Landslide Susceptibilty Mapping of Rawalakot Using Remote Sensing and GIS

By

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(NUST201362930MSCEE62513F)

A thesis submitted in partial fulfillment of the requirements for degree of Master of Science in Remote Sensing and GIS

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December, 2015

CERTIFICATE

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Landslide Susceptibilty Mapping of Rawalakot Using Remote Sensing and GIS.

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DEDICATION

I dedicate this research to my parents, brothers and sister for their moral support, strength, encouragement and prayers. Whose effort and sacrifices has made my dream of having this degree a reality

ACKNOWLEDGEMENTS

Apart from my efforts, the success of this project depends largely on the encouragement and guidelines of many others. I take this opportunity to express my gratitude to the people who have been instrumental in the successful completion of this project.

In the first place, therefore, I express my utmost thanks to Almighty Allah the omnipresent and the creator of the worlds, who has endowed us brain and instable instinct construction of knowledge and body to accomplish our work in the form of this project report.

I offer my gratitude to the last Prophet MUHAMMAD (Sallallaho Alaihe Wasallam), who has given the lesson of LOVE, HUMANITY, PARITY, and JUSTICE and also broke the cage of servitude through His golden sayings; to seek knowledge is obligatory for every Muslims.

I would like to gratefully acknowledge my supervisor Dr. Javed Iqbal for the valuable guidance and advice. His willingness to motivate me contributed tremendously to my project. He provided me with direction, technical support and became more of a mentor, than a professor. Without his guidance and encouragement this project would not have materialized.

I remain indebted to the committee members Dr. Ejaz Hussain-IGIS, Mr. Ehtisham Khalid-NDMA and especially Mr. Ahsan Mehboob-IGIS who encouraged me in the first place for this research.

My appreciation goes to the entire faculty, staff of IGIS especially students of MS 13 for all support and guidance they provided me during the period of this research. I extend my thanks to Mr. Sajid–IGIS and department staff for facilitating me in every manner they can.

I am sincerely obliged to Fazaia Welfare Scheme Scholarship (FEWS) for the award which helped to alleviate my financial burden needed to complete my postgraduate studies. I also acknowledge NDMA and PMD for the provision of free data which I used in this project.

I have no words to express my feelings and gratitude for my dignified Parents, who supported me in every stage of my life. Their prayers helped me to become what I am today. I am indebted to my parents, my every family member and all friends for their moral support and encouragement when it was required the most.

Zahra Hassan

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Abbreviation	**Explanation**
SPI	Stream Power Index
TWI	Topographic Wetness Index
LULC	Land Use Land Cover
WLC	Weighted Linear Combination
DEM	Digital Elevation Model
SRTM	Shuttle Radar Topography Mission
AHP	Analytical Hierarchy Process
SPSS	Statistical Package for the Social Sciences
MCDM	Multi-Criteria Decision Making
LSI	Landslide Susceptibility Index
OLI	Operational Land Imager

ABSTRACT

Landslide susceptibility mapping is one of the most important researches in the landslide prone areas. The aim of the study was to produce landslide susceptibility maps based on GIS modeling and to conduct field surveys to get the local community's point of view about the landslides. The area selected for this purpose was Rawalakot, located in district Poonch, Azad Kashmir. It is a mountainous region with catastrophic landslides occurrences that pose a serious threat to the infrastructure. Landslide susceptibility index maps were prepared utilizing different parameters namely topographic (slope, aspect, elevation, plan curvature, land use/land cover etc.); hydrological (distance from streams, SPI, TWI, precipitation etc.) and geological (lithology, distance from faults, distance from roads etc.) in GIS environment. All the parameter layers were assigned a certain weight and score using an analytical hierarchical process (AHP) based on heuristic approach and weighted overlay combination (WLC) to produce the final landslide susceptibility index map. AHP weights with 0.04 threshold consistency ratio (CR) values were used for identification of four different landslide susceptibility zones i.e. low, moderate, high and very high. Results showed that these zones covered 3 %, 33%, 45 % and 18% of the total area, respectively. The results showed that factors that contributed most in triggering the landslides were slope, lithology, rainfall, distance from thrusts, and land-cover, respectively. All these parameters combined showed that 63% of the total area of Rawalakot lies in the highly susceptible zone. Local community based field survey revealed that standard building codes should be adopted for construction of infrastructure in the area. The results of this study could be shared with national disaster management authority and other relevant agencies for designing mitigation strategies of landslides prone areas mapped in this study.

Chapter 1

INTRODUCTION

Natural hazards include, landslides, floods, avalanches, earthquake, tsunamis and extreme meteorological events. Mountainous areas frequently expose to serious natural hazards in the form of landslides which cause massive damage to human lives, their assets and natural resources. The loss of human lives, indemnities of property, severe human injuries and collapse of business activities are main consequence of landslide hazards (Varnes, 1984). A 0.5% of the gross national product per year of developing countries has been vanished due to landslides (Gorsevski et al., 2003). Losses can be minimized to some extent if we have awareness and knowledge about the possibly landslides susceptible areas. Landslide susceptibility map can present the evidence and information regarding landslide prone areas.

Different natural hazards have tendency to combine, superimpose and chain-up their effects (MARJANOVIĆ, 2013) e.g. an earthquake near the coastline can bring a tsunami wave, and they both can then initiate landslides, result in subsidence, or cause technological and other hazards, and in turn, completely devastate an area (like in a tragic episode that stroke Pakistan in October 2005 and Japan in 2011). In such scenarios, the component-wise effects of each hazard is challenging. Floods, earthquakes, landslides, and volcanoes are the most common form of natural disasters. In this study, the landslides phenomenon is discussed in detail and remote sensing based products for the susceptibility are presented.

In terms of its broad effects, landslide are considered as third kind of natural hazard. It causes billions of dollars in destruction and thousands of life fatalities every year worldwide. Like many other developing countries, Pakistan has been frequently subject to a variety of natural hazards including landslides having sizable impact on rural (or national) economy. The bulk of landslide phenomena occur in the Northern part of the country, inflicting occasionally significant damages upon settlements and road networks due to its exceedingly rough and rugged topography. This region comprises of three very high mountain ranges which have caused from the northward up-drift of the Indian plate and its hitting with the Asian Plate: the Hindu Kush, the Karakoram and the High Himalayas Mountain. Northern areas covers 72, 496 km2 area with high snow covered peaks varying from 1000-8000 meter a.s.l. (Its Pakistan, n.d.). These ranges are seismically active areas at the margin between two striking continents (Billington et al., 1977; Quittmeyer and Jacob, 1979; Barazangi and Ni, 1982; Replumaz and Tapponnier, 2003). Due to rapidly changing climate, glacial erosion, intense rainfalls and increased population pressure, the occurrence of the landslide events has significantly increased in the Himalaya and Karakoram Ranges.

Landslides are basically the mass movement e.g. rock fall, debris flow or slope failure. Different external or internal factors may trigger landslides. The information of the composite factors and parameters inducing landslides about an area is necessary for the susceptibility mapping. The quantity and value of data is associated with the consistency of the landslide vulnerability map. The consistency of result is also influenced by the scale and the selection of the appropriate analysis and modeling procedures. Variety of quantitative and qualitative methods can be used to formulate these maps (Guzzetti et al., 1999; Soeters et al., 1996 and Aleotti et al., 1999). Formerly landslide vulnerability maps were produced using qualitative methods like overlaying the geological and morphological slope characteristics on landslide records (Nielsen et al., 1979). AHP, bivariate, multivariate, fuzzy logic, logistics regression, artificial neural network and other methods are now used for fundamental assessments.

It is beneficial to combine computer-based tools in landslide risk mapping, like geographic information system, spatial analysis and remote sensing. Burrough and McDonnel (1998) defined GIS as an influential system for spatial data management, storing, recovering, presenting and its assembling, developed hazard/risk incidence models are likely to produce using this knowledge by varying the input parameter and to find the results. By using accessible spatiotemporal information, this system can also store, check and treat various landslide studies. Some of the input parameters can be obtained from satellite images. With the development in competent digital computing capacities, the remote sensing data and their examination techniques have achieved extensive importance. Remote sensing and ground based information can be used to obtain the spatial and time-based thematic evidence for studying landslide prone zones. This can be very well proficient by means of GIS which has the capability to manage the enormous spatial data. The influence of controlling parameters on landslide incidence can be assessed with the aid of GIS to integrate various layers of spatial data. Presently, numerous quantitative and qualitative technique can be used in GIS environment for landslide vulnerability. For regional evaluation, it is found that expert judgment based qualitative approaches are very beneficial (Aleotti et al., 1999 and Soeters et al., 1996).

Quantitative procedures used the association between landslides and its controlling variables (Guzzetti et al., 1999).

In this research, the two different approaches specifically, AHP and WLC models are used to produce landslide vulnerability map of the research area. AHP is principal technique which is semi-qualitative in nature; influencing features involved in landslides are matched pairwise in a matrix for landslide vulnerability mapping. AHP is recognized as Multi-Criteria Decision Making (MCDM) tool, is used to provide relative importance among the features to a set of total weights. The subsequent technique, WLC is used to associate all the factor layers and to make landslide vulnerability map that is categorized into landslide susceptibility zones (LSZ).

This research is the first attempt to assess gendered perceptions towards landslides in Rawalakot Azad Kashmir. In that respect, the research is an important step towards the incorporation of traditional knowledge into the scientific understanding of landslide mechanisms of generation while bearing in mind gender-based perceptions. This would bring a well understanding of the complex association between humans, physical environment and the occurrence of landslides.

1.1 Objectives

Landslide susceptibility mapping is an important step prior for damage assessment, planning, management and mitigation (Coraminas, 1987). This research has emphasis on the following three main objectives in Rawalakot Azad Kashmir:

i. To identify landslide controlling factors in the research area.

ii. To produce landslide susceptibility maps based on GIS modeling.

iii. To conduct questionnaire based field surveys to get the local community’s view.

Chapter 2

LITERATURE REVIEW

Landslide is mainly the downward movement of slope, soil, rock, or certain combination of the two, under the influence of gravity. Landslides are natural procedures, but can be driven or enhanced by one or more of the features, particularly when the factors occur in combination.

2.1 Introduction

According to Cruden (1996) landslide is the downward movement of rocks, debris or a portion of earth mass from slopes. The downward and outward movement of earth material due to gravity without any support of conveying agent like water or air is called landslide (Crozier, 1986). The above descriptions are acknowledged universally and broadly used to describe this natural phenomenon. Though, various descriptions can be established, but in principle, they all lead to the same deduction that landslide is involved in downward movement of earth mass which can be detrimental for humans.

2.2 Types of Landslides

Landslide types can be distinguish by the type of movement and the material. Table 2.1 illustrates the description of classification system founded on these factors. According to Varnes (1984), landslides can be categorized in two techniques; primarily on the basis of material forms that aids in failure and the secondly, the type of movement.

Basically, there are three types of mass that cause the incidence of five main types of landslides. Slides, falls, sideways spreads, topples and drifts can happen in debris, bedrock or earth. Furthermost landslides are composite of basic kinds of landslides. Similarly some classification systems used other parameters such as ice content, water, and movement rate.

2.3 Landslides Influencing Parameters

Uncertainties of slope are generally correlated to the source of landslides. In one landslide initiate, it is mostly possible to identify one or more reasons. There might be diverse reasons for landslide incidence at a place at the same period.

2.3.1 Morphological Features

a. Tectonic uplift
b. Glacial erosion of slope toe or lateral margins, fluvial
c. Deposition/heaping slope or its top
d. Underground erosion
e. Glacial rebound
f. Thawing
g. Exclusion of flora by fire or scarcity
h. Freeze
i. Shrink and swell

2.3.2 Geological Features

a. Sheared, or articulated materials
b. Unfavorably oriented incoherence (bedding, fault, abnormality, interaction, and so forth)
c. Weathered materials
d. Stiffness of constituents and/or contrast in permeability
e. Weal or sensitive materials

Table 2.1. Categorization of slope movements (Varnes, 1984).

Movement Type	Material Type		
	Bedrock	Engineering Soils	
		Coarse	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		

2.3.3 Human Features

a. Deforestation
b. Mining
c. Simulated vibration
d. Heaping of slope or its top
e. Irrigation
f. Excavation of hill
g. Drawdown (of reservoirs)
h. Water leakage from utilities

2.4 Effect of Water on Landslides

A main source of landslides incidence is the gradient accumulation by water. Snow thaw, modifications in ground-water stages, and water-level fluctuations alongside shorelines, heavy precipitation, water barrages and the banks of lakes, basins, streams, and canals are the sources of slope accumulation by water. A close connection has been established in landslides and flood as both influenced by same features like precipitation, water overflow, and excess of land by water (Narumon Intrawichian, 2008). The incidence of debris flow and mudflows has been typically noted in small and sheer stream networks. It has also been documented that both procedures happened at same period.

It has been noted that lakes formed by landslides frequently chunk basins and stream networks that vigor the huge extent of water to substantiate. It can produce two kinds of inundating, downstream saturating and backwater saturating.

2.5 Landslide Vulnerability Assessment Using Remote Sensing and GIS

Landslides frequently distract the earth's surface; consequently it has produced opportunities of investigation in both space and airborne distant sensing. It is a natural process occurring on earth's surface aids researchers to discover by remote sensed data. Occasionally this phenomenon limits the scientists as it covers a very minor space in terms of distant sensing. Conversely, planar remotely sensed data (2D) offer very small material while 3-D data perhaps DEM has enormous extent of information. In this way stereo-remote sensing data is beneficial which signify an accurate environment of landslides. The type of movement of landslide can be known efficiently using this data (Crozier, 1973). A common study area in this branch is to distinguish chronological modifications in landslide incidence to explore the possible danger prone areas.

Remotely sensed data offers information regarding flora, and hydrological and morphological environments of the region which can be associated to landslides. It is best method to obtain hill morphology by stereo imageries. Certain previous studies (Soeters and Van Westen, 1996; Herves, 2003) used remotely sensed data, aerial photos and ground survey in various methods to formulate inventory maps for landslide risk assessment. Findings demonstrates the spatial dissemination of movement of mass either in the form of points or polygons (Wieczorek, 1984). This map indicates the spatial locality of landslides prone areas (Dai et al., 2002). According to Matovani et al. (1996), it is beneficial to obtain remotely sensed data in small time periods to discover temporal variations in surface movement. It aids to improve landslide action map which is produces by using multi temporal imageries or airborne photographs (Nagarajan et al. (1998), Zhou et al. (2002), Cheng et al. (2004).

GIS has an influential set of tools like collecting, managing, input, spatial inquiries conversion, enhanced imagining, combination, data examination, modeling and output, with its outstanding spatial data handling ability, to evaluate natural vulnerability process (Carrara et al., 1999).

GIS functions are capable of managing spatial data of numerous kinds for distinctive landslide examination and achieve the prerequisite to execute the analysis. Spatial data (vector or raster data) can be kept and operate in GIS environments for analysis but other non-spatial data which is used in non-conventional risk mapping examination can also be used to support spatial data study (Miles and HO, 1999). Spatial association can also be established between quantitative and qualitative data in GIS surroundings to produce significant outcomes (Frost et al., 1997).

