Land Slide Susceptibility Analysis Using GIS, Remote Sensing, and Multi-Criteria Decision Analysis: A Case Study of Chitral District.

By

SAHIBZADA SHAHRUKH KHAN

(2020-NUST-MS-GIS-329349)

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

Institute of Geographical Information Systems
School of Civil and Environmental Engineering
National University of Sciences and Technology
Islamabad, Pakistan

September 2024

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Sahibzada Shahrukh Khan (Registration No. MSRSGIS 00000329349), of Session 2020 (Institute of Geographical Information Systems)** has been vetted by undersigned, found complete in all respects as per NUST Statutes/Regulation, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature:
Name of Supervisor: Dr Ejaz Hussain
Date: 2-Sep-24

Dr. Ejaz Hussain
Associate Dean IGIS. SCEE (NUST)
H-12, ISLAMABAD

Signature (HOD):
Date: 13-9-24

Dr. Muhammad Ali Tahir
HoD & Assoc. Prof. SCEE (IGIS)
NUST, H-12, Islamabad.

Signature (Principal & Dean SCEE):
Date: 19 SEP 2024

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

ACADEMIC THESIS: DECLARATION OF AUTHORSHIP

I, **Sahibzada Shahrukh Khan,** declare that this thesis and the work presented in it are my own and have been generated by me as the result of my original research.

" Land Slide Susceptibility Analysis Using GIS, Remote Sensing, and Multi-Criteria Decision Analysis: A Case Study of Chitral District."

I confirm that:

1. This work was done wholly by me in candidature for an M.S. research degree at the National University of Sciences and Technology, Islamabad.
2. Wherever I have consulted the published work of others, it has been attributed.
3. Wherever I have quoted from the work of others, the source has always been cited.
4. I have acknowledged all main sources of help.
5. Where the work of the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
6. None of this work has been published before submission. This work is not plagiarized under the H.E.C. plagiarism policy.

Signed: Sahibzada Shahrukh Khan

Date: 23/09/2024

`

DEDICATION

To

Family and My Late Mother

A special feeling of gratitude to my father, my late Mother, and my brother and sisters for their unwavering support and encouragement throughout my journey.

ACKNOWLEDGMENTS

All praises to Almighty Allah to whom everything belongs and to whom we all will return. I am obliged to show my sincere gratefulness to all the people and the institution that contributed to making this research possible and successful. Their help and encouragement have led to the completion of this research. I feel obliged to show my appreciation for my supervisor, Dr Ejaz Hussain for supervising, guiding, and teaching me with all the patience and support throughout my research phase.

Secondly, I would be delighted to thank my Guidance Examination Committee (GEC) members, Dr Javed Iqbal (IGIS-NUST), and Dr Hamza Farooq Gabriel (NICE-NUST) for their constant support and guidance throughout the research work time phase. Their valuable advice and comments helped me improve my research and take it in the right direction.

Lastly, I am pleased to acknowledge the support of my late mother, my family, and friends for showing me their love, support and wishes throughout my educational time. I am highly thankful for their continuous motivation and contribution to my self-confidence and success.

SAHIBZADA SHAHRUKH KHAN

`

TABLE OF CONTENTS

`

LIST OF FIGURES

`

LIST OF TABLES

`

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AUC	Area Under Curve
GIS	Geographic Information System
LULC	Land Use Land Cover
MCDM	Multicriteria Decision Making
NDSI	Normalized Difference Snow Index
NDWI	Normalized Difference Water Index
NIR	Near Infra-Red
RGB	Red Green Blue
RS	Remote Sensing
LSZ	Landslide Susceptibility Zones

`

ABSTRACT

Geological hazards posed by landslides, debris flows, rock avalanches, and mudflows have always been a major threat to communities worldwide, causing extensive damage and destruction of infrastructures and facilities. The upper Chitral region, located in the eastern Hindu Kush ranges, is particularly vulnerable to these hazards, necessitating a comprehensive assessment of landslide risks and their socio-economic and environmental impacts to support disaster risk reduction efforts. This study aims to assess the landslide hazard assessment utilizing the Analytical Hierarchy Process (AHP) with Geographical Information System (GIS) to make a susceptibility map of the potential landslides in Chitral. Several landslide-causing factors (slope, aspect, curvature, land use, lithology, elevation, distance from faults, distance from streams, and precipitation data) were selected for the susceptibility assessment. Various thematic layers relative to these factors were combined and weights for each factor were assigned using the AHP technique to generate the landslide susceptibility map. The landslide susceptibility map was classified into five zones: very highly susceptible zones, highly susceptible zones, medium susceptible zones, low susceptible zones, and very low susceptible zones. To ensure the accuracy and reliability of the model, the results were validated using NASA's landslide inventory data. This validation confirmed the robustness of the susceptibility map in accurately identifying areas at risk. The study findings indicate that certain regions within Chitral are highly susceptible to landslides due to steep slopes, fragile geological formations, and heavy rainfall. Mitigation measures such as early warning systems, retaining walls, land use planning, and regular mapping of vulnerable sites should be applied.

`

Chapter 1

INTRODUCTION

Natural disasters refer to various severe and extreme natural events with destructive characteristics that can harm human lives, properties, and the whole ecosystem. The main causative factors for these disasters are natural phenomena and anthropogenic activities. Natural phenomena are all related to movement and processes within the Earth's crust, resulting in earthquakes, volcanoes, landslides, etc. In contrast, earthquakes occur when the impulsive release of energy happens along the fault plane and when two geological boundaries interact. Volcanic eruptions also cause earthquakes where they expel magmatic material, ash, and gases out of the volcano's cone (Smith et al., 2022). Geological Hazards majorly include landslides, which are downward movement of strata along the slope. Droughts can be classified as climatic hazards, where there is little to no rainfall, impacting the whole cycle of agriculture, resulting in a low supply of food, and causing water scarcity. Hydrological Hazards are water-related events such as floods, which are triggered by the high level of precipitation in a region, melting of natural snow on the mountain due to global warming, and dam failure that can submerge even the dry land. Atmospheric disasters can cause various adverse climatic conditions. These weather-related disasters include blizzards, tornadoes, hurricanes, thunderstorms, and heatwaves. Last but not the least, there is another type of hazard in which microorganisms become a cause of the pandemic in the form of diseases such as Covid 19, Cholera, etc. called Biological Hazards (Kourkouli., 2023).

Natural disasters have the potential to cause significant damage. Some disasters can target and affect properties, infrastructure, and life, while others also give rise to food and water security issues like floods, droughts, etc. These disasters are also a menace to the economy as “0.5%” of the annual GNP of developing countries is disappearing due to landslides (Islam et al., 2022).

Mountainous areas are the most vulnerable to various natural calamities, the most common among which are landslides that can cause a wide range of adverse impacts such as asset loss, fatalities, and damage to natural resources and infrastructure. Given the statistics mentioned earlier, it is necessary to prevent (as much as possible), assess, monitor, and mitigate these hazards to alleviate the intensity and magnitude of the damage that results from them. Various tools such as “landslide susceptibility maps” can be used for proper planning of land usage as they provide data regarding landslide-prone areas.

The adverse impacts of disasters are worsened when multiple natural hazards superimpose their effects on each other and work jointly. This phenomenon is often demonstrated during earthquakes that can also trigger tsunamis and contribute to cumulative disastrous impacts. Every disaster has its own way of having individual destructive impacts. This study delves into the depths of the landslide phenomenon by utilizing remote sensing-based products that calculate its susceptibility (Shao & Xu, 2022).

Landslides are considered as the third most crucial disaster worldwide and can occur over a wide range of velocities. They can directly impact the socio-economic systems as they are usually triggered without warning and give less time to people to evacuate and find a safe place. As many developing countries, Pakistan also faces numerous hazards that impact socioeconomic factors such as loss of properties and agricultural, industrial, and forest productivity. Moreover, they are responsible for a significant loss of life and livestock, which is usually the main source of income for people living in mountainous regions (Sim et al., 2022). The northern region of Pakistan covers approximately 72, 496 km^2 of area. The highest peaks reach an elevation from 1000 meters to more than 8000 meters above sea level. These ranges are often seismically active and demarcate the tectonic collision zones. The rate of erosion caused by glacier melting and heavy downpours is becoming more and more intense due to anthropogenic activities and has consequently caused an increase in the frequency of landslides in the northern regions of Pakistan (Rehman et al., 2020).

The prime factors that trigger landslides include seismicity, precipitation, and rock deterioration. These factors can provide information about the slope stability of an area, which is important for effective susceptibility mapping. Landslides usually occur in areas where the slope is greater than 45 degrees. However, other factors besides slope gradient play a key role in defining the likelihood of a landslide event in a given region. Therefore, it is crucial to determine all these key factors and appropriate analysis and modeling methods for generating landslide susceptibility maps (Wu et al., 2023).

Landslide risk mapping is essential in recognizing the landslide-prone areas and optimizing mitigation measures in mountainous regions. A landslide susceptibility map can identify areas that are susceptible to landslides and measure them from low to high in terms of hazard probability. Hazard mapping involves various steps, including data collection and preparation of a spatial database from which relevant factors such as distance to roads and faults can be extracted. Remote sensing data and GIS have made it possible to map landslide susceptibility by using thematic layers as causative factors data.

According to Chang., (2019) GIS is a significant tool that can collect, store, retrieve, display, and assemble spatial datasets and help in creating risk/hazard models. The input parameters for generating these landslide susceptibility maps are taken from field surveys and satellite imagery. Different quantitative and qualitative techniques exist for analyzing/mapping landslide vulnerabilities in a GIS environment. For regional assessment, it is noted that both expert judgment-based qualitative approaches and traditional technical methods are found effective. Quantitative methods gave input on how slope, rainfall, and other landslide-controlling elements are interrelated.

In this study Multicriteria Decision Making (MCDM) methodology namely AHP (Analytical Hierarchy Process) is used to develop the landslide vulnerability map for the study area. AHP is a qualitative but semi-quantitative technique in which factors responsible for landslide hazards are compared in an array. Following the “Factor balancing technique” the area prone to landslides is marked and divided into landslide susceptibility zones (LSZ) (Ibrahim et al., 2022).

This study is an effort to the landslide threat in Chitral and the highly complex connection among physical settings, people, and landslide occurrences.

1.1 Objectives

This research has emphasized the following main objectives:

1. To generate a Landslide susceptibility map for the study area of Chitral district using AHP.
2. To validate the Landslide susceptibility map using historical Landslide data.
3. To suggest suitable mitigation measures specific to the study area to reduce and prevent the adverse impacts of landslides.

`

Chapter 2

LITERATURE REVIEW

Landslides are natural phenomena that generally involve the downward movement of mass over a slope. This mass can include snow which turns into an avalanche, or the mass can include soil or rocks which refer to landslides and rockfalls. The downward movement is generated because of gravity, which is one of the factors that cause landslides, along with other factors such as slope destabilization caused by earthquakes, along with liquefaction which is because of rainfall.

As stated above, a landslide is the downward movement of mass over a slope, which is further defined by Gariano & Guzzetti, (2016) as the downward movement of rock debris and soil mass. Landslides can be caused by heavy rain, earthquakes, or other factors such as volcanic eruptions that can make the slope unstable. The three major causes of landslides involve morphology, geology, and anthropogenic activities. Morphology refers to the land structure, such as the slopes that have lost vegetation due to fire or drought and are more vulnerable to landslides. Another morphological cause can be eroded land that is weakened with the movement of water in the form of heavy rainfalls or melted snow. Geology refers to the characteristics of rock materials such as shales (rocks composed of silt-sized grains and clay), which are more commonly associated with landslides. Anthropogenic activities such as deforestation, construction, agriculture, and excavation can also destabilize slopes and trigger landslides. They can have extensive impacts such as the destruction of infrastructure, loss of life, damage to properties, and loss of scarce natural resources.

`

2.1 Types of Landslides

2.1.1 Falls

There are different types of landslides categorized mainly by the mass, which is moving a slope downwards, in the case of falls this mass determines the type and effect of the landslide. If the mass is snow, such a landslide is called an avalanche. On the other hand, if the mass is composed of rocks that move downwards due to various factors such as seismic activity, mechanical weathering, or freeze-thaw cycles then such a landslide is a rock fall. The categorization of rock falls, impacts, and potential threats were discussed in the study conducted by Doren et al., (2007).

2.1.2 Topples

In general, such a downward movement of mass is caused primarily by soil erosion, which can be caused by various factors, primarily anthropogenic factors such as mining or differential weathering. Soil erosion in this case causes rocks or debris to move downwards about the pivot point as explained in the study conducted by Stead & Walter, (2015), this research also utilized various geomechanical models and others to simulate and predict slope failures.

2.1.3 Slides

Slides in general also refer to the downward movement of mass on a slope, now as discussed before in the case of an avalanche the mass sliding on a slope would be the snow accumulated on said slope. Slides are further classified into two categories: translational and rotational slides which in general correspond to the moving pattern of sliding material, rapid accumulation resulting into rapid mobilization of mass (material) along a planar/ relatively flat surface or fault line referred to as translational slides while rotational slides refer to the rotational movement of mass along a parallel axis with respect to the slope. A study was conducted to further understand translational slides by utilizing the nature of the material, slope grade, and water content (Tiranti., 2012). Rotational slides can occur in areas with slopes or hillsides having a concave shape. The risk of rotational landslides can be assessed using data collected from geotechnical monitoring. Slope rotation against the centers of slip surfaces can cause surface deformation of landslide masses when the slope is sliding, considering the path of sliding masses being parallel to slip surfaces (Xie et al., 2020).

2.1.4 Flows

In general, flow represents the movement of mass, like fluids, mass can be composed of various materials such as rocks, debris, or mud. The categorization of fluids is based on the material movement and the speed at which the material moves.

Debris Flows, as the name implies refers to the flow of debris primarily composed of rocks, soil, or organic matter, this flow is very fast and rapid.

Mudflows refer to the downward movement of mud along a slope categorized by the material, which is a fine grade, affecting the flow and causing it to travel longer distances like liquid flow. Mudflows are considered an intermediate phenomenon between landslides and floods. They can cover distances of several miles at high speeds with no visible warning signs.

Earthflows are the downward movement of material such as clay or silt, caused by slope destabilization. The movement of earth flows caused by various factors such as earthquakes and rainfall are discussed in the research conducted by Mazza et al., (2023) according to which the flow of this disaster can be slow, sluggish, and fast based on factors such as the amount of rainfall.

Creep represents the continuously slow displacement of soil or rock under gravity. There are three types of creeps, including continuous creep where the soil debris cannot resist gravity, progressive creep which involves the downward movement of material when soil and rock debris reach a critical state and can trigger a landslide when combined with other factors such as rainfalls, earthquakes, etc. and seasonal movements that occur due to seasonal changes in temperature and soil moisture. According to Kaczmarek & Dobak, (2017) the main driving factors of creeps are thermal expansion, freeze-thaw, and soil moisture.

2.1.5 Lateral Spreads

A slope with a small area and an unstable base would cause propagation sideways in primarily flat areas, caused by natural phenomena such as tectonic movement. The failure starts in a small area and spreads rapidly. Lateral spreading often occurs along the shorelines and riverbanks where saturated, loose sandy soils are present at shallow depths. Liquefication-induced lateral spreads are alluvial floodplains' most prevalent seismic hazard (Chung et al., 2014).

2.1.6 Complex Landslides

Landslides are hazards that are propagated by other hazards such as earthquakes, floods, and heavy rainfalls, which result in different kinds of landslides. There are instances where various kinds of landslides occur in one incident. These landslides composed of various types are referred to as complex landslides. A study was conducted to understand and simplify the complexity of said landslides and bring attention to multi-disciplinary approaches (Hunger et al., 2013).

2.2 Factors Affecting Landslides

Understanding and fully comprehending the various factors that cause landslides is essential. Various factors such as topography and climate conditions were discussed in research conducted by Zhao & Lu, (2018). The literature review section of this research utilizes various studies and research to explain various factors affecting landslides fully.

`

2.2.1 Intrinsic Factors Affecting Landslides

Intrinsic refers to internal; hence intrinsic factors are related to the slope's material and the environment.

2.2.1.1 Geology

i. **Rock Type:**

The internal structure of a rock categorizes its type, if a rock is composed of granites that are weather-resistant and long-lasting then such a rock would not trigger a landslide but on the other hand, if the material has low strength such as sedimentary strata, then such rocks would be vulnerable to landslides. Miscevic & Vlastelica, (2014) discussed rock types concerning landslide classification.

ii. **Structural Features:**

This mentions the environment and the formation of the planes upon which landslides are caused. Faults, joints, bedding planes, and other structures in general destabilize a slope which causes landslides. Faults contain material that can slip under stress (crushed material) while joints open a path for water flow causing erosion and cohesion leading to landslides. A study was conducted to determine the importance of structural factors in causing landslides (Majdi & Amini, 2011).

2.2.1.2 Soil Properties

i. **Soil Type:**

The type of soil greatly affects the occurrence of landslides as different types of soils react differently with the environment, such as sandy soils which in general lose moisture content more easily when compared to clay soils, the accumulation of moisture in clay soils causes them to become unstable leading to landslide the effects of different type of soils is discussed in detail in the research conducted by Batumalai et al., (2023).

ii. Soil Structure and Cohesion:

The internal arrangement of soil particles is referred to as soil structure which greatly impacts landslides as the stabler the soil structure the less likely is the chance for occurrence of landslides and vice versa. A stable soil structure resists erosion which promotes proper drainage, while on the other hand unstable structure leads to weakened soil. Cohesion on the other hand is the binding force that keeps the soil particles together hence greater the cohesion greater the strength of the soil which leads to less chances of landslides (Bek et al., 2021).

2.2.1.3. Slope Gradient and Morphology

Gradient refers to the angle of the slope and hence the greater the gradient the greater the steepness of the slope. Steep slopes are more prone to gravity which causes landslides. Morphology on the other hand refers to the structure and shape of the features of a slope which affect the stress distribution along the slope. The research was conducted to explain and understand the effect of steepness of the slope on landslide occurrence by Evans et al., (2006).

2.2.1.4 Vegetation

Vegetation has great effects on landslide susceptibility as plants in general nourish the soil upon which they grow, and they can act as natural retaining walls. Through nourishing the soil, the stability of the slope can also be improved. Plants also accommodate rainfall and other environmental phenomena. Khalilnejad et al., (2011) discussed the importance of vegetation in landslide mitigation as well as the causes of landslides based on a lack of vegetation.

