GIS-BASED LANDSLIDE SUSCEPTIBILITY MAPPING OF MUZAFFARABAD

By

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DEDICATION

This research is dedicated to my loving, caring and industrious parents whose efforts and sacrifice has made my dream of having this degree a reality. Words cannot adequately express my deep gratitude to you. I pray

"O My Sustainer, Bestow on my parents your mercy even as they cherished me in my childhood".

ACADEMIC THESIS: DECLARATION OF AUTHORSHIP

I, Muhammad Athar Siarj declare that this thesis and work presented in it are my own and this thesis has been generated by me as a result of my own original research.

"GIS-Based Landslide Susceptibility Mapping of Muzaffarabad"

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ABSTRACT

In this study, landslide susceptibility map has been prepared to identify the areas which are prone to landslides under specific weather and climate conditions. Pre-event identification of such areas can help to take preventive/remedial measures to reduce the effects and the resultant damages. Natural disasters are the common phenomenon on the surface of the earth. Some of these are so intense that they cause huge loss to human and infrastructure. These disasters cannot be prevented to happen, but measures can be taken to minimize their effects. Landslides are also common disasters that are harmful for humans and their property as well. Area along the Neelum River in district Muzaffarabad is selected to identify landslide susceptible areas. Naturally, topography of the area is hilly. The area received heavy precipitation in the form of rain and snowfall. It causes the downward movement of water from mountain tops and cause land sliding in the study area. Some other factors e.g. slope, elevation, LULC, soil, stream network, geology and aspect are also considered in preparing landslide susceptible map. Analytical hierarchy process (AHP) and weighted linear combination (WLC) methods were used to achieve the objectives of the study. Factor weights were calculated using AHP and standardized ranks were computed for each factor class using WLC. It is found that 14.99 % of study area falls in very high susceptibility zone and 32.37 %, 31.97 %, 16.25 % and 4.42 % of areas were fall in high, Moderate, low and very low susceptibility zones respectively. The landslide susceptibility map validated with landslide inventory map. This map can be used by the hazard management authorities to reduce the loss in terms of life and infrastructure.

Chapter 1

INTRODUCTION

1.1 INTRODUCTION TO THE STUDY

Hilly areas regularly face critical natural hazards in the form of landslides which cause huge loss to natural resources and human lives and their assets. The damages of property, loss of human lives, collapse of business activities and sever human injuries are major effects of landslides (Varnes, 1984). Damages can be reduced to a certain level if we have knowledge about the potentially landslides prone areas. Landslide susceptibility map can present the information related to landslide susceptible areas.

The knowledge of the complex factors, influencing landslides and slope information about an area is needed for susceptibility mapping. The amount and quality of data is co-related with the reliability of the landslide susceptibility map. The reliability of results is also dependent on the working scale and selection of proper analysis and modeling techniques. A number of qualitative or quantitative approaches can be used to prepare these maps (Guzzetti et al., 1999, Soeters et al., 1996 and Aleotti et al., 1999). Previously, landslide susceptibility maps were prepared using qualitatively overlay of morphological and geological slope attributes on landslide inventories (Nielsen et al., 1979). Bivariate, fuzzy logic, AHP, multivariate, artificial neural network, logistics regression, and other analysis are now used for advanced assessments.

Expert opinions are the basis for qualitative methods. Landslide records are commonly used in qualitative methods to identify vulnerable sites having different geomorphological and geological properties. The use of ranking and weighting process converts the nature of qualitative methods into semi quantitative. Saaty's analytical hierarchy process (AHP) method has been applied for landslide susceptibility assessment by different authors e.g., Barredo et al., 2000; Mwasi, 2001; Nie et al., 2001; Yagi, 2003, and Ayalew et al., 2004. In AHP, decision elements e.g. slope, elevation, precipitation, soil types, geological structure, land use land cover (LULC), aspect and stream network are used to build hierarchy and then compare possible pairs in the matrix for calculating weights and consistency ratio. AHP is working on the principle of decomposition, comparative judgment and synthesis of priorities (Malczewski, 1999). Standardized rank of each class of a controlling factor and the weights are combined using WLC. The expert knowledge plays a vital role in the studies of landslide susceptibility mapping and results can vary in different studies. In regional studies qualitative and semi quantitative methods are used frequently (Soeters et al., 1996 and Guzzetti et al., 1999).

Quantitative techniques are developed on numerical statements of the association between governing factors and landslides. Slope instability in context of engineering principles is the basis of deterministic quantitative methods in term of safety factor. The effectiveness of these methods is limited to small areas only as more extensive slopes data is needed. An analysis has been performed between factors affecting landslides and the distribution of landslides in all the multivariate and bivariate statistical approaches that are used to assess landslide susceptible areas (Guzzetti et al., 1999).

In landslide hazard mapping, it is more beneficial to use combined computer-based tools like geographic information system, remote sensing and spatial analysis. A geographic information system (GIS) is one of such important tools for landslide hazard mapping. GIS is generally defined as a powerful system for spatial data handling, storing, retrieving, displaying and its collecting (Burrough and McDonnel, 1998). Refined hazard occurrence models are possible to generate using this technology by modify the input variables and to measure the results. This system can check, store and treat in landslide studies using available spatiotemporal data. Some of the input features can be extracted from satellite images. With the growth in efficient digital computing abilities, the digital remote sensing data and their analysis have gained substantial importance. Remote sensing data and ground based information can be used to extract the spatial and temporal thematic information for analyzing landslide susceptible areas. This can be very well accomplished using GIS which has the competences to handle huge spatial data. The impact of controlling factors on landslide occurrences can be evaluated with the help of GIS to incorporate different layers of spatial data. At present several qualitative and quantitative methods can be used in GIS environment for landslide susceptibility. For regional assessments, it is found that expert opinion based qualitative methods are very useful. (Aleotti et al.,1999 and Soeters et al., 1996). Quantitative methods used the relationship between landslides and its controlling factors (Guzzetti et al., 1999).

In this study, the two different methods namely, AHP and WLC models were used to prepare landslide susceptibility map of the area. The first method, AHP is semi-qualitative in nature; controlling factors involved in landslides are compared pairwise in a matrix for landslide susceptibility mapping. AHP is known as Multi-Criteria Decision Making (MCDM) tool, is used to give relative significance among the factors to a set of overall scores or weights. The second method, WLC, is used to combine all the weighted factor maps and to prepare landslide susceptibility map that is classified into landslide susceptibility zone (LSZ).

Five classes including, very high susceptibility (VHS), high susceptibility (HS), moderate susceptibility (MS), low susceptibility (LS) and very low susceptibility (VLS) zones are prepared. At the end, the validity of the resultant map was compared and evaluated using landslide inventory map.

1.2 SCOPE OF THE STUDY

The purpose of this study was to use GIS and multi criteria decision making (MCDM) capabilities in the identification of landslide susceptible areas. The parameters considered for landslide susceptibility mapping are slope, elevation, land use/land cover, rainfall, geology, soil, stream network and aspect. In landslide susceptibility mapping, a number of factors used for decision making and GIS is the only system that is capable to handle such a huge spatial data received from various sources. User can store analyze, retrieve and display spatial data efficiently according to their requirement (Siddiqui et al., 1996). As huge amount of spatial data easily managed using GIS and thus, it potentially saves time that would usually be spent in identifying landslide susceptible areas. However, GIS may be restricted by the current sources of data needed in susceptibility analysis. GIS can be used as a powerful set of tools by decision makers for managing and analyzing spatial information. In this study, analysis of landslide susceptibility mapping has been carried out using GIS and MCDM. It is used to assign weights in the study. MCDM techniques also have the ability to handle multi attribute decision making process which makes the selection process easy for decision maker.

1.3 OBJECTIVES

The research has emphasis on the following three main objectives:

i. Understand and identify landslide causative factors in the study area

ii. Explore utilization of Remote Sensing data and GIS techniques to develop landslide causative factor maps

iii. Identify potential landslide sites/ susceptible areas to prepare landside susceptibility map integrating Remote Sensing data and GIS techniques

Chapter 2

LITERATURE REVIEW

Landslide is basically the down slope movement of soil, rock, or some mixture of the two, under the impact of gravity. Landslides are natural processes, but can be prompted or accelerated by one or more of the factors, especially when the factors happen in combination.

2.1 INTRODUCTION

Cruden (1991) defines the landslide as the downward movement from slopes of debris, rocks or a part of earth mass. The movement of earth material both downward and outward by gravity without any aid of transporting agent like running water or air is called mass movement (Crozier, 1986). The above definitions are accepted universally and widely used to define this phenomenon. Although, numerous definitions may be found, but in essence, they all lead to the same conclusion that landslide is involved in downward mass movement which can be harmful for humans.

2.2 LANDSLIDE TYPES

The type of movement and the material can be used to differentiate landslide types. Table 2.1 shows a descriptive classification system based on these parameters. Landslides can be classified in two ways; first on the base of material types that helps in failure and the second, the movement type (Varnes, 1978).

There are three types of material that cause the occurrence of five basic types of landslides. Falls, topples, slides, lateral spreads, and flows can occur in bedrock, debris, or earth. Most landslides are complex, or composed of combinations of basic types of landslides. Some classification systems also used additional variables such as water, ice content and rate of movement.

2.3 FACTORS INFLUENCING LANDSLIDES

Slope uncertainties are usually related to the causes of landslides. In one landslide trigger, it is usually possible to recognize one or more causes. There could be different causes for landslide occurrence at a location at the same time.

2.3.1 Morphological Factors

a. Glacial erosion of slope toe or lateral margins, fluvial
b. Tectonic or volcanic uplift
c. Deposition loading slope or its crest
d. Glacial rebound
e. Subterranean erosion (solution, piping)
f. Removal of vegetation by fire or drought
g. Thawing
h. Shrink and swell weathering
i. Freeze and thaw weathering

2.3.2 Geological Factors

a. Sheared, jointed, or fissured materials
b. Weathered materials
c. Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)

d. Weak or sensitive materials
e. stiffness of materials and/or Contrast in permeability

2.3.3 Human Factors

a. Deforestation
b. Artificial vibration
c. Mining
d. Loading of slope or its crest
e. Excavation of slope or its toe
f. Irrigation
g. Water leakage from utilities
h. Drawdown (of reservoirs)

2.4 INFLUENCE OF WATER ON LANDSLIDES

A primary source of landslides occurrence is the slope inundation by water. Snowmelt, alterations in ground-water levels, and water-level changes along coastlines, heavy rainfall, water dams, and the banks of lakes, reservoirs, rivers and canals are the causes of slope inundation by water. A close association has been found in landslides and flood as both are controlled by same factors like water runoff, rainfall and overload of ground by water (Narumon Intarawichian 2008). The occurrence of mudflows and debris flow has been mostly recorded in small and steep stream channels. It has also been recorded that both events occurred at same time.

It has been found that lakes produced by landslides often block valleys and stream channels that force the huge amount of water to back up. It can generate two types of flooding, backwater flooding and the downstream flooding, if the dam fails.

2.5 LANDSLIDE HAZARD ASSESSMENT USING REMOTE SENSING

Landslides regularly disturb the earth's surface; thus it has created opportunities of research in both space and aerial remote sensing. It is a natural phenomenon happening on earth surface helps earth scientists to explore using remotely sensed data. Some times this phenomenon bounds the researchers because it covers a very small area in terms of remote sensing. On the other hand planar 2-D remotely sensed data give very short information while 3-D data e.g. DEM has huge amount of information. In this sense stereo-remote sensing data is helpful which represents a true nature of landslides. The type of landslide movements can be recognized effectively using this information (Crozier, 1973). A common research area in this field is to detect temporal changes in landslide occurrence to find out the potential hazard areas.

Remote sensing data provides information about vegetation, morphology and hydrological conditions of the area which can be related to landslides. It is best practice to extract slope morphology with stereo images.

Some earlier works (Soeters and Van Westen, 1996; Van Westen et al., 1997) used remote sensing data in different approaches to prepare inventory maps for landslide hazard assessment. He et al. (2003) used satellite images, aerial photos historical landslide occurrence database and ground survey to prepare landslide inventory map. Result shows the spatial distribution of mass movements in the form of points or polygons (Wieczorek, 1984). This map shows the spatial location of landslide areas and can be used as a basic hazard map but it cannot be used as susceptible map (Dai et al., 2002). Matovani et al (1996) describes that it is useful to acquire remote sensing data in short periods to find temporal changes in mass movement. It helps to refine landslide activity map which is prepared using multi temporal image or aerial photos (Nagarajan et al. (1998), Zhou et al. (2002), Van Westen and Getahun (2003), Cheng et al. (2004).

2.6 GIS AND LANDSLIDE ANALYSIS

For spatial analysis and data processing, GIS has a powerful set of tools like data capturing, manipulation, input, spatial queries transformation, better visualization, combination, data analysis, modeling and output, with its excellent spatial data processing capacity, to assess natural hazard phenomenon (Carrara et al., 1999).

Hazard assessments can be performed with complex analysis covering factors involved in landslide occurrences. For hazard mapping it is found that computer based utilities are very helpful. GIS technology provides possibilities to assess and modify the input variables for refining landslide hazard models. Inquiries relating landslides can also be performed to analyze and manage available data.

GIS utilities can manage spatial data of various types for typical landslide analysis and fulfill the need to perform analysis. Two types of spatial data can be stored and manipulate in GIS environments. First is vector data which comprises of points, lines and polygons and second is the raster (continuous) data in the form pixels. GIS environments are basically designed for spatial data analysis but other non-spatial data which is used in conventional hazard mapping analysis can also be used to assist spatial data analysis (Miles and Ho, 1999). Spatial relationship can also be developed between qualitative and quantitative data in GIS environment to extract meaningful results (Frost et al., 1997).