2.6 Landslide Susceptibility Methods

Different researchers classify landslide risk assessment methods in GIS environment. (Van Westen, 2000; Aleotti et al., 1999; Guzzetti et al., 1999; Soeters et al., 1996; and Carraraet al., 1995, 1999). Classification of these scientists is broadly categorized into four different methods:

i. Probabilistic method
ii. Statistical method
iii. Heuristic method
iv. Deterministic method

Some researches on landslide vulnerability mapping are incapable to present their method used in it, however recently certain good studies on landslide vulnerability approaches have been printed (Cruden and Fell, 1997; Guzzetti, 2000; Dai et al., 2002;

Lee and Jones, 2005). The level of quantification categorizes the landslide vulnerability assessment techniques into:

i. Qualitative techniques
ii. Semi-quantitative techniques
iii. Quantitative techniques

By reviewing the literature, it is noticed that numerous researchers took part in the growth of landslide vulnerability assessment methods in previous couple of years. This review emphasize to find some significant literatures about the development of the assessment methods.

Variety of quantitative and qualitative methods can be adopted by different researchers to produce maps of landslide susceptible zones (Guzzetti et al., 1999; Soeters et al., 1996 and Aleotti et al., 1999). Qualitative methods are subjective and dependent on expert's experience and prior knowledge. While quantitative methods are more objective and data dependent. The reliability of results depends on the quantity, quality and reliability of the input data. Analytical hierarchy process (AHP) technique is developed by Saaty (1980) for the formation of landslide susceptible areas, performed by various researchers like Barredo et al. (2000), Mwasi (2001), Nie et al. (2001), Ayalew et al. (2005), Komac (2006) and Yalcin (2008).

Landslide hazard or susceptibility mapping/zonation is a measure of spatial analysis. According to Varnes (1984) zonation is mainly isolating the parcel of alike areas and rank it with respect to the level of probable hazard triggered by the mass movement. Hence information of features of the zone which are involved in landslide incidence should be necessary. These features can be characterized into two sets: the parameters of the first set make the gradient/slope vulnerable for failure before generating, these elements contain: elevation, slope, LULC, drainage linkage, geology and soil kinds (Dai et al., 2002). The factors of the second set are the causing factors which contains heavy precipitation and glacial eruption.

According to Guzzetti et al. (1999), landslide hazard mapping predicts the locations which are prone to landslides and pre and post dissemination of deposits at regional level. The subsequent evidence is useful for land use development of the gradients which is vulnerable to fail. It would be beneficial to reduce the consequence of losses triggered by any hazard occurred in the research area.

Chapter 3

MATERIAL AND METHODS

Explanation of the research area and materials and techniques adopted in this study are defined in this chapter. Every objective of the research and procedures are described in detail in following sections.

3.1 Study Area

Study area include Rawalakot located in the district Poonch, AJK. It is selected as an appropriate area to assess landslide hazard analysis as it has suffered abundant landslide damage after heavy rains. (Figure 3.1). This region also exhibit high topographic relief, climate change variability and is subjected to soil erosion due to which this area is very susceptible to landslides. This is a strong motivation to study/map the landslide prone region in the Northern areas of Pakistan. Its estimated population is more than 70,000 (2009 estimates). It lies between latitude from 33° and 36° (E/W) and longitude from 73° and 75° (N/S) covering about 1,010 km^2. It is in a saucer-shaped valley. It is about 120 km from Islamabad, the capital of Pakistan and 76 km from Kahuta.

3.1.1 Physiography

The geography of the region is primarily mountainous and steep by nature with moderate to sharp slopes. The altitude varies from 360 m in the south to 6325 m in the north. In winter, the snowline reaches around 1200 m beyond sea level whereas in the summer it increases up to 3,300 m. The area is occupied with dense forest, fast running rivers and winding tributaries. Drainage network of the Rawalakot depend on on Jehlum river, Neelum river and Poonch river and its streams.

3.1.2 Climate

Rawalakot is sightseer attraction in northern parts of Pakistan. In summers weather is mild whereas winters are frosty with snow. The sky is generally vibrant and pleasant in autumn. The study area is considered by a moderate sub-humid weather with annual precipitation varying from 500 to 2000 mm, maximum of which is uneven and drops as extreme storms throughout the monsoon and occasionally in wintertime. In summer, mean yearly temperature is around 20 °C whereas in winter temperature fluctuating even below freezing point. Figure 3.2 indicating the rainfall pattern in study area.

3.1.3 Geology and Soil Types

In maximum part of the research area, Murree formation and Patala formation exist. Murree formation comprises of purple, red and green siltstone, sandstone and shale with secondary conglomerates while the Patala formation comprises of marl and shales with sandstone and limestone. Shale is brown to greenish gray in color whereas limestone is white to mild grey. The age of the development is Late Paleocene. The Geology of Rawalakot city is shortened in Table 3.1.

The soil texture of the study area ranges from clay to silt loam. It is noted that soils exist on the forest and grassland contain high amount of all the nutrients and favorable physical environments like high porosity and low BD. On the contrary, soil from the arable showed extensive deprivation over plant nutrient reduction and deprived physical environments well described the susceptibility of the arrangement and function of the high elevated environments.

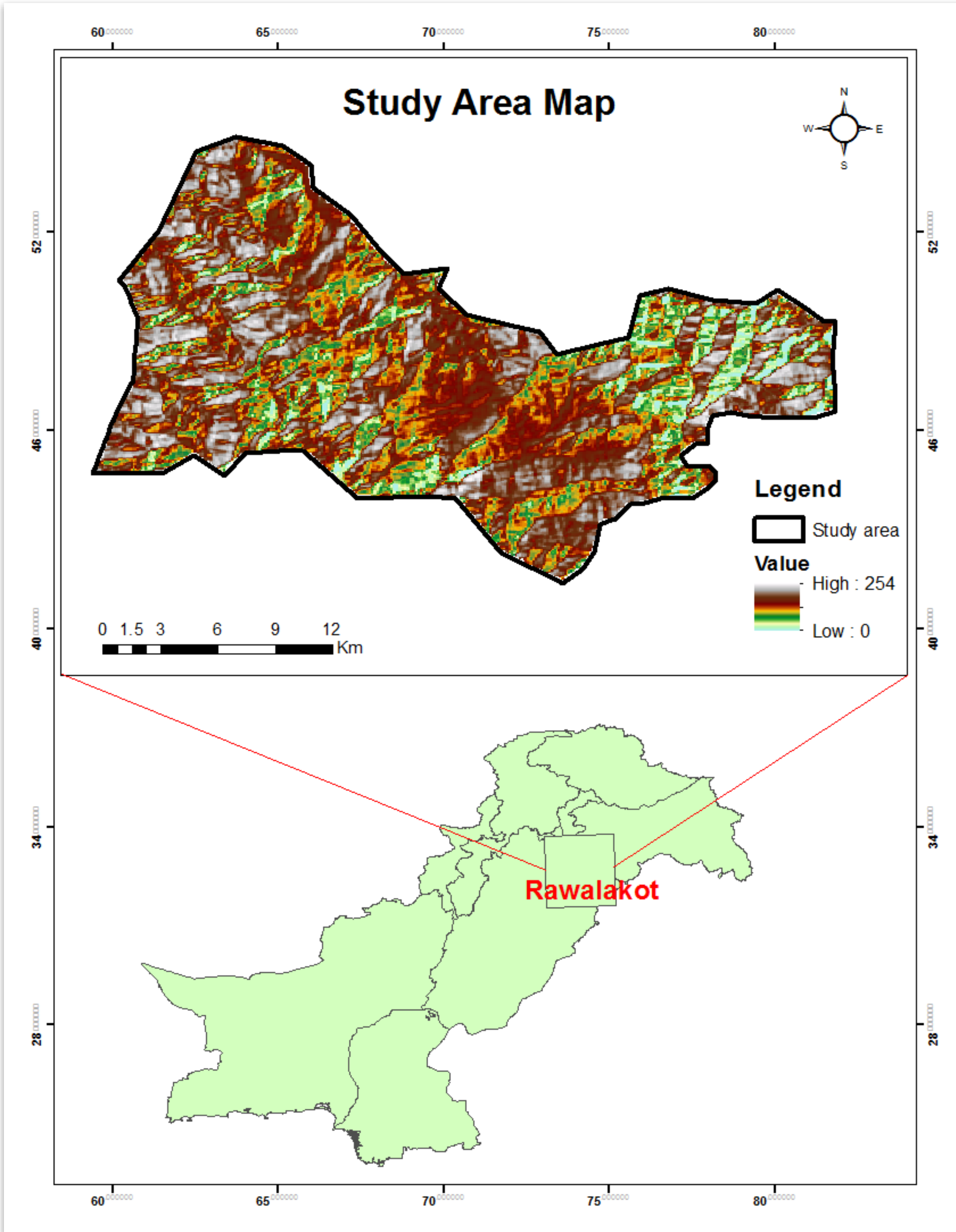


Figure 3.1. Location map of the study area Rawalakot, Azad Jummu Kashmir (AJK).

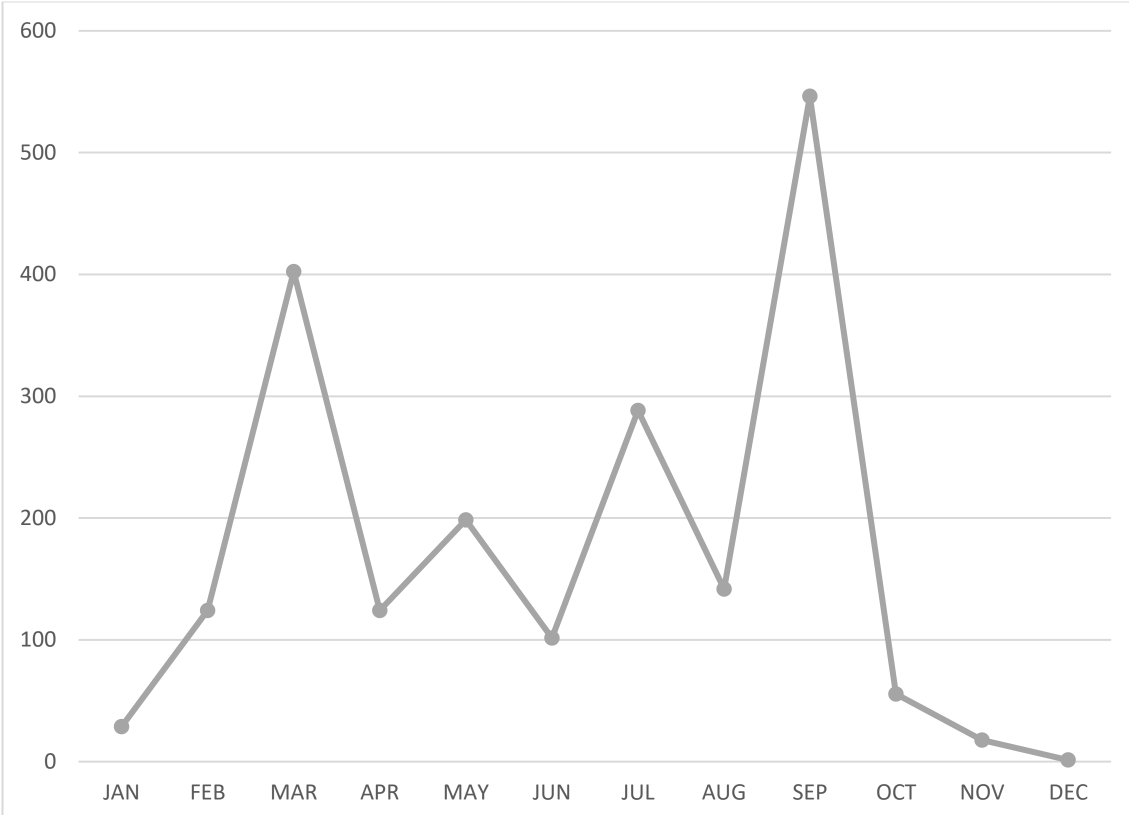


Figure 3.2. Graph indicating rainfall variation (2014) in Rawalakot.

Table 3.1. Types of rock formation in Rawalakot

Formation	**Age**	**Width**	**Lithology**
Murree formation	Primary Miocene	682	Clays, shales and sandstone.
Patala formation	Secondary Paleocene	70	Shales and limestone.

3.2 Social Survey

The social review is carried out to govern people opinion or perceptions on the landslides incidences, their information on the reasons and ecological and economic effects of the landslides. The survey envisioned to identify the responsibility of the administration of hill instability issues, and mitigations techniques are being place to resolve these difficulties. Queries of managing and dealing plans are also addressed.

3.3 Dataset Used

In landslide susceptibility assessment studies, identification of the causative features for the landslides is the main phase. In fact, the local landslide evaluation should be appropriate and practical for that specific zone to be investigated for which the input factors should be illustrative, consistent and easily available (Oh and Pradhan, 2011). Slope failure has been reported as main cause of triggering landslides in the region. Many factors such as rainfall, drainage and proximity to roads may contribute to slope-failure. But not all of these can be acquired, mapped and used cost-effectively Sin landslide hazard assessment. Therefore a total of twelve landslide controlling parameters are measured in this study.

The basic landslide controlling parameters for instance slope, aspect, lithology, distance from streams, distance from faults and thrusts, topographic wetness index (TWI), major land covers, stream power index (SPI), rainfall and plan curvature are employed in the landslide hazard analysis. All the input factors are divided into four main groups.

First group consists of human induced factors i.e. land cover map and distance from roads. Second group includes slope, plan curvature and aspect factors. The third group contains factors representing hydrological conditions in the study area and contains distance from stream network, stream power index (SPI) and topographic wetness index (TWI) parameters. Fourth group consists of lithology and distance from faults and thrust factors which are prepared from geological maps of the study area.

3.3.1 Satellite Images

Landsat satellite remote sensing program started in 1972 with its 1st satellite Landsat 1 and Landsat 8 being the latest satellite. The high spatial resolution and presence of variety of bands makes Landsat suitable for this study. Two new spectral bands (band 1 and band 9) facilitates Landsat 8 OLI sensor project improved from previous Landsat instruments.

Landsat 8 OLI image datasets with less than 10% cloud cover are selected for this study. Landsat 8 OLI image consists of 11 bands. For convenience in image handling, bands 2-7 are stacked together to generate a final image containing 6 bands. All the bands have pixel size of 30m except band-8 i.e. 15 m. Therefore all images are pan sharpened to have 15m resolution images for better land cover classification in this mountainous study area. Further for ease in computer processing and computation purpose, study area is clipped from the stacked dataset as shown in Figure 3.3.

3.3.2 Digital Elevation Model (DEM)

Digital elevation model of 30 m resolution is taken freely from SRTM website. This DEM is registered with respect to WGS 1984 UTM Zone 43 system. A shapefile defining the study area is used to clip the SRTM DEM for Rawalakot only (Figure 3.4). This DEM is further processed in ArcGIS 10 using the ArcGIS HEC-HMS Module to generate depression less DEM, then extract different landslide controlling factors like elevation, slope, aspect, drainage network, SPI and TWI for the study area.

