navarro and Garcia, 1996). The structure and composition of every rock type is different. Hence the weaker lithological formations are susceptible to landslides, while the stronger lithological formations are less susceptible or resistant to landslides (Daneshvar, 2015).

Seismicity can also cause mass movements by generating vibration, which may lead to failure by increasing the downhill stress or by decreasing the internal strength of the hill slope sediments through particle movement. In general, earthquakes with magnitudes 4.0 or bigger are often sufficient to cause landslides. Fault lines are one of the main factors in triggering landslides. The distance to fault lines is a key factor in slope instability in the hilly slopes (Hessami and Jamali, 2006).

Runoff is another most important factor which causes slope instability. In Extended wetter periods there is an increased chance of slope failures. For this reason rainfall is a significant landslide triggering factor. Landslides are common in the areas with steep slopes and heavy rainfall. As well as most of the landslides are observed after rainfall. The heavy rainfall causes infiltration of water which saturates the soil quickly and causes landsliding (Pourghasemi *et al.*, 2009).

Distance from road has been well thought-out as an environmental factor, which can cause landslide because of road constructions (Ayalew and Yamagishi, 2005). Other than natural causes, the distance to road factor shows the landslide can be caused by human actions as well (Pourghasemi *et al.*, 2009). Furthermore, landslide could occur on the divided slopes by roads causing instability (Nielsen *et al*, 1979). Recent studies suggest that the vibrations caused by cars in the slopes which are cut for road constructions are susceptible to landslides (Mittal *et al.*, 2008).

The categorization of land into types of woods, rangeland, grassland residential area and cultivated land in an area is described as land cover (Dai *et al*, 2001). Land cover is not a direct link to slope stability (Anbalagan and Singh, 2001). Thin vegetation in an area may enhance the cause of weathering and erosion in that particular area. According to literature the soil/rock short of vegetation cover are more prone to landsliding and erosion because of the greatest contact to weathering agents (Intarawichian and Dasananda, 2010). In general it is thought that areas covered with vegetation are less prone to landslide. The landslides events are inversely linked to the vegetation density (Kanungo *et al.*, 2006).

The landslide events are affected by loose soil cover up resting on the slopes. The clayey soil has fine texture and possesses small pores and hence, has slow water liberating potential. In clayey soils water saturation is high as compare to sandy soils. Consequently, the mass of clayey soil increases by the accumulation of water which makes it more susceptible to landslide, Porosity of a soil tells the soil texture. The clayey soil is less porous and has lesser permeability. While silt and sandy soil, are more porous and have high permeability than clayey soil. That makes clayey soil more exposed to landslides (Wati *et al.*, 2010). Thus, soil with less permeability gets a more chance of landslide.

Landslide is one of the hazardous natural processes. According to many reported Landslides, it had not only caused damage to infrastructure but also lead to loss of life (Cheng *et al.*, 2007). For this reason, landslide susceptibility mapping is required in favor of recognition of landslide prone areas. Landslide susceptibility maps illustrate the comparative possibility of future landsliding based exclusively on the fundamental properties of a setting or site. Mapping of landslide- or rock fall-prone areas should be helpful to recognize the areas, where human settlements must be avoided, and as a result it provides to the stakeholders a significant updatable tool for territorial planning (Guzzetti *et al.*, 2012). Effective planning and management will lessen the social and economic losses due to landslides (Rajakumar *et al.*, 2007).

Different software's are found to be beneficial in the mapping of landslides. One such kind is Geographic Information Systems (GIS) for the assimilation of different types of data. GIS is generally described as "an influential set of tools for collecting, storing, retrieving at will, displaying, and transforming spatial data". Significant developments have been made to GIS over past years for spatial data analysis. GIS is a helpful tool for susceptibility mapping (Carrara *et al.*, 1999).

Spatial data of diverse layers can be integrated with the help of GIS, to find out influence of the factors on landslide occurrence. According to Scaioni (2013) and Qiao *et al.*, (2013) the ease of access and range of remote sensing data and thematic layers as causative factors using GIS has made it possible to map landslide susceptibility. Remote Sensing (RS) can play a part in the creation of thematic maps associated to landslide occurrences. The remote sensing and GIS based landslide susceptibility mapping was studied by (Kanwal *et al.*, 2016; Mancini *et al.*, 2010). Remote sensing is actually the science of acquiring information about the surface of earth without actually being in contact with it, which is on the second-hand used for monitoring and mapping of landslides (Akbar and Ha, 2011).

The quantitative strategy, Analytical Hierarchy Process (AHP) proposed by Saaty (1980) takes into account deterioration, similar judgment, and combination of needs is regularly helpful for susceptibility studies. The factors are arranged hierarchically and numerical value is given to every factor. In this manner the factors are combined and every factor is assigned by importance (Sahnoun, 2012). Aside from that, reciprocal pair-wise comparison network is set up to use AHP. In the comparison matrix every factor is assigned a value from 1-9 as created by Saaty. After the weights acquired from AHP, the Weighted Linear Combination (WLC) is used for combining all the factor maps into a landslide susceptibility index.

In Karakoram Mountains eight various types of mass movements have been observed, rock falls, avalanche, rockslides, debris flow, flow slides, rotational slip, slumps and creep (Owen, 1996). Among these debris flow and flow slides are the most prevailing and frequent type of the mass movement noted in Karakoram. Debris flow is abrupt mass movement which

2.0. Materials and Methods

2.1. Study Area

The district Ghizer lies in Hindu Kush region of Pakistan in the northern part of Gilgit-Baltistan, between latitude 36.2797° N and longitude 73.2765° E covering an area of 12042 km² (Fig.2.1). The population of district Ghizer was estimated at 121278 (1998 censuses). The region involves four Tehsils i.e. Gupis, Ishkoman, Punial and Yasin. The estimate terrain elevation above sea level is 3661 meters. The habitat of the district is arid to semi-arid. The area is prone to different natural disasters such as floods, debris/mud flow, land/rock slides, and GLOF. Moreover, snow avalanches, landslides and earthquakes are also frequent in the area (Pakistan GLOF report, 2014). The valleys are present in steeps hills and accessibility to most of the remote villages is poor. The villages in upper parts of the region get isolated for several months in the winter season because of heavy snow fall, landslides and snow avalanches. The drainage network in the area is very vast as the area is covered with glaciers. Various stream and waterways originate from the high steep mountains which apparently join the river Indus.

