Master Thesis, Department of Geosciences

Bivariate Statistical Analysis of Landslide Susceptibility in Western Nepal

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Discipline: Environmental Geology

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Faculty of Mathematics and Natural Sciences

University of Oslo

1 June 2011

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ABSTRACT

Landslide susceptibility mapping is very crucial for planning and development in a disaster prone region in Nepal. Nepal is one of the landslide prone countries of the World. Very high relief, steep slopes, complex geology and diverse vegetation cover has made Nepal vulnerable to landslides. Some national level and individual research initiatives have been published about landslide process, mechanisms and hazard zonation. But there are a few studies carried out in the Western region of Nepal which is one of the landslide affected regions of the country.

The main purpose of the study was to prepare landslide susceptibility maps of the five sample sites of Western Nepal (Palpa/Gulmi, Palpa, Baglung/Myagdi, Parbat and Kaski) and validate the result by model replication. A number of qualitative and quantitative landslide susceptibility assessment methods exist to evaluate the landslide susceptibility. They are briefly reviewed here. In this study, a bivariate statistical method-Landslide Nominal Susceptibility Factor (LNSF) is employed to analyze the data. Database of related landslide casual factor maps: slope, lithology and land cover were derived in Arc GIS environment. Landslide Susceptibility Index (LSI) maps were generated by establishing a relationship between landslides and the factor maps. Distinct color variations between boundaries of the lithology were visible in the maps. The reason for this was the weighting process.

The analysis of relationship between landslide inventory and the thematic maps inferred that casual factors such as slope gradients, lithology and land use pattern contributed to landslide process. But the contribution of each parameter was site dependent. The optimum range of slope gradient from where the landslide distribution recessed varied between study areas. The landslides in sedimentary rocks failed in lower angles. Terai, Siwaliks, Lower Nuwakot, Upper Nuwakot and Tansen lithological zones composed of alluvial soils, sedimentary and metamorphic rock; were prone to landslides. Although Higher Himalayan zone consists of relative stable rock masses; it consisted of some landslides. High slope gradients and bare rocks induce landslide in this zone. The intensive land use in fragile geology also contributed positively for landslide failure in lower slope angles. In Palpa/Gulmi and Palpa, Parbat and Kaski cropland and forests were most sensitive to landslides. Large proportions of landslides were confined to cropland and forests. The forests

in these areas are intensively used as a result forests are degraded. The other most important aspect is that presence of forests in highly prone lithology might induce landslides due to added canopy and stem weights of trees during monsoons. Another reason is that the vegetated areas in steep slopes with little soil also affects the soil-root anchorage of the vegetation and consequently affect the landslide process.

The effect of each parameter was analyzed using rating curves. The analyses indicated that the effect of susceptibility parameters is site specific. The effect of lithology was distinct in Palpa/Gulmi, Palpa and Baglung/Myagdi while slope, lithology and land cover had similar effect for Parbat and Kaski. Including an input parameter in susceptibility analysis does change the output. The exclusion of land cover when susceptibility mapping did not show any changes in the rating curves. Therefore, identifying the most influential parameter is important for susceptibility modeling.

Model replication proved moderately successful for areas of similar lithology conditions. The rating curves were slightly higher than the hypothetical diagonal curve of 0 to1. The first 20% high susceptibility zone occupied around 38% and 39% of the landslides in Palpa/Gulmi and Parbat respectively.

Model validation produced moderately satisfactory results when area distribution by susceptibility class between calibrated and validated model was compared. An increase in percentage of area in very low and low susceptibility classes in both replications was observed. In Palpa/Gulmi, calibrated map occupied 33% of the total area while model replicated map yielded 37% of the total area. In Parbat, calibrated map hosted 6% of the total whereas model replicated map owned 36% of the total area. Larger areas in lower susceptibility zones have implications over land use management. Larger area in lower susceptibility zones means large proportion of area can be used. Similarly, it improved the predictive capacity of the model by reducing the area of most susceptible zones by 32% compared to the area predicted in the original map (susceptibility map developed using the landslides of the same area) in Parbat.

ACKNOWLEDGEMENT

I am grateful to my supervisors Professor Farrokh Nadim and Dr. José Mauricio Cepeda for their constructive guidance and supervision throughout the research period.

I would like to thank Bård Romstad, Trond Eiken and Helge Christian Smebye for their advices in data analysis in Arc GIS.

My thanks go to University of Oslo and Norwegian Geotechnical Institute (NGI)/International Centre for Geohazards (ICG) for providing me data and space to conduct the research.

Finally, I am grateful to my family for their enormous and continuous moral support to complete my study.

Last but not the least, I wish to submit my gratitude to all my friends who contributed in miscellaneous ways for the completion of this work.

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1. INTRODUCTION

Nepal is a mountainous country in between India and China constituting one third of the Himalayan arc that resulted from Indian and Eurasian plate collision (Powell and Conaghan 1973, Molnar and Tapponnier 1975, Bilham et al. 1997). The distinct features of the Nepal are steep slopes, extreme relief, rugged topography, and high elevation ranging from 60m to 8848 m from a.s.l. within around 200 km north-south extent (Duncan et al. 2003). Presence of complex geology, diverse climatic conditions and floral diversity within a small elevation range makes Nepal a unique place of the world. However, these distinct physiography and biogeography, which are the consequence of seismic, tectonic, hydro-logic and geomorphologic processes, have made it vulnerable to natural disaster (Hasegawa et al. 2009, Pokhrel et al. 2009).

Nepal experiences various geohazards such as earthquakes, landslides, flood, forest fire, windstorm, avalanche, and epidemics. Landslides are the most common natural hazards affecting people and property (Upreti 1999, Lave et al. 2005, Petley et al. 2007, Hasegawa et al. 2009, Pokhrel et al. 2009, Poudyal et al. 2010).These are scale dependent ranging from massive failure of single peaks to small slopes failures (Shroder Jr and Bishop 2004).

Landslides occur due to a combination of trigger mechanisms and susceptibility factors such as fragile and complex geology, steep slopes, rugged topography, variable climatic and microclimatic conditions, rainfall, earthquake and vegetation degradation (Gerrard and Gardner 2002, Wobus et al. 2003, Hasegawa et al. 2009). Landslide susceptibility varies from one region to another in Nepal. This variation is often attributed to rainfall. Rainfall-induced landslides occur almost annually during monsoon and distribution of rainfall is uneven throughout Nepal (Kansakar et al. 2004). Similarly, human activities have also aggravated landslide susceptibility due to improper land use practices, unplanned infrastructure development and over exploitation of natural resources (Kienholz et al. 1983, Mahat et al. 1986, Tiwari 2000).

Landslides affect people, infrastructures and property regularly in Nepal. Unfortunately, the effects of landslides are poorly quantified in terms of economic costs (Petley et al. 2004). Even many susceptible sites are not identified yet. Therefore, understanding landslides susceptibility and their effects is a crucial issue given the cost of landslides.

Different research and implementation efforts are in progress to address the landslide process and its causes and consequences. For example World Bank sponsored landslide mapping in Nepal (NGI 2004), rural access programs, Disaster Management and Early Warning System (organized by different local organization but funded by donor agencies).

However, the national and international efforts to address the landslide vulnerability have been less successful. Heavy investment is being made in Nepal by many international organizations including Department for International Development-UK (DFID-UK), Japan International Cooperation Agency (Japan), and Deutsche Gesellschaft fur Internationale Zusammenarbeit (GTZ-Germany), World Bank, Asian Development Bank for programs such as rural access program where landslide occurrence is a key issue (Dahal et al. 2006). But, in the majority of cases international supports are confined to collaborative road projects in specific locations where the road is being built. The government effort is limited to post disaster support programs.

Within the last two decades, several papers have been published on geomorphic, tectonic and seismic activities in the Himalayas. Although landslides are also the result of these seismic and tectonic processes these papers are either not giving sufficient explanation on the linkages of these processes with landslides or their effects were considered as seismic events such as earthquake in most cases (Caine and Mool 1982, Gerrard 1994, Dhakal et al. 1999, Hasegawa et al. 2009, Poudyal et al. 2010). Similarly, in case of flood studies, landslides were not distinguished from flood events because they occurred in tandem. Consequently, landslides were under estimated in these studies (Paudel et al. 2003, NGI 2004).

A number of research case studies have been published about different aspects of landslides but they are scattered in different locations. Most of these case studies cover a very small part of a place as a study unit (Ives and Messerli 1981, Wagner 1983, Heuberger et al. 1984, Gerrard 1994, Upreti and Dhital 1996, Gerrard and Gardner 2002, Petley et al. 2007, Hasegawa et al. 2009, Poudyal et al. 2010). The findings of the case studies are yet to be synthesized and integrated in local and national landslide planning and management. Therefore, many potential areas are yet to be explored about landslides. Particularly, regions and sites with large population density and valuable resources are in urgent need of the landslide susceptibility evaluation.

2. BRIEF OVERVIEW OF LANDSLIDE INVESTIGATION IN NEPAL

In Nepal, landslides occur due to combined effects of landslide-inducing and causal factors (Gerrard 1994, Gerrard and Gardner 2002, Hasegawa et al. 2009, Ghimire 2011). These landslide activating agents such as rainfall, earthquake and seismic events are also called trigger mechanisms. Susceptibility factors include intrinsic material properties of earth and physical topography such as steep slopes, rugged topography, sparse vegetation cover, fragile geological formations and structurally fragmented rock materials (Wieczorek 1996). In addition to, human activities also aggravate landslide susceptibility due to insufficient attention being given in the land use practices, infrastructure development and over exploitation of natural resources (Paudel et al. 2003, Petley et al. 2004, Petley et al. 2007). Natural factors causing landslides in Nepal are discussed in section 4. A short summary of landslide studies in Nepal is discussed in this section.

In Nepal, landslides have occurred since prehistoric times. Moraines and rock mineral deposits are the evidence of past landslides. For example, the Langtang landslide occurred during the last glacial and inter glacial periods and landslide deposits as moraines and different forms of rock minerals from the same period are found in the Langtang valley. But records of these prehistoric landslides are scarcely available (Heuberger et al. 1984).

Laban (1979) pioneered the task of landslide investigation in Nepal. The next landslide investigation initiative started when the Mountain Hazards Mapping Project, sponsored by the Nepal National Committee for Man and Biosphere (MAB) and the United Nations University was established in 1980s (Caine and Mool 1982). The main objectives of the project were (1) the production of prototype maps to show slope stability and mountain hazards in Nepal and (2) the development of corresponding methods for assessing mountain hazards.