2.7 LANDSLIDE SUSCEPTIBILITY APPROACHES

To classify GIS-based landslide hazard assessment approaches, work of some researchers can be used e.g. Van Westen (2000), Aleotti et al., (1999), Guzzetti et al. (1999), Soeters et al., (1996), and Carrara et al. (1995, 1999). Broadly classifications of these researchers may be divided into four different approaches:

i. •Inventory-based landslide probabilistic approach
ii. •Heuristic approach
iii. •Statistical approach
iv. •Deterministic approach

Some publications on landslide susceptibility mapping are unable to clear their approach used in it, but recently some good overview on landslide susceptibility methods have been published (e.g., Cruden and Fell, 1997; Guzzetti, 2000; Dai et al., 2002) and a recent textbook by Lee and Jones (2004). A classification of landslide susceptibility mapping has been proposed by sub-committee on Landslide Risk Management of the Australian Geomechanics Society, but it also fails to provide details on the classification methods. The level of quantification is the basis of the classification and it divides the landslide susceptibility assessment methods into:

i. •Qualitative methods (losses and probability expressed qualitatively)
ii. •Semi-quantitative methods (indicative probability, qualitative terms)

iii. •Quantitative methods (probability and losses quantified)

Through review of literature, it is found that several authors took part in the development of landslide susceptibility assessment approaches in last couple of decades. Focus of this review was to identify some important literatures regarding the advancement of the assessment approaches.

Expert opinions are the base of qualitative or semi-quantitative methods. Areas of similar geological and geomorphological properties that are susceptible to failure are identified using landslide inventories in most of qualitative methods. Ranking and weighting approach also used in some qualitative approaches, that leads the approach to semi quantitative in nature. Regional studies often used qualitative or semi-quantitative methods (Soeters et al., 1996 and Guzzetti et al., 1999). Landslide susceptibility mapping using analytical hierarchy process (AHP) method, developed by Saaty (1980), performed by Barredo et al. (2000), Mwasi (2001), Nie et al. (2001), Yagi (2003), Ayalew et al. (2005), Komac (2006) and Yalcin (2008). Different type of methods used in landslide susceptibility mapping is shown in Figure 2.1.

2.8 LANDSLIDE HAZARD OR SUSCEPTIBILITY MAPPING

Landslide hazard or susceptibility mapping process can varies by difference in concepts. Hazard is a term used by Varnes (1984) as occurrence probability of a phenomenon which potentially damages a specific area in a specific period of time. Landslide hazard zonation is a part of spatial analysis. Varnes (1984) said that zonation is basically dividing the land of similar areas and rank it according to degree of potential hazard caused by the movement of mass. Therefore knowledge of factors of the area which are involved in landslide occurrence should be required. These factors can be categorized into two groups (Dai et al. 2002): the factors in the first group are those which make favorable conditions in happening landslides and make the slope susceptible for failure before triggering, these factors includes: slope, elevation, aspect, LULC, drainage network, geology and soil types. The factors in second group are the triggering factors which includes glacier outburst and heavy rainfall.

According to Guzzetti et al. (1999), prediction of the sites which are susceptible to failure for landslides and pre and post distribution of deposits is called landslide hazard mapping. The time period or movement direction of the deposits may not be the same as defined by analysis. Generally, highlighting the distribution of the slopes which are susceptible for landslides at regional level based on the factors is the purpose of landslide hazard mapping. The resulting information is helpful for land use planning of the slopes which is susceptible to fail. It would be valuable to minimize the effect of damages caused by any hazard happened in the study area.

Table 2.1. Types of landslides: Abbreviated version of Varnes' classification of slope movements (Varnes, 1978).

Type of Movement	Type of material		
	Bedrock	Engineering soils	
		Predominantly coarse	Predominantly fine
Falls	Rock fall	Debris fall	Earth fall
Topples	Rock topple	Debris topple	Earth topple
Slides	Rock slide	Debris slide	Earth slide
Lateral spreads	Rock spread	Debris spread	Earth spread
Flows	Rock flow	Debris flow	Earth flow
Complex	Combination of two or more principle types of movement		

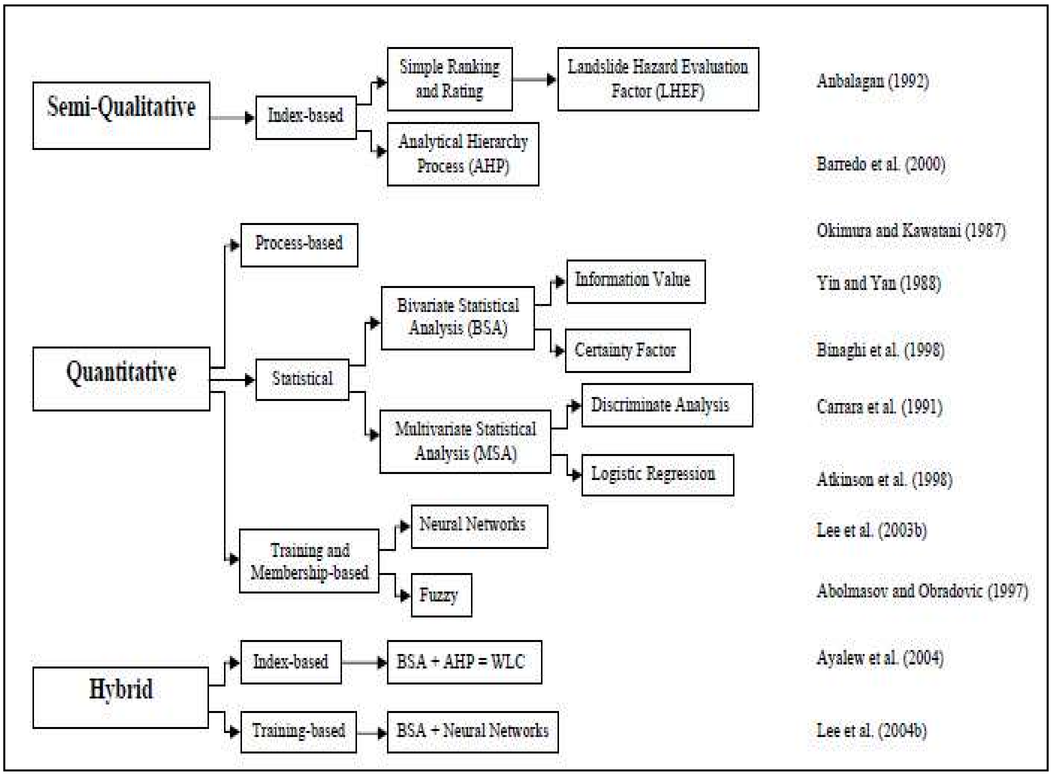

Figure 2.1. A schematic diagram of presently used landslide susceptibility methods

Chapter 3

MATERIALS AND METHODS

Detailed description of the study area and the material and methods used in this research are described in this chapter. Each objective of the study and methods are discussed in details in following paragraphs.

3.1 STUDY AREA

Study area is located in district Muzaffarabad, AJK. A strip of 12 km along Neelum River with 3 Km buffer has been selected to extract landslide susceptible areas. The study area lies in upper north part of district Muzaffarabad, lies between 34°38' to 34°47' Latitude North and 73°59' to 73°72' Longitude East and covers almost 80 km^2 of land. It starts from Nuseri (Nushada) from the edge of district boundary and extends till Panjgran village. Major localities within the study area are Nuseri, Khatimbal, Kailgiran, Dhani, Balgran, Bankhador, Jing, Parla and Panjgran.

3.1.1 Physiography

The topography of study area is hilly by nature with gentle to steep slopes Elevation ranges from 846 m to 2466 m above sea level. Drainage system of the study area relies on Neelum River and its tributaries. In the study area, stream channel deposits and terrace deposits found due to Neelum River valley. Basaltic lava flow deposits are also found in the study area. Mineral deposits like Green Tourmaline, Marble, Ruby, Dolomite and Limonite are found the district Muzaffarabad.

3.1.2 Climate

Muzaffarabad is tourist place in northern areas of Pakistan. The summers are mild while the winters are chilly with snowfall. In autumn the sky is mostly clear and pleasant. Microclimate of Muzaffarabad has influence of Neelum River which joins Jhelum River near Domail. The mean maximum and minimum temperatures during the month of July are about 35°c and 23°c; and in January 16°c and 3°c respectively. It is recorded that the district received 1511 mm of precipitation annually.

3.1.3 Geology

In most parts of the study area, Murree formation exists, which consists of red, purple and green sandstone, siltstone, shale with subordinate intraformational conglomerates. A strip of Panjal Meta-sediments is also found in the north east of study area. It comprises of gray to brownish gray meta-carbonates, quratizite and graphitic pylite components. Below the Panjal meta-sediments strip, another strip of Panjal volcanics exists. As the name indicate, the composition of Panjal meta-sediments comprised of green to greenish gray basaltic lava flow with tuffaoceous layers. In this composition subordinate intercalations and lenses of limestone and schistose rocks are common. Along the Neelum River banks, stream channel deposits and terrace deposits exists. Stream channel continuously deposits and spread silt, sand and gravel along the river. Semi consolidated sand, silt, gravel and moraines are the compositions of terrace deposits and found along the river channel at some places.

3.1.4 Soil Types

According to the Soil Survey of Pakistan maps, two major soil types were found in the study area. These are Rock lands and Maira. These types were identified during reconnaissance survey and soil series/phases were described in associated table attached with this map.

Rockland type consists on Rockland, Shaldar, AHL and Shaldar moderately deep variant. Rockland found in wide range of slopes in the study area and consistof exposed bedrock. In this type severe erosion has been recorded and lack of soil cover seen. Shaldar found in upper parts of mountains at the slopes of 25-50% with the composition of gravelly loams. Erosion rate is moderate in this area and have a limited soil depth. Shaldar moderately deep variant found in the lower and middle parts of mountains within 13-25% slopes. The type consists of gravelly loams with minor erosion. AHL is also found in upper parts of mountains within 25-50% slopes with gravelly sandy loams. Soil depth is also limited in this area.

Maira type has two series/phases named as Maira and rock land. Maira found on middle parts of mountains within 15-30 % slopes. Cherty loam is the major component of this type. Very limited soil thickness exists here with moderate erosion. Rockland spread over wide range of slopes in the study area with severe erosion. The area has lack of soil cover with exposed bedrock.

3.2 DATASET USED

Following datasets were used for this study.

3.2.1 Satellite Images

ALOS satellite Images of 10 m spatial resolution having four bands blue, green, red and near infrared were taken from WWF - Pakistan. Images were of

September 10, 2009. Google earth imagery was also to visually interpret and to identify areas of already occurred landslides to prepare landslide inventory map of the study area.

3.2.2 Digital Elevation Model (DEM)

Digital elevation model of ASTER of 30 m resolution was downloaded freely from ASTER website. It was used to extract four landslide controlling factors, the aspect, elevation, slopes and stream network.

3.2.3 Geological Map

Geological map of the study area was taken from Geological Survey of Pakistan. Sheet No. 43 F/11 of Geological Survey of Pakistan covers the study area and it is prepared on 1:50,000 scale.

3.2.4 Soil Map

During reconnaissance survey of Azad Jammu & Kashmir, Soil Survey of Pakistan prepared Soil map of the study. This map was used in the research and classes were identified using associated tables.

3.2.5 Precipitation Data

Precipitation data of nearby three meteorological stations was taken from Pakistan Meteorological Department Islamabad office. These stations were located in Muzaffarabad, Garhi Dupatta and Balakot.

3.3 SOFTWARE USED

- ERDAS IMAGINE 9.2
- ArcGIS 9.3
- Microsoft Word/Excel/PowerPoint

3.4 DATA PREPARATION

3.4.1 LULC Map

Supervised classification was performed on ALOS satellite image to extract LULC of the study area. Following major classes were extracted from satellite image: (a) Dense Conifer (b) Medium Conifer (c) Sparse Confiner (d) Grasses/Shrubs (e) Bare Land (f) Water and (g) Settlements. The LULC map of the study area is shown in Figure 3.1.

3.4.2 Slope Map

Digital elevation model was used to prepare slope map of the study area. It is considered as the most important landslide controlling factor. It controls the runoff of water in hilly areas. Steep slope makes more favorable conditions for landslide as it helps water to flow frequently on ground surface. In the study area slope values varies from 0° to 57.3°. Slope values were divided into the following six classes in the reclassified map: (a) 0°-5°, (b) 5.1°-10° (c) 10.1°-20° (d) 20.1°-30° (e) 30.1°-40° (f) 40.1°-57.3°. Slope map of the study area is shown in Figure 3.2.

3.4.3 Elevation Map

The relationship between landslide occurrence and elevation is not highly correlated. However, influence of elevation cannot be neglected in landslide susceptibility mapping. It is not necessary that higher elevated areas are more susceptible for land sliding. Elevation values in this study area ranges from 846 m to 2466 m and divided into five classes: (a) 846 m-1000 m, (b) 1001 m-1300 m (c) 1301 m-1600 m (d) 1601 m-1900 m (e) 1901 m-2466 m. Elevation map of the study area is shown in Figure 3.3.