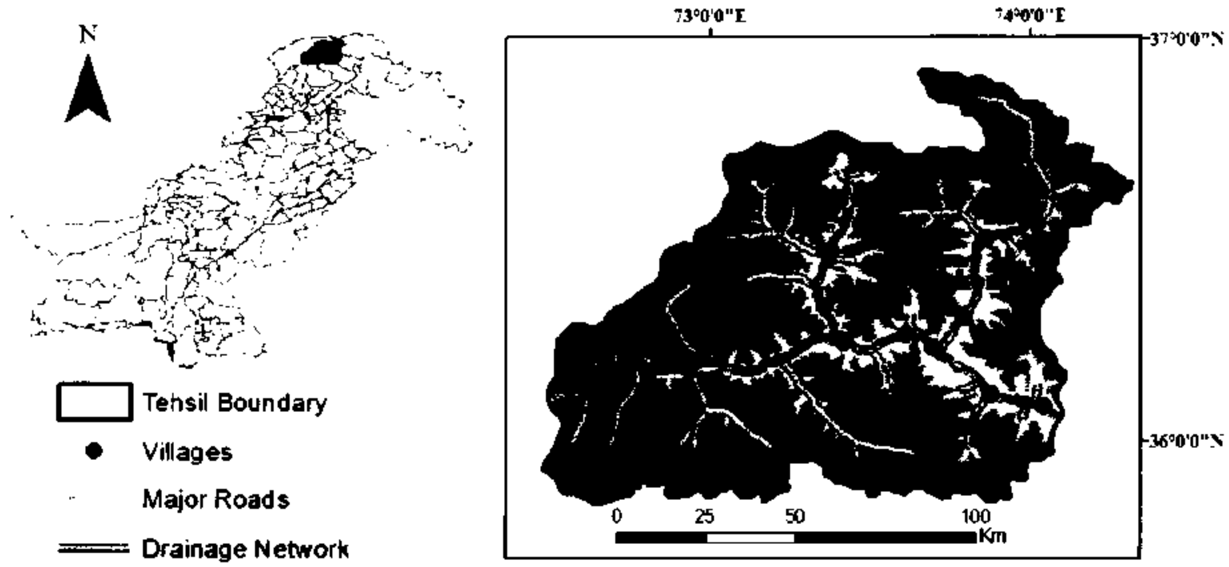

Figure 2.1: Map of Study Area

Hindukush mountain region is considered as seismically active zone because of the occurrence of low intensity earthquakes at frequent intervals. Various fault lines spread through entire Gilgit Baltistan region. Low to medium intensity earthquakes is frequent, which are may cause by intense rainfall on unconsolidated steep hills (Chevalier *et al.*, 2013). They can cause damage to human life and property in mountainous areas, particularly in regions with increased spontaneous development activities.

The Himalaya, Hindukush and Karakoram ranges consist of very high mountain peaks covered by snow and most of the northern part of Pakistan is located in these mountains. The steep relief, snow and glaciers, in the region are exceptional but strong precipitation and a high seismicity contributes to the origin of widespread natural processes like debris flow, flash floods, earth quakes, rock fall or landslides (Karim, 2006).

According to Khan *et al.*, (2011) Hindu Kush Karakoram Himalaya (HKKH) region is facing increased flash flood and related hazards. The HKKH Mountains are especially prone to hydro geological disasters, such as flash floods, landslides, and Glacial Lake Outburst Floods (GLOFs). Gilgit Baltistan (GB) is comprised of a rugged mountainous topography where mountains comprise 90% out of total 72496 sq. km area .The entire Gilgit Baltistan region, where the Central Karakoram National Park (CKNP) lies, is predominantly susceptible to landslides, lakes formation and GLOF.

1.1. Objectives

- To derive main landslide causative factors in the study area.
- To generate GIS based landslide susceptibility map from thematic data layers.
- To study the temporal assessment of land cover change for past years and its impact on landslides.

mainly held responsible for the occurrence of GLOF, avalanche, rock fall, edge failure and landslides in the study area.

The road and the area along the right bank of the river Ghizer to Gilgit is highly susceptible to landslides because of erosion and rock fall as the slopes are made of muddy dust and loose sediments. In the months of March to April and July to September the road to Gahkuch passing all the way through various villages, is prone to landslides and rock fall because of water seepage. There exists sixteen major landsliding areas and thirteen small villages prone to rock fall so, as a whole 53 villages are considered to be at the high risk to hazards in the district Ghizer (Pakistan GLOF report, 2014).

2.2. Data Acquisition and Preparation of Causative Factors

In this study, the landslide susceptibility map was prepared from twelve factors: slope, aspect, elevation, drainage, SPI, TWI, lithology, fault lines, rain fall, roads, land cover and soil. The selection of the factors was based on their effectiveness and availability. According to Oh and Pradhan (2011) the assessment of the local landslide areas should be convenient and relevant and the factors should be illustrative and effectively available.

2.2.1. Slope

The slope was extracted from DEM of 30m resolution, acquired from USGS Earth explorer. The slope angle ranges from 0°-73.76° for the study area (Fig.2.2a). Slopes were reclassified in to five classes i.e. very gentle slopes <5°, gentle slopes 5°-15°, moderately steep slopes 15°-30°, steep slopes 30°-45° and escarpments >45°. According to Kanwal *et al.*, (2016) highest landslide susceptible class is 30° - 40° slope angle which consist of steep slopes.

2.2.2. Aspect

The aspect map was prepared from DEM of 30m resolution (Fig.2.2b) and divided in to nine classes based on dimensions, flat (−1)°, north (337.5°–360°, 0°–22.5°), north-east (22.5°–67.5°), east (67.5°–112.5°), south-east (112.5°– 157.5°), south (157.5°–202.5°), south-west (202.5°–247.5°), west (247.5°–292.5°), and north-west (292.5°–337.5°). According to Ahmed *et al.*, (2014) the southwest and northwest facing slopes are highly susceptible to landslides. Ruff and Czurda (2008) suggest assigning higher weights to southwest, west and northwest facing slopes.

2.2.3. Elevation

The lowest point of district Ghizer is at elevation of 1662 m and the highest point of elevation is at 6789m (Fig.2.2c). It was categorized into five classes 1162- 2894m, 2894- 3668m, 3668-4265m, 4265- 4829m, 4829- 6789m. Landslide occurrence is linked to certain elevations (Hatamifar *et al.*, 2012). Ahmed *et al.*, (2014) investigated that 64% of reported landslides were recorded at elevation of 2000-4000m and 24% were observed at elevation of 1000-2000m.

2.2.4. Distance from Drainage Network

The drainage network of the study area was extracted from DEM of 30m resolution. Buffers were created around the drainage network and classified into 0- 500m, 500- 1500m, 1500- 2500m, 2500-5000m and <5100m (Fig.2.2d). Landslides increase if the distance to streams or rivers is decreased, due to slope instability which leads to erosion. Irregularities and fragmentations are caused in a river's longitudinal profile due to slope failures (Ahmed and Rogers, 2014).

2.2.5. Stream Power Index (SPI)

SPI is a secondary attribute extracted from DEM of 30m resolution (Fig.2e). It tells the net erosion and net deposition in the areas of increased flow rate and decreased flow rate (Pourghasemi *et al.*, 2012). Furthermore, landslide susceptibility is higher with the higher SPI values. It was reclassified into four class values -13 - 0, 0 – 5, 5- 10 and 10 – 14.

2.2.6. Topographic Wetness Index (TWI)

It is also a secondary attribute extracted from DEM of 30m resolution (Fig.2.2f). The extent of water accumulation at a place is calculated with TWI, higher TWI values show higher accumulation causing more landslide susceptibility (Pouydal *et al.*, 2010). It was reclassified into three classes i.e. 3-9, 9- 28 and <28.