`

2.2.2 Extrinsic Factors

Extrinsic factors involve external factors that influence slope destabilization such as rainfall, earthquakes, and climatic conditions.

2.2.2.1 Weather and Climate

i. Precipitation:

Rainfall in large amounts can affect the cohesive forces acting on the soil which causes it to liquefy leading to greater chances of landslides. Rainfall-induced landslides can be initiated due to the facilitating role of infiltrating water that can decrease slope stability, increasing the soil's groundwater pressure and unit weight. Landslides occur in clusters and may occur together with flash floods in extreme rainfall events (Yang et al., 2020).

ii. Temperature:

Slope destabilization is also affected by temperature as freeze-thaw cycles crack the soil and rocks. The factors are discussed in detail in the research conducted by Guo et al., (2013) who also studied permafrost conditions.

iii. Climate Change:

This refers to the change in atmospheric conditions over a long period. In general, climate change via factors like global warming can affect the weather of a region, leading to natural hazards such as landslides. Climate change can alter the landslide and sediment processes through sea level rise, increasing air temperatures and causing more frequent and heavy rains.

`

2.2.2.2 Hydrology

1. **Groundwater Level:**

The greater the groundwater level the more likely the slope destabilizes, leading to slope failure as soil saturation increases with greater groundwater level which causes a decrease in the cohesion forces. On the other hand, low groundwater levels can decrease the chances of a landslide but can result in droughts. Soil structure is affected by the pore pressure generated by the accumulation of groundwater in the subsurface. Jestin et al., (2020) studied the effect of groundwater level on the causation of landslides and concluded that considering groundwater in landslide susceptibility is important depending upon the topology of the region.

ii. **Surface Water:**

The amount of water accumulated over a surface is referred to as surface water; it affects the moisture quantity of the soil and causes erosion. Slope stability is affected by surface runoff that washes away soil. The cohesion forces within the soil are also affected by runoff, as they are weakened which causes destabilization of the soil. A study was conducted by Earth zine., (2015) to reflect upon the importance of hydrological factors in the causation of landslides in which surface runoff of water was one of the most important factors.

2.2.2.3 Seismic Activity

A landslide is a natural hazard that is propagated by other hazards, one of which is earthquakes, which can also trigger landslides due to the higher impact of seismic activity, causing catastrophic landslides.

`

2.2.2.4 Human Activities

i. Construction and Excavation:

Anthropogenic activities such as the construction of commercial zones and other things cause destabilization in the slope especially when construction is performed on slope regions. Worldeargay., (2013) conducted a study regarding the effect of anthropogenic activities such as construction on landslide occurrence.

ii. Deforestation:

Refers to cutting of trees and other vegetation for construction or due to natural reasons such as forest fires, as discussed earlier a lack of vegetation can lead to greater chances of slope stabilization. Imaezumi et al., (2008) conducted a study in which the relationship between deforestation and landslide causation was discussed in detail for tropical regions.

2.2.2.5 Agriculture

Agriculture practices that lead to soil erosion can cause landslides due to slope instability. Garcia-Chevice et al., (2020) conducted a study in which the relationship between different agricultural practices and the causation of landslides was underlined.

2.2.2.6 Effect of water on Landslide

One of the most important factors that influence the causation of landslides is water, the amount of water interacting with the material on the slope is important as phenomena such as intense rainfall, runoff due to snowmelt, and an increase in groundwater determine whether a landslide would occur or not. Rainfall would cause an increase in soil pore water pressure, reducing the forces of cohesion and triggering landslides. Surface runoff on the other hand can cause soil erosion also triggering landslides. Steep stream systems are also prone to mudflows and other forms of landslides which refers to the fact that floods and landslides are both affected by water and a study was conducted regarding the similarities of floods and landslides and how they cause each other (Bosco & Sander, 2015).

2.3. Analyzing Landslide Vulnerability through Spatial Analysis

GIS is an important tool that can be used for landslide susceptibility analysis owing to its visual advantages and applications in contemporary research. Landslide occurrence can be predicted based on spatial information such as rainfall, hydrology, geology, geomorphology, etc. Various techniques such as multicriteria evaluation using AHP can be used for landslide susceptibility mapping and analysis.

Torizin et al., (2017) conducted a study to determine landslide susceptibility for the regions of Mansehra and Torghar using statistical models namely the WofE (Weight of evidence) also referred to as the Bayes Classification model while the assessment was done by following the "Georisk Assessment Northern Pakistan" (GNAP). The accuracy of the result was calculated using the Receiver Operation Characteristic (ROC) method and the historical data inventory was created through Google Earth images.

Another study was conducted by Rahim et al., (2018) for Gilgit Baltistan to determine the landslide susceptibility analysis through the use of a Multi-Criteria Decision Analysis technique primarily the Analytical Hierarchy Process (AHP) model and AUC method to assess the accuracy using historical landslide data of the study region.

Hussain et al., (2022) conducted a study regarding landslide inventory and susceptibility mapping in the Chitral district of Pakistan. This study estimated slope deformation velocity through the Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) technique. Moreover,

`

logistic regression (LR) and frequency ratio (FR) models were applied for forecasting the correlation between landslide occurrence and causative factors. The results revealed that the logistic regression method was more accurate and helpful if applied in mitigating landslide disasters.

Basu & Pal, (2020) modified the AHP model used in a study in order to determine landslide susceptibility analysis for the Gish River Basin of India, 16 triggering factors were used in the 6-factor cluster in order to determine Landslide susceptibility, while correlation and regression techniques were used to determine which factor was dominant to determine Landslide susceptibility while the prediction accuracy was determined through the use of AUC method.

Rahman et al., (2022) conducted a study in Shahpur Valley regarding landslide susceptibility by applying information value (IV) and weight of evidence (WoE) models. Seven contributive factors were identified, and their relationship was calculated with the landslide occurrence. The results of the models revealed the highly susceptible zones that covered about 14.5% of the area. The resultant maps were also validated through prediction rate and success curves. The study was concluded by generating risk maps of the area after combining the hazard and vulnerability maps.

Islam et al., (2022) combined the three bivariate models of frequency ratio, weight of evidence, and information value for landslide susceptibility mapping of Swat district in Pakistan. The first step was creating an inventory map of 495 district landslides using satellite and ground data. Moreover, ten conditioning factors include LULC, slope, aspect, rainfall, curvature, and lithology. LSM was generated based on the three models and success rate and prediction rate curves were generated.

`

GIS referred to as Geographic information systems corresponds to the hardware and software utilized to manage, manipulate, understand, and delete spatial information (spatial data). GIS includes various spatial techniques to solve various spatial problems and deals with data in various forms, but the dominant ones are vector data and raster data. Spatial information includes information about a spatial feature of the earth in the form of vector or raster data. Using this data various tools, algorithms, functions, and techniques exist to solve complex spatial problems regarding said data. Landslide susceptibility is another spatial problem that can be solved using GIS, in fact through matching quantitative and qualitative spatial data, special association can be well taken care of too as specified by the study conducted by Guzzetti., (2020).

Landslides are highly dangerous hazards that can cause significant disruption and damage to infrastructure, the environment, and human lives. There is a need to identify the susceptibility zones and implement mitigation measures to minimize the said losses.

`

Chapter 3

MATERIALS AND METHODS

3.1. Study Area

The study area is the Chitral district which has a latitude of 36° 15′ 0″ N and a longitude of 72° 15′ 0″ E and is situated in northern Pakistan in the Hindu Kush range and it represents most of the northern region of Pakistan's Khyber Pakhtunkhwa province. It is divided into two districts, upper and lower Chitral, and covers an area of 14,850 square kilometers. As of 2017 census, the total population of Chitral is 447,362. Chitral is bordered in the east with Gilgit Baltistan, in the southeast with Swat, in the west with Nuristan and Kunar provinces of Afghanistan, in the south with upper Dir district of Khyber Pakhtunkhwa and in the north and northeast by China and Wakhan corridor of Afghanistan. It lies mainly in a mountainous terrain with an elevation ranging from 1000 to 7700 meters above sea level and it is drained by the Chitral River which is a total of 300 kilometers in length and extends from northeast to southwest. The terrain of Chitral consists of undulating submontane areas, mountain ranges, and plains surrounded by hills. Chitral has a diverse climate due to its varying elevations and mountain proximity. The climate ranges from temperate in the valleys to alpine in the higher elevations. Chitral receives varying amounts of precipitation depending on the altitude and location. Chitral has both sedimentary and meta-sedimentary rocks that are thrusting southward, are deformed, and have a complex structure. There is significant seismic activity in Chitral due to its tectonic formations. This earthquake activity, along with rainfall patterns, geology of the area, terrain, slope, and land cover makes it highly susceptible to landslides. Figure 1 shows the study area map, particularly emphasizing the Chitral district.

`

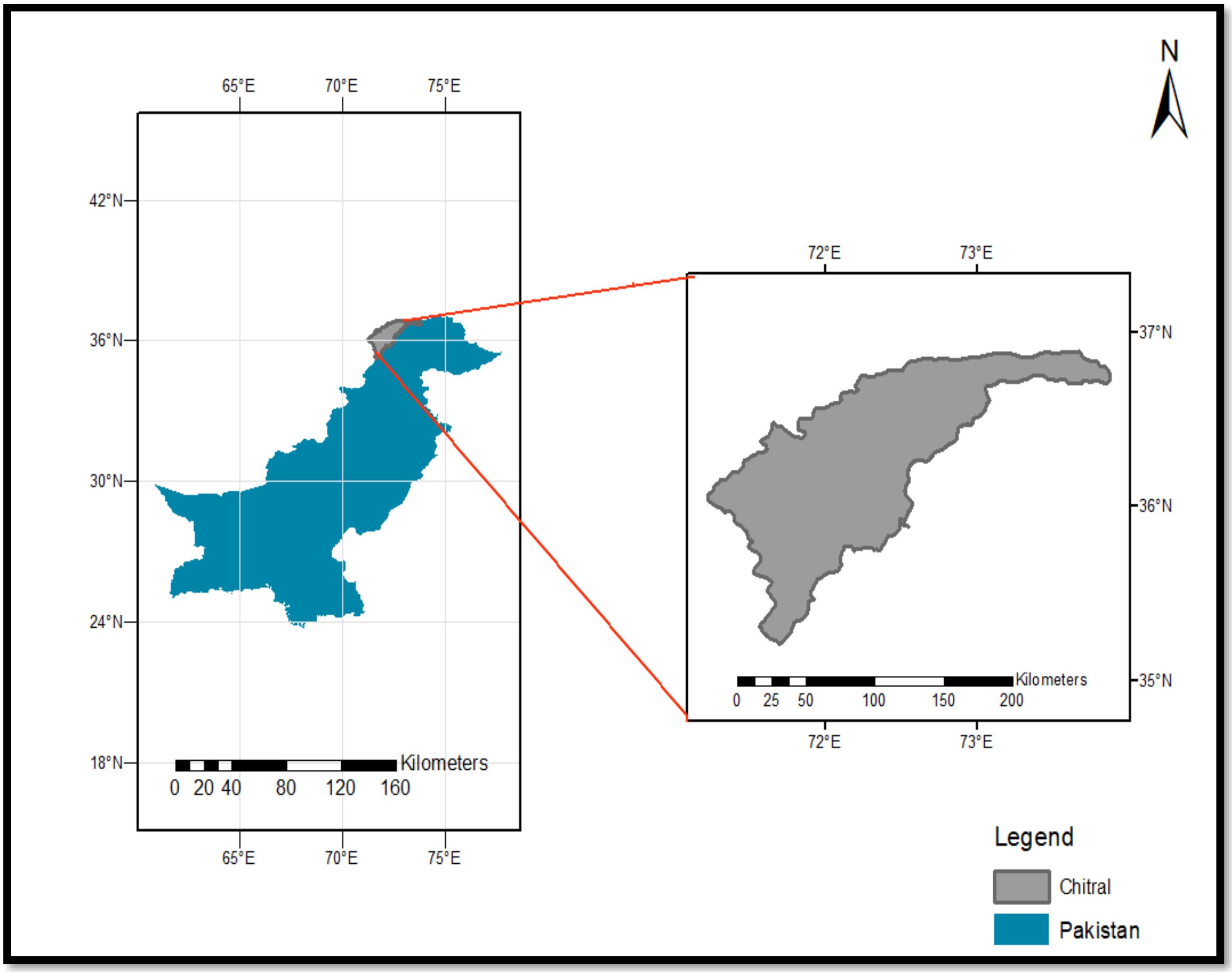

Figure 1. Study area map of Pakistan and Chitral district.

`

3.2 Datasets Used

A combination of spatial datasets representing a variety of factors are used for the analysis. These key datasets include slope, aspect, curvature, land use, lithology, elevation, distance from faults, stream distance, and precipitation data. Various thematic layers relative to these factors were combined and weights for each factor were assigned using the AHP technique to generate the landslide susceptibility map. Table 1 shows the datasets that were collected for conducting the AHP analysis. The complete methodological flowchart with all the main steps is shown in Figure 14.

3.2.1 Satellite Data

The satellite data used imagery from Sentinel 2 that is a high resolution (10 to 60m), wide swath, multi-spectral imaging mission with a 5-day revisit time. Sentinel 2 offers an unprecedented combination of a high revisit frequency, global coverage of land surfaces, a wide field view and a high spatial resolution (Shahabi et al., 2022). This satellite was used to get cloud-free imagery of the year 2022 for conducting further analysis such as mapping the land use land cover (LULC) patterns. The high-resolution multi-spectral imagery made it possible to classify various types of LULC through which the areas that were susceptible to landslides were identified. Another imagery of MODIS for the year 2022 was also used which is a satellite sensor consisting of 36 spectral bands ranging from 250m to 1km resolution.

3.2.2 LULC Map

Land use land cover is a major factor in mapping landslide susceptibility as land cover can be altered due to human activities. Abandoned cultivated lands are highly susceptible to landslides and deforestation due to land use changes can also compromise slope stability (Rabby et al., 2022).

Anthropogenic activities such as urban infrastructure development and plantation agriculture can cause rapid land use land cover change that can have a significant impact on landslide susceptibility. Land use map was generated using Sentinel imagery through applying the supervised classification likelihood method in ArcGIS and the area was reclassified into eight classes that are defined as under and are shown in Figure 2.

- **Water**: represents the water bodies in the region.
- **Trees**: represents the tree cover of the region.
- **Vulnerable Vegetation:** represents the vegetation near the banks and along the rivers and water bodies that have the potential to be flooded.
- **Crops:** represents the crop cover in the region.
- **Built Area**: Represents the built-up area of the region.
- **Bare ground**: represents the bare land in the study area.
- **Snow/ice**: represents the snow ice cover over the region.
- **Range land**: Rangelands are grasslands, shrublands, woodlands, wetlands, and deserts that are grazed by domestic livestock or wild animals.

`

Table 1. Datasets collected for conducting the AHP analysis.

S. No	Data	Description	Source
01	**Satellite Imagery and data**	- Sentinel-2 (2022) - MODIS (2022)	USGS Earth Explorer.
02	**Terrain Data**	DEM (Aster DEM) a. Aspect, b. Slope, c. Curvature	USGS
03	**Environmental Data**	Precipitation Data set yearly averages	Global Climatic Data
04	**Topographical data**	- Road - Stream	Open Street Map
05	**Lithology data**	- Geomorphological data - Faults	Survey of Pakistan
06	**Land use land cover data**	Raster Dataset that represents the classified land use/landcover data.	Supervised classification

`

3.3.3 Rainfall Data

Rainfall data was obtained from global climatic data through yearly averages. This data was acquired as heavy rains can weaken soils and rock-forming slopes and can increase the potential for a landslide. Rainfall-triggered landslides can result in catastrophic loss of life and property over densely populated areas through hill slope erosion. High-magnitude rainfall events trigger large landslides each year globally, causing loss of life, significant socio-economic costs, and environmental impacts. Rainfall data was taken for the year 2022 and it was divided into 5 classes with values ranging from 376.325 – 457.155, 457.155 – 553.835, 553.835 – 628.325, 628.325 – 696.477 and 696.477 – 780.476 with the unit of measurement as millimeter per year. The rainfall data of the study area is shown in Figure 3.

3.3.4 Lithology Map

Lithology constitutes the general characteristics of sediments and rocks and substantially impacts the spatial variation of landslide types, depth, and prevalence. Landslide occurrences are significantly related to a particular type of rock lithology, such as claystone which are easily degraded (Trisnawati et al., 2022). A more significant part of the considered region has granite gneiss and limestone/shale. The granite gneiss is a comparatively more substantial lithology than the limestone/shale and is less prone to landslides. The northeast region is dominated by unconsolidated lithology. In contrast, the marginal northern part is primarily composed of limestone/dolomite/sandstone, which have comparatively weaker lithologies and are highly prone to landslides (Aslam et al., 2022). The unconsolidated lithology is composed of loosely arranged particles and thus is prone to landslide hazards. In Figure 4, various rock types are identified in the lithology map and are as follows, alluvium, limestone, granite gneiss, sandstone, metamorphic and volcanic rocks.

`

3.3.5 Slope Map

Slope is considered a highly significant causative factor in landslide investigation as it can trigger the downward movement of weakened sediment material. The slope for the study area was calculated from the Digital Elevation Model (DEM) acquired from the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in ArcMap. Slope completely controls the movement of materials based on gravity and slope angles have a high influence on landslides as areas where slope angles are high, the soil material may be unable to reach the expected thickness value (Çellek,.2022). The Slope map of the study area is shown in Figure 5 and was generated using the Slope calculation tool in the Spatial Analyst toolset in Arc Toolbox. The slope values were reclassified into 9 classes as 0° – 10°, 10° – 18°, 18° – 25°, 25° – 31°, 31° – 37°, 37° – 42°, 42° – 47°, 47° – 54°, 54° – 77°. These values ranged from gentle to steep slopes, and the areas with steeper slopes (above 40°) were identified as being more prone to landslides.