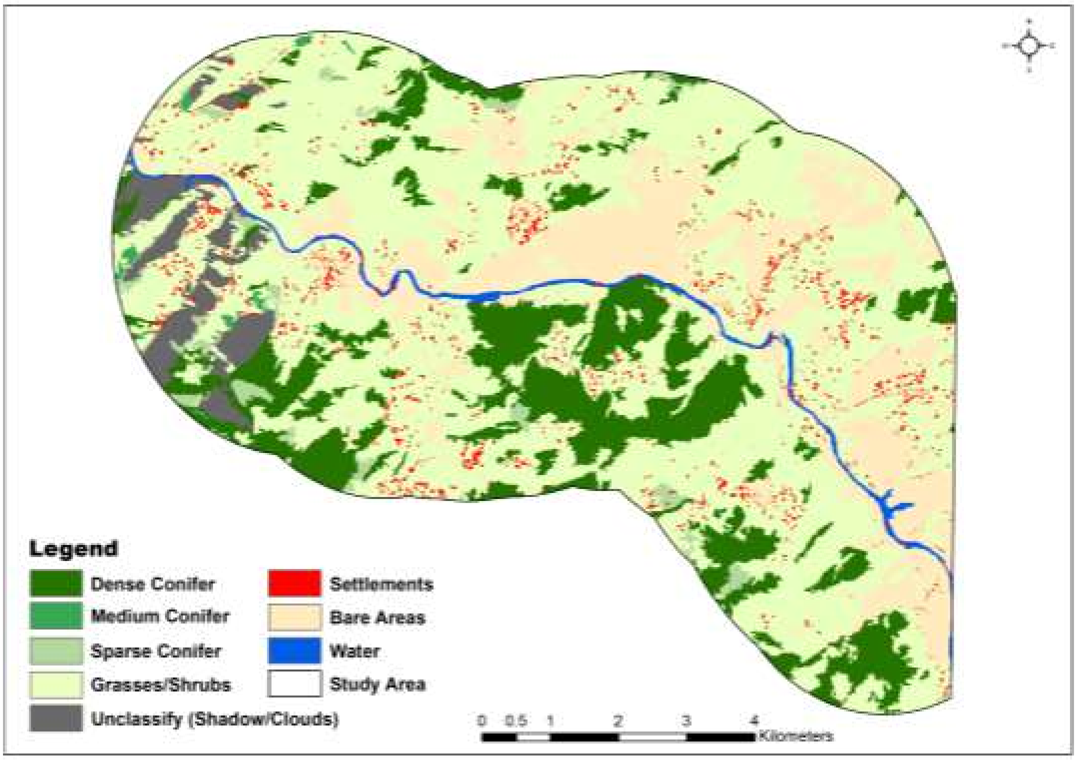

Figure 3.2. LULC map of the study area

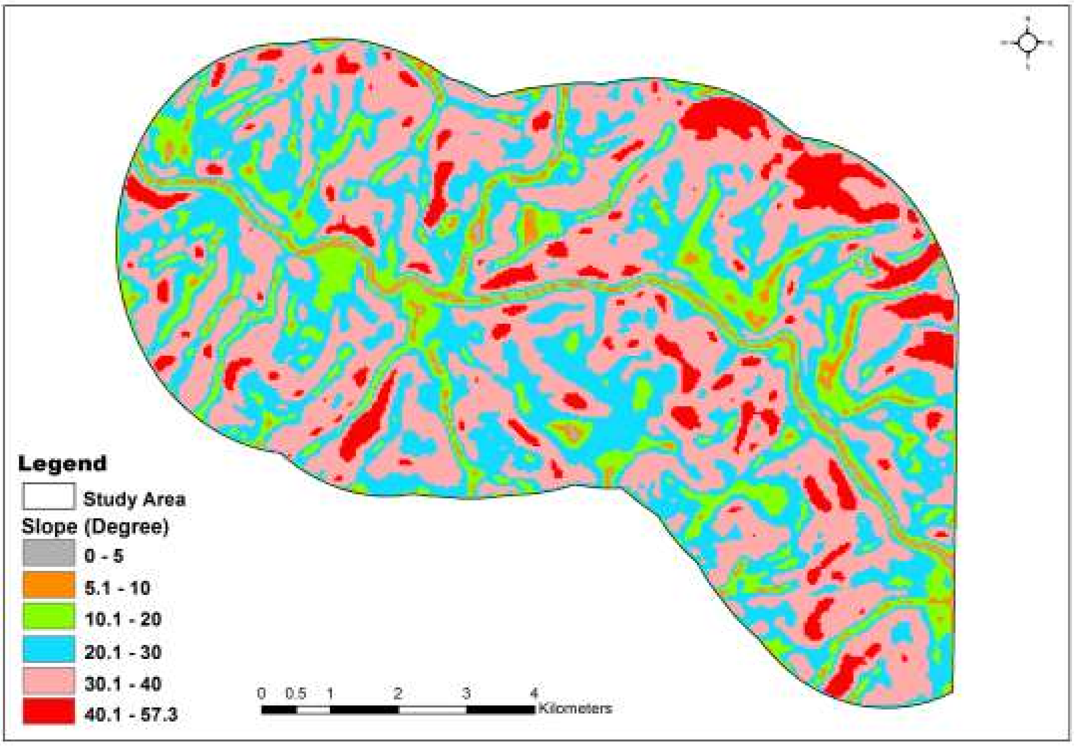

Figure 3.2. Slope map of the study area

3.4.4 Aspect Map

In landslide susceptibility, aspect is also considered an influencing factor. Although its influence is much low but some parameters like exposure to sunlight, wind direction and rainfall may control landslides. Aspect raster map classified into nine classes shown in Figure 3.4, representing angular sectors of 45° wide, namely, N, NE, E, SE, S, SW, W, NW, N and flats.

3.4.5 Distance from Streams Map

Stream network of the study area was delineated from digital elevation model (Figure 3.5). Many of landslide occurred along the streams due to erosion and saturation by water in the lower part of bed materials. Three different buffer areas of 50 m, 100 m and 150 m were created on stream network of the study area.

3.4.6 Geology Map

It is considered the most relevant factor in land sliding. Different rock types behave different with erosion material. Generally, hard rocks are more resistant to driving forces than weaker rocks. In study area, the stratigraphic unit founds are: (a) Murree formation, (b) Panjal Meta-sediments, (c) Panjal Volcanics, (d) Stream Channel deposits and (e) Terrace deposits, shown in Figure 3.6.

3.4.7 Soil Map

In landslide susceptibility mapping, the effect of soil is widely considered. Soil texture is much important to create conditions that are favorable for land sliding. Fine and less pore spaced soils helps the upper layers to move easily when it is saturated with water. It is reported that thick soil has more capacity to retain water thus it is more susceptible to land sliding. In the study area, major soil types

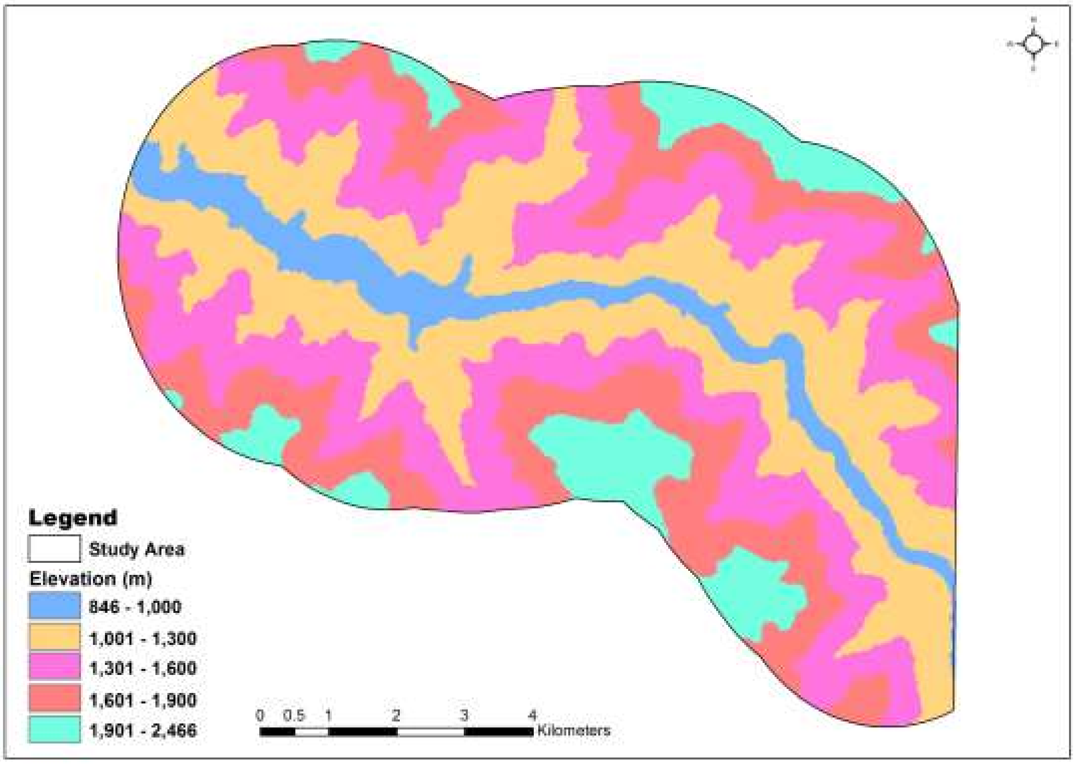

Figure 3.3. Elevation map of the study area

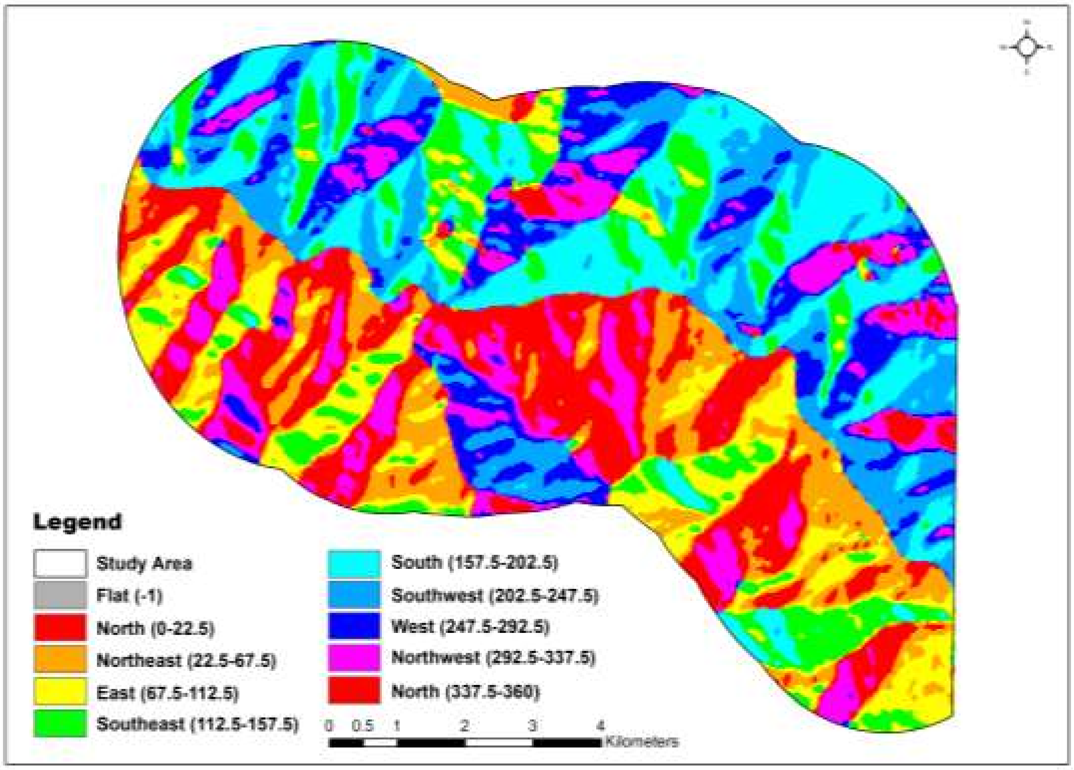

Figure 3.4.Aspect map of the study area

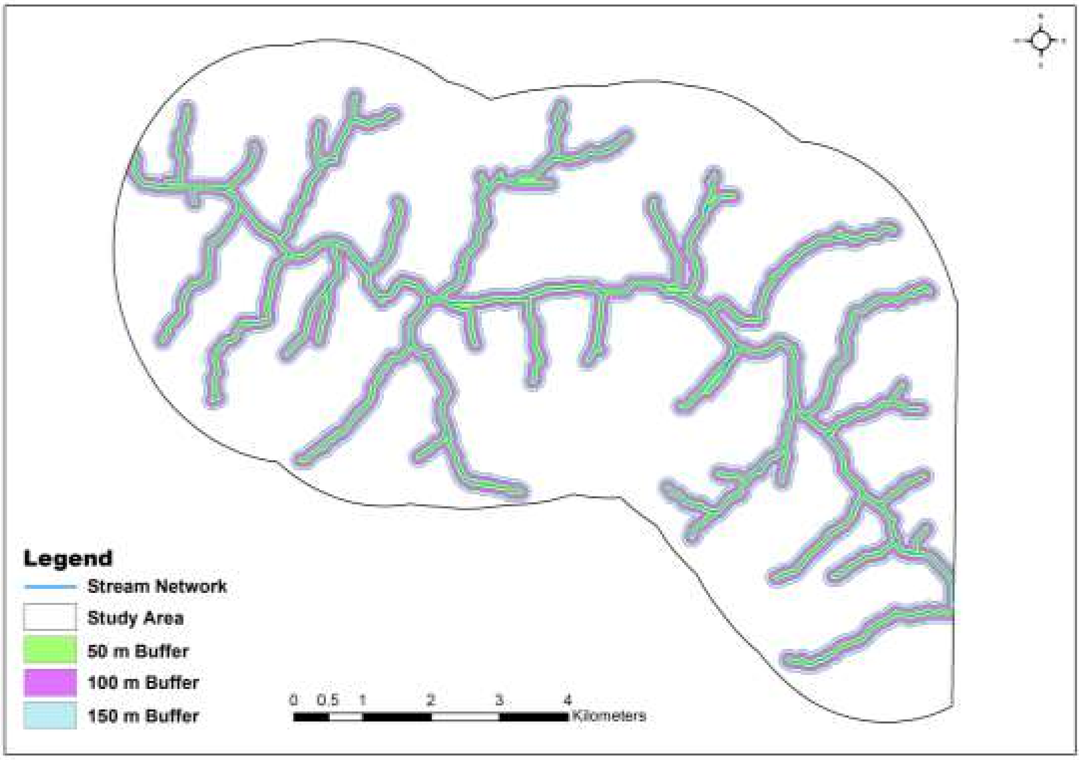

Figure 3.5. Distance from stream network map of the study area

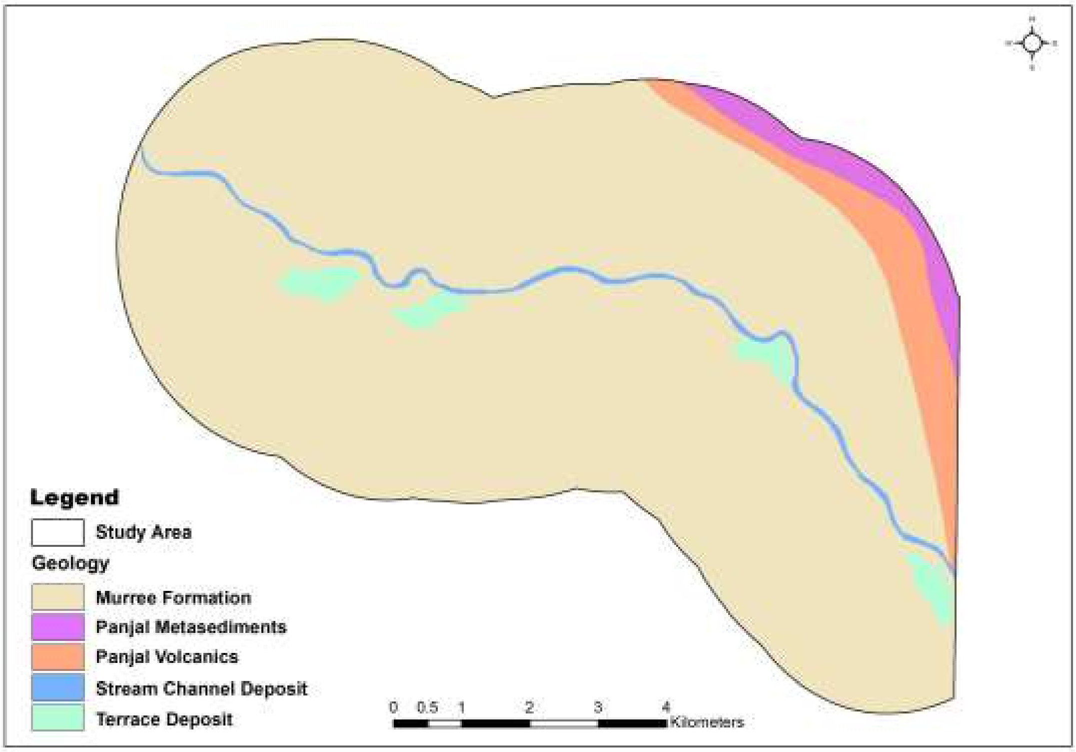

Figure 3.6. Geological map of the study area

that were found are: (a) Gravelly Loams (Moderately Deep) (b) Loams: Massive (c) Exposed Bedrock (d) Gravelly Sandy Loams. Soil map of the study area is shown in Figure 3.7.