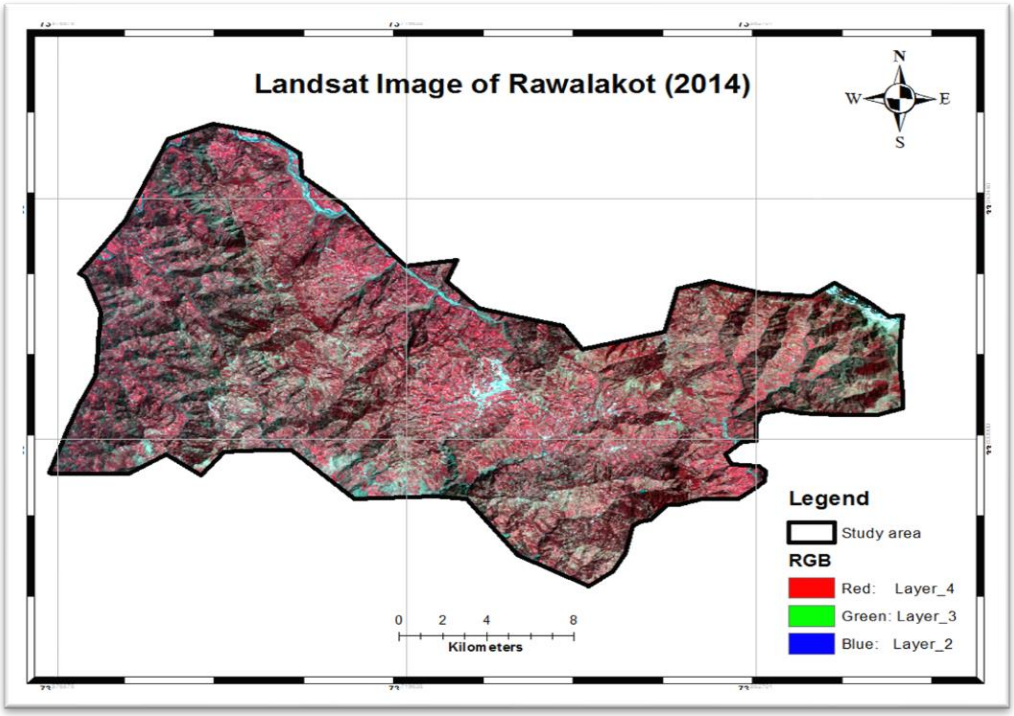


Figure 3.3. Map indicating the Landsat 8 OLI imagery of Rawalakot, AJK

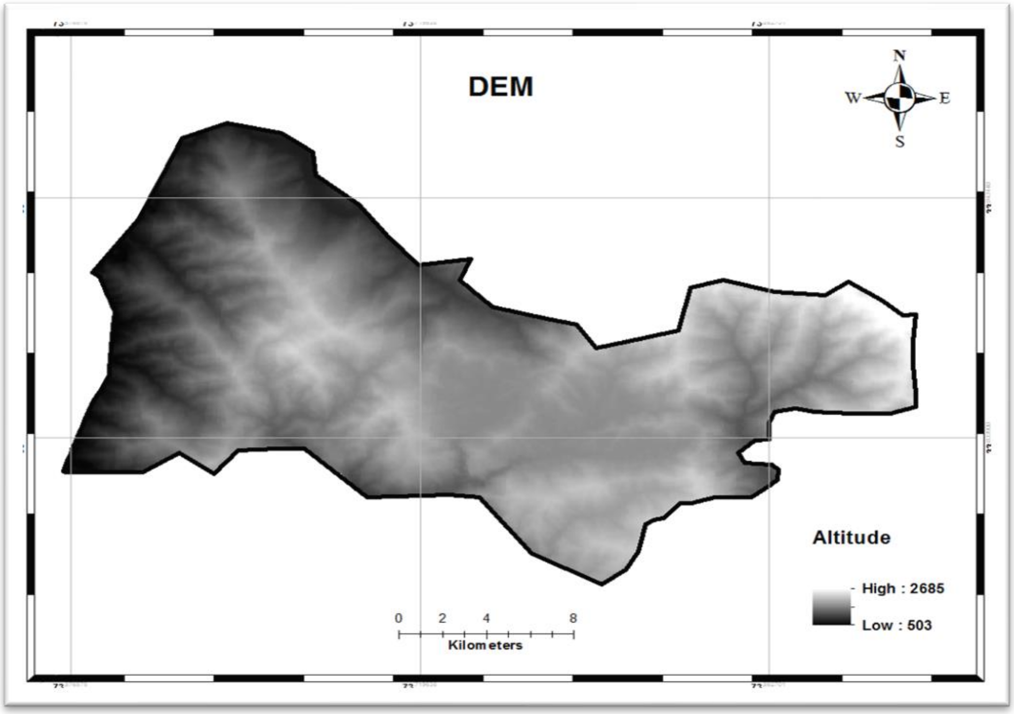


Figure 3.4. Map indicating the Digital Elevation Model of Rawalakot, AJK

3.3.3 Lithological Map

Lithological map of the research area is occupied from Geological Survey of Pakistan (GSP). The study area is covered by the Sheet No. 43 F/11 of Geological Survey of Pakistan and it is arranged on 1:600, 000 scale.

3.3.4 Rainfall Data

Rainfall data of neighboring four meteorological observatories is taken from Pakistan Meteorological Department Islamabad office. These observatories are situated in Rawalakot, Balakot, Muzaffarabad, Garhi Dupatta.

3.4 Software Used

- ArcGIS 10.2

- ERDAS IMAGINE 9.2
- Microsoft Word/Excel/PowerPoint

3.5 Data Preparation

3.5.1 LULC Map

Classification of land cover involves assigning pixels to the information classes which informs about the use of land. It tells us what the land surface is covered by for example, urban areas, agriculture etc. Land cover classification is an important component of remote sensing and an input for many analyses like change detection, urbanization studies etc. Classification methods are basically divided into two groups i.e., per-pixel and object based. Per-pixel classification approach is most common of the two.

In this study, per pixel supervised classification method is used to map major land cover in the study area. The classification involved: (1) identification and selection of training features, (2) evaluation of training signature and their spectral pattern, and (3) finally classification of the images. For each land-cover class, 40 to 60 sample plots containing a minimum of 60-70 pure pixels are chosen as training areas. Supervised classification has been performed using Erdas Imagine 2011. Following major classes are identified from satellite image as shown in Figure 3.5 (a):

- Water bodies,
- Built up,
- Forest, and
- Sparse vegetation.

Landuse data is extracted from Landsat 8 OLI sensor imagery taken in April 10, 2014. The interpretation of the imagery is done visually and then reinforced by supervised classification.

Theoretically, barren land is more susceptible to landslide than any other land uses. It is because there may be no deep root which could hold the soils firm in place. Contrarily, vegetative areas tend to curb the landslide occurrences by providing anchorage through their roots. It also offers both mechanical and hydrological effects that usually are helpful to the strength of hills. Therefore vegetative parts are considered less prone to landslide due to erosion hazard. Removing vegetation covered areas for agriculture, even an inappropriate way of cultivation may play a significant role in initiating landslides.

3.5.2 Distance from Roads Map

The presence of road is a triggering factor for landslide mainly due to change in stress and slope stability resulting from the undercutting of the slope, excavation, additional loads, changes in hydrological conditions, and drainage (Pourghasemi et al., 2012). Increase in distance from the roads, the chances of slope instability hazard resulting from roads proximity decreases (Figure 3.5 (b)).

3.5.3 Slope Map

It is recognized as the most significant landslide controlling parameter. The amount and type of vegetation, precipitation, and soil water content over a given area are affected by the slope. Generally, a high slope angle will result in more landsliding, which is significant when locating landslides. Slope gradient also manages the velocity of subsurface drift after precipitations, the overflow rate and the amount of soil water.

Increase in gradient also increases the shear strain in unconsolidated soil cover. The original raster imagery is acquired directly from the depression corrected 30m SRTM DEM. It is administered in degrees with slope values varying from 0° to 87.5° for the research area. These slope values are further reclassified into the following five classes using the multi-criteria analysis: (i) Very gentle slopes, <5°, (ii) Gentle slopes, 5°-15°, (iii) Moderately steep slopes, 15°-30°, (iv) Steep slopes, 30°-45° and (v) Cliffs/Escarpments, >45°. Usually, landslides are not predictable to happen on gentle slopes due to less steep stress. It is estimated that landslide vulnerability increase alongside with the increase in gradient sharpness getting the maximum in the 4th class. Slope map of the study area is shown in Figure 3.5(c).

3.5.4 Elevation Map

The association between landslide incidence and altitude is not directly interrelated. Though, effect of elevation cannot be ignored in landslide vulnerability mapping. It is not essential that greater elevated zones are more vulnerable for landsliding events. Values of elevation for Rawalakot ranges from 503 m to 2685 m and distributed into five classes: (i) 503 m-1056 m, (ii) 10561 m-1431 m, (iii) 1431 m-1727 m, (iv) 1727 m-2007 m, (v) 2007 m-2685 m. Elevation map of the study area is shown in Figure 3.5(d).

3.5.5 Aspect Map

In landslide vulnerability mapping, aspect is also measured as inducing factor. It is the reflection of sunlight, drying winds and rainfall, affecting ultimately other features such as the flora dispersal, the level of saturation and evapotranspiration of the gradients and soil loss (Calligaris et al., 2013; Ahmed et al., 2014). It increases soil erosion on slope facing sun directly. This factor is responsible for asymmetric deterioration and disintegration of slope surfaces, so it is categorized into nine classes, signifying angular divisions of 45° wide: 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°) as presented in Figure 3.5(e). The literature review (Rashid 2004; Ahmed et al. 2014) suggests that the predominant southwest-to-southeast azimuth of seasonal Monsoon rainfall exerts more impact on the slopes facing south to northwest. This makes the hill slopes facing southwest most vulnerable to landsliding and those facing northwest scores next.

3.5.6 Plan Curvature

Curvature is representation geo-morphology of topography of an area. It is selected as an input parameter because it distresses the hydrological settings of soil cover and surface erosion by converging or diverging the runoff flow down the slopes. It can be calculated as plan curvature, profile curvature and common curvature. Positive values gives an indication that the surface is convex. Contrarily, negative values shows concave surfaces. While zero value in curvature raster represents flat surface. Zero to lower positive and lower negative numbers correspond to low lying areas. A flat surface has the lowest probability of initiating landsides. Compared to convex slope, soil cover on a concave slope tend to encompass more water after precipitation and may hold it for a longer time. Therefore, concave slopes increases the probability of landslides occurrence. On the other contrary, convex gradients show the outcrop of resilient bedrock between slacker rocks at many places. For the study area, the plan curvature map is prepared from depression corrected ASTER GDEM2 using ArcGIS 10. Literature shows that increase in negative values increases the probability of landslide occurrence whereas the more positive values decreases the probability. The range of curvature values are divided into three classes as shown in Figure 3.5(f).

3.5.7 Topographic Wetness Index (TWI)

Topographic wetness index (TWI) also recognized as the compound topographic index (CTI) is considered as a very important terrain attribute for landslide susceptibility studies and is defined as:

TWI= (a tan)

Where, 'a' is the catchment area and β is the slope in degree measurement. The natural log within this equation helps the outcome to fall within a normalized range. The TWI equation assumes that steady state conditions occur spatially across the region, where a few assumptions need to be made in order for this equation to hold true. These assumptions are: the precipitation is constant over the region, soil type and thickness is consistent, and no subsurface drainage network occurs within the region (Brown, 2012). TWI map is shown in Figure 3.5(g).

The values of the TWI are a positive non zero which increases as the catchment area increases and the slope angle decreases (Hengl and Reuter, 2009). This attribute has been used in various studies to help describe how the topography affected the saturation of the land within a particular location. An increase in the wetness index increases the potential for landslide (Lee et al., 2002; Yao et al., 2008; Hengl and Reuter, 2009). Previous studies have shown that the higher the TWI values are associated with the landslide deposits compared to lower TWI values with non-landslide deposits.

3.5.8 Stream Power Index (SPI)

The SPI calculates stream loss power and contributes toward steadiness within the research area. The SPI can be demarcated as: SPI= As×tan β

Where As is the particular catchment's area and β is the local slope measured in degrees.

Higher values of stream power normally represent sheer, straight, weathered reaches, and bedrock valleys whereas lower values of stream power indicate broad sandy flats, floodplains, and slowly settling areas, where the valley fill is typically intact and excavating as shown in Figure 3.5(h).

3.5.9 Distance from Streams Map

In mountainous region of Rawalakot, terrain hill slopes are disturbed and modified by rills, gullies and streams through erosion. Slope instability particularly increases in the area where drainage follows toe cutting, bank and headward erosion (Miller and Sias, 1998). Therefore drainage is a major parameter to analyze vulnerable zones of landslide. Stream network are extracted from a depression corrected SRTM 30m DEM using HEC-HMS tool of ArcGIS 10 as shown in Figure 3.5(i).

Distance classes are included 0–200 m, 200–400 m, 400–600 m, 600–800 m, 800-1000, and up to 1200 m. Reclassified map (Figure 3.5(j)) is prepared using a buffer around the drainage network in the study area. Six buffer zones with 200 m intervals are produced to see the effect of distance from the drainage channel on landslide. This factor is considered on the basis of the hypothesis that streams have ability to affect the slopes stability both by inundating and undercutting them. As the distance from streams increases, the probability of landslide hazard reduces.

3.5.10 Lithology

Lithology and faults considered the most relevant factor that affects the rocks strengths and soil permeability thereby controlling the susceptibility to land sliding. Different rock types behave different with erosion material. Highly foliated, sheared and fragile types of rocks are more prone to land sliding. Lithology map is prepared from geological map. Many researches have considered this as input factor. Based on geological map at scale 1:600, 000 numerous rock formations in the research area have been assembled into different classes to formulate lithology data layer as shown in Figure 3.5(k).

3.5.11 Faults and Thrusts

Northern Pakistan straddles the tectonic boundary between Eurasian and Indian Plates which is characterized by the complex crustal closure, forcing compression and tectonic uplift. Moreover, active tectonic collision has also resulted in pervasive thrusting in the region. Based on tectonics map of the study area, it is identified that there is main active fault passing through the study area (Figure 3.5(l)), named Karakorum Fault. Additionally, there are two other main thrusts in this area viz.,

- Main Karakorum Suture (MKS) Zone and
- Main Karakoram Thrust (MKT).