3.3.6 Aspect Map

Aspect affects factors that contribute to landslides such as soil thickness, soil moisture, and vegetation cover as it affects the exposure to sunlight, precipitation, and wind. Aspect can influence the hydrology behavior of slopes and the pore water pressure, resulting in a higher probability of landslides. An aspect map can show both the direction and the grade of a terrain simultaneously, which is considered an important factor in analyzing and producing landslide susceptibility maps. The most important factor affecting aspect is precipitation. Slopes that receive precipitation and are in the shade are more susceptible to landslides. Aspect (slope orientation) affects the exposure to sunlight, wind, and precipitation thereby indirectly affecting other factors that contribute to landslides such as soil moisture, vegetation cover, and soil thickness. The aspect of study area is classified into flat, north, northeast, east, southeast, south, southwest, west, and northwest-facing

`

classes. The Aspect map of Chitral is shown in Figure 6 and was created by calculating the Aspect from the Digital elevation model using The Aspect calculation tool from Spatial Analyst toolset in Arc-Toolbox.

3.3.7 Curvature Map

Plan curvature is the curvature of contours on a topographic map or the curvature of a hillside in a horizontal plane. Profile curvature can be defined as the curvature in the downslope direction along a line formed by the intersection of an imaginary vertical plane with the ground surface. Both plan and profile curvatures can affect the susceptibility of landslides. Plan curvature can also control the convergence or divergence of water and landslide material in the direction of landslide motion. The respective positive and negative values represent convex and concave surfaces in both profile and plan curvature maps. Profile curvature is parallel to the direction of the maximum slope. A negative value indicates that the surface is upwardly concave at that cell. A positive profile indicates that the surface is upwardly convex at that cell. A value of zero indicates that the surface is flat. The higher the positive curvature value of an area, the higher the probability of landslide occurrence and vice versa. The curve map is also prepared from DEM; its values range from -13.48 to 13.08 degrees and are divided into five classes as shown in Figure 7.

3.3.8 Distance to Road

Distance to road is an important factor for landslide susceptibility due to several reasons such as natural slopes can be destabilized during road-cutting operations that can also influence the natural drainage patterns leading to increased infiltration of water. Vibration frequency generated by the road construction works is also effective in the occurrence of landslides as it causes the loss of toe support in the places where the road passes the slope. Cracks can occur on the slopes that were balanced before construction due to increased tension in the back of the slope after construction.

These cracks can also trigger landslides along with other factors such as water input (Çellek, 2023). The road data for the current study was acquired from Open Street Map (OSM). The Euclidean Distance tool from the Spatial Analyst toolset in Arc-Toolbox was used to create the Buffer around the road network. These buffers were created based on proximity to road data and are shown in Figure 8.

3.3.9 Distance to Stream

Hydrology is a significant external parameter in the instability of strata that can trigger landslides in an area. The proximity of a slope to a stream can affect the stability of a slope as the stream current can speed up the erosion process and the degree of saturation of slope materials is also increased, enhancing the landslide potential (Semlali et al., 2019). As the distance from the stream increases, the probability of landslide decreases as streams adversely affect the slope stability. The proximity of a location to streams can affect the soil moisture content and groundwater levels. Areas closer to streams may have higher soil moisture content, contributing to slope instability and increasing the likelihood of landslides, especially during heavy rainfall or rapid snowmelt periods. The stream data was also acquired from OSM to create a stream buffer map shown in Figure 9, representing proximity analysis as distance to and from the stream networks. The Euclidean Distance tool from the Spatial Analyst toolset in Arc-Toolbox was used to create the Buffer around the stream network.

3.3.10 Distance to Fault

Areas with geological faults are more susceptible to landslides as surrounding rock strength can decrease due to tectonic breaks. Landslides are more abundant along the major and minor faults. In the study area of Chitral, certain major faults are identified such as the Main Karakoram fault, Tirich mir fault, Reshun fault, and Chaman fault. Landslides are more likely to occur when an

`

earthquake creates a movement along the fault line. Distance to fault is a critical factor in landslide occurrence. The maximum distance from the fault line is the less likely a landslide will occur. Landslides are more likely to happen when an earthquake creates movement along the fault line. The Euclidean Distance tool from the Spatial Analyst toolset in Arc-Toolbox was used to create the buffer around the faults which is shown in Figure 10. This is proximity analysis based on the fault data acquired from the digitization of topographic maps.

3.3.11 Normalized Difference Snow Index (NDSI)

The normalized difference snow index is related to the presence of snow in a pixel and can accurately detect snow cover compared to other measurement indices such as fractional snow cover. NDSI is a normalized difference of two bands; one in the near-infrared or shortwave infrared parts of the spectrum and one in the visible part of the spectrum as snow is highly absorptive in the near-infrared or shortwave infrared parts of the spectrum and is highly reflective in the visible part. This was calculated through MODIS imagery using the formula shown in Eq.#1.

$$\text{NDSI} = \frac{Green - SWIR}{Green + SWIR} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. \# 1}$$

The probability of the presence of snow is proportional to how close the NDSI pixel value is to 1 with the values ranging between -1 to +1. The NDSI map shown in Figure 11 depicts the range of values regarding the probability of snow presence in the study region.

3.3.12 Normalized Difference Vegetation Index (NDVI)

Normalized Difference Vegetation Index (NDVI) is the quantity used to understand the vegetation density and quantify the vegetation greenness. It is the growth of vegetation and distribution of soil characteristics based on the spectral changes of green vegetation. Enhanced vegetation growth can reduce the occurrence of landslides and vice versa. NDVI is the normalized difference of two

`

bands, one in the near-infrared region and the other in the red region of the visible spectrum. This was calculated using the formula shown in Eq.#2.

NDVI = $\frac{NIR-Red}{NIR+Red}$................................ Eq. # 2

NDVI values range from -1 to +1 where values close to +1 indicate dense green vegetation, values close to -1 may indicate water while values close to 0 indicate urban area or bare land as depicted in Figure 12.

3.3.13 Normalized Difference Water Index (NDWI)

Normalized Difference Water Index (NDWI) is used to monitor changes related to water content in the water bodies. NDWI uses green and near-infrared bands to highlight water bodies as they absorb light strongly in the visible-to-infrared spectrum. It is calculated using reflectance values in specific wavelengths, typically in the spectrum's near-infrared (NIR) and green parts. Soil moisture is a critical factor influencing slope stability, which makes NDWI a critical factor in landslide susceptibility mapping. The following formula used for calculating NDWI is shown in Eq.#3.

NDWI = $\frac{Green-NIR}{Green+NIR}$................................ Eq. # 3

NDWI values typically range from -1 to 1. Water bodies tend to have high reflectance in the near-infrared spectrum and low reflectance in the green spectrum, resulting in a high NDWI value close to 1. Non-water features like soil and vegetation usually have lower NDWI values. These ranges are shown in Figure 13.

`

3.4 Analytical Hierarchy Process (AHP) Method

This study utilizes the AHP method, a semi-quantitative analytical method where decisions are made using weights by relative comparison in pairs. It is a mathematical method used for multicriteria decision analysis. Thomas L. Saaty developed this method in the 1970s and has been vastly used in research for the quantitative analysis of triggering factors of geological disasters. This method is based on three principles, decomposition of problem, relative judgement, and synthesis of relative rankings. It considers both the qualitative and quantitative aspects of decisions and reduces complex relations to a series of comparisons among criteria. The Pair-wise Comparison Matrices are used to calculate relative weights for each element in the hierarchy. These weights represent the importance of each element in relation to the overall objective. Criteria are compared to each other in terms of relative importance using a numerical scale as shown in Table 2.

Table 2. AHP comparison scale.

Intensity	**Definition**
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Intermediate Values

`

The consistency of the weights assigned for relative importance is checked using the formula shown in Eq. # 4.

Consistency Ratio (CR) = $\frac{CI}{RI}$…………………………… Eq. # 4

where CI = Consistency Index,

RI= Randomness Index

Consistency Index is calculated by the following formula shown in Eq. # 5.

CI = $\frac{(\lambda\max - n)}{(n-1)}$…………………………… Eq. # 5

Where λ max = major eigenvalue and n = order of matrix

The following triggering factors have been chosen to perform landslide susceptibility analysis,

- Slope
- Aspect
- Distance to Road
- Distance to stream.
- Distance to Fault
- Land use/Land cover
- Lithology
- Curvature
- Annual Precipitation
- NDVI
- NDSI

Landslide susceptibility map was created in ArcGIS 10.8 and was divided into five levels: very highly susceptible zones, highly susceptible zones, medium susceptible zones, low susceptible zones, and very low susceptible zones.

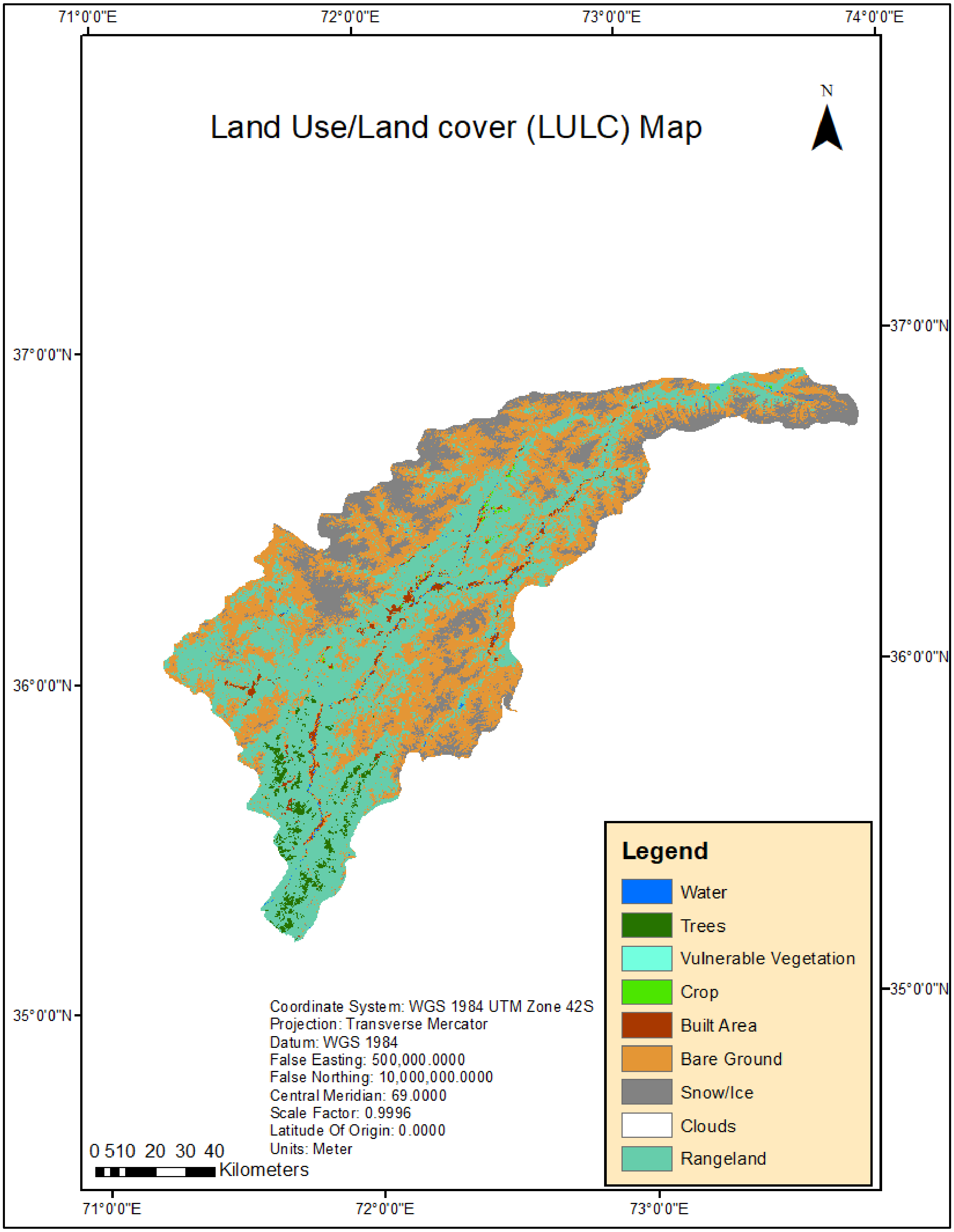

Figure 2. LULC map of district Chitral.

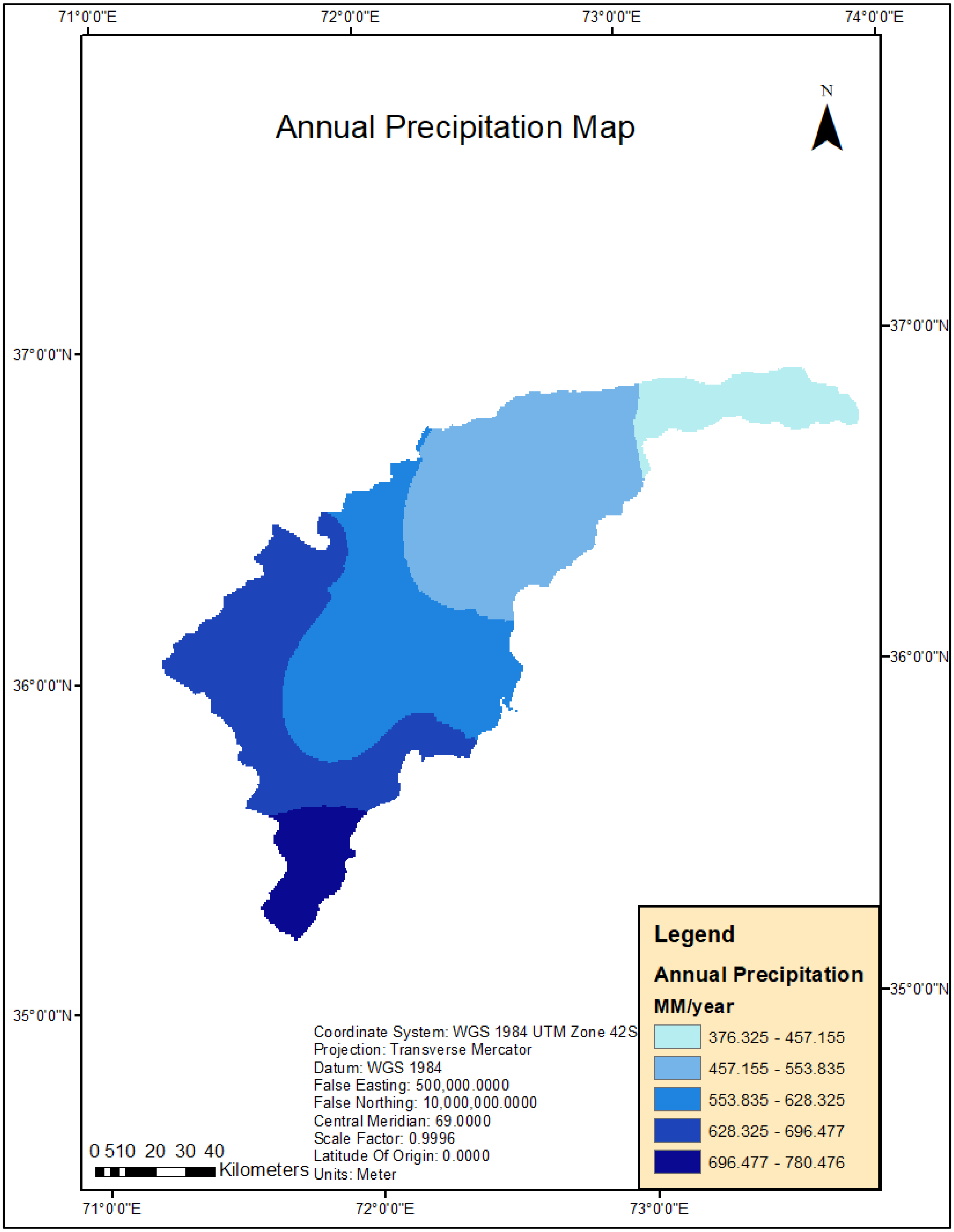

Figure 3. Precipitation map of district Chitral.

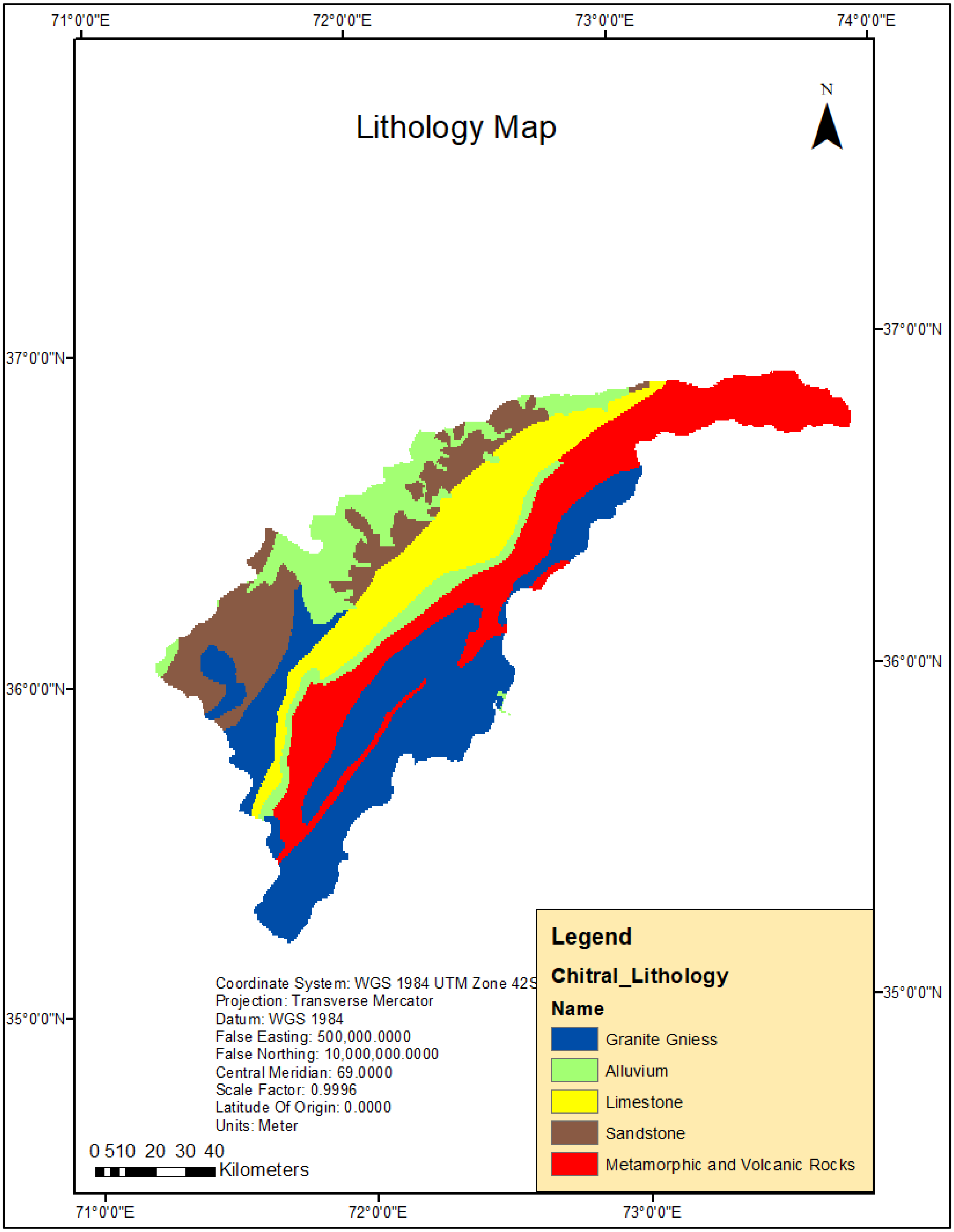

Figure 4. Lithology map of Chitral having different lithologies throughout the district.