A number of papers have been published about landslides that significantly contribute to the knowledge of landslide processes, mechanisms, causes and associated hazards (Laban 1979, Ives and Messerli 1981, Caine and Mool 1982, Kienholz et al. 1983, Wagner 1983, Heuberger et al. 1984, Gerrard 1994, Rowbotham and Dudycha 1998, Dhakal et al. 1999, Gerrard and Gardner 2002, Gabet et al. 2004b, Petley et al. 2004, Petley et al. 2007, Hasegawa et al. 2009, Poudyal et al. 2010, Ghimire 2011).

But a few studies on landslide hazard, causes and its impact are focused on the Western Region of Nepal (Waltham 1996, Rowbotham and Dudycha 1998, Dhittal et al. 2008, Regmi et al. 2010, Gurung et al. 2011). Western Region of Nepal is one of the landslide prone regions of the country.

Recently, a national level landslide hazard mapping process has been initiated in Nepal. This process was executed by Norwegian Geotechnical Institute, Norway and sponsored by World Bank (NGI 2004). Landslide Hazard Maps for Nepal are being prepared using the global datasets. Therefore, once finalized they can certainly provide an extent of general hazard situation of Nepal.

Prior to this study, an assessment of landslide hazards and risk for SAR countries including Nepal was conducted by Norwegian Geotechnical Institute (NGI) and World Bank in 2004 (NGI 2004). The study concluded that Nepal is one of the highly landslide exposed countries of the world due to its topography, geology, climatic factors and human interference such as urbanization and deforestation.

This initiative started as a result of World Bank sponsored ‘‘Global landslide and avalanche hotspots study’’. The study identified the most exposed countries of the world to landslide hazard. South Asia Region (SAR) including India and Nepal were identified as highest risk areas on the basis of risk maps developed using hazard maps and population exposure maps (Nadim et al. 2006).

3. LANDSLIDE DEFINITION AND THEORY

The term ‘landslide’ refers to geological phenomena which include a wide range of ground movements. It also describes processes that involve downward and outward movement of earth materials including rocks and soils that result in slope modification. Various authors have attempted to explain the term landslide including many types of mass movements.

Cruden (1991) defined ‘‘landslide as the movement of a mass of rock, earth or debris down a slope’’. The joint ISSMGE, ISRM and IAEG Technical Committee on landslides and Engineered Slopes (JTC-1) defined ‘‘landslides as the downslope movement of mass of rocks, debris and soil or earth’’ (Fell et al. 2008). All these definitions describe the movement of earth material without any landslides inducing agents. These processes are categorized on the basis of i) kind of material involved ii) type of movement, and iii) state of phenomena.

Cruden and Varnes (1996) provided a classification of slope movement on the basis of nature of material and type of movement. Type of material involved in slope movement is grouped into rock, debris and earth. ‘Rock’ is- a hard mass that was intact and in its natural place before the initiation of movement. ‘Earth’ -constitutes soil material with 80 percent or more particles smaller than 2mm in size. ‘Debris’- contains coarse material with 20-80 percent of the particles larger than 2mm in size.

According to Cruden and Varnes (1996) mass movement types include fall, topple, slide, spread and flow. Falls and topples are sudden movement of mass of earth material mainly induced by gravity. Falls are abrupt movement of mass of rocks and/or soils from steep slopes or cliffs. Falls occur by free fall and rolling which are highly influenced by gravity, mechanical weathering and inertial water. Falls occur along discontinuities such as fractures, faults, joints and bedding planes. Topple is the forward rotation out of the slope of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass. Topple is driven by gravity and ice or water present in the mass.

Other types of mass movements are slide, spread and flow. Slide is the mass movement from a distinct zone of weakness that separates the slide material from stable underlying material. Two main types of slides are rotational slide and translational slide. In rotational slide the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse to across the slide. In translational slide the landslide mass moves nearly in planer surface with little or backward tilting. Spread slow movement of cohesive mass of rock or soil combined with subsidence of the fractured mass of cohesive material into softer underlying material. Spreads occur due to liquefaction of flow of softer material. Flow is a continuous movement of soil or rock materials in which surface of shear are short lived. Combining the type of movement and materials involved in landslide process different names are formed. The most common types slope movements based on the type of material moved are rock fall, debris flow and landslide.

Landslides can be grouped into three types based on the state of phenomena: active, passive and reactivated. Active landslide is a landslide that is moving at present either for the first time or reactivated. Passive landslide is that which occurred in the past such as prehistoric landslide but bears a potentiality to be reactivated. Reactivated landslide is a landslide that is active after being inactive (Fell et al. 2008).

Since this study assesses landslide susceptibility, it is important to define the term susceptibility also. The term landslide susceptibility refers to qualitative or quantitative assessment of future landslide occurrence. The probability of landslide occurrence is defined on the basis of correlation between the controlling factors for slope instability and the spatial distribution of landslide that occurred in the past (Lee and Min 2001, Fell et al. 2008) . Spatial distribution of landslides is evaluated on the basis of existing landslides or potential landslides that may occur in near future. These are identified on the basis of their sources. The location of landslide source could be in the area or may have their source outside the area but may travel onto or regress into the area.

The basic principle behind landslides is slope instability. Slope stability expresses a balanced relationship between shear stress and shear strength (Duncan 1996). In every slope gravity-induced shear stress exists which increases with slope height, slope inclination, and unit weight of the materials forming slope. Shear stresses are also added due to thermal expansion and contraction of surface zones, freezing-thawing actions and other factors. Under normal conditions, slope surfaces are in equilibrium between the shear stress and shear resistance. A loss of balance between the resisting and driving forces can create a landslide (Duncan 1996, Holtz and Schuster 1996).

Driving forces are those forces which move earth materials downslope. These include components of weight of material including fill material, vegetation, or buildings. Resisting forces are those forces which oppose the movement. These include strength of material.

Shear stresses increases by steepening slopes due to removal of material from bottom of slopes, by imposition of surcharges, by transitory stresses resulting from explosions or seismic activities or uplifting or tilting of land surfaces (Holtz and Schuster 1996).

Shear strength affects slope stability. Shear strength of a rock and/or soil material is reduced by physical (such as weathering) and chemical processes. Material properties including composition and arrangement of particles affect landslide process. Material property may be naturally weak or may become weak due to natural process such as water saturation. For example organic materials and clays have low natural strengths. Mass properties of soils and rocks can be weakened by discontinuities such as faults, foliation, bedding surfaces, cleavages, joints, fissures, shears, and sheared zones (Keaton and Beckwith 1996).

These parameters that increase shear stress and reduce shear strength of the slope could be categorized into external and internal factors. Internal factors include topographic parameters such as slope, ground water, soil moisture, lithology; geological structures such as faults, joints, bedding planes. Most common external factors influencing landslides are the vibrations due to earthquakes, blasting due to explosives and volcanic eruptions etc.

In this study, landslide susceptibility is evaluated on the basis of relationship between landslide causal factors and past landslides. The internal factors influencing slope stability in Nepal are summarized below.

4. FACTORS CAUSING LANDSLIDE SUSCEPTIBILITY IN NEPAL

Natural and man-made factors contribute to landslide occurrence in Nepal (Gerrard 1994, Gerrard and Gardner 2002, Hasegawa et al. 2009, Ghimire 2011). These elements are called trigger mechanisms (for example rainfall, earthquake and seismic events) and susceptibility factors (such as steep slopes, rugged topography, sparse vegetation cover, fragile geological formations and structurally fragmented rock materials) (Wieczorek 1996). Human activities also aggravate landslide susceptibility due to insufficient attention being given in the land use practices, infrastructure development and over exploitation of natural resources (Paudel et al. 2003, Petley et al. 2004, Petley et al. 2007). In this study, however, the important natural factors responsible to induce landslides such as topography, lithology, land cover, soil moisture and climate are included. These factors are discussed as follows:

4.1 TOPOGRAPHY

Nepal is located on the southern border of Himalayan range in between China and India where eight of the ten highest peak of the world are distributed. Nepal occupies an area of 147,181 km^2 which is divided into three distinct geographic units based on the topography: High mountain (27%), Mid-hills (56%) and Terai (low land) (17%). Nepal has an uneven topography with high relief and complex geology resulted from tectonic processes and active seismicity (Duncan et al. 2003). The topographic elevation of Nepal ranges from 60 m a.s.l in the southern plain to 8848 m a.s.l on Mt. Everest in the north. Approximately 83% of the country lies in the mountainous region. Such a sharp topographic variation across a horizontal distance of around 200km makes it prone to landslide hazard (Caine and Mool 1982, Wagner 1983, Duncan et al. 2003).

4.2 LITHOLOGY

The Himalayan orogeny has nurtured a fragile and complex geology. These are young fragile continuously evolving mountains of the World. The Himalayan belt originated as a consequence of two landmass collision. There are mainly two types of collision illustrated in the literatures. The first one is the Indian and Eurasian plates collision which started 50 Million years ago (Patriat and Achache 1984). The second process is northward subduction of Indian subcontinent plate along the crustal fracture within the Indian block created during Late Eocene and Oligocene periods. The subduction of the Indian plate has continued due to northward movement of Indian plate since past 80 million years. The evidences of this subduction process can be seen as detached Himalayan thrust belt in the south of suture zone which delineates the Indian and Eurasian plate boundaries (Powell and Conaghan 1973). The mountain building process and the continuity of the collision activity is manifested in the present day northward movement of India at the rate of around 5cm per year (Bilham et al. 1997, Pandey et al. 1999).

Nepal is stratified into eight major geomorphic zones on the basis of lithology, tectonics, structure and geological history (Table 1). These geomorphologic units depict the fragility and genesis of Himalayas in Nepal which are prone to landslides.

Table 1 Geomorphic units of Nepal

Geomorphic units	Width (Km)	Altitudes (m)	Main rock types	Age
Terai (Northern edge of Gangetic Plain)	20-50	100-200	Alluvium: coarse gravels in the north Near the foot of the mountains, Gradually becoming finer southwards	Recent
Churia Range (Siwaliks)	10-50	200-1300	Sandstone, mudstone, shale and conglomerate	Mid-Miocene to Pleistocene
Dun Valleys	5-30	200-300	Valleys within the Churia Hills Filled up by coarse to fine Alluvial sediments	Recent
Mahabharat Range	10-35	1000-3000	Schist, phylite, gneiss, quartzite, Granite and limestone belonging To the Lesser Himalayan Zone	Precambrian and Paleozoic and Cenozoic
Midlands	40-60	300-2000	Schist, phylite, gneiss, quartzite, Granite and limestone belonging To the Lesser Himalayan Zone	Precambrian and Paleozoic to Mesozoic
Fore Himalaya	20-70	2000-5000	Gneisses, schists, phylites and	Precambrian

			Marbles mostly belonging to the Northern edge of the Lesser Himalayan zone	
Higher Himalaya	10-60	>5000	Gneisses, schists, phylites and Marbles mostly belonging to the Northern edge of the Lesser Himalayan zone	Precambrian
Inner and trans Himalaya	5-50	2500-4500	Gneisses, schists, and marbles of the Higher Himalayan Zone and Tethyan sediments (limestone, Shale, sandstone etc.) Belonging to Tibetan-Tethys Zone	Precambrian and Cambrian to Cretaceous

Source:adopted from Upreti (Upreti 1999)

4.3 LAND COVER AND VEGETATION

Nepal covers sub-tropical to alpine zones with around 29% of vegetation to the total area of Nepal. Biodiversity is very high in Nepal due to topography and climatic variations. Vegetation types changes with altitude and topography from south to north (Vetaas and Grytnes 2002, Bhattarai and Vetaas 2003).

