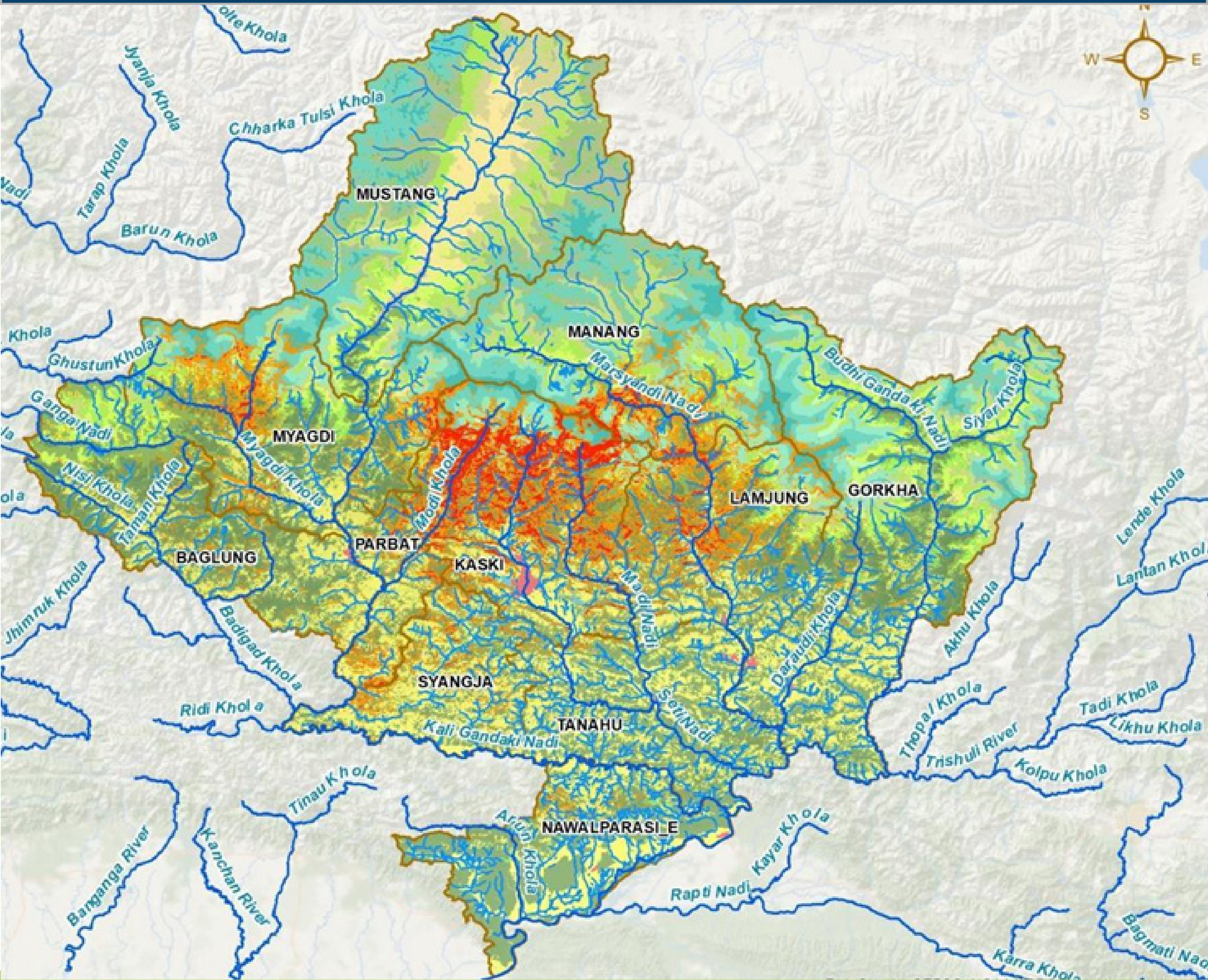
Soil Erosion, Landslides and Hazard Mapping as well as profiling in Gandaki Province



Provincial Government

Ministry of Forest, Environment and Soil Conservation

Forest Directorate, Gandaki Province

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Study of Soil Erosion, Landslides and Hazard Mapping as well as profiling in Gandaki Province

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Disclaimer:
This report is prepared to assist Ministry of Forest, Environment and Soil Conservation, Directorate of Forest, Gandaki Province to manage Soil erosion and Landslides. The information provided may need to be validated and updated annually.

Layout designed by Rabin Raj Niraula
Photographs by Ajaya Shrestha

Front Cover: Map of Gandaki province showing major districts, major rivers, Hydrology and Landslide Risk zones

Back Cover: False Color Composite Sentinel- 2 image of Pokhara Sub-Metropolitan City

Acknowledgement

Nepal is vulnerable to soil erosion due to its fragile topography and annual rainfall pattern. After the enforcement of new constitution of Nepal in 2072, the responsibility for watershed management has been shared among local government, provincial government and federal government.
Gandaki Province is vulnerable to soil erosion due to its sloppy topography and high rainfall around Pokhara Valley. Due to bare and sparse vegetation, Mustang and Manang districts are vulnerable to wind erosion. This study of Soil Erosion, Landslides and Hazard Mapping as well as profiling in Gandaki Province is expected to be helpful for integrated watershed management and to minimize the rate of soil erosion. Hazard mapping will definitely inform the people about the risk of hazards. Profile of landslides is expected to provide the ground information for managers and all stakeholders. This study will be the base line for the Gandaki Government for prioritizing Soil conservation and Watershed Management Programs and delivering Services effectively.
Realizing these issues, Gandaki government considered Study of Soil Erosion, Landslides and Hazard Mapping as well as profiling in Gandaki Province. For this, Inclusive-CCER-EERC JV deserves special thanks for completing the entire task on stipulated time. I also thank Senior Watershed Management Officer Indra Prasad Adhikari and Ranger Mr. Dipendra Kshetri of Forest Directorate for coordinating and facilitating this task. I hope, This unique study will help the Gandaki Government for prioritizing soil conservation and watershed management programs and delivering services effectively.

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Kedar Prasad Paudel
Provincial Forest Director

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1. Introduction

1.1 Background

Nepal has a diverse topography, complex geology and highly varying climate, and is exposed to multiple natural and human-induced hazards. Nepal ranks 4th in terms of climate risk according to the Global Climate Risk Index which assesses the impacts of meteorological events in relation to economic losses and human fatalities (Eckstein et al., 2020). According to Central Bureau of Statistics, 2018, Nepal's population has surpassed 29 million people, of which almost 80% depend on agriculture-based livelihoods. More than 80% of the population is exposed to the risk of natural hazards (MoHA, 2017), which include earthquakes, droughts, floods, landslides, extreme temperature, and glacier lake outburst floods (GLOFs). Located in the central Himalayas, Nepal is among the most disaster-prone countries in the world due to its topography and climatic condition. Earthquakes, landslides, floods, fire, thunderbolts are the major causes of disaster events that caused major damage in the past, weakening the fragile ecosystem of the country. Economic Vulnerability Analysis shows that Nepal exhibits the largest losses due to large exposure at risk and the high level of hazards. These phenomena not only cause loss of lives and properties, but also pose severe threats to physical infrastructure, and also disrupt economic development. Limited domestic economy, geographically scattered population, as well as diverse ethnic and indigenous communities adds social vulnerability to disasters.

Nepal is situated in the central part of the Himalaya covering an area of 147,516 km^2 and an elevation ranges from 58 m to 8848 m. above sea level. Nepal has diverse climates due to the large variation in elevation. The climate varies from humid tropical type in the tropical lowlands in the south to alpine cold semi-desert type in the Trans-Himalayan zone (Wangda & Ohsawa, 2006). The average annual rainfall is around 1000 – 2000 mm, but sometimes it exceeds 3000 mm in some lower parts of the country (Karki et al., 2017). Nepal has diverse geography that ranges from permanently snow and ice covered very rugged Himalayan Mountains in the north to the tropical alluvial plains in the south. Due to variation in climate and topography, Nepal is classified into five physiographic zones i.e., Terai, Siwalik, Middle mountain, High mountain and Himalaya (Shrestha et al., 2010). About 75% of the total land area of 147,516 km2 is made up of mountains and hills.

As a mountainous country, Nepal is most susceptible to precipitation extremes and related hazards, including severe floods, landslides and droughts that cause huge losses of life and property, impact the Himalayan environment, and hinder the socioeconomic development of the country (Karki et al., 2017). Land cover change is a critical driver for enhancing the soil erosion risk in Nepal and loss of the topsoil has a direct as well as indirect effect on human life and livelihoods (Uddin et al., 2018). Nepal is a soil erosion vulnerable country due to its fragile geography, steep topography and intense monsoon rainfall. Surface erosion rate is affected by land cover and slope gradient in the Mid Hills region of Nepal. A recent study shows soil erosion rates ranging from 0.03 to 100.33 t/ha/year in the hilly watershed of western Nepal. In Nepal, intense rainfall and conventional tillage practices coupled with poor soil structure and steep slopes are the main drivers of soil erosion (Chalise et al. 2019).

The climate in this region is dominated by the Indian summer monsoon system; about 80% of the precipitation falls between June and September. During this season, heavy rainfall commonly leads to Water-related disasters such as landslides in the hills, flash floods in the Siwaliks, and riverine floods in the plains. The spatial distribution of precipitation varies across the zones and topographies. In the hills, springs are a major source of water and depend on annual rainfall to recharge the aquifers that feed them. The river discharge varies through the year influenced by both snow-melt and precipitation. The hydrograph of the Devghat stations in Chitwan district (below the confluence of the Kali Gandaki and Trishuli rivers) showed a seasonal variation in average monthly discharge in the period 1963—2010 ranging from 277 m3/sec in March to 4,634 m3/sec in August. The maximum daily discharge recorded was 14,100 m3/sec on 05 August 1974.

In Gandaki Province, the areas around Pokhara Valley are vulnerable to water erosion due to its sloppy topography, fragile geology and high rainfall. On the other hand, Mustang and Manang districts are highly sensitive to erosion due to fragile topography. Study of soil erosion and landslides is essential for integrated watershed management and to minimize the rate of soil erosion. Hazard mapping is also essential to inform the people about the risk of hazards.

1.2 Soil Erosion

Soil erosion contributes substantial changes in basin hydrology and the outcomes are linked to multiple aspects including social, economic, and political areas. Water-induced erosion in the mountain and hill areas of these basins is very high because of the steep slopes, terraced agricultural practices with poor management. The river in such high gradients and large basins transport heavy loads of sediments which are deposited downstream. Soil erosion has been reported to reduce crop production, degrade vegetation cover and also leads to sedimentation in dams. Information on the spatial distribution patterns and dynamic changes in erosion across the river basins is needed to develop plans and determine priorities for controlling soil erosion at the river basin level.

Soil erosion is a major issue, causing the loss of topsoil and fertility in agricultural land in mountainous terrain. Estimation of soil erosion in Nepal is essential because of its agriculture-dependent economy (contributing 36% to national GDP) and for preparing erosion control plans (Koirala et al., 2019).

1.3 Landslides

Landslides are one of the common natural hazards in the hilly region of Nepal. Both natural and human factors such as steep slopes, fragile geology, high intensity of rainfall, deforestation, and unplanned human settlements are the major causes of landslides. The risk of landslides is further exacerbated by anthropogenic activities like improper land use, encroachment into vulnerable land slopes and unplanned development activities such as construction of roads and irrigation canals without proper protection measures in the vulnerable mountain belt. The hilly districts of Nepal located in the Siwalik, Mahabharat range, Mid-land, and also fore and higher Himalayas are highly susceptible to landslides because of steep topography and fragile ecosystem.

Landslide hazard map (LHM) can be useful in estimating, managing and mitigating landslide hazards. LHM is a fundamental tool for disaster management activities in fragile mountainous terrains.

1.4 Problem statement

Nepal is exposed to multiple disasters including earthquakes, floods, landslides, droughts, storms, avalanches, hailstorms, fires, lightning, road accidents, epidemics and ecological hazards. A wide range of physiological, geological, ecological, meteorological and demographic factors contribute to the vulnerability of the country to disasters. Major factors contributing to disasters are rapid population growth, slow economic development, a high degree of environmental degradation, fragility of the land mass and high elevation of the mounting slopes. The lessons of the 1988 earthquake and 2015 Gorkha Earthquake, 1993 flood and landslide, 2008 Koshi floods and 2013 floods and landslide in Far Western Region, 2014 flood and landslide in Mid-Western Region and 2017 floods and landslides in Eastern and Central Region have brought about a shift of attitude on the part of planners, government, donor agencies, NGOs and INGOs towards the need for a coordinated disaster preparedness and response mechanism.

The landscape of the Gandaki province is extending from nearly 104 m. mean sea level in the Triveni at Nawalpur district near to the Dhaulagiri 8167m, Manaslu 8163 m, and Annapurna I 8091 m. peaks are in the great Himalayas within a short aerial distance of 150 kilometers. The province covers about 15 % of the total area of the country. The Manang and Mustang districts are completely located at the Inner Himalayan valley or High Himalayan valleys of Gandaki Province. The upper part of Gorkha, Lamjung, Kaski, Mygdi and Baglung districts are along the high Himalayan Massif including some areas in the North across the massif. Lower part of these districts including Tanahun, Syangja, Parbat are at the middle part. Nawalpur falls mainly within the inner Terai from Gaindakot to Dumkibas and the rest of the district are located in the area of Mahabharat range and Chure (Siwalik) and outer Terai too. This small area within outer Terai falls under Binayee, Triveni Rural Municipality. This is the only Gandaki Province to share its international border with India. Therefore, the Province has high heterogeneity in its landscape. Gandaki River system is the only drainage network. The Province has 5,98,180 households with a 25,02,355 number of total populations according to the 2011 census. Despite few urban concentrations like Pokhara, Damauli, Kusma Bazar, Baglung Bazar, Beni Bazar, Putali Bazar and Waling Bazar the households are widely distributed even up to the inaccessible mountain terrain. The Province landscape is highly susceptible for different types of hazards, vulnerability and risk including geological, climatic and human induced. Therefore, assessment of the landscape within the hazard and vulnerability perspective is highly needed for future development. Hence, the extension of the Province landscape within the High Mountain to deep river valleys and Terai plain comprise heterogeneity of its database, therefore, manual collection of data, integration and analysis by using conventional methods may not be feasible.

In this scenario, the Ministry of Forest, Environment and Soil Conservation, Directorate of Forest, Gandaki province has conducted the study for identification and mapping of disaster risk areas of the entire province. In this study the major two disasters (soil erosion and landslides) were modeled and mapped by the help of GIS (Geographical Information System) and remote sensing technology.

1.5 Rationale

This study covers multi-hazard risk assessment mainly soil erosion and landslide and maps the same for Gandaki Province by using state of the art methods. This is achieved by integrating methods used with a geographic information system (GIS) and Remote Sensing. The blending of the different methods in GIS enhances the decision-making process with better illustration and mapping capabilities to facilitate the development of hazard maps. Such mapping helps to identify the highly susceptible areas for single hazard as well as multi-hazards that can play a significant role to address disaster risk reduction and also provide a guide for policymakers. Profiling of the landslide is also necessary to provide the ground information for managers and all stakeholders.

The aim of the study reported here is to compile and evaluate data regarding the temporal trends in soil erosion and landslide occurrence in Gandaki Province in the period 2015-2020 and to use these data to attempt to understand the underlying causes of changes in landslide impacts through time. To do this, we have constructed a database of fatal landslides (that caused casualties) for the study period. This database has been analyzed in terms of spatial and temporal distributions, with a particular emphasis upon the relationships with the distributions in time and space of potential triggering factors.

1.6 Objective of the study

The major objective of the study is outlined as follows.

- To identify the soil erosion status in Gandaki Province
- To identify the major landslides (all landslides causing human casualties for last 3 years and other major landslides causing threat to human settlements and important Development Infrastructure) in Gandaki Province
- To map the landslide hazard risk area of Gandaki Province
- To prepare the profile and brief indicative plan of landslides and their treatment measures of the major landslides (all landslides causing human casualties for last 3 years and other major landslides causing threat to human settlements and important Development Infrastructure) in Gandaki Province

2. Literature review

Land degradation and Soil erosion are the major global problem (Guerra et al., 2017). The United Nations report shows that every year the world loses 24 billion tons of fertile land and dry land degradation reduces National domestic product in developing countries by up to eight percent (UN, 2019). It is the most vulnerable threat affecting millions of people worldwide. Previously, also mention about land degradation by accelerated erosion as a serious problem, especially in developing countries of tropics and subtropics. About 87 tonnes of top soil per hectare per year on sloping terraces are found as eroded in Nepal. In Nepal due to fragile geology from almost 2/3 of the total area, soil erosion is exceedingly high. Land degradation and soil erosion in Nepal are due to geographical and social diversity, Intense cultivation, Increasing population, lack of governmental plan etc (Gardner and Gerrad, 2003).

Landslide hazard zonation is defined as the mapping of areas with an equal probability of occurrence of landslides within a specified period of time (Varnes 1984). Moreover, intrinsic (bedrock geology, geomorphology, soil depth, soil type, slope gradient, slope aspect, slope convexity and concavity, elevation, engineering properties of the slope material, land use pattern, drainage pattern) and extrinsic (rainfall, earthquakes, and volcanoes) variables are used to determine landslide hazard in an area (Atkinson and Massari 2011). The extrinsic variables are site specific and possess temporal distribution. Moreover, they are difficult to estimate because of lack of information about the spatial distribution.

A region is considered to be susceptible to landslides when the terrain conditions at that site are comparable to those in the region where a slide has occurred (van Westen 2002). The integrated analysis of all intrinsic variables in relation to the spatial distribution of landslides has gained enormous success by the introduction of Geographic Information Systems (GIS), the ideal tool for the analysis of parameters with a high degree of spatial variability. For a landslide hazard assessment, the assumption is made that conditions, which led in the past to landslides, will also result in potential unstable conditions in the present.

Landslides are the common problems of mountainous terrains of tropical, subtropical and temperate regions and are demonstrated in a variety of processes. They cause considerable damage to highways, railways, waterways and buildings. Potential sites that are particularly prone to landslides should therefore be identified in advance to reduce disaster damages. Landslide hazard assessment can be a vital tool to understand the basic characteristics of the terrains that are prone to failure especially during extreme climatic events.

Landslide susceptibility zoning requires an inventory map of landslides occurred in the past together with assessment of the areas with the potential to occurrence of landslides in future but with no assessment of frequency (annual probability) of occurrence (Cascini 2011). Landslide susceptibility map includes landslides which have their source in the area, or may have their source outside the area but may travel through the area or return into the area (Frattini et al. 2010).

Landslides and floods are common phenomena for land degradation in Nepal Himalayas causes tremendous loss of property and lives; eg., the massive landslide in Jure, Nepal resulting Sunkoshi river damming for 37 days from 2 Aug., 2014 eventually cause death of 156 people and USD 1.4 million property losses (news sources). Human induced factors such as; improper land use practices, unmanaged infrastructures development, increasing urbanization trigger the susceptibility of landslide (Rajbhandari et. al. 2014) of the Hill slope of Nepal. In addition, Terai flat land and Churia range of Nepal also experiences the land degradation. Surface soil erosion mainly in agricultural land is quite significant varies form 2 tonnes/ha./yr. to 105 tonnes/ha./yr. in hilly region (Acharya, 2005).

3. Study Methods

3.1 Study area

Study covers Gandaki Province which includes 11 districts: Nawalpur, Tanahun, Gorkha, Lamjung, Kaski, Syanjya, Parbat, Baglung, Myagdi, Manang, and Mustang. The Gandaki province covers major areas of Gandaki Basin which extends from the Tibetan Plateau towards north to the Gangetic plains towards south. It has diverse topography, geology, vegetation, lithology, climate and a wide variety of land use practices that affect soil erosion processes. There are 85 local governments composed of 1 Metropolitan City, 26 municipalities and 58 rural municipalities with 757 wards.

Rapid population growth, deforestation, flooding, haphazard management also adds to the processes resulting in soil erosion. The topography of the region varies from high mountains with deepest gorges, rugged terrain, fragile hill slopes, low hills and plains. The predominant land cover of the region includes forests and agriculture in the lower and mid elevation while the majority of high altitudes are bare areas and snow-covered mountains. Climate of the region varies distinctly in the southern part of Annapurna range and Northern part of Trans Himalayas.

Gandaki Province is bordered by Trishuli River, Budhi Gandaki River and Bagmati Province in the east, Lumbini Province in the west, China in the north and Lumbini Province and Uttar Pradesh of India in the south.

It has an area of 21976 sq.km and that is 15% of the total area of the country. 38.01% of provincial land is covered by forest. (MoF; Economic Survey 2076/77) 17.8% land is arable and 24.7% of the Province land is covered by snow, and 0.4% of land is covered by water.

In the central part of Nepal, the Gandaki Province (270 26’ 15’’ N - 290 19’ 15’’ N and 820 52’ 45’’ E - 850 12’ 01’’ E) is spread from Himal to Terai with north to south direction (Figure 1). Near the border of India, the lowest part towards south has altitude 104 meters above sea level. This elevation goes up gradually to the highest

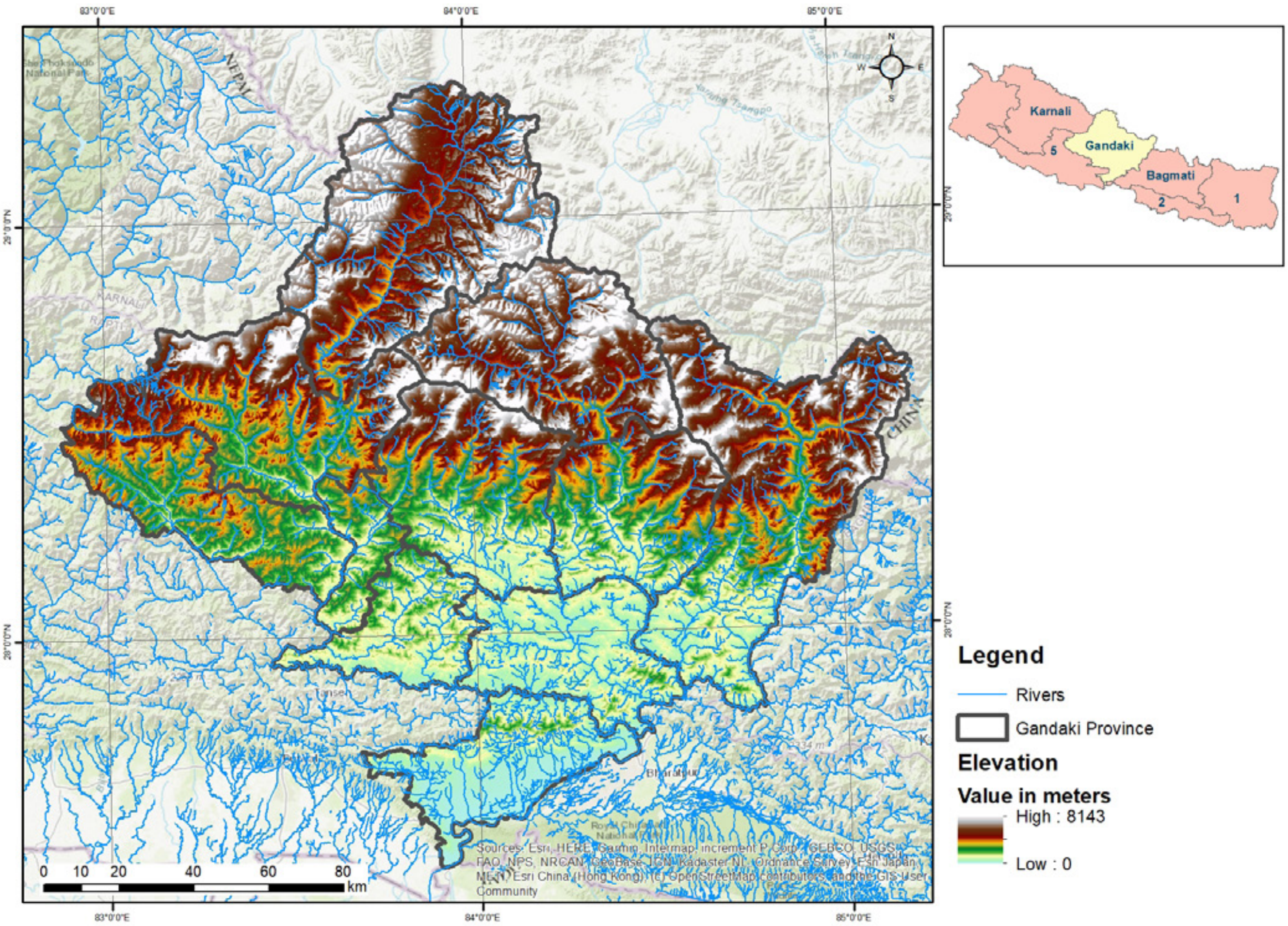


Figure 1 Topographical Map of the Gandaki Province

elevation at Dhaulagiri with 8,167 meters. In this province almost all part of Himalayan mountain range has fallen to the interior parts. These interior parts are Mustang, Manang and Northern Part of Gorkha (Larke-Kutang-Vote) which are known as High Himalayan Valley (MoITFE, 2018).

Gandaki province is rich in protected areas. Around 45.68 % of the Gandaki province is covered by protected areas. Annapurna Conservation Area, Manaslu Conservation Area, some parts of Dhorpatan Hunting Reserve and Chitwan National Park are in this province. Annapurna Conservation area is famous for mountain trekking and unique landscape, Dhorpatan Hunting Reserve is popular for trophy hunting of blue sheep and Himalayan tahr. Similarly, Chitwan National Park is famous for rhino and tiger and Manaslu conservation area is famous for trekking, unique landscape and mountain biodiversity.

3.1.1 Climate

Gandaki Province has climatic variations, which is associated with the diverse nature of its topography and altitude pronounced by Bhabar, Chure, Inner Madhesh and valleys formed by various rivers and mountains less than 1500 m in subtropical climate. Similarly, an area ranging from 1500 – 3000 meters has a temperate climate and Himalayan regions at an altitude of 3000 to 4500 meters with Alpine climate. In the High Himalayan region of the province we can find Tundra climatic conditions. The mean annual precipitation of Gandaki province was found to be around 1800mm. The highest annual precipitation is recorded in Lumle of Kaski District with mean annual precipitation of about 5500mm.. The High Himalayan district of Mustang has the lowest annual rainfall of 146mm.

3.1.2 Social and Cultural Diversity

Total population of the Gandaki Province is 2,403,757. Out of the total population, 60.11% of the provincial population is residing in the urban area. There are 88 ethnic groups in the province. The major ethnic groups are Brahman Hill (21.6%), Magar (18.9%), Chhetri (13.4%), Gurung (11.4%), Kami (8.7%), Newar (4.1%) etc. Among the 47 spoken languages in the province 73.5% speak Nepali, 9.9% speak Magar and 8.8% speak Gurung.