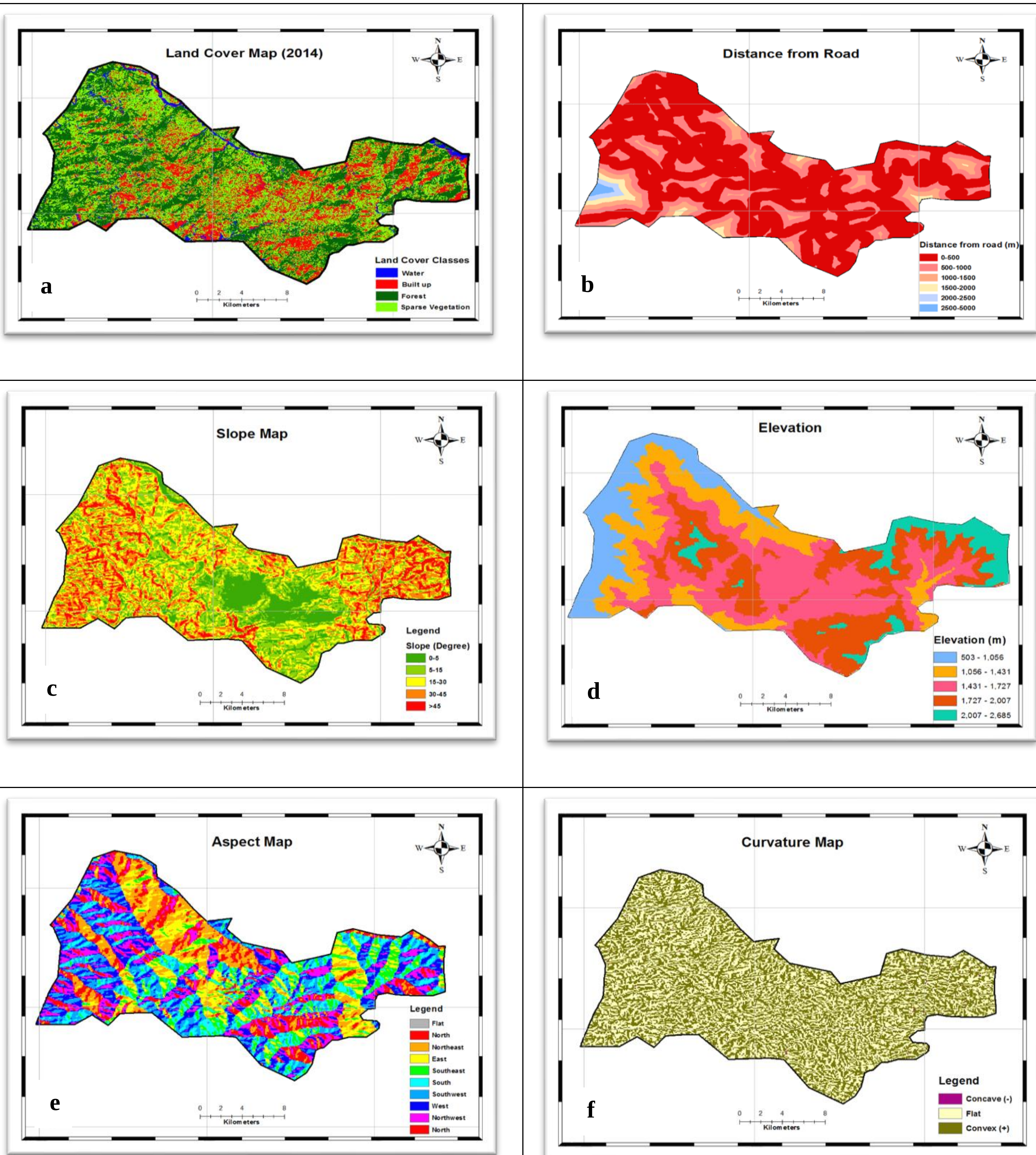
These active fault systems are responsible for increased seismicity in the study area. It is witnessed that landslides are more abundant along these major faults and thrust. Due to geologic and tectonic setting, it is reasonable to expect that this area in Northern Pakistan will continue to experience massive landslide which might have potential for massive destruction. Landslide occurrences increases with proximity to geological and tectonic structures. Faults are manually prepared from tectonic maps available in literature. The distance to faults and geological structures is prepared in meter scale using ArcGIS 10 and it tends to evaluate the local situation (Figure 3.5(m).

3.5.12 Precipitation Map

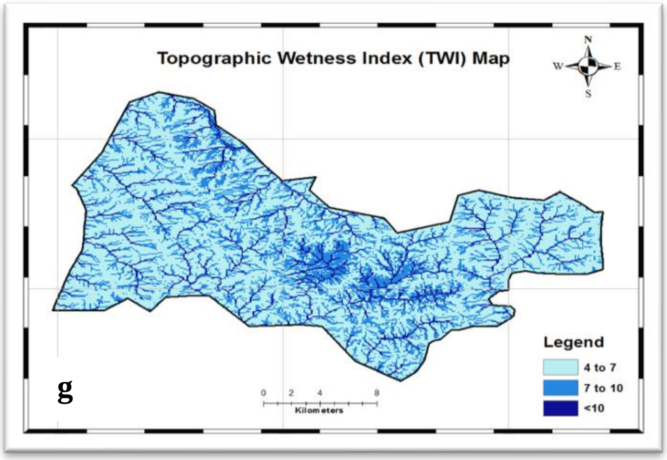
Precipitation is a major inducing parameter for land sliding. Monthly rainfall data is collected from nearby four rain gauges installed by Pakistan Meteorological Department. Using monthly rainfall data, annual average rainfall map is produced using interpolation techniques. The study area received 600 mm to 1650 mm average rainfall per year in last ten years (2004-2014). Precipitation map of the study area is shown in Figure 3.5(n).

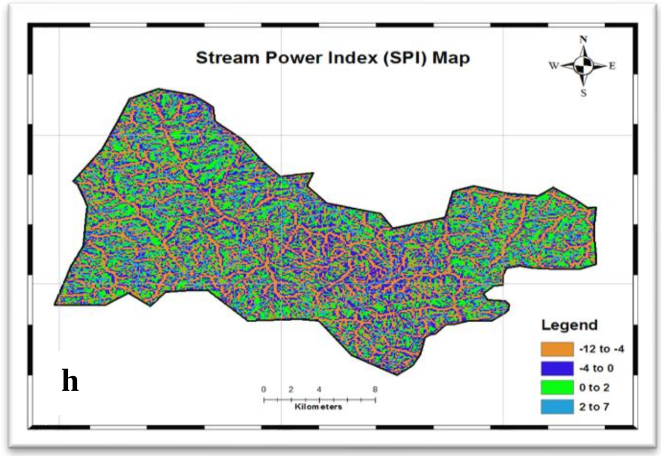
3.6 Field Survey (Perceptive GIS)

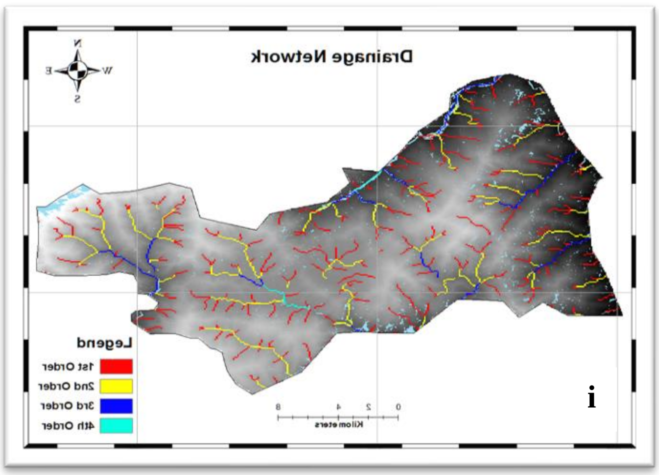
The foremost practices adopted to assess the understanding and observations of the local people as regards landslides incidences in their areas are questionnaire and interviews. This research used a cross-sectional exploration of the observations of native people in the susceptible areas, eyewitnesses to the landslide events. The best method is characterized and the emphasis is on appropriateness, simplicity, consistency and clarity. The questionnaires are comprises of 100 samples and pre-tested for accuracy. Samples of filled

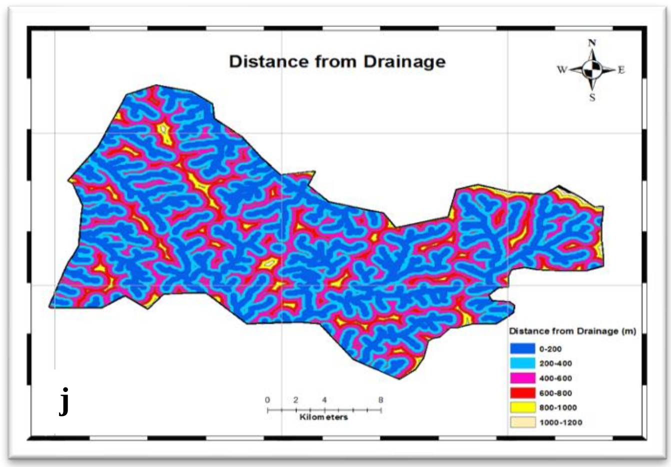


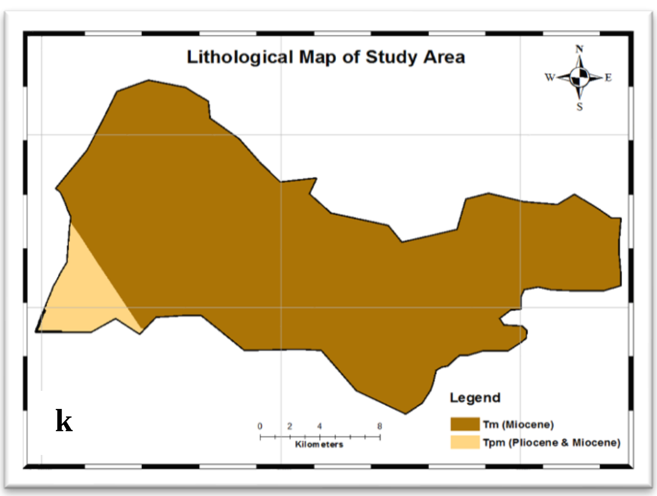
Land Cover Map (2014)
Land Cover Classes
Water
Built up
Forest
Sparse Vegetation
Kilometers
a
Distance from Road
Distance from road (m)
0-500
500-1000
1000-1500
1500-2000
2000-2500
2500-5000
Kilometers
b
Slope Map
Legend
Slope (Degree)
0-5
5-15
15-30
30-45
>45
Kilometers
c
Elevation
Elevation (m)
503 - 1,056
1,056 - 1,431
1,431 - 1,727
1,727 - 2,007
2,007 - 2,685
Kilometers
d
Aspect Map
Legend
Flat
North
Northeast
East
Southeast
South
Southwest
West
Northwest
North
Kilometers
e
Curvature Map
Legend
Concave (-)
Flat
Convex (+)
Kilometers
f

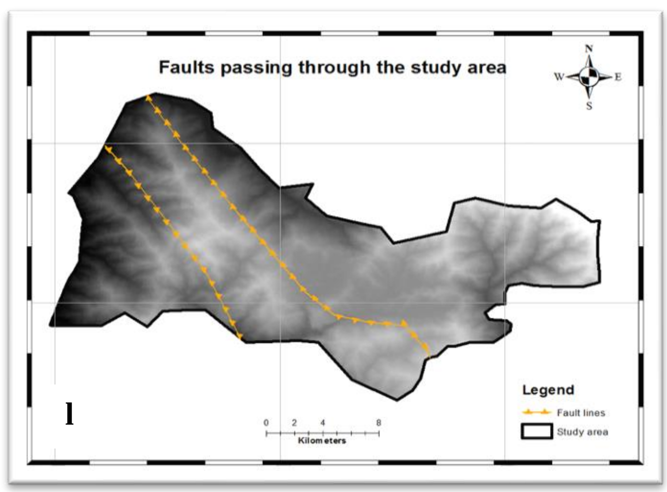

Topographic Wetness Index (TWI) Map
N
W
E
S
Legend
4 to 7
7 to 10
<10
0 2 4 8
Kilometers
g


Stream Power Index (SPI) Map
N
W
E
S
Legend
-12 to -4
-4 to 0
0 to 2
2 to 7
0 2 4 8
Kilometers
h


Drainage Network
Legend
1st Order
2nd Order
3rd Order
4th Order
0 2 4 8
Kilometers
i


Distance from Drainage
N
W
E
S
Distance from Drainage (m)
0-200
200-400
400-600
600-800
800-1000
1000-1200
0 2 4 8
Kilometers
j


Lithological Map of Study Area
N
W
E
S
Legend
Tm (Miocene)
Tpm (Pliocene & Miocene)
0 2 4 8
Kilometers
k


Faults passing through the study area
N
W
E
S
Legend
Fault lines
Study area
0 2 4 8
Kilometers
l

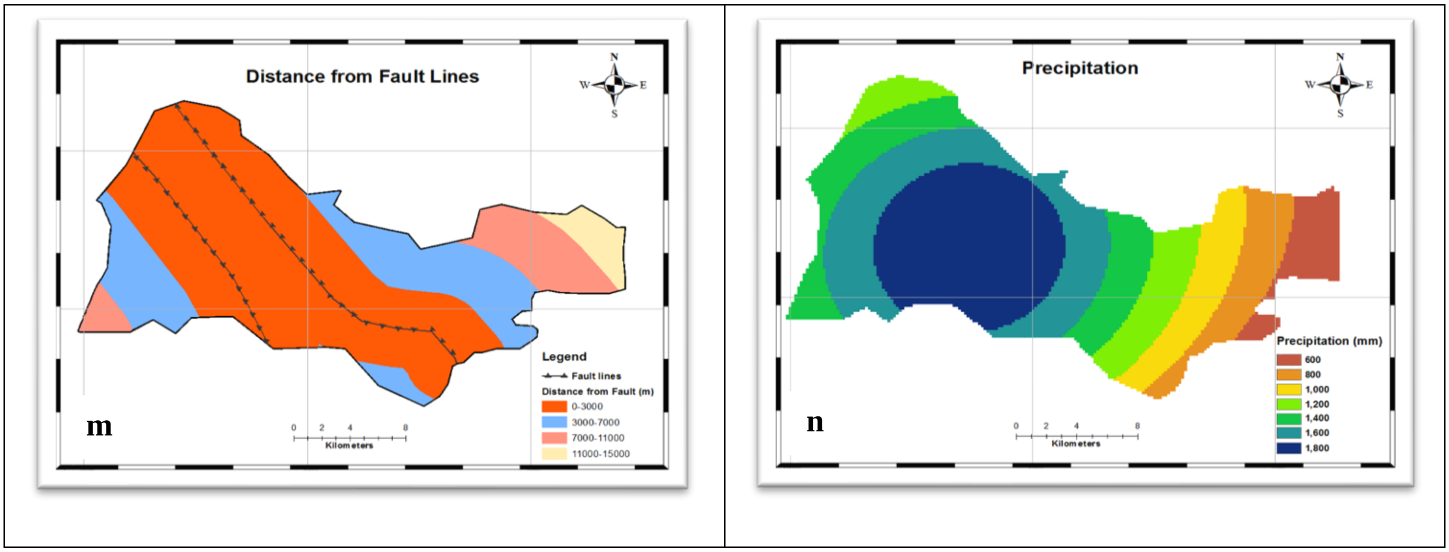


Figure 3.5. Derivation of twelve landslide causative parameters

questionnaire are attached (**Appendix**). The questionnaire form are also coded for easy statistical examination and administration.

3.7 Methodology

Two techniques Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) are employed to formulate landslide vulnerability map of the research area. Factor/feature maps are arranged using remotely sensed data and GIS methods.

Data is collected from various groups in the form of scanned maps, satellite imageries and tabulated data. Parameters like slope, aspect, stream network, SPI, TWI and elevation of the research area are obtained from digital elevation model. Digitized vector maps are then transformed into raster layout for analysis purpose in ArcGIS. The pixel size of all controlling factor maps is set to 30 by 30 meter. After the preparation of all the factor layers, AHP and comparison matrix of factors are developed for the calculation of Landslide Susceptibility Index (LSI). Values of LSI are categorized into four landslide vulnerability zones in ArcGIS to produce landslide susceptibility map of Rawalakot. The classes are: (i) very high, (ii) high, (iii) moderate and (iv) low.

3.7.1 Analytical Hierarchy Process

To solve general problem, analytical hierarchy process (AHP) is employed. In this technique, different landslide factors are compared by producing a matrix. This method is developed by Saaty in 1980. In pairwise comparison matrix, the weights for every single standard are identified using literature review and professional knowledge. In the production of pairwise comparison matrix, a comparative value ranges from 1 to 9 is allocated and every parameter is valued in contrast to every other parameter in transecting cells. If the parameter in the vertical axis is more significant than the parameter on the horizontal axis then the values of parameters ranges among 1 and 9. Conversely, the values ranges between the reciprocals of 1/2 and 1/9 (Ladas et al., 2005). A scale for set preferences among the parameters is formulated by Saaty as mentioned in Table 3.2. A pairwise comparison matrix is constructed among the parameters using these preferences and the weights for each parameter is calculated.