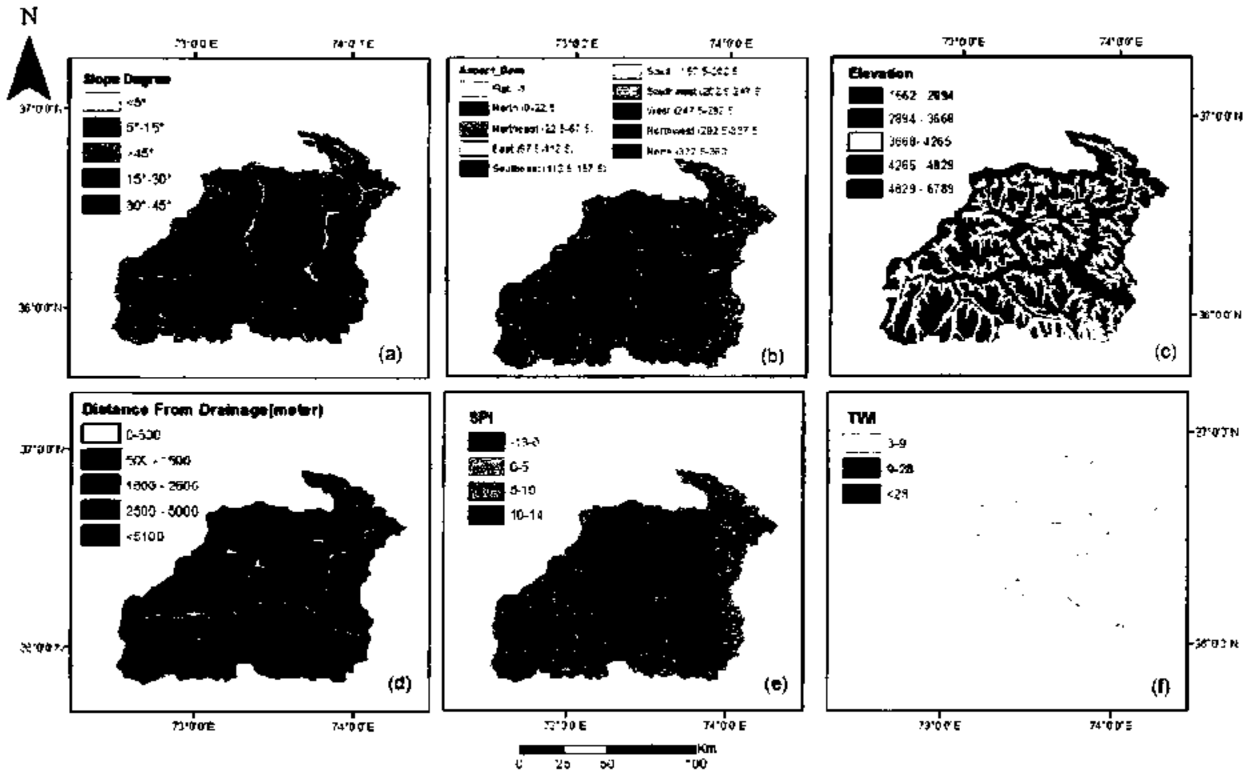

Figure 2.2: Landslide causative factor maps of study area; (a) slope Degree, (b) Aspect, (c) Elevation, (d) Drainage, (e) SPI, (f) TWI

2.2.7. Lithology

Fourteen rock types were identified in the study area from geological map (scale 1:5000, 000) which was acquired from Geological Survey of Pakistan (Fig.2.3a). All the lithological units were categorized in view of their capability to trigger landslide. Each lithological unit has its own susceptibility towards landslides, so it needs to categorize lithological units accordingly (Duman *et al.*, 2006). Ranking of the rock types was based on their stability and potential to cause landslide (Karim, 2006). Detailed information about lithological units is given in Table 2.4 (Appendix).

2.2.8. Distance from Fault Lines

Fault lines were digitized from geological map (scale 1:5000, 000) of study area acquired from Geological Survey of Pakistan (Fig.2.3b). Buffers were created for distances of 0-3000m, 3000- 7000m, 7000- 11000m, 11000- 15000m and <16000m. Shearing causes rocks weak which are close to fault lines, consequently leading to landslide susceptibility (Leir *et al.*, 2004).

2.2.9. Rainfall

Monthly average Rainfall data was acquired for different locations from Tropical Rainfall Measuring Mission (TRMM) for the years 2006 – 2015 (Fig.2.3c). Rainfall is an important landslide triggering factor, but it is limited to the monsoon season (Ahmed *et al.*, 2014). Rainfall raster data map was prepared using the Inverse Distance Weighted (IDW) interpolation.

2.2.10. Distance from Roads

The infrastructure of the study area is poor and no such complex road network exists (Fig.2.3d). Road network data was acquired from an online source www.mapcruzin.com. Buffers were created for roads in the study area at distance of 0-500m ,500- 1500m, 1500- 2500m, 2500-5000m and <5100m. Cutting of slopes for road construction or road widening in the hilly regions could lead to slope failures causing landslide susceptibility (Yalcin, 2008).

2.2.11. Land Cover

Landsat 8 (2015) and Landsat 4-5 TM (1999) satellite images were acquired from USGS Earth explorer. Land cover maps were prepared using supervised classification techniques in ERDAS Imagine 14 (Fig. 2.3e). The classes prepared were glacier, vegetation barren soil/ exposed rocks and water. Land cover images for year 1999 and 2015 were compared for the land cover change and its impact on landslide. Accuracy assessment of the classified images (1999 and 2015) was calculated to check the classification accuracy. The accuracy assessment was generated using 50 random points.

2.2.12. Soil Sampling and Analysis

Soil texture was acquired from primary data of soil and its analysis. Total twelve composite soil samples from each tehsil at different locations were collected, along with the GPS coordinates from the study area. The samples were air dried and sieved through 2mm size sieve. Forty ml of 1% sodium hexa meta-phosphate and 150 ml of distilled water was added to soil sample (40g) and was kept overnight. The mixture was stirred for almost 10 minutes and was put in a graduated cylinder for readings, which was recorded with Boyoucos Hydrometer method (Gee and Bauder, 1986). Soil texture raster map was prepared using the IDW interpolation method. (Fig. 2.3f)