3.1.3 Agriculture

Agriculture and tourism is the mainstay of the province's economy. Productivity of paddy in the province is 3.76 MT per ha, which is below the national average productivity of 3.8MT per ha. Out of the total paddy production in the country, Gandaki Province comprises 7.4%. Similarly 4.7% of Wheat and 16.0% Maize is produced in the province (MoF; Economic Survey 2076/77).

According to the National Sample Census of Agriculture 2010/11 there are 163926.7 ha of arable land in the province. According to the irrigation department, only 11.6% of the provincial area is useful for agriculture. Out of this area only 45.88% agriculture land is under various irrigation systems i.e. 55% of the provincial agriculture is based on monsoon rain.

According to the Economic Survey 2076/77, 38568 small and cottage industries are registered under the department of industry in the province empowering approximately 269,590 people. There are 12539 companies registered under the company act in the province.

11298 km of road were constructed in the Province. Out of which 9370 km is blacktopped.

3.1.4 Geology

Geologically the formation of the Himalaya is dynamic due to the active lithospheric plate. Nepal lies within Himalaya with the same origin. The Indian plate in the South and Eurasian plate in the north started to collide with each other about 45 million years ago. As a result, the land under the bottom of the Tethys Sea buckled in the form of Himalaya or ultimately Himalaya originated. With a catastrophic event of upliftment ages long Tethys Sea located in between these two landmasses disappeared. The collision process is still active which is associated with the fragile geological structure of the Himalaya. The dynamics of the collision of these mega plates underneath the earth surface of this geographical part of the world is basically connected with the fragile environmental character of the Himalaya. Geologically young and tectonically active Himalayan Range is characterized by highly elevated mountains and deep river valleys.

Nepal occupies the central sector of Himalayan

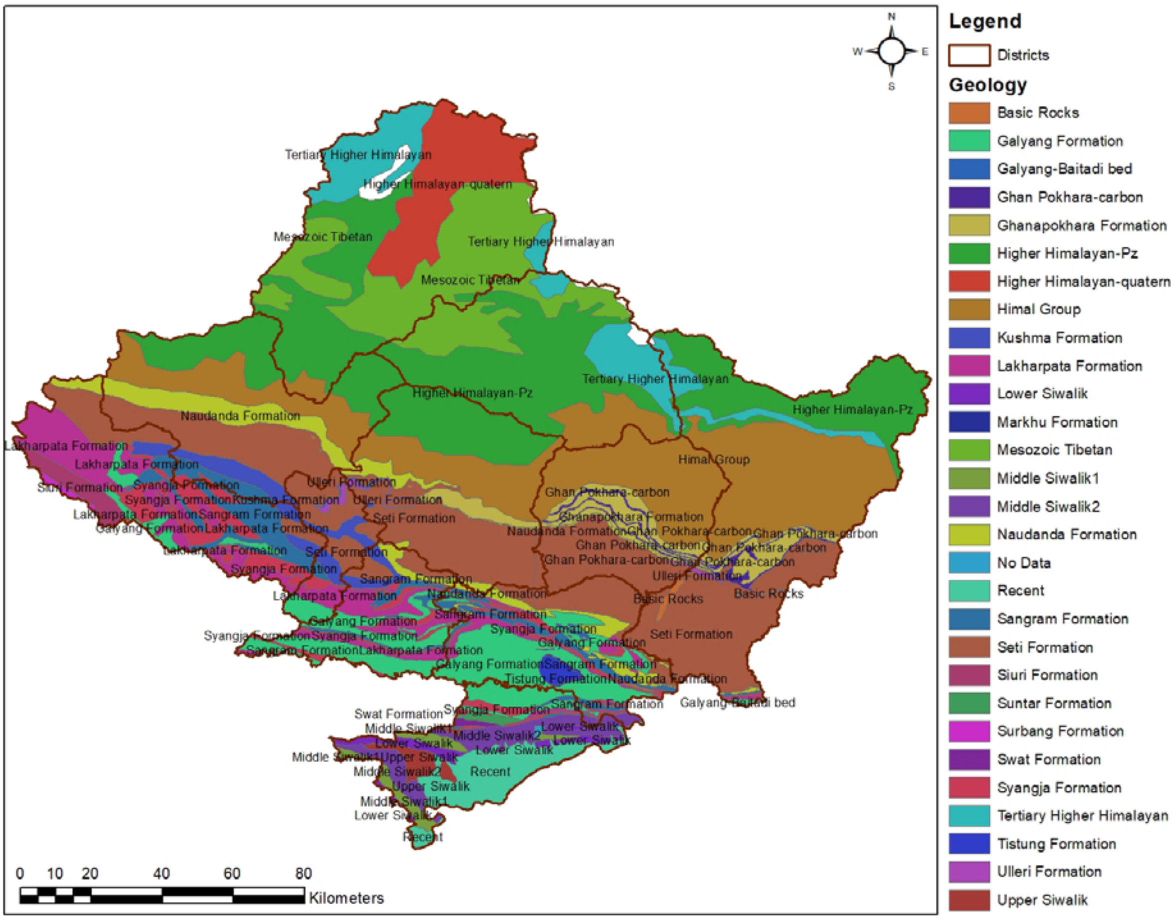


Figure 2 Geological Map of the Gandaki Province

arc. Nearly one third of the 2400 km long Himalayan range lies within Nepal. Similar to other parts of the Himalaya, from south to north, Nepal can also be subdivided into the following five major tectonic zones.

i. Gangetic Plain

ii. Sub-Himalayan (Siwalik) Zone

iii. Lesser Himalayan Zone

iv. Higher Himalayan Zone

v. Tibetan-Tethys Himalayan Zone

Each of these zones is characterized by diverse lithology, tectonics, structures and geological history. These alltectonic zones are separated from each other by the thrust faults. The southernmost fault, the Main Frontal Thrust (MFT) separates the Sub-Himalayan (Siwalik or Chure) Zone from Gangetic Plains. The Main Boundary Thrust (MBT) separates the Lesser Himalayan Zone from Siwalik. The Main Central Thrust (MCT) separates the Higher Himalayan Zone from the Lesser Himalayan Zone. The South Tibetan Detachment System (STDS) marks the boundary between the Higher Himalayan Zone and the overlying fossiliferous sequence of the Tibetan-Tethys Himalayan Zone. The Indo-Tsangpo Suture Zone is the contact knot between Indian plate and Tibetan (Eurasian) Plate in terms of plate tectonics.

3.1.5 Gangetic Plain or Terai

The Gangetic Plain is also called the Terai zone and the Nepalese portion of the Gangetic Plain that extends from the Indian border to the Foothill of Chure area in the North. To the north, this zone is separated by an active thrust system called the Main Frontal Thrust (MFT) with Chure around the North end of Terai and east-west extension along the foothill of Chure.

3.1.6 Sub-Himalayan (Siwalik or Chure) Zone

The Sub-Himalaya Zone is also called as Siwalik or Chure zone in Nepal and is delimited on the south by the Main Frontal Thrust (MFT) and on the north by the Main Boundary Thrust (MBT). It consists basically of fluvial deposits of the Neogene age (23 millions years to 1.6 millions years old). This zone extends all along the Himalaya forming the southernmost hill range with a width of 8 to 50 km. The Lesser Himalayan (Mahabharat and Midhill range) rocks thrust southward over the rocks of Chure along the MBT. The general dip of beds of Chure has a northward trend with varying angles and the overall strike is east-west. The Chure zone has a number of east-west running thrusts. Chure zone is also rich with fossils. Fossils of plants, pisces, reptiles and mammals (Carnivora, Proboscidea, Artiodactyla, Rodentia and Primates) have been reported from Chure. The three-fold classification of Siwalik in Potwar region of Pakistan and western Indian Himalaya was freely applied to the equivalent Chure of Nepal from the beginning of the geological studies in Nepal.

3.1.7 Lesser Himalayan Zone

The western Nepal Lesser Himalaya, lying between the Marsyangdi-Narayani and Bheri Rivers, is generally free from crystalline nappes and exposes the sedimentary and metasedimentary rock sequences in a wide zone between the MBT and the MCI Geologically, the area is complicated by the presence of a number of folds, thrusts and imbricate zones. Despite the complicated geology, excellent studies have been carried out in recent years on the stratigraphy of this region. However, individual work has been confined in areas separated by wide intervening parts that are not as well studied. Many researchers have proposed different stratigraphic nomenclatures in their respective study areas, and their stratigraphic subdivisions do not always correspond well with each other. Therefore, confusion and uncertainties have remained in the stratigraphic interpretation of the western Nepal Lesser Himalaya. An attempt has been made here to appraise and synthesize the work done so far to bring out a clearer picture of the problems and prospects in the stratigraphic investigations in western Nepal.

The Lesser Himalayan zone is bounded to the north by the Main Central Thrust (MCT) and to the south by Main Boundary Thrust (MBT). MBT can be traced out in the whole Nepal Himalaya and it can be also well observed in aerial photographs also. The rocks of Lesser Himalayan Zone in the Gandaki province can be correlated with Kunchha formation and Nuwakot complex of Central Nepal rock sequences. The central part of the Lesser Himalaya of Gandaki province comprises Kuncha formation rocks mostly and the southern, western and the northern part has Nuwakot complex rock. The both sequences of the Lesser Himalaya mainly have unfossiliferous, sedimentary, and metasedimentary rocks such as slate, phyllite, schist, quartzite, limestone, dolomite, etc, ranging in age from Precambrian to Eocene. There are also some granitic intrusions in this zone.

3.1.8 The Higher Himalayan Zone

The Higher Himalayan zone mainly consists of huge piles of strongly metamorphosed rocks. Geologically, the Higher Himalayan Zone includes the rocks lying north of the Main Central Thrust (MCT) and below the highly fossiliferous Tibetan-Tethys Zone. This zone is separated from the Tibetan-Tethys Zone by a normal fault system called the South Tibetan Detachment System (STDS). Higher Himalayan Zone consists of an approximately 10 km thick succession of strongly metamorphosed coarse grained rocks. It extends continuously along the entire length of the country as in the whole Himalaya, and its width varies from place to place. The kyanite - sillimanite minerals bearing gneisses, schists, and marbles of the zone form the basement of the Tibetan-Tethys Zones. Granites are found in the upper part of the unit (Dahal et al 2020). The Higher Himalayan zone on Gandaki province has two mica gneiss garnet biotite gneiss augen gneiss kyanite-biotite gneiss garnetiferous mica schist migmatites and thin band of marble rocks (DMG 1983).

3.1.9 The Tibetan-Tethys Zone

The Tibetan-Tethys Himalayas generally begins from the top of the Higher Himalayan Zone and extends to the north in Tibet. In Nepal these fossiliferous rocks are well developed in Thak Khola (Mustang), Manang and Dolpa area. The Himalayan peaks of this province such as Manaslu, Annapurna, and Dhaulagiri have rocks of Tibetan-Tethys Zone. This zone is composed of sedimentary rocks, such as shale, limestone, and sandstone.

The area north of the Annapurna and Manaslu ranges in central Nepal consists of metasediments that overlie the Higher Himalayan zone along the South Tibetan Detachment system. It has undergone very little metamorphism except at its base where it is close to the Higher Himalayan crystalline rocks. The thickness is currently presumed to be 7,400 m.

3.2 Major Faults

The active faults are the major trigger to develop the landslides because of its movement during the seismic event and plate tectonic movement. The major geological unit separators are the thrusts; these are the low angle reverse faults. During the time of the formation of Himalayas in the northern part of Nepal three fault lines were formed in the province and they are:

1. Main Central Thrust (MCT)

2. Main Boundary Thrust (MBT)

3. Main Frontal Thrust (MFT)

The Main Central Thrust is extended to the south western part to east west of Baglung district and the Main Boundary Thrust is extended from the northern part of Nawalpur district up to Devchuli and Bhadchuli of Mahabharat range. There is a long fault line which has created anticline and syncline in Myagdi, Kaski, Lamjung and Gorkha which falls in Central Thrust. The dynamics of plate movements together with diverse geological conditions and high degree of topography change in the Gandaki province have contributed to the evolution of geological hazards, most prominently earthquake, landslides, floods, soil erosion and debris flow. Apart from this the high rate of glacier melting due to global warming has posed a serious threat of Glacial Lake Outburst as well. However, the amount of risk of all these hazards is not the same throughout the province.

Besides these major thrusts, there are few active faults as shown in Figure 3 above, Northern side of the province in Higher himalaya to Tethys himalaya zones and few on western part and the eastern part of the province. The continuation length of these faults varies from 25 km to 150 km. Most of the active faults extended towards east-west direction except few north-south extensions. These fault lines exhibit the probability of landslides if a driver or trigger event has occurred.

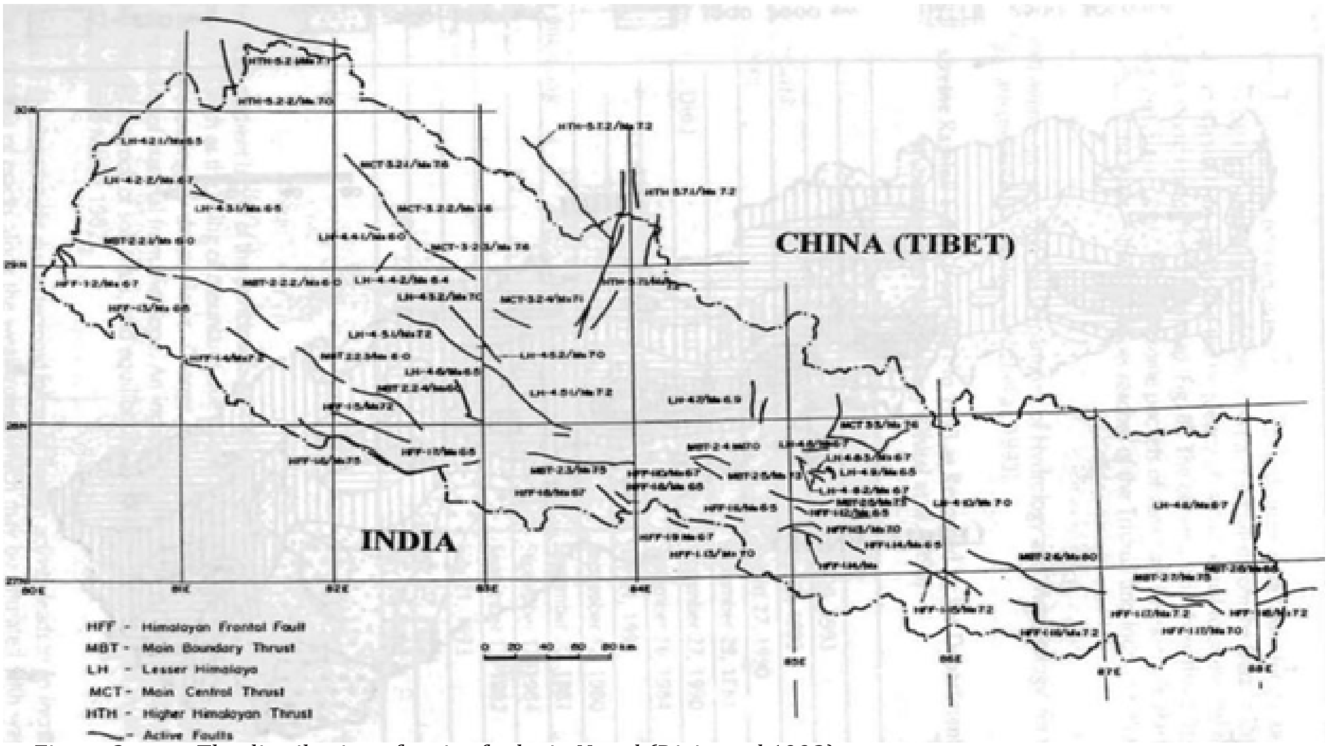


Figure 3 The distribution of active faults in Nepal (Dixit et al 1993)

3.3 Environmental Data

3.3.1 Topography

Topographically the altitude of the Gandaki province extends from 104 m (Tribeni) to 8167 m (Mt. Dhaulagiri) above sea level. It has unique landscape having Terai, Siwalik, Hills, Middle mountain, and High mountain. On this basis the province is divided into different physiographic zones as below (Figure 4).

Terai and Inner Terai: Terai and Inner Terai lie to the south of this province. It covers an area of 812.22 sq.km. The lowest point in Tribeni lies about 104m and 300 m above sea level. This region is formed with fertile alluvial soil deposited by the rivers. The major places in this belt are Gaindakot, Pragatinagar, Dumkibaas, Kawasoti, Chourmara etc.

Churia/Siwalik: To the south and west of Lumbini province lies the Churia range. This region is believed to have formed during the time of the formation of the Himalayas. Its altitude extends from 300m – 600 m above sea level. The third grade rivers like the Ombara, the Raipur, the Madari, the Chukarung, the Motiya, the Khor, the Sisini streams flow to this region.

Hill (Mahabharat range): Hill regions is located in between Churia and Mid Mountain. It ranges in altitude from 600m to 1200m above sea level. The regular tectonic movements leads to the increase of height of the Himalayas this region is formed by the deposition activities of the rivers like the Kaligandaki, the Madi, the Daraundi, the Setigandaki and so on.

Mid Mountain: Mid Mountain lie in the middle of the Gandaki province. This belt lies in the southern part of Himalaya mountain. The altitude varies from 1200m to 3300 m above sea level. The second grade rivers originating from the Mahabharat range like the Vijaypur, the Suraudi, the Harpan, the Rudi, the Iindhi, the Medium, the Arun, the Chepe etc drains this region. The hills above 2500m like the Devchuli, the Badchuli and the Panchase lie here which attract thousands of tourists every year.

High Mountain: The high mountains lie above 3300m above sea level. The highest part of

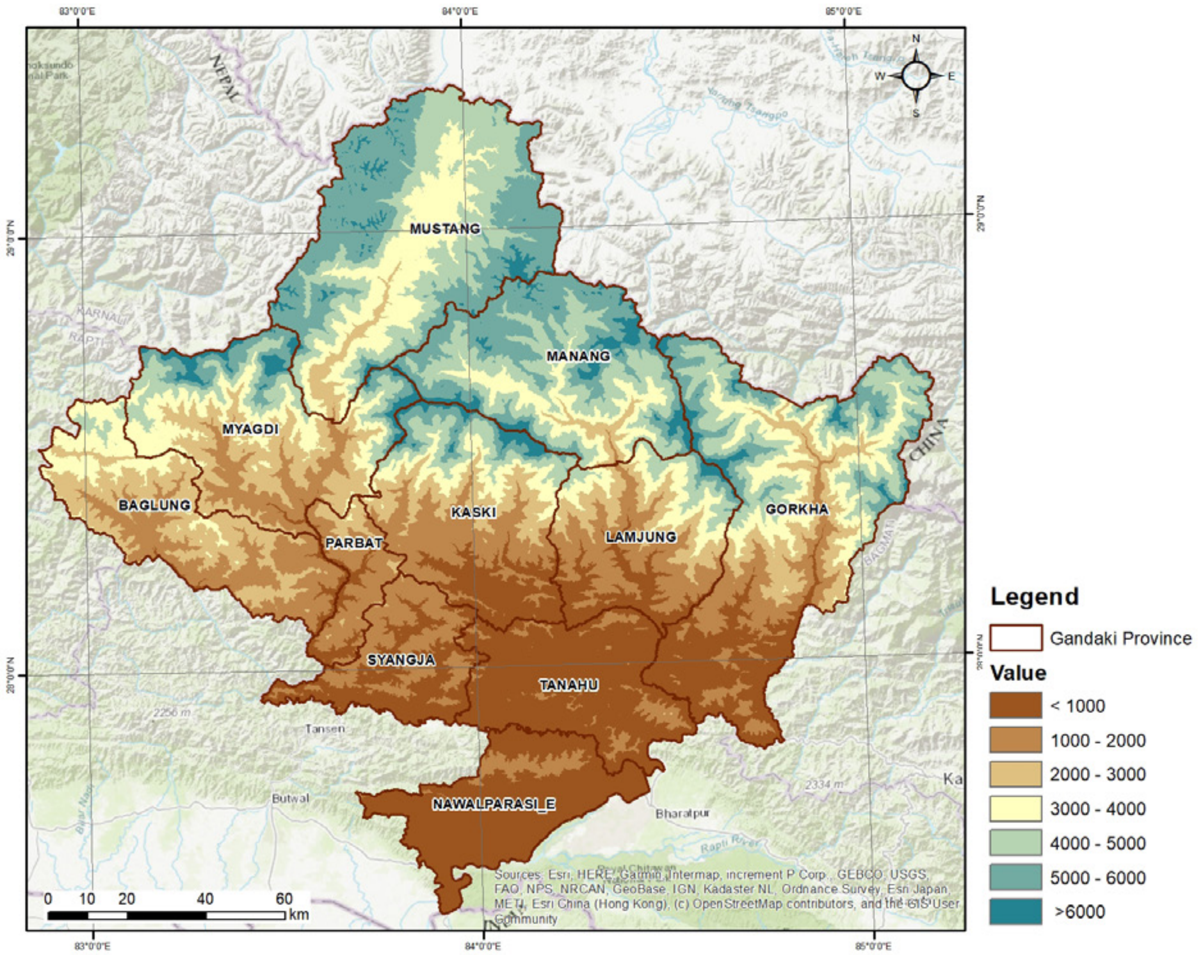


Figure 4 Elevation zones for Gandaki Province (Data: USGS SRTM DEM)

Gandaki province is known as the main Himalaya. It extends upto 8167m above sea level. This region is covered with snow all year round. There are 3 mountain peaks above 8000m which are Dhaulagiri (8156m), Manaslu (8156m) and Annapurna I (8091m). Apart from this the important mountain peaks are Annapurna II, Annapurna III, Annapurna IV, Gangapurna, Lamjung Himal, Mardi Himal, Himalchuli, Churen, Nilgiri north, Mid Nilgiri, Nilgiri South, Ganesh etc.

Bhot Valleys: In between the Marginal Himalaya and Main Himalaya between 3300- 5000m lies the Bhot Valleys. It covers an area of 2429.75 sq.km, which is 11.04 percent of the total area of the province. This valley extends in Manang and Mustang and up to Gorkha. This region lies in the rain shadow area and the temperature is low during winter and the precipitation is in the form of snow. The villages like Muktinath, Jhong, Cusang, charang, lomanthang, ghami, Choser, Chondup of Mustang, Humde, Pisang, Naar, Nogru, Fu of Manang and Larkebazar, Samdo, Logaun, Niigaun are the major villages of Gorkha located in this valley.

Marginal Himalay or Boarder Himalaya: Marginal Himalaya lies to the extreme northern part of the Gandaki province in boarder of Tibet. Its altitude varies from 5000- 7000m above sea level. It covers an area of 2375.57 sq.km which is just 10.79 percent of the total area of the province. This region spreads in the northern part of Mustang, Manang and Gorkha district. The famous Korala pass which is going to be the main entrance to this province from China, lies here.

3.3.2 Elevation

Elevation zones of the province are identified based on Digital Elevation Model data from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/). The elevation covering the province is derived by applying ArcGIS software and illustrated with in Digital elevation model with contour lines of 500 meters.

3.3.3 Slope Map

Slope (Sl) indicates the degree of inclination (angle in degrees) of the surface and shows the rate of elevation change. It helps to explain

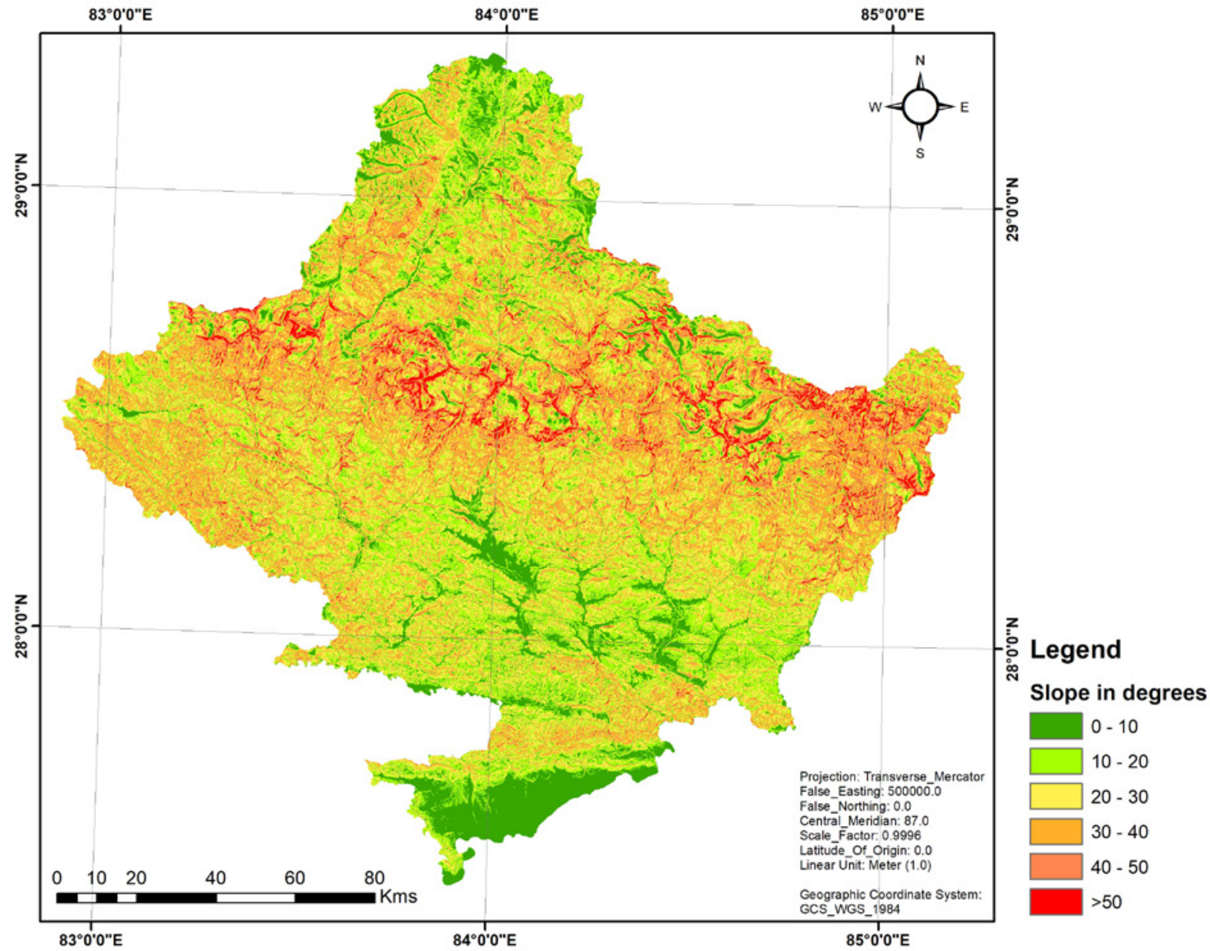


Figure 5 Slope Map of Gandaki Province

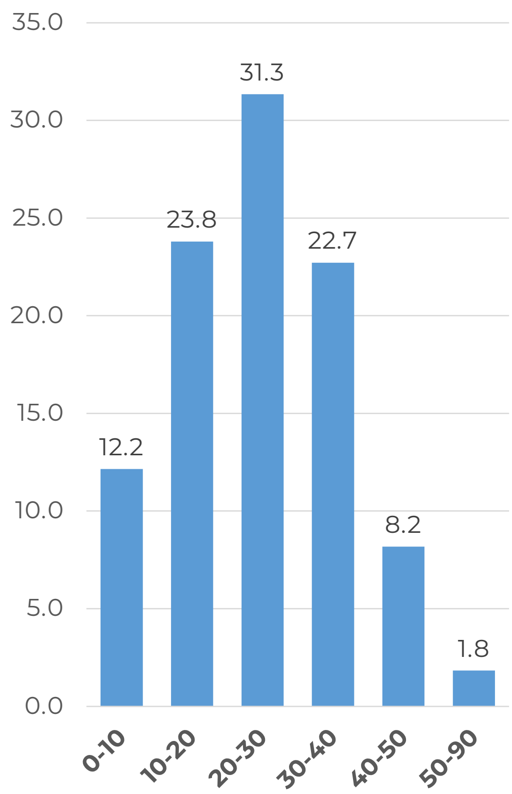


Figure 6 Distribution of Slope Class

the movement under gravity, flow of water, soil profile and vegetation as well. Drainage is highly affected by slopes and steep slopes reduces infiltration. Slopes are also the result of many geomorphological processes and can be related to hydrological processes as well.