Many studies have highlighted the positive and negative effects of vegetation on landslides. However, the main effects of vegetation on slope stability are mechanical stabilization of soil due to presence of roots, soil moisture reduction by transpiration, surcharge from the weight of the trees and wind breaking (Lawrance et al. 1996).

Vegetation plays an important role in slope stability and soil erosion control in Nepal. The vegetative cover prevents the surface erosion by increased shear strength of the soil with its root network through mechanical reinforcement, anchoring and compaction; reduce surface flow by evapotranspiration and absorption of ground water (Gilmour et al.

1987, Sharma et al. 2000, Shrestha and Zinck 2001). However, landslides increase during monsoons as the sub soil becomes saturated with soil moisture. If the landslide is deeper than the root penetration zones; than the slope failure occurs even in the presence of good vegetation cover.

In this study, land cover is referred as different kinds of land use for example urban areas (settlements), bare land, forest land, shrub land, grass land etc. Vegetation composition is the proportion of land occupied by different vegetation types such as trees, herbs, and shrubs, grasses occurring in natural areas, plantations and cultivated lands. Land cover composition of Nepal is given in table 2. Nepal occupies an area of 141718 square kilometers of which 5% is covered with snow. Forests occupy approximately 29% of the total land cover, while 18% of the total land area is under agriculture (Table 2).

Table 2 Land use classification of Nepal

Category	Area (in million hectares)
Agriculture land cultivated	3091
Agriculture land uncultivated	1030
Forest	4268
Shrub land	1560
Grass and pasture land	1766
Water	383
Others	2620
Total	14718

Source (CBS 2008)

4.4 SOIL MOISTURE

A landslide is sudden failure of slope with or without the influence of water. Prior to slope failure, there is a slope movement. Sometimes the slope movement turns into landslide and sometimes it does not. Most of the slope failures are caused by soil moisture or ground water that increases pore water pressure and decreases shear strength of soil. Landslides are generally resulted from a combined effect of intense rainfall and antecedent wet soil moisture conditions (Gabet et al. 2004a, Dahal and Hasegawa 2008). For slope failure soil moisture plays an important role because water reduces the soil strength and increases stress. Increase in pore water pressure results into increased shear stress and decrease in shear strength of the soil. In addition, saturation level of soil moisture content is considered as key cause for landslides. For example landslides are caused by surface and subsurface layer saturation (Ray & Jacobs, 2007). Since soil moisture is a very crucial factor for triggering landslides, it is therefore an important parameter for landslide studies.

The soils of Nepal are highly variable and are derived mainly from young parent material (Kaddah 1967, CBS 2008). Soils have been classified on the basis of soil texture, mode of transportation, and color, and are broadly classified into:

- Alluvial soil
- Sandy and alluvial soil
- Gravelly soil
- Residual Soil
- Glacial soil

4.5 CLIMATE

The climate of Nepal varies from subtropical to arctic, all within a distance of approximately 200 kilometers. In addition to the large variations in climate, there is a great variety of micro climatic conditions, resulting in a diversity of land use and land practices within the country. In general, the climate of the Terai, Dun valleys, and part of the Siwaliks (up to 1000 m) is subtropical. The climate of the Middle Mountains (1000-3000 m) ranges from warm temperate to cool temperate, and the high Mountains (2600-4000 m) from cool temperate to sub-alpine.

The snowline lies in approximately 2500 meters during the winter. Snow rarely falls below the 1500 meters level. On shaded north slopes, snow lingers on considerably longer than on south facing slopes. Sources of many of the Nepal’s perennial river systems are snow covered mountains. Farmers make use of this unique water storage and realizing feature since these river systems supply irrigation water in a steady pace. In this way, many of the higher snow fields supply irrigation water to the lower agricultural land during most of the year (Sharma 1993).

5. AIM OF THE STUDY

The main aim of the study is to prepare landslide susceptibility maps of Palpa/Gulmi, Palpa, Baglung/Myadgi, Parbat and Kaski using bivariate statistical method (LNSF) and validate the results by model replication. The specific objectives include:

1. To prepare landslide susceptibility maps of the selected study areas using bivariate statistical method (Landslide Nominal Susceptibility Factor-LNSF) in Arc GIS environment.
2. To validate the results by split sample and model replication strategy.

6. LIMITATIONS OF THE STUDY

Accuracy of the landslide susceptibility maps depends on the nature of the database. In this study, to prepare the landslide susceptibility maps of the study areas, the published global database were used. These databases such as DEM-SRTM3, lithology and land cover - GLOVECOVER v2.v have lower resolution but these were the only published database freely available for Nepal. Landslide inventory database contained landslides polygons without any supporting details. Time factor posed another limitation to the study.

7. DESTRIPTION OF THE STUDY AREA

Nepal is divided into five development regions: Eastern, Central, Western, Mid-Western and Far-Western Region. This study is concentrated in parts of Western Region. The Western Region extends from low land (150m) to Himalayas (Annapurna and Dhaulagiri). The climate in the hills and mountains is warm temperate and with heavy monsoon rains in between June and September (Kansakar et al. 2004). The Western Region receives larger amount of rainfall compared to other regions of Nepal. However, the total quantity of rainfall varies widely depending on altitude and topography. The amount of rainfall ranges from 1000 mm to 2000 mm at altitudes of around 1000 m (Ichiyanagi et al. 2007). The geology consists of phyllites, shales, quartzites, schists, granites, limestone, weathered rocks, boulders, sand and clay. Vegetation varies with altitude and topography: in altitudes less than 1000 m, mixed, evergreen broadleaved and deciduous forests prevail. At higher altitudes, mixed deciduous broadleaved forest and evergreen conifer forests are dominant.

Western Region is one of the landslide affected areas among the five development regions of Nepal. Frequent landslides often result in significant harm to people and property, the most recent having occurred in 2002, 2005, 2009, and 2010 (*"DesInventar -Disaster Information Management System"*). In the study areas, much damage has been caused during these events. There have been very little previous efforts to predict or assess such events.

In the Western Development Region, Department of Geology and Mines, Nepal sampled five study areas and prepared landslide inventories for the areas. These landslide inventories were field verified (Dr. Rijal, Personal communication) [1]. These sample areas having landslide inventory records were selected for the study. The study areas are as follows (Figure 1, 2, 3 and 4):

Palpa/Gulmi (Figure 2, left): Latitude 27°45´0´´N and 28°00´0´´N; longitude 83°15´30´´E and 83°31´0´´E covering 838.7 km^2 of area. The elevation range is 263 m to 1987 m from mean sea level. The lithology is composed of Siwaliks, Lower Nuwakot, Upper Nuwakot, Tansen and Recent deposits.

*Palp (Figure 2, right):*Latitude 27°44´30´´N and 28°00´0´´N; longitude 83°29´0´´E and 83°44´0´´E covering an area of 865.03 km^2. The elevation range is 310m to 2086 m from a.s.l. The geology consists of Siwaliks, Lower Nuwakot, Upper Nuwakot, Tansen and Recent deposits.

Baglung/Myagdi (Figure 3, left): Latitude 28°17´0´´N and 28°29´30´´N; longitude 83°17´30´´E and 83°30´0´´E covering an area of 636.4 km^2. The elevation range is 913 m to 3700 m from mean sea level. The geology consists of Lower Nuwakot and Upper Nuwakot units.

Parbat (Figure 3, right): Latitude 28°00´0´´N and 28°15´0´´N; longitude 83°30´0´´E and 83°45´0´´E covering an area of 824.6 km^2. The elevation range is 524 m to 2748 m from mean sea level. The geology consists of Lower Nuwakot and Upper Nuwakot units.

Kaski (Figure 4): Latitude 28°15´0´´N and 28°30´0´´N; longitude 83°45´0´´E and 84°00´0´´E covering an area of 881.4 km^2. The elevation range is 819 m to 6906 m from a.s.l. The Lower Nuwakot and Higher Himalayan zone were the geological units of this area.