Consistency ratio (CR) is computed using this formula:

$CR = CI/RI$

Where

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

λMax= Average of consistency vector

n= Number of factors

Saaty provided random index (RI) which relies on the number of factors (n) as shown in Table 3.3.

3.7.2 Weighted Linear Combination

It is established on weighted average in which a usual numeric series has been organized among the parameters to normalize them. After the standardization, weights of factor classes are combined and Landslide Susceptibility Index (LSI) is calculated. Values of LSI are classified into four susceptible zones of landslide in ArcGIS by natural breaks to prepare landslide susceptibility map Rawalakot. The classes are: (i) very high, (ii) high, (iii) moderate and (iv) low. Google Earth imagery of the study area is visually interpreted to produce map of landslide inventory of the research area. The precision of subsequent map is evaluated by superimposing this map on landslide susceptibility map. The flow chart of methodology adopted in this study is shown in Figure 3.19.

Table 3.2. Saaty Scale for Degree of Preferences

Scale	**Degree of preference**	**Description**
1	equal importance	Two activities contribute equally to the objective
3	moderate importance	Experience and judgment slightly to moderately favor one activity over the other
5	essential or strong importance	Experience and judgment strongly or essentially favor one activity over the other
7	very strong or demonstrated importance	Experience and judgment strongly favored one activity over the other and its dominance is shown in practice
9	extremely high importance	The evidence of favoring one activity over the other is of the highest degree possible of an affirmation
	2, 4, 6, 8 intermediate values	Used to represent compromises between the references in weights 1,3,7, and 9
Reciprocals	Opposite	Used for inverse comparison

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		

Table 3.3. Random index (RI) provided by Saaty

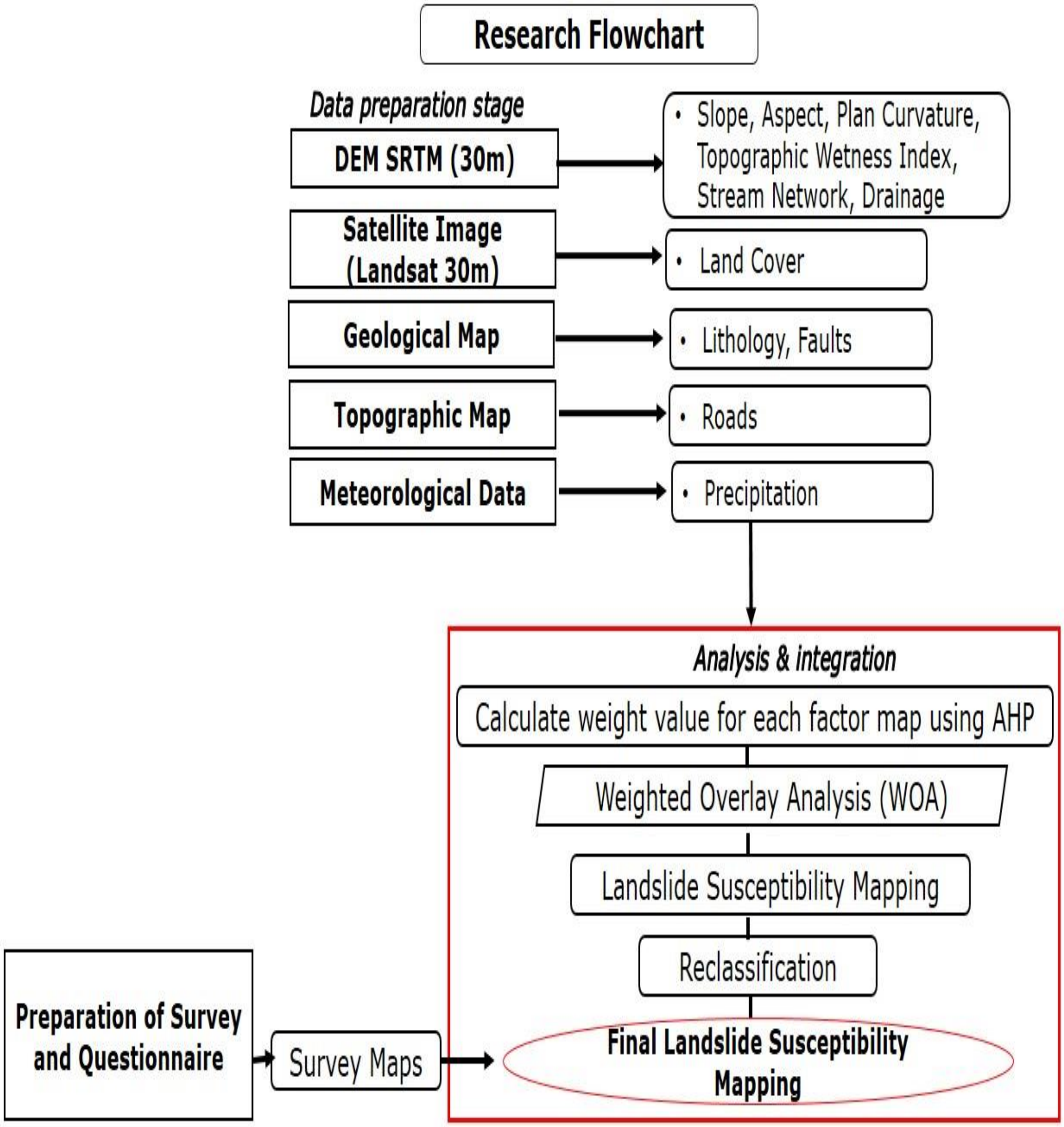


Figure 3.6. Complete methodological flow chart of the study

Chapter 4

RESULT AND DISCUSSION

The aims of research on the basis of all investigation are explained in this chapter. Results of the study area are presented in the form of maps, statistical tables and charts in this chapter.

4.1 Analysis in GIS Environment

A geographic information system permits handling and manipulating interfaces between data and geographical sites. GIS technology has also the capability to go beyond mapping and can be used to execute composite spatial exploration. It is probable to associate connections of ecological features with terrestrial factors to evaluate the effects of these features on human beings. Ultimately, GIS has assisted the possibility to classify parameters that would not be achieved in characteristic data analysis.

4.2 Calculation of Criterion Weights

The weight allotted to every factor has to reveal its significance in the landslide incidence and together with the scoring values for the distinct classes should represent the amount of hazard they signify. Hence, each factor is distributed into number of classes and each class is given a weighing score between 1(equally) and 9 (extremely). Similarly, the 12 factors are allocated scores varying between1 and 9 based on their comparative potential to cause gradient instability triggered landslides in the Rawalakot. Slope, rain, distance to faults and thrusts and lithology parameters are found to be the most influencing factors in Rawalakot. Hence they receive a value of 9 through 7 respectively. Land use is the next most influencing factor and it receives a value of 6. The factors SPI, TWI, aspect, curvature, elevation, distance to drainage and distance to roads are relatively less influencing factors and are given weight values 5-1 as shown in Table 4.1.

4.3 Weighted Linear Combination

Values varying from 9 (extremely) to 1 (equally) and 1/9 (opposite extremely) are assigned by subjective expert's judgment given in previous studies to every pair of factors producing a square reciprocal matrix given in Table 4.2. The obtained weight values of causative parameters Wj and the rating values wij of the various classes in these factor layers are also given in Table 4.2.

The score values of causative parameters illustrate that slope is the most significant contributing factor. Then, the order of degree of influence for landsliding is distance from thrusts and faults, lithology, land covers, distance from roads, plan curvature, SPI, TWI, distance from drainage and aspect. This is almost the same as the subjective expert's judgments, also given in the literature.

The consistency of the weights and ratings are evaluated by taking the principal eigenvectors of all matrix and calculating the consistency index and consistency ratio. The values are given in Table 4.3 shows that all CR values are less than 0.1 and therefore this verifies the preferences applied to prepare the comparison matrixes are reliable.

In this research, the resulting CR for the pairwise comparison matrix for 12 layers was 0. 076 (see Table 4.3). This value indicates that the comparisons of characteristics are consistent. Therefore, relative weights given in table 4.4 are appropriate to be subsequently used in the landslide vulnerability analysis.

Table 4.1. Details of the twelve different contributing factors.

Factor	Factor Rating	Class Range	Class Rating Value
Slope	9	0-5° (Very gentle slopes)	2
		5°-15° (Gentle slopes)	4
		15°-30° (Moderately steep slopes)	6
		30°-45° (Steep slopes)	8
		>45° (Escarpments)	9
Lithology	7	Tm	9
		Tpm	3
Precipitation	8	<600 mm	3
		600-800 mm	5
		800-1000 mm	6
		1000-1200 mm	7
		1200-1400 mm	8
		1400-1600 mm	9
		>1600 mm	9
Distance from Thursts and Faults	8	0-3000 m	9
		30000-7000 m	8
		7000-11000 m	7
		11000-15000 m	6
Land Covers	6	Water	7
		Built up	5
		Vegetation	1
		Forest	1
Distance from Roads	5	0-500 m	9
		500-1000 m	8
		1000-1500 m	8
		1500-2000 m	7
		2000-2500 m	7
		2500-5000 m	4
Plan Curvature	4	-0.1932 (Concave)	9
		0 (Flat)	2
		0-1.6 (Convex)	5

SPI	3	(-12) -(-4)	3
		(-4) - 0	4
		0-2	5
		2-7	6
TWI	3	4-7	4
		7-10	5
		>10	7
Distance from Drainage	2	0-200 m	9
		200-400 m	8
		400-600 m	8
		600-800 m	7
		800-1000 m	7
		1000-1200 m	4
Aspect	1	-1 (flat)	0
		337.5°-22.5° (N)	3
		22.5°-67.5° (NE)	2
		67.5°-112.5° (E)	4
		112.5°-157.5° (SE)	6
		157.5°-202.5° (S)	8
		202.5°-247.5° (SW)	9
		247.5°-292.5° (W)	9
		292.5°-337.5° (NW)	9
Elevation	1	503 m – 1056 m	2
		1056 m – 1431 m	4
		1431 m – 1727 m	5
		1727 m – 2007 m	6
		2007 m – 2685 m	7

Table 4.2. Pair-wise comparison matrixes, principal eigenvectors and consistency ratios of class parameters and the data layers.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Class weight**	**Factor weight**
Slope	**0-5**	**5-15**	**15-30**	**30-45**	**>45**						**0.20**
0-5	1	1/3	1/5	1/7	1/4					0.04	
5-15	3	1	1/3	1/5	1/2					0.09	
15-30	5	3	1	1/5	3					0.22	
30-45	7	5	5	1	4					0.51	
>45	4	2	1/3	1/4	1					0.14	
Lithology	**Tm**	**Tpm**									**0.19**
Tm	1	5								0.83	
Tpm	1/5	1								0.17	
Precipitation(mm)	**<600**	**600-800**	**800-1000**	**1000-1200**	**1200-1400**	**1400-1600**	**>1600**				**0.15**
<600	1.00	0.50	0.33	0.20	0.17	0.13	0.11			0.03	
600-800	2.00	1.00	0.50	0.25	0.20	0.14	0.13			0.04	
800-1000	3.00	2.00	1.00	0.33	0.25	0.17	0.14			0.05	
1000-1200	5.00	4.00	3.00	1.00	0.50	0.25	0.20			0.10	
1200-1400	6.00	5.00	4.00	2.00	1.00	0.33	0.25			0.14	
1400-1600	8.00	7.00	6.00	4.00	3.00	1.00	0.50			0.27	
>1600	9.00	8.00	7.00	5.00	4.00	2.00	1.00			0.38	
Distance from thursts and faults	**0-3000 m**	**30000-7000 m**	**7000-11000 m**	**11000-15000 m**	**>15000 m**						**0.09**
0-3000 m	1	2	3	4	5					0.42	
30000-7000 m	1/2	1	2	3	4					0.26	
7000-11000 m	1/3	1/2	1	2	3					0.16	
11000-15000 m	1/4	1/3	1/2	1	2					0.10	
>15000 m	1/5	1/4	1/3	1/2	1					0.06	
LULC	**Water**	**Built up**	**Vegetation**	**Forest**							**0.09**
Water	1	3	5	7						0.57	
Built up	1/3	1	3	5						0.26	
Vegetation	1/5	1/3	1	3						0.12	
Forest	1/7	1/5	1/3	1						0.05	

Distance from roads	**0-500 m**	**500-1000 m**	**1000-1500 m**	**1500-2000 m**	**2000-2500 m**	**2500-5000 m**					**0.07**
0-500 m	1	2	3	4	5	6				0.38	
500-1000 m	1/2	1	2	3	4	5				0.25	
1000-1500 m	1/3	1/2	1	2	3	4				0.16	
1500-2000 m	1/4	1/3	1/2	1	2	3				0.10	
2000-2500 m	1/5	1/4	1/3	1/2	1	2				0.07	
2500-5000 m	1/6	1/5	1/4	1/3	1/2	1				0.04	
Plan curvature	**-0.1932**	**0**	**1.6**								**0.07**
-0.1932	1	3	5							0.63	
0	1/3	1	3							0.26	
1.6	1/5	1/3	1							0.11	
SPI	**(-12)-(-4)**	**(-4)-0**	**0-2**	**2-7**							**0.05**
(-12)-(-4)	1	1/3	1/5	1/7						0.05	
(-4)-0	3	1	1/3	1/5						0.12	
0-2	5	3	1	1/3						0.26	
2-7	7	5	3	1						0.57	
TWI	**4-7**	**7-10**	**10-18**								**0.03**
4-7	1	1/3	1/5							0.11	
7-10	3	1	1/3							0.26	
10-18	5	3	1							0.63	
Distance from drainage	**0-200 m**	**200-400 m**	**400-600 m**	**600-800 m**	**800-1000 m**	**1000-1200 m**					**0.03**
0-200 m	1.00	3.00	5.00	7.00	8.00	9.00				0.46	
200-400 m	0.33	1.00	3.00	5.00	6.00	7.00				0.25	
400-600 m	0.20	0.33	1.00	3.00	4.00	5.00				0.14	
600-800 m	0.14	0.20	0.33	1.00	2.00	3.00				0.07	
800-1000 m	0.13	0.17	0.25	0.50	1.00	2.00				0.05	
1000-1200 m	0.11	0.14	0.20	0.33	0.50	1.00				0.03	
Aspect	**flat (−1)°**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**		**0.02**
flat (−1)°	1	1/2	1/3	1/4	1/6	1/8	1/9	1/9	1/8	0.02	
N	3	1	2	1/2	1/3	1/5	1/6	1/6	1/5	0.04	
NE	2	1/2	1	1/2	1/4	1/6	1/7	1/7	1/6	0.03	

E	4	2	2	1	1/2	1/4	1/5	1/5	1/4	0.05	
SE	6	3	4	2	1	1/2	1/3	1/3	1/2	0.09	
S	8	5	6	4	2	1	1/2	1/2	1	0.15	
SW	9	6	7	5	3	2	1	1	2	0.23	
W	9	6	7	5	3	2	1	1	2	0.24	
NW	8	5	6	4	2	1	1/2	1/2	1	0.15	
Elevation	**503 m – 1056 m**	**1056 m – 1431 m**	**1431 m – 1727 m**	**1727 m – 2007 m**	**2007 m – 2685 m**						**0.02**
503 m – 1056 m	1	1/2	1/3	1/4	1/5					0.06	
1056 m – 1431 m	2	1	1/2	1/3	1/4					0.10	
1431 m – 1727 m	3	2	1	1/2	1/3					0.16	
1727 m – 2007 m	4	3	2	1	1/2					0.26	
2007 m – 2685 m	5	4	3	2	1					0.42	

Table 4.3. Calculation of consistency of the preferences used for ranking parameters and types.