3.3.4 Climate

The climate of Gandaki Province along with Nepal is affected by two major weather systems, summer monsoon circulation (June to September) and westerly circulation (November to May). The influence of these two circulation systems is different, with summer precipitation greater in the southeast and westerly-derived winter precipitation greatest in the northwest. Gandaki Province as a whole receives approximately 80 % of its annual precipitation during the summer monsoon.

3.3.5 Mean Precipitation

The highest rain occurs when the monsoon comes from the Bay of Bengal. The western disturbances during the winter season affects

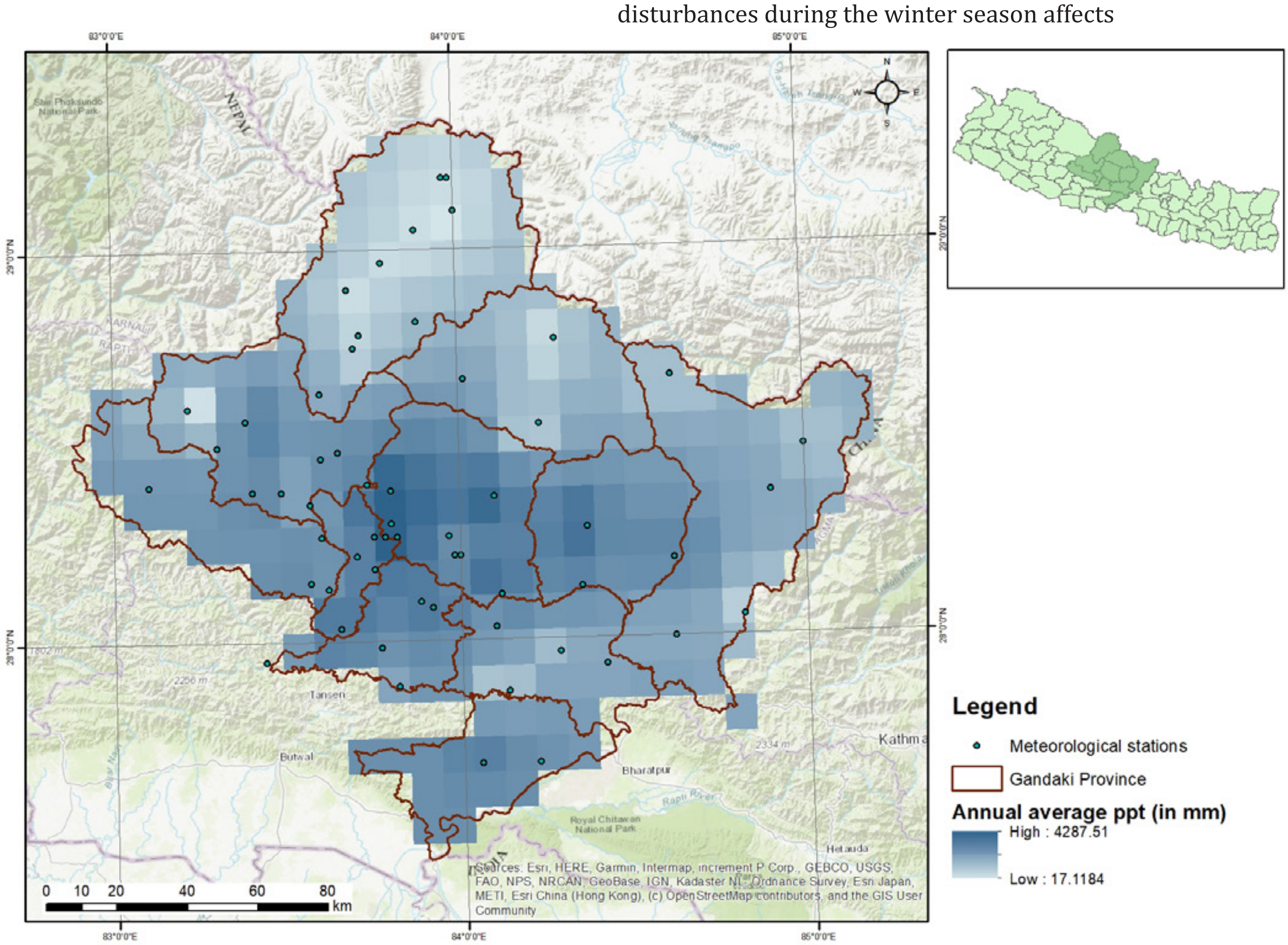


Figure 7 Annual Precipitation interpolated for 51 stations in Gandaki province of Nepal

mostly the western parts of the country and results in snowfall in the high mountains and the Himalayas. The interaction of the complex topography with monsoon and westerly weather systems results in high variation in spatial distribution of precipitation. The windward side of the mountains receives more precipitation while the leeward side receives less. The mean annual precipitation of Gandaki province was found to be around 1800mm with the highest annual precipitation recorded in Lumle of Kaski District with mean annual precipitation of about 5500mm. The lowest precipitation site is recorded in the Lomanthang area of Upper Mustang, Mustang District with mean annual precipitation of less than 150mm. Both of these highest and lowest precipitation sites of the Gandaki Province especially in Annapurna Conservation Area.

3.3.6 Mean Temperature

In Gandaki Province, temperature is lowest during winter (December - January) and increases as spring advances due to increase in solar insolation. However, the arrival of monsoon rain checks the increase in temperature making generally May or early June the hottest months. The temperature starts decreasing from October and reaches the minimum in December or January. Temperature is directly related to season and altitude of the location. The hottest part of the province is the Southern belt and the coldest part lies in the high mountain or the Himalayas in the north.

3.3.7 Landcover Map

Land cover in Gandaki province has 32.8% Dense forest cover which is mainly in the Siwalik, Mahabharat range and Mid- mountains. 18.9% of agriculture land in the province suggests low density of human intervention in the province as majority of the land of the province is mountainous which is also corroborated by the coverage of 16.3% snow.

As per the NDVI analysis for Sentinel 2 Imageries of April 2020 (Most recent cloud free scene), 30% of the area in Gandaki province lacks vegetation, which is mainly the grey shaded region in Figure 10 that includes majority of Manang, Mustang

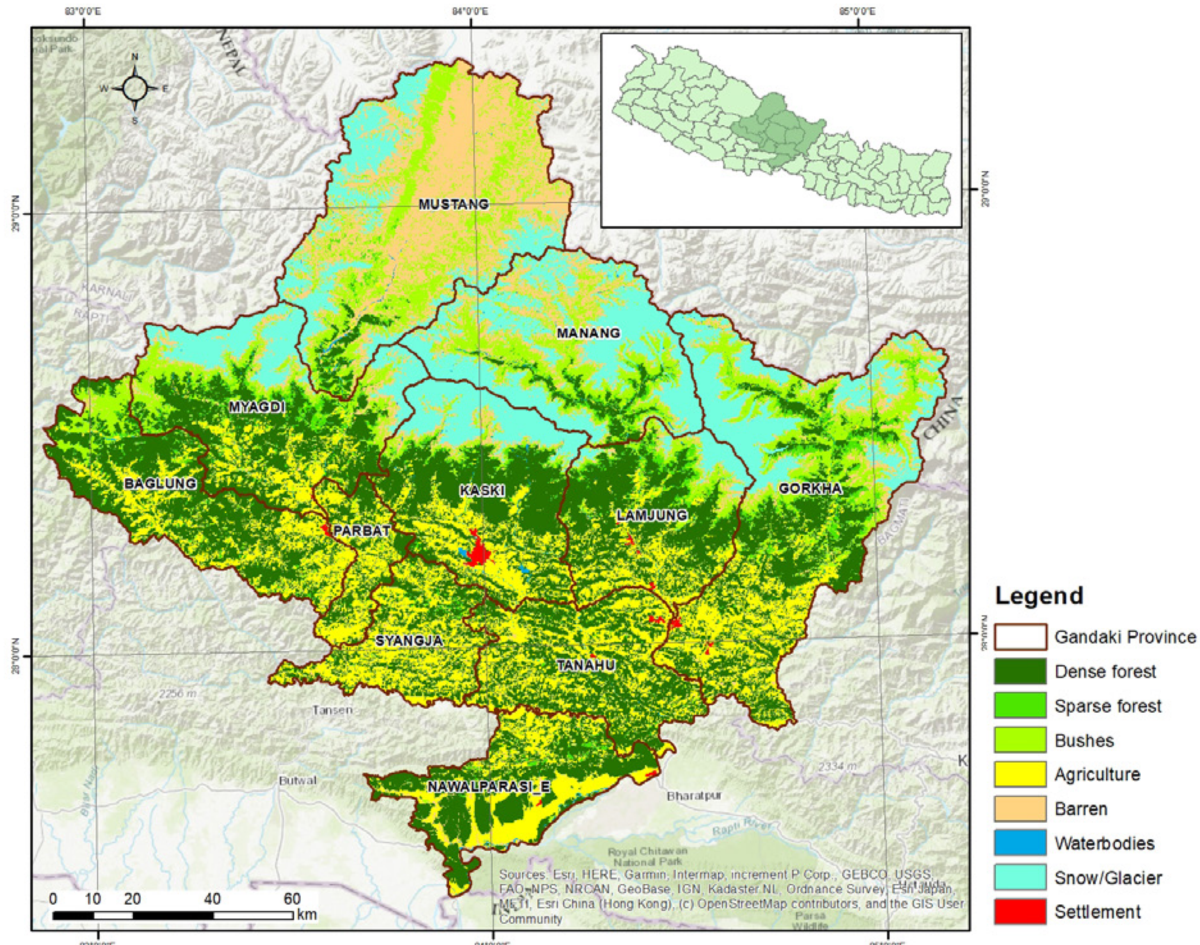


Figure 8 Land Cover map for 2010 of Gandaki Province in Nepal

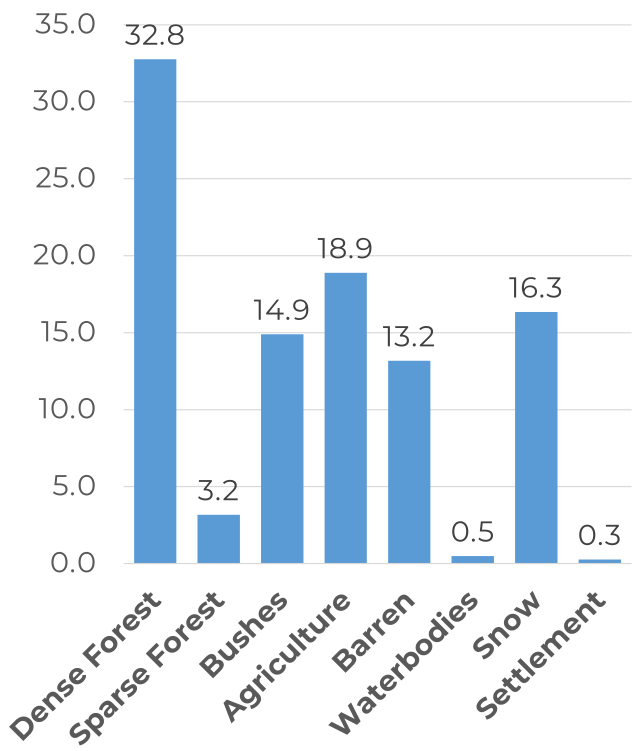


Figure 9 Land Cover districbution by % cover

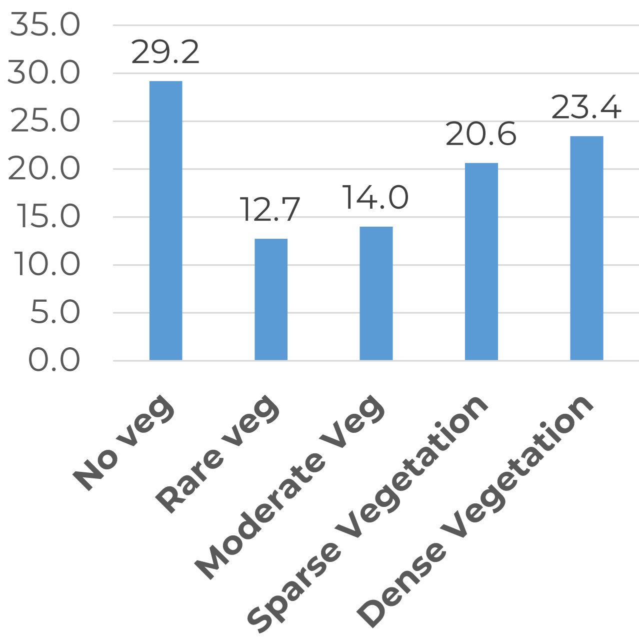


Figure 10 NDVI based on Sentinel 2 –April 2020

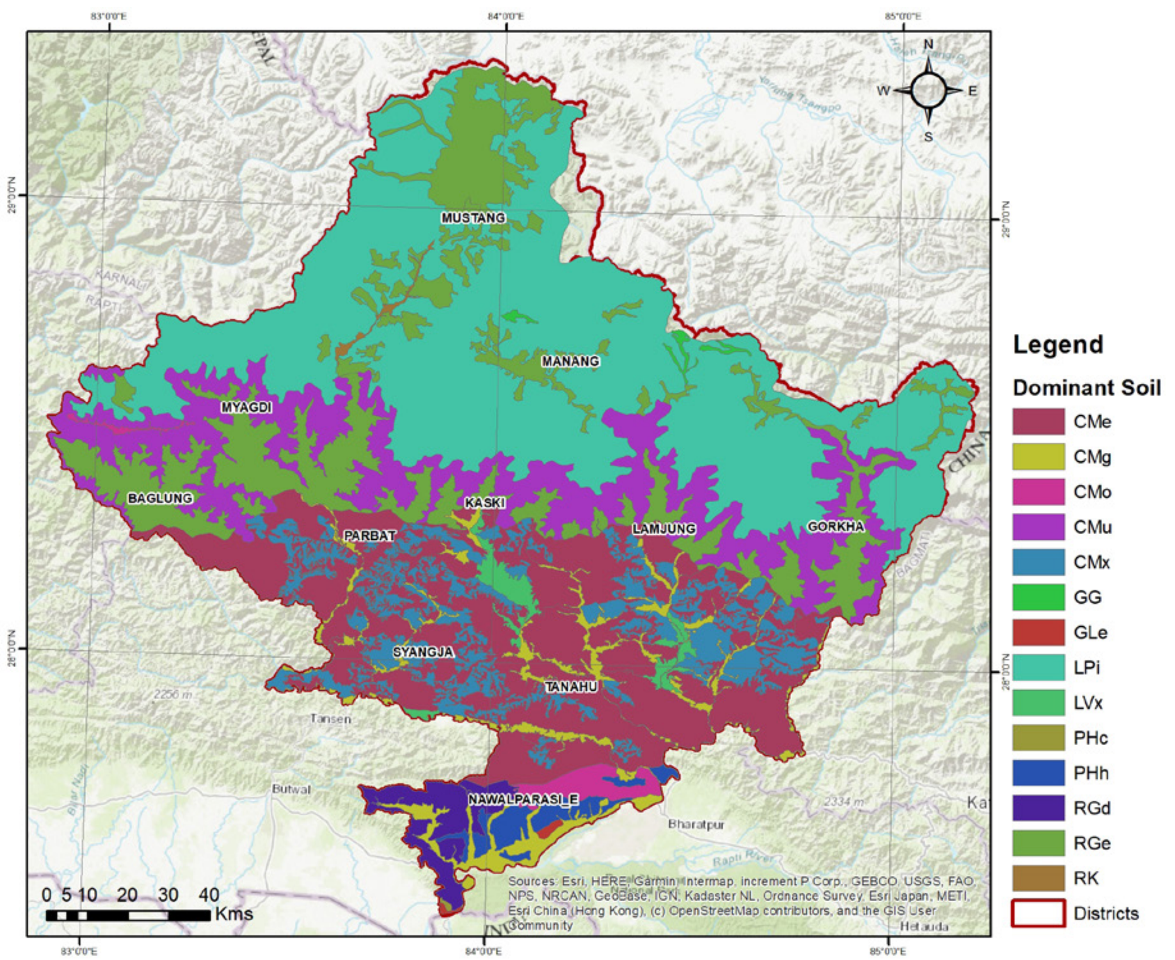


Figure 11 Dominant soil type in the Gandaki province

and high mountains.

3.3.8 Soil Map

Soil map is a geographical representation showing diversity of soil types and/or soil properties (soil pH, textures, organic matter, depths of horizons etc.) in the area of interest. [1] It is typically the end result of a soil survey inventory, i.e. soil survey. Soil maps are most commonly used for land evaluation, spatial planning, agricultural extension, environmental protection and similar projects.

3.4 Data Collection

3.4.1 Primary Data Collection

The primary data collection in this study was conducted by collecting data related to soil erosion and landslides. As the study is mainly GIS and Remote sensing based, most of the primary data are mased on geographic data acquired from Department of Survey, Government of Nepal. Google Earth Based survey of Landslides is a major part of the study.

Field study for landslide observation, delineation, was conducted during May, June months of 2021.

3.4.2 Secondary Data Collection

Satellite images and GIS layers were acquired from various sources as mentioned below:

Table 1 Data collected and sources

Data	***Description***
Sentinel 2 Satellite Image	The satellite data that we used in this study were derived from the Sentinel-2 MultiSpectral Instrument (MSI), and were acquired from April 1 to April 30, 2021. Sentinel-2 is a high-spatial resolution (10 m), mul-ti-spectral constellation, used for monitoring of vegetation, soil and water cover.
Soil Data	Soil type, Organic Matter, clay %, Sand % and Silt % rasters from NARC
Rainfall Data	Annual rainfall data for 51 stations in Gandaki province from DHM
DEM	SRTM, USDA 30m Digital Elevation Model
Landslide data	Disaster inventory from GoN, Global Landslide catalog- NASA
Landslide inventory	Disaster inventory from GoN
Geology Data	Spatial map from Department of Mines, GoN

4. Erosion Modeling

4.1 RUSLE Model

The RUSLE model, which is the most widely applied empirical model, was adopted for this study. The essential supposition in the RUSLE model is that detachment and deposition are governed by the sediment load of the runoff. Soil erosion is limited by the transporting capacity of the flow instead of lack of materials eroded from the sources. If the sediment load of runoff exceeds the transporting capacity of the flow, soil detachment can no longer take place (Ganasri and Ramesh 2016).

Soil erosion can be estimated using empirical or physically based models. Empirical soil erosion models include the Universal Soil Loss Equation (USLE). The empirical RUSLE model remains the most popular tool for assessing water erosion hazards due to its modest data demands and easily comprehensible model structure, especially in developing countries where the possibilities for applying more complex models are often limited by a lack of adequate input data. In recent decades, RUSLE and its adapted versions have been applied worldwide in different regions and at different spatial scales. The RUSLE-GIS interface has several advantages in terms of easy updating, integration of spatially referenced data, and the facility to present the mapping results in different forms. A number of studies have shown good results using RUSLE together with GIS methods and RS data to model soil erosion.

However, the model only addresses rill and interrill erosion induced by the impacts of raindrops and surface runoff without accounting for other forms of erosion such as gully development and sliding of lands (Renard et al. 1997). Moreover, the RUSLE model has the tendency to overestimate soil loss for a higher range of slopes and heterogeneous landscapes (Renard et al. 1991).

USLE and RUSLE are widely used to estimate rill erosion on overland flow areas. The equations use a combination of geophysical and land cover factors to estimate the likely annual soil loss from a unit of land. RUSLE was used to assess the spatial patterns of erosion risk in the study area. Recent advances in GIS and remote sensing technology have enabled a more accurate estimation of the factors used in the calculation. Each of the factors was derived separately in raster data format and the erosion calculated using the map algebra functions.

RUSLE is expressed as:

A = R x K x L x S x C x P ……… (i)

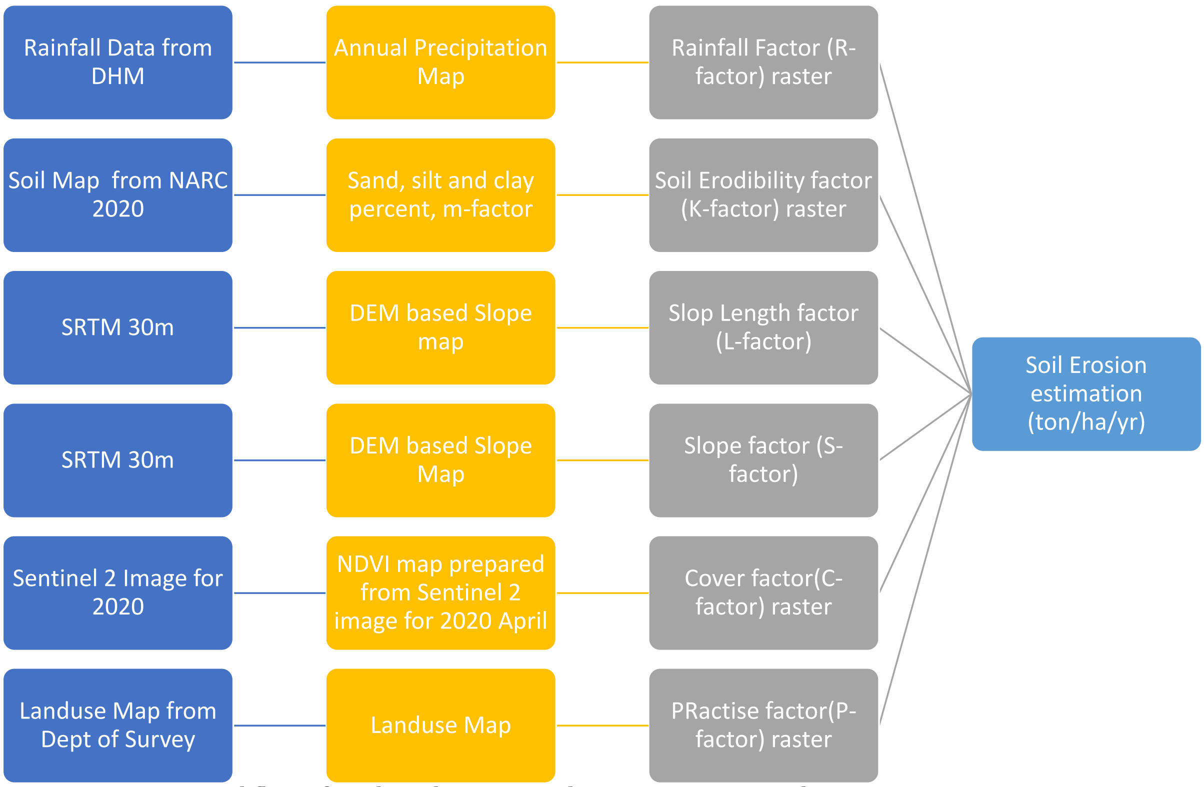


Figure 12 Workflow of GIS based RUSLE application in ArcGIS and QGIS

where,

A = the estimated average annual soil loss (ton per ha per year);

R = the rainfall and runoff erosivity index. This describes intensity and duration of rainfall in a given geographical area. It is the product of the kinetic energy of raindrops and the maximum 30-min intensity. [MJ mm ha^{-1} h^{-1} $year^{-1}$]; derived from daily precipitation data;

K = the soil erodibility factor (measured in [ton ha h MJ^{-1} mm^{-1}]) is derived from information on soil types;. K is related to soil physical and chemical properties that determine how easily soil particles can be dislodged. It is related to soil texture, aggregate stability, and soil permeability or ability to absorb water. It ranges from 1 (very easily eroded) to 0.01 (very stable soil).

LS = a dimensionless topography factor determined by length and steepness of a slope. The LS factor is related to the velocity of runoff water. Water moves faster on a steep slope than a more level one, and it picks up speed as it moves down a slope. Therefore the steeper and longer the slope, the faster runoff water will flow. The faster water flows, the more kinetic energy it can impart to the soil surface.

C = the cover and management factor derived from LULC classification of satellite image data; Cover of any kind can help protect the soil surface from raindrop impact and can force runoff water to take a longer, more tortuous path as it moves downslope, slowing the water and reducing its kinetic energy.

P = the factor for supporting practices (dimensionless) is derived from field observation and literature. This factor takes into account specific erosion control measures. Erosion control practices reduce the P factor.

4.2 GIS Based RUSLE

GIS based RUSLE method is robust method using computer application for the analysis of spatial parameters for soil erosion estimation. It applies the spatial data on rainfall factor, soil erodibility factor, length- slope factor, conservation factor and management practice factor to generate spatial raster of erosion estimation.