`

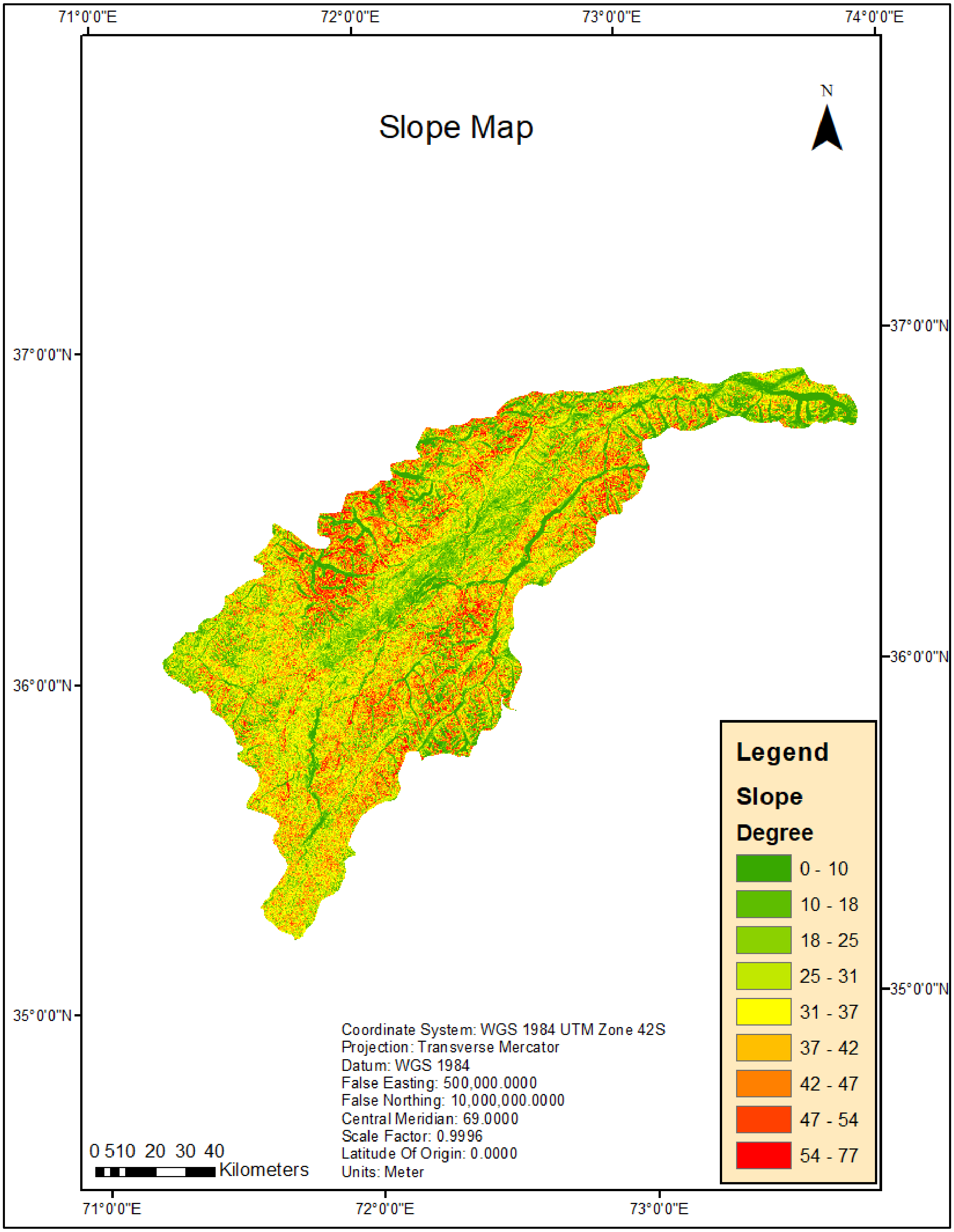

Figure 5. Slope map of district Chitral.

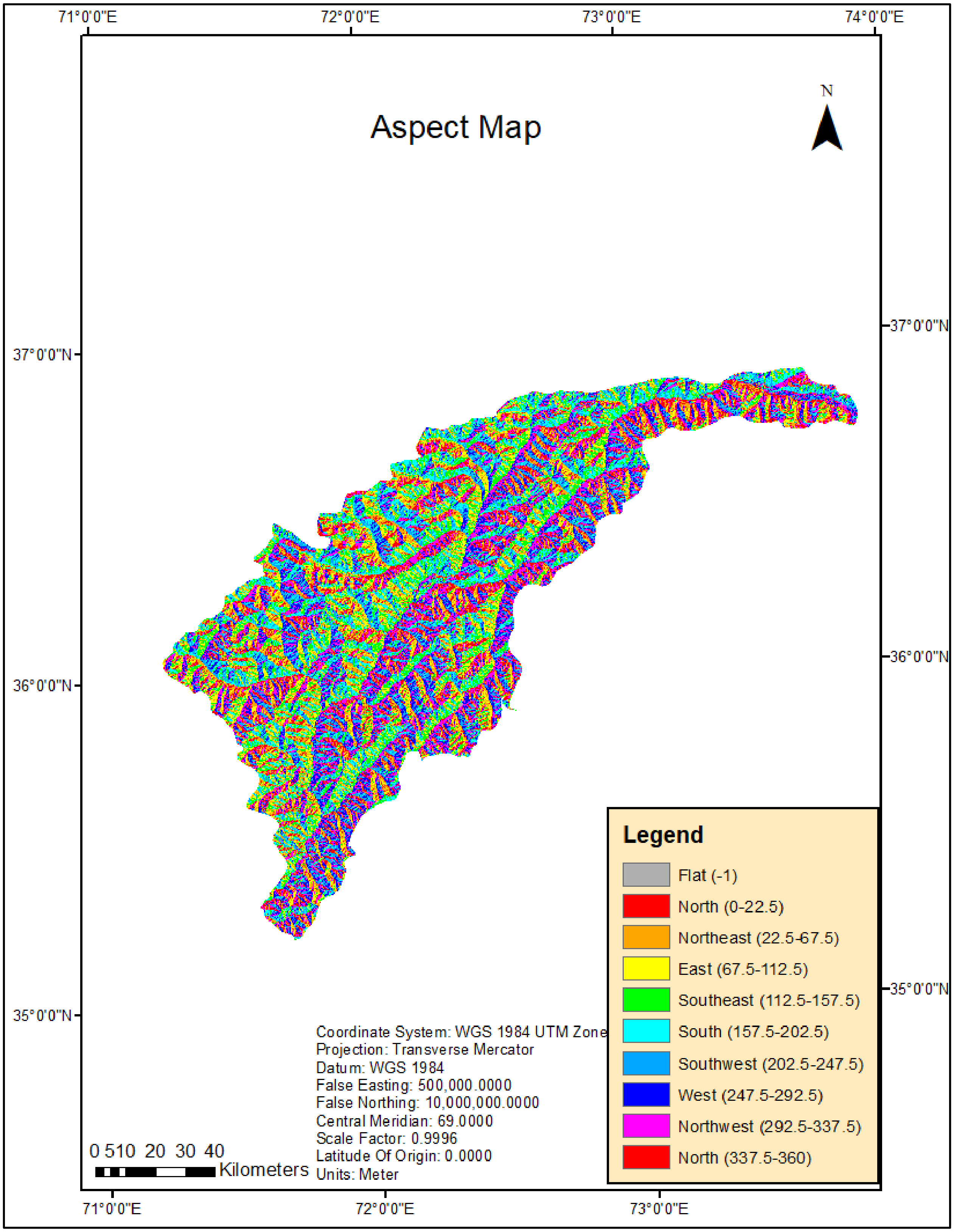

Figure 6. Aspect map of Chitral district.

`

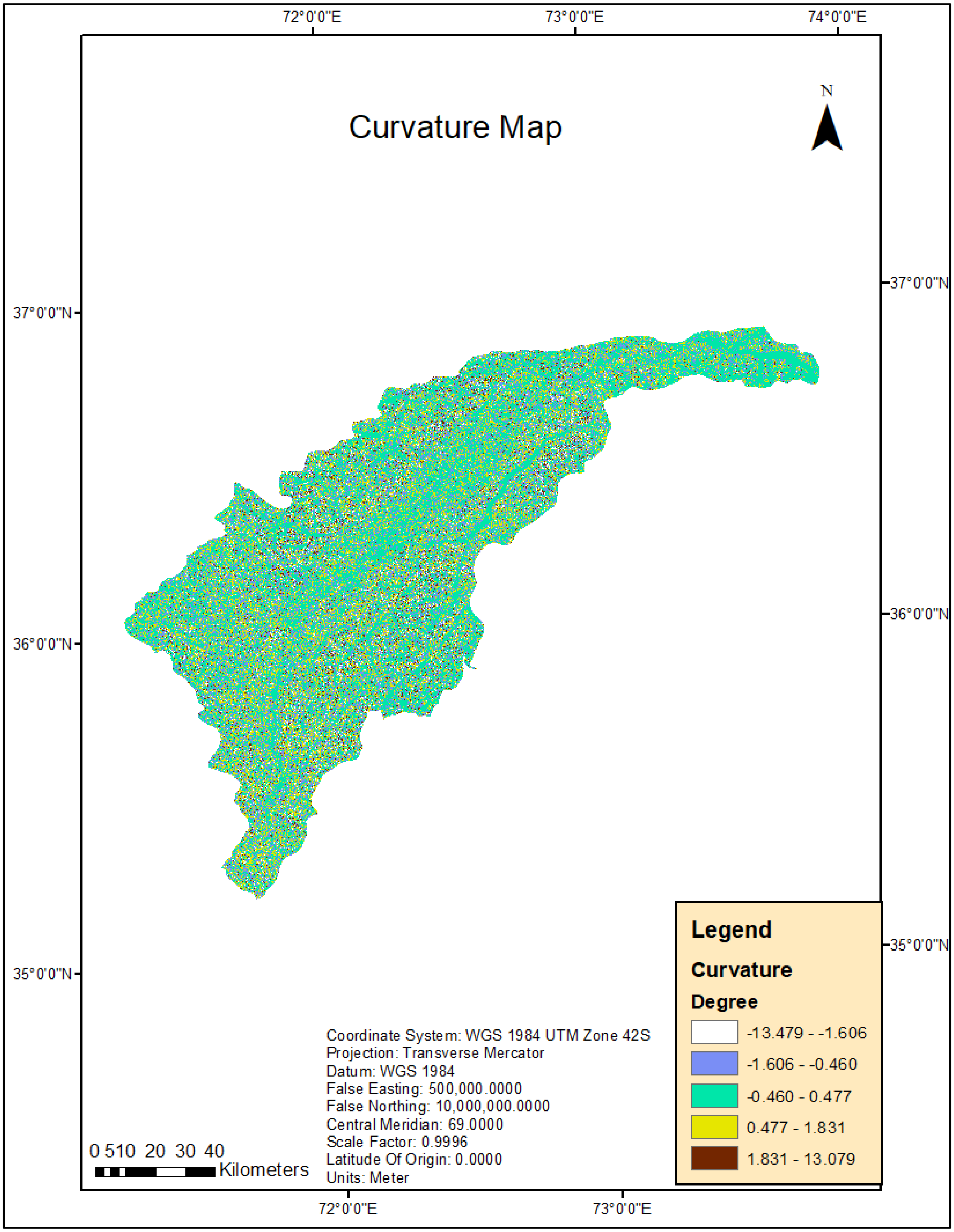

Figure 7. Curvature map of Chitral district.

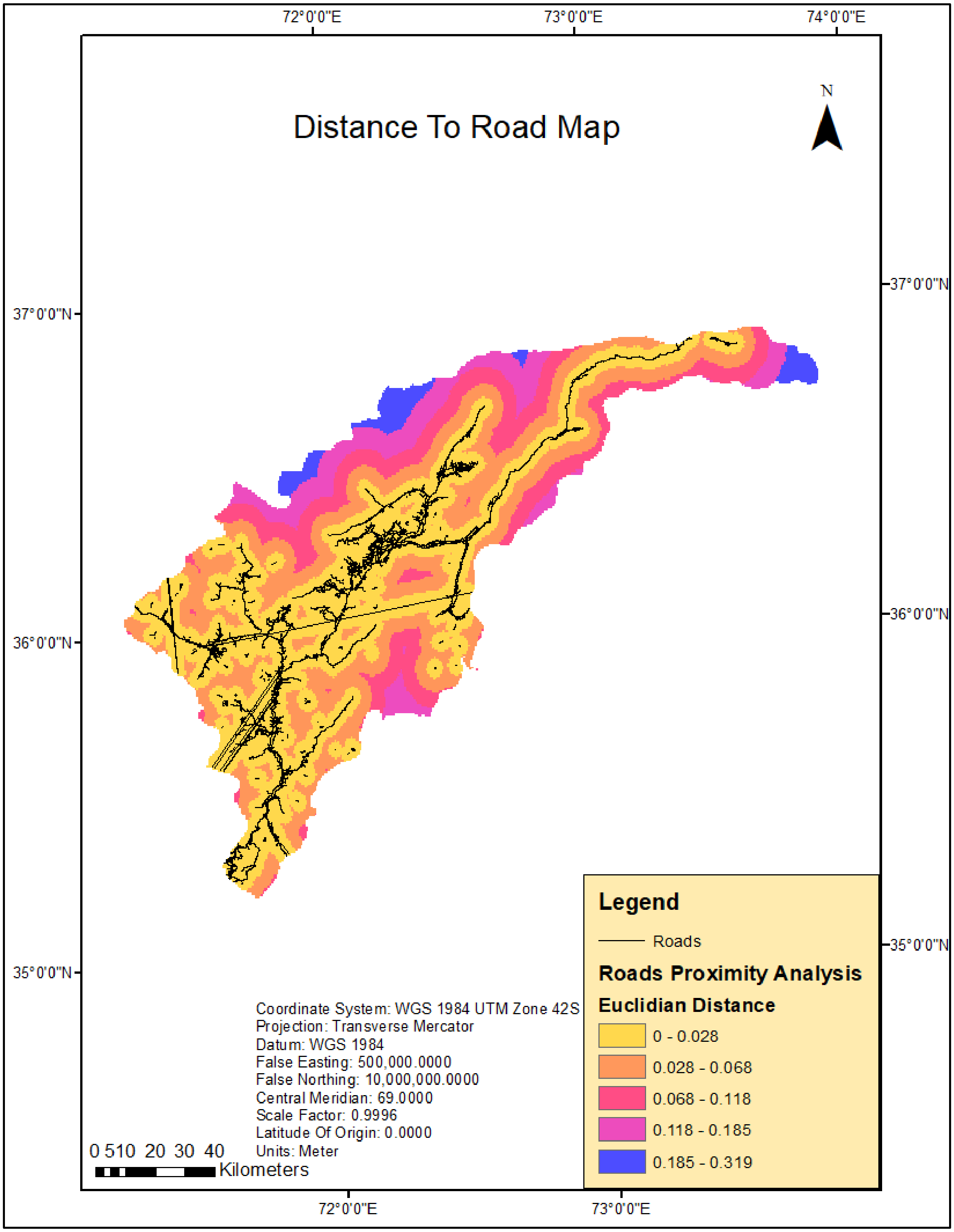

Figure 8. Distance to roads map of Chitral district.