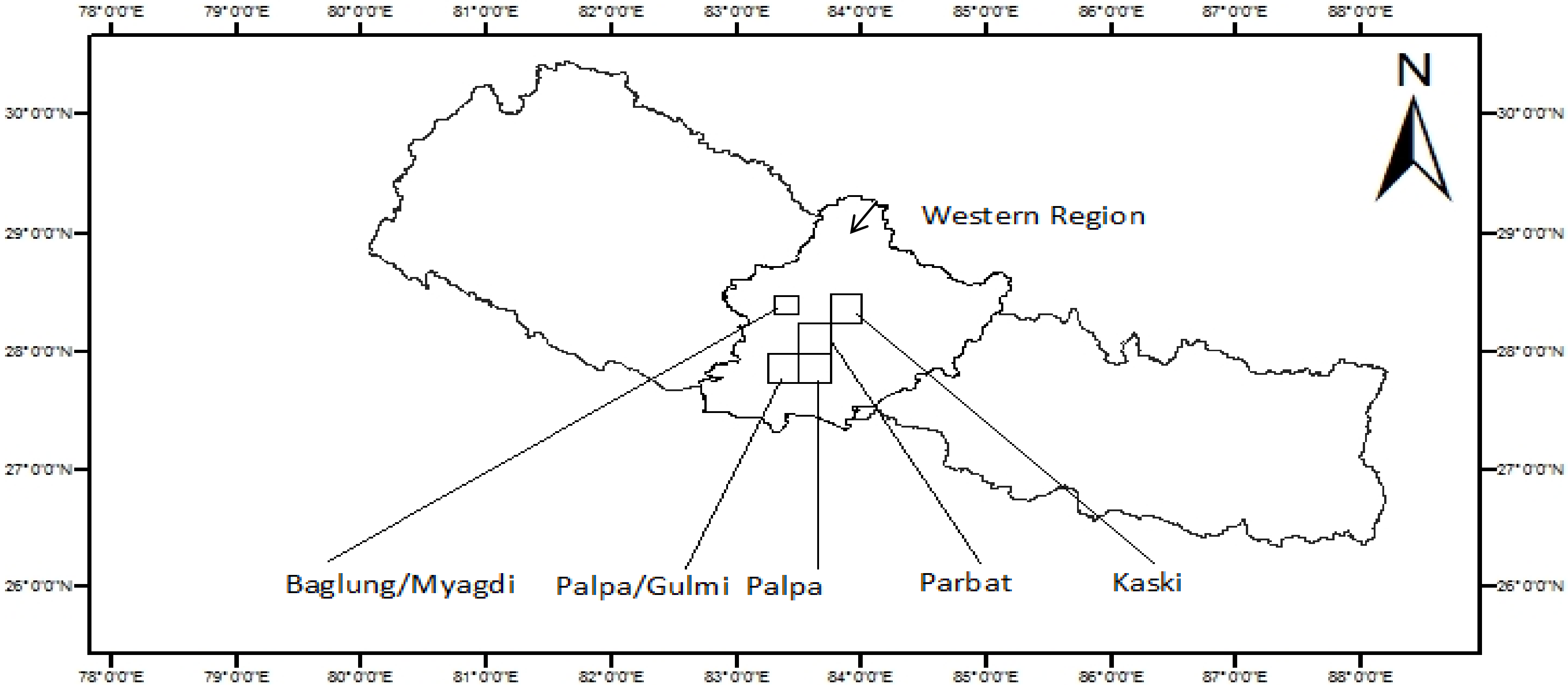

Figure 1 Map of the study area

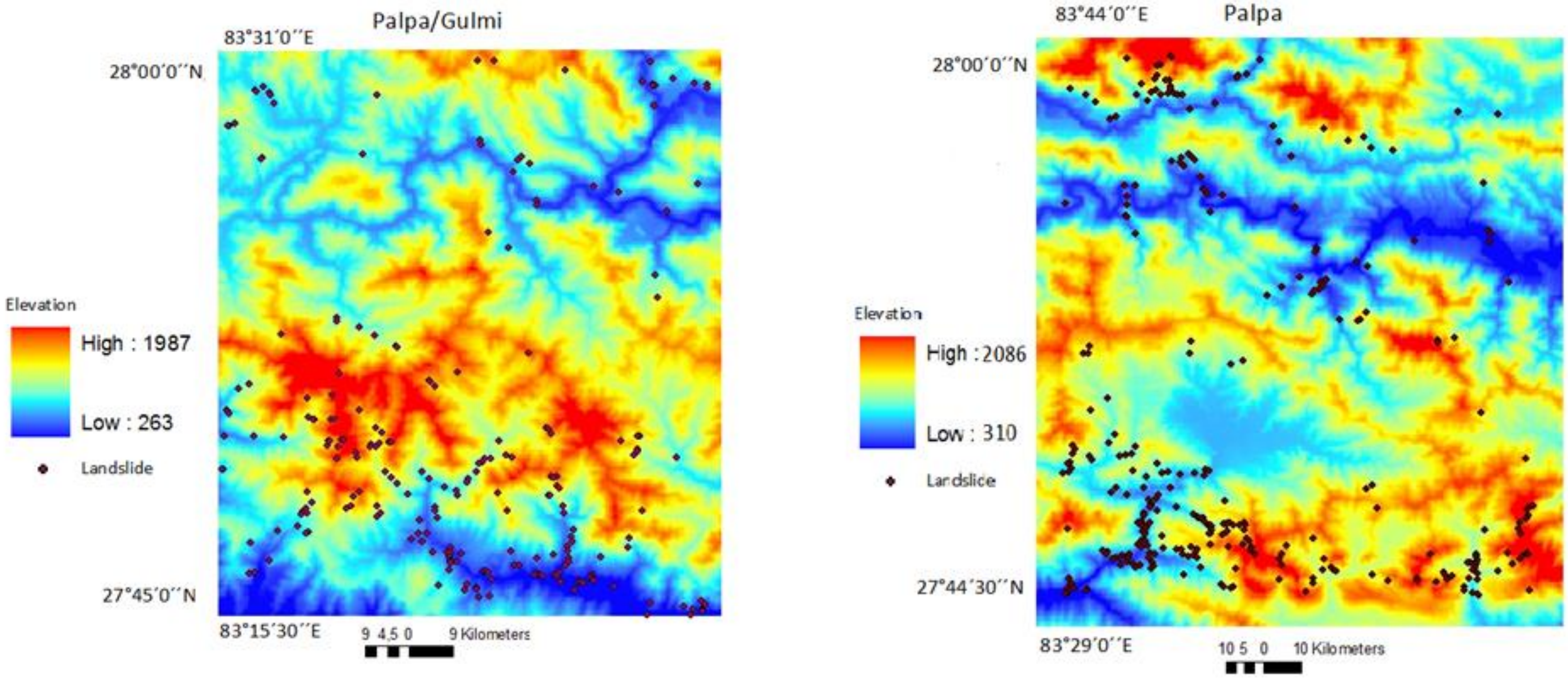

Figure 2 DEM of Palpa/Gulmi and Palpa with landslide inventory

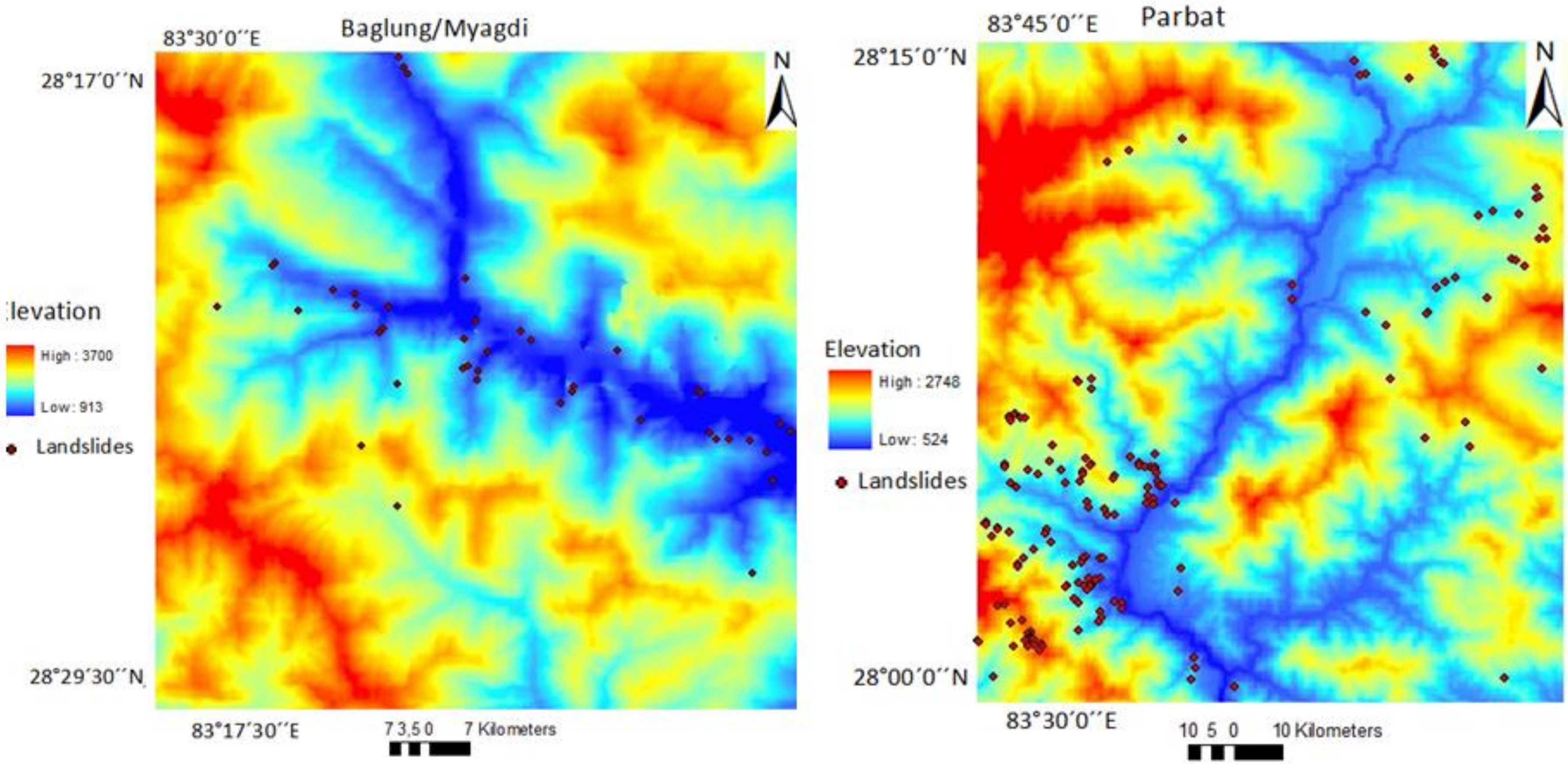

Figure 3 DEM of Baglung/Myagdi and Parbat with landslide inventory

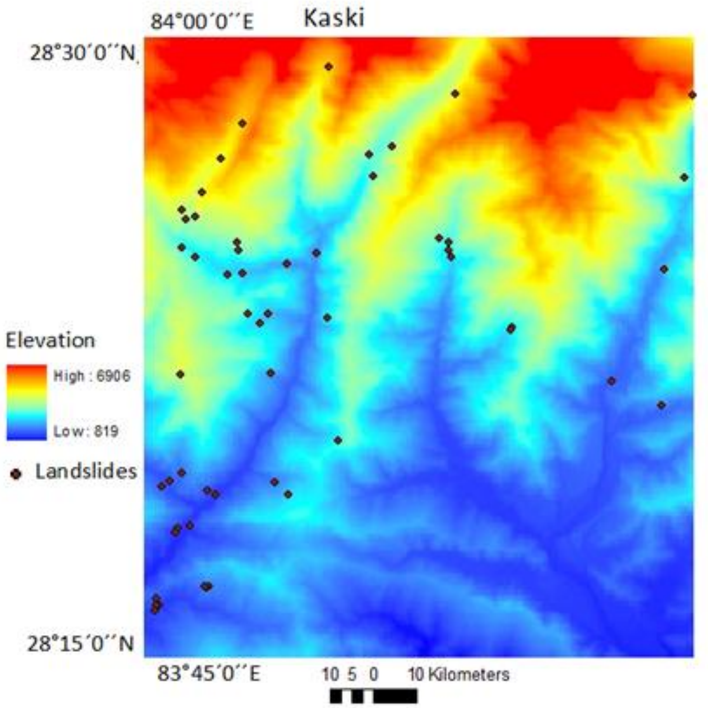

Figure 4 DEM of Kaski with landslide inventory

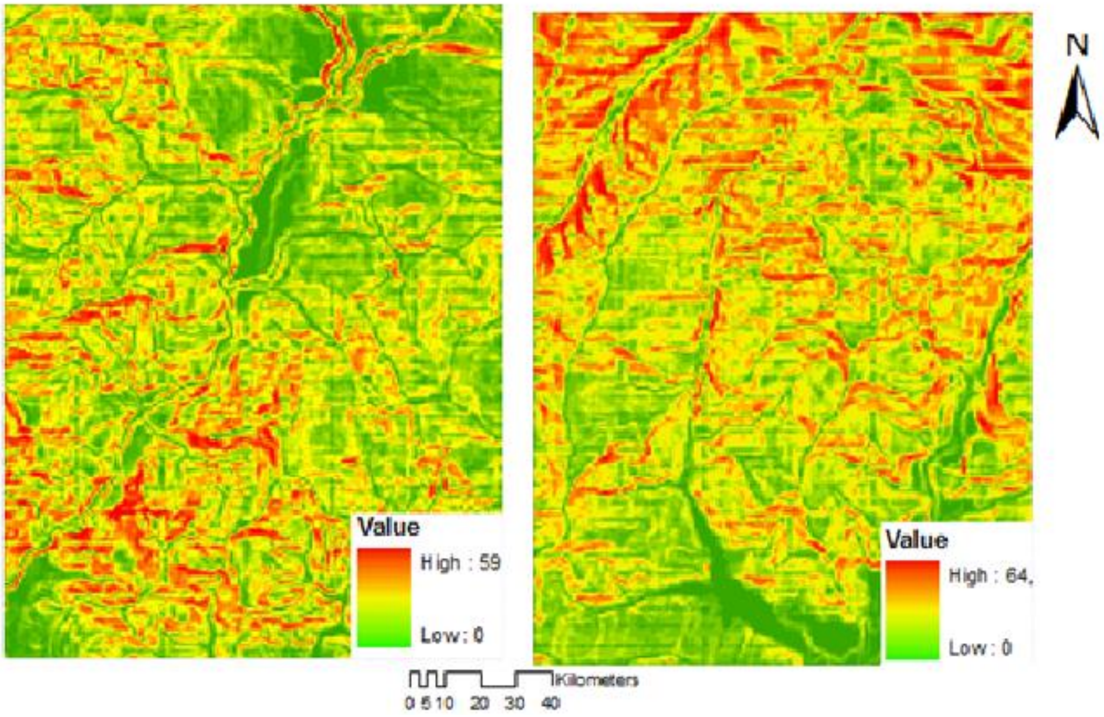

Figure 5 Slope maps of Parbat, and Kaski

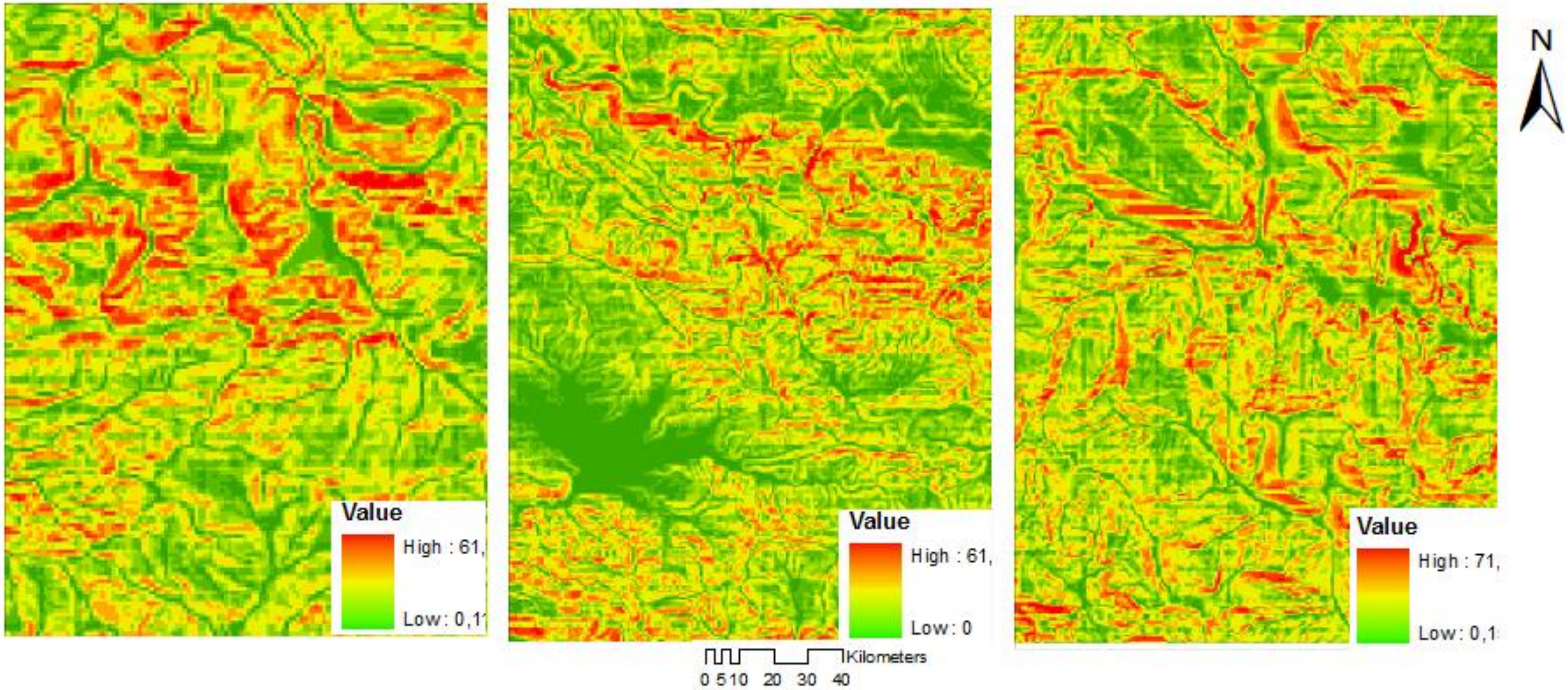

Figure 6 Slope maps of Palpa/Gulmi, Palpa and Baglung/Myagdi

8. METHODOLOGY

8.1 LANDSLIDE SUSCEPTIBILITY ANALYSIS METHODS

Several landslide susceptibility assessment methods are presented in the literature. These methods can be broadly grouped into direct and indirect and qualitative and quantitative (Van Westen et al. 1997, Van Westen et al. 2006). In direct method, the researcher determines the degree of susceptibility based on her/his knowledge and experience. But in indirect mapping, the researcher uses either statistical models or deterministic models to predict landslide prone areas, based on the information obtained from the interrelation between landslide controlling factors and landslide distribution (Van Westen et al. 2003).

Qualitative assessment method evaluates the landslide susceptibility without landslide inventories. This method evaluates the actual landslide based on the spatial distribution of landslide controlling factors. This method is dependent on the experience and skills of the expert preparing the map. It requires a prior knowledge on factors controlling landslides. Heuristic method is example of qualitative method (Soeters and Van Westen 1996). Quantitative methods include statistical and deterministic modeling of landslide susceptibility combining landslide inventory and landslide controlling factors (Van Westen et al. 1997).

Landslide inventory also called frequency method are the simplest form of landslide mapping. The susceptibility estimation is based on the number of landslide occurrence (Wright et al. 1974). Landslide inventory maps provide quantitative measure on landslide distribution. They provide straight forward comparison of different regions. However, landslide inventories assume continuous landslide density in space and cannot provide estimates on future landslides. An inventory of landslide can be prepared by collecting the historical information on individual landslide events and by using satellite images and aerial photographs and field survey (Soeters and Van Westen 1996, Duman et al. 2005).