4.3 Factor Maps

The various RUSLE factor maps were generated in a digital GIS environment using ArcGIS 10.8, QGIS 3.8 and Google Earth Engine, and the associated GIS packages. These factor maps were integrated employing the RUSLE model to compute annual soil erosion rates and its severity. All the inputs for RUSLE model execution were generated in the GIS platform using remote sensing and field collected information. The various factor maps were generated and converted into raster format keeping uniform projection as well as cell size, to avoid erroneous execution and misinterpretation of results.

4.3.1 R factor (Rainfall Erosivity Factor)

The R factor is a measure of the erosive force of specific rainfall. It quantitatively expresses the erosivity of local average annual rainfall. R-factor computation requires long-term data of rainfall amounts and intensities. Since rainfall intensity of the study area could not be estimated in the absence of a recording type rain gauge, well established empirical equations using total rainfall (monthly, seasonal or annual) are widely employed. R factor was estimated using the rainfall data of the past 10 years (2011-2020) obtained from DHM for 51 stations in the province using empirical relationships.

R=38.5+0.35P (Morgan 1985); Where, P: Average Annual Rainfall (mm)

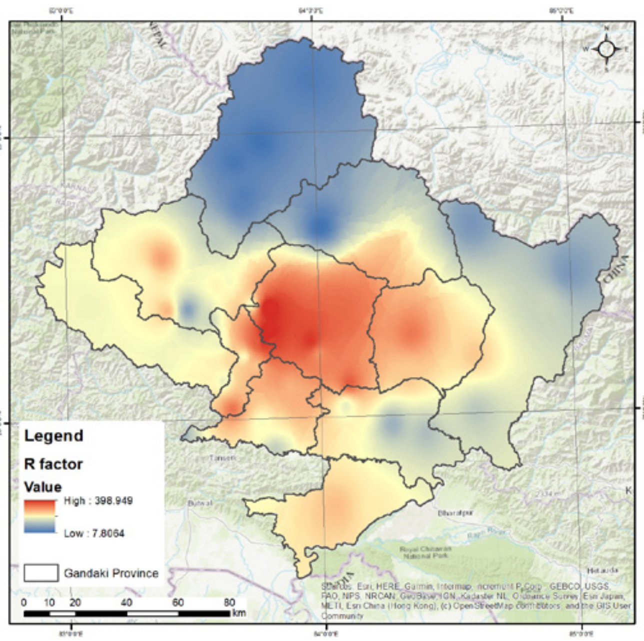


Figure 13 R factor map prepared for RUSLE estimation

4.3.2 K factor

Soil erodibility factor (K) is a quantitative expression of the inherent susceptibility of soil to detachment and transport of soil particles (grains or crumbs), under an amount and rate of runoff for a specific rainfall, measured under standard plot. The erodibility factor depends on physico-chemical properties of texture, organic matter content, permeability of soil and soil structure. Physiographic soil map was generated by using Soil data rasters on clay%, sand%,silt% and organic matter content published by NARC in 2021. The following equation was used to compute K factor (Tiruwa et al. 2021)

K = 27.66 * m1.14 *10-8 * (12-a) + 0.0043 * (b-2) + 0.0033 * (c-3)

Where:

K = soil erodibility factor (ton .ha. h.ha-1.MJ-1.mm-1)

m = (Silt % + Sand %) x (100-clay %)

a = % organic matter

b = structure code: 1) very structured or particulate, 2) fairly structured, 3) slightly structured, 4) solid

c = profile permeability code: 1) rapid, 2) moderate to rapid 3) moderate, 4) moderate to slow, 5) slow 6) very slow

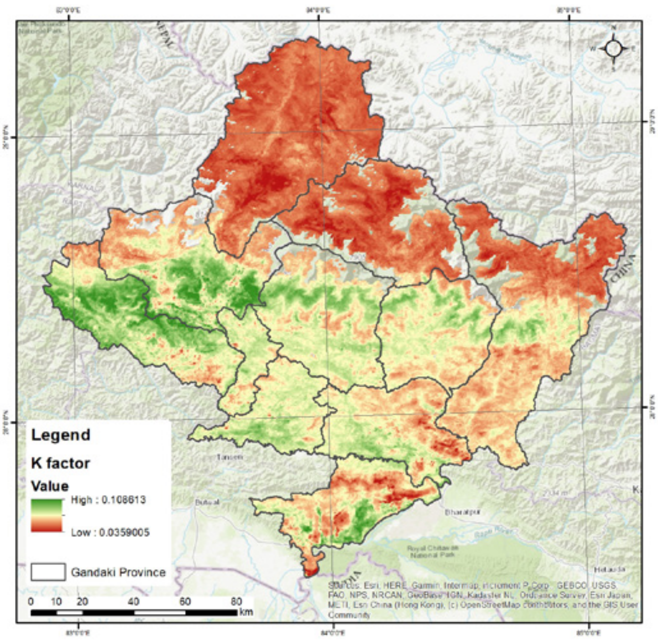


Figure 14 K factor map prepared for RUSLE estimation

4.3.3 LS factor (Slope Length and Steepness Factor)

The total erosion or sediment yield from a watershed depends not only on slope length but on steepness also. The LS factor expresses the effect of local topography on soil erosion rate, combining effects of both slope length (L) and slope steepness (S). Various other factors such as compaction, consolidation and disturbance of the soil were also considered in addition to steepness and length while generating the LS-factor. SRTM DEM with 30m resolution was used to compute LS factor using the spatial analyst and SAGA hydrology toolkits in QGIS software, following the method described by Moore and Burch (1986).

4.3.4 C factor (Crop Cover Factor)

C factor represents the effects of vegetation % and crop types on soil erosion (Renard et al., 1997). Its value ranges from 0 (water bodies) to 1 (barren land), because of the lack of vegetation,

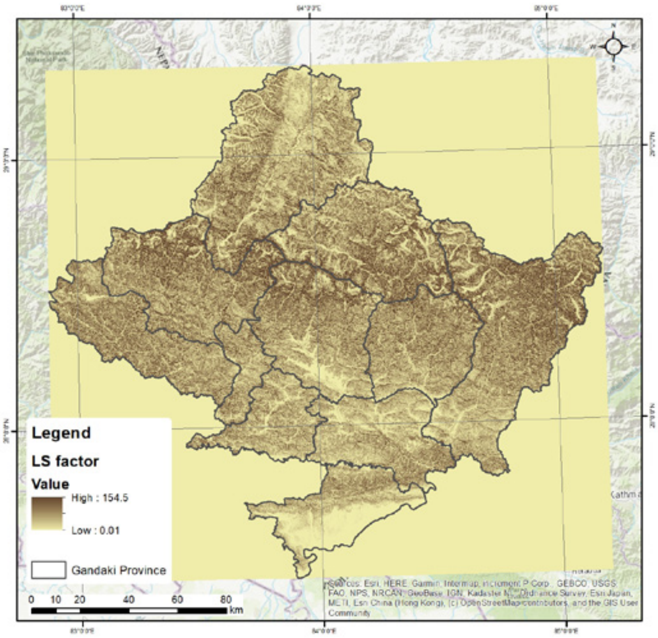


Figure 15 LS factor map prepared for RUSLE estimation

root biomass or other surface covers to resist soil erosion. Thus, it expresses the relation between soil erosion on bare areas and erosion observed under a particular cropping system and indicates the role played by cover-type as well as density on soil protection. The C factor thus incorporates the effects of plant cover, level of production as well as the various associated cropping techniques into one single value. In the study, C factor map was generated using the land use/land cover (LULC) map prepared by visual interpretation of satellite data. The boundaries of the various LULC classes were verified and corrected during the field survey. The major crops grown in the study area are rice, maize, wheat, fruit trees and various vegetables. Majority of the study area is dependent on rainfall as the sole water source for agricultural activities. Only very few areas, near the channels at low elevation, have irrigation facilities. Low input subsistence farming using local varieties, traditional farming practices and inputs is practiced in the entire area. The land use/land cover map was reclassified based on C factor values using tools in ArcGIS, which assigned C factor values based on as well as previous studies undertaken in similar regions including Himalayas (Uddin et al. 2018).

The values of C factor ranges between 0 and 1 in which higher values represent dense vegetation cover and vice versa (Koirala et al. 2019). The C factor was determined using the following table

Land Use	Cfactor
Forest	0.03
Agri	0.21
Shrub	0.21
Barren	0.45
Waterbody	0
Built up	0

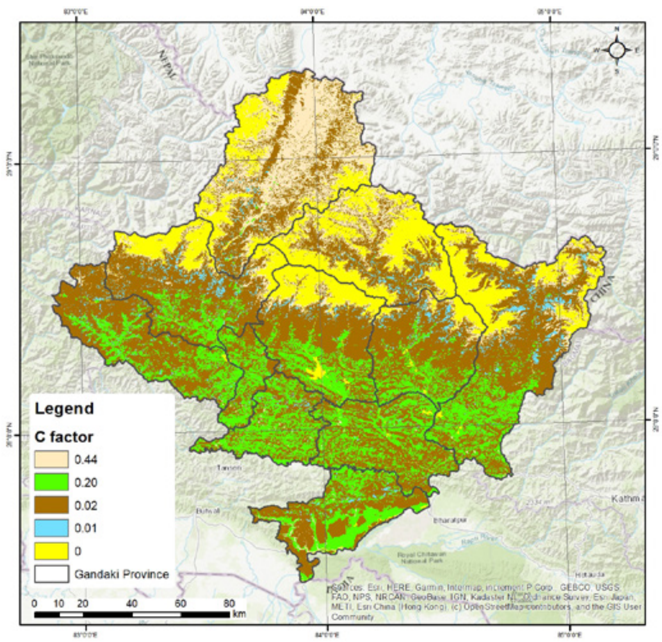


Figure 16 C factor map prepared for RUSLE estimation

4.3.5 P factor (Conservation Practice Factor)

The P factor represents the effect of various conservation and support practices being taken up in the study area, on soil erosion. The various practices normally reduce the amount and rate of runoff water by influencing drainage patterns, runoff concentration, runoff velocity and hydraulic forces exerted by runoff on soil, eventually reducing soil erosion. It includes the effect of various practices such as contouring, terracing, strip cropping, bunds etc (Hyeon and Julien, 2011). In the study area various management practices like terracing, bunding, grass bunding etc are followed by farmers depending on the slope steepness and resource availability. In this study, P factor map was generated using the land use land cover map by assigning P values for each of the land use land cover types (Koirala et al. 2019; Uddin et al. 2018).The map was reclassified based on P factor values using tools in ArcGIS, to yield P factor map in raster form.

Class	P -factor	LC Class
Dense Forest	1.0	1
Open forest	0.8	2
Water Body	1.0	6
Agriculture	0.5	4
Hill agriculture	0.8	4
Settlement	1.0	8
Fallow Land	0.9	3
Barren land	1.0	5

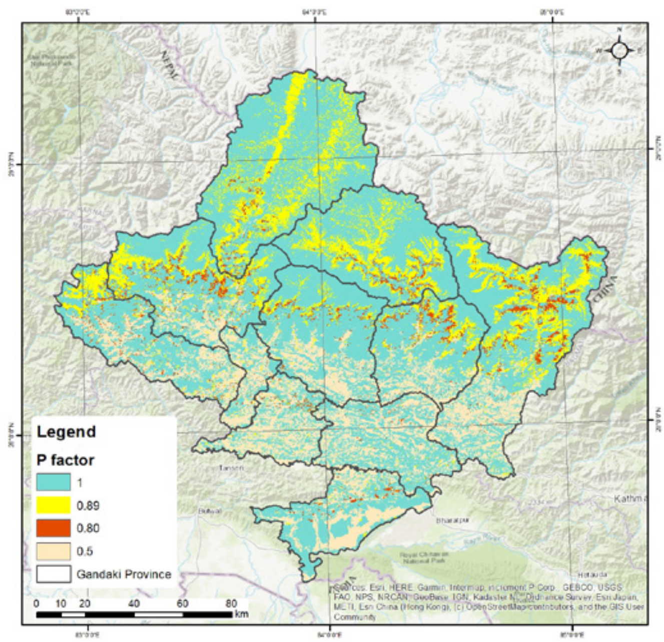


Figure 17 P factor map prepared for RUSLE estimation

4.4 Soil Erosion Estimation

Application of RUSLE model is efficient in estimation of Soil erosion based upon the predefined factors. The map shows Gandaki province with erosion density classes in tonnes per hectare per year. A maximum of 1120 tonnes per hectare per year of erosion was estimated in the province. The erosion rate is studied in different elevation, land uses and watersheds to determine the high erosion categories.

As per the RUSLE estimation method, the study estimates that from an area of 2.19 million hectare in Gandaki province, 14.24 million tonne of soil is lost every year. Among the 11 districts, Gorkha and Mustang have the highest weightage, as they are the largest districts. Manang has the highest average erosion rate due to high erosion ongoing in the landscape.

- Erosion weightage is total contribution of the district.
- Erosion weightage % can be affected by total area of the district.
- Average Erosion rate is average contribution of the district per unit area.
- Average Erosion rate % is not affected by total area of the district.

Manang has the highest average erosion rate due to high erosion ongoing in the landscape.

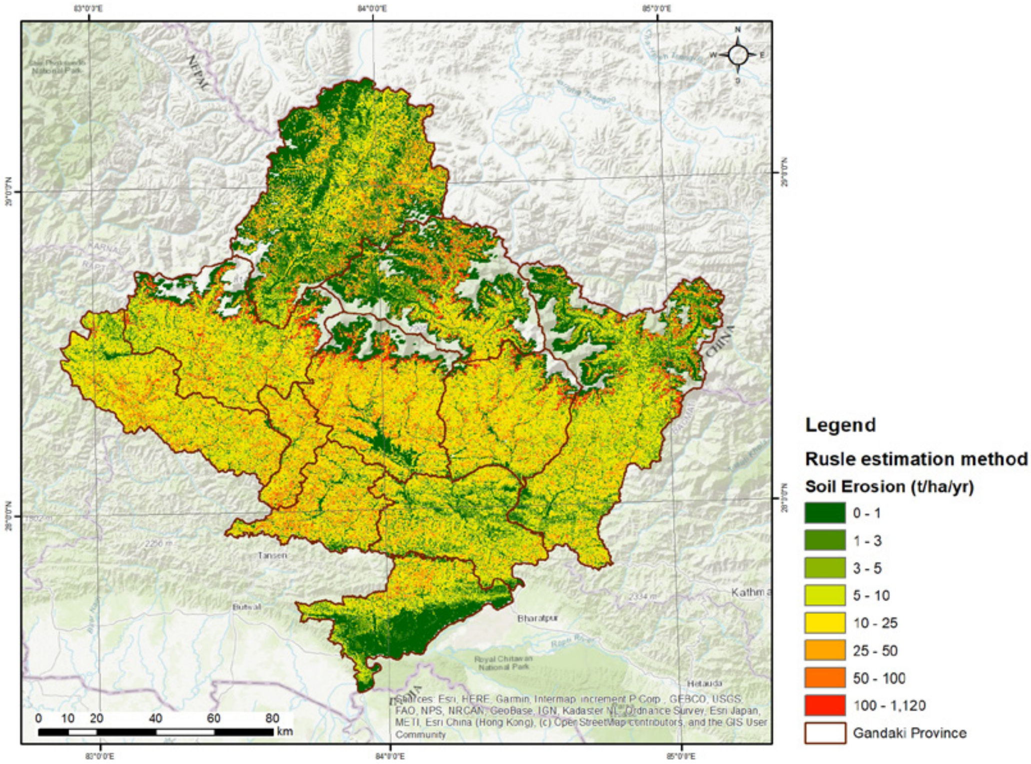


Figure 18 Soil Erosion estimation by GIS based RUSLE method in Gandaki Province

Table 2 Districtwise Erosion rate and weightage in Gandaki province

District	Average erosion rate (ton/ha/yr)	Total erosion (ton / yr)	Area (ha)	Erosion weightage (%)
Baglung	31.1	841183.2	183574.2	8.4
Gorkha	25.3	2482022.6	364586.6	16.6
Kaski	39.7	2139096.1	208437.6	9.5
Lamjung	32.3	1332599.2	166239.5	7.6
Manang	77.5	2194017.2	232060.4	10.6
Mustang	28.8	1146057.7	356343.8	16.2
Myagdi	44.6	2515760.2	228479.0	10.4
Nawalparasi east	7.9	276715.2	142582.5	6.5
Parbat	43.8	350343.1	54155.4	2.5
Syangja	36.7	563274.1	103747.8	4.7
Tanahu	15.9	400176.3	157184.2	7.2
		14241244.8	2197391.0	100.0

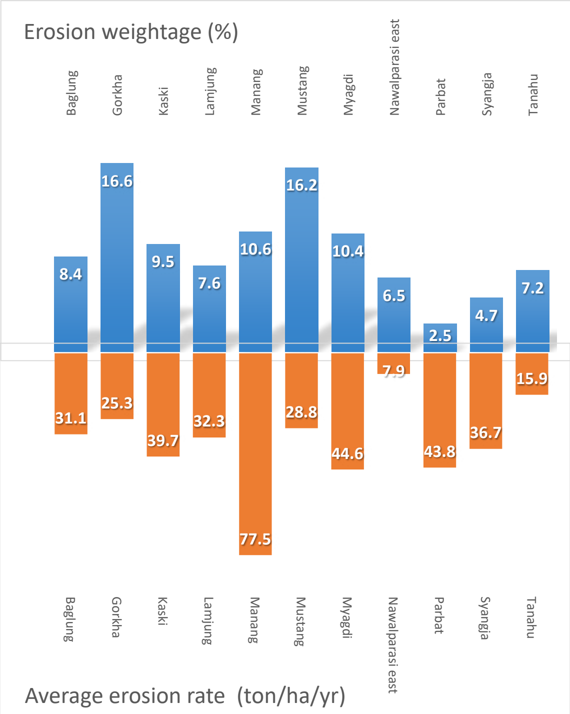


Figure 19 RUSLE based districtwise erosion weightage vs erosion rate comparision

4.4.1 Elevation Wise Distribution of Soil Erosion

Elevation range at 1000-2000m has high soil erosion at rate of 5-100 tonnes per hectare per year. Elevation range above 6000m has high erosion at rate of >100 tonnes per hectare per year.

4.4.2 Land Cover wise distribution of Soil Erosion

Dense Forest has high erosion rate at 1-25 tonnes per hectare per year. Barren land has high erosion rate at >100 tonnes per hectare per year.

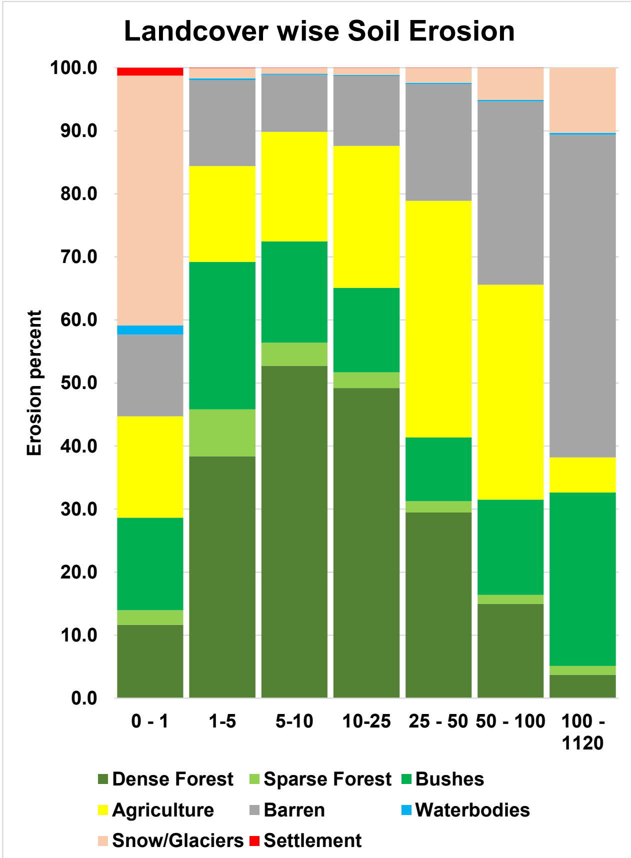


Figure 21 Landcover wise soil erosion in Gandaki Province

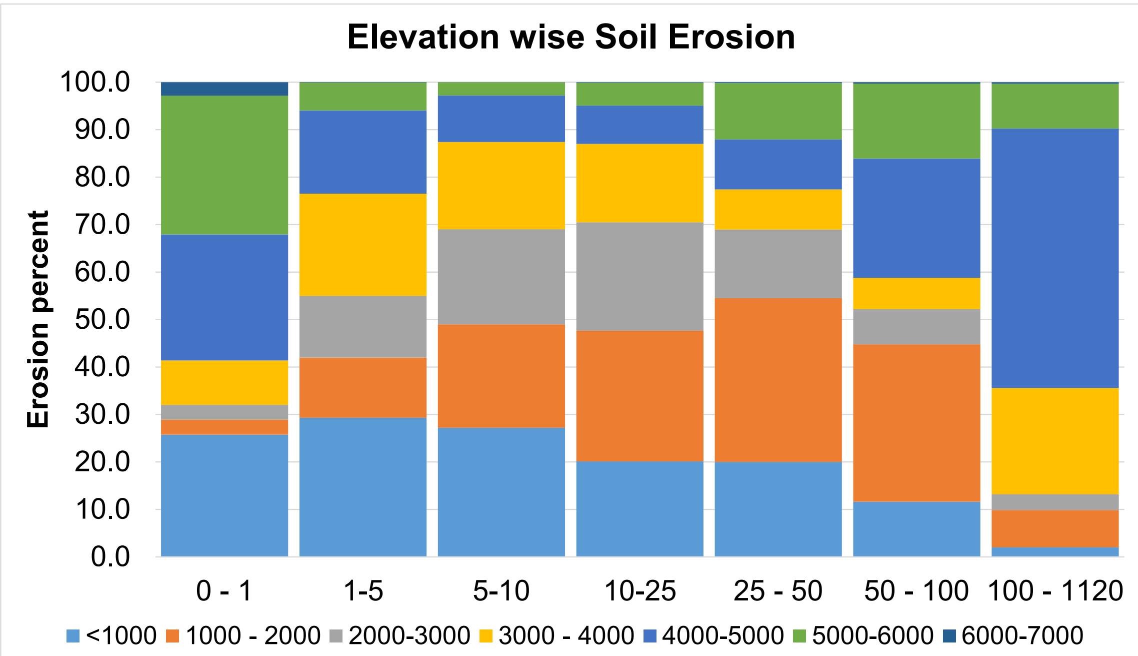


Figure 20 Elevation wise soil Erosion in Gandaki Province

Figure 22 Watersheds in Gandaki Province

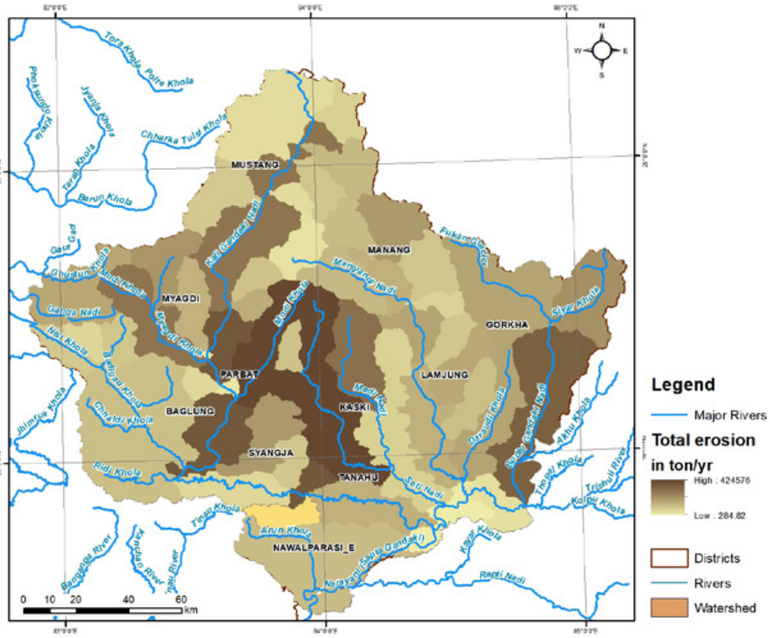


Figure 23 Watersheds wise soil erosion

4.4.3 Erosion in Watershed

The study classified watersheds and subwatersheds in the gandaki river system as :

Watershed wise erosion clearly shows the watersheds with dark color as higher contributor in soil erosion. Madi and Seti watershed in Kaski are among the highest contributor while kali Gandaki, budhi Gandaki and other major watersheds are moderate contributors. The dissection of watersheds into smaller watershed causes variation in the erosion quantity and hence areas of the sub-watersheds needs to be considered.

4.4.4 Palika wise Erosion

The erosion proportion in each palika is measured as erosion weightage. The color density in erosion weightage determines high erosion in red color, moderate erosion in yellow color and low erosion in green color. The ward level erosion is provided as annex.