3.4.8 Rainfall Map

Rainfall is a major influencing factor for land sliding. Daily rainfall data was collected from nearby three rain gauges installed by Pakistan Meteorological Department. Using daily rainfall data, annual average rainfall maps were produced using interpolation techniques. The study area received 1177 mm to 1213 mm average rainfall per year in last five years (2008-2012). The values of precipitation were divided in to 5 equal classes: (a) 1177-1184, (b) 1185-1192 (c) 1193-1199, (d) 1200-1207 and (e) 1208-1214. Rainfall map of the study area is shown in Figure 3.8.

3.5 METHODOLOGY

Analytical hierarchy process (AHP) and weighted linear combination (WLC) were used to prepare landslide susceptibility map of the study area. Factor maps were prepared using remote sensing data and GIS techniques.

Data were collected from different organizations. It was in the form of scanned maps, processed satellite images and tabulated data. Maps were geo-referenced and digitized in ArcGIS in vector format. Satellite images were classified using supervised classification method in Erdas Imagine. Factors like slope, elevation, aspect and stream network of the study area were extracted using digital elevation model. Precipitation Data were in the tabular format which was converted in raster maps in ArcGIS. For analysis purpose, digitized vector maps were then converted into raster format using vector to raster conversion method in

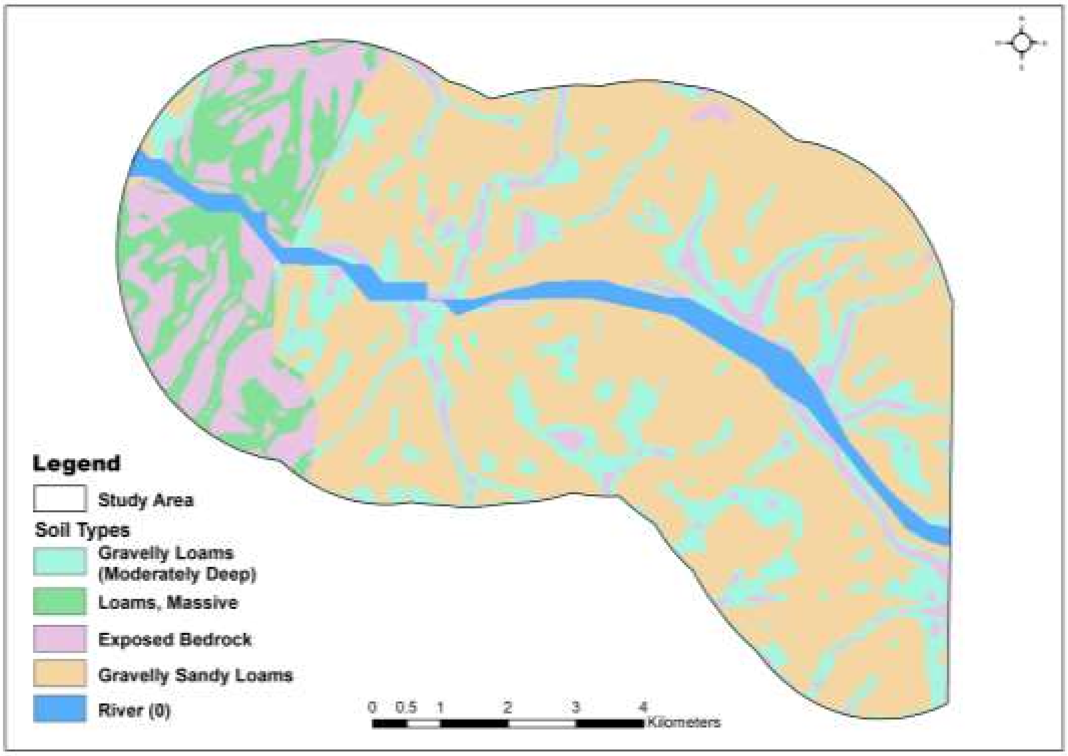

Figure 3.7. Geological map of the study area

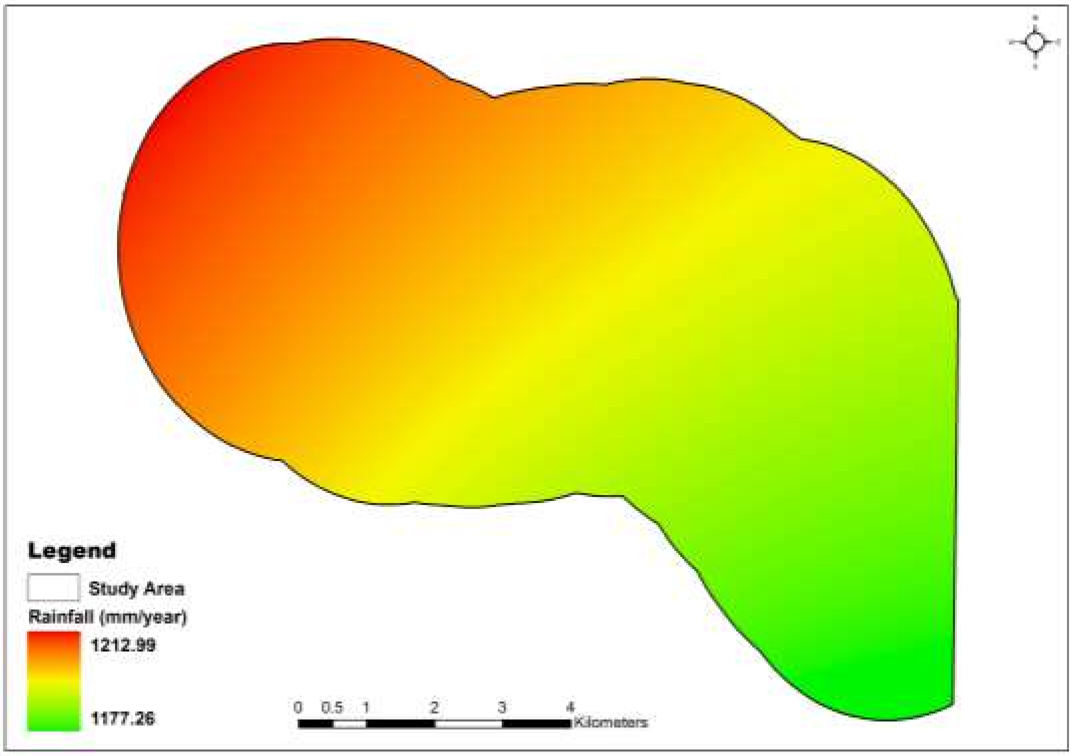

Figure 3.8. Rainfall map of the study area

ArcGIS. The pixel size was set to 15 by 15 meter. Classes in each factor map were determined and classified raster maps of factors were prepared. In AHP, comparison matrix of factor maps was developed and weights of factors extracted. Using weighted linear combination (WLC) method, weights of factor classes were combined and Landslide Susceptibility Index (LSI) was calculated. Values of LSI were classified into five landslide susceptibility zones in ArcGIS using natural breaks to prepare landslide susceptibility map of the study area. The classes were: (i) very high (ii) high (iii) moderate (iv) low and (v) very low. Google Earth imagery of the study area was visually interpreted to prepare landslide inventory map of the study area the accuracy of the resultant map was assessed by overlying this map on landslide susceptibility map.

3.5.1 Analytical Hierarchy Process

To solve general problems, analytical hierarchy process (AHP) was used. In this method, a matrix has been produced to compare different landslide factors. Saaty develop this method in 1980. The weights are determined by a pairwise comparison matrix for each criterion. In AHP, a relative value varies from 1 to 9 was assigned in the construction of pairwise comparison matrix, and each factor is rated against every other factor in intersecting cells. If the factor is on the vertical axis it is more important than factor on the horizontal axis and the values of factors varies between 1 and 9. On the other hand, the value varies between the reciprocals 1/2 and 1/9 (Ladas et al. 2005).

Analytical Hierarchy Process (AHP) consist on three steps

i. Development of the pair-wise comparison matrix

ii. Computation of the criterion weights

iii. Estimation of the consistency ratio

To prepare pairwise comparison matrix of factors involved in landslide occurrences, preferences among the factors were determined using literature review and expert knowledge. Saaty prepare a scale for set preferences among the factors. (Table 3.1)

Using these preferences a pairwise comparison matrix was prepared among the factors taken for this study and the weights were calculated for each factor. (Table 3.2)

For the estimation of consistency ratio, weighted sum vector was determined by multiplying the criterion weights with the values of the original pairwise comparison matrix and finally sum these values over rows. (Table 3.3)

For the estimation of consistency ratio, next, consistency vector was calculated by dividing the weighted sum vector over the criterion weights (Table 3.4)

Consistency ratio (CR) computed using this formula.

$$CR = CI/RI$$

Where

$$CI = \lambda - n/n - 1$$

$\lambda =$ Average of consistency vector

$\lambda =$ 8.8080+8.9155+8.9409+8.8686+8.6550+8.4442+8.0488+8.2400/8

$\lambda =$ 8.6151

$n =$ Number of factors used in the study

$CI = 8.6151 - 8/8 - 1 \qquad CI = 0.0878$

Table 3.1. Scale for pair-wise comparison

Intensity of importance	**Definition**
1	Equal Importance
2	Equal to moderate
3	Moderate importance
4	Moderate to strong
5	Strong
6	Strong to very strong
7	Very strong
8	Very strong to extremely strong
9	Extreme importance

Table 3.2. Pairwise comparison matrix

Name	Slope	Geology	LULC	Soil	Rainfall	Distance from Streams	Elevation	Aspect	Weight
Slope	0.369	0.438	0.404	0.361	0.311	0.266	0.224	0.187	**0.320**
Geology	0.184	0.219	0.269	0.271	0.249	0.221	0.192	0.187	**0.224**
LULC	0.123	0.109	0.134	0.180	0.187	0.177	0.160	0.145	**0.152**
Soil	0.092	0.073	0.067	0.090	0.124	0.177	0.192	0.145	**0.120**
Rainfall	0.074	0.054	0.044	0.045	0.062	0.088	0.096	0.104	**0.071**
Distance from Streams	0.061	0.043	0.033	0.022	0.031	0.044	0.096	0.104	**0.054**
Elevation	0.052	0.036	0.026	0.015	0.020	0.014	0.032	0.104	**0.037**
Aspect	0.041	0.024	0.019	0.012	0.012	0.008	0.006	0.020	**0.018**

Table 3.3. Weighted sum vector

Name	Slope	Geology	LULC	Soil	Rainfall	Distance from Streams	Elevation	Aspect	SUM
Slope	0.320	0.449	0.457	0.481	0.356	0.328	0.265	0.164	2.822
Geology	0.160	0.224	0.304	0.361	0.285	0.273	0.227	0.164	2.001
LULC	0.106	0.112	0.152	0.240	0.213	0.218	0.189	0.127	1.362
Soil	0.080	0.074	0.076	0.120	0.142	0.218	0.227	0.127	1.068
Rainfall	0.064	0.056	0.050	0.060	0.071	0.109	0.113	0.091	0.617
Distance from Streams	0.053	0.044	0.038	0.030	0.035	0.054	0.113	0.091	0.461
Elevation	0.045	0.037	0.030	0.020	0.023	0.018	0.037	0.091	0.305
Aspect	0.0356	0.024	0.021	0.017	0.014	0.010	0.007	0.018	0.150

Table 3.4. Consistency vector

Name	Sum/Weight	Consistency Vector
Slope	2.822/0.320	8.808
Geology	2.001/0.224	8.915
LULC	1.362/0.152	8.940
Soil	1.068/0.120	8.868
Rainfall	0.617/0.071	8.655
Distance from Streams	0.461/0.054	8.444
Elevation	0.305/0.037	8.048
Aspect	0.150/0.018	8.240

Table 3.5. Random index (RI) provided by Saaty

No. of Factors	RI	No. of Factors	RI
1	0.00	9	1.45
2	0.00	10	1.49
3	0.58	11	1.51
4	0.90	12	1.48
5	1.12	13	1.56
6	1.24	14	1.57
7	1.32	15	1.59
8	1.41		

RI is the random index provided by Saaty and it depends on the number of criterion (n) (Table 3.5). In this study eight factors used to prepare landslide susceptibility map therefore RI against eight was used in the formula for estimation of CR.