In physically based models, the landslide susceptibility is determined using slope stability models resulting in the calculation of factor of safety (Soeters and Van Westen 1996). These models provide the best quantitative information on landslide susceptibility that can be directly used in the engineering works.

Physically based models are based on sound physical models and are capable of predictive landslide analysis. They render information on landslide hazards. However, these methods require high accuracy of input parameters. These predictive models are difficult to evaluate. It involves complex modeling and is hard to perform at smaller scales (Soeters and Van Westen 1996).

In statistical methods, landslide casual factors or parameters are derived and combined with the landslide inventories to predict the future occurrence of landslides (Carrara et al. 1991, Guzzetti et al. 1999, Dai et al. 2001). Statistical methods can be distinguished into multivariate and bivariate.

In multivariate method, all relevant landslide casual factors or parameters are treated together (Carrara 1983, Carrara et al. 1991, Lee and Min 2001, Süzen and Doyuran 2004a). As a result, interaction effects of multiple factors are displayed by this method. Logistic regression (Dai et al. 2001) and determinant analysis are the main types of multivariate statistics used in landslide susceptibility analysis. Artificial neural network (ANN) classifiers are another type of multivariate method.

In bivariate statistical method, each landslide casual factor map (for example geology, slope, land use, vegetation) is combined with the landslide inventory. The weights are derived from either landslide abundance or densities in each attribute class within each factor (Gupta and Joshi 1990, Van Westen et al. 1997, Süzen and Doyuran 2004b). Mainly three types of weight estimation methods have been employed in bivariate statistical method: Information value method, weight-of-evidence modeling and landslide nominal susceptibility factor (LNSF).

8.2 LANDSLIDE NOMINAL SUSCEPTIBILITY FACTOR

This study employs landslide susceptibility factor (LNSF) – a form of bivariate statistical method to evaluate the landslide susceptibility of the study areas.

Gupta and Joshi (1990) proposed Landslide Nominal Susceptibility Factor (LNSF) method as Landslide Nominal Risk Factor (LNRF). But Saha et.al (2005) modified it into Landslide Nominal Susceptibility Factor (LNSF). They also improved the weight assignment process by the direct use of weights to the factor maps. LNSF is related to each attribute class of the factor map by equation 1.

$$LNSF_i = \frac{Npix_{(Si)}}{\sum_{i=1}^{n} \frac{Npix_{(Si)}}{n}} \qquad (1)$$

Where, $Npix_{(Si)}$ is the number of cells values with landslides in ith thematic class of a respective factor map and n is the number of classes in the factor map.