Table 3 Erosion rate and weightage in palikas (green<yellow<red)

District	Palika	Average erosion rate (ton/ha/yr)	Total erosion (ton/ yr)	Area (ha)	Erosion weightage (%)
BAGLUNG	Badigad	36.8	86364.0	17867.5	0.8
	Baglung	31.1	50716.0	9890.5	0.5
	Bareng	20.8	22181.0	7528.4	0.3
	Dhorpatan	35.8	101838.0	22284.7	1.0
	Dhorpatan Hunting Reserve	34.9	161529.0	31213.2	1.4
	Galkot	22.3	64023.0	19439.0	0.9
	Jaimuni	31.8	56461.0	11871.1	0.5
	Kanthekhola	30.9	36446.0	8288.1	0.4
	Nisikhola	36.7	113053.1	24437.2	1.1
	Taman Khola	36.3	98079.0	17801.8	0.8
	Tara Khola	24.7	50493.0	12952.6	0.6

District	Palika	Average erosion rate (ton/ha/yr)	Total erosion (ton/ yr)	Area (ha)	Erosion weightage (%)
GORKHA	Aarughat	26.8	61181.0	16079.4	0.7
	Ajirkot	46.2	207063.0	19805.1	0.9
	Bhimsen	16.4	23886.0	10124.9	0.5
	Chum Nubri	66.1	1256736.2	164865.1	7.5
	Dharche	40.1	673702.1	65151.6	3.0
	Gandaki	25.1	43783.0	12386.4	0.6
	Gorkha	11.8	24063.0	13186.5	0.6
	Palungtar	10.4	25626.0	15861.9	0.7
	Sahid Lakhan	23.1	45063.1	14896.6	0.7
	Siranchok	18.7	35017.0	12166.0	0.6
	Sulikot	22.0	85902.0	20063.2	0.9
KASKI	Annapurna	83.7	568678.0	41773.7	1.9
	Machhapuchchhre	60.3	869363.0	54458.5	2.5
	Madi	42.3	467606.0	56300.5	2.6
	Pokhara Lekhnath	18.3	199065.0	46423.5	2.1
	Rupa	22.7	34384.0	9481.4	0.4
LAMJUNG	Besishahar	28.9	56163.0	12763.8	0.6
	Dordi	44.8	348815.0	35093.2	1.6
	Dudhpokhari	30.4	92615.0	15332.8	0.7
	Kwholasothar	39.3	110797.0	17537.3	0.8
	MadhyaNepal	21.3	36836.0	11385.7	0.5
	Marsyangdi	59.8	642853.0	59724.7	2.7
	Rainas	18.5	20880.0	7197.0	0.3
	Sundarbazar	20.8	23640.0	7205.0	0.3
MANANG	Chame	82.3	75430.0	7885.8	0.4
	Narphu	102.0	1040834.0	83753.9	3.8
	Nashong	85.9	718654.1	70957.8	3.2
	Neshyang	52.8	359099.1	69463.0	3.2
MUSTANG	Barhagaun Muktikhsetra	19.6	225838.2	88577.8	4.0
	Dalome	17.4	398840.2	134723.9	6.1
	Gharapjhong	23.1	107172.1	31686.8	1.4
	Lomanthang	9.9	137387.2	72402.2	3.3
	Thasang	73.9	276820.0	28953.3	1.3
MYAGDI	Annapurna	60.0	855173.0	55641.9	2.5
	Beni	24.9	31137.0	7657.3	0.3
	Dhaulagiri	59.7	896400.1	85862.6	3.9
	Dhorpatan Hunting Reserve	94.4	245886.0	17803.0	0.8
	Malika	45.6	103230.0	14717.4	0.7

District	Palika	Average erosion rate (ton/ha/yr)	Total erosion (ton/ yr)	Area (ha)	Erosion weightage (%)
	Mangala	23.5	33466.0	8883.8	0.4
	Raghuganga	46.8	350468.1	37913.0	1.7
NAWALPARASI EAST	Binayee Tribeni	8.7	35773.0	28806.8	1.3
	Bulingtar	29.3	64771.0	14767.5	0.7
	Bungdikali	28.3	38261.0	9186.8	0.4
	Chitawan National Park	6.4	7564.0	9466.3	0.4
	Devchuli	3.7	13683.0	11271.5	0.5
	Gaidakot	4.0	17965.0	15993.4	0.7
	Hupsekot	19.7	76223.0	18920.6	0.9
	Kawasoti	1.6	3942.0	10834.3	0.5
	Madhyabindu	3.1	18533.0	23335.2	1.1
PARBAT	Bihadi	49.6	33137.0	4479.9	0.2
	Jaljala	35.0	38709.0	8225.8	0.4
	Kushma	32.7	49304.0	9317.6	0.4
	Mahashila	54.5	39402.0	4937.9	0.2
	Modi	55.5	105111.0	14359.7	0.7
	Painyu	76.2	47467.0	4264.6	0.2
	Phalebas	27.2	37213.0	8570.0	0.4
SYANGJA	Aandhikhola	34.2	36068.0	6961.5	0.3
	Arjunchaupari	44.3	38806.0	5721.9	0.3
	Bhirkot	48.9	63927.0	7823.4	0.4
	Biruwa	39.1	54581.0	9579.1	0.4
	Chapakot	22.3	40670.0	12058.5	0.5
	Galyang	47.3	81799.0	12271.0	0.6
	Harinas	36.3	47116.0	8747.7	0.4
	Kaligandagi	45.4	44386.0	7351.4	0.3
	Phedikhola	33.1	29587.0	5672.7	0.3
	Putalibazar	22.9	47504.0	14720.8	0.7
	Waling	38.2	78830.0	12839.9	0.6
TANAHU	Anbukhaireni	28.4	49017.0	12799.8	0.6
	Bandipur	10.4	18013.0	10154.0	0.5
	Bhanu	13.1	38002.1	18429.4	0.8
	Bhimad	22.5	48107.0	12929.5	0.6
	Byas	8.7	40847.1	24773.4	1.1
	Devghat	18.3	43466.0	15944.7	0.7
	Ghiring	22.8	39939.0	12635.0	0.6
	Myagde	13.0	23299.0	11536.2	0.5
	Rhishing	16.5	51678.1	21505.6	1.0
	Shuklagandaki	16.6	47808.0	16476.7	0.8
	Grand Total	31.1	14241244.8	2197391.0	

5. Landslide Hazard

A landslide can be influenced by various factors such as slope conditions and slope angle, lithology, soil type, and hydrologic or meteorological conditions. Another potential factor is induced by human activities such as deforestation, changes caused by construction of structures on the slope, undercutting the toe of the slope for road construction, etc. Human changes to the slope can make the slope become less stable. The negative impact of landslides includes damage to infrastructure (houses, buildings, roads, bridges, irrigation, canals, etc.), geological and environmental damage (fractures, creeping, and slumping), and serious injuries and loss of human life due to the landslide events.

Landslides are defined as an event or series of events where a mass of rocks, soil, or debris moves down a slope. Landslide mechanisms include sliding, falling, or flowing of material down a slope due to gravitational pull (Paudel et al. 2015). From 2015 to 2020, there has been a significant increase in the number of landslide events in Gandaki Province.

The inventory of landslides in Gandaki province shows the frequency in municipalities of 11 districts:

5.1 Landslide Hazard Mapping/ Modelling

Hazard mapping is the process by which the probability of occurrence of any damaging phenomena can be predicted in any given area (Gnyawali et al. 2020; Das 2011). To conduct landslide hazard mapping, it is necessary to identify the elements at risk such as population, infrastructures, economic activities, environment that are exposed to the known hazard and that are likely to be adversely affected by the impact of the hazard (Dahal and Hasegawa 2008). A landslide hazard map indicates the possibility of a landslide occurring in a given area, potential instability, or as complex as a quantitative map incorporating probabilities based on variables such as rainfall thresholds, slope angle, soil type, and level of earthquake shaking (Kopackova and Sebesta 2007). In the hazard map, the area is divided into low, medium and high hazard zones. The low hazard zone is considered to be more stable whereas the medium hazard zone may have a possibility of landslide disaster. Very dangerous and active landslide area represents the high hazard zone. The sign of instabilities occurs in the high hazard zone, which has a high possibility of failure in the future (Bhattarai and Pradhan 2013). So hazard mapping is an important tool in predicting the probability of occurrence of any damaging phenomena within any given area. Thus, if the prediction is signicant, the damage to lives property and ecosystem can be minimized to a large extent.

Identifying areas with higher risk of landslides requires evaluation of the distribution and frequency of historical landslides. Historical landslides can be mapped efficiently with Geographic Information System (GIS) tools and the application of remote sensing. Quantitative spatial analysis can be used for mapping the landslide susceptibility of a region and providing the scientific information relevant for mitigation and prevention of future landslides in that region (Yilmaz 2009). Quantitative methods are used to assess the landslide events as it increases the ability to predict where, when and how frequent the occurrence of landslides in an area will be. It presents a complete and comprehensive assessment of landslide susceptibility, which includes analysis of model performance, prediction skills evaluation, uncertainty and estimation of errors (Guzzetti et al. 1999; Motamedi 2013).

Landslide Susceptibility (LS) is an assessment to quantify the volume or area and the spatial probability of a landslide event, by providing a relative estimation of the spatial events of landslides in a mapping unit based on the conditions of local terrain, and it may also include the information related to the temporal probability of the expected landslide event, the intensity and velocity rates of the existing or potential landslide events (Fell et al. 2008; Guzzetti et al. 1999; Lepore et al. 2011; Rossi and Reichenbach 2016). This method has various approaches. In this study, the statistical model was chosen because it has been largely used to assess LS and widely used by combining and integrating statistical models with the geographical data and open source of GIS applications. Many studies have tried to assess landslide susceptibility by increasing GIS applications using different models. Many of those studies have applied probabilistic models such as the frequency ratio (Audisio et al. 2009;

Choi et al. 2012; Ehret et al. 2010; Lee et al. 2004; Lee and Pradhan 2006; Lepore et al. 2011; Mandal and Mondal 2019; Mezughi et al. 2011; Mohammady et al. 2012; Oh et al. 2009; Pal and Chowdhuri 2019; Pradhan and Youssef 2010; Rossi and Reichenbach 2016; Yalcin 2008; Yalcin et al. 2011; Yilmaz 2009; Yilmaz and Keskin 2009).

The basic idea is to use the information in combination with geo-environmental conditioning factors to extract the level of detail offered by the landslide data itself for determining landslide susceptibility in the study area. In this study, a bivariate statistical method called the Frequency Ratio (FR) was applied to derive a landslide susceptibility map for Gandaki Province. FR was chosen for this research as a basic analysis for a preliminary probabilistic assessment, the mathematical simplicity and data extraction in a limited time period (rapid assessment).

5.2 Landslide Inventory

When adopting a statistical probabilistic approach, the landslide inventory is the first step in any landslide-mapping project intended to provide a susceptibility, hazard or risk assessment. It is perhaps the most important set of data in the entire assessment process and greatly influences the quality of the final results.

In this study, a database containing 395 landslides polygons from local survey and 98 points from Global Landslide Catalog (data.nasa.gov). The data were prepared in raster for the assessment model, described with internationally accepted terms and classifications (Varnes 1978; Cruden and Varnes 1996), was first implemented by collecting data gathered through a phase of interpretation of satellite imageries followed by field surveying / google earth validation. The definitive inventory of slope movements were made at a scale of 1:10,000. This landslide

Table 4 Landslide inventoriy digitized in Gandaki province

District	Municipality	No. of Landslide Hazard	Total infra structure destroyed	House destroyed	Total House affected	Total livestock destroyed	Total - People Death
Baglung	Badigad	6	0	0	3	0	4
	Baglung	2	2	2	0	0	0
	Bareng	2	1	1	0	0	0
	Dhorpatan	35	25	25	5	20	25
	Galkot	8	5	5	1	0	1
	Jaimini	5	3	3	0	3	2
	Kanthekhola	3	1	1	0	0	2
	Nisikhola	4	2	2	0	0	4
	Taman Khola	2	5	5	3	13	5
Baglung Total		67	44	44	12	36	43
Gorkha	Aarughat	3	1	1	0	0	0
	Ajirkot	1	1	1	0	0	0
	Bhimsen	1	1	1	0	3	0
	Chum Nubri	1	0	0	0	0	1
	Dharche	19	8	8	18	0	12
	Gandaki	2	1	1	0	0	1
	Gangadev	3	2	2	1	0	0
	Gorkha	6	1	1	1	0	0
	Palungtar	2	1	1	0	0	0
	Sahid Lakhan	3	1	1	2	0	3
	Siranchok	1	0	0	0	1	0
Gorkha Total		42	17	17	22	4	17
Kaski	Annapurna	5	0	0	2	0	0
	Machhapuchchhre	19	32	32	14	15	46
	Madi	2	0	0	0	0	0
	Pokhara Lekhnath	23	11	11	7	0	7
	Rupa	1	1	1	0	0	1
Kaski Total		50	44	44	23	15	54

District	Municipality	No. of Landslide Hazard	Total infra structure destroyed	House destroyed	Total House affected	Total livestock destroyed	Total - People Death
Lamjung	Besishahar	7	3	3	0	0	3
	Dordi	3	1	1	0	0	0
	MadhyaNepal	2	0	0	0	0	0
	Marsyangdi	32	35	35	2	42	5
	Sundarbazar	3	0	0	1	0	0
Lamjung Total		47	39	39	3	42	8
Manang	Nashong	3	0	0	0	0	0
Manang Total		3	0	0	0	0	0
Mustang	Barhagaun Muktikhsetra	1	0	0	0	0	0
	Gharapjhong	1	0	0	0	0	0
	Loghekar Damodarkunda	3	0	0	0	0	2
	Thasang	9	3	3	0	0	1
Mustang Total		14	3	3	0	0	3
Myagdi	Annapurna	14	4	4	3	0	2
	Beni	2	0	0	0	0	1
	Dhaulagiri	2	20	20	0	0	19
	Malika	3	14	14	0	0	8
	Mangala	1	0	0	4	0	0
	Raghuganga	13	7	7	1	324	8
Myagdi Total		35	45	45	8	324	38
Nawalparasi East	Binayee Tribeni	1	0	0	0	0	1
	Bulingtar	3	0	0	0	0	5
	Hupsekot	1	2	2	0	0	0
	Kawasoti	1	1	1	0	0	0
	Madhyabindu	2	1	1	0	0	0
Nawalparasi East Total		8	4	4	0	0	6
Parbat	Bihadi	1	0	0	0	0	0
	Jaljala	5	1	1	0	0	0
	Kushma	18	13	13	2	7	17
	Modi	2	0	0	0	0	0
	Phalebas	3	1	1	0	0	1
Parbat Total		29	15	15	2	7	18
Syangja	Aandhikhola	2	1	1	0	0	0
	Arjunchaupari	2	1	1	0	0	0
	Bhirkot	11	3	3	2	8	6
	Biruwa	3	1	1	0	0	0
	Galyang	10	3	3	1	15	2
	Harinas	1	1	1	0	0	0
	Kaligandagi	3	3	3	0	10	4
	Phedikhola	1	1	1	0	0	0
	Putalibazar	1	0	0	0	0	0
	Waling	5	4	4	0	0	9
Syangja Total		39	18	18	3	33	21
Tanahu	Anbukhaireni	1	0	0	0	0	0
	Bandipur	3	4	4	1	0	0
	Bhanu	3	3	3	6	0	2
	Bhimad	1	0	0	0	0	0
	Byas	3	1	1	1	0	5
	Myagde	1	1	1	0	0	1
	Rhishing	4	2	2	1	0	6
	Shuklagandaki	1	1	1	0	0	0
Tanahu Total		17	12	12	9	0	14

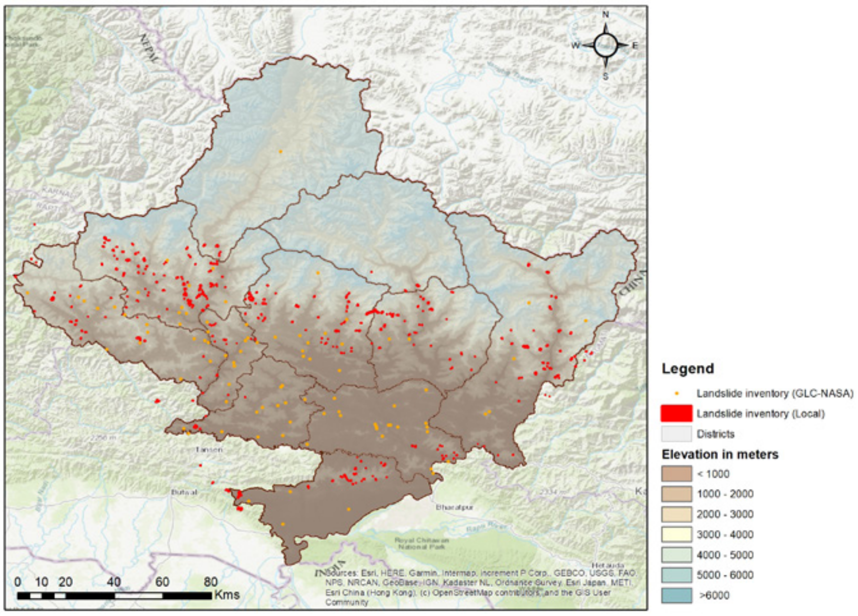


Figure 24 Landslide inventoriy digitized in Gandaki province

inventory is based on movements generated before 2020. The inventory includes a total of 69 slides (translational slides, mainly in phyllite and marble), 52 flows (debris flows, mainly in phyllite), 31 falls (rock falls, mainly in marble) and 17 complexes (complex slides, mainly in quartzite), all identified and mapped (Tables 1, 2 and Fig. 1). The landslides, considered from the source areas to the deposits, were found to affect 3.79% of the total study area. Phyllite units resulted to be the most unstable materials, comprising 38% of the inventoried landslides, followed by marble units at 25%.

5.3 Digitization

Digitization was done in Google earth pro with the data landslide disaster database from Government of Nepal converted into landslide occurrence zone at ward level where landslides were visually identified. Additionally, Landslides from Global Landslide catalog (data.nasa.gov) were used to complement the digitization.

5.4 Frequency Ratio

The frequency ratio (FR) is a bivariate statistical method that has high accuracy compared to other similar methods. The FR is widely used in landslide susceptibility mapping (Choi et al. 2012; Ehret et al. 2010; Lee 2014; Lee and Pradhan 2006; Mezughi et al. 2011; Mohammady et al. 2012; Torizin 2011; Yalcin et al. 2011; Yilmaz 2009), and it is highly compatible with GIS technology (Lee 2014; Yilmaz and Keskin 2009; Yalcin et al. 2011). FR was used to calculate the ratio of the cell with landslide occurrence in each class for a reclassified factor or categorical factor (i.e., geology and land cover), and the ratio was assigned to each factor class again. The FR is the ratio of landslides in a desired class as a percentage of all landslides to the area of the class as a percentage of the entire map. So, a FR of 1 is the average value from the ratio of the area where landslides occurred to the total area (Ehret et al. 2010; Mezughi et al. 2011). Finally, the landslide susceptibility by FR was created using the overlay function in GIS, which is used to merge different factors assigned to the ratio. If the probability is high (the value > 1), there is a greater susceptibility for landslides. A lower

Figure 25 Landslide from Birgha Archal, Syangja digitised in Google earth (Left), recent False Image for January 2021(Right)

value indicates a lower degree of landslide susceptibility in the region (the value < 1). The formula is as follows (Ehret et al. 2010):

$$FRi=(Mi/M)/(Ni/N), (1)$$

where Mi is the number of pixels with landslides for each subclass conditioning factor, M is the total number of landslides in the study area, Ni is the number of pixels in the subclass area of each factor and N is the number of total pixels in the study area (Ehret et al. 2010).

5.5 Causal Factors

All Causal fator maps were prepared as raster in ArcGis 10.9 software as shown in next page. (Figure 28)

5.6 Landslide Risk Zonation

The susceptibility of a given area to landslides can be determined and depicted using hazard zonation. A landslide hazard map can be prepared early in the planning study and developed in more detail as the study progresses. It can be used as a tool to help identify land areas best suited for development by examining the potential risk of land sliding. Furthermore, once landslide susceptibility is identified, investment projects can be developed which avoid, prevent, or substantially mitigate the hazard.

A landslide susceptibility map which identifies areas of differing landslide potential may be generated. The need for such landslide potential information may vary according to the future land use. The degree of landslide hazard present is considered relative since it represents the expectation of future landslide occurrence based on the conditions of that particular area. Another area may appear similar but, in fact, may have a differing landslide hazard due to a slightly different combination of landslide conditions. Thus, landslide susceptibility is relative to the conditions of each specific area, and it cannot be assumed to be identical for a similar appearing area.

Even with detailed investigation and monitoring, it is extremely difficult to predict landslide hazards in absolute terms. Sufficient understanding of landslide processes does exist, however, to be able to make an estimation of landslide hazard potential. The planner can use this estimation to make certain decisions regarding site suitability, type of development, and appropriate mitigation measures. Thus, the planner is determining acceptable risk.

The landslide risk Zonation map shows the category of risk areas with Very high risk in Red, High risk in orange, Moderate risk in yellow, Low risk in Light green and no risk in dark green. The risk zones are studied as per their distribution in different districts and environmental factors.

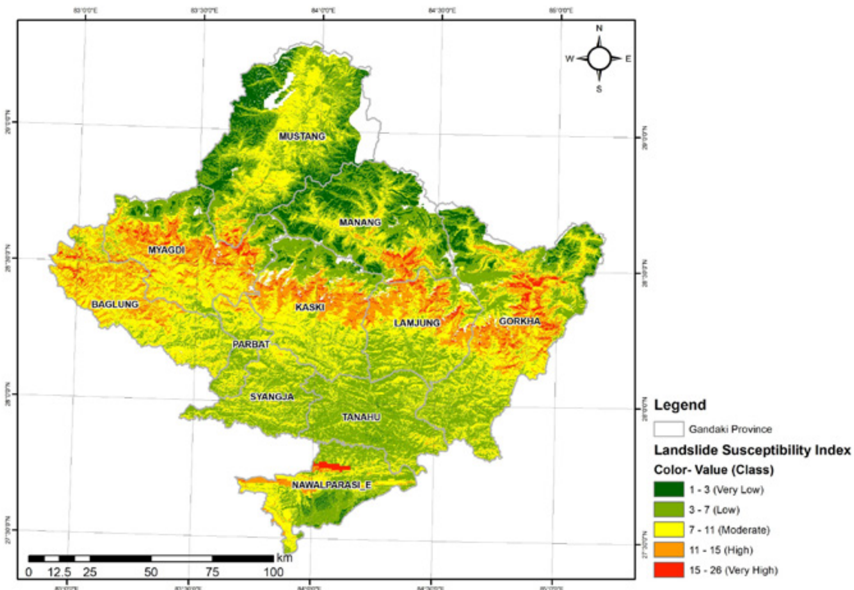


Figure 26 Landslide susceptibility map based on FR method

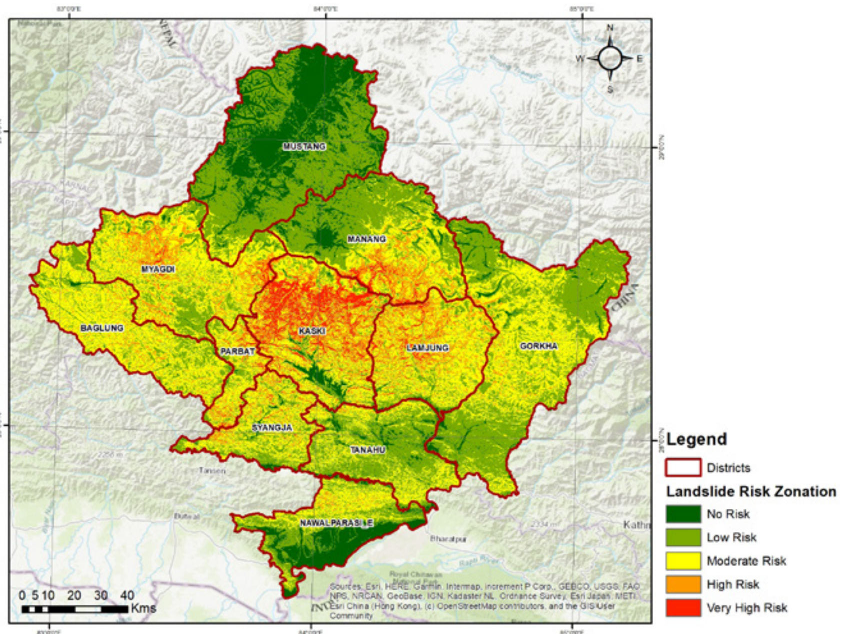


Figure 27 Landslide susceptibility map based on Rainfall and Slope

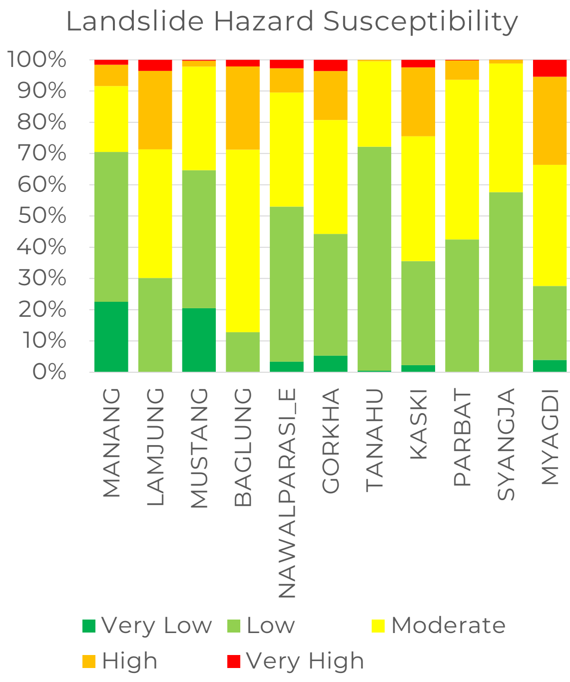


Figure 29 Districtwise Landslide susceptibility

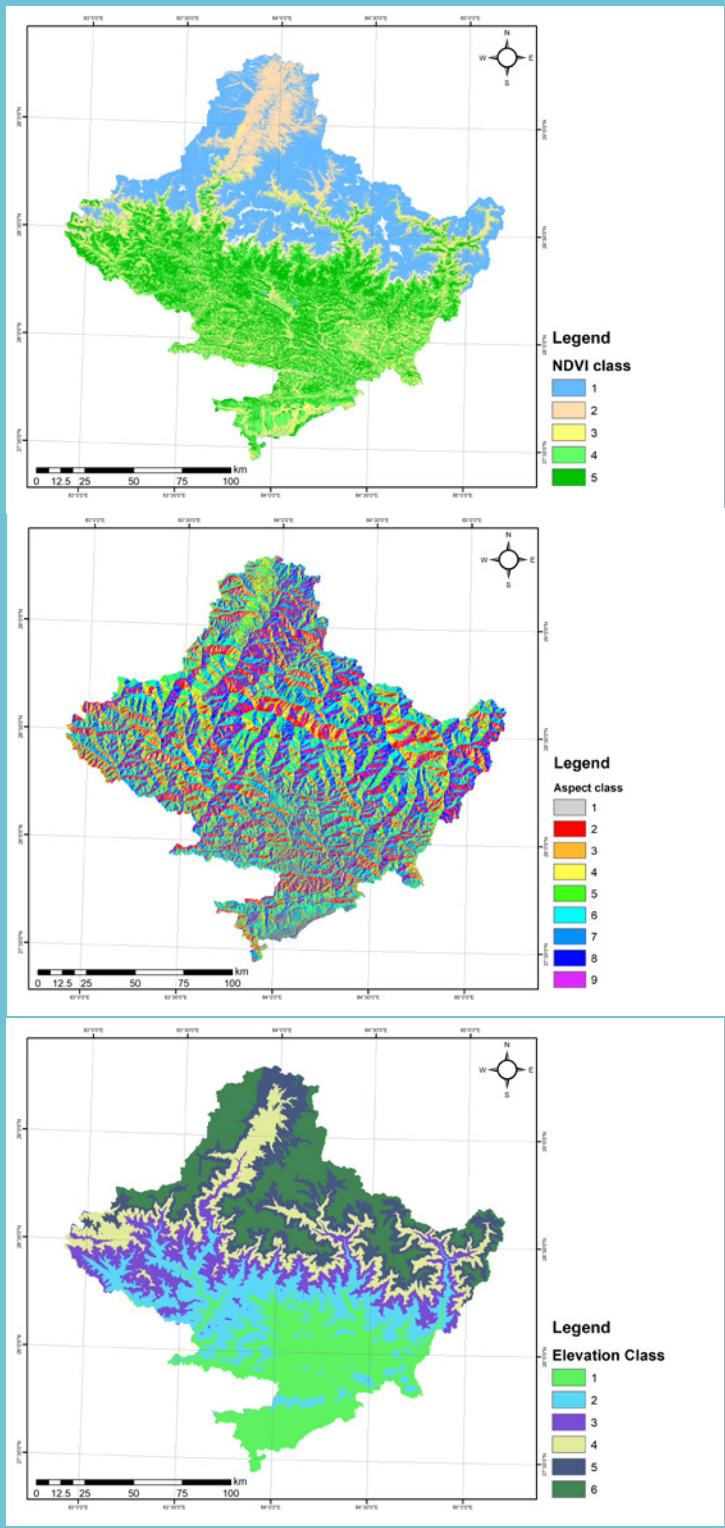


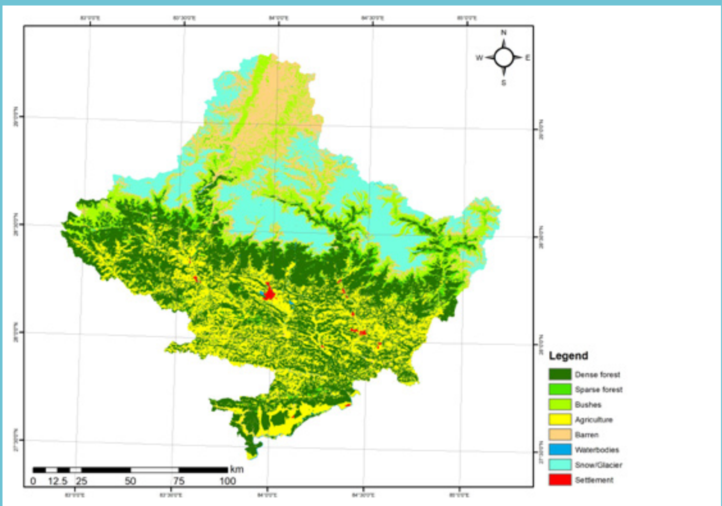
Figure 28 Causal factors used in Frequency ratio method for landslide prediction model

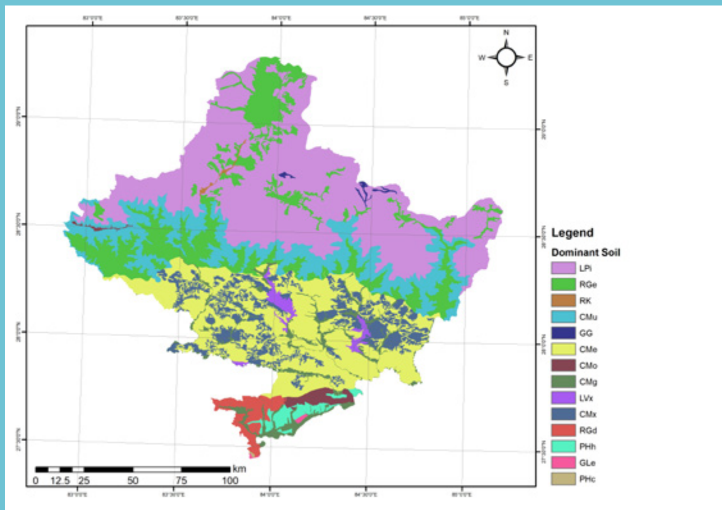
Rainfall induced landslide are typical when extreme rainfall increases the soil moisture causing detachment under the influence of gravity. Slope increases the risk of such landslides occurring during extreme rainfall.