`

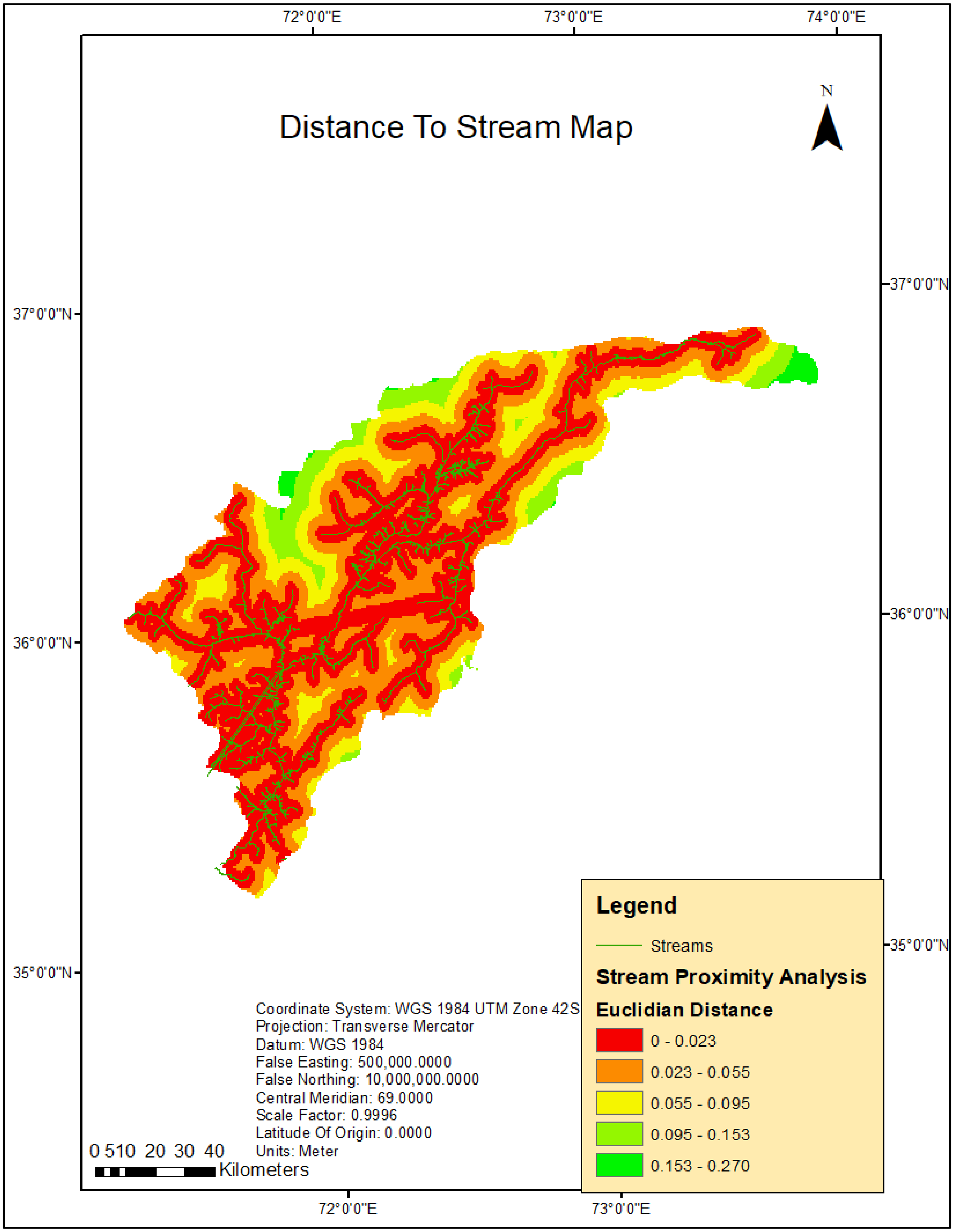

Figure 9. Distance to streams map for the Chitral district.

`

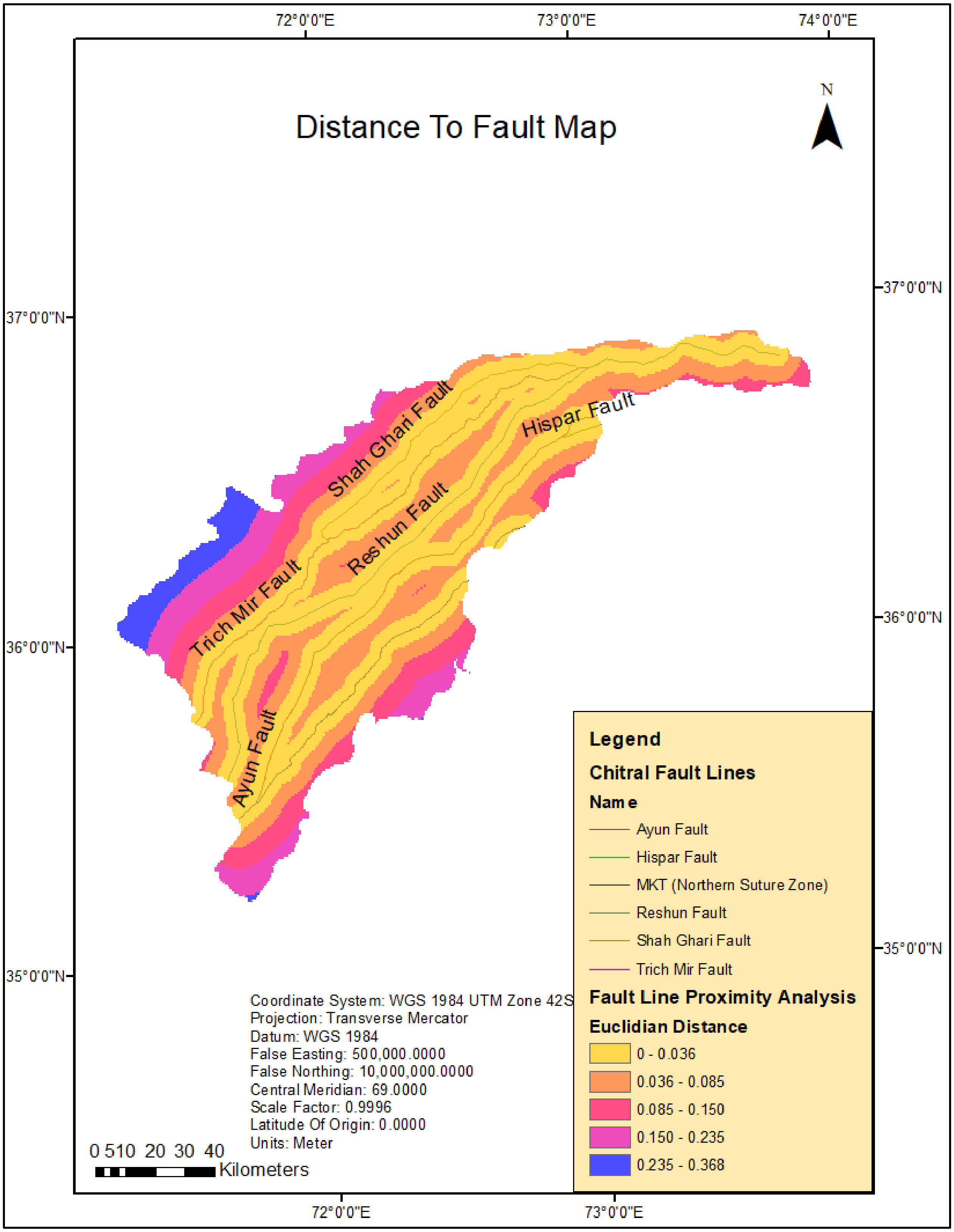

Figure 10. Distance to faults map for Chitral district.

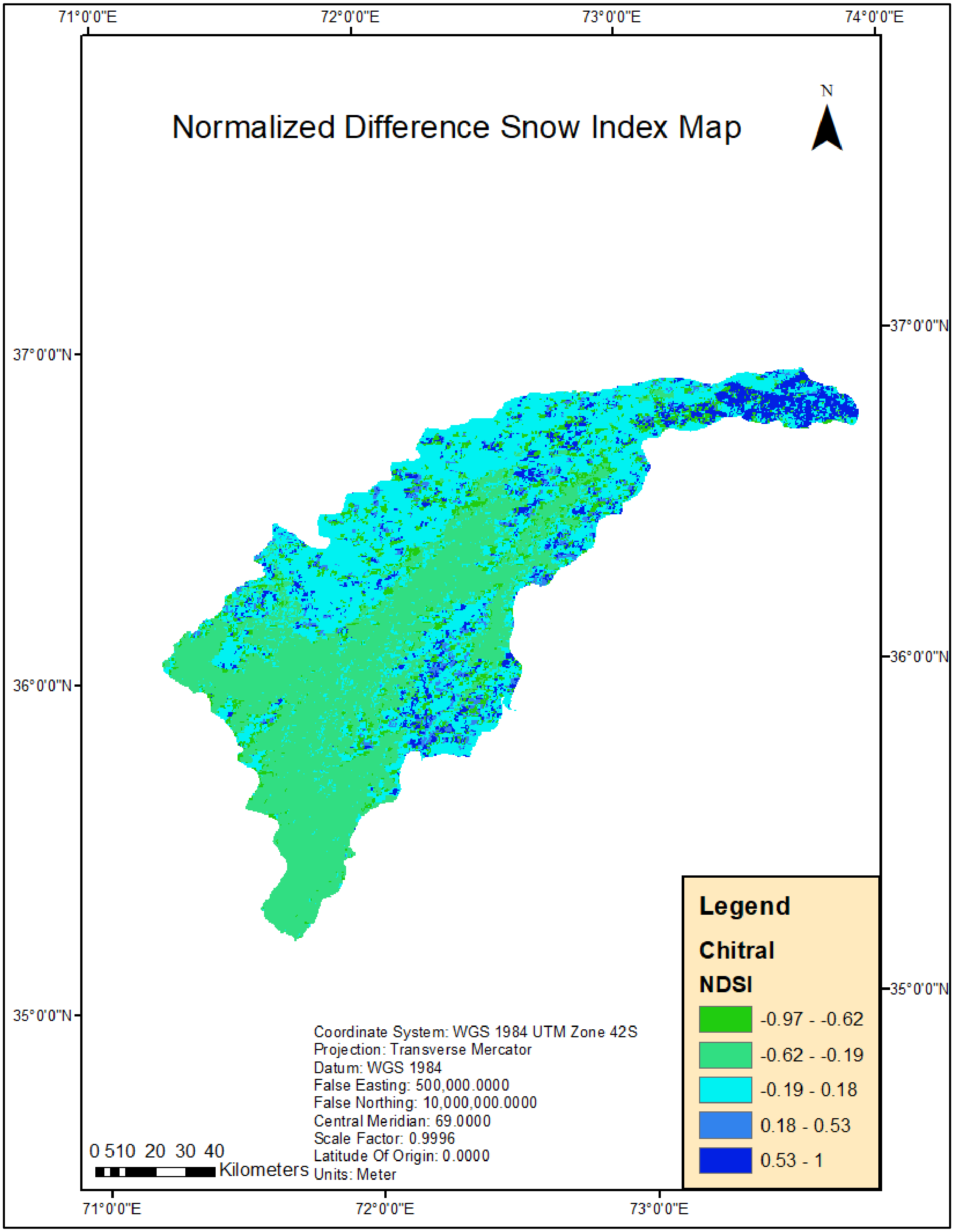

Figure 11. NDSI map of Chitral district.

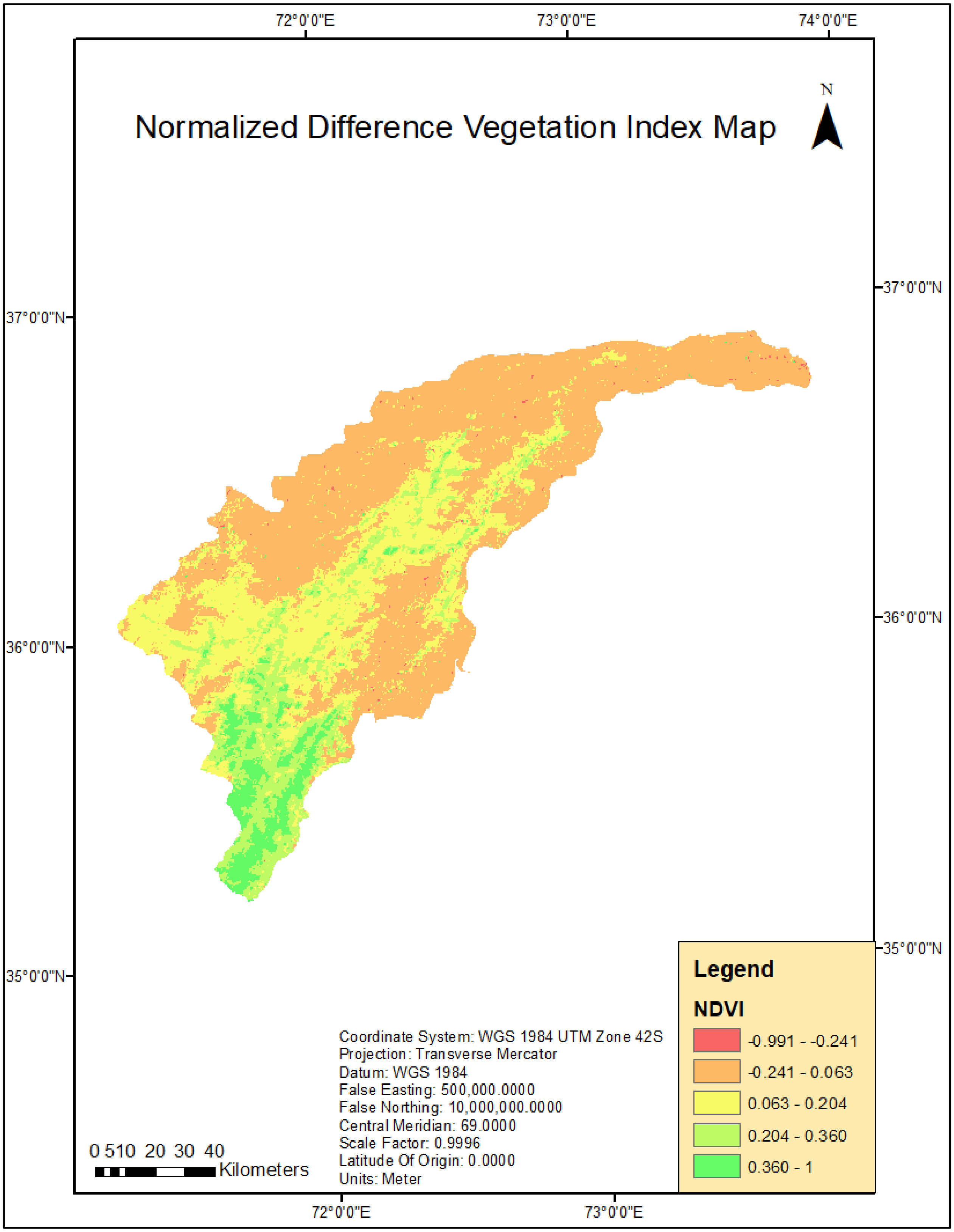

Figure 12. NDVI map for the Chitral district.

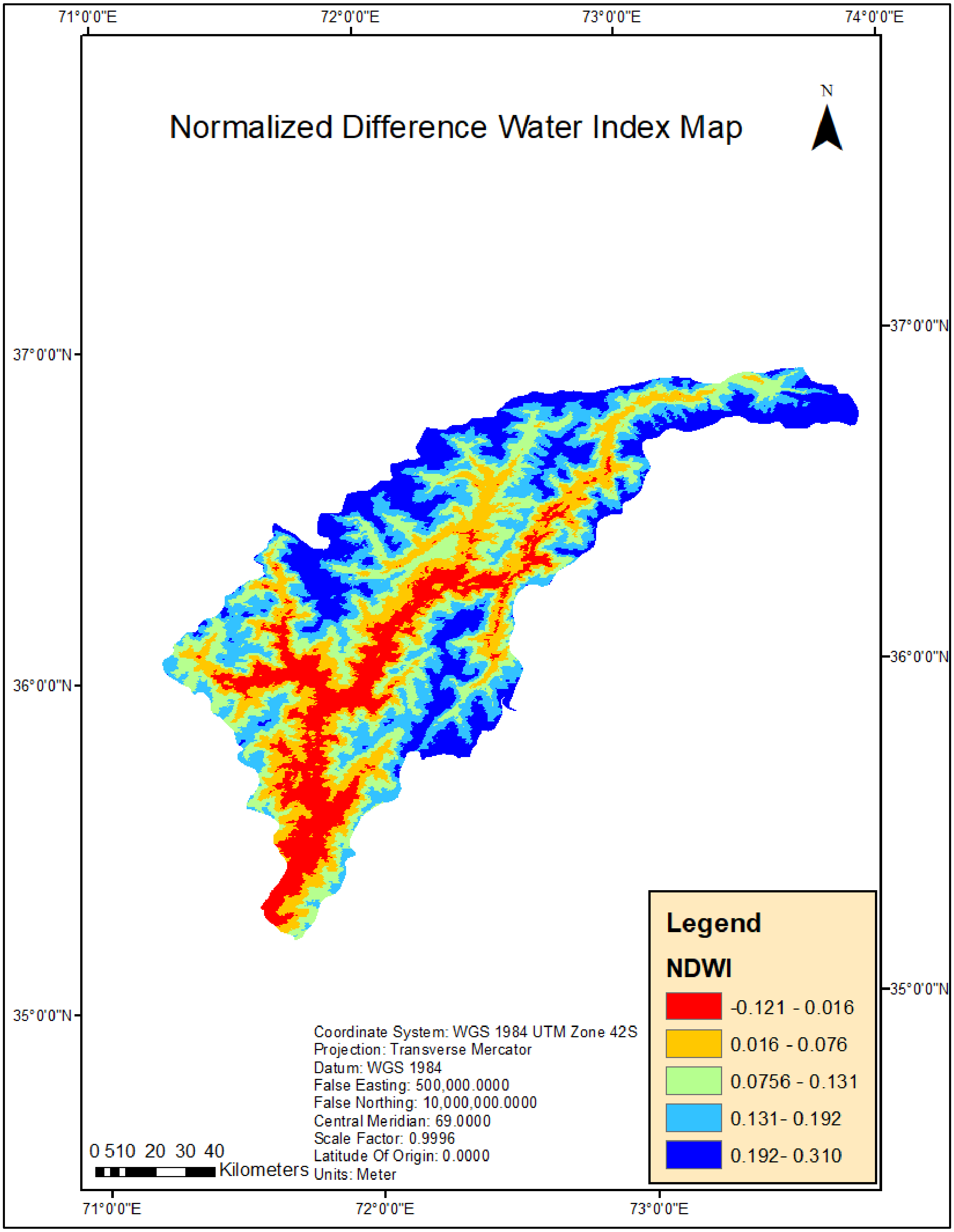

Figure 13. NDWI map for the Chitral district.