Putting values in the formula the CR was estimated as below:

$$CR = CI/RI$$

$$CR = 0.0878/1.41$$

$$CR = 0.062$$

If CR<0.10 the ratio indicates a reasonable level consistency

3.5.2 Weighted Linear Combination

Weighted linear combination is based on weighted average in which a common numeric range has been set among the factors to standardize them. After the standardization, factors layers are combined for composite map layer. Weights are assigned to each factor class according to relative dominant value. Any GIS system can be used having overlay capabilities to perform this analysis. Standardization of criterion factors is necessary to apply this method.

Weighted Linear Combination method (WLC) consists of two steps.

i. Rank Value Standardization

ii. Evaluation of landslide susceptibility index (LSI)

Rank Value Standardization was achieved by dividing each rank value by the maximum rank value for the specific factor and afterwards multiplies it by 100 for standardized rating

$$X'ij = Xij/Xjmax*100$$

Where

X'_{ij} = Standardized rank value for the *ith* class for the *jth* factor

X_{ij} = Primary rank value

X_{jmax} = Maximum rank value for the *jth* factor

100 = Standardized range

Using the factor weights (Table 3.2) of AHP and standardized ratings calculated for each factor class, computation of landslide susceptibility index (LSI) performed by the sum of each factor rating multiplied by each factor weight using the following Equation.

$$LSI = \sum Fw * Fr$$

Where

LSI = Landslide susceptibility index

Fw = Weight of each factor

Fr = Weights of each factor class

3.5.3 Methodology Flowchart

The methodology flow chart adopted in this study is shown below:

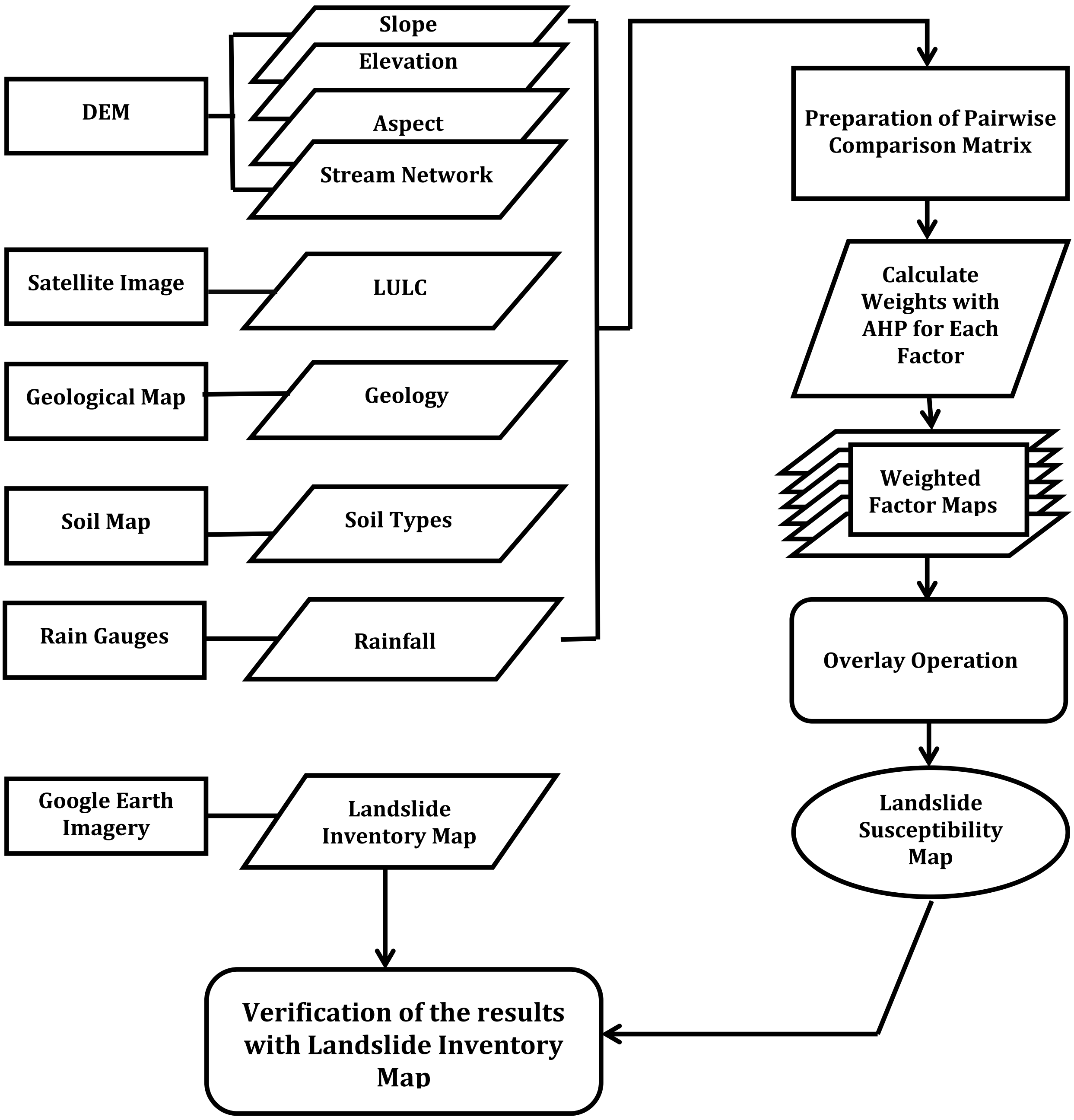

Figure 3.9: Flowchart of the research work methodology

Chapter 4

RESULTS AND DISCUSSION

The objectives of study on the basis of all the analysis are described in this chapter. To present the results of the study; maps, charts, statistical tables are included in this chapter. These include GIS analysis and short briefing of methods applies to carry out this research.

4.1 GIS ANALYSIS

A geographic information system allows managing and manipulating interactions between data and geographic locations. GIS technology has the ability to go beyond mapping and can be used to perform complex spatial analysis. It is possible to link interactions of environmental factors with geographical features to assess the impact of these factors on human beings. Eventually, GIS has aided the possibility to identify variables that would not be performed in distinctive data analysis.

4.1.1 Weighted factor maps

Weights were determined using analytical hierarchy process and expert knowledge and assigned to all the factors involved in preparing landslide susceptibility mapping covers aspect, elevation, slope, stream network, soil, geology, LULC and rainfall.

4.1.1.1 LULC weighted factor map

Seven major LULC classes have been identified in the study area performing supervised classification method in ERDAS IMAGINE. Bare land has been considered as the most susceptible land type causing landslides phenomenon therefore it was rated as the highest. While the dense conifer land type has lowest effect therefore it was rated as lowest in LULC weighted factor map. The ranks of other land cover types were in between these two LULC types shown in Table 4.1 and graphical representation of the LULC types shown in Figure 4.1.

4.1.1.2 Slope weighted factor map

Slope has been considered as the most important factor in landslide susceptibility mapping. As the slope increases, chance of its failure also increases. Two factors i.e. soil strength and thickness vary in different slopes and found in both failure and non-failure sites. (Borga, et al. 2002). Slope has been classified in 6 classes with 5 and 10 degree interval. Slopes <40° were ranked at highest value in assigning weights. Other slope classes are shown in Table 4.2. Slope weighted factor map of the study area is shown in Figure 4.2.

4.1.1.3 Elevation weighted factor map

The surface elevation was classified into five categories as shown in Figure 4.3. A huge number of anthropogenic actions and biophysical parameters are affected by slope. In response, slope failure and instability are mostly caused by these factors. (Vivas,1992). It is considered that soil characteristics are also disturbed by elevations. Elevation values ranges from 846 m to 1000 m have assigned lowest rank while the elevation values ranges from 1901 m to 2466 m have been given highest rank for landslide susceptibility. Weights of different elevation classes have been listed in Table 4.3.

4.1.1.4 Aspect weighted factor map

In the preparation of landslide susceptibility maps, the role of slope aspect is very significant. (Lee, 2005; Lee et al., 2004; Ercanoglu et al., 2004; Cevik and Topal, 2003; Saha et al., 2002; Nagarajan et al., 2000; Guzzetti et al., 1999).

Table 4.1: Weights of LULC factor classes

Factor	Factor Weight	Class	Rank	Standardized Rating	1-9 Rating
LULC	0.1524	Water	0	0	0
		Dense conifer	1	16	1
		Medium conifer	2	33	3
		Sparse conifer	3	49	4
		Grasses/Shrubs	4	67	6
		Settlements	5	83	8
		Bare land	6	100	9

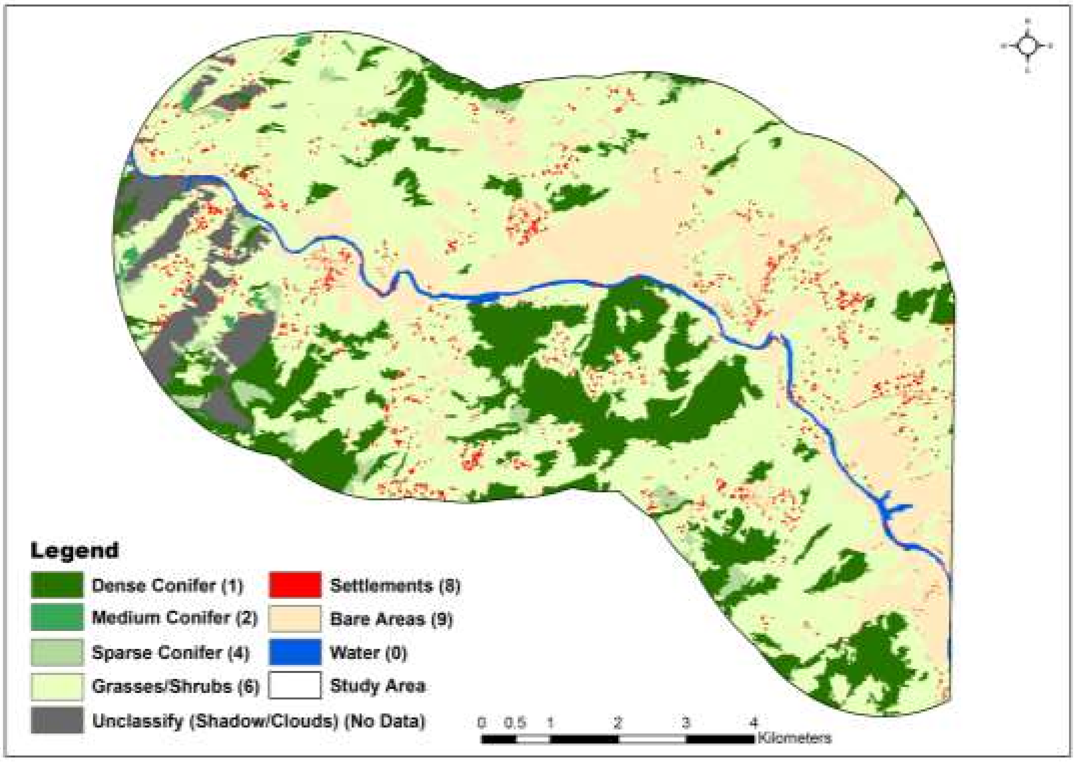

Figure 4.1: LULC weighted factor map of the study area

Table 4.2: Weights of slope factor classes

Factor	Factor Weight	Class	Rank	Standardized Rating	1-9 Rating
Slope (Degree)	0.3205	0-5	1	16	1
		5.1-10	2	33	3
		10.1-20	3	49	4
		20.1-30	4	67	6
		30.1-40	5	83	8
		<40	6	100	9

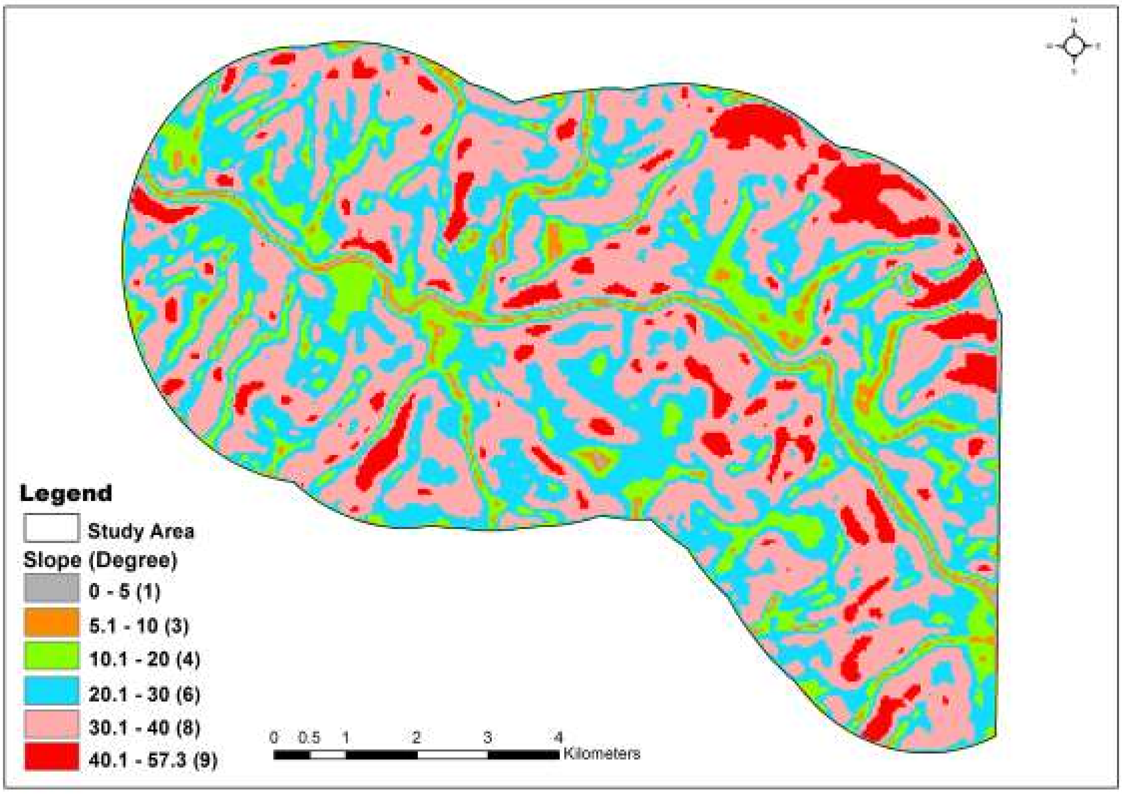

Figure 4.2. Slope weighted factor map of the study area

Table 4.3: Weights of elevation factor classes

Factor	Factor Weight	Class	Rank	Standardized Rating	1-9 Rating
Elevation	0.0379	841-1000m	1	20	2
		1001-1300m	2	40	4
		1301-1600m	3	60	5
		1601-1900m	4	80	7
		1901-2474m	5	100	9