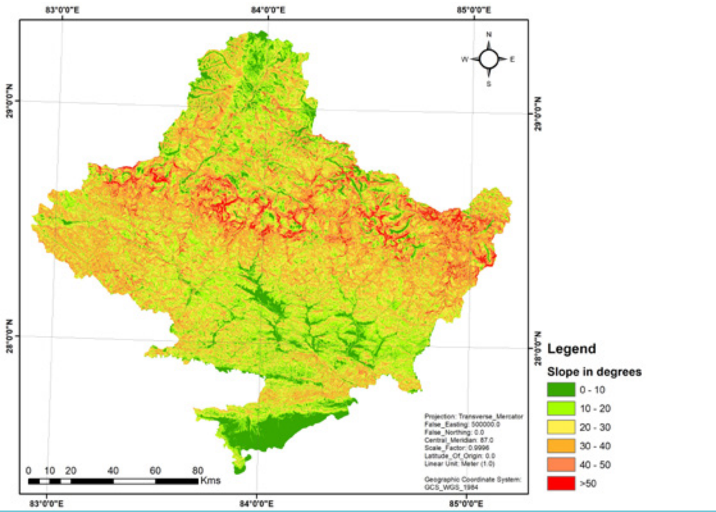
5.7 The study of Landslide

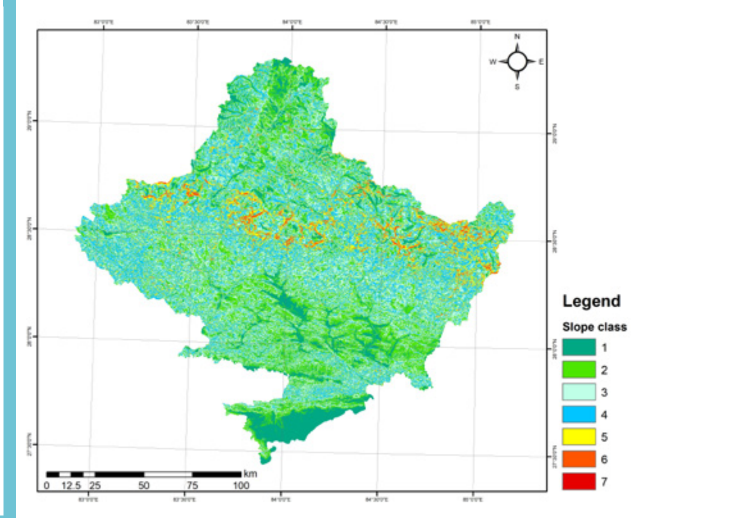
Determining the extent of landslide hazard requires identifying those areas which could be affected by a damaging landslide and assessing the probability of the landslide occurring within some time period. In general, however, specifying a time frame for the occurrence of a landslide is difficult to determine even under ideal conditions. As a result, landslide hazard is often represented by landslide susceptibility (Brabb, 1985). Similar to the concept of flood-prone areas, landslide susceptibility only identifies areas potentially affected and does not imply a time frame when a landslide might occur. To simplify these concepts, landslide susceptibility will be referred to as landslide hazard. Comparing the location of an area of proposed development to the degree of landslide hazard present enables the planner to estimate the landslide risk. This can be used to define land use capability and identify appropriate mitigation measures.

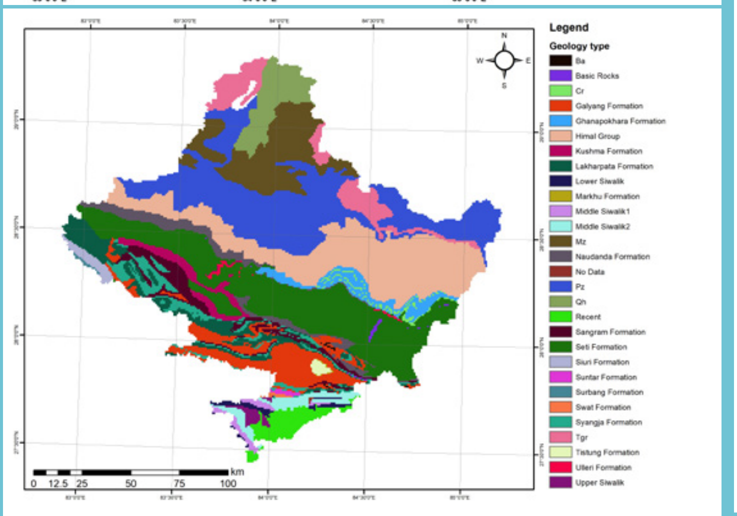
Determining whether there is a need for landslide hazard information is the first step in ensuring that landslide risk does not exceed an acceptable level in planning future land use. The objective of landslide information is to identify which relatively landslide-susceptible areas are best suited for what types of development activities. For example, assessing landslide hazard would have a low priority in planning areas to be set aside for national parks or botanical garden in forest areas. Conversely, landslides can be an important factor in the development of newly

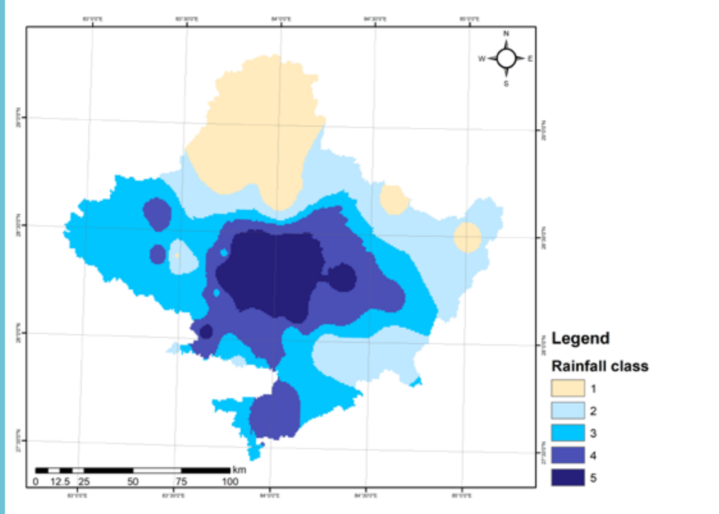












cleared forest areas or in building infrastructure in mountainous or hilly terrain specially roads in the context of Nepal. Clearly, the amount of landslide hazard information needed is based on the level and type of anticipated development for an area. Failure to understand the potential effects landsliding can have on a project or how the project might affect landslide potential can bring increased risk.

Natural changes as well as human-induced changes can affect the susceptibility to landslides and must be understood when assessing the landslide potential of an area. It is critical for a planner to appreciate these issues early in the planning process. A decision is ultimately made

Table 5 Frequency Ratio Table

CLASS	RASTER VALUE	NO OF LANDSLIDE PIXELS	% LANDSLIDE (X)	TOTAL CLASS PIXELS	% CLASS (Y)	FR (X/Y)
SLOPE						
0-10	1.0	285.0	1.4	2960879.0	12.2	0.11
10-20	2.0	1833.0	8.7	5796242.0	23.8	0.37
20-30	3.0	5529.0	26.3	7633343.0	31.3	0.84
30-40	4.0	7948.0	37.8	5533172.0	22.7	1.66
40-50	5.0	4664.0	22.2	1991161.0	8.2	2.71
50-90	6.0	778.0	3.7	445554.0	1.8	2.02
ASPECT						
FLAT(-1)	1.0	0.0	0.0	14329.0	0.1	0.00
N	2.0	456.0	2.2	3153209.0	12.9	0.17
NE	3.0	1667.1	7.9	2856523.0	11.7	0.68
E	4.0	2245.2	10.7	2566627.0	10.5	1.01
SE	5.0	4994.4	23.7	3244738.0	13.3	1.78
S	6.0	7218.6	34.3	4001538.0	16.4	2.09
SW	7.0	3527.3	16.8	3426830.0	14.0	1.19
W	8.0	825.1	3.9	2534128.0	10.4	0.38
NW	9.0	120.0	0.6	2616040.0	10.7	0.05
ELEVATION						
0-1000	1.0	2865.2	13.6	5371969.0	22.0	0.62
1000-2000	2.0	5733.5	27.2	4271678.0	17.5	1.56
2000-3000	3.0	8199.7	38.9	3230769.0	13.2	2.95
3000-4000	4.0	3954.3	18.8	3423062.0	14.0	1.34
4000-5000	5.0	306.0	1.5	3839878.0	15.7	0.09
5000-6000	6.0	0.0	0.0	4317733.0	17.7	0.00
PPT						
100-1000	1.0	0.0	0.0	4585083.0	18.7	0.00
1000-2000	2.0	4412.1	21.0	5873205.0	24.0	0.88
2000-2600	3.0	8814.3	42.0	7026962.0	28.7	1.46
2600-3400	4.0	3685.1	17.6	4555525.0	18.6	0.94
3400-5150	5.0	4060.1	19.4	2429633.0	9.9	1.95
NDVI						
-1.03	1.0	2538.3	12.3	6946712.0	29.2	0.42
0.03-0.23	2.0	8386.6	40.6	3031304.0	12.7	3.19
0.23-0.45	3.0	6654.5	32.2	3331093.0	14.0	2.30
0.45-0.64	4.0	2156.0	10.4	4913213.0	20.6	0.51
0.64-0.99	5.0	926.9	4.5	5576922.0	23.4	0.19
LANDCOVER						
Dense forest	1.0	3841.4	18.3	8005682.0	32.8	0.56
Sparse forest	2.0	966.4	4.6	775258.0	3.2	1.45
Bushes	3.0	7782.2	37.1	3639042.0	14.9	2.49
Agriculture	4.0	5293.6	25.2	4616184.0	18.9	1.34
Barren	5.0	2950.0	14.1	3217674.0	13.2	1.07
Waterbodies	6.0	145.0	0.7	119016.0	0.5	1.42
Snow	7.0	0.0	0.0	3992751.0	16.3	0.00
Settlement	8.0	0.0	0.0	64568.0	0.3	0.00

CLASS	RASTER VALUE	NO OF LANDSLIDE PIXELS	% LANDSLIDE (X)	TOTAL CLASS PIXELS	% CLASS (Y)	FR (X/Y)
GEOLOGY						
Ba	1.0	0.0	0.0	14735.0	0.1	0.00
Basic rocks	2.0	13.0	0.1	38575.0	0.2	0.39
Cr	3.0	160.0	0.8	139655.0	0.6	1.32
Galyang formation	4.0	469.0	2.2	1516207.0	6.2	0.36
Ghanapokhara form	5.0	497.0	2.4	585038.0	2.4	0.98
Himal group	6.0	7919.0	37.6	3855755.0	15.9	2.37
Kushma formation	7.0	134.0	0.6	425920.0	1.8	0.36
Lakharpata formation	8.0	1239.0	5.9	1085447.0	4.5	1.32
Lower siwalik	9.0	608.0	2.9	145425.0	0.6	4.83
Markhu formation	10.0	0.0	0.0	8990.0	0.0	0.00
Middle siwalik1	11.0	158.0	0.8	140438.0	0.6	1.30
Middle siwalik2	12.0	589.0	2.8	380791.0	1.6	1.79
Mz	13.0	0.0	0.0	1945932.0	8.0	0.00
Naudanda formation	14.0	1517.0	7.2	786757.0	3.2	2.23
No data	15.0	0.0	0.0	5714.0	0.0	0.00
Pz	16.0	1010.0	4.8	4620844.0	19.0	0.25
Qh	17.0	0.0	0.0	920754.0	3.8	0.00
Recent	18.0	0.0	0.0	513084.0	2.1	0.00
Sangram formation	19.0	737.0	3.5	713356.0	2.9	1.19
Seti formation	20.0	4554.0	21.6	4198263.0	17.3	1.25
Siuri formation	21.0	237.0	1.1	162770.0	0.7	1.68
Suntar formation	22.0	373.0	1.8	35269.0	0.1	12.21
Surbang formation	23.0	8.0	0.0	23812.0	0.1	0.39
Swat formation	24.0	125.0	0.6	23143.0	0.1	6.24
Syangja formation	25.0	659.0	3.1	722252.0	3.0	1.05
Tgr	26.0	0.0	0.0	1088924.0	4.5	0.00
Tistung formation	27.0	0.0	0.0	61691.0	0.3	0.00
Ulleri formation	28.0	50.0	0.2	50235.0	0.2	1.15
Upper siwalik	29.0	0.0	0.0	109316.0	0.4	0.00
DOMINANT SOIL						
LPI	1.0	1528.0	7.3	8485594.0	35.3	0.21
RGE	2.0	5865.0	27.9	3755587.0	15.6	1.78
RK	3.0	0.0	0.0	37501.0	0.2	0.00
CMU	4.0	9440.0	44.8	3104852.0	12.9	3.47
GG	5.0	0.0	0.0	55011.0	0.2	0.00
CME	6.0	2008.0	9.5	4764925.0	19.8	0.48
CMO	7.0	16.0	0.1	246715.0	1.0	0.07
CMG	8.0	26.0	0.1	808234.0	3.4	0.04
LVX	9.0	9.0	0.0	250039.0	1.0	0.04
CMX	10.0	885.0	4.2	1789286.0	7.4	0.57
RGD	11.0	1272.0	6.0	437009.0	1.8	3.33
PHH	12.0	0.0	0.0	288155.0	1.2	0.00
GLE	13.0	0.0	0.0	20984.0	0.1	0.00
PHC	14.0	0.0	0.0	4961.0	0.0	0.00

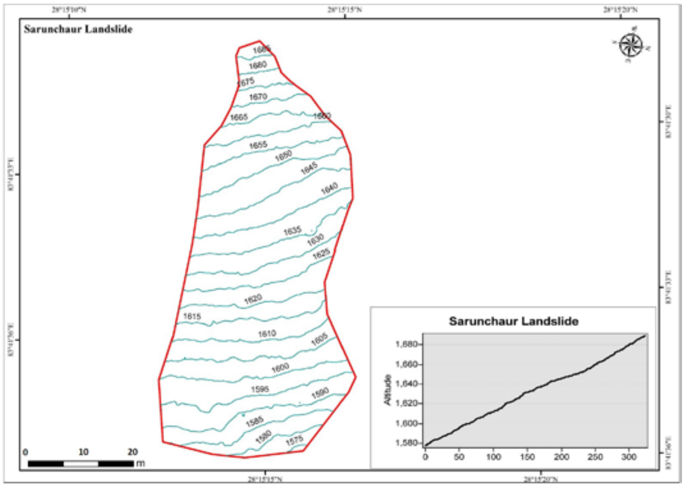
regarding the degree of risk that is acceptable or unacceptable to a project. Mitigation strategies are then designed to reduce risk.

Early consultation with landslide technical specialists is recommended so that they can assess the risk of proposed activities in a landslide hazard area. The planner, while not expected to be a technical expert, must know the questions to ask of a landslide specialist. By asking the appropriate questions, the planner will be able to identify and evaluate measures to minimize or avoid landslide vulnerability.

From the overall study, it is seen that large and complex landslides are related to deep rock weathering and old colluvial debris or old landslide areas followed by the active gullies nearby, specially in the rainy season. Deep seated landslides are dependent more on geological structures as faults, joints and fractures, weathering conditions and infilling materials. However Shallow landslides are developed in the slope covered by colluviums or residual soil. Specially, debris slides and debris flows occur in colluviums or residual soil-covered slopes except some rockfall in high gradient slope.

5.7.1 Kusma Municipality Ward no. 3, Kaule, Sarunchaur Landslide (P-1)

Landslide details: This landslide is located on the uphill side north-east faced slope of the Northern hill of Kusma Bazar. The slide has its crown on the northern side of the Durlung Kot village. Geologically the area lies in Kusma formation. Kusma formation consists of greenish grey white fine to medium grained at places ripple marked massive quartzite intercalated with green phyllite. As observation of the exposures of rocks, most of the area of this geological zone has weathered and fractured rock of quartzite and phyllites. In the main scarp and crown portion, there is loose colluvial debris with a high gradient (70°-75°) slope. The landslide is classified as debris slide and debris flow where the slide materials are classified into two zones i) zone of depletion ii) zone of accumulation. The total length of the landslide from tip to crown is about 150 m and covers an area around 4500 sqm. The slide material is composed of various sizes of rock fragments with woody debris such as logs and tree stumps less than 50% of fines. This slide was triggered by heavy rainfall that had developed



Features	Details
LOCATION	Kusma Municipality Ward no. 3, Kaule, Sarunchaur Landslide (PKu-2), Parbat district
GEOLOGY	Kusma formation consists of greenish grey white fine to medium grained at places ripple marked massive quartzite intercalated with green phyllite. The slide area is composed of these rock fragments and clays as colluvial debris with more than 40 m of thickness. The slope gradient varies from 15° to 70°.
SIZE	~4500 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 15000 cum extended to the 300 m downstream/Composed of various sizes of rock fragments with woody debris such as logs and tree stumps less than 50% amount of fines, size varies from clay to boulder sized rock fragments
SLIDE TYPE	Debris slide and debris flow
AGE	Initiated on 31 Jestha 2077 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season
HAZARD LEVEL ZONE	High
CASUALTIES AND FURTHER RISK	9 people killed, affected 27 house including 3 completely, 2 moderately and 22 slightly damage, 22 people displaced
PROPOSED MITIGATION MEASURES	RCC wall, wet masonry, gabion wall, bioengineering

the rupture line beneath the surface about 10 m along the existing slope towards the downhill side. The heavy rainfall, slope gradient, existing cracks on the crown area, and the slop materials are the major contributing factors that developed the rupture line inside the overburden material that could move material downwards making a major scarp of 105m. The existing slope gradient varies from 65° in the upside area to 35° around the zone of accumulation. The slide slope was covered with forest. The thickness of the soil is estimated more than 25 m as overburden because the rock exposure around the area has not been observed. This slope is an old landslide area consisting of colluvial debris. The aspect of the slope is North east with 348° azimuths of sliding path direction. The accumulated zone comprises the upside of the scattered residential houses.

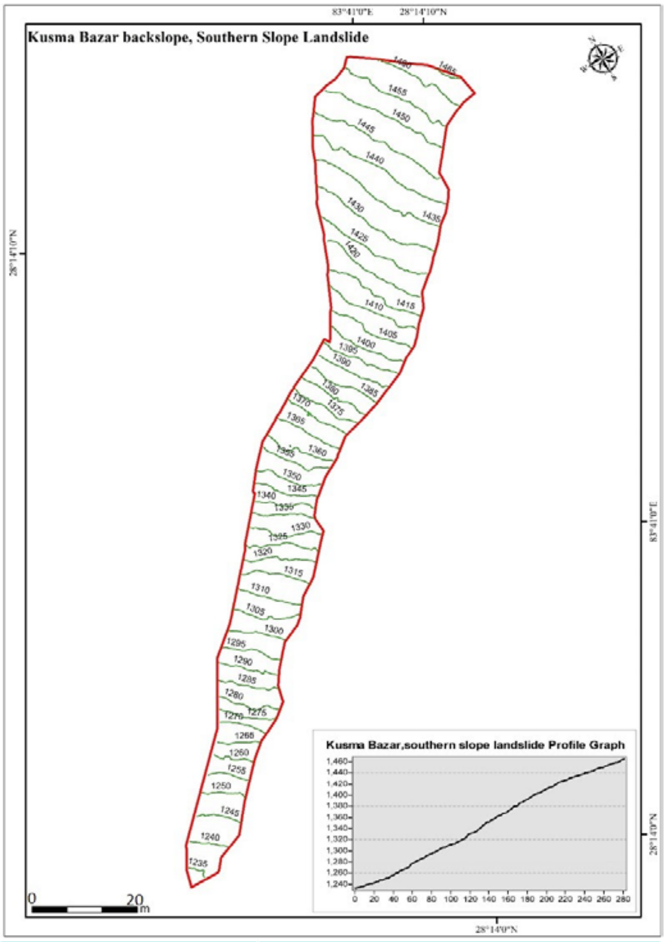
The soil material comprises mostly colluviums along with a significant amount (50-60%) of the rock fragment. The most of the rocks fragments are phyllite, sandstone and quartzite as a form thick the overburden. On the consideration of stability, most of the area is unstable and observing creeping the slope except few areas.

Casualties and further risk: The landslide killed 9 people with 22 displaced. Altogether 27 houses were affected including 3 completely, 2 partially and 22 slightly. A settlement is situated just below and nearby the accumulated zone. The existing situation of creeping on the slope creating a risk zone and immediate action is necessary to prevent further damage. The head to crown part of the slide is still active, therefore necessary intervention should be applied for the protection of further expansion of the slides. All of this aspect slope is made of old landslide area therefore necessary action on geological stability is required. However, no major water sources, springs and water tables nearby the area have been observed.

Few cracks are observed around 200 m downside of the toe area therefore and risk on the further slides is potential and has risk damaging and casualties if a landslide occurs. As per site geological condition, bioengineering, RCC protection around the toe area could be useful.

5.7.2 Kusma Bazar backslope, southern slope landslide (P-2)

Landslide details: This landslide is located at the uphill side south faced slope of the western Kusma Bazar. The slide crown is situated almost on the road to Durlung Kot. Geologically the area lies on the border of Seti formation and Kusma formation. In Seti formation has greenish grey gritty chlorite muscovite sandstones, gritstone with conglomerates and white massive quartzites in the upper part and Kusma formation consist of greenish grey white fine to medium grained



Features	Details
LOCATION	Kusma Bazar backslope, southern slope landslide, Kusma Municipality, Parbat district (PKu-3)
GEOLOGY	Kusma formation consists of greenish grey white fine to medium grained at places ripple marked massive quartzite intercalated with green phyllite. The slide area is composed of these rock fragments and debris as colluvial debris and residual soil with 2m of average thickness. The slope gradient varies from 20° to 87°.
SIZE	~~3000 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 1400 cum extended to the 300 m downstream/Composed of various sizes of rock fragments with less than 50% amount of fines, size varies clay to boulder sized rock fragments
SLIDE TYPE	Debris slide, rock fall, debris fall
AGE	Initiated on Jestha 2075 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season
HAZARD LEVEL ZONE	High
CASUALTIES AND FURTHER RISK	15 houses slightly damage, Risk to Kusma Bazar
PROPOSED MITIGATION MEASURES	RCC wall, wet masonry, gabion wall

at places ripple marked massive quartzite intercalated with green phyllite. In the main scarp, and crown portion there are conglomerate and quartzite bedrocks and the slide area has colluvial debris that had collapsed and slide downwards as a form of accumulation zone in the lower portion, it is just the northern end of the Kusma Bazar. The derived debris has reached the foothill area where residential houses exist. This landslide was triggered by the heavy rainfall of 2075 BS. The type of landslide is debris slide and rock falls, but develops into debris flow along the lower rich of the mountain. Several houses are at risk and vulnerable to damage from the slide if not protected. The slope is mostly covered by vegetation with trees and with thin covered topsoil. The slope varies between 20° to 87°. The lowest slope gradient is observed near the foothill side area and the highest at the cliff near to the road, from where the rock failure occurred.

Casualties and further risk: This landslide has damaged partially and slightly to the foothill side of the area. The foothill or just below the accumulation zone has residential buildings of the Kusma city. The immediate protection is necessary to protect the further damage. The continuous debris and rock slides and fall are continued till present. On the other hand, the slide has followed an active gully, therefore, necessary protection should be considered for the protection of further expansion of the slides and damaging the sensitive area of the Bazar. As per site geological condition, RCC protection wall and gabion wall are necessary to protect direct hit of the debris.