Gupta and Joshi (1990) explained an LNSF value greater than 1 as high susceptibility to landslides and a value less than 1 as low susceptibility. An LNSF value equal to 1 refers to average landslide susceptibility. They reclassified the LNSF values into 0, 1 and 2 for LNSF <0.67 (low susceptibility), 0.67 <LNSF<1.33 (moderate susceptibility and LNSF>1.33 (high susceptibility). Saha et.al (2005) suggested direct use of the weights to the thematic maps instead of classifying them into 0, 1 and 2. Then, the weighted thematic layers are summed to prepare a landslide susceptibility index (LSI) map. The LSI map is classified into low, moderate and high susceptibility zones (Gupta and Joshi 1990).

To evaluate the landslide susceptibility of the study areas, a bivariate statistical method in Arc GIS environment was followed as presented in figure 7. To evaluate the contribution of each factor towards landslide susceptibility, thematic factor maps separately overlayed with landslide inventory. The number of landslide pixels falling on each class of the thematic factor map was recorded and weights calculated based on the LNSF method using equation (1). The weights were directly assigned to the respective thematic layers to produce the weighted thematic maps. The weighted thematic maps were summed up to produce a landslide susceptibility index (LSI) map according to equation (2).

$$LSI = Sl + Li + Lc \qquad (2)$$

Where, LSI is the Landslide Susceptibility Index

Sl, Li and Lc are landslide distribution derived weights for slope, lithology and landcover. LSI classification was done using standard deviation ± 1 to reduce the subjectivity in the analysis.

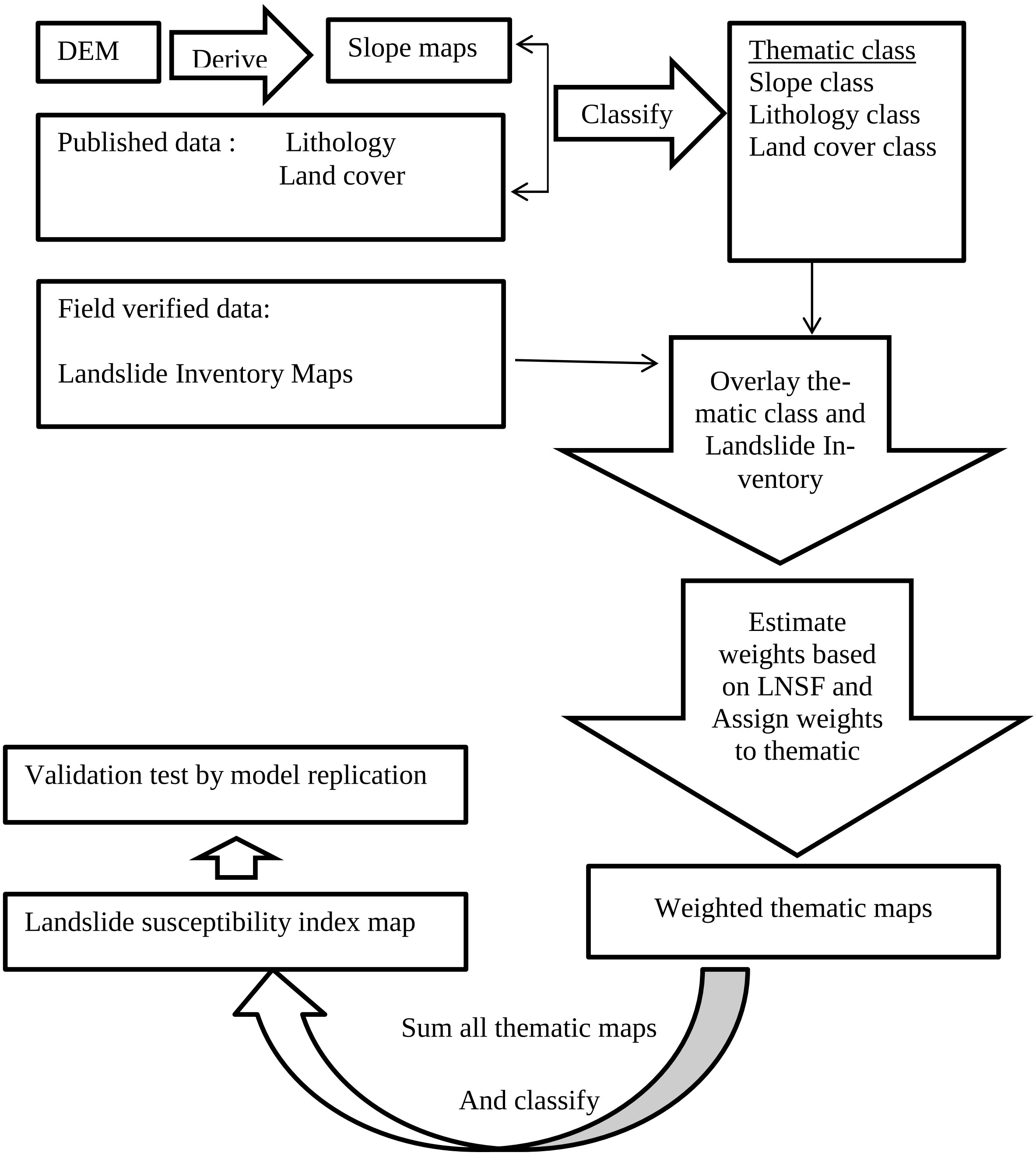

Figure 7 Flow chart of landslide susceptibility analysis by bivariate statistical method

8.3 VALIDATION STRATEGY

There are different ways to test the validity of the model. In landslide susceptibility analysis; the same landslide inventory databases that were used for preparing landslide susceptibility maps may be used to test the goodness of fit. The basic assumption underlying the goodness of fit test is that future landslides will occur in the same places as the past or existing movements in the study areas. If the susceptibility maps coincide well with the landslides then the maps are considered as satisfactory.

However, map validation is considered best when they are tested using independent population of landslides (Lee and Min 2001, Lee 2007, Pradhan and Buchroithner 2010). Independent landslide data samples can be obtained by a) sample split strategy in which the landslide inventory are split into two parts, one for analysis and one for validation; b) model replication in which the analysis is done in one part of the study area and the results obtained are replicated in other parts with different landslides; and c) Validation with respect to time: In this validation method the model is prepared with a landslide database that occurred in a certain period and is validated by using the landslides that occurred in a different period (Remondo et al. 2003, Pradhan and Buchroithner 2010). In this study model b) is used to validate the model.

To test the goodness of fit of the replicated models; the cumulative percentage of landslide occurrence with respect to susceptibility class were plotted in a graph called as rating curve. To prepare the rating curves, the landslide susceptibility index maps were sorted in descending order and were sliced into100 equal-area classes. Similarly, the landslide database was also sliced into 100 equal-area classes. Then, the cumulative percentages of the susceptibility class corresponding to cumulative percentage of landslides were plotted in graphs.

The rating curves are analyzed based on two assumptions: a) a hypothetical validation curve coinciding with a diagonal of 0 to 1 would be equivalent to total random prediction. The further up and away the validation curve from the diagonal the better the predictability of the model and susceptibility map (Remondo et al. 2003, Lee 2007). And b) The higher the proportion of landslides in most susceptible zones the better the predictability of the model (Remondo et al. 2003).

8.4 DATA COLLECTION AND PREPARATION

GIS databases are required to prepare landslide susceptibility maps of the study areas. The spatial database of the study areas were collected from different sources. The database type, their sources, coordinate system and scale are given in table 3. Databases for the study areas were prepared by data projection, resampling and factor map derivation. All databases were projected in WGS_84 (Mercator World Projection) datum/coordinate system and resampled to approximately 90m x 90m resolution.

Table 3 Database of study areas

Datasets	GIS data type	Scale	Coordinate system	Source of data collection
DEM(SRTM-3)	GRID	90m x 90m	WGS_84	NASA (through ICG)
Lithology map	Polygon	1:1000,000	GCS_WGS_84	Department of Geology and Mines, Nepal (through ICG)
Land cover map	GRID	300m x 300m	WGS_84	European Space Agency (through ICG)
Landside inventory	Lines	1:100,000	GCS_Calrke_86	Department of Geology and Mines Nepal.

8.4.1 Slope map preparation

In February 2000, National Aeronautics and Space Administration of United States (NASA) collected a global elevation dataset called SRTM3 named after the mission; Shuttle Radar Topography Mission. The database was released with resolution of 1 arc-second for United States and 3 arc-seconds (or approximately 90m x 90m cell per data sample near the equator) for rest of the world (Isciences 2000). The slope maps were derived from the digital elevation model (DEM) of the study areas (Appendix 1). The DEM of the study areas were extracted from SRTM3.

Classification of continuous variables such as slope has remained an issue. No specific guidelines exist for the classification of continuous parameters. Different methods of continuous data classification have been suggested by different researchers. Slope parameter was classified into 10 classes based on the natural breaks (Figure 5 and 6).

8.4.2 Lithology map preparation

Lithology database was created from a geological map of Nepal provided by International Centre for Geohazards (ICG). This map was published by Department of Geology and Mines, Nepal in 1994 (DMG 1994). Lithology maps of the study were resampled to 90m x 90m resolution, rasterized and projected in WGS_84.

The lithological classification is based on the classification given by Upreti (1999) for Western Nepal (Figure 8). A classification of the lithology units of the study areas is summarized in table 4. Lesser Himalayan zone covers most of the study areas, so it was divided into Lower Nuwakot, Upper Nuwakot and Tansen units. Zone of recent filling was referred as Terai zone and Higher Himalayan zone was referred by the same name.

Figure 9 is the lithology classification of study areas on the basis of sensitivity of rock materials to landslide susceptibility. Norwegian Geotechnical Institute (NGI) has classified lithology of Nepal into five classes on the basis of rock material composition.

It can be seen from figure 9 and table 4 that majority of the study areas are highly prone to landslides. This map provides the sensitivity of lithological units to landslides. The detailed classification of lithological structures given by NGI is provided in Appendix 3.