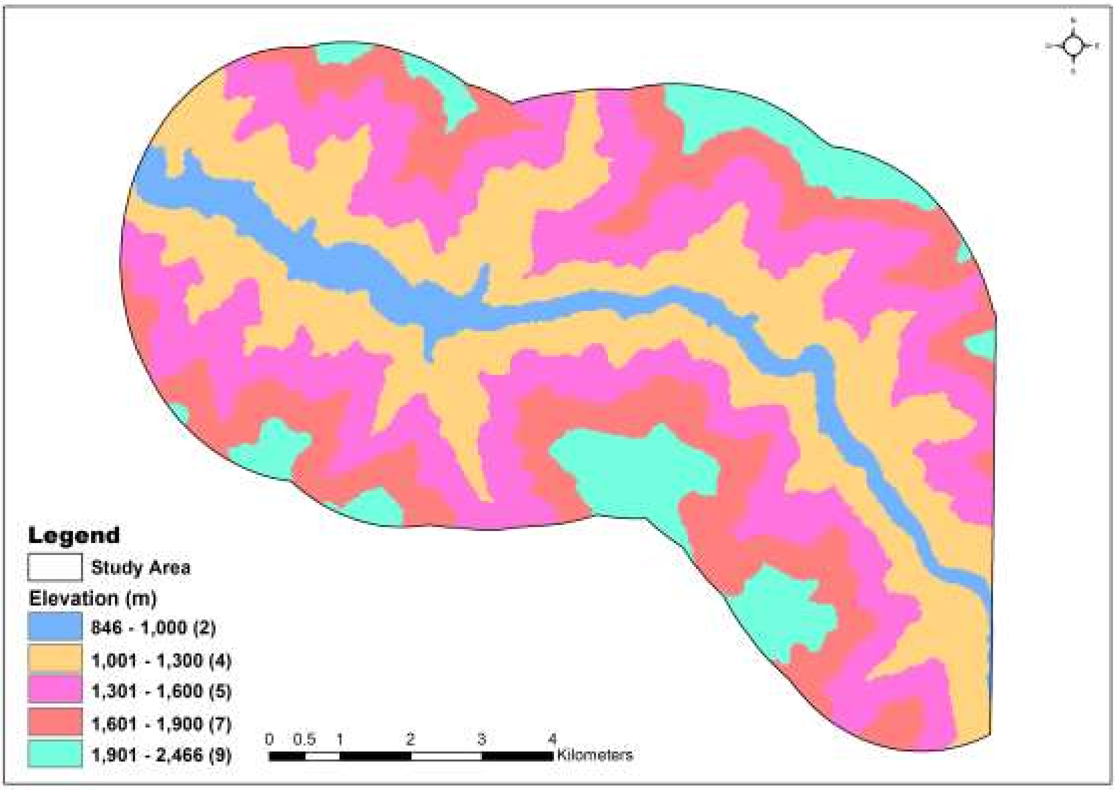

Figure 4.3. Elevation weighted factor map of the study area

Landslide occurrences may be controlled by parameters that are directly related to slope aspect, these parameters are drying winds, exposure to sunlight, rainfall, and discontinuities (Komac, 2006; Suzen and Doyuran, 2004; Cevik and Topal, 2003; Dai et al., 2001). The purpose of preparing aspect map in this study was to highlight relationship between landslides and aspect. To identify the potential site prone to landslides analyses were performed on data of landslide known locations and aspect map. Aspect classes are listed in Table 4.4 and map is shown in Figure 4.4.

4.1.1.5 Distance from streams weighted factor map

Hilly areas face number of landslides occurrences due to the erosion activity caused by dense drainage system. The distance from river and stream network is therefore considered one of the significant factors in symbolizing vulnerable terrain. Therefore, data layer comprising of stream network of the study area has been prepared using digital elevation model. Saturation point of the mass covering slopes is an important factor that causes the slope stability. Saturation degree disturbs the slope stability in lower part of mass along drainage streams. (Yalcin, 2005; Cevik and Topal, 2003; Saha et al., 2002; Dai et al., 2001; Gokceoglu and Aksoy, 1996). The closest buffer which comprises on 50 m around the streams has largest rank value while the buffer having distance from 100 m to 150 m have lowest rank value. Table 4.5 showing the classes of stream network buffers and Figure 4.5 showing the map of stream network of the study area with weighted buffers.

Table 4.4. Weights of aspect factor classes

Factor	Factor Weight	Class	Rank	Standardized Rating	1-9 Rating
Aspect	0.0183	All Others	1	33	3
		Southeast	2	67	6
		Southwest	2	67	6
		South	3	100	9

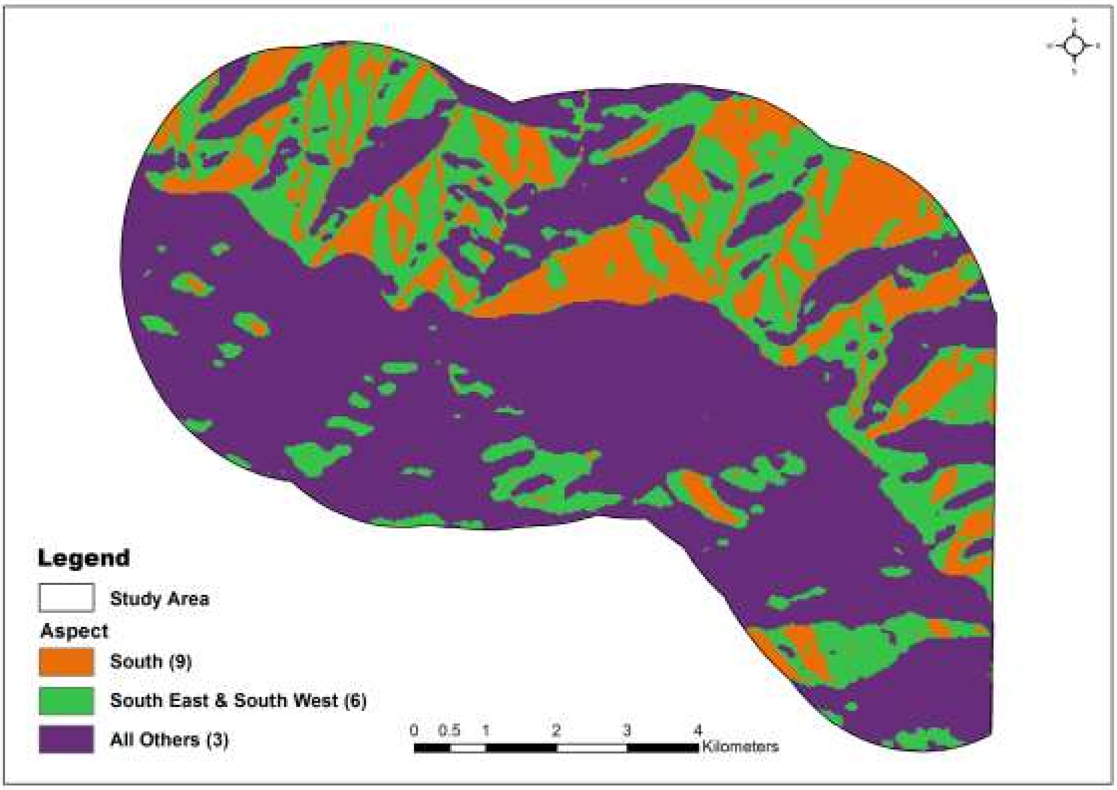

Figure 4.4. Aspect weighted factor map of the study area

Table 4.5: Weights of distance from streams factor classes

Factor	Factor Weight	Class	Rank	Standardized Rating	1-9 Rating
Distance from Streams	0.0547	101-150m	1	33	3
		51-100m	2	67	6
		0-50m	3	100	9

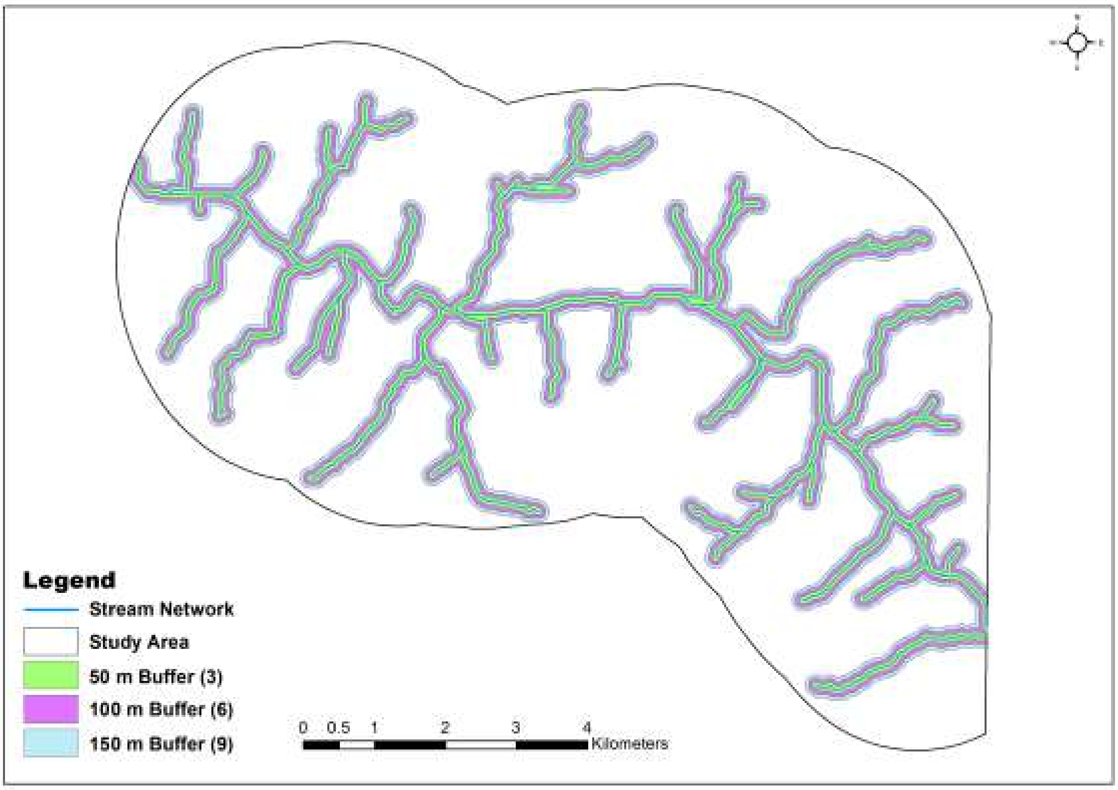

Figure 4.5. Distance from streams weighted factor map of the study area

4.1.1.6 Geology weighted factor map

In landslide hazard mapping, another important parameter is geological setup in the study area. Natural conditions and erosion agents works differently on rocks to erode them for mass movement. The strength of material depends on the composition and structure of the rocks. Driving forces face more resistance against the stronger rocks compared to weaker rocks. Therefore stronger rocks are less susceptible to landslides. In study area it is found that Panjal metasediments rock type has most susceptibility for landslide occurrence. Therefore it has ranked highest value in assigning weights. Murree formation has spread large part of study area but due to its composition it has less susceptibility. Geological units of the study area has been listed in Table 4.6 with assigned weights. Figure 4.6 showing the map of geological units of the study area.

4.1.1.7 Soil weighted factor map

Landslide studies cannot be completed without studying the effect of soil. To identify landslide prone areas Liener et al. (1996) used soil properties as one of the main factor. Landslide distribution also depends on soil depth and cohesiveness. The effect of material and thickness are the cause of difference between shallow and deep-seated landslide in steeper slopes. Gravelly Loams soil type has been considered the most susceptible type for land sliding in the study area. Soil classes of the study area has been listed in Table 4.7 with assigned weights. Figure 4.7 showing the map of soil classes found in the study area.

4.1.1.8 Rainfall weighted factor map

Rainfall is generally considered as the triggering factor for land sliding. The study area has been strongly affected by rainy season of tropical monsoon

Table 4.6. Weights of geology factor classes

Factor	Weight	Class	Rank	Standardized Rating	1-9 Rating
Geology	0.2245	Murree Formation	1	33	3
		Stream Channel Deposits	1	33	3
		Terrace Deposits	2	67	6
		Panjal Volcanics	2	67	6
		Panjal Metasediments	3	100	9