5.7.3 Annapurna Rural Municipality, Ward no. 3, Adheri khola landslide (K-1)

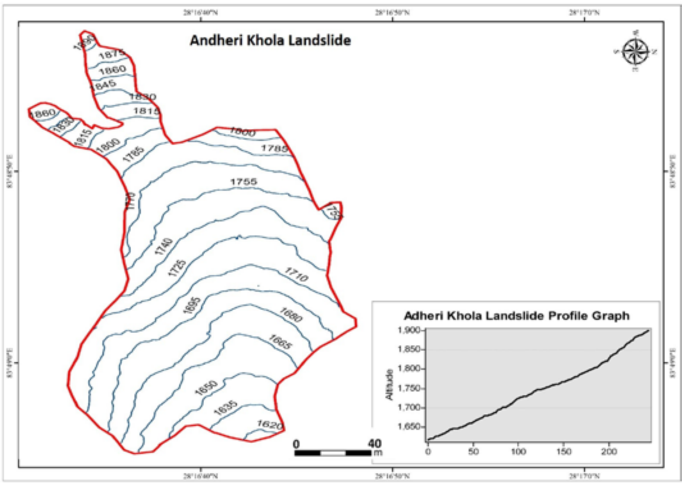
Landslide details: Physio-graphically, the project area lies in the hilly region of Lesser Himalayas consisting of hilly terrain and Aadheri river origin catchment. In the regional geological framework, the slide area lies in Seti formation of Lesser Himalaya of Pokhara Sub group, which is correlated with Kunchha formation of central Nepal. In this formation, the rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The Seti formation is mainly composed of basically phyllite and quartzite. The total thickness of this Formation is more than 3,000m. The major geomorphic features of the area include active gullies, earth and debris slides, residual soils and colluviums.

The landslide is classified as a complex landslide consisting of debris flow, debris slide and debris falls, where the slide materials are accumulated and extended to flow to the Phewa Lake covering around 25000 sqm. The slide material is composed of various sizes of rock fragments with woody debris such as logs and tree stumps less than 50% of fines. The heavy raining, high slope gradient, state of rock fractures and weathering are the major contributing factors that drive the material to move downwards. A gully and rills are present along the middle of the slides that extends to the Phewa lake with a mix of the Harpan river. The gully gradient varies from 75° in the upside area to 25° around the downside area. The slope is made of weathered phyllite rock with 3-4 m thickness of topsoil. The aspect of the slope is NE with the slide path direction of 081° azimuth.

The soil material comprises mostly colluviums along with a significant amount (50-60%) the rock fragments. The most encountered rocks are Phyllite, sandstone and quartzite beneath the overburden. Slide potential classification (Krahenbunl & Wagner, 1983) of Rock of Nepalese Mountains also shows the area lies on Group II and III as per the composition of the rock. The classified groups lie on medium to high lithological slide potential. Loose overburden soil and weathered rock slope are high potential slides whereas the rocky area is stable. On this consideration the stability, the most of the area is unsafe except further away to the slide area. However, except proximity of gully area and stream area, the remaining most of the overburden soil slope is considered as safe from geological stability point of view because the estimated peak angle of shear resistance of the material varies from 25° to 340.

Casualties and further risk: This landslide has destroyed the forest land and contributing heavy sediment to the Phewa lake. Downstream scouring on the banks of the river and damage to cultivated land are the major problems from this huge slide.

The immediate protection is necessary to prevent further damage. The continuous debris and high sediment flow is present in the Andheri river from this slide especially during the rainy season.



Features	Details
LOCATION	Annapurna Rural Municipality, Ward no. 3, Adheri khola (KAn-1)
GEOLOGY	In this formation, the rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The slide area is composed of these rock fragments and clays as colluvial debris and rocks with 3-5m of thickness. The slope gradient varies from 25° to 75°.
SIZE	~25000 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	More than 25000 cum extended to the Harpan Khola and eventually to the Phewa lake towards downstream/ Composed of various sizes of rock fragments with woody debris such as logs and tree stumps less than 50% amount of fines, size varies clay to boulder sized rock fragments
SLIDE TYPE	Complex landslides consisting of debris flow, debris slide and debris falls.
AGE	More than 15 years
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season
HAZARD LEVEL ZONE	High
CASUALTIES AND FURTHER RISK	Destroyed forest cover area, heavy sedimentation on cultivated land and major sediment contributor to the Phewa lake.
PROPOSED MITIGATION MEASURES	RCC wall, wet masonry, gabion wall, bioengineering

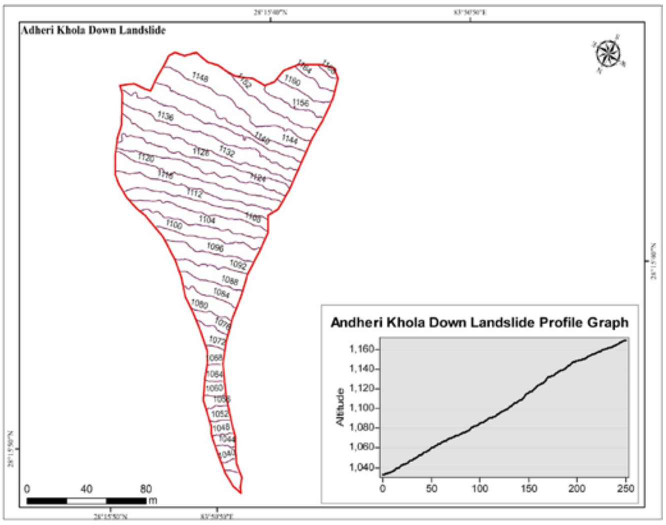
On the other hand, the upper part of the slide has an active gully, therefore necessary protection should be considered for the protection of further expansion of the slides. As per site geological condition, bioengineering, RCC protection wall along the riverside and upside of the existing active gulley could be useful.

5.7.4 Annapurna Rural Municipality, Ward no. 2, Adheri khola Down (K-2)

Landslide details: Physio-graphically, the project area lies in the hilly region of Lesser Himalayas consisting of hilly terrain and river valleys of the Aadheri Khola and Harpan Khola and its tributaries. In the regional geological framework, the study area lies in Seti formation of Lesser Himalaya of Pokhara Sub group, which is correlated with Kunchha formation of central Nepal. In this formation, the rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The Seti formation is mainly composed of basically phyllite and quartzite. The total thickness of this Formation is more than 3,000 m. The major geomorphic features of the area include active gullies, earth and debris slides, residual soils and colluviums.

The landslide is classified as a debris slide where the slide materials are accumulated and extended to the Aadheri khola of covering around 4500 sqm. The slide material is composed of various sizes of rock fragments with woody debris such as logs and tree stumps less than 50% of fines. This slide was triggered by heavy rainfall that had developed the slip line beneath the soil along the existing slope towards the Andheri river. The heavy raining, high slope gradient, scouring by the Andheri river and the slop materials were the major contributing factors that developed the rupture line inside the overburden material that could move material downwards. A gully is present along the middle of the slides that extends to the 300 m upside from the crown of the slide. The gully gradient varies from 65° in the upside area to 35° around the downside area. The half left side slope is made of weathered phyllite rock slope with 1-2 m thickness of topsoil. The aspect of the slope is NW with the slide path direction of 348° azimuth.

The soil material comprises mostly colluviums along with a significant amount (50-60%) of the rock fragment. The most encountered rocks are Phyllite, sandstone and quartzite beneath the overburden. Slide potential classification (Krahenbunl & Wagner, 1983) of Rock of Nepalese Mountains also shows the area lies on Group II and III as per the composition of the rock. The classified groups lie on medium to high lithological slide potential. Loose overburden soil and weathered rock slope are high potential



Features	Details
LOCATION	Annapurna Rural Municipality, Ward no. 2, Adheri khola Down (KAn-3)
GEOLOGY	In this formation, the rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The slide area is composed of these rock fragments and clays as colluvial debris with 2-5m of thickness. The slope gradient varies from 35° to 65°.
SIZE	~4500 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 15000 cum extended to the Aandi Khola downstream/Composed of various sizes of rock fragments with woody debris such as logs and tree stumps less than 50% amount of fines, size varies clay to boulder sized rock fragments
SLIDE TYPE	Debris slide
AGE	Initiated on 25 Ashadh 2072 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season
HAZARD LEVEL ZONE	High
CASUALTIES AND FURTHER RISK	2 people killed, 1 injured, 1 house completely damage, 1 people displaced
PROPOSED MITIGATION MEASURES	RCC wall, wet masonry, gabion wall, bioengineering

slides whereas the rocky area is stable. On this consideration of stability, most of the area is safe except the existing slide area. However, except proximity to the gully area, the remaining most of the overburden soil slope is considered as safe from geological stability point of view because the estimated peak angle of shear resistance of the material varies from 25° to 340.

Casualties and further risk: This landslide killed 2 people with 1 person injured in the same family.

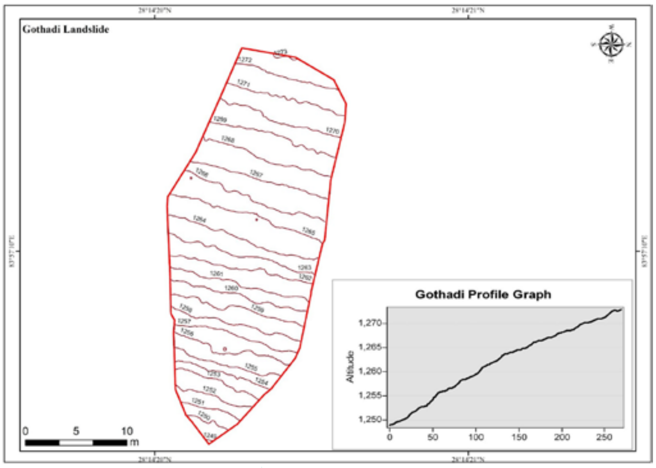
The damaged house was situated on the crown of the slide. Only 1 house was completely damaged. The slide had partially blocked the Aandhi Khola during the event however no other long-term damming on the river.

A settlement is situated just near the crown area. The immediate protection is necessary to protect the further damage. The continuous debris and high sediment flow is present in the Andheri river especially during the rainy season. On the other hand, the upper part of the slide has an active gully, therefore necessary protection should be considered for the protection of further expansion of the slides. As per site geological condition, bioengineering, RCC protection wall along the riverside and upside of the existing active gulley could be useful.

5.7.5 Pokhara metropolitan, ward no. 18, Gothadi, Landslide (K-3)

Landslide details: The landslide is classified as earth slide where the slide materials are accumulated downwards cultivated area of covering around 350 sqm. The slide material is composed of various sizes of rock fragments and organic matter with more than 50% fine. This slide was triggered by heavy rainfall that had developed the slip line beneath the soil along the existing slope from the existing road as crown area. The heavy raining, slope gradient and the slope materials are the major contributing factors that developed the slip line inside the overburden material that could move downwards. The slope gradient varies from 80° in the base to 35° around the top area. The half downside part is made of rock with a steep gradient. The aspect of the slope is South-East and the path of slide direction is 110° azimuth with moving 50m down from the crown.

The soil material comprises mostly earth colluviums along with a significant amount (40-45%) of the rock fragments. The most encountered rocks are Phyllite, sandstone and quartzite beneath the overburden. Slide potential classification (Krahenbunl & Wagner, 1983) of Rock of Nepalese Mountains also shows the area lies on Group II and III as per the composition of the rock. The classified groups lie on medium to high lithological slide potential. Loose overburden soil and weathered rock slope are high potential slides whereas the rocky area is stable. From a



Features	Details
LOCATION	Gothadi, Pokhara metropolitan, Ward no. 18, Kaski district
GEOLOGY	Seti formation of Lesser Himalaya of Pokhara Sub group, which is correlated with Kuncha formation of central Nepal. In this formation, the rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The slide area is composed of these rock fragments and clays as colluvial debris with 2-5m of thickness. The slope gradient varies from 35° to 80°.
SIZE	~350 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 500 cum extended to the 80 m downstream/Composed of significant amount of fines with various sizes of rock fragments, size varies clay to boulder sized rock fragments
SLIDE TYPE	Debris slide
AGE	Initiated on 25 Ashadh 2077 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season
HAZARD LEVEL ZONE	High
CASUALTIES AND FURTHER RISK	5 people killed, 3 injured, 1 house completely damage, 3 people displaced
PROPOSED MITIGATION MEASURES	RCC wall, wet masonry

geological stability point of view, most of the area is safe on this slope except gullies. The estimated peak angle of shear resistance of the material varies from 25° to 340. No major water sources and water tables nearby the area have been found. However, the small gullies in eastern side need to be protected especially during the rainy season.

Casualties and further risk:The landslide killed 5 people with 3 persons injured in the same family because of damaging a house that was on just 50 m downside of the base of the slide area. Only 1 house was completely damaged. A 15m long RCC supporting wall was swept out during the event. The slide was started gradually and eventually damaged and killed the people of the downslide areas when heavy rainfall occurred.

The reported earth slide duration was about 10 minutes. On the lower side of the slide slope, there are cultivated terraces. From site observation and the geology of the slope protection is prominent to save the existing road that is around the crown area and the protection of agriculture land in the downside area. As per site geological condition, simple type protection wall like, RCC, wet masonry on the upside slope that is near to existing road could be useful.

5.7.6 Vyas municipality, ward no. 9, Majhkot landslide (T-1)

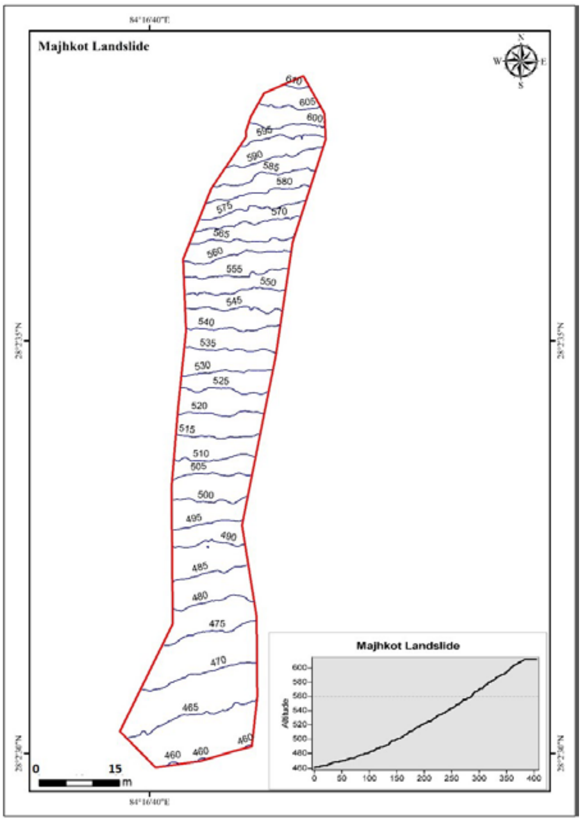
Landslide details: Physio-graphically, the project area lies in the hilly region of Lesser Himalayas consisting of hilly terrain and river valleys of the Madi river and its tributaries. In the regional geological framework, the study area lies in the Seti formation of Lesser Himalaya of Pokhara Sub group, which is correlated with Kunchha formation of central Nepal. In this formation, the rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The Seti formation is mainly composed of basically phyllite and quartzite. The total thickness of this Formation is more than 3,000m. Anticlinal hills with northward and southward dipping limbs bed with inclination 20°-42°. No major faults are reported around the study area. The major geomorphic features of the area include active gullies, small soil slides, residual soils and colluviums.

The landslide is classified as debris flow where the flowed materials are accumulated near to settlement areas covering around ~1700 sqm. The slide material is composed of various sizes of rock fragments with woody debris such as logs and tree stumps with significant fines. This debris flow was triggered by heavy rainfall that had taken severe lateral scouring the surrounding slope soils along the existing gully with cutting the top soil and regolith along its path. The 2015

Gorkha earthquake and following aftershocks also are the major contributing factors that developed the cracks around the overburden material that could erode easily. The gully gradient varies from 15°in the base to 75° around the crown area. The aspect of the slope is South-Eastward and the path of direction of the slide is 150° azimuth.

The soil material comprises mostly colluviums and residual soil along with the rock fragments of various sizes. The most encountered rocks are Phyllite, sandstone and quartzite. Slide potential classification (Krahenbunl & Wagner, 1983) of Rock of Nepalese Mountains also shows the area lies on Group II and III as per the composition of the rock. The classified groups lie on medium to high lithological slide potential. Debris area and weathered rock area are high potential slides whereas the rocky area is stable for the slide. On this consideration of stability, most of the area is safe except around and downstream of gullies and stream area from a geological stability point of view. The estimated peak angle of shear resistance of the material varies from 22° to 36°. No major water sources and water tables nearby the area have been found. However, the active slide gullies, a small gully in the southern side, need to be protected for proper drainage during the rainy season.

Casualties and further risk: The landslide killed 4 people with 1 person injured and 1 adult missing on the toe (base) area where the scattered houses and agriculture area existed. Altogether 4 houses were damaged where 3 partially and one house completely around the proximity of slide path direction on the lower part of the toe area. thirty meters of irrigation canal, 50 m of village trail, and 15 m of the supporting wall were swept out during the event. The reported debris flow duration was about 20m. Three houses exist almost on the path of the slide and have not been removed or shifted yet. Therefore, the chances of further slide is high because of the nature of slope material and active gully specially during the rainy season. On the lower side gully, there are cultivated terraces with scattered houses. Urgent need of protection is prominent to save the existing settlement and the protection of agricultural land. As per site geological condition, a simple type protection wall like wet masonry or gabion on the toe side of the slide could be useful.

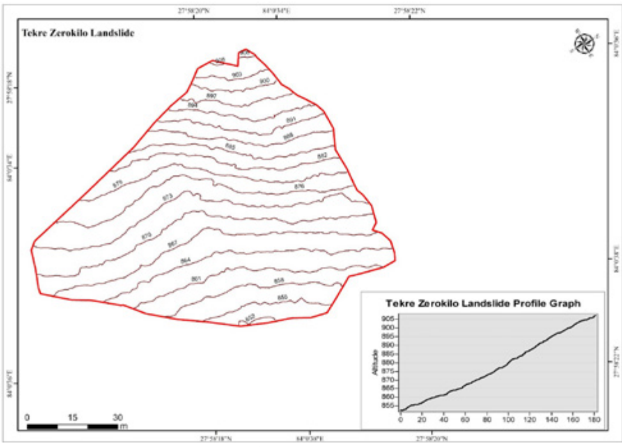


Features	Details
LOCATION	Majhkot, Byas Municipality Ward no. 9, Tanahun district (T-1)
GEOLOGY	rock type comprises grey to greenish grey phyllites, gritty and quartzites with minor conglomerate as sedimentary rocks. The slide area is composed of these rock fragments and clays as colluvial debris with 1-2 m of thickness. The slope gradient varies from 15° to 60°.
SIZE	~1700 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 6400 cum extended to the 300m downstream/ Composed of various sizes of rock fragments with woody debris such as logs and tree stumps with a significant amount of fines, size varies clay to 1m dia boulder
SLIDE TYPE	Debris slide
AGE	Initiated on 29 Ashadh 2077 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season active gully
HAZARD LEVEL ZONE	Moderate
CASUALTIES AND FURTHER RISK	4 people killed, 4 houses are damaged including 1 completely damaged
PROPOSED MITIGATION MEASURES	Gabion Walls, wet masonry, gully water controlling

5.7.7 Bhimad Municipality, Tekre Zerokilo landslide (T-2)

Landslide details: The Zerokilo Tekre landslide is located at Bhimad Municipality-2 near Tekre village and it is one of the most active landslides in the south-western part of the Tanahun district. This landslide was initiated during the monsoon of 2077. Initially a small landslide occurred on the cutslope of the road and later it was expanded and activated because of gully water diversion from the northern side of the slide area and developed the huge debris slide obstructing the Bhimad-Rampur Road. There is a prominent 5m long scarp on the upper part of the head of the landslide to its crown. The almost vertical (85°) scarp and the slide carried debris with big boulders (~2-5m dia.) These fell from the crown area and slope area. After the debris slides the gully water activated the debris flows to the accumulated zone as debris material. The earth (fine material) is also observed about 45-50% and it can be termed as a complex type of landslide because the debris fall is also observed on the crown to head area. The top of the slide material almost reaches the downside houses, situated below the road, while its toe also lies below the road along with the path direction 110° azimuth. The old landslide slide colluvial debris has been activating, the material consists of rock fragments of grey to black limestone, grey dolomitic limestone, dark grey shale with carbonaceous slate and calcareous sandstone along with phyllites of Galyang formation. The slide material is composed of various sizes of rock fragments with woody debris such as logs and tree stumps with less than 50% fine. The flanks of the landslide are covered by residual soil with a thickness of 2–5 m. On the left side (Northern side) a gully is present and the major driver to that made the slide because of the diversion of its water flow direction due to the fractures made by the Gorkha earthquake 2015. The gully is narrow (across 3 m), and its depth is about 2 m. It flows just north along the landslide slope. As the rocks nearby have 30°-40° inclination with north east direction, therefore the bedding inclination is favorable for the slide on the same constructed roads. Therefore, the many slides are present along the cut slopes of the road.

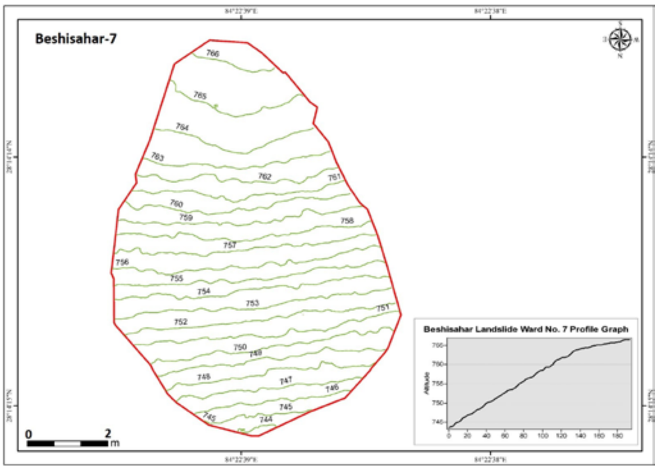
Casualties and further risk: No major human casualties and house damage is reported except the damaging of 150 m of blacked topped road with 30m gravel road. However, debris, rock slides and falls continue till present. On the other hand, the slide has an active gully, therefore a necessary support structure should be considered for the protection of further expansion of the slides and damaging the important road and the lower settlement. As per site geological condition, RCC protection wall, gabion wall and bioengineering with proper management of the gully are necessary.



Features	Details
LOCATION	Bhimad Municipality, Tekre Zerokilo landslide, Tanahun District (TBh-2)
GEOLOGY	Grey to black limestone, grey dolomitic limestone, dark grey shale with carbonaceous slate and calcareous sandstone along with phyllites of Galyang formation. The slide area is composed of these rock fragments and debris as colluvial debris and residual soil with 4m of average thickness. The slope gradient varies from 70° to 85°.
SIZE	~5000 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 40000 cu m extended to the 250m downstream/ Composed of various sizes of rock fragments with less than 50% amount of fines, size varies clay size to boulder sized rock fragments
SLIDE TYPE	Debris slide, rock fall, debris fall (Complex)
AGE	Initiated on Ashadh 2077 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season and north side gully
HAZARD LEVEL ZONE	Moderate
CASUALTIES AND FURTHER RISK	Blacked topped road
PROPOSED MITIGATION MEASURES	RCC wall, wet masonry, gabion wall, bioengineering

5.7.8 Beshishahar Municipality ward no. 7 landslide (L-1)

Landslide details: This landslide is located at the colluvial dominant fluvial mixture old terrace deposit on the right bank side of the Marsyangdi river. The soil types in the area are fine mix colluvium with little alluvial/fluvial sediments, this can be observed in the scarp section and surrounding. The thick (>50m) debris covers the underlying rocks, so no rock exposures are seen around the area. The aspect of the slide slope is NW (340°). The landslide is a simple type of slide consisting of debris as slide material having up to 1m diameter boulder. The slope is mostly covered by vegetation and soil. The slope varies between 20° to 60°. Seasonal springs also are present mid of the slope and it is very near to the existing house. The downside of the slope has berm and agriculture terraces and the gradient is low towards the downside.

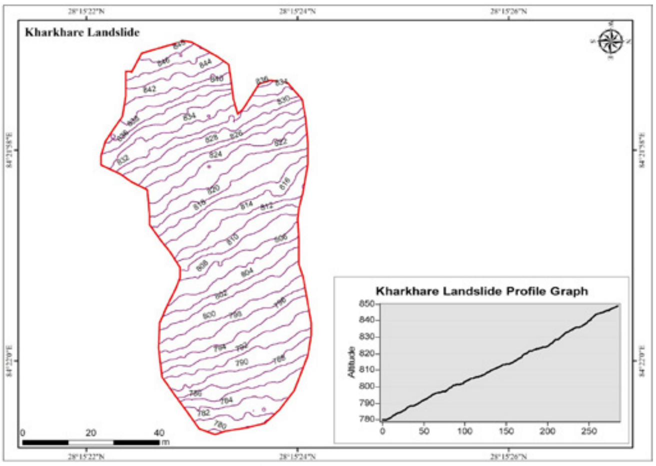


Features	Details
LOCATION	Beshishahar Municipality-7 landslide, Lamjung district (LBe-1)
GEOLOGY	Colluvial dominant fluvial mixture old terrace deposit on the right bank side of the Marsyangdi river. The soil types in the area are fine mix colluvium with little alluvial/fluvial sediments, The slope gradient varies from 35° to 65°.
SIZE	~ 63 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	Around 63 cu m extended to the 50 m downstream/Composed of various sizes of rock fragments with less than 50% amount of fines, size varies clay to boulder sized rock fragments
SLIDE TYPE	Debris slide with shallow rupture line
AGE	Ashadh 2077 BS
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, rainy season
HAZARD LEVEL ZONE	Moderate
CASUALTIES AND FURTHER RISK	3 people killed, 1 house
PROPOSED MITIGATION MEASURES	Gabion wall, bio-engineering or shifting the house

Casualties and further risk: One house was destroyed partially, and 3 people were killed by this landslide being collapse of house wall towards the slope by hitting the slide materials. The house existed in the middle of the slope and has not been removed or shifted yet. Therefore, the chances of further slide is high because of the nature of slope material and the seasonal springs that are just near to the existing house. The lower side of the whole slope has cultivated terraces without houses and settlement, therefore except the existing house no more risk for human casualties if a slide occurs again. The need for protection is prominent to save the existing house. It would be a simple type of protection wall like wet masonry or gabion on the toe side of the slide, it is just the southern side of the existing house.