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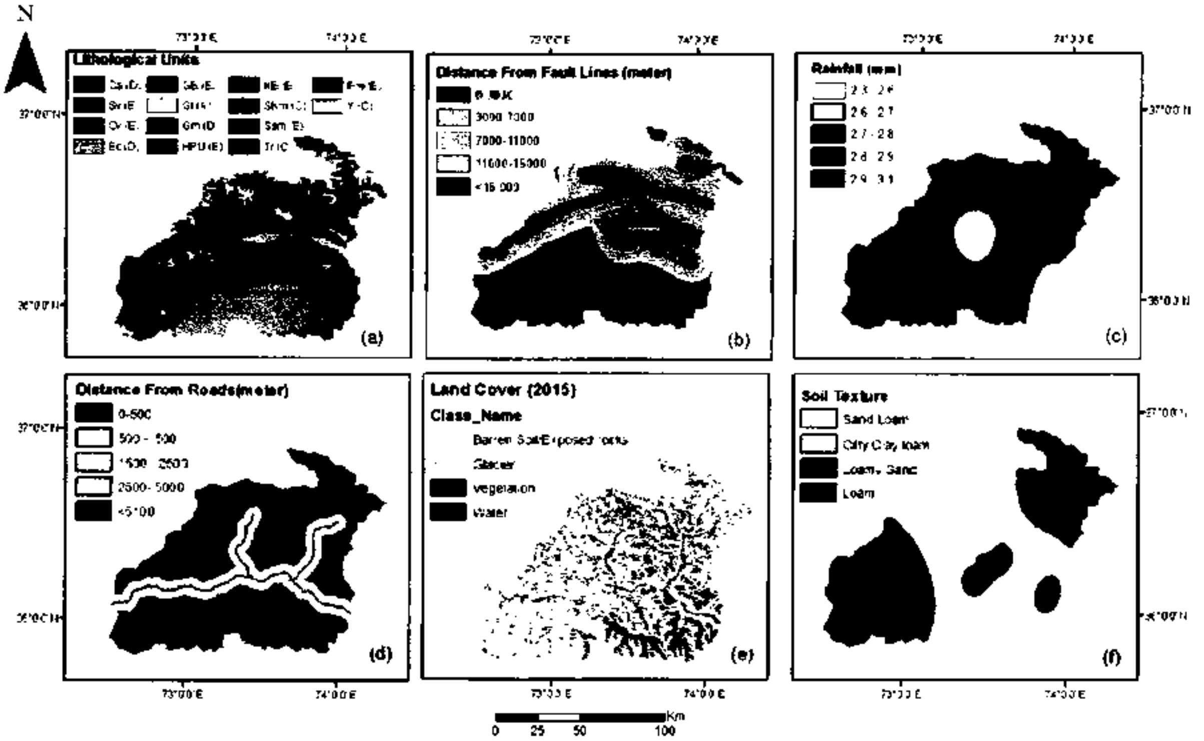

Figure 2.3: Landslide causative factor maps of study area; (a) Lithology, (b) Fault Lines, (c) Rainfall, (d) Roads, (e) Land Lover, (f) Soil

2.3. Data Analysis

2.3.1. Analytical Hierarchy Process (AHP)

The AHP is an adaptable tool which is created by Saaty (1980) and it is used for various decisions makings such as suitability analysis and susceptibility analysis. It is a rational decision making process for multi-criteria as well as for multi-target approach. In the pair wise comparison matrix, the numerical value for each factor was between 1 and 9 (Table.2.1). The factors were organized hierarchically in the matrix and the Prioritized Factor Rating Value (PFRV) technique was used to assign numerical value to the factors in the AHP on the basis of their importance as compare with other factors.

Table 1.1: Saaty's proposed numerical scale.

Scale	Degree of preference	Explanation
1	Equal importance	Contribution to objective is equal
3	Moderate importance	Attribute is slightly favored over another
5	Strong importance	Attribute is strongly favored over another
7	Very strong importance	Attribute is very strongly favored over another
9	Extreme importance	Evidence favoring one attribute is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

The average of the hierarchically arranged factors was used to calculate the weights and rating value/eigenvalue along with the Consistency Ratio (CR), based on the prepositions of (Saaty, 1977). Saaty and Vargas (2000) expressed that the eigenvalue 'λmax' and the total number of factors 'n' are same for a consistent comparison matrix.

CI is the Consistency Index that is expressed as:

$$CI = \frac{\lambda\text{max} - \text{n}}{\text{n} - 1} \qquad (2.1)$$

The consistency of the comparison matrix is checked through CR (Saaty, 1977).

$$CR = CI / RI \qquad (2.2)$$

Where, RI is the Random Consistency Index.

Saaty and Vargas (2000) have created RI by utilizing scales 1/9, 1/8, 1/7… 1… 8, 9. The average RI of 12 matrixes is given in Table 2.2.

Table 2.2: Random Consistency Index

N	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.90	1.12	1.2	1.32	1.41	1.45	1.49	1.51	1.53

Source: Saaty (1977)

In this study, the CR of the pair wise comparison matrix for 12 layers was 0.028. This value demonstrates that the matrix of the factors is acceptable. Hence, weights derived were used to prepare the landslide susceptibility map. The result of AHP showing weights of causative factors (Wj) and the factor rating values (wij) are given in the Table 2.3.

Table 2.3: Pair wise comparison matrix, factor weights and consistency ration of the data layers

Factors	1	2	3	4	5	6	7	8	9	10	11	12	Weights	Factor Rating
Slope (1)	1	2	3	4	5	5	6	7	7	8	8	9	0.2598	9
Distance to fault (2)	1/2	1	2	3	4	4	5	6	6	7	7	8	0.1916	8
Lithology (3)	1/3	1/2	1	2	3	3	4	5	5	6	6	7	0.1397	7
Land Cover (4)	1/4	1/3	1/2	1	2	2	3	4	4	5	6	6	0 1002	6
Elevation (5)	1/5	1/4	1/3	1/2	1	1	2	3	3	4	4	5	0.0696	5
Distance to Roads (6)	1/5	1/4	1/3	1/2	1	1	2	3	3	4	4	5	0 0696	5
Distance to Drainage (7)	1/6	1/5	1/4	1/3	1/2	1/2	1	2	2	3	3	4	0.0476	4
Soil (8)	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1	1	2	2	3	0 0319	3
Rainfall (9)	1/7	1/6	1/5	1/4	1/3	1/3	1/2	1	1	2	2	3	0.0319	3
TWI (10)	1/8	1/7	1/6	1/5	1/4	1/4	1/3	1/2	1/2	1	1	2	0.0212	2
SPI (11)	1/8	1/7	1/6	1/6	1/4	1/4	1/3	1/2	1/2	1	1	2	0.0212	2
Aspect (12)	1/9	1/8	1/7	1/6	1/5	1/5	1/4	1/3	1/3	1/2	1/2	1	0.0157	1

CI (consistency index) = 0.0439
RI (random consistency index) = 1.53
CR (Consistency ratio)= 0.028, <0.1 acceptable

2.3.2. Weighted Linear Combination

WLC is comprised of both subjective and quantitative strategies and depends on the qualitative map combination approach (heuristic analysis) (Ayalew, 2004). It is the last step in making the landslide susceptibility map in which all the weighted layers were combined using weighted overlay technique in ArcGIS 10.1. All the layers were reclassified to a typical scale and the vector layers were rasterized. The weights of the factors were linearly combined (WLC) to obtain the Landslide susceptible Index (LSI) according to the formula:

$$LSI = \sum_{j=1}^{n} Wjwij \qquad (2.3)$$

Where, LSI is Landslide susceptibility index, Wj is weight value for parameter j, wij is rating value or weight value of class I in parameter j and N is no. of classes.