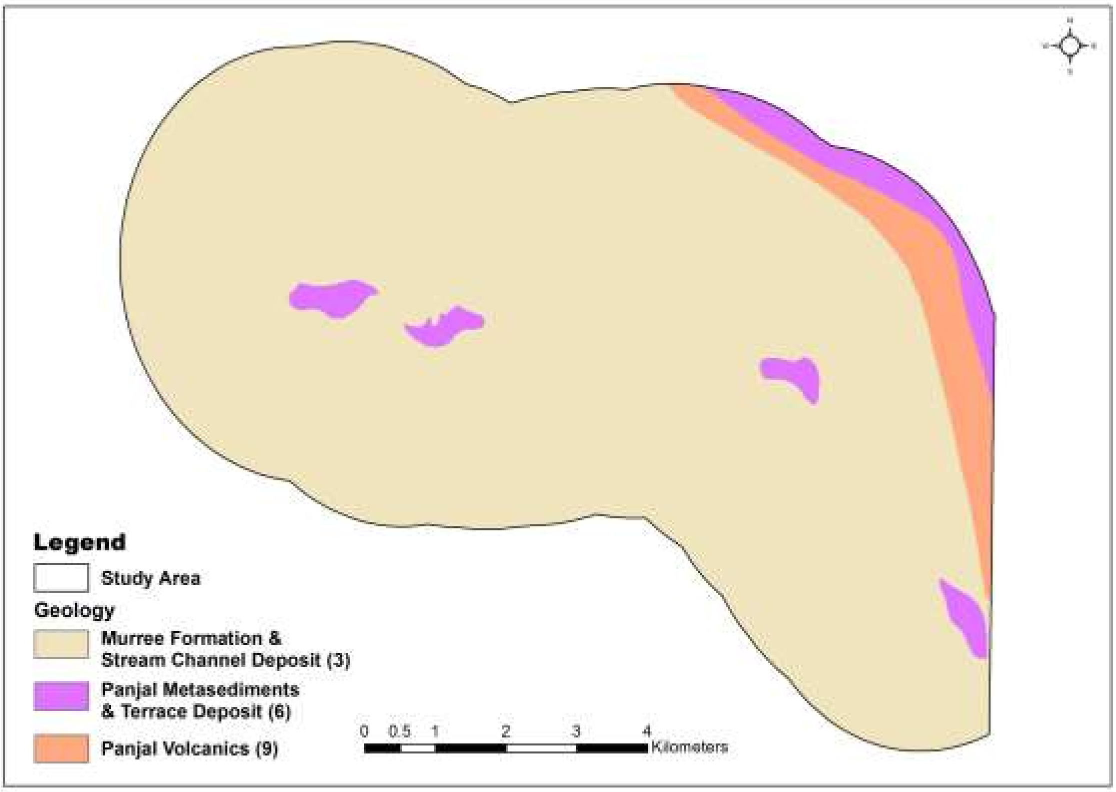

Figure 4.6. Geology weighted factor map of the study area

Table 4.7. Weights of soil factor classes

Factor	Factor Weight	Soil Characteristics	Series, phase or misc. area	Limitation and hazard	Rank	Stand. Rating	1-9 Rating
Soil Type	0.1205	Gravelly sandy Loams	AHL	Moderate erosion Very limited soil depth	1	33	3
		Exposed bedrock	Rockland	Severe erosion; Lack of soil cover	2	67	6
		Loams; massive; very shallow	Maira	Moderate erosion, very limited soil thickness	2	67	6
		Gravelly loams; Moderately deep	Shaldar moderatel y deep	Minor erosion Limited soil depth	3	100	9

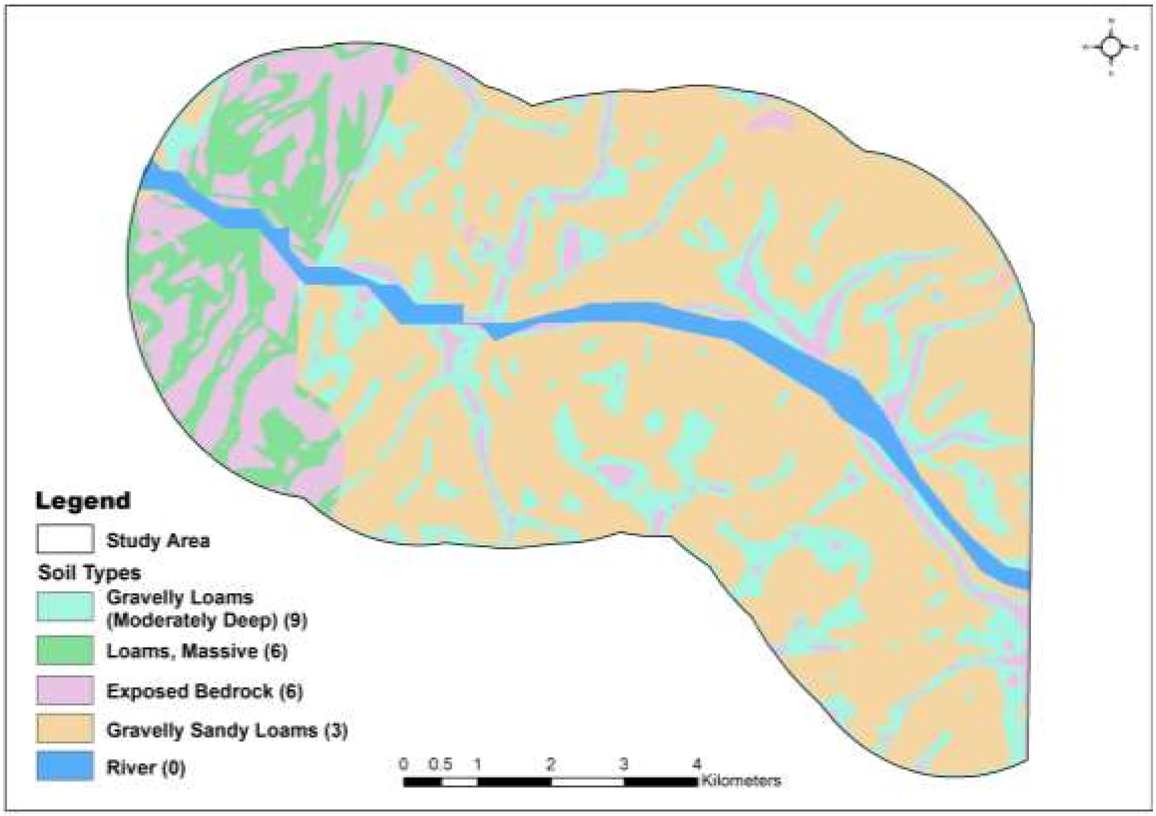

Figure 4.7. Soil weighted factor map of the study area

Table 4.8: Weights of rainfall factor classes

Factor	Weight	Class	Rank	Standardized Rating	1-9 Rating
Rainfall (mm/year)	0.0713	1177-1184	1	20	2
		1185-1192	2	40	4
		1193-1199	3	60	5
		1200-1207	4	80	7
		1207-1213	5	100	9

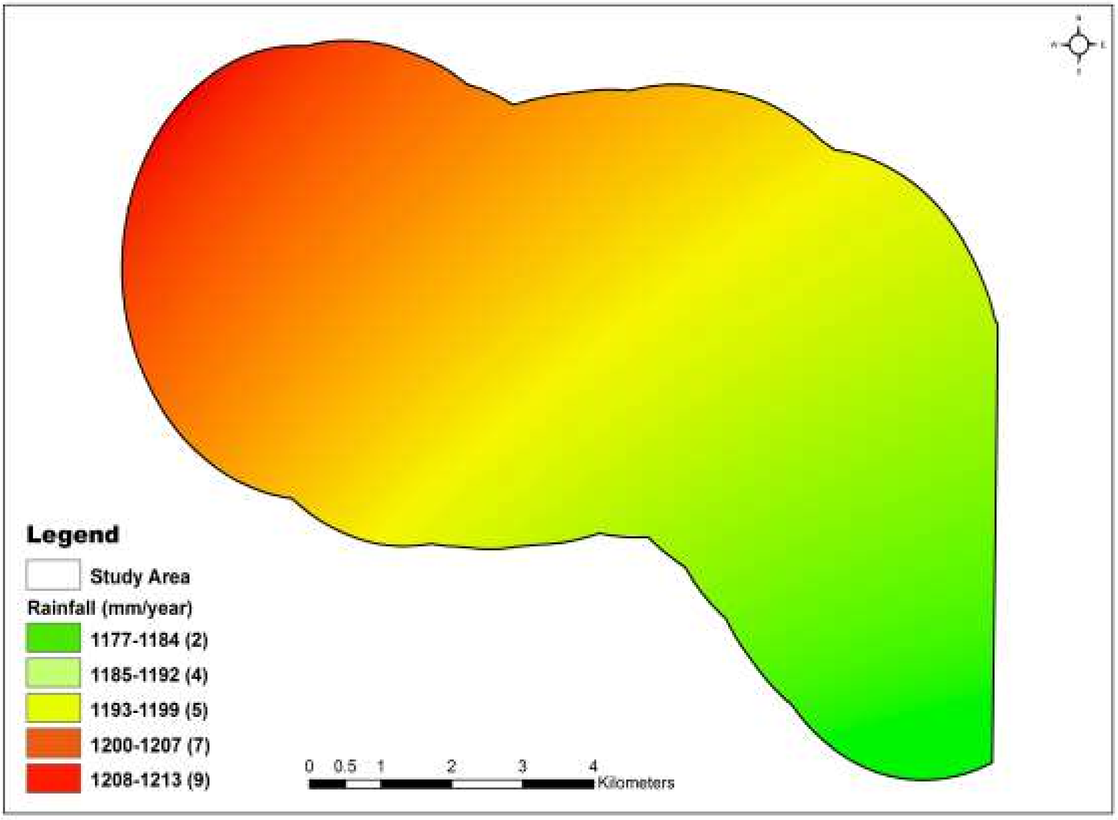

Figure 4.8: Rainfall weighted factor map of the study area

climate. In landslide susceptibility mapping model, the significance of rainfall factor is much important. Four kinds of rainfall factors for landslide hazard mapping are normally used: total rainfall, short-term intensity, antecedent wetness, and storm duration. Because, the selection of rainfall type data should be based on considerations of relevance, availability and scale attributes. For this study, long-term annual total precipitation (LATP) is selected as the rainfall factor for landslide analysis, because it gives more accurate results. It is also found that precipitation is strongly linked to elevation, which could not be taken into account in preparing the rainfall factor map in this study, due to lack of data that enables to quantify this relationship more precisely. Division of rainfall is listed in Table 4.8 with assigned weights and the map has been shown in Figure 4.8.

4.2. ANALYTICAL HIERARCHY PROCESS AND LANDSLIDE SUSCEPTIBILITY MAP

Factor and class weights with calculated consistency ratio (CR) of pairwise comparison matrix are shown in Table 3.2. In AHP, consistency ratio is used to check the consistency of factors involved in landslide occurrence and depends on the number of parameters. The computed weights are acceptable in the matrix if the consistency ratio is less than 0.1. The average of index gained by generation of random matrices is called random index. If the weights are generated randomly, the CR will close to 0 (Saaty, 1980; 1994).

In AHP analysis, models that have CR lees than 0.1 are accepted and in case of CR greater than 0.1 they rejected automatically (Narumon I., et al. 2010). Values of factor weights are defined using AHP. Landslide susceptibility calculated using acquired weights with weighted linear sum procedure (Voogd, 1983). In this study, the acquired CR is 0.062 showing a reasonable level of consistency. It shows that pairwise comparison performed accurately. In the study, it is found that slope and aspect have the highest and lowest weight respectively. (Table 3.2)

In the computation of LSI, values vary from minimum 2.19 to maximum 7.78. The results have relative susceptibility to landslide occurrence and higher index shows more susceptibility to landslide. High LSI values show the higher susceptibility to landslides and lower values show less susceptibility to landslides. A landslide susceptibility map showing five different classes prepared based on natural breaks in LSI. These classes are named as very high susceptibility (VHS), high susceptibility (HS), moderate susceptibility (MS), low susceptibility (LS) and very low susceptibility (VLS) zones (Figure 4.9), and areas percentage of each susceptible zone is shown in Table 4.10

4.3 VERIFICATION OF THE RESULTS

Finally, the susceptibility maps prepared from AHP was verified using 14 known landslide locations extracted by Google Earth Imagery. The result of verification is shown in Table 4.11. It is found that 51.9 percent of landslides fall in very high susceptible zone. In high susceptible zone 24.5 percent of known landslides fall. Moderate susceptible zone has 15.98 percent of known landslides. 4.89 percent of landslides fall in low susceptible zone. The least percent of known landslides fall in very low susceptible area with only 2.73 percent (Figure 4.10). Zonal histogram of the 14 known landslides shown in Figure 4.11.

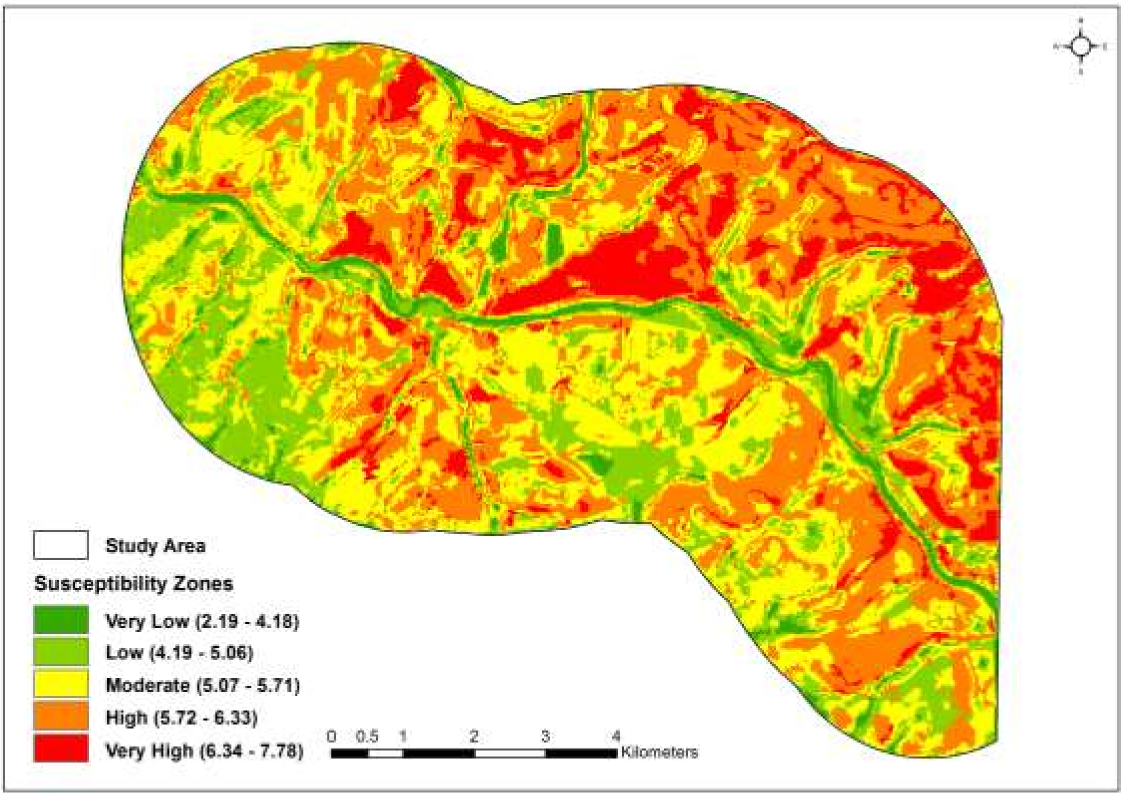

Figure 4.9. Landslide Susceptibility map of the study area.

Table 4.9. Percentage of each susceptible zone's covering area.