5.7.9 Beshishahar Municipality, ward no. 6, landslide, Kharkhare Bhir (L-2)

Landslide details: The Kharkhare Bhir landslide is a rock slide, falls and flows mix up and denoted by the complex type of landslide along Besishahar Manang road section. The landslide is 90 m wide and the total length is 182 m long and about 3-4 m deep. It is also an active landslide since the last 10 years, especially during the monsoon rainfall. Actually this landslide started with a cut slope of the road of Beshishahar-Manang as small debris slides and further it was expanded due to the disturbance on the road with vibration of loaded vehicles, rainfalls and widening of the road on the toe area without protecting the slope. The landslide is mainly classified as complex types because of more than one single type of the slide. This landslide is mainly divided into 3 parts, source area that is the upper part around the crown, where the rock falls occurs, transportation zone with scarps and depositional zone on the base of landslide. The rupture line is believed to be about 3m beneath the slope surface of and its extension is 5m down side of the existing road. The road area is also creeping and sliding downwards slowly because there are many cracks around the road surface and slope. The



Features	Details
LOCATION	Beshishahar Municipality, ward no. 6, Kharkhare Bhir landslide, Lamjung district (L-2)
GEOLOGY	Colluvial deposit that is made of old landslide deposits. The rock fragments are mainly of white crushed quartzite of different sizes from 2mm to 2m of boulders in loose condition. Undisturbed outcrops major discontinuity near the hill slope is diping almost parallel to the cut slope with an attitude of 020°-045°/23°-43°. It is under seti formation of Lesser Himalayas.
SIZE	~13000 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	More than 40000 cu m extended to the 50 m downstream/Composed of various sizes of rock fragments with less than 20% amount of fines, size varies clay to boulder sized rock fragments
SLIDE TYPE	Debris slide with shallow rupture line
AGE	More than 10 years
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, toe cutting, vehicle movement
HAZARD LEVEL ZONE	High
CASUALTIES AND FURTHER RISK	1 bus, 1 Jeep and 1 motorbike damaged
PROPOSED MITIGATION MEASURES	RCC supporting wall, Gabion wall, shotcrete with wire mesh in crushed rock

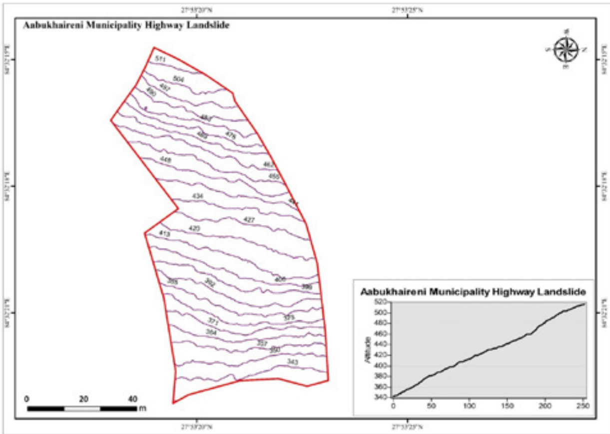
rock fragment source area is the existing colluvial deposit that is made of old landslide deposits. The main scarp of the landslide length is measured about 3 m with an 85° gradient. The rock fragments are mainly of white crushed quartzite of different sizes from 2 mm to 2 m of boulders in loose condition. The aspect of the slope is towards the north east and ends of its base on the Masyangdi river. The accumulation zone has rock fragments with a maximum 5 m of thickness. Undisturbed outcrops major discontinuity near the hill slope is diping almost parallel to the cut slope with an attitude of 020°-045°/23°-43°. The lower portion of the landslide is mostly covered by thick deposits of debris material along the road. Around the slide area, no rock exposure is found except a few 100s meters further. This landslide does not contain any gullies and springs, and hence, there is no any role of flowing water.

Casualties and further risk: Three vehicles including motor bike, jeep and bus fell because of this landslide. No human casualties have been recorded. However, this landslide damaged only one important road to Manang district headquarters and the district's other remote villages. Importantly, the settlement is present on the upside hill of the crown area, it is just 300-500 m further westward. If it is not properly managed the sliding problem, then the risk of collapse may occur around the upside settlement. The need of protection is prominent to save the existing roads and the upside settlement. This landslide covered more than 12500 square meter with more than 182 m height from the toe, therefore the landslide treatment would be difficult and could not be helped with a simple supporting system. Need to clear the loose and accumulated debris, make burns across the slope with proper drainage and design the RCC structures, shotcrete with wiremesh would be the solution to protect the slide and to save the important road.

5.7.10 Aabukhaireni Municipality, along the Pokhara-Muglin highway (G-1)

Landslide details: The slide area is made of strong rock quartzite, however the weathered rock underlain of topsoil made of debris is weak for the landslide. This lies along the cut slope of the busy Pokhara-Muglin highway. The debris slide of the uppermost soil along the rock surface, the joint plane of the rock, is daylight to the natural slope. The upper part of the slide has wedge failures and rockfalls, therefore the landslide can be considered as complex. However, the starting failure is the debris slide and followed by the wedge and rockfalls from the crown area. There is still a very active landslide along this road section. The rock debris moved as landslides with a mix of rockslide and rockfall since the last 5 years especially in the rainy season. The total area covered by the landslide is around 5500 sqm, and can be considered a big landslide, with more than 100 m length, about 80 m of width and about 1-2 m thickness. This landslide is characterized by a combination of rock topples, rockslides, rockfalls and debris slides. It is a complex type of landslide. The landslide is located in the rock formation belonging to Kunchha Formation, the formation consists of metasandstone, phyllite, quartzite and intercalation of carbonate rocks. The thickness of the rock debris was about 3 m, and it covered the road and the slide materials rolled and reached the Marsyangdi river, around the foothills of the slope. The volume of this debris is measured at more than 15000 cum. The debris consists of materials ranging in size from boulders to clay. No water is observed around the landslide slope. Gabion walls have been constructed to protect the road and casualties along the roadside or around the toe area. This gabion wall also is in a tilted condition because of the rock fragment load that is deposited from upside-down slides. The slope has highly fractured, moderately weathered quartzite rocks with carbonates. The attitudes of the rocks in this area are 045°/36°, 140°/35° and 340°/55°. Amongst these discontinuities, the 045°/36° is the most active for the landslide because of the favorable condition with the aspect NE to fall towards the roadside because of daylight condition to the natural slope. Around the crown of the landslide, there are forest lands that extend to the top of the hill. The field observations suggest that the area is prone to future landslides as a form of rock falls and rockslides and it is a risk to the vehicles and human life on the highway.

Casualties and further risk: No human casualties have been recorded. However, this landslide damaged the important and busy highway. The need for protection is prominent to save the existing roads for the further risk of casualties. This landslide coverage area is around 5500 sqm, therefore the landslide treatment could be difficult and could not be helped with a simple supporting system. Need to clear the loose and accumulated debris, hanging rock blocks around the crown area and making rock bolting, rock anchoring, RCC structures across the slope around the toe area with proper water drainage would be the protective solution to save the important road and casualties.



Features	Details
LOCATION	Aabukhaireni Municipality, Highway landslide, along the Pokhara-Muglin highway (Gab-1)
GEOLOGY	Kunchha Formation, the formation consists of metasandstone, phyllite, quartzite and intercalation of carbonate rocks. The attitudes of the rocks in this area are 045°/36°, 140°/35° and 340°/55°. Amongst these discontinuities, the 045°/36° is the most active for the landslide because of the favorable condition with the aspect NE to fall towards the roadside because of daylight condition to the natural slope.
SIZE	~5500 sqm
SLIDE MATERIAL VOLUME/ MATERIAL TYPE	More than 15000 cu m extended to the 115 m downside/ Composed of various sizes of rock fragments with less than 25% amount of fines, size varies from clay to boulder sized rock fragments
SLIDE TYPE	complex landslide including mix of Rockslide, debris slide, wedge failures and rockfalls, with shallow sliding thickness
AGE	More than 5 years
MAJOR TRIGGERING FACTOR	Heavy rainfall, steep slope, slope material, toe cutting, vehicle movement
HAZARD LEVEL ZONE	Low
CASUALTIES AND FURTHER RISK	No casualties reported
PROPOSED MITIGATION MEASURES	Removing all hanging rock blocks, RCC supporting wall, Gabion wall, shotcrete with wire mesh in crushed rock

6. Indicative Plan for Hazard Mitigation

Landslide hazard is a function of susceptibility (spatial propensity to landslide activity) and temporal frequency of landslide triggers, and its assessment may be done on local (individual slope), regional, national, continental, or even global scales. The most appropriate method in each scale depends on the extent of the study area and on the available data. Various methodologies for landslide hazard assessment for the use as precaution by indicative plan on different scales can be assessed in different ways as per the geological features.

In any type of landslide hazard assessment as an indicative plan, there is a need to consider topography and other factors that influence the propensity to landslide activity (susceptibility factors), as well as landslide triggering factors (precipitation, earthquakes, human activity).

Identifying the landslides in the mountainous region is a difficult task. The nature of slope, nature of slope material, hydrological condition, vegetation presence, slope geology are the main parameters that need to be assessed in detail. For the understanding and examination of the material and physical condition on the slope contributes to determining the proximity as indicative features of the potential to the landslides. Indicative plan associates the examination of soil slope along with slope susceptibility and rock slope study along with discontinuities & fractures as described below

6.1 Soil Slope Study

There are few methods of examination of the existing soil and condition in the field and the available information like in the form of maps, which includes for example topographical, land use and vegetation cover maps, all including the surroundings. The identification of first sharp break in slope above and below the site or at least a minimum 500 m upslope and downslope of the site whichever is applicable. Identification of the first Maps on a scale of 1:5000 or nearest equivalent and the following features should be identified:

- Drainage lines (permanent, intermittent and dry valleys)
- Erosion features such as rills, gullies, badlands, mass movement, bank erosion etc.)
- Areas of sedimentation, including streams
- Man-made features such as settlement, tracks, roads etc.
- Water users and intake points downstream
- Type of vegetation cover
- Soil type and depth.

6.1.1 Slope Susceptible to Failure

Slopes that are too steep with the weathered material are subject to periodic failure. Instability may be associated with moderate to steeply sloping terrain which has been disturbed by man. Natural slopes that have been stable for years may suddenly fail because of construction activities on hill slope, which may bring about:

- Changes in the slope topography
- Changes in ground water conditions
- Loss of cohesive strength of soil
- Stress changes in the soil underlying the slope
- Acceleration of the rate of weathering of rock
- Springs, seeps, or saturated ground in areas that have not typically been wet before.
- New cracks or unusual bulges in the ground, street pavements or sidewalks.
- Soil moving away from foundations.
- Ancillary structures tilting and/or moving relative to the main permanent structure.
- On existing old landslides.
- On or at the base of slopes.
- In or at the base of minor drainage hollows.
- At the base or top of an old fill slope.
- At the base or top of a steep cut slope.
- Developed hillsides where leach field septic systems are used.

6.2 Mitigation of Slope Instability and Soil Erosion

The impact of slope instability and erosion will be huge in terms of damage of agricultural land, forest area, other properties as well as reduction in agricultural production. The following mitigation measures shall be adopted:

- Correction of maintenance of the slope protection measures and drainage works
- Minor landslide and mass wasting shall be immediately cleared and slope restored with appropriate technology (bioengineering)
- Soil conservation shall be promoted in the right of way and vulnerable areas beyond the road alignment
- Re-vegetation of cut and fill slope or exposed areas as soon as possible by using native plant species
- Adoption of bioengineering techniques
- No or reduce construction work during rainy season
- Community Forest User Groups shall be promoted to conserve and manage road alignment located at their CFs properly
- Earth excavation, particularly in unstable zones, drainage work, quarrying and spoil disposal shall be discouraged as it aggravates slope instability and soil erosion.

6.2.1 Drainage and Cross Drainage works

The concentrated water from the road outlet causes erosion and landslide eventually affecting the stability of the road itself. For this, following mitigation measures should be adopted as appropriate:

- Adequate numbers of drainage structures should be provided in order to have minimum interference on natural drainage pattern of the area
- Drain water discharge into farmland or risky locations should be avoided.
- No diversion of water away from natural water course as far as possible

6.2.2 Spoil stabilization:

Spoil is the earth material excavated during road construction and disposed at site. Most of the downslope of road is found to be used as spoil disposal site. This provides poor drainage for water and is very vulnerable to erosion. This causes toe cutting of constructed road. Moreover, such spoil is loosely placed and sheet erosion is very active. If this spoil is well managed against erosion it provides better support for road. Bioengineering techniques for spoil management can be pointed out as follows:

- Creating managed channel for water,
- Creating vegetation cover for soil stabilization,
- Covering with rock material to prevent erosion.

6.2.3 Slope stabilization:

Cut slopes of road are exposed due to excavation and flowing water can easily erode creating gullies which may further cause mass movement in such slopes. Such slopes should be managed with proper understanding of stability.

- Vegetation can be applied to achieve following objectives in slope stabilization:
- Catching materials against movement
- Armoring soil against surface erosion
- Supporting slopes
- Reinforcement of shear strength of soil,
- Drainage to prevent saturation and slumping,
- Improvement of the local environment.

6.2.4 Gully Management:

Gullies are very responsible for scouring of road and erosion. Bioengineering techniques should be applied as:

- Strengthening of gully bed,
- Reduction of water current,

- Vegetation in side walls

6.2.5 Minimizing Soil loss:

Soil erosion is a cause of various factors. All factors can be minimized by use of vegetation and proper drainage.

- At sites with low shear strength, sliding can be prevented by applying deep rooting shrubs and trees.
- At sites with excessive surface erosion, grasses can provide better support.
- At sites with excessive gullying activities check walls and vegetation and decrease strength of water current.
- At sites with water logging and slumping effect, proper drainage can reduce saturation effect.

6.2.6 Vegetation Techniques:

Rehabilitation of the studied landslides and slope failures by using plants can be performed by following vegetation techniques:

Tree and shrub planting:

Methods: plantation at regular interval to establish better environmental ambience.

Sites: Can be easily applied at slopes up to 35°. It can be carefully applied at slopes between 35° and 45° also. If slope failure is the only vulnerability this technique should be applied.

Benefits:

- Shrubs have following advantages:
- Moderately deep rooting,
- Lighter weight and less turning movement than trees,
- Usually more resilient than trees, growing in harser sites.
- Thorny bushes prevents damage caused by cattles,
- Works better with structures without exerting pressure.
- Trees have following advantages:
- Deep rooting provides best anchoring
- Provides shade to decrease dryness and prevents splash erosion,
- Improves microclimate supporting vegetation growth.

Best species:

Recommended shrubs are as follows:

- Lyonia ovalifolia (Angeri)
- Pyracantha crenulata (ghangaru)
- Daphne papyracea (Lokta)
- Vitex Negundo (simali) - Upto 1750m, Good for stony gullies, moist and shady places, Also grows on hot, dry road cut slopes.
- Lantana camara (phul kada) - Upto 1750m, Grows well on dry, stony degraded sites

Recommended trees are as follows:

- Alnus nepalensis (utis)
- Fraxinus floribunda (Lankuri)
- Pinux roxburghii (khote salla) - Upto 2000m, Grows well on harsh dry sites, Also suitable for eroded clayed red soils
- Ficus auriculiformis (nebharo) - Best of the figs on degraded sites
- Ficus semicordata (khasre khanyu)
- Schima wallichii (chilaune) - Middle mountains, Grows well in damp shady places
- Prunus cerasoides (painyo) - Useful throughout middle and lower mountains, More Tolerant to poor soil conditions
- Psidium guajava (guava) - Upto 2000m, Tolerates hot and dry sites

Grass lines:

Method: grasses should be planted in lines vertically, horizontally or diagonally so as to achieve proper drainage system and decreased runoff.

Sites: In slopes less than 35°, plantation in horizontal lines. In slopes greater than 35° and less than 60°, vertical or diagonal plantation can be applied. For slopes greater than 60° grass lines plantation are difficult to operate but grass palisades can be applied.

Benefits:

Small stature grasses have following advantages:

- light in weight,
- relatively quick to establish
- usually tough plants adapted to harsh sites

Best species:

- Cynodon dactylon (dubo) -For slopes lesser than 35°- Upto 1800m, Tolerates fairly intense grazing
- Pennisetum clandestinum (thulo dubo/ kikuyu)- Upto 2000m, Fairly fertile soil
- Sachharum spontaneum (kans) – for steeper slopes, Upto 2000m, Dry harsh sites, coarse alluvial soils, stony areas
- Pennisetum purpureum (Napier) - Upto 1750m, Grows well on poor, south facing slopes, Also grows well on eroded, clayed red soils (rato mato)
- Frianthus rufipilus (rato kans), 900 to 2200m, North facing slopes, easily colonises road cut slopes and landslides
- Cymbopogon microtheca (Khar)- 400 to 2000m, Grows well on harsh dry sites
- Arunduella nepalensis (Phurke)- 700 to 2000m, Relatively Damp southwest to north facing slopes
- Pogonatherum paniceum (musekharuki)- Upto 2500m, Steep excavation sites, damp areas
- Thysanolaena maxima (amliso)- Upto 2000m, Also grows on Fairly dry, stony sites

Palisades of cuttings:

Method: To create strong barrier and trap materials moving down the slope, Cut-Stems of Hardwood bushes should be applied along contour lines.

Sites: cultivated slopes lesser than 35° can develop contour hedges. Can be applied at slopes up to 75°.

Benefits:

- Can be planted with less damage to slope,
- Cheaper and quicker to produce,
- Plant is not easily damaged,
- Produces stronger vegetation that grass lines,

Best species:

Many trees and hardwood shrubs can be planted as cuttings in slopes. Even fodder species can be applied for this technique. Few recommended species are:

- Vitex Negundo (simali)
- Adhatoda vasica (assuro)
- Ipomoea fistulata (saruwa)
- Lantana camara (phul kada)

Grass seedings:

Method: Direct sowing of grass species to create vegetation cover for exposed slopes.

Sites: almost any bare sites with slopes upto 45°, in steeper slopes seeds may be washed off.

Benefits and species recommended are same as for section Grass Lines

Tree and shrub seeding:

Method: direct sowing or broadcasting.

Sites: steep, rocky and unstable slopes where seedlings and cuttings cannot be planted.

Benefits same as of section Tree and shrub planting

Best species:

- Alnus Nepalensis (utis)
- Ficus semicordata (khasre khanyu)
- Fraxinus floribunda (lankuri)

Bamboo planting:

Method: plantation of rooted culm cuttings or single node cutting.

Sites: moist slopes where scouring should be prevented and upslope requires reinforcement. Also stone walls or gabions can be reinforced by using bamboo planting.

Benefits:

- Easier and cheaper to plant,
- Provides proper Reinforcement,
- Grazing animals cannot damage.
- huge, dense root system,
- heavy, with a low weight mass.

Best species:

- Locally available species of bamboo.

Turfing:

Method: Plantation of shallow rooting grass along with soil layer

Sites: best for gentle slopes, even in steeper slopes this technique can be applied with support from wooden pegs by hammering to prevent sliding,

Benefits:

- Provides immediate cover to bare surface,
- Regeneration is quicker.

Best species:

- Cynodon dactylon (dubo)
- Trifolium species (clover)

Fascine constructions

Method: bundling of live branches and laying in shallow trench that puts out roots and shoots forming strong line of vegetation.

Sites: best applied in consolidated debris or soft cut slopes.

Benefits:

- Checks scouring,
- Can survive better,
- Produces stable vegetation

Best species:

- Lantana camara (phul kada)
- Pennisetum purpureum (napier)

Fence construction:

Method: preparation of live stem cuttings of about 1 m long to be hammered in horizontal contour lines.

Sites: non-cultivated slopes upto 35° only

Benefits:

- Establishes contour structure
- Prevents sliding and movement of materials,
- Increases shear strength of soil,

Vegetated rip-rap:

Method: combined application of stone walls and vegetation to reinforce smaller slopes and gully beds.

Sites: slopes not more than 2m high and gully with limited amount of debris flowing

Benefits:

- Best way to permanently strengthen gully floor,
- Stone walls are reinforced by the vegetation.

Best species:

- Recommended species are grasses and shrubs as already mentioned.

Small scale Engineering:

Check dams

Method: simple construction using stones to provide staircase to flowing water

Sites: gullies with moderate slopes and less debris flowing where side cutting and undercutting should be prevented.

Benefits:

- Decreases gradient of gully and reduces current,
- Provides staircase to flowing water ceasing potential energy that causes scouring.
- Best method to stop gully erosion permanently.

Promoting Livelihoods:

Application of bioengineering techniques requires better understanding of livelihoods of the local people. As Plantation is the fundamental concept of bioengineering for rehabilitation of slopes. The concept must include the direct participation of local people or community to sustain the rehabilitation activity. This should prioritize the plantation species according to the need of local communities. The activity should be able to generate fodder, firewood, timber and NTFPs to some extent that can generate direct benefit for the community promoting their livelihood. This generates conservation stewardship among the local people. The eroded areas to be rehabilitated can be managed by handing over to communities developing proper management plan for sustaining the activity and sharing the benefits.

Most of the recommended plants species are of direct benefits as follows:

Grasses:

- Cynodon dactylon (dubo) - Fodder
- Pennisetum clandestinum (thulo dubo) - Fodder
- Pennisetum purpureum (Napier) - Fodder
- Cymbopogon microtheca (Khar) - Thatch, fodder
- Thysanolaena maxima (amliso)- NTFP

Shrubs:

- Daphne papyracea (Lokta) - NTFP
- Vitex Negundo (simali) - Hedges

Trees:

- Alnus nepalensis (utis)- Firewood, timber, fodder
- Fraxinus floribunda (Lankuri)- Firewood, fodder
- Pinux roxburghii (khote salla)- Timber, firewood
- Ficus auriculiformis (nebharo)- Fodder, firewood
- Ficus semicordata (khasre khanyu)- Fodder, firewood
- Schima wallichii (chilaune)- Timber, firewood
- Prunus cerasoides (painyo)- Fodder, firewood
- And variety of Bamboo species- NTFP

7. Conclusion and Recommendation

The study is significantly important in identifying soil erosion and landslide risks in the Gandaki province classified according to different environmental as well as administrative variables. This study aims to facilitate policy formulation and management intervention in the area for reduction of damage caused by soil erosion and landslide hazards.

The findings of the study area:

- Gandaki Province with 11 districts has a very fragile and challenging topography while soil erosion and landslide problem is highly sensitive. There are 6 major River watersheds under Gandaki Basin while there are multiple sub-watersheds with dynamic characteristics. Soil erosion and landslide problem and processes vary significantly between these watersheds and no single principle can be applied in all such watersheds. In this scenario, the study derives erosion weightage in each district, palika, wards and watersheds which is expected to facilitate prioritization and implementation of soil conservation activities under the ministry of Forest Environment and soil conservation.
- Landslide inventory of 11 districts summarized 351 landslides polygons and 90 landslide points. Based on the data Inventory, Digitized layer, and input layers, FR ratio method is prepared for analysis of Landslide Hazard susceptibility modeling.
- The erosion estimation and landslide hazard susceptibility model clearly identifies that unique watersheds in Gandaki province requires special treatment to reduce and manage the risks.
- Soil conservation and Slope stabilization are crucial interventions required in fragile topography of Gandaki province to safeguard the environment as well as human settlements and infrastructures. Currently there are only two offices, which is inadequate in implementing the soil conservation and slope stabilization practices.
- Landslide profiling has clearly suggested variety of landslides based on size, characteristics and future risks. These needs special attention in order to reduce the loss in future.
- Brief Indicative plan suggest the implementation of various activities that can help in achieving the soil conservation and slope stabilization. It can be low cost bioengineering to engineering reinforcement structures.
- Human induced activities like road construction and unmanaged irrigation has caused severe challenges in soil conservation and slope stabilization and proper integration of development activities is required in order to continue sustainable development practises.
- Climate change has uneven and uncertain impacts in the climate as well as topography. Increase in extreme events are already evident and this can aggravate the situation of soil erosion and landslide. It is utmost urgency to reduce such damage and address the climate change issues.
- Livelihood of communities are directly or indirectly affected by soil erosion and livelihood and proper management of these issues can be also integrated with livelihoods of local communities creating opportunities as well as environmental benefits for the communities.

The mountainous terrains of Gandaki Province are characterized by highly dynamic physical processes, and therefore, implementation of infrastructure development projects is a big challenge. Similarly, more pragmatic approaches of construction and maintenance of infrastructure are needed in Nepal compared with other mountain terrains of the world. A better understanding of the geological nature of the terrain and the interaction of various triggering factors of natural hazards will greatly help in the development of safer infrastructures, mitigation of natural hazards, and control of land degradation in the Himalaya.

8. References

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9. Annex

9.1 Photographs

Inventory 1: Vyas Municipality Ward No. 9

Inventory 2: Harpan Khola-Side Kaski



Inventory 3: Annapurna Rural Municipality

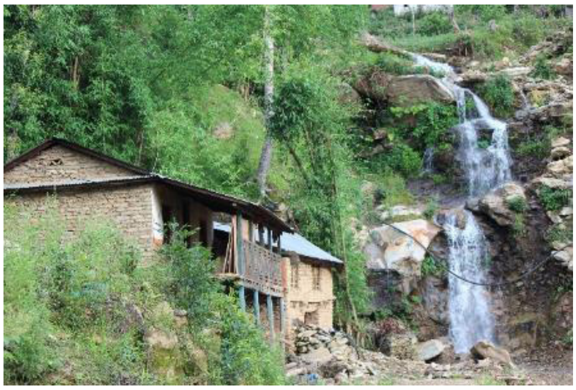



Inventory 4: Nauledanda Annapurna Rural Municipality

Inventory 5: Gothadi Sarankot

Inventory 6: Jaljala Parbat

Inventory 7: Durlungkot Parbat



Inventory 8: Falewash

Inventory 9: Tokray- Bhimad-Tanahun

Inventory 10 Besisahar Municipality

Inventory 11: Besisahar Municipality

Inventory 12: Abukkhaireni

Landslide above Kushma Bazar

Landslide as seen on the way to beni from Kushma

Consultation with Parbat Officials

Consultation with Tanahun Officials

Consultation with Beni Officials

Consultation with officials from Soil Conservation

Consultation with Parbat Officials

Consultation with officials from Soil Conservation

Consultation with Locals at Pyaudi Bazar

Consultation with Locals at Gothadi Sarankot

Consultation with Locals at Jaljala Parbat

Consultation with Locals at Durlungkot Parbat

Consultation with Locals at Besisahar

Bright View of Pokhara sub-metropolitan city during the field trip by ajay shrestha