Table 4 Lithology units of study areas

Stratigraphic zones	Units	Group	Geological age	Main rock types	Class	Prone to landslides
Lesser Himalayan	Siwaliks	Lower Siwalik	Mid Miocene – Pleistocene	Sandstones, shales, clays, conglomerates	1	Medium
		Middle Siwaliks 1	Mid Miocene – Pleistocene	Sandstone, Shales, mudstones, conglomerates	1	Medium
		Upper Siwaliks	Mid Miocene – Pleistocene	Coarse boulders, sandstone and clays	1	High
	Lower Nuwakot	Galyan Formation	Upper pre Cambrian – Late Paleozoic	Slates and carbonates	2	Medium
		Kushma Formation	Upper pre Cambrian – Late Paleozoic	White massive quartzite and green phyllites	2	Medium
		Sangram Formation	Upper pre Cambrian – Late Paleozoic	Green shales, limestones and quartzite	2	High
		Seti Formation	Upper pre Cambrian – Late Paleozoic	Phyllites and quartzite	2	Medium

		Ghanapokhara Formation	Upper pre Cambrian – Late Paleozoic	Carbonaceous slates and green slates	2	High
		Ulleri Formation	Upper pre Cambrian – Late Paleozoic	Augen gneisses, muscovite biotite gneiss and slates	2	Low
		Naudanda	Upper pre cambrian - Late Paleozoic	White massive quartzites and shales	2	Medium
	Upper Nuwakot	Lakharpata Formation	Upper pre-Cambrian – Late Paleozoic	Grey shales with intercalation of limestones and quartzite	3	Mediun
		Syangja Formation	Upper pre Cambrian – Late Paleozoic	Calcareous quartzite and quartzitic limestone intercalated with shales	3	Medium
	Tansen	Suntar Formation	Cretaceous -Eocene	Sandstone and shales	4	High
		Swat Formation	Cretaceous –Eocene	Shales with fine grained fossiliferous limestones	4	High
Higher Himala-		Himal	Precambrian	Garnet biotite gneiss, Biotite and quartzitic	5	Low

yan			mica schists, thin bands of marbles		
Terai	Null	Recent	Alluvium, boulders, sand, clays	6	Very High

Source: (Upreti 1999)

Note: Class 1-6 represent lithology zones in maps (Figure 8).

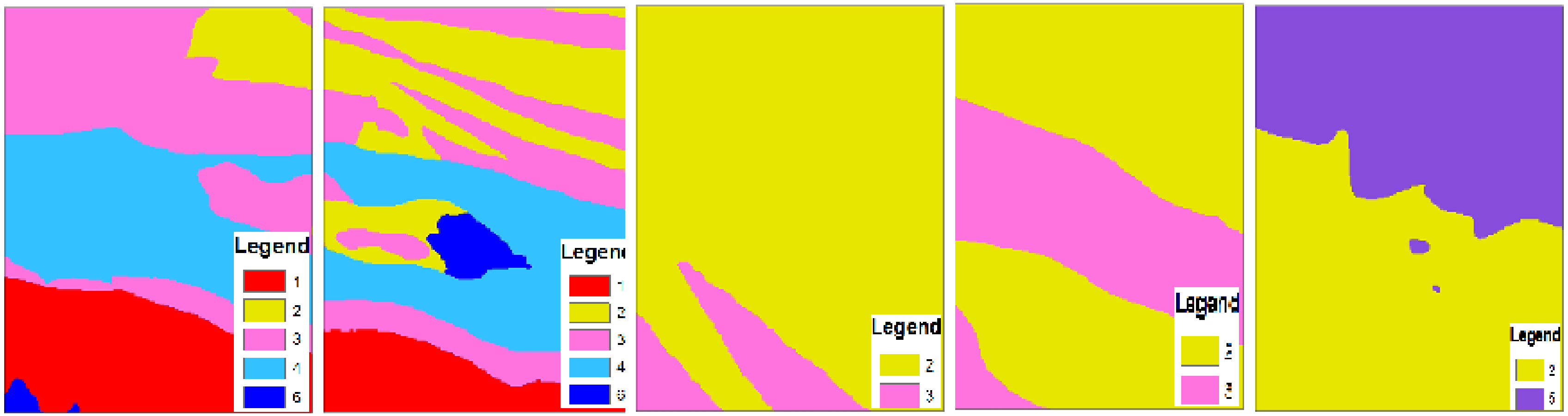

Figure 8 Classified lithology maps of Palpa/Gulmi, Palpa, Baglung/Myadgi, Parbat and Kaski.

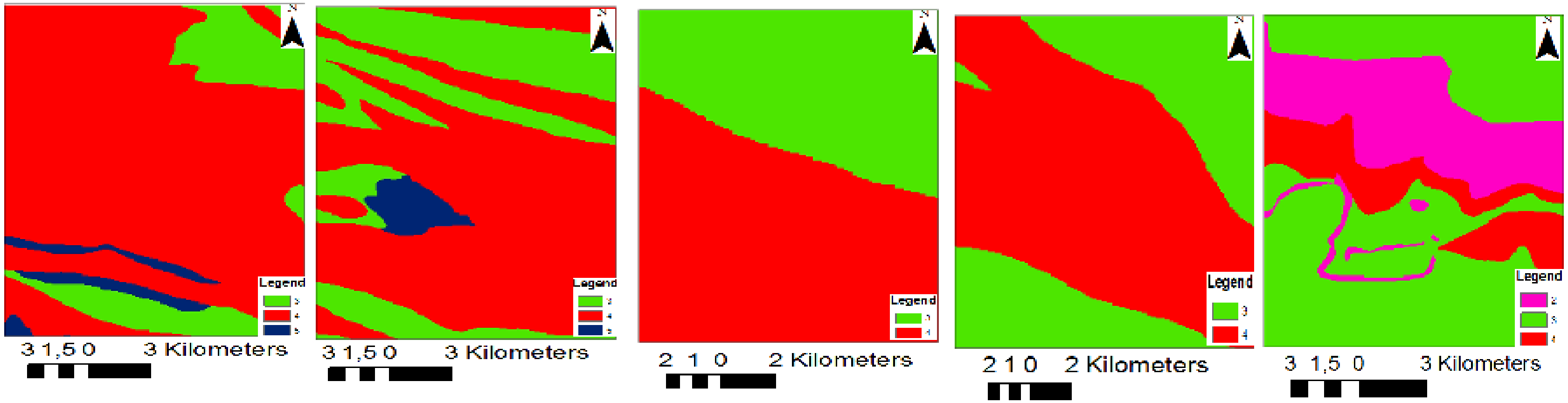

Figure 9 Classified lithology maps of Palpa/Gulmi, Palpa, Baglung/Myadgi, Parbat and Kaski by NGI classification

8.4.3 Land cover map preparation

The GLOBCOVER v2.2 is a global land cover database with approximately 300 m ground resolution collected by European Space Agency from 2004 -2006 using Envisat's Medium Resolution Imaging Spectrometer-MENRIS (ESA 2008). This global land cover map with 300 m resolution was released in 2008.

The GLOBECOVER v2.2 database has classified land cover of the world into 22 main classes. In this study, land cover system for global and continental application was used (Bicheron et al. 2008). This classification system has classified land cover types into 220 types and it includes the main land cover types of Asia region.

Land cover maps of the study were resampled to 90m x 90m resolution, and projected in WGS_84. Then, the land cover of the study areas was classified into eight main types (table 5 and figure 10 and 11).

Table 5 Land cover classification.

Land cover type	Class values
Cropland	1
Mosaic of crop and vegetation	2
Mosaic of forest and grassland	3
Forest	4
Shrubland	5
Bare land	6
Grassland	7
Snow/ice	0