`

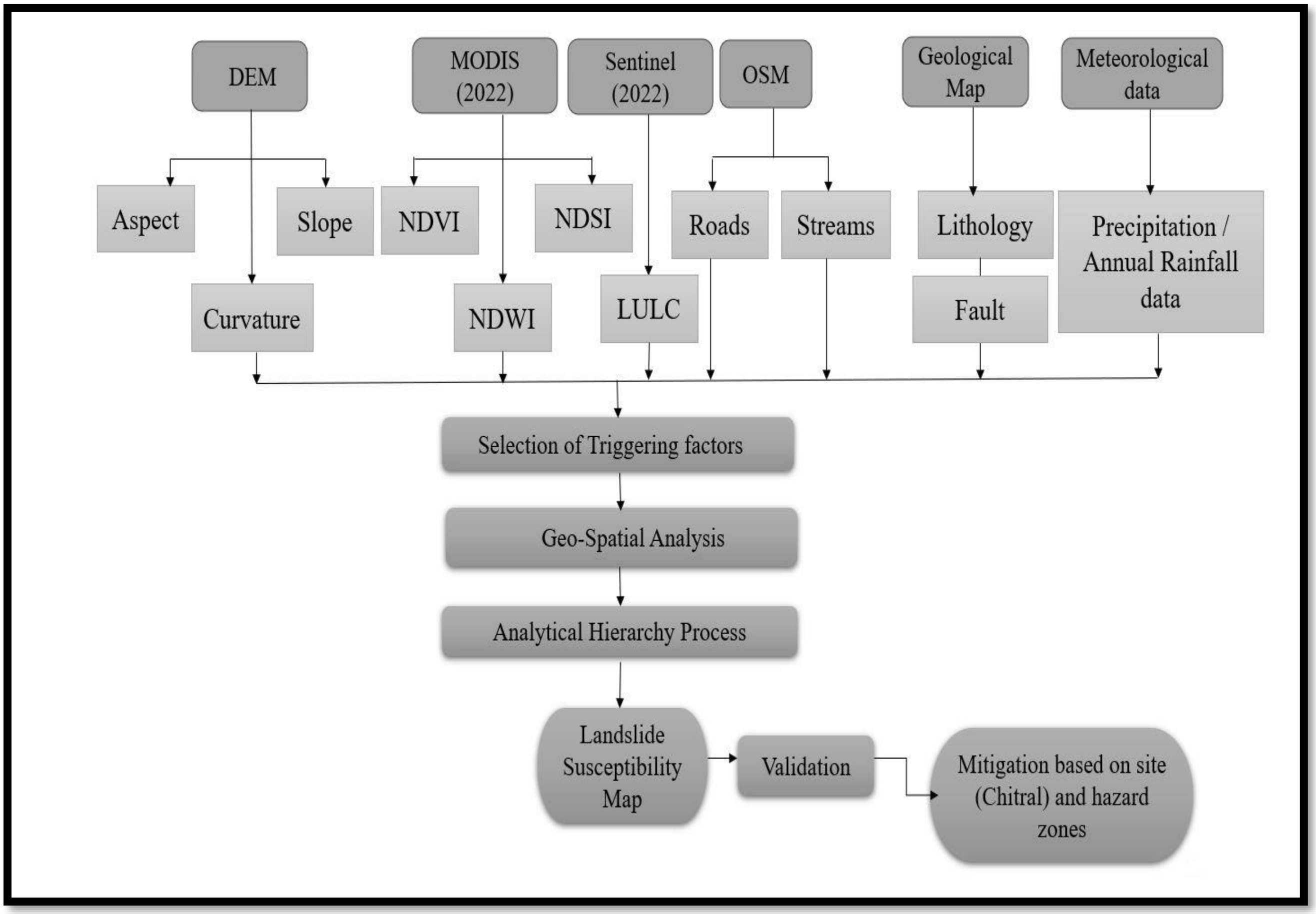

Figure 14. Complete methodology flowchart.

`

Chapter 4

RESULTS AND DISCUSSION

In the methodology section of this research, the AHP model was defined in detail, and the hierarchy of the landslide factors was determined using a pairwise comparison matrix, the table of which is shown below.

The pairwise comparison matrix is diagonal, as observed in Table 4, as the AHP method is a repetitive process. To observe whether the comparison matrix is accurate, the Consistency index and Consistency Ratio values need to be considered. In simpler terms, the consistency index (CI) is the measurement of the consistency of the pairwise comparison result, which is used in the CR value (Consistency Ratio) Value.

For the results of the pairwise comparison matrix to be consistent the CR value should be < 0.1. Table 3 shows the CR and CI values for the model used in this research while Table 4 shows the overall AHP pairwise comparison matrix.

Table 3. CR value.

Consistency index CI	**0.045**
Consistency ratio CR	**0.029**
CR<0.1	**Weights are accepted**

`

Table 4. The AHP pairwise comparison matrix.

Factors	Slope	Distance Fault	Precipitation	NDVI	NDWI	NDSI	LULC	Lithology	Aspect	Curvature	Distance Road	Distance Stream
Slope	**1**	2	3	4	5	5	6	7	7	8	8	9
Distance Fault	0.5	**1**	3	3	4	4	5	6	6	7	7	8
Precipitation	0.3	0.3	**1**	2	3	3	4	5	5	6	6	7
NDVI	0.25	0.3	0.5	**1**	2	2	3	4	4	5	5	6
NDWI	0.2	0.2	0.3	0.5	**1**	0.5	2	3	3	4	4	5
NDSI	0.2	0.2	0.3	0.5	2	**1**	2	3	3	4	4	5
LULC	0.17	0.2	0.25	0.3	0.5	0.5	**1**	2	2	3	3	4
Lithology	0.14	0.16	0.2	0.25	0.3	0.3	0.5	**1**	4	2	2	3
Aspect	0.14	0.16	0.2	0.25	0.3	0.3	0.5	0.25	**1**	2	2	3
Curvature	0.13	0.14	0.17	0.2	0.25	0.25	0.3	0.5	0.5	**1**	5	2
Distance Road	0.13	0.14	0.17	0.17	0.25	0.25	0.3	0.5	0.5	0.2	**1**	2
Distance Stream	0.11	0.13	0.14	0.17	0.2	0.200	0.250	0.3	0.3	0.500	0.500	**1**

`

As observed from the table the CR value for said model is 0.029 which is less than 0.1 hence the pairwise comparison matrix results are consistent.

4.1 AHP Results

After considering all the factors that can influence landslides in the region of Chitral. The result was generated by using the analytical hierarchy process, providing the required factors. These landslide-causing factors were taken to generate a hierarchy to show which factor impacts landslides the most in the region. The result was generated in a raster map that classified the pixels into regions of high susceptibility to low susceptibility. The classification was done in five classes starting from Very High to Very Low (Very high, high, moderate, low, and very low).

As observed in Figure 15, five classes have been used to classify landslide susceptibility. The red region represents high susceptible zones, the green region represents low susceptible zones, and the yellow region shows moderate susceptible zones. The accuracy assessment of the resultant imagery was done utilizing the area under the curve technique (AUC) as well as using ground data from Google Earth images to see whether the landslide events happened where the model was showing the susceptible zones. Along with the AHP result map, two maps were generated to represent the validation of the model. Figure 16 represents the AHP result overlayed with the NASA landslide inventory points representing the historical landslides in the Chitral region.

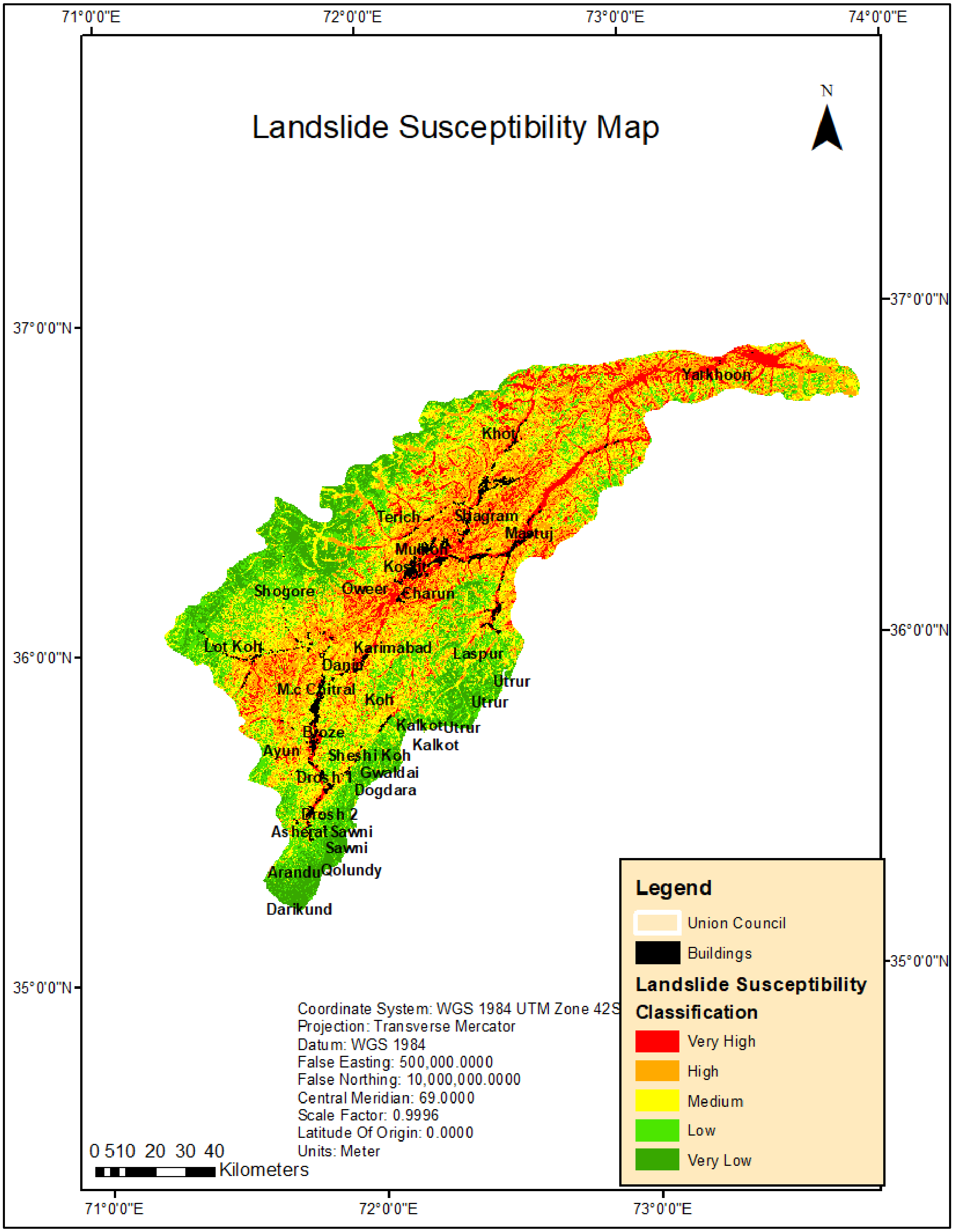

Figure 15. LSM with Chitral Buildings.

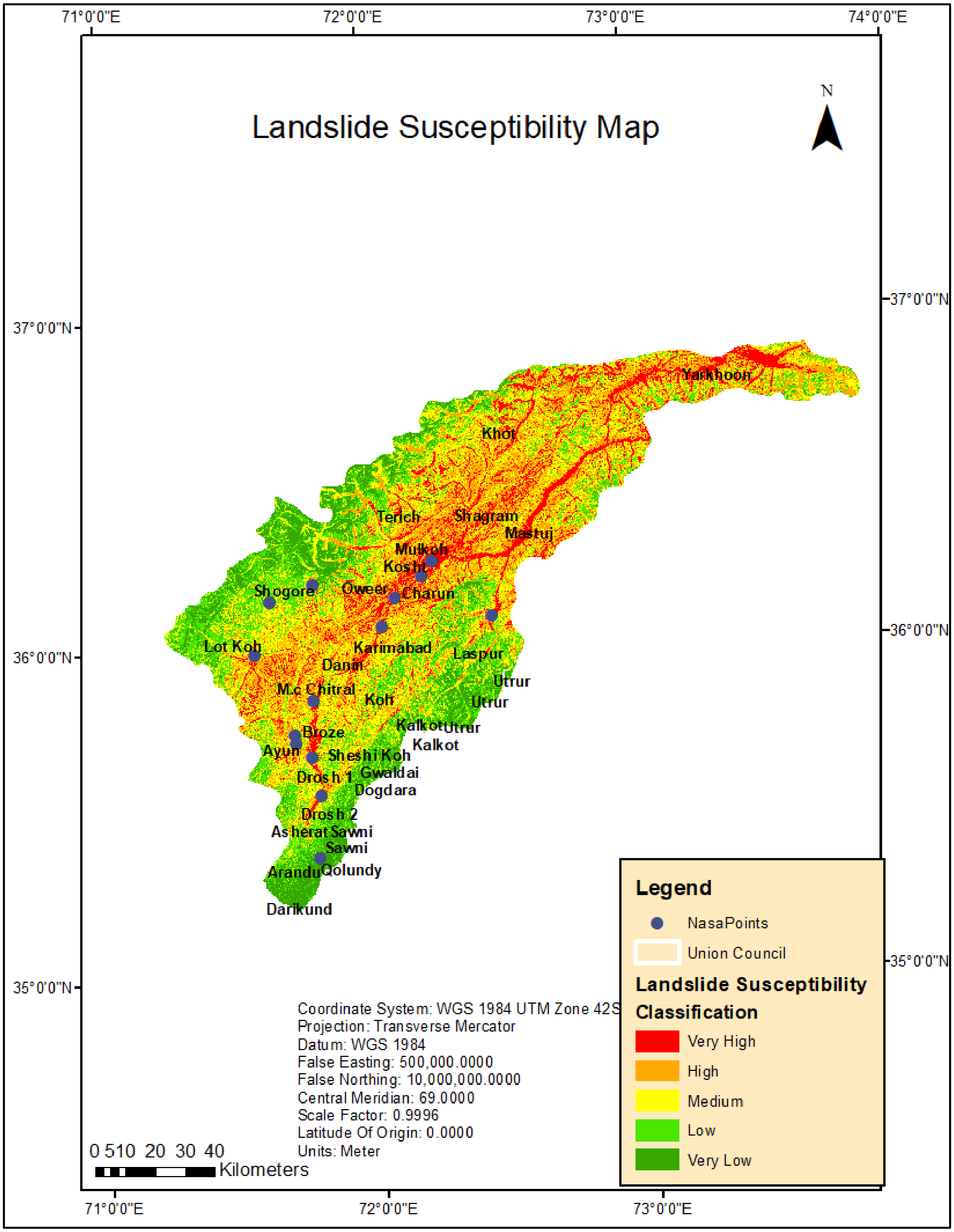

Figure 16. LSM with landslide inventory points.

The NASA inventory points are spread over the zones of landslide susceptibility, the concentration of points in those zones can be observed from Table 5.

Table 5. Concentration of inventory points

Percentage of Points on High Zone	57%
Percentage of Points on Medium Zone	29%
Percentage of Points on Low Zone	14%
Total No of Landslide Inventory Points	14

Figure 17 represents the NASA landslide inventory, and the buildings data obtained from the Open Street Map overlayed with the result of AHP to represent the lack of consideration of hazard zonation while constructing buildings in Chitral.

4.2 Accuracy Assessment

The area under the curve method was used to calculate the accuracy of the AHP model. The Area under the curve method utilizes Receiver Operating Characteristics ROC to determine the prediction accuracy of the AHP model. The ROC method compares the true positives with the false positives, the true positives are the historically occurred landslide events in the region of Chitral while the false positives are the zones predicted by the AHP model. This comparison determines the predicted accuracy of the AHP model. Figure 18 shows the result generated by utilizing the Area under the Curve method.

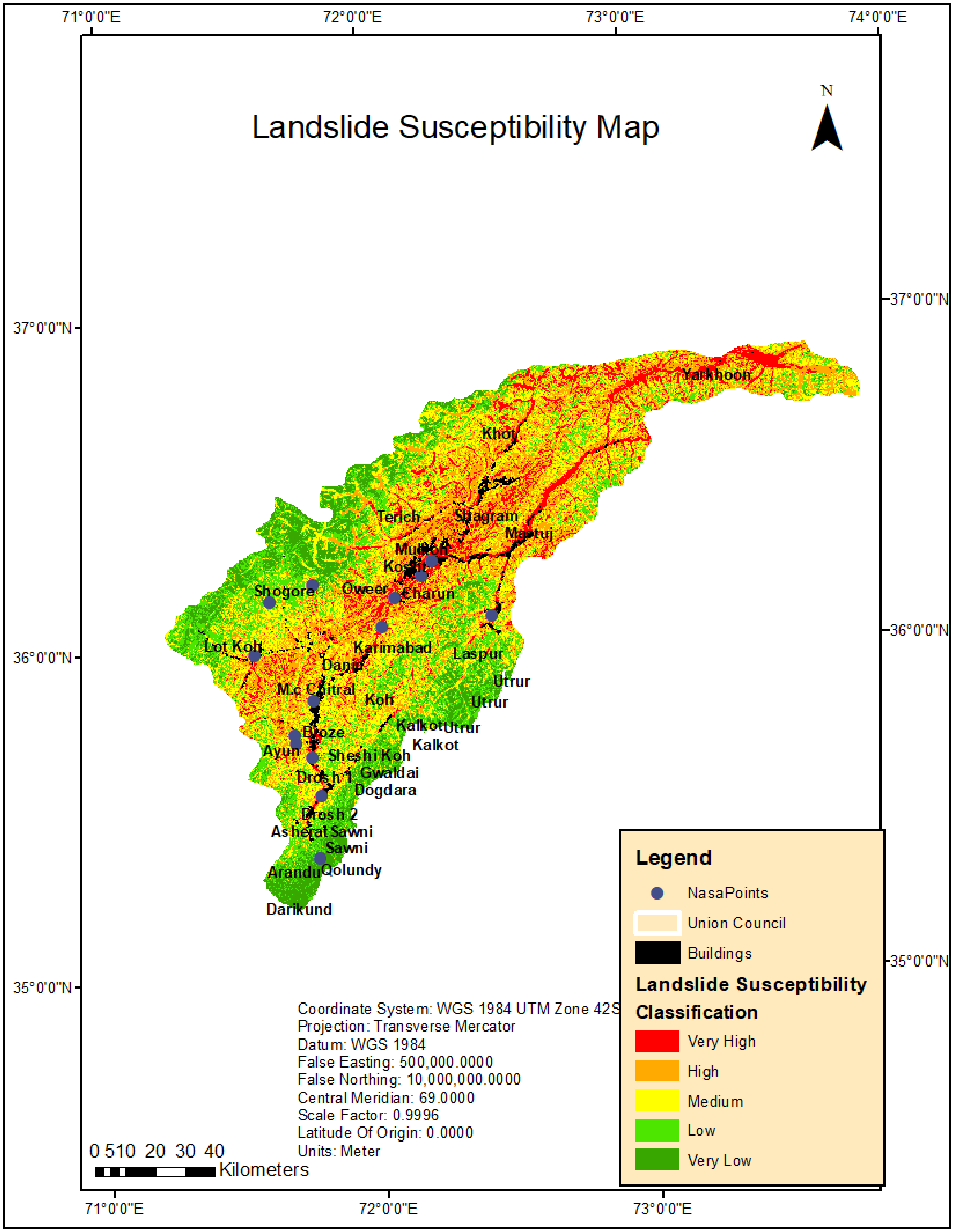

Figure 17. LSM maps with Nasa Inventory points and buildings data.