Factor	n	λ_{Max}	CI	RI	CR	CR %
Slope	5	5.46	0.12	1.12	0.10	10
Lithology	2	2.02	0.02	0.00	0.02	2
Rain	7	7.51	0.085	1.32	0.064	6.4
Distance from faults	5	5.06	0.02	1.12	0.01	1
LULC	4	4.02	0.006	0.9	0.007	0.7
Distance from roads	6	6.13	0.026	1.24	0.02	2
Plan curvature	3	3.08	0.04	0.58	0.068	6.8
SPI	4	4.02	0.006	0.9	0.007	0.7
TWI	3	3.08	0.04	0.58	0.068	6.8
Distance from drainage	6	6.52	0.104	1.24	0.084	8.4
Aspect	9	9.30	0.04	1.45	0.03	3
Elevation	5	5.09	0.02	1.12	0.02	2
All factors	**12**	**13.25**	**0.11**	**1.48**	**0.076**	**7.6**

Table 4.4. Pairwise comparison matrix for contributory of landslide vulnerability study.

	Slope	Lithology	Rain	Distance from Faults	LULC	Distance from Roads	Plan curvature	SPI	TWI	Distance from drainage	Aspect	Elevation	Weight
Slope	**1**	2	2	3	4	3	3	4	5	5	6	7	**0.20**
Lithology	1/2	**1**	3	3	3	4	3	4	5	5	6	7	**0.19**
Rain	1/2	1/3	**1**	3	2	3	4	4	5	5	6	7	**0.15**
Distance from Faults	1/3	1/3	1/3	**1**	2	2	1	2	4	4	5	6	**0.09**
LULC	1/4	1/3	1/2	1/2	**1**	2	2	2	4	4	5	6	**0.09**
Distance from Roads	1/3	1/4	1/3	1/2	1/2	**1**	2	1	3	3	4	5	**0.07**
Plan curvature	1/3	1/3	1/4	1	1/2	1/2	**1**	2	3	3	4	5	**0.07**
SPI	1/4	1/4	1/4	1/2	1/2	1	1/2	**1**	2	2	3	4	**0.05**
TWI	1/5	1/5	1/5	1/4	1/4	1/3	1/3	1/2	**1**	2	2	3	**0.03**
Distance from drainage	1/5	1/5	1/5	1/4	1/4	1/3	1/3	1/2	1/2	**1**	2	3	**0.03**
Aspect	1/6	1/6	1/6	1/5	1/5	1/4	1/4	1/3	1/2	1/2	**1**	2	**0.02**
Elevation	1/7	1/7	1/7	1/6	1/6	1/5	1/5	1/4	1/3	1/3	1/2	**1**	**0.02**

4.4 Landslide Susceptibility Index Maps

To obtain the landslide vulnerability map, as previously stated, all the factors are assigned a weights calculated from pairwise comparison method (PCM) and a weighted linear combination of all the parameters is obtained.

WLC map with continuous numerical scale is obtained showing different levels of landslide susceptibility. Zones delineating different levels of susceptibility are obtained by overlapping incorporated controlling factor layers and dividing these into three main groups, according to their respective level of hazard. These zones are described in Table 4.5 below with correspond areas covering in percentage. A vector layer representing road network and water bodies are overlapped on the final susceptibility map, shown in Figure 4.1.

The landslide vulnerability mapping is assessed qualitatively to confirm the selection of the most appropriate technique and to advance the prediction accuracy of the landslide vulnerability map. For the AHP based landslide susceptibility map, very high and high susceptible zones cover around 63 % of the total area whereas about 33% is categorized as being moderately susceptible and 3 % is classified as being a low vulnerable zone.

Among different factors selected for this study, slope has been documented as the most critical factor causing massive landslides in this region. Moreover, presence of active thrust and fault system in this highly rugged mountainous region makes it more susceptible. After geology, land covers has been considered as next very critical factor because land use over the identified land covers may change more rapidly and totally alter the land cover.

Closeness to road features also poses certain risk mostly due to undercutting of the slope and may result in slope failure leading to landslides. In addition to slope, rainfall and curvature are also included in this study because of its high importance for landslide processes. Aspect, TWI and SPI have been preferred to include in assessment of landslide risk, as mentioned in literature review section, therefore they are also incorporated in this study.

4.5 Verification of the Results

Finally, the susceptibility maps prepared from AHP is tested using 15 identified landslide sites extracted by Google Earth Imagery (Figure 4.21). The outcome of verification is presented in Table 4.7. It is found that 64.9% of landslides occur in very high landslide prone area. In high susceptible zone 23.4% of known landslides occur. Moderate landslide prone area has 11.7% of known landslides. Zero percent of known landslides occur in low prone area. Zonal histogram of the 15 known landslides given in Figure 4.22.

4.6 Analysis of Questionnaire

This section emphases the outcomes of socio-economic reviews carried out in Rawalakot. Most of the landslide researches highlighting the mechanism that cause landslides, overlooking the social feature which also subsidizes to and is affected by landslides hazard. It is organized in the following parts (Table 4.6); the study of socio-demographic characteristics of the respondents which comprise period of residence, education accomplishment and gender; knowledge of people on landslide incidences; apparent weather settings preceding to the landslides; traditional theories on the landslides incidences; supposed causes and impacts of landslides hazard; managing approaches; slope strength management practices and gender awareness towards the landslides incidences.

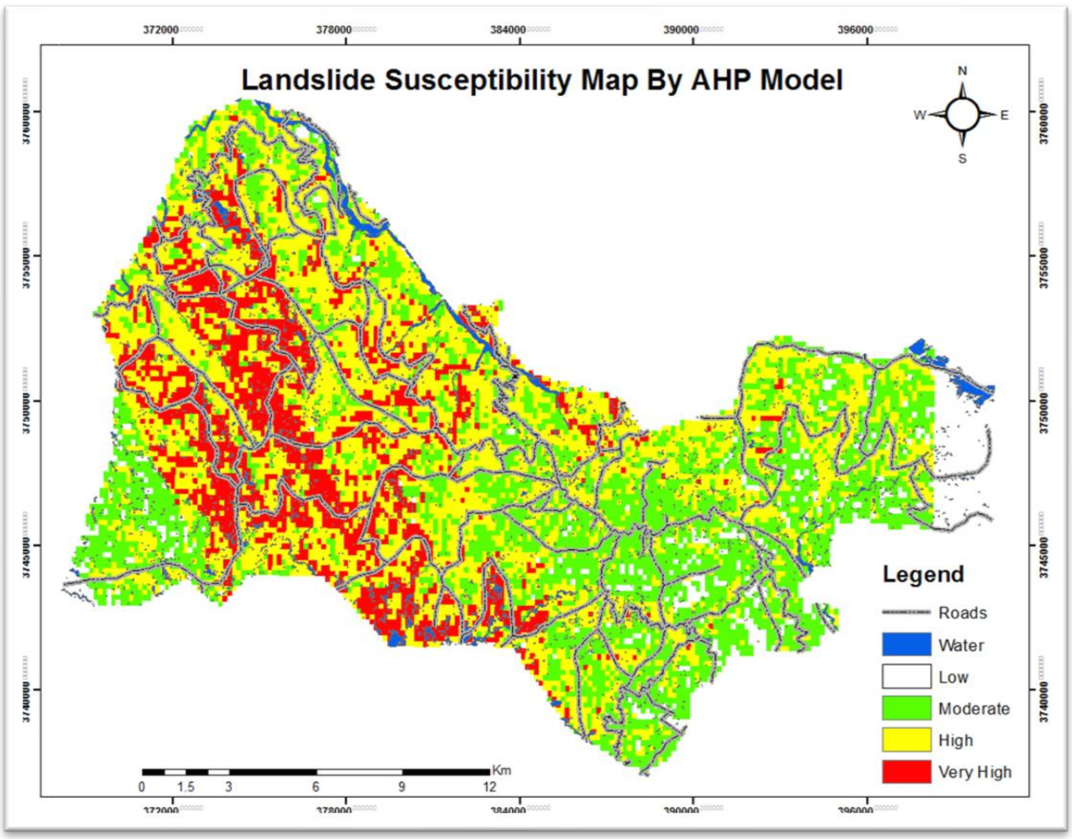


Figure 4.1. Final landslide susceptibility map of Rawalakot through WLC

Table 4.5. Measurements of landslide susceptibility zones.

Group	No. of Pixels	%	Susceptibility Class
1	466	3	Low
2	3941	33	Moderate
3	5311	45	High
4	2231	18	Very High

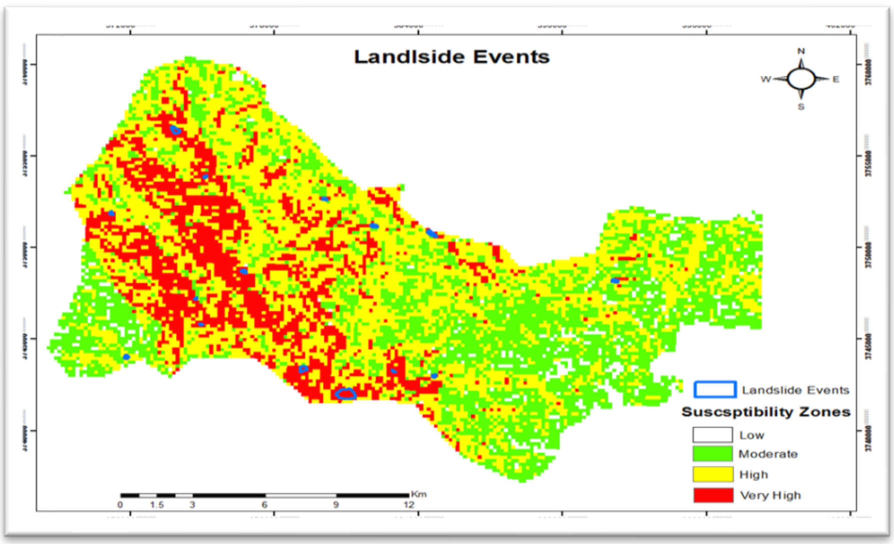


Figure 4.2. Landslide susceptibility map of Rawalakot with identified landslide locations

Table 4.6. Number of pixels and percentage of zones occupied by each landslide disposed zone.

Landslide (LS)	Low	Moderate	High	Very High
LS 1	0	0	3	4
LS 2	0	3	2	3
LS 3	0	1	3	4
LS 4	0	0	0	2
LS 5	0	0	3	5
LS 6	0	0	4	2
LS 7	0	0	3	1

LS 8	0	0	2	3
LS 9	0	0	0	4
LS 10	0	4	0	5
LS 11	0	1	0	6
LS 12	0	2	1	7
LS 13	0	0	0	4
LS 14	0	0	1	6
LS 15	0	0	0	5
Total	0	11	22	61
Percentage	**0**	**11.7%**	**23.4%**	**64.9%**

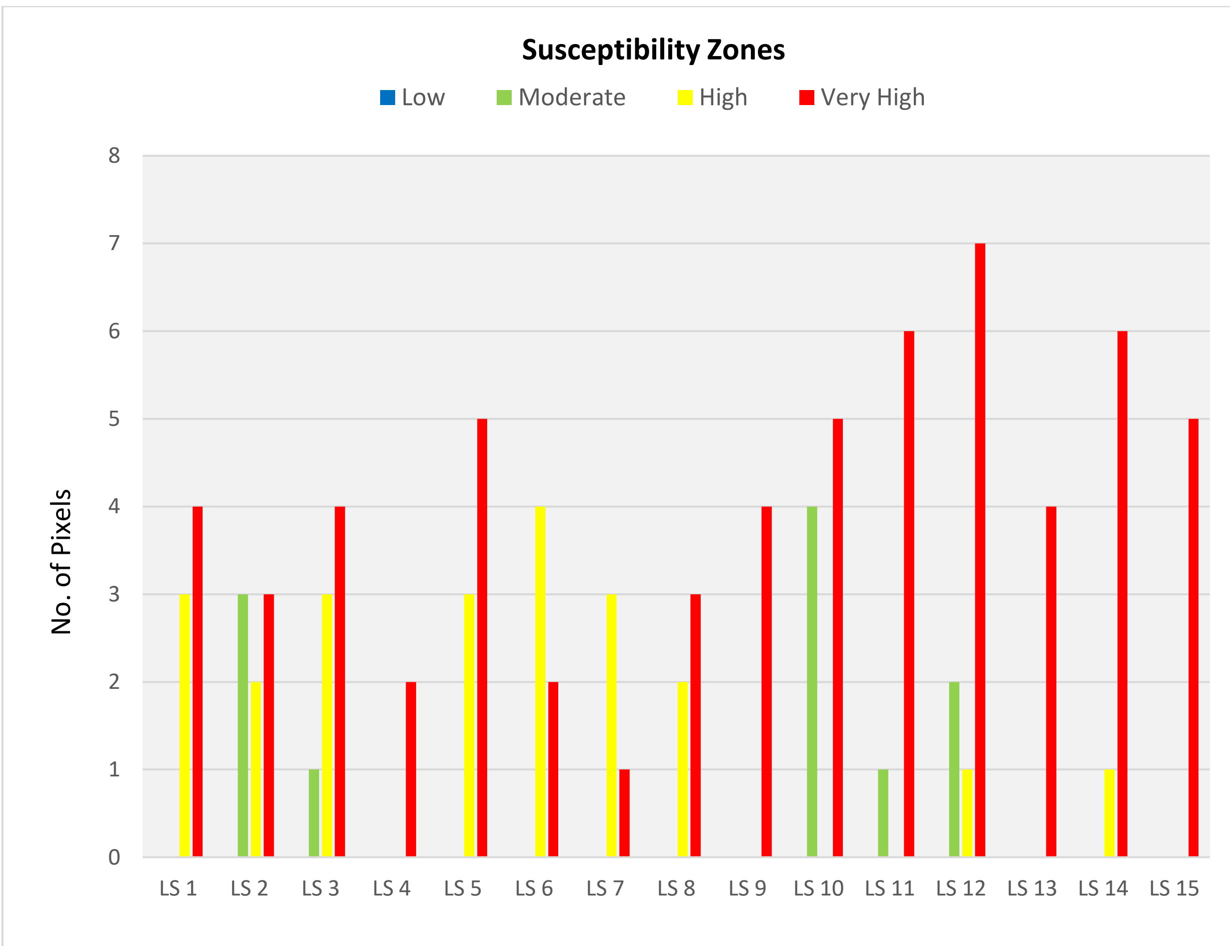


Figure 4.3. Zonal histogram of the 15 identified landslides

4.6.1 Duration of Residence

The sample comprises of 100 respondents from the study area. Of all the respondents, 8% have lived in the regions for less than ten years, whereas 92% have lived in Rawalakot for more than 10 years, with the majority having subsisted for more than twenty years as shown in Figure 4.4(a). The period of dwelling is ensuring a good possibility of understanding the physical environment of Rawalakot. This also gives a probability of respondents indorsing landslides, which might have happened more than ten years ago.

4.6.2 Education Accomplishment of Respondents

The degree of educational completion is evaluated for its significance in the understanding of scientific reasons and causative features to land sliding. Within Rawalakot, educational achievement is presented in Figure 4.4(b). The majority of the respondents had accomplished tertiary teaching, signified by 47%, from study area. Only 8% of the respondents had attained no education. Literacy is noted to be high (47%) in study area. It shows that the majority of the respondent from these parts were either uneducated or semi-literate.