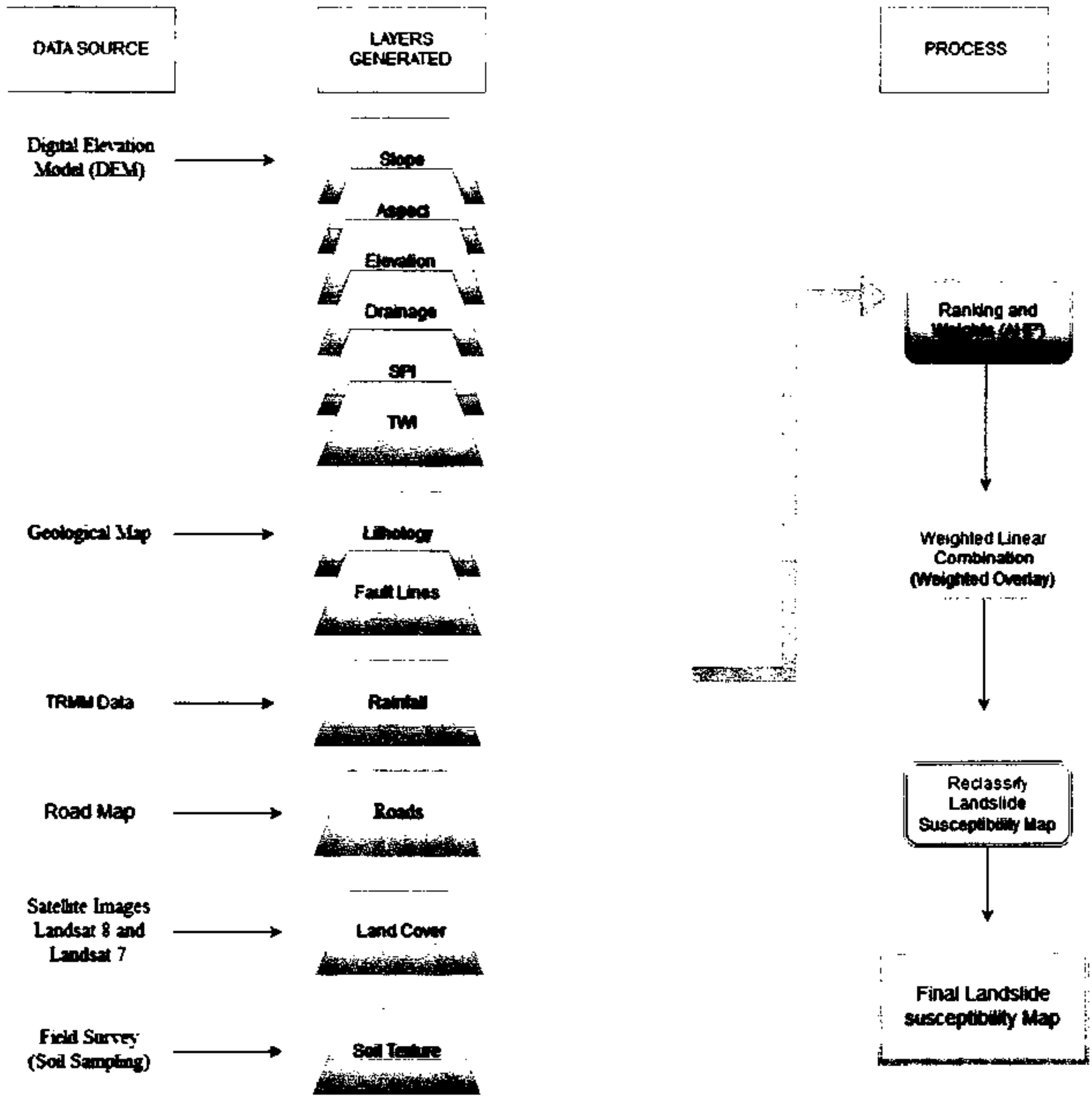

Figure 2.4: Flow Chart for Landslide Susceptibility Mapping

3.0. Results

3.1. Landslide Susceptibility Mapping

The weights of the factors; slope, aspect, elevation, drainage network, SPI, TWI, lithology, fault lines, rainfall, roads, land cover land use and soil were derived using AHP by Prioritized Factor Rating Value (PFRV) Table.3. The final landslide susceptibility map was generated using these weights in the WLC. The resultant map showed that the pixel ranking value for Landslide Susceptibility varies from very low (1.53) to very high (4.43) (Fig 3.1). The areas with high pixel values have more chance of landsliding as compare to the low pixel values. The categorization of the pixel ranking values was obtained by natural breaks in GIS.

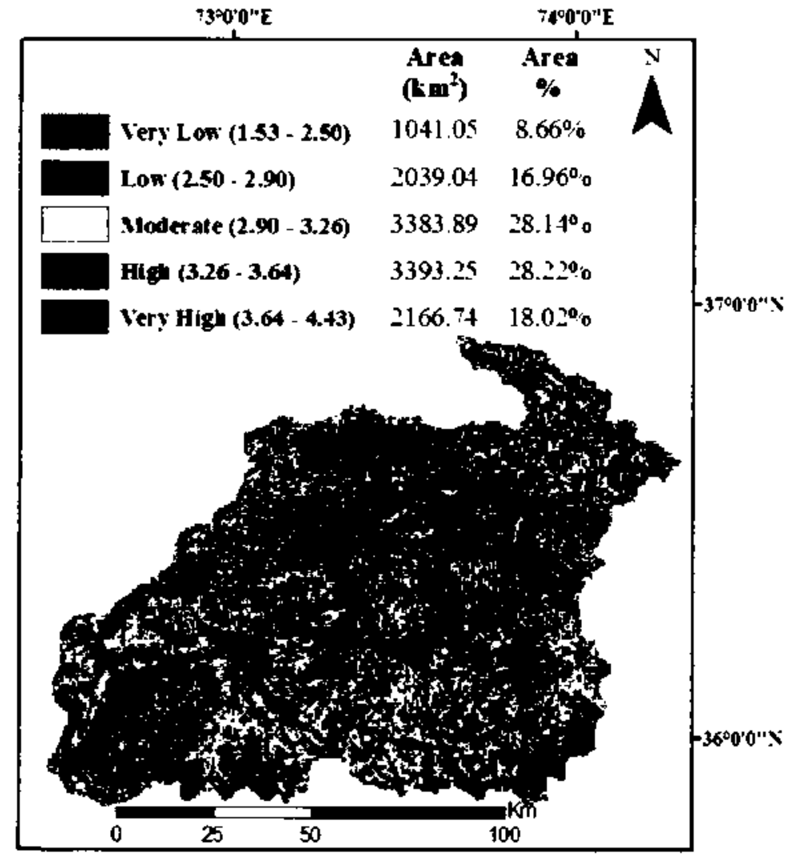

Figure 3.1: Landslide Susceptibility Map of District Ghizer

Based on the above categorization, the area and percentage of the five susceptibility classes were also determined. Very low susceptibility class covers an area of 8.66 % while; low susceptibility class covers 16.96 % of the area. In addition, a larger extent of the area lays in the moderate category i.e. 28.14 %. Furthermore, the high susceptibility class is the one which covers a larger area in the district Ghizer i.e. 28.22 %. The very high susceptibility class in the district falls over an area of 18.02%. Hence, in district Ghizer, a total of 74.38 % of the surface area falls into the moderate to very high landslide susceptible zones whereas 25.62% of the area falls into low to very low landslide susceptible zones.