`

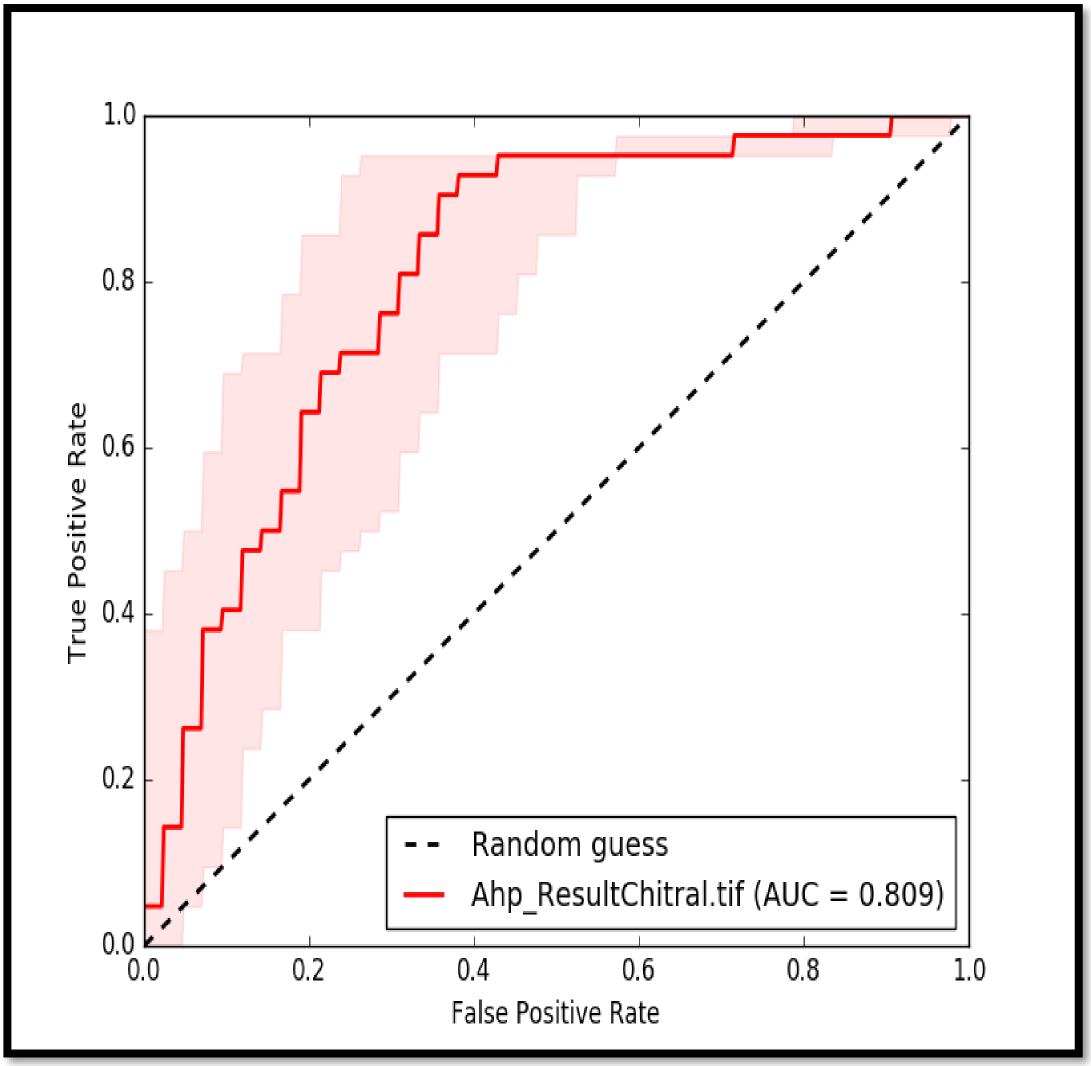

Figure 18. AUC curve for the AHP model.

`

From Figure 18, it can be inferred that the AUC value is 0.809. The results of AHP are consistent and the prediction accuracy is valid if the AUC value is equal to or greater than 0.5. The closer to the value of 1 (100%), the greater the prediction accuracy.

Another method was used to determine the accuracy of the AHP model, which used satellite imagery and the NASA landslide inventory points to determine the validity of the zonation. The resulting map in Figure 19 represents the landslide points overlayed over satellite imagery with red color representing the effect and track of the landslide and most of the points are in the susceptible region.

4.3 Mitigation Measures

As stated, a landslide is a natural phenomenon described as the downward movement of a slope, an avalanche is a kind of landslide where the mass being moved downwards a slope is snow. There are two kinds of mitigation measures: structural and non-structural.

4.3.1 Structural Mitigation Measures

Structural mitigation measures for landslides involve construction, engineering, or other improvements and mechanical changes that are aimed at reducing the likelihood or consequence of a hazard. These measures include structures such as retaining walls that can be created from reinforced materials like concrete, steel, and wood.

Retaining walls are used to block the movement of soil (mass) downwards the slope hence reducing the impact of landslides. In the Sikkim region of India retaining walls are used to reduce the impact of landslides along the highway. Research conducted to provide the best optimal design of retaining walls based on static stress and dynamic impact distributions (Korula et al., 2022).These walls are dug by excavating deep enough and adding lagging that can be wooden

`

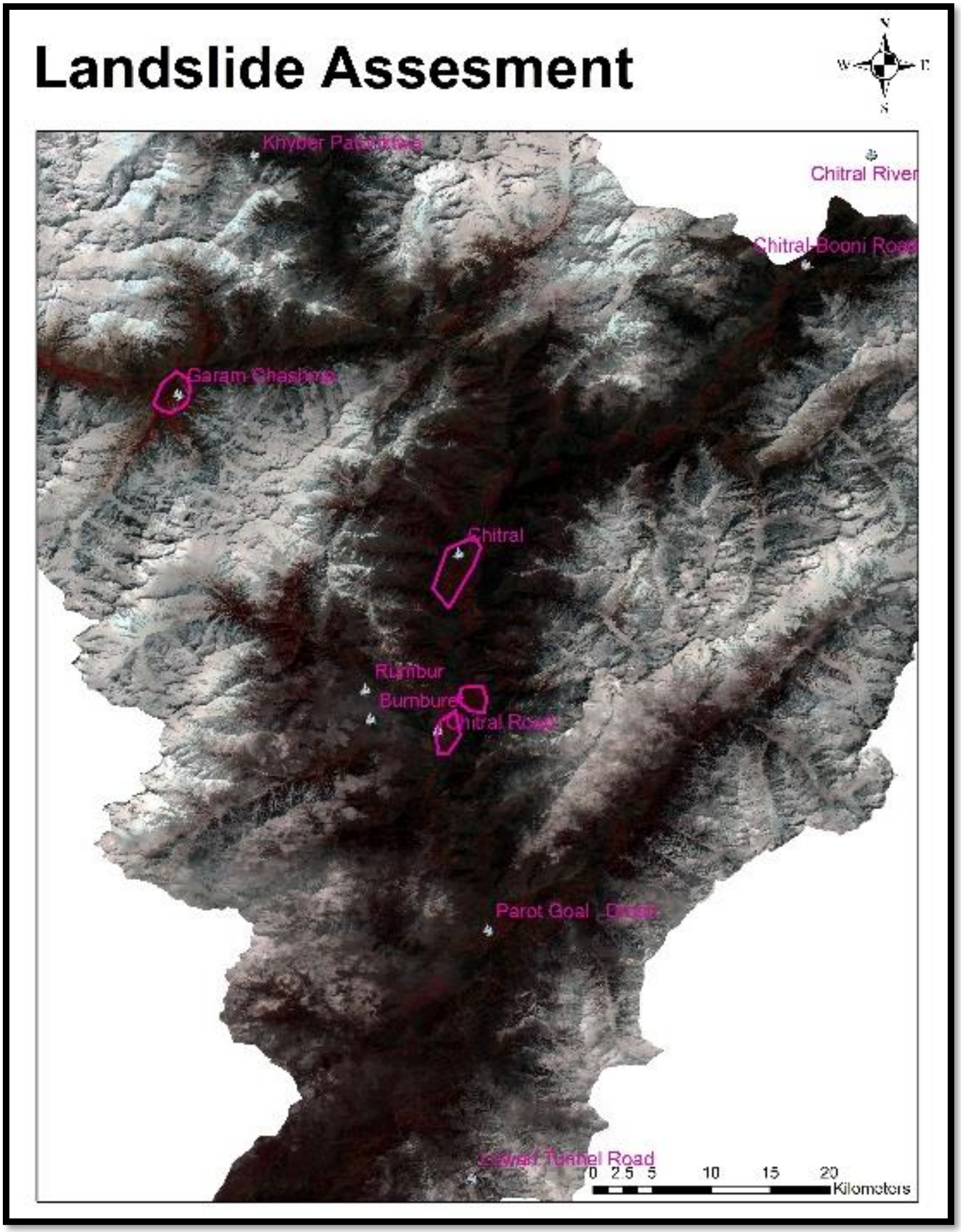

Figure 19. Accuracy assessment through satellite imagery.

`

beams, metal, or concrete, horizontally between the construction piles. Retaining walls are designed to restrain soil at a steeper angle and create level areas on sloping sites to avoid failure of natural slopes and to provide additional support. There are four main types of retaining walls: cantilever retaining walls, gravity retaining walls, reinforced soil retaining walls, and embedded retaining walls.

Another type of structural mitigation is the creation of a proper drainage system that prevents the accumulation of water which prevents liquefaction reducing the risk of landslides. These drainage systems include horizontal drains and subsurface drains. Research was conducted regarding the mitigation of landslide impacts through drainage systems which quantified drainage systems as key mitigation measures and classified drainage systems into two types such as surface drainage including roadside drains, and catch/interceptor drains (Li, 2020). Other mitigation methods include nets and soil nailing; however, these structural measures greatly depend upon the economic conditions of the region of interest.

As Chitral is a complex and rugged terrain, different mitigation techniques should be applied to perfectly minimize the landslide hazards based on the geology and topography of the region. The area of Chitral has varying types of geology and topography so different techniques can be applied across various areas that are also shown in Figure 20.

1. **Urban Areas: (Near Settlements)**
    a. **Retaining Walls and Early Warning System**: In areas near human settlements and areas near human settlements that are susceptible to landslides, protecting the infrastructure and human life is a top priority. Retaining walls are crucial for

immediate slope stabilization and can stay in place for decades providing the most durable protection against landslides. Building a wall at the base of the slope is a common method to prevent landslides. The wall supports the slope, which prevents the soil from moving downwards, saving the infrastructure and masses living in the vicinity. Reinforced soil walls and gravity retaining walls are more suitable as they are ideal for unstable and steep slopes and the latter can be constructed using locally available materials such as concrete or stones.

Location: Urban hubs like Chitral town and the surrounding village where the population is dense, landslide risk directly threatens homes and infrastructures.

2. **High Elevation Areas (Steep Slope)**

   a. **Soil Nailing and Grouting:** Soil nailing and grouting are two techniques in which first, large steel rods are inserted in the soil to reinforce and prevent it from collapsing and then grout is injected into the rock formations to enhance their stability. Soil nailing provides reinforcements by driving steel rods into the rock while grouting helps to bind loose rock and soil together. Soil nailing is particularly useful in stabilizing steep slopes as grouting is effective in areas where sedimentary rocks are porous or fractured rock.

   Location: The ideal location for this technique would be high-elevation areas such as the Karakoram and Hindukush Mountain ranges where the terrain is steep, and its composition is mostly fractured rock.

3. **Mid Elevation Areas (Moderate to Steep Slope)**

   a. **Terracing and Retaining Walls:** terracing is a technique in which a steep slope is converted into a series of steps hence reducing the angle of the slope and eventually minimizing soil erosion whereas retaining walls provide essential support to prevent soil from sliding along the slope. These techniques are effective where agricultural practices are common in settings that include both loose soil and moderate slopes.

Location: These techniques are applicable in the mid-elevation region like Kalash valley where agricultural practices take place.

4. **Low Elevation Valleys and Riverbanks (Gentle to moderate slopes with Deep soils)**
    a. **Vegetative Cover and Surface Drainage Control:** Vegetative cover is a technique, in which deep-rooted vegetation is planted that helps stabilize the soil in a natural way over for long period of time whereas surface drainage control is installing drainage systems that can divert surface water away from vulnerable slopes to prevent landslides. By installing the diversion channels, one can manage water flow and prevent soil saturation, a common trigger for landslides.

    Location: These techniques can be applied to a setting with low elevation valleys and near riverbanks areas such as Chitral river basin where slopes are moderate, and soil is deep and fertile.

5. **River-gorges and Streams (Erosion-prone Areas and Floodplains)**
    a. **Surface Water Diversion and Check Dams:** Check dams and surface water diversions are two techniques that are effective mitigations against flash floods. Check dams reduce the speed of the flow of water in streams and gullies, reducing the risk of abrupt landslide by minimizing the erosion whereas surface water divergence keeps water away from slopes. These techniques are effective in areas prone to frequent flooding and erosion.

`

b. **Location:** The above technique can be applied to the areas along gorges and streams of Chitral such as Yarkhun Valley and Mastuj Valley where water flow is strong making the terrain more susceptible to erosion.

4.3.2 Non-structural Mitigation Measures

Non-structural mitigation measures are the measures that generally focus upon the practices and principles that lead to the reduction of risk of landslides without the need for any physical construction and refer to the creation of policies that lead to the reduction of the impact of landslides. The simplest and most basic type of non-structural mitigation measure is spreading awareness of the natural hazards which refers to spreading awareness about landslides including their causes, impacts, and strategies to tackle them. This awareness should be spread to the region's general population of interest, an example of which is to have regular drills regarding landslide mitigation in schools and universities. Research was conducted regarding the importance of educating the public about landslides and it was concluded that educating the public about a region of landslide susceptibility and involving the public in monitoring landslide activities can enhance the effectiveness of mitigation efforts (Ahmad et al., 2017).

Another method of non-structural measures is proper land use planning, which considers the landslide-affected areas and avoids construction on or near said regions. It also involves plantation as vegetation in general acts as natural retaining walls reducing the risk of landslides. In specific research (Li & Duan, 2024), it was concluded that proper vegetation enhances the slope stability of a region through mechanical reinforcement and hydrological effects, reducing the risk of landslides. Another method is the creation of automated early warning systems which provide early warning regarding landslides.

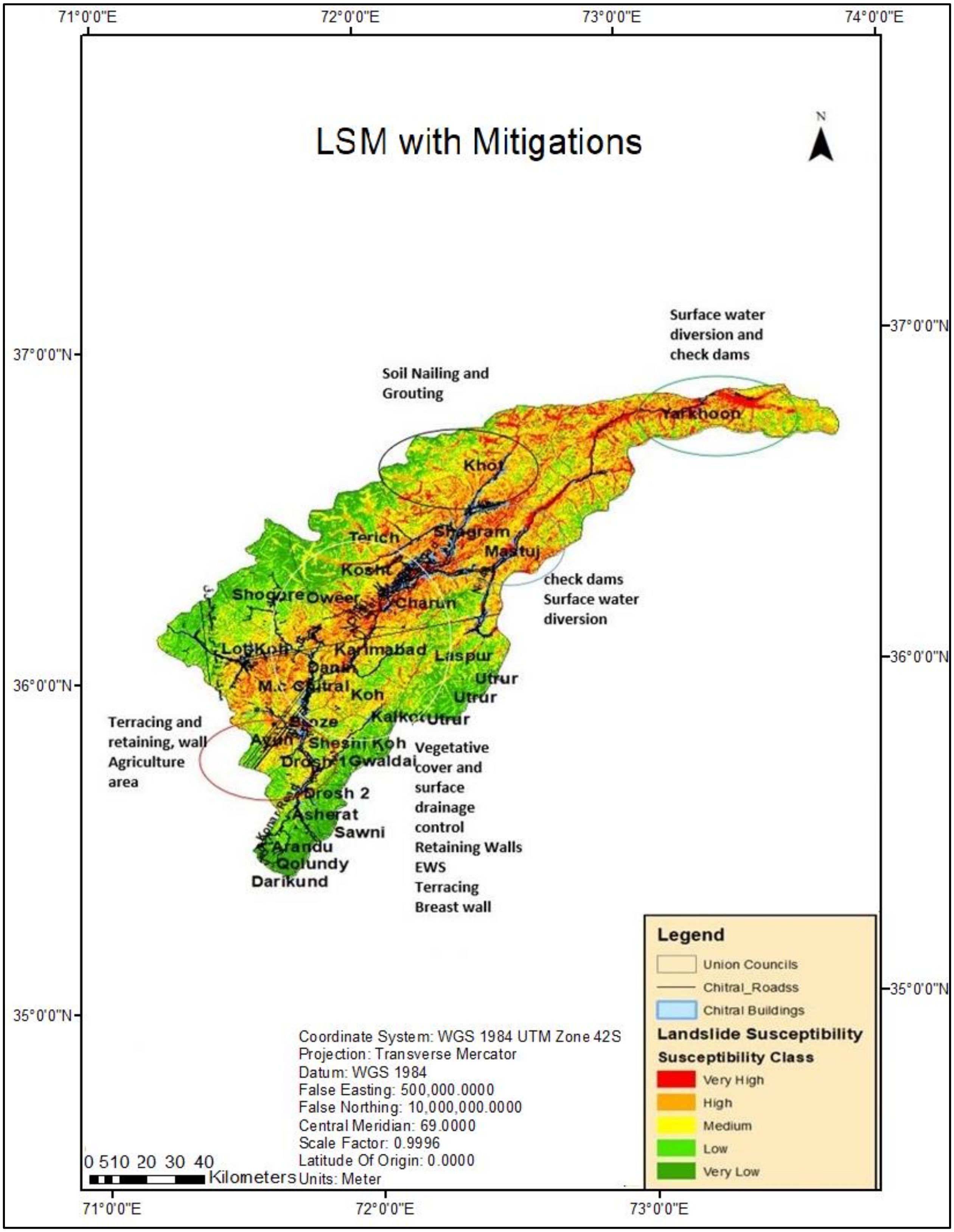

Figure 20. LSM map with mitigation measures for Chitral.