4.6.3 Nature of Housing

The nature/type of housing is assessed with the purpose of estimating the houses vulnerability to land sliding and also as a extent of poverty. The consequences are shown in Figure 4.4(c). In Rawalakot, 76% of the respondents are living in permanent houses while 24% are living in temporary houses.

4.6.4 Location of Settlements

It is perceived that the locality of households are assumed in relation to where one lives or cultivates. Most of the settlements are located along the valley (53%). In the study area, 20% of the houses are located at the foot of hills, 17% along the slopes and 10% along the ridge. In general, houses are scattered. The aims for the locality of the houses are identified, and the outcomes are given in Figure 4.4(d). It is found that most of the houses are situated on ancestral property. Similarly, the replacement of respondent from these lands has shown to be hard. Even if their land is vulnerable by natural adversities, these people will preserve their right to stay and die on these land.

4.6.5 People's Understanding on Landslide Incidences

Understanding of previous landslides is important in illuminating landslides records. Questions are examined to establish people's knowledge on the incidence of landslides, and the outcomes are given in Figure 4.4(e). It is found that majority of the local people (85%) are aware of landslides events. Respondents also specified that the frequency of landslides amplified after the earthquake of 2005 and the growth of population in the research area.

4.6.6 Did Event occur as a Surprise?

According to the local people, landslide events occurred in Rawalakot by surprise. They mentioned ecological deprivation as an indicator. They could also describe the incidences based on historical landslide hazards. Though, the majority of the respondents (85%) could not forecast the incidence of landslides as presented in Figure 4.4(f). Landslide calculation is always challenging in terms of timing and scale. This constitutes a serious task in mitigating the influences.

4.6.7 Weather Situations Prior to Landslides

Weather situations have been observed to influence the timing of landslide events. Questions are tested to determine whether the people could remember the weather situations before the events. The results are shown in Figure 4.4(g). The majority of the respondents revealed prolonged rainfall (75%) prior to land slide hazard. This suggests that these people are aware of modifications occurring in their physical environment and preserve histories of extreme occasions. Such indication formulates the majority of indigenous understanding which is significant in environmental conservation.

4.6.8 Repetition and Occurrence of Landslide

Questions are examined to validate whether the majority of the landslides are of current incidence or recurrences of the previous landslides. The outcomes are given in Figure 4.4(h). They indicate association between field interpretations and the people's observations. Most of the local people (83%) specified that landslides arose in areas, which had previously experienced disaster whereas 17% showed that landslides happened in new zones. The statistic that 17% of the respondents stated that landslides arose in new areas, specifies that slope variability is spreading to other areas as land depletion increase. This also intends that respondents notice modifications taking place in their areas, and retain record of such fluctuations. Therefore, it can be suggested that irrespective of being uneducated and semi-literate, individuals had awareness of their physical atmosphere.

Up to 84% of the respondents indicated that landslides occur every year in Rawalakot. 8% of the respondents showed landslide occurrence every two years. Landslide occurrence are summarized in Figure 4.4(i).

4.6.9 Observed Causes and Causative Factors to Landslides

The study of the perceived causes and causative aspects to landslides is principal in addressing misunderstandings in the traditional understanding. Questions are surveyed whether there are dissimilarities in the observed causes and causative influences in the research area. The outcomes have been shown in Figure 4.4(j) and Figure 4.4(k).

From the examination of data, it is exhibited that the respondents have problems in distinguishing between the sources and causative features to landslides. For instance, in Rawalakot, deforestation and weathering of the basement are observed as one of the sources (14% proposed for deforestation and 3% intended for weathering). Nevertheless, these are the preliminary factors to the incidence of landslides. Hence, it can be determined that the respondents finds it hard to differentiate between what **subsidizes to** and what **causes** landslide hazards.

4.6.10 Vulnerable Areas

In terms of perceived susceptible areas, 47% of the local people specified deforested areas as unsuitable for human livelihood (Figure 4.4(l)). Sharp slopes rated second, with 37% of the majority of people from research area. 10% of local people rated degraded land as vulnerable zone. The outcomes demonstrate increasing awareness of the parts of the hills which are susceptible to land sliding. The outcomes also govern a knowledge of hazard prone areas inadequate for human occupation. However, in spite of the presence of this information, the area of settlements and fiscal actions are in zones which local people supposed to be prone to landslide hazards. It should be prominent that the site of substructure and monetary activities (in marginal/fragile areas regardless of being aware of the danger) is due to restricted land accessible which is also rough.

When question is examined “which part of the slope is susceptible to landslide” then majority of the respondents (74%) indicated upper slopes as more susceptible or vulnerable. Outcomes are presented in Figure 4.4(m).

4.6.11 Impacts of Landslides

Landslides become a hazard when they cause loss of human beings, assets and livestock. The loss created also describes how human beings adapt to the changing environment. Questions are inspected to assess the impacts of landslides, and the findings are given in Figure 4.4(n). Generally, the most devastating impacts of landslide are devastation of infrastructure (47%), and demolition of households (30%). Those who have their houses destroyed have to think of means and time to build new houses. It should also be observed that houses are prepared from mud and unburnt blocks which makes it difficult to start building in rainy season; thus, the affected people short in decent accommodation.

4.6.12 Action Taken During and After the Landslides

Dissimilarities are also observed in the practices adopted by the respondents (Figure 4.4(o)). Those with houses on the wreckage trace have to transfer to safer place whereas most of the people resumed after the hazards. A total of 64% of the local people indicated that they relocated to safer place. Merely 20% moved themselves permanently to new areas. Various researches have shown that during natural tragedies such as landslides and floods, individuals would move keenly to safer place only to return after the rainwaters have reduced. People consider that such occurrences are one of those calamities which hardly occur. However, their continuous stay in these prone zones, abolishes the land further, consequently increasing their vulnerability to disasters. Up to 16% of the respondent assumed that Government and NGOs came for the rescue and injured taken to the hospital.

4.6.13 Landslides Coping Approaches

When natural calamities such as floods or landslides arise and disturb the sources of living, human beings develop new strategies to persist in such situations. Such approaches, may encompass changes in technological developments, land-use schemes, and economic disparity that moderate the effects. Numerous coping approaches implemented are given in Figure 4.4(p). Most of people in the study area (47%) trusted on help from the Government. From the analysis of the outcomes, 37% respondents specified managing food from their monthly revenue. The results display that 5% of the respondents trust in replanting and 5% relied on aid from the NGOs. Researches have shown that rural individuals will wait before proposing into any economic action to inhibit dangers. 2% of respondents resorted to vending house property. This is also shown in the small number of people handling to sell livestock (4%).

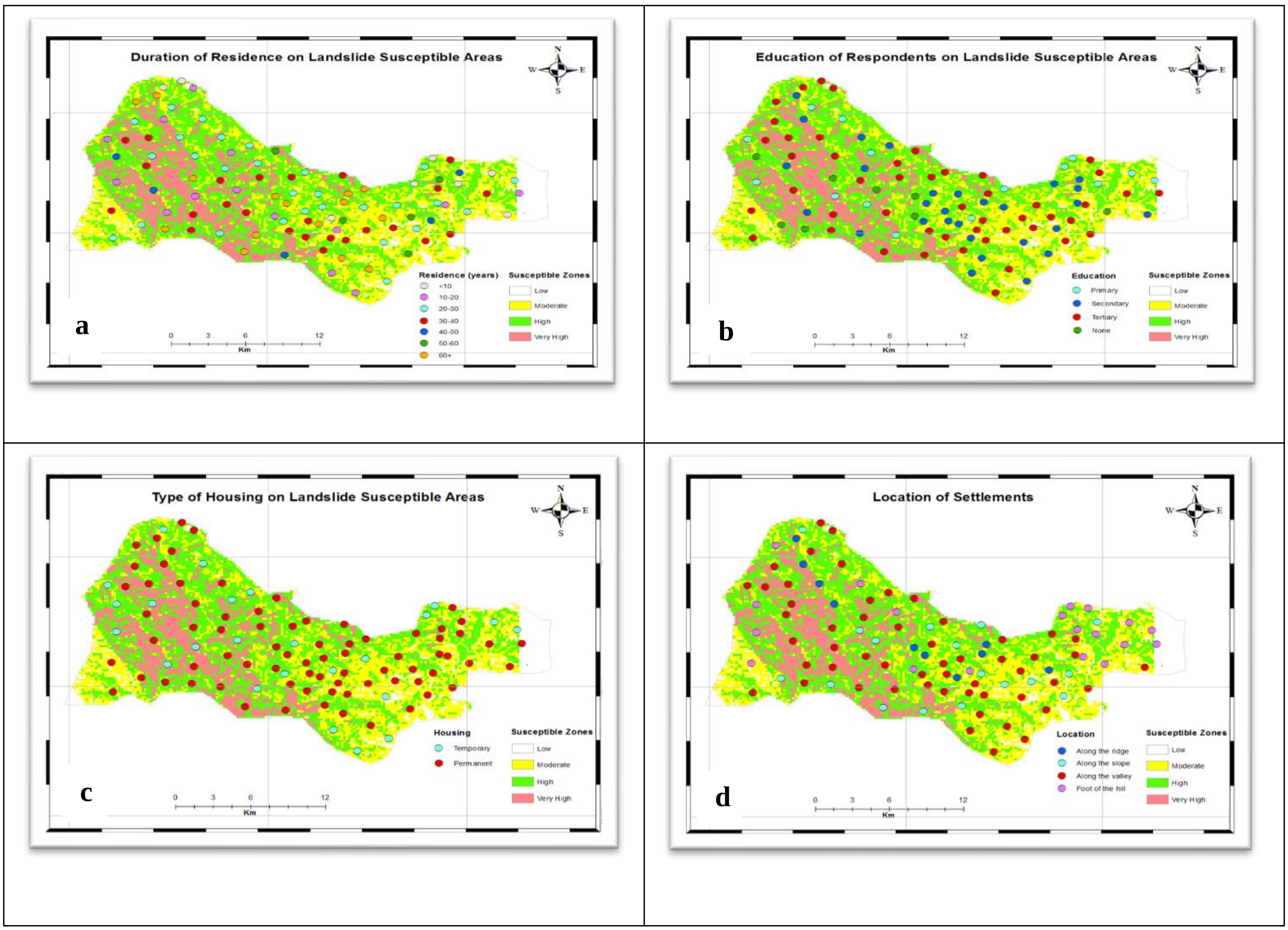
4.6.14 Methods Taken to Inhibit Landslides

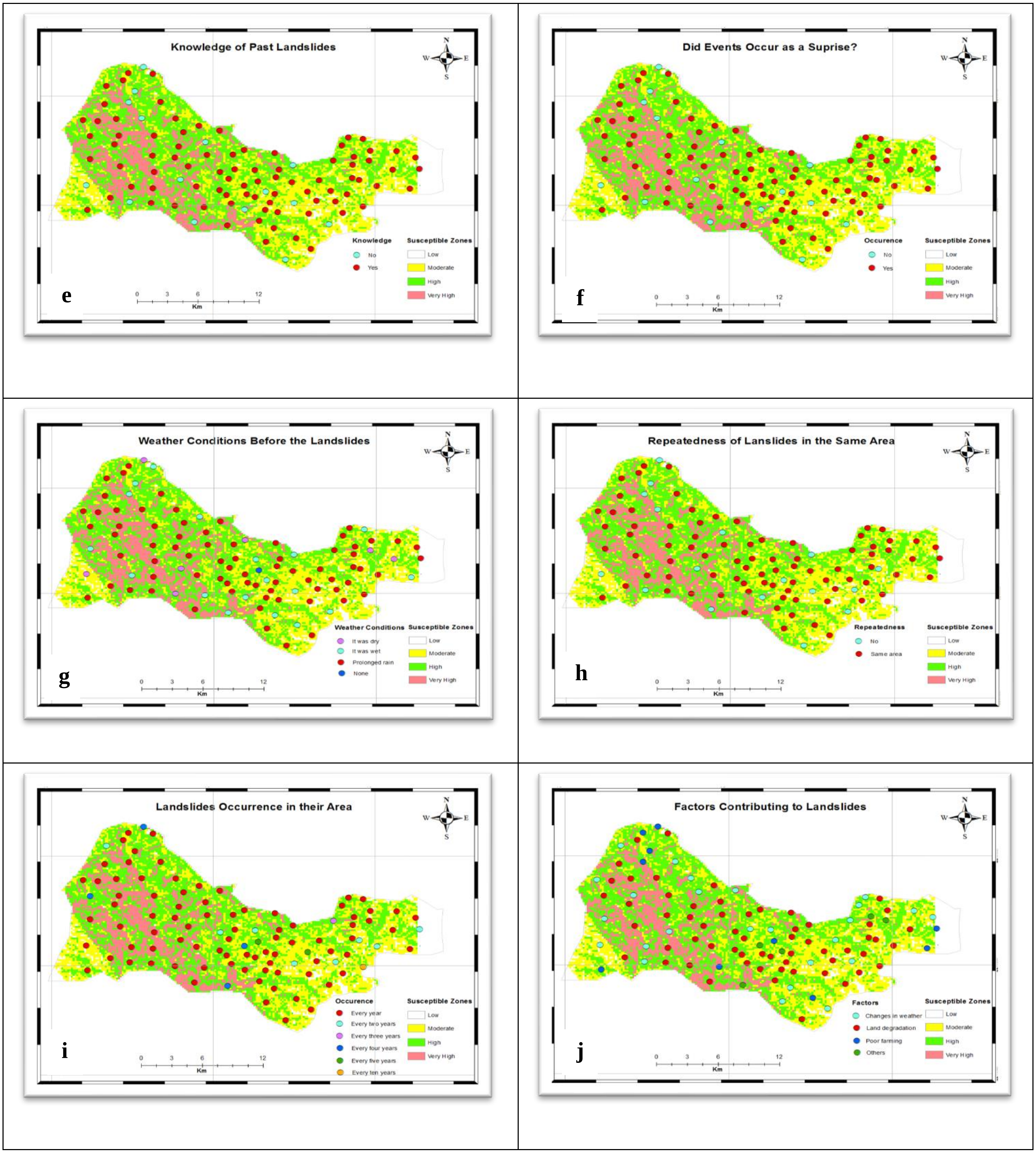
Methods taken to inhibit landslides are vital to the mitigation of their influences. The perceived measures conveyed by the local people are presented in Figure 4.4(q). Up to 70% of the respondents from Rawalakot, indicated carrying out afforestation programmes. 13% of the respondents, presented deserting cultivation on steep gradients or marginal land, while 59.6% designated relocation of settlements and proper building codes. 5% of the respondents indicated the proper sitting of buildings. The findings from these investigations have shown that once the effects of natural dangers have been abridged, little or nothing is done to reestablish the sharp areas by the inherent themselves.