3.2. Susceptibility in Reaction to Land Cover Change in District Ghizer

The topographic, geologic, and hydrologic factors causing landslides are considered as stationary, while land cover is the factor that can change within short time; therefore it is in a direct relation to landslide occurrence (Malek *et al.*, 2015). In this regard, Temporal assessment of land cover change was studied for the years 2002 and 2015, to analyze the difference in the land cover change over sixteen years in the district Ghizer and its impact on landslides. Hence, it showed that between years 2002 till 2015 a number of landslide events have occurred and significant changes in land use land cover (LULC) have been observed. The changes are visible in the classified maps (Fig 3.2). It further showed devastated increments in the barren soil/exposed rocks from 41.32% to 78.46% and a major decline in the glaciers from 52.44% to 6.63%. As the district Ghizer is largely covered by barren soil/ exposed rocks, it poses more vulnerability to landslides. Barren slopes have more chances of erosion as compared to areas with vegetation so they are more susceptible to landsliding (Sarkar and Kanungo 2004). Vegetation cover has increased from 5.76% to 12.09%, while water class which was least area covering class in 2002, increased from 0.46% to 2.82%.

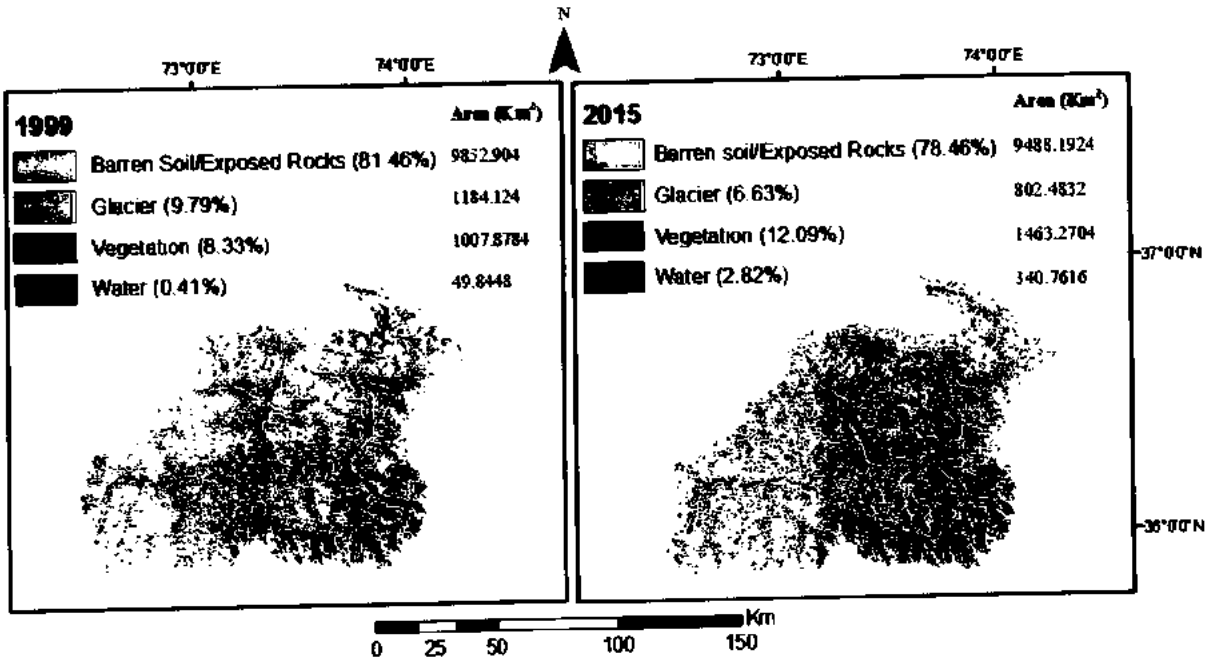

Figure 3.2: Classified Land Cover Land Use Change Detection Maps of District Ghizer

The area coverage of each LULC class for the year 1999 and 2015 is summarized in Table 3.1. The result of overall classification accuracies for the year 1999 and 2015 from the accuracy assessment were 80.0% and 80.01% respectively. In most of the studies overall classification accuracies target below of 85% (DeGloria *et al.*, 2000; Ung *et al.*, 2000).

Table 3.1: Statistics of Land Cover in District Ghizer 2002 and 2015

Land Cover Class	Area (Km^2)	
	1999	**2015**
Bare Rock/Land	9852.904	9488.1924
Vegetation	1007.8784	1463.2704
Water	49.8448	340.7616
Glacier	1184.124	802.4832

3.3. Validation of Susceptibility Map

There are number of methods to validate a susceptibility map. One such method is computing landslide frequency/density in the susceptibility classes (Kumar and Anbalagan, 2016). In this study landslide susceptibility map validation is done by computing landslide frequency in the susceptibility classes. For this, 34 observed landslide sites were taken into account (Fig 3.3).