`

Non-structural mitigations focus on reducing vulnerability and improving preparedness via policies planning education and early warning systems, particularly in the region like Chitral only structural interventional approach may not be sufficient alone so non-structural mitigation measures require role of both the government and civilian entities to work together to minimize landslide.

1. **Early Warning Systems:** Early warning systems are widely used in first-world countries that can warn the audience or communities to be prepared for and respond to landslide risk more efficiently and effectively early warning systems are developing systems based on rainfall thresholds ground movement sensors and local observations. There is a communication line between the observatory sensors and locals, so those warning systems would notify the locals if any of the triggers happen.
2. **Community Training Program:** The government needs to initiate a program to educate local communities about landslide-associated risks and mitigation strategies. The training programs should include first aid, recreation drills, and land use planning to reduce vulnerability. These training programs can teach residents how to recognize early signs of landslides and the essential steps to take during a landslide event. Regular training sessions and workshops involving local communities are needed. Schools can play a vital part by incorporating disaster preparedness material into the curriculum to educate young people on identifying and responding to landslide threats.
3. **Land Use Planning and Zoning:** The government needs to start implementing policies related to land use to restrict development in idiotic zones or highly

susceptible areas. Zonation or zoning regulations can be implemented to ensure limitations on construction and agricultural activities only to safer areas, which can directly reduce people's and infrastructure's exposure to landslide risk. The landslide-prone areas can be designated as conservation zones to minimize anthropogenic activity hence protecting villages and infrastructure located near steep slopes or along river bends.

4. **Policy and Regulatory Framework:** This refers to the management of the regional and the provincial government to create policies and frameworks that may assist in the mitigation of landslides such as providing relevant funds to the Provincial Disaster Management Authority (PDMA) of said region and ensuring that the PDMA is effectively working, along with creating frameworks and policies that consider hazard susceptibility in creating houses and commercial buildings in those areas.

`

Chapter 5

CONCLUSION AND RECOMMENDATIONS

This research completed its primary objective which was to create a landslide susceptibility map for the region of Chitral using the Multi-Criteria Decision Analysis technique primarily the Analytical hierarchy process integrated with GIS. It is concluded that landslide-susceptible maps can increasingly be considered as a reference 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. Furthermore, the landslide susceptibility map produced in this study provides a valuable tool for local authorities and planners, enabling more informed decision-making to mitigate landslide risks and enhance community resilience.

Using the AHP model the susceptibility map was classified into 5 classes from very low susceptible to very high susceptible zones. This study demonstrated that approximately 13%, 27%, 28%,20%, and 11.5% of Chitral are categorized in very high, high, medium, low and very low susceptible landslide zones respectively. The result findings indicate that northern and central regions within Chitral are at a high risk of landslides, largely due to a combination of steep slopes, fragile geological formations, and significant rainfall. In terms of mitigations, while vegetative cover is the most cost-effective solution, retaining walls offers the most durable protection against landslides. A comprehensive landslide management strategy for Chitral should integrate both short-term and long-term solutions, combining engineering techniques with community-based approaches to enhance resilience and protect lives and livelihoods in this vulnerable region.

The accuracy of the said model was calculated through the AUC method and validation was performed through usage of satellite imagery. The accuracy was determined to be around 80 percent, which is satisfactory but as there is a degree of biasness in AHP, the model can be further improved. The result and model can be improved through the following measures.

a. Continuous Data Update:

Updating the input data such as soil properties and rainfall data can maintain the relevance and accuracy of the susceptibility maps.

b. Stakeholder Engagement:

It is very important to involve the local population, including local communities, PDMA, and land use planners in terms of creating accurate susceptibility maps.

c. Data Acquisition:

One of the problems with using the Analytical hierarchy process is that it is very reliant on input data that is not readily available in Pakistan, so researchers must utilize open-source global datasets which can damage the accuracy of the model.

d. Scenario Analysis:

Utilizing AHP for scenario analysis, such as the impact of climate change on landslide susceptibility, can provide forward-looking insights that help in long-term planning and resilience building.

e. Validation and Calibration:

The results derived from AHP should be validated and calibrated against historical landslide data to improve the model's predictive power. Continuous refinement of the criteria and weights based on empirical evidence will enhance the reliability of the susceptibility assessments.

`

REFERENCES

1. Basu, T., & Pal, S. (2020). A GIS-Based Factor Clustering and Landslide Susceptibility Analysis Using AHP For Gish River Basin, India. Environment, Development and Sustainability, 22(5). https://Doi.Org/10.1007/S10668-019-00406-4
2. Batumalai, P., Mohd Nazer, N. S., Simon, N., Sulaiman, N., Umor, M. R., & Ghazali, M. A. (2023). Soil Detachment Rate of a Rainfall-Induced Landslide Soil. Water, 15(12), 2149. https://doi.org/10.3390/w15122149
3. Bek, A., Jeftić, G., Strelec, S., & Jug, J. (2021). Influence of shear rate on the soil’s shear strength. Environmental Engineering, 8(1-2), 39–47. https://doi.org/10.37023/ee.8.1-2.6
4. Bosco, C., & Sander, G. (2015). Estimating the effects of water-induced shallow landslides on soil erosion. ArXiv:1501.05739 [Cs]. https://arxiv.org/abs/1501.05739
5. Çellek, S. (2022). Effect of the slope angle and its classification on landslides. Himalayan Geology, 43(1).
6. Çellek, S. (2023). Linear Parameters Causing Landslides: A Case Study of Distance to the Road, Fault, Drainage. Kocaeli Journal of Science and Engineering, 6(2). https://doi.org/10.34088/kojose.1117817
7. Chang, K. (2019). Geographic Information System. International Encyclopedia of Geography, 1–10. https://doi.org/10.1002/9781118786352.wbieg0152.pub2
8. Chung, J. won, Rogers, J. D., & Watkins, C. M. (2014). Estimating severity of seismically induced landslides and lateral spreads using threshold water levels. Geomorphology, 204. https://doi.org/10.1016/j.geomorph.2013.07.024
9. Dorren, L., Berger, F., Jonsson, M., Krautblatter, M., Mölk, M., Stoffel, M., & Wehrli, A. (2007). State of the art in rockfall – forest interactions. Schweizerische Zeitschrift Fur Forstwesen, 158(6), 128–141. https://doi.org/10.3188/szf.2007.0128
10. Earthzine. (2015, January 2). Estimating the Effects of Water-Induced Shallow Landslides on Soil Erosion. Earthzine. https://earthzine.org/estimating-the-effects-of-water-induced-shallow-landslides-on-soil-erosion/
11. Evans, S. G., Mugnozza, G. S., Strom, A. L., Hermanns, R. L., Ischuk, A., & Vinnichenko, S. (2006). Landslides From Massive Rock Slope Failure and Associated Phenomena. NATO Science Series, 03-52. https://doi.org/10.1007/978-1-4020-4037-5_1

`

12. Fan, Y., Zhang, F., Liu, Y., & Ma, D. (2022). Numerical investigation of impact characteristics of rigid retaining wall for blocking landslides: A case study of the Shum Wan Road landslide. Geofluids, 2022, 1-11. https://doi.org/10.1155/2022/7835780
13. Garcia-Chevesich, P., Wei, X., Ticona, J., Martínez, G., Zea, J., García, V., Alejo, F., Zhang, Y., Flamme, H., Graber, A., Santi, P., McCray, J., Gonzáles, E., & Krahenbuhl, R. (2020). The Impact of Agricultural Irrigation on Landslide Triggering: A Review from Chinese, English, and Spanish Literature. Water, 13(1), 10. https://doi.org/10.3390/w13010010
14. Gariano, S. L., & Guzzetti, F. (2016). Landslides in a changing climate. Earth-Science Reviews, 162, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011
15. Guo, Y., Shan, W., Jiang, H., Sun, Y., & Zhang, C. (2013). The Impact of Freeze–thaw on the Stability of Soil Cut Slope in High-latitude Frozen Regions. Environmental Science and Engineering, 85–98. https://doi.org/10.1007/978-3-319-00867-7_7
16. Guzzetti, F. (2020). On the Prediction of Landslides and Their Consequences. ICL Contribution to Landslide Disaster Risk Reduction, 3–32. https://doi.org/10.1007/978-3-030-60196-6_1
17. Hungr, O., Leroueil, S., & Picarelli, L. (2013). The Varnes classification of landslide types, an update. Landslides, 11(2), 167–194. https://doi.org/10.1007/s10346-013-0436-y
18. Ibrahim, M. B., Mustaffa, Z., Balogun, A. B., Indra, S. H. H., & Nur Ain, A. (2022). Landslide's analysis and Hazard mapping based on Analytic Hierarchy Process (AHP) using GIS, in Lawas, Sabah-Sarawak. IOP Conference Series: Earth and Environmental Science, 1064(1), 012031. https://doi.org/10.1088/1755-1315/1064/1/012031
19. Imaizumi, F., Sidle, R. C., & Kamei, R. (2008). Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. Earth Surface Processes and Landforms, 33(6), 827–840. https://doi.org/10.1002/esp.1574
20. Islam, F., Riaz, S., Ghaffar, B., Tariq, A., Shah, S. U., Nawaz, M., Hussain, M. L., Amin, N. U., Li, Q., Lu, L., Shah, M., & Aslam, M. (2022). Landslide susceptibility mapping (LSM) of Swat District, Hindu Kush Himalayan region of Pakistan, using GIS-based bivariate modeling. Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.1027423
21. Jelani, J., Nur Amirah Adnan, Husen, H., Mohd, & Suriyadi Sojipto. (2020). The effects of ground water level fluctuation on slope stability by using slope. Zulfaqar Journal of Defence Science, Engineering & Technology, 3(1). https://doi.org/10.58247/jdset-2020-0301-01

22. Kaczmarek, Ł., & Dobak, P. (2017). Contemporary overview of soil creep phenomenon. Contemporary Trends in Geoscience, 6(1), 28–40. https://doi.org/10.1515/ctg-2017-0003
23. Khalilnejad, A., Faisal Hj. Ali, & Osman, N. (2011). Contribution of the Root to Slope Stability. Geotechnical and Geological Engineering, 30(2), 277–288. https://doi.org/10.1007/s10706-011-9446-5
24. Korulla, M. (2020). Significance of Drainage Measures on Landslide Mitigation Measures. https://doi.org/10.1007/978-981-13-8828-6_9
25. Kourkouli, P. (2023). Natural disaster monitoring using ICEYE SAR data. In Geoinformatics for Geosciences: Advanced Geospatial Analysis using RS, GIS, and Soft Computing. https://doi.org/10.1016/B978-0-323-98983-1.00010-7
26. Li, Y., & Duan, W. (2023). Decoding vegetation's role in landslide susceptibility mapping: An integrated review of techniques and future directions. Biogeotechnics, 2, 100056. https://doi.org/10.1016/j.bgtech.2023.100056
27. Majdi, A., & Amini, M. (2011). Analysis of geo-structural defects in flexural toppling failure. International Journal of Rock Mechanics and Mining Sciences, 48(2), 175–186. https://doi.org/10.1016/j.ijrmms.2010.11.007
28. Mazza, D., Cosentino, A., Romeo, S., Mazzanti, P., Guadagno, F. M., & Revellino, P. (2023). Remote Sensing Monitoring of the Pietrafitta Earth Flows in Southern Italy: An Integrated Approach Based on Multi-Sensor Data. Remote Sensing, 15(4), 1138. https://doi.org/10.3390/rs15041138
29. Miščević, P., & Vlastelica, G. (2014). Impact of weathering on slope stability in soft rock mass. Journal of Rock Mechanics and Geotechnical Engineering, 6(3), 240–250. https://doi.org/10.1016/j.jrmge.2014.03.006
30. Rabby, Y. W., Li, Y., Abedin, J., & Sabrina, S. (2022). Impact of Land Use/Land Cover Change on Landslide Susceptibility in Rangamati Municipality of Rangamati District, Bangladesh. ISPRS International Journal of Geo-Information, 11(2). https://doi.org/10.3390/ijgi11020089
31. Rahim, I., Ali, S. M., & Aslam, M. (2018). GIS Based Landslide Susceptibility Mapping with Application of Analytical Hierarchy Process in District Ghizer, Gilgit Baltistan Pakistan. Journal of Geoscience and Environment Protection, 06(02). https://doi.org/10.4236/gep.2018.62003

`

32. Rahman, G., Bacha, A. S., Ul Moazzam, M. F., Rahman, A. U., Mahmood, S., Almohamad, H., Al Dughairi, A. A., Al-Mutiry, M., Alrasheedi, M., & Abdo, H. G. (2022). Assessment of landslide susceptibility, exposure, vulnerability, and risk in shahpur valley, eastern hindu kush. Frontiers in Earth Science, 10. https://doi.org/10.3389/feart.2022.953627
33. Ahmad, A., Amin, Z., Abdullah, C., & Ngajam, S. (2017). Public awareness and education programme for landslide management and evaluation using a social research approach to determining "acceptable risk" and "tolerable risk" in landslide risk areas in Malaysia (IPL-194, IPL-207). In Advancing culture of living with landslides (pp. 437-447). https://doi.org/10.1007/978-3-319-59469-9_39
34. Rehman, M. U., Zhang, Y., Meng, X., Su, X., Catani, F., Rehman, G., Yue, D., Khalid, Z., Ahmad, S., & Ahmad, I. (2020). Analysis of Landslide Movements Using Interferometric Synthetic Aperture Radar: A Case Study in Hunza-Nagar Valley, Pakistan. Remote Sensing, 12(12), 2054. https://doi.org/10.3390/rs12122054
35. Semlali, I., Ouadif, L., & Bahi, L. (2019). Landslide susceptibility mapping using the analytical hierarchy process and GIS. Current Science, 116(5). https://doi.org/10.18520/cs/v116/i5/773-779
36. Shahabi, H., Rahimzad, M., Ghorbanzadeh, O., Piralilou, S. T., Blaschke, T., Homayouni, S., & Ghamisi, P. (2022). Rapid Mapping of Landslides from Sentinel-2 Data Using Unsupervised Deep Learning. 2022 IEEE Mediterranean and Middle-East Geoscience and Remote Sensing Symposium, M2GARSS 2022 - Proceedings. https://doi.org/10.1109/M2GARSS52314.2022.9840273
37. Sim, K. B., Lee, M. L., & Wong, S. Y. (2022). A review of landslide acceptable risk and tolerable risk. Geoenvironmental Disasters, 9(1). https://doi.org/10.1186/s40677-022-00205-6
38. Smith, V. K., Carbone, J. C., Pope, J. C., Hallstrom, D. G., & Darden, M. E. (2022). Adjusting to natural disasters. In www.elgaronline.com. Edward Elgar Publishing. https://www.elgaronline.com/monochap/book/9781035301614/book-part-9781035301614-30.xml
39. Shao, X., & Xu, C. (2022). Earthquake-induced landslides susceptibility assessment: A review of the state-of-the-art. Natural Hazards Research, 2(3). https://doi.org/10.1016/j.nhres.2022.03.002

`

40. Stead, D., & Wolter, A. (2015). A critical review of rock slope failure mechanisms: The importance of structural geology. Journal of Structural Geology, 74(1), 1–23. https://doi.org/10.1016/j.jsg.2015.02.002
41. Tiranti, D., Rabuffetti, D., Salandin, A., & Tararbra, M. (2012). Development of a new translational and rotational slides prediction model in Langhe hills (north-western Italy) and its application to the 2011 March landslide event. Landslides, 10(2), 121–138. https://doi.org/10.1007/s10346-012-0319-7
42. Torizin, J., Fuchs, M., Awan, A. A., Ahmad, I., Akhtar, S. S., Sadiq, S., Razzak, A., Weggenmann, D., Fawad, F., Khalid, N., Sabir, F., & Khan, A. J. (2017). Statistical landslide susceptibility assessment of the Mansehra and Torghar districts, Khyber Pakhtunkhwa Province, Pakistan. Natural Hazards, 89(2). https://doi.org/10.1007/s11069-017-2992-2
43. Trisnawati, D., Najib, Hidayatillah, A. S., & Najib. (2022). The Relationship of Lithology with Landslide Occurrences in Banyumanik and Tembalang Districts, Semarang City. IOP Conference Series: Earth and Environmental Science, 1047(1). https://doi.org/10.1088/1755-1315/1047/1/012026
44. Woldearegay, K. (2013). Review of the occurrences and influencing factors of landslides in the highlands of Ethiopia: With implications for infrastructural development. Momona Ethiopian Journal of Science, 5(1), 3. https://doi.org/10.4314/mejs.v5i1.85329
45. Wu, W., Guo, S., & Shao, Z. (2023). Landslide risk evaluation and its causative factors in typical mountain environment of China: a case study of Yunfu City. Ecological Indicators, 154. https://doi.org/10.1016/j.ecolind.2023.110821
46. Yang, H., Yang, T., Zhang, S., Zhao, F., Hu, K., & Jiang, Y. (2020). Rainfall-induced landslides and debris flows in Mengdong Town, Yunnan Province, China. Landslides, 17(4). https://doi.org/10.1007/s10346-019-01336-y
47. Xie, J., Uchimura, T., Wang, G., Selvarajah, H., Maqsood, Z., Shen, Q., Mei, G., & Qiao, S. (2020). Predicting the sliding behavior of rotational landslides based on the tilting measurement of the slope surface. Engineering Geology, 269. https://doi.org/10.1016/j.enggeo.2020.105554
48. Aslam B, Maqsoom A, Khalil U, Ghorbanzadeh O, Blaschke T, Farooq D, Tufail RF, Suhail SA, Ghamisi P. Evaluation of Different Landslide Susceptibility Models for a Local Scale in

`

the Chitral District, Northern Pakistan. Sensors. 2022; 22(9):3107. https://doi.org/10.3390/s22093107