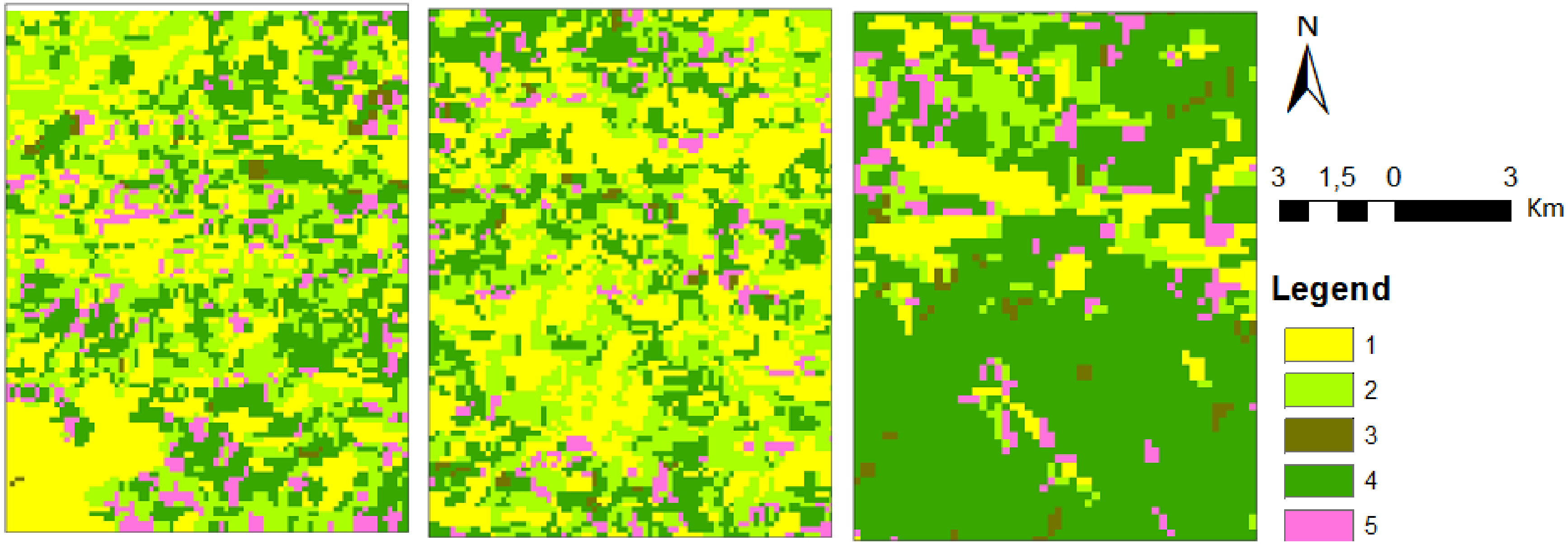

Figure 10 Classified land cover map of Palpa/Gulmi, Palpa and Baglung/Myadgi

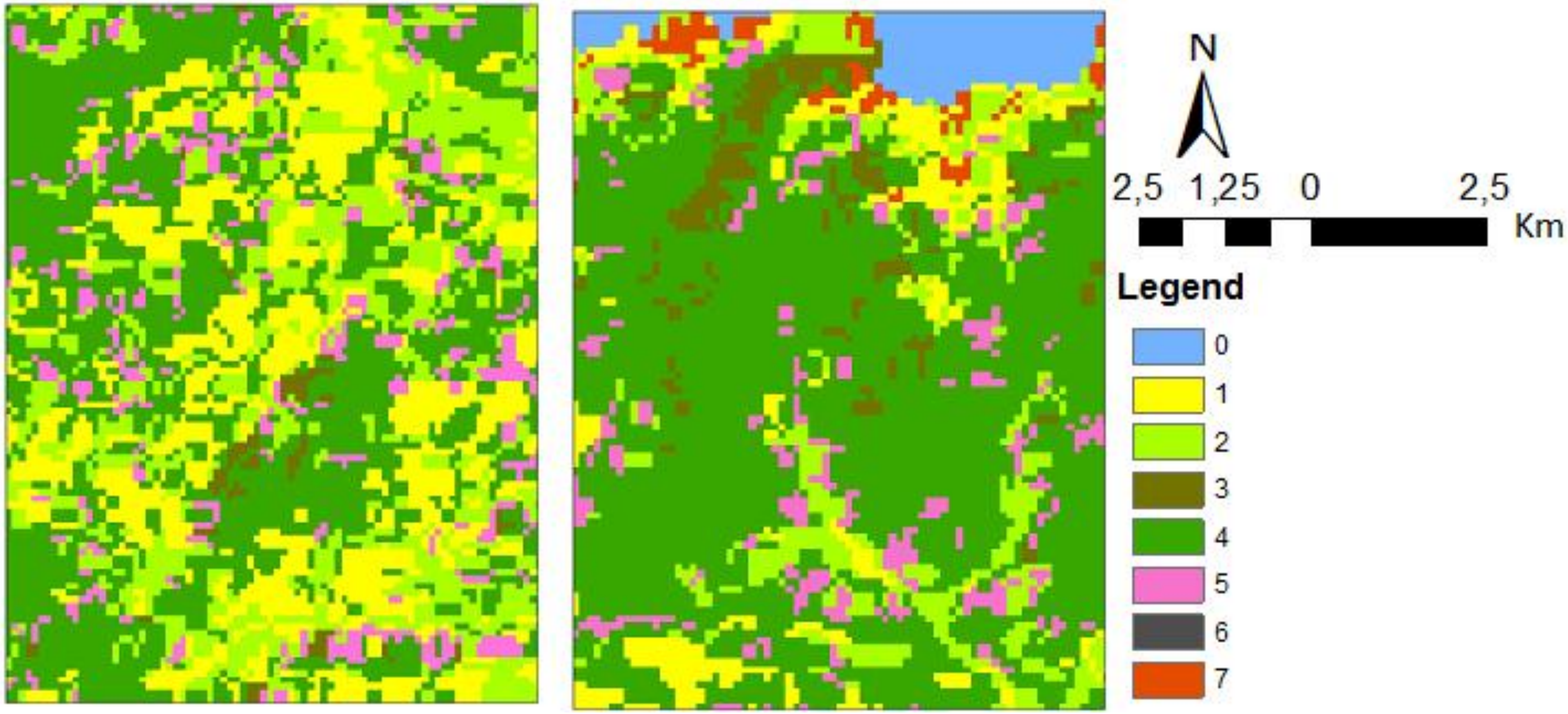

Figure 11 Classified land cover map of Parbat and Kaski

8.4.4 Landslide inventory database preparation

Landslide inventory database were collected from Department of Geology and Mines, Nepal. The database included polylines in a scale of 1:250,000 in GCS_Clarke_1886 coordinate system. The landslide inventory maps were transformed to WGS_84 (Mercator World Projection) coordinate system from GCS_Clarke 1866.Slope, land cover, and lithology database were in WGS_84. The datasets were resampled to a resolution of 90m x 90m grid size. The landslide inventory database was prepared by Department of Geology and Mines, Nepal. These datasets were collected from aerial photo interpretation and satellite images and field verified during a pilot study in the region (Dr. Rizal, personal communication) [1].

Table 6 Landslides records of study areas

Study area	No. of landslides recorded	Data collection year	Area of landslides (Km^2)	Number of landslide pixels
Palpa/Gulmi	230	2008	2,138	264
Palpa	302	1992/2006	4,042	499
Parbat	156	2006	1,466	123
Kaski	54	2005	2,049	181
Baglung/Myadgi	45	2009	0,996	253

A total of 787 landslides were recorded in these five study sites with an area of approximately 10.7 km^2.

9. RESULTS AND DISCUSSION

The main aim of the study was to prepare landslide susceptibility maps of Palpa/Gulmi, Palpa, Baglung/Myadgi, Parbat and Kaski using bivariate statistical method (LNSF) and validate the results by model replication. The thematic (slope, lithology and land use) maps and landslide inventory maps were converted to polygons, resampled to approximately 90mx90m resolution and projected in WGS_84 coordinate system. Then the percentages of landslide distribution in each thematic class of the slope, lithology and land cover were estimated. This provides an idea of how the landslides are distributed over the thematic classes in each thematic map. Landslide susceptibility index (LSI) maps were generated using equation (1 and 2). Rating curves were plotted to analyze the effect of each parameter on susceptibility. Maps were validated by model replication.

9.1 RELATIONSHIP BETWEEN LANDSLIDES AND CASUAL FACTORS

The relationship between landslide distribution and the casual factor was compared and percentage of landslides within each class of the slope, lithology and land cover map was estimated.

9.1.1 Landslide distribution in slope gradient

Slope maps of the study areas were extracted from DEM (SRTM3). Slope parameter was classified into 10 classes based on the natural breaks (Figure 6). For better comparison of landslide distribution according to slope class between five study areas, 10 slope classes were regrouped into five classes. This regrouping is limited only to this section. In rest of the analysis 10 slope classes are used. The slope angle and landslide distribution was compared and percentage of landslides within each slope class was estimated. Figure 12 shows an initial increase in percentage of landslides with increased slope gradient.

But the range of slope gradient from where the landslide distribution decreased varied between study areas. Landslide percentage increased with increase in slope gradient up to 30 degrees in Palpa/Gulmi, Palpa, and Kaski. After 30 degrees the landslides distribution decreases. In Baglung/Myagdi the percentage of landslides increased with increased slope gradient up to 40 degrees followed by sudden drop in the landslide percentage after 40 degrees. In contrast, Parbat showed increased percentage of landslides up to a slope gradient of 20 degrees and then the distribution of landslide percentage decreased. Further analysis indicated that landslides in sedimentary rocks failed in lower angles. The land use for crop production and human settlement and roads construction in sedimentary rocks also contributed positively for landslide failure in lower slope angles.

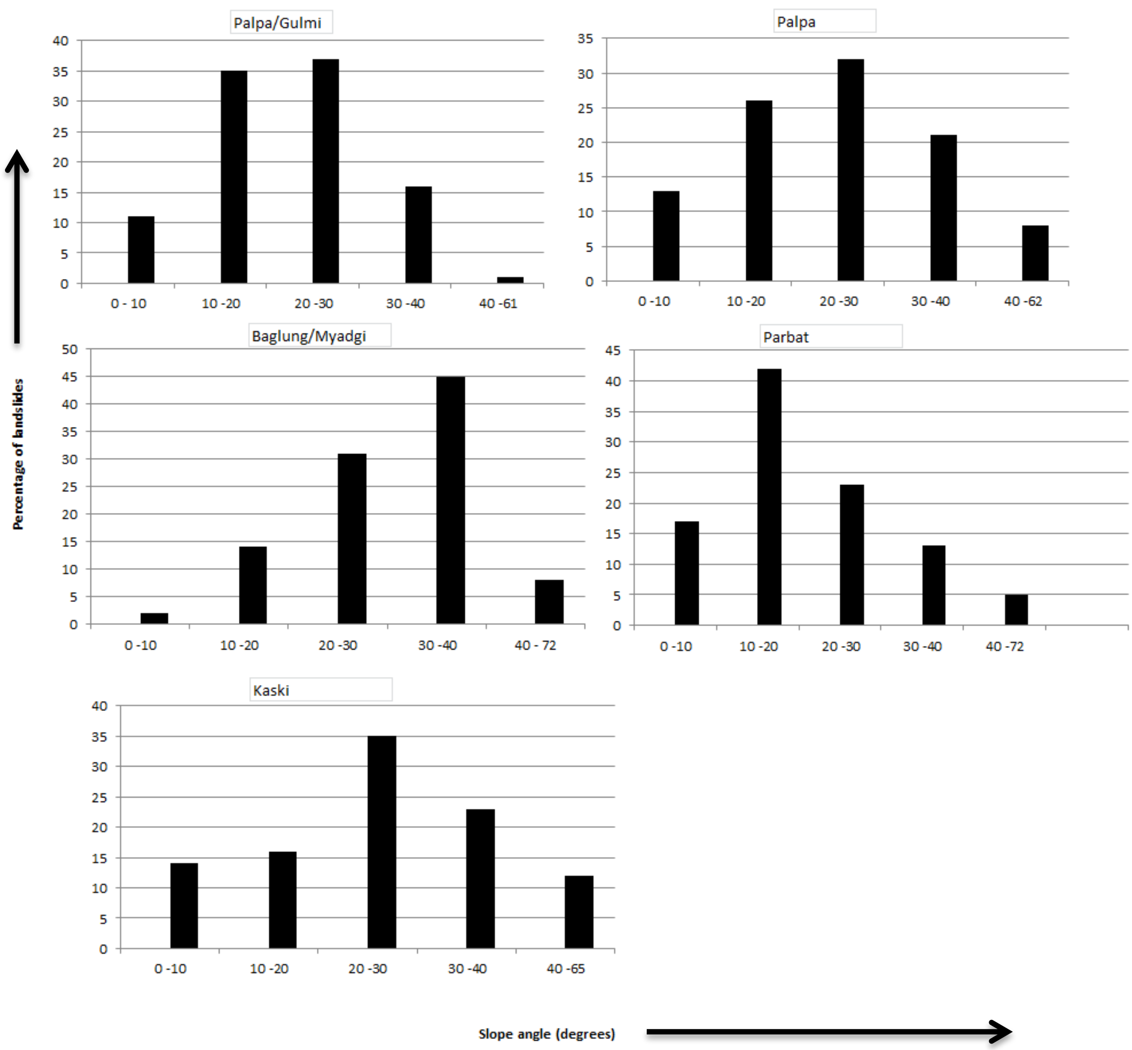

Figure 12 Landslide distribution according to slope class.

9.1.2 Landslide distribution in lithology class

Lithology maps of the study areas were derived from the geological map of Nepal. The classification of the lithology units of the study areas is summarized in table 4 (Upreti 1999). A large proportion of the study area is occupied by Lesser Himalayan Zone. Therefore, the lithology of the study areas was classified into six classes: Siwaliks, Lower Nuwakot, Upper Nuwakot, Tansen, Terai and Higher Himalaya. The landslide distribution map was compared with lithological map and the percentage of landslides in each lithology class was estimated (Figure 13).