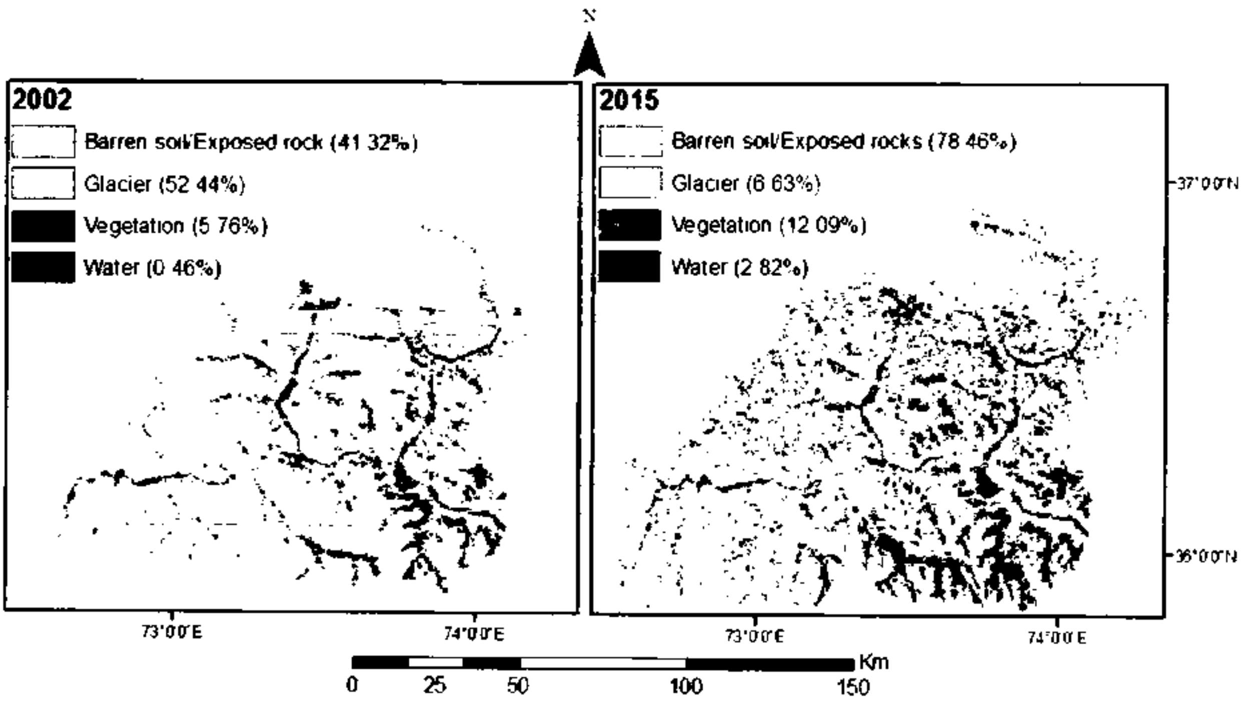

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Table 3.1: Statistics of Land Cover in District Ghizer 2002 and 2015

Land Cover Class	**Area (Km²)**	
	2002	**2015**
Bare Rock/Land	4999.9904	9488.1924
Vegetation	697.1904	1463.2704
Water	55.5264	340.7616
Glacier	6341.9992	802.4832

3.3. Validation of Susceptibility Map

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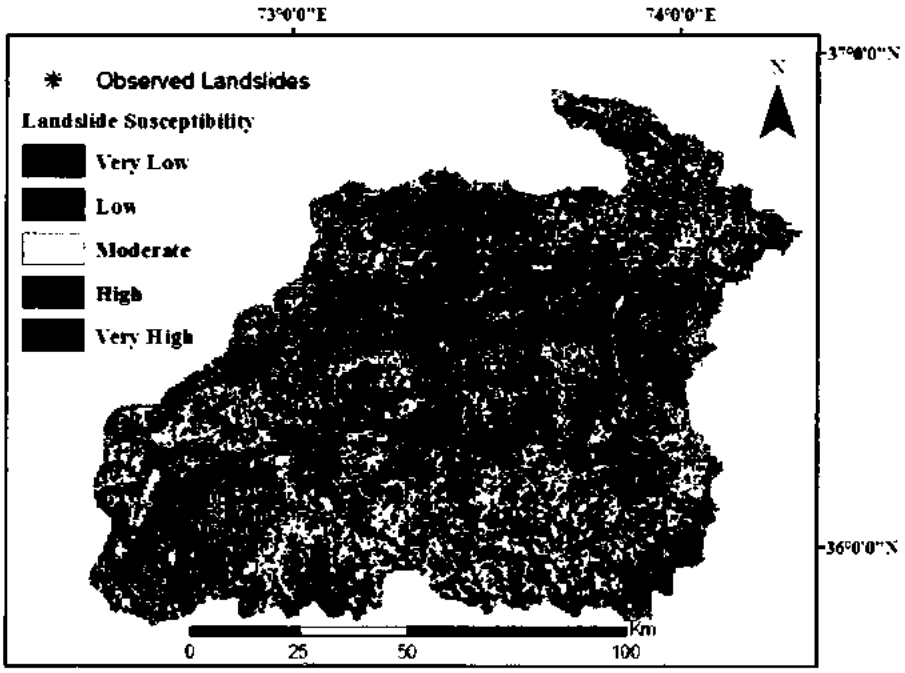

Figure 3.3: Observed landslides overlaid on LSM

The observed landslides in the very high susceptible zone were 38.2% with a landslide frequency of 0.0059, which was found to be the largest among other susceptibility classes. The high, moderate, low and very low classes showed frequencies of 0.0035, 0.0014, 0.0004 and 0.0028 respectively. The overall validation result shows that 88.1% of the landslides in the study area have occurred in the hazard zones of moderate to very high susceptibility (Fig 3.4).

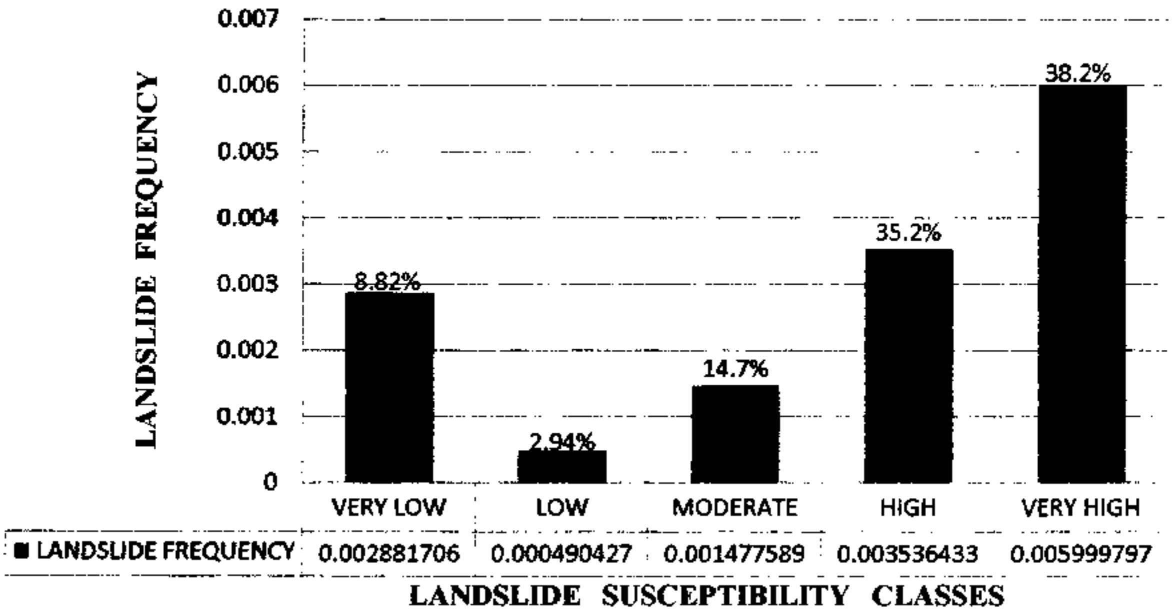

Figure 3.4: Observed Landslide Frequencies in Landslide Susceptibility Classes

4.0. Discussion

It is not possible to predict the frequency and time of landslides, but the identification of the landslide prone areas is possible through landslide susceptibility mapping. These weighting values of each factor in AHP, shows the level of impact of those factors in the landslide. Results showed that slope, distance from fault lines and lithology of the study area have the greatest impact on landslide hazard.