Susceptible Zone	Pixels	Susceptibility Index Value	Area (sq.km)	Area (%)
Very Low	15609	2.19 – 4.18	3.512	4.42
Low	57373	4.19 – 5.06	12.909	16.25
Moderate	112835	5.07 – 5.71	25.388	31.97
High	114262	5.72 – 6.33	25.709	32.37
Very High	52895	6.34 – 7.78	11.901	14.99

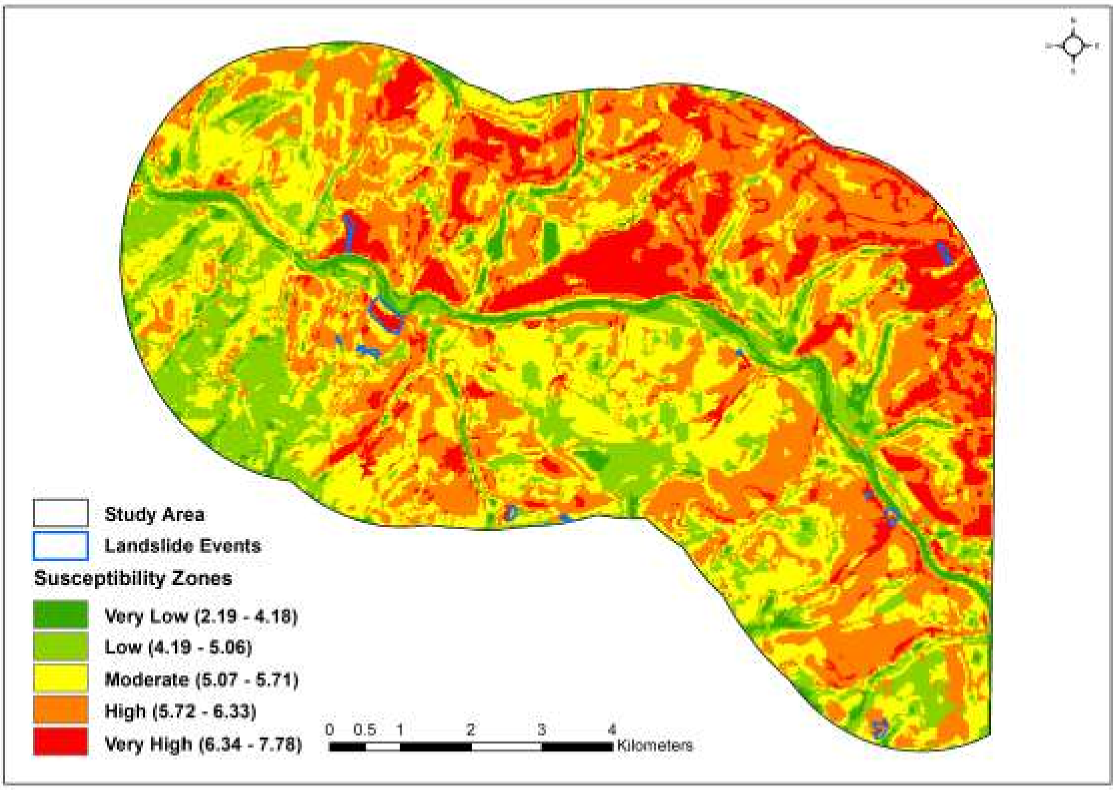

Figure 4.10: Landslide susceptibility map of the study area with known landslide locations

Table 4.10: Number of pixels and percentage of areas occupied by each landslide susceptible zone

Landslide (LS) No.	Very Low	Low	Moderate	High	Very High
LS 1	0	1	31	67	34
LS 2	0	10	5	5	17
LS 3	0	15	29	14	18
LS 4	0	0	0	13	0
LS 5	0	0	0	31	0
LS 6	0	0	0	6	0
LS 7	0	0	10	1	0
LS 8	0	0	5	13	0
LS 9	18	9	16	41	33
LS 10	0	0	0	1	9
LS 11	0	0	7	8	2
LS 12	15	24	90	89	339
LS 13	0	0	0	1	101
LS 14	0	0	0	6	74
Total	33	59	193	296	627
Percentage	**2.73**	**4.89**	**15.98**	**24.5**	**51.9**

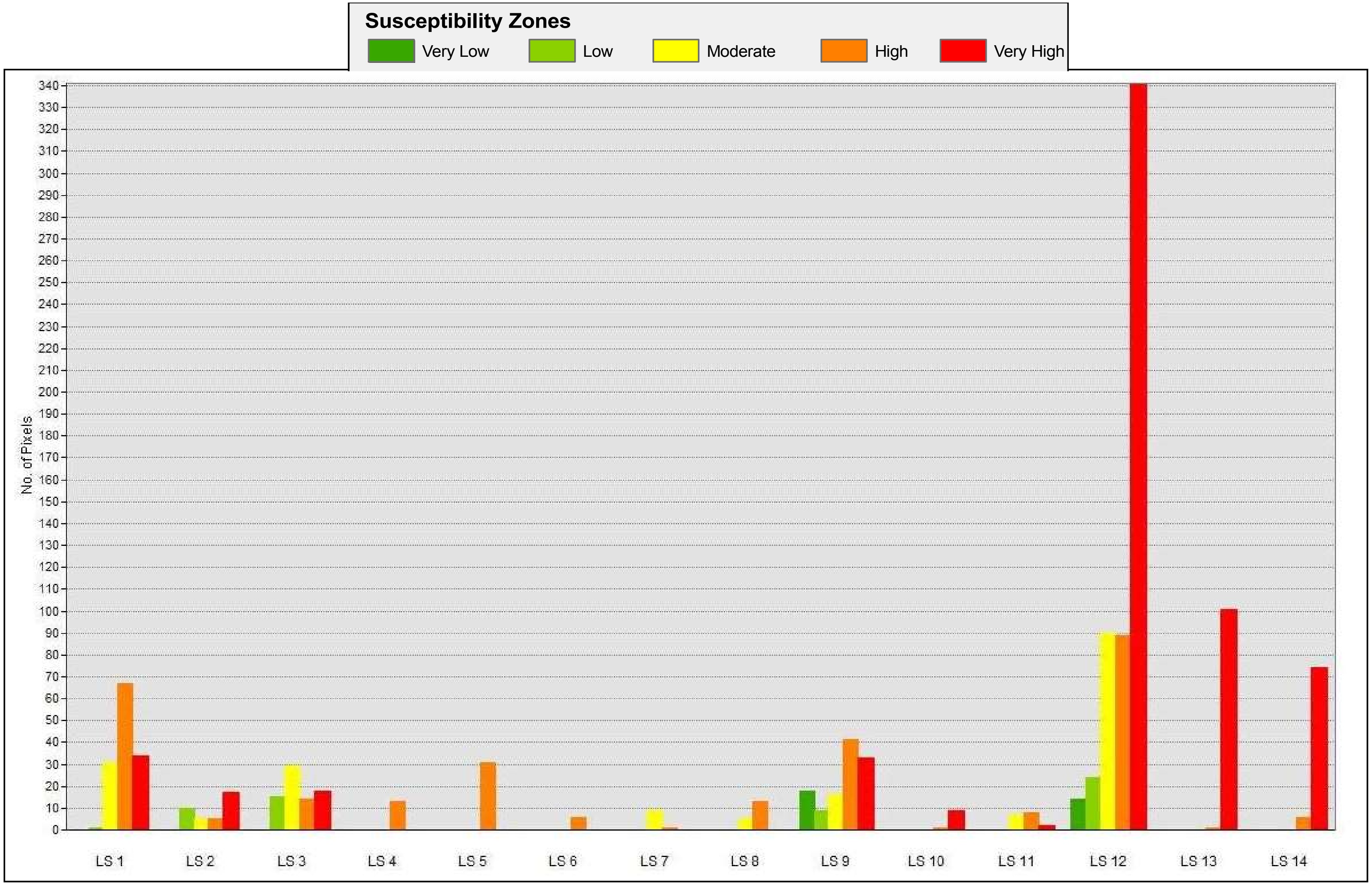

Figure 4.11: Histogram of each known landslide location

Chapter 5

CONCLUSION AND RECOMENDATIONS

In this study, landslide susceptibility map of an area located in district Muzaffarabad (AJK) prepared using analytical hierarchy process (AHP). Eight landslide inducing factors namely elevation, aspect, slope, distance from streams, geology, soil, precipitation and land use/land cover (LULC) were used. Digital elevation model was used to extract first four factors of the study area; geology and soil were extracted from published maps while LULC map was derived from ALOS satellite images. Weights were assigned to factors and their classes according to requirements of the model used.

These assigned weights for each factor class were then combined to prepare susceptibility maps (Figure 4.9). From Table 4.10, about 14.99%, 32.37%, and 31.97% of the study area were classified to be in very high, high and moderate susceptible zones respectively.

Classes of LULC like bare land, grasses and shrubs are the most susceptible for landslide susceptibility. Slope <40 degree has most susceptibility for land sliding in slope factor. In geology, the most susceptible classes are Panjal Volcanics and Panjal Metasediments respectively. Gravelly sandy loams have found the most susceptible soil type in this research.

Based on results of the pair-wise comparison using AHP method (Table 3.2), slope, geology and LULC are the most influencing factors to induce land sliding activity in the study area with 0.320, 0.224, and 0.152 weights respectively. And the three least influencing factors are distance from streams (0.054), elevation (0.034), and aspect (0.018).

It is found that about 47 % of study area falls in high and very high susceptible zones. Therefore, infrastructure constructions and master planning of economic projects should carefully be started in these zones.

It is found that only 5.02 % of dense conifer area is susceptible for landslides. Therefore, forested area should be increased to minimize the chances of landslides in bare land, grasses and shrubs areas which cover almost 60 % of the study area.

Rescue/emergency centers should be established near these susceptible areas to reduce the damages in case of landslide hazard.

REFERENCES

Akgun, A. and Bulut, F. (2007). GIS-based landslide susceptibility for Arsin-Yomra (Trabzon, North Turkey) region. Environ Geol, 51(8):1377–1387

Aleotti, P. and Chowdhury, R. (1999). Landslide hazard assessment: summary review and new perspectives. Bulletin of Engineering Geology and the Environment, 58, 1, 21 – 44.

Ayalew, L. and Yamagishi, H. (2004). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. Geomorphology 65 (2005) 15–31

Ayalew, L., YAmagishi, H, Manti, H., and Kanno, T., 2005. Landslides in Sado Island of Japan: Part n. GIS-based susceptibility mapping with comparisons of results from two methods and verifications, Engineering Geology, 81, 432-445.

Barredo, J.I., Benavides, A., Hervas, .I., and Van Westen, C..r., 2000. Comparing heuristic landslide hazard assessment techniques using GIS in the Trijana basin, Gran Canaria Island, Spain, Int. J Appl. Earth Obser. Geoinj:, 2,9-23.

Bijukchhen, S.M., Gyawali, B.R., Kayashtha, P. and Dhital, M.R. (2009). Delineation of landslide susceptibility zones using heuristic method: A case study from Ghurmi-Dhad Khola, East Nepal. Journal of South Asia Disaster Studies.2(2)

Carrarra, A., Cardinali, M., Detti, R., Guzzeti, F., Pasqui, V., and Reichenbach, P, 1991. GIS techniques and statistical models in evaluating landslide hazard, Eearth Surface Processes and landforms, 16(5),427-445.

Dahal, R.K., Hasegawa, S., Nonomura A., Yamanaka, M., Masuda, T., Nishino K., (2008). GIS-based weights-of-evidence modelling of rainfall-induced landslides in small catchments for landslide susceptibility mapping, Environmental Geology 54 (2) 314-324.

Dhakal, A.S., Amada, T., and Aniya M., (1999). Landslide hazard mapping and the application of GIS in the Kulekhani watershed, Nepal. Mountain Research and Development, Vol. 19, pp. 3-16.

Franks, C.A.M., (1998). Characteristics of some rainfall-induced landslides on natural slopes, Lantau Island, Hong Kong. Quarterly Journal of Engineering Geology, Vol. 32, pp. 247-259.

Gupta, R.P. and Joshi, B.C., (1989). Landslide hazard zoning using the GIS approach: A case study from the Ramganga catchment, Himalayas. Engineering Geology, Vol. 28, pp. 119-131.

Intarawichian, N. and Dasananda, S. (2010). Analytical hierarchy process for landslide susceptibility mapping in Lower Mae Chaem watershed, Northern Thailand. Suranaree J. Sci. Technol. 17(3): 277-292.

Kanungo, D. P., Arora, M. K., Sarkar, S. and Gupta, R. P. (2009). Landslide Susceptibility Zonation (LSZ) Mapping - A Review. Journal of South Asia Disaster Studies.2(1)

Komac, M. (2006). A landslide susceptibility model using the Analytical Hierarchy Process method and multivariate statistics in perialpine Slovenia. Geomorphology, 74, 1 – 4, 17 – 28.

Malczewski, J., 2000. On the use of Weighted Linear Combination Method in GIS: common and best practice approaches, Transactions in GIS, 4(I), 5-22.

Malczewski, J., 2006. GIS-based multicriteria decision analysis: a survey of the literature, International Journal ofGeographical Iriformation Science, 20(7), 703-726.

Mancini, F., Ceppi, C. and Ritrovato, G. (2010). GIS and statistical analysis for landslide susceptibility mapping in the Daunia area, Italy. Nat. Hazards Earth Syst. Sci., 10, 1851–1864.

Pareta, K. and Pareta, U. (2012). Landslide Modeling and Susceptibility Mapping of Giri River Watershed, Himachal Pradesh (India). International Journal of Science and Technology 1(2).

Raju, P.P., and Saibaba, J., (1999). Landslide hazard zonation mapping using remote sensing and geographic information system techniques - A case study of Pithoragarh Area, Uttar Pradesh. IEEE Transactions on Geosciences and Remote Sensing, pp. 577-579.

Sarkar, S. and Kanungo, D.P. (2004). An Integrated Approach for Landslide Susceptibility Mapping Using Remote Sensing and GIS. Photogrammetric Engineering & Remote Sensing 70(5) 617–625.

Varnes, D.J. (1984). Landslide Hazard Zonation: a Review of Principles and Practice. Natural Hazards. No. 3. 1st ed. UNESCO, Paris, France, 63p.