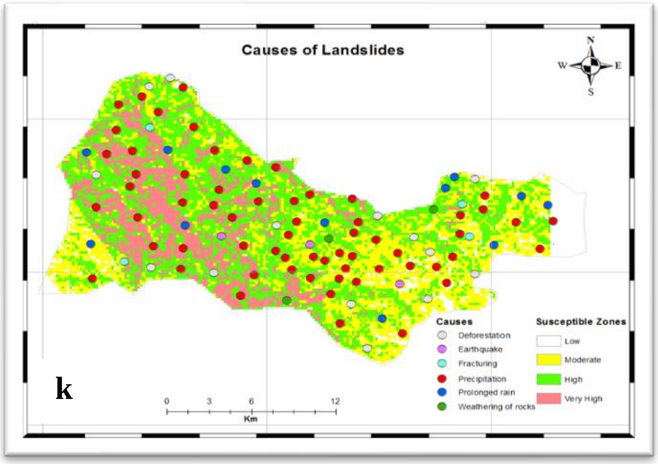
4.6.15 Responsibility for Slope Constancy and Government/NGOs Observed Roles

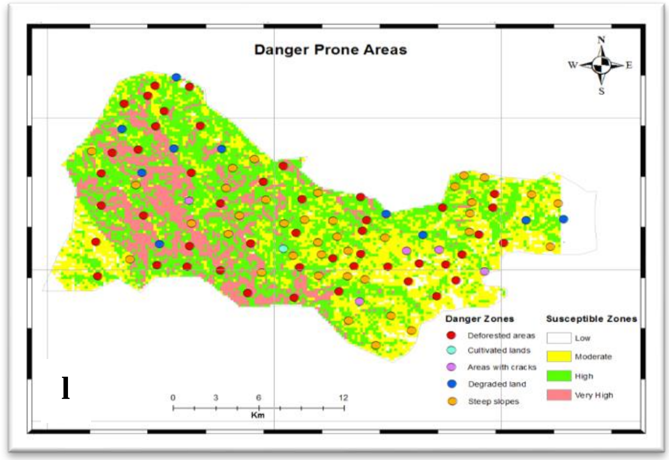
The question of accountability of the conservation of slope strength is examined to describe the cause of people's unwillingness to restore, cope and guard the degraded zones. The results are shortened in Figure 4.4(r). Eighty-five percent of the people strongly consider that the management of the hills strength is the responsibility of Government. Up to 12% of the people believe that the role of handling hills lies in the hands of the local people. The outcomes also indicate that only 3% of the respondents, consider that the NGOs have the responsibility of activating their materials to do community work. So, it can be determined that people within Rawalaot relies more on external provision to bring out the slope restoration.

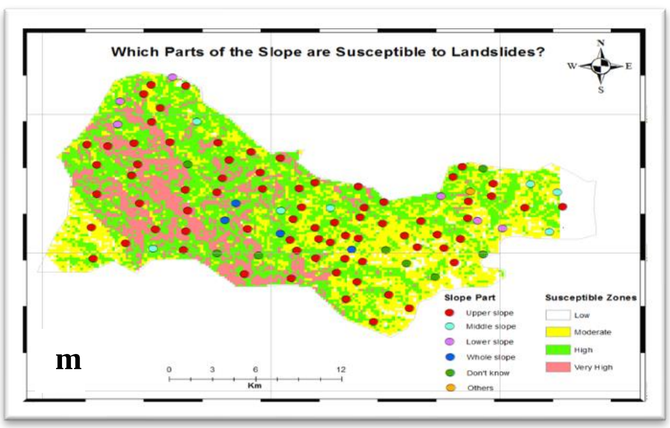
Respondents are questioned what they remark as the roles to be performed by the Government and Non-Governmental Organizations (NGOs) in order to alleviate the impacts of landslide hazards. The results have been summarized in Figure 4.4(s). 56% of the respondents identified that the Government and the NGOs should recommend the restoration of deforested and ruined hills by providing tree saplings (afforestation approach). 25% of the people assumed in initiating awareness movements on landslide vulnerable zones and the hazards of deforestation. 8% of the respondents designated the replacement of settlements to safer lands although 7% specified the initiation of township (housing schemes) to replacing of temporary old-fashioned households. It is also not compulsory that the Government should offer food relief, restore damaged infrastructure such as water supply pipes and bridges. However, it also illustrates the knowledge within groups of the implication of fixing the issue.

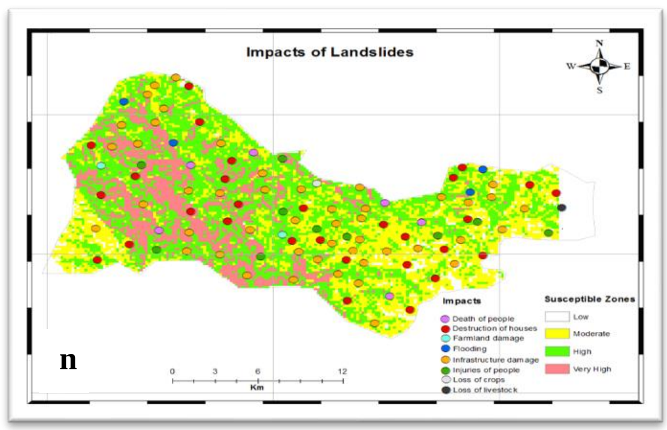


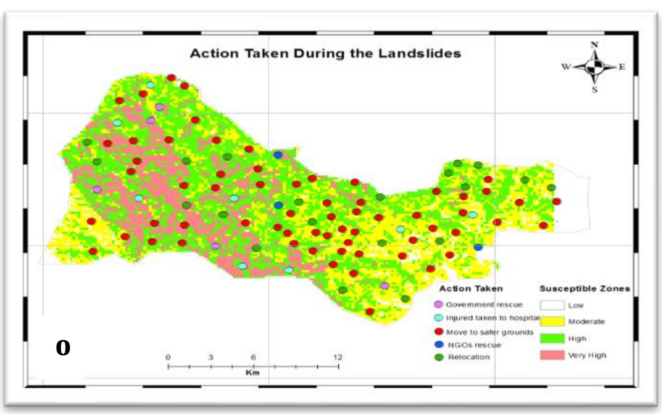

Knowledge of Past Landslides
Knowledge
No
Yes
Susceptible Zones
Low
Moderate
High
Very High
e
Did Events Occur as a Suprise?
Occurence
No
Yes
Susceptible Zones
Low
Moderate
High
Very High
f
Weather Conditions Before the Landslides
Weather Conditions
It was dry
It was wet
Prolonged rain
None
Susceptible Zones
Low
Moderate
High
Very High
g
Repeatedness of Lanslides in the Same Area
Repeatedness
No
Same area
Susceptible Zones
Low
Moderate
High
Very High
h
Landslides Occurrence in their Area
Occurence
Every year
Every two years
Every three years
Every four years
Every five years
Every ten years
Susceptible Zones
Low
Moderate
High
Very High
i
Factors Contributing to Landslides
Factors
Changes in weather
Land degradation
Poor farming
Others
Susceptible Zones
Low
Moderate
High
Very High
j

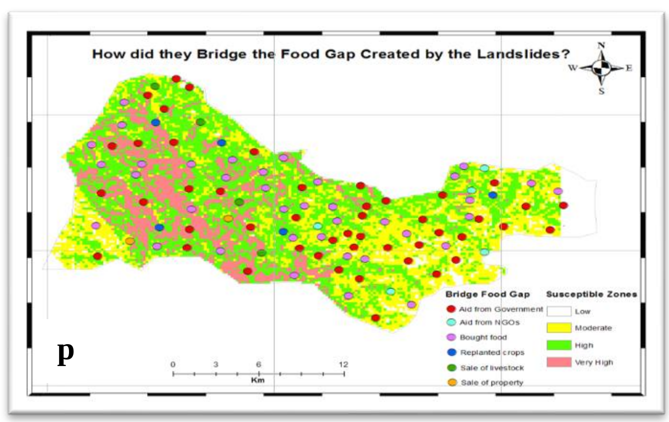

Causes of Landslides
Causes
Deforestation
Earthquake
Fracturing
Precipitation
Prolonged rain
Weathering of rocks
Susceptible Zones
Low
Moderate
High
Very High
0 3 6 12
Km
k


Danger Prone Areas
Danger Zones
Deforested areas
Cultivated lands
Areas with cracks
Degraded land
Steep slopes
Susceptible Zones
Low
Moderate
High
Very High
0 3 6 12
Km
l


Which Parts of the Slope are Susceptible to Landslides?
Slope Part
Upper slope
Middle slope
Lower slope
Whole slope
Don't know
Others
Susceptible Zones
Low
Moderate
High
Very High
0 3 6 12
Km
m


Impacts of Landslides
Impacts
Death of people
Destruction of houses
Farmland damage
Flooding
Infrastructure damage
Injuries of people
Loss of crops
Loss of livestock
Susceptible Zones
Low
Moderate
High
Very High
0 3 6 12
Km
n


Action Taken During the Landslides
Action Taken
Government rescue
Injured taken to hospital
Move to safer grounds
NGOs rescue
Relocation
Susceptible Zones
Low
Moderate
High
Very High
0 3 6 12
Km
o


How did they Bridge the Food Gap Created by the Landslides?
Bridge Food Gap
Aid from Government
Aid from NGOs
Bought food
Replanted crops
Sale of livestock
Sale of property
Susceptible Zones
Low
Moderate
High
Very High
0 3 6 12
Km
p

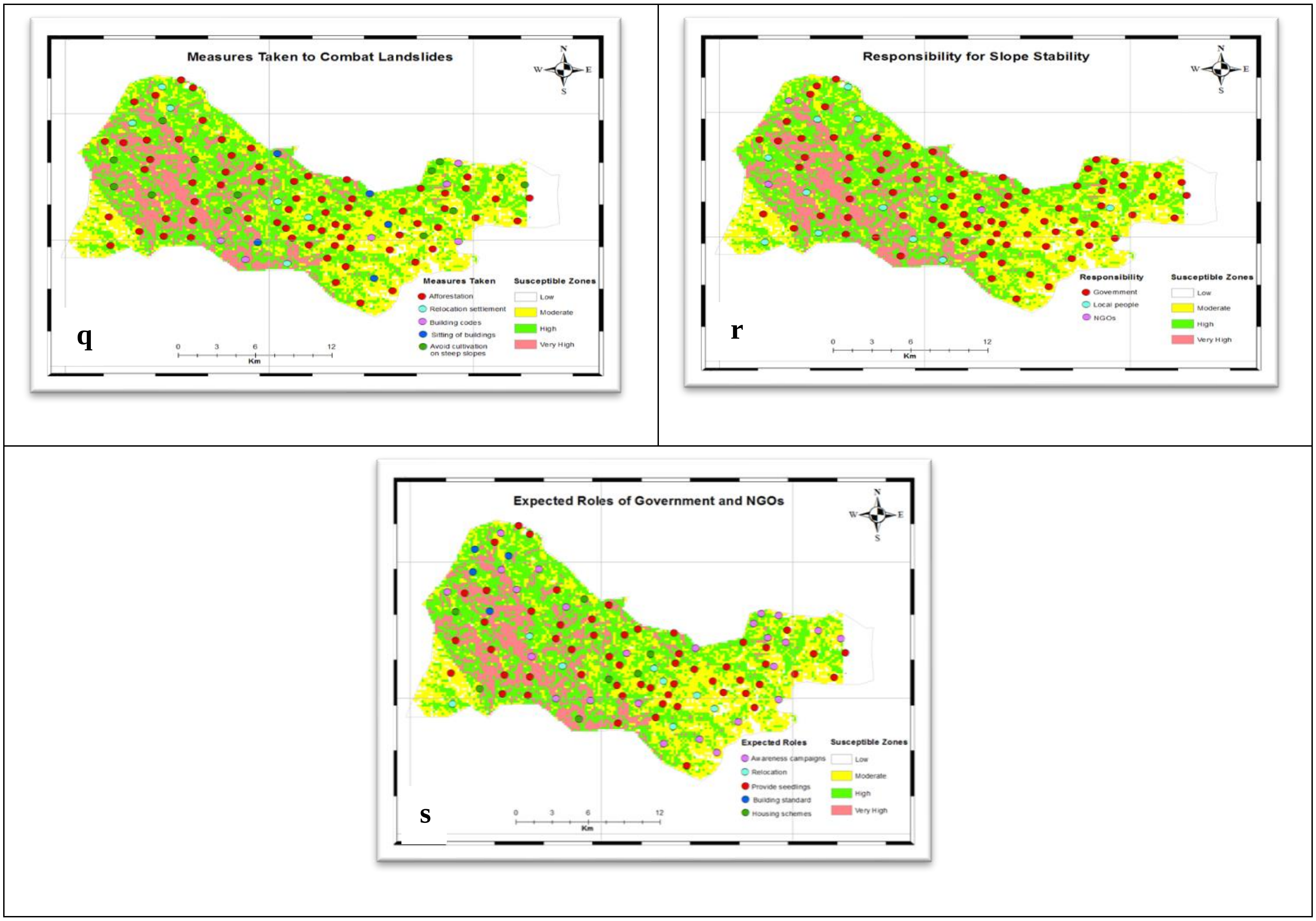


Figure 4.4 Summarization of analysis of questionnaire over landslide susceptible zones

Chapter 5

CONCLUSION AND RECOMMENDATIONS

The chapter presents the conclusions and recommendations for future research. The main purpose of the research is identify and map the spatial susceptibility of the study area to landslides, for future preparedness and mitigation purposes.

5.1 Conclusion

In this study, map of landslide susceptible zones of Rawalakot located in district Poonch (AJK) produced using analytical hierarchy process (AHP). Twelve landslide controlling parameters namely slope, elevation, aspect, plan curvature, SPI, TWI, distance from streams (drainage), distance from roads, geology, distance from faults, rainfall, and land cover are employed. Satellite imageries, geological sheets, and excel sheets are used for the extraction of the aforementioned factors. Weights are given to these parameters and their classes with respect to the condition of the model employed.

The allotted weights for each parameter class are then joined to produce final susceptibility map (Figure 3). Approximately 18%, 45%, 33%, and 3% of the Rawalakot are categorized to be in very high, high, moderate and low susceptible zones of landslide respectively.

Based on results of the pairwise comparison using AHP method, slope, lithology, rainfall and distance from thrusts and land cover are the most inducing factors for landslide phenomenon in Rawalakot with 0.20, 0.19. 0.15, and 0.09 weights respectively. And the least contributing factors are TWI (0.03), SPI (0.03), Plan curvature (0.02) and elevation (0.02). It is found that 63% of research area occurs in high and very high landslide prone areas. Therefore infrastructure constructions and master planning of economic projects should carefully be started in these zones. It is concluded that landslide susceptibility maps can increasingly be considered as base map for landslide hazard evaluation in the study area when intending to avoid or reduce the impacts of future hazards and improve decision-making prior to any development in this mountainous region requiring significant investigation.

Social survey showed that the information delivered by the native people about landslide proneness shall aid engineers, citizens, decision makers and scientist, to minimize damages produced by current and forthcoming landslides through prevention, mitigation and avoidance. The survey results in the form of tables and maps are therefore useful for explaining the driving factors for triggering landslides, for supporting emergency decisions and for supporting the efforts on the mitigation of future landslide hazards in Rawalakot Azad Kashmir.

5.2 Recommendations

Reliable and consistent data in support of the slide occurrences of the recent past should be used to improve the results. This may help to establish a temporal analysis of landslide hazard in the region and also to check if any past slides are still fresh and/or reactivated. In this study, more focus has been on landslide triggering due to slope instability. Other datasets like top soil cover may also be included to understand the role of this factors in landslides in the region and identify other slide type like rainfall triggered. Geological Survey of Pakistan (GSP) has been working on the first national project of Landslide Inventory Database Project (LIDP) to keep the record of landslide events in Pakistan especially in Northern Pakistan. These maps can be shared with them for field validation and verification due to huge hazard suspected in the area. As previously mentioned, landslide is an underestimated, in turn, less studied subject in Pakistan. This study may serve as an initiative and suggests that efforts should be initiated to investigate the landslide hazard in other regions of Northern Pakistan.

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