It is evident from the results that most of the landslides occur in the gentle to moderate slopes. It has been observed that, 20° to 40° slope angles are considered very susceptible to landslides (Ruff and Czurda, 2008). From the literature, it was determined that slope angle was given highest value (Kayastha *et al.*, 2013). For this reason, slope has been considered as an important factor in this study as well. Ahmed et al. (2014) expresses that, according to the documented land and rock slides 44% of the slope instabilities are documented in the slope angles of 30° and 45°. Hence gentle to moderate slopes are more susceptible to landslides. Moreover, the mountainous areas are more vulnerable to landslides with the presence of active fault lines. Main Karakorum Thrust and Trich Mir fault run across the district Ghizer. The two categories; high landslide susceptibility (28.22%) and very high landslide susceptibility (18.02%) are mostly present in the region where slope is steep and the distance to fault lines is less. Thus, this shows that the slope angle and the fault lines are most important factors in landslide susceptibility.

Moreover, the finding demonstrated that the weaker rocks which are loosely held are more prone to falling. It is widely recognized that geology of an area, greatly influences the occurrence of landslides and rock falls in that particular area. Because every rock type has different composition and that leads to difference in permeability (Pradhan and Lee, 2011). The lithology of an area consists of different formations which are represented by the characteristics of rock type, which can cause landslides. The Kohistan Batholith Formation (KB) and Southern Karakoram Metmorphic Complex (Skm) were observed in high susceptibility classes, while low susceptibility classes were observed in rocks belonging to Eclogites (Ec), Shyok Suture Zone (Sv) and Hunza Plutonic Unit (HPU) Formations. Rocks belonging to KB and Skm Formation are highly deformed and lie in the most to medium sediment productivity class and inherently failure prone. Rainfall is taken into account in this respect, but it is almost same in all the parts of the study area and it receives 0-150 mm rainfall per year (Calligaris *et al.*, 2013).Therefore it is given a low weight. The drainage networks impact the weight of the soil only if storm or substantial rain came. The streams can erode the slopes and cause landsliding. In the study area, the drainage network only impacts the slopes during monsoon season (Calligaris *et al.*, 2013). The two factors soil and distance to drainage are associated to the rainfall in the study area therefore these are given a less value in the AHP. Aspect, TWI and SPI are included in the study, but these are given less value according to literature.

Land cover has been considered an important factor in the study because barren slopes are widespread as the vegetation is mainly around the villages and few rangelands are present in the high mountains (Rao 2014). The landslide susceptibility map reveals that the areas covering vegetation were mostly observed in low landslide susceptibility zones. The land cover trend analysis of district ghizer from year 1999 to 2015 shows that glaciers are melting at a high pace and have reduced from 9.79 % to 6.63 %. The reason for this melt down is global warming as the glaciers throughout the Himalayas are decreasing (Roohi et al. 2008). The debris material in these mountains is loosely held and is prone to flow or slide, which can cause flash floods, GLOFs, snow avalanches, and debris flows. The classified image of 2015 also shows number of lakes and small water bodies exist near the areas where glacier was present previously. And the water statistics shows that water has increased from 0.41% to 2.82%. Retreating glacier can frequently form glacial lakes near the glaciers (ICIMOD report 2011).

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Conclusion

In this study, the susceptibility mapping of landslides was done by application of GIS techniques and AHP. The final map indicated that a large area in the district consists of moderate and high landslides prone zones. To validate the susceptibility map, landslide frequency/density was computed from observed landslides in the study area, which also indicated that highest frequency of landslides is in the very high susceptibility zone. Further, the temporal assessment of land cover change in the district Ghizer for the years 1999 and 2015 showed that vegetation and water class has increased within the sixteen year time span while, the glaciers and barren soil/ exposed rock classes have reduced in this time span.

Conclusion

In this study the application of GIS techniques and AHP was utilized to identify the landslide prone areas of district Ghizer. Twelve factors were used to generate a landslide susceptibility map. The final map showed that moderate and high landslide susceptibility zones cover larger area in the district. The susceptibility map was validated from the observed landslides in the study area which showed that the highest landslide frequency was found in the very high susceptible zone. The temporal assessment of land cover change in the district Ghizer for the years 2002 and 2015 showed two major changes; one is "barren soil/exposed rocks" which has enormously increased from 41.34% to 78.46% that can pose more vulnerability to landslides and the other class which has shown drastic change is the glacier which has reduced to 6.63% from 52.44%. That can pose serious threats, such as debris flow, GLOF and snow avalanches.

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Table 2.4: Lithological units in the District Ghizer.

Lithological Unit	Formation Group	Description	Stability Class	Category
Ca	Northern Karakorum Terrane	Black slate, phyllite, arkose, Lun Shale,Gircha and Misgar Slate.	Highly Stable	D
Cv	Kohistan Terrane and Shyok Suture Zone –Kohistan Arc Sequence	calc-alkaline andesites , high Mg tholeiites and boninites	Very Highly Stable	E
Sv	Kohistan Terrane and Shyok Suture Zone –Kohistan Arc Sequence	Basaltic andesite, rhyolite, pryroclastic flows, ignimbrite and volcanic breccias	Very Highly Stable	E
Pm	Northern Karakorum Terrane	Permian Sedimentary Rocks: Permian massive limestone	Less Stable	B
Kb	Karakoram Batholith	Trondhjemite, calc-alkaline gabbo-diorite, hornblende cumulates, Plutons. Biotite ± muscovite± garnet leucogranite	Less Stable	B
Ssm	Kohistan Terrane and Shyok Suture Zone	Suture mélange (limestone, quartize and serpenite in a shely matrix	Less Stable	B
Skm	Southern Karakoram Metamorphic Complex	Paragneisses including interhanded pelite , marble, amphibolite with rare ultramafic lenses (Panmah unit) . Pelites containing micas, garnet , staurolite, kyanite, sillimanite + muscovite and sillimanite + K-feldsparassemblings metamorphosed.Low P-T pelites aroun the Chinkiang valley contain chloritoid + chlorite + biotite.	Moderately Stable	C
Tr	Northern Karakorum Terrane	Triassic Massive Limestone and Dolomite with distinct conglomerate horizon; Slate	Moderately Stable	C
Y	Kohistan Terrane and Shyok Suture Zone –Kohistan Arc Sequence	Limestone containing Orbitolina sp. And Radist sp. Sandstone, shale and meta-volcanic rocks	Moderately Stable	C
HPU	Karakoram Batholith	Plagioglacase +Quartz+horneblende+biotite±garnet±K-feldspar	Very Highly Stable	E
GB	Karakoram Batholith	Plutonic unit (k- feldspar+quartz+plagioclase+bioite+garnet)	Very Highly Stable	E
GL	Glacier/ snow		Least Stable	A
Gm	Kohistan Terrane and Shyok Suture Zone –Kohistan Arc Sequence	Meta-sedimentary rocks, greenschist facies slate, phyllite and psammite; protoliths; Peshmal schists; granties	Highly Stable	D
Ec	Besal Eclogites	Omphacite -garnet + Quartz + rullite ± amphibolite ± metamorphosed phengite eclogites, Protoliths	Highly Stable	D

Categories contribution in the hazard in the study area on the basis of their stability.
A (Very Highly Stable), B (Highly Stable), C (Moderately Stable), D (Less Stable), E (Least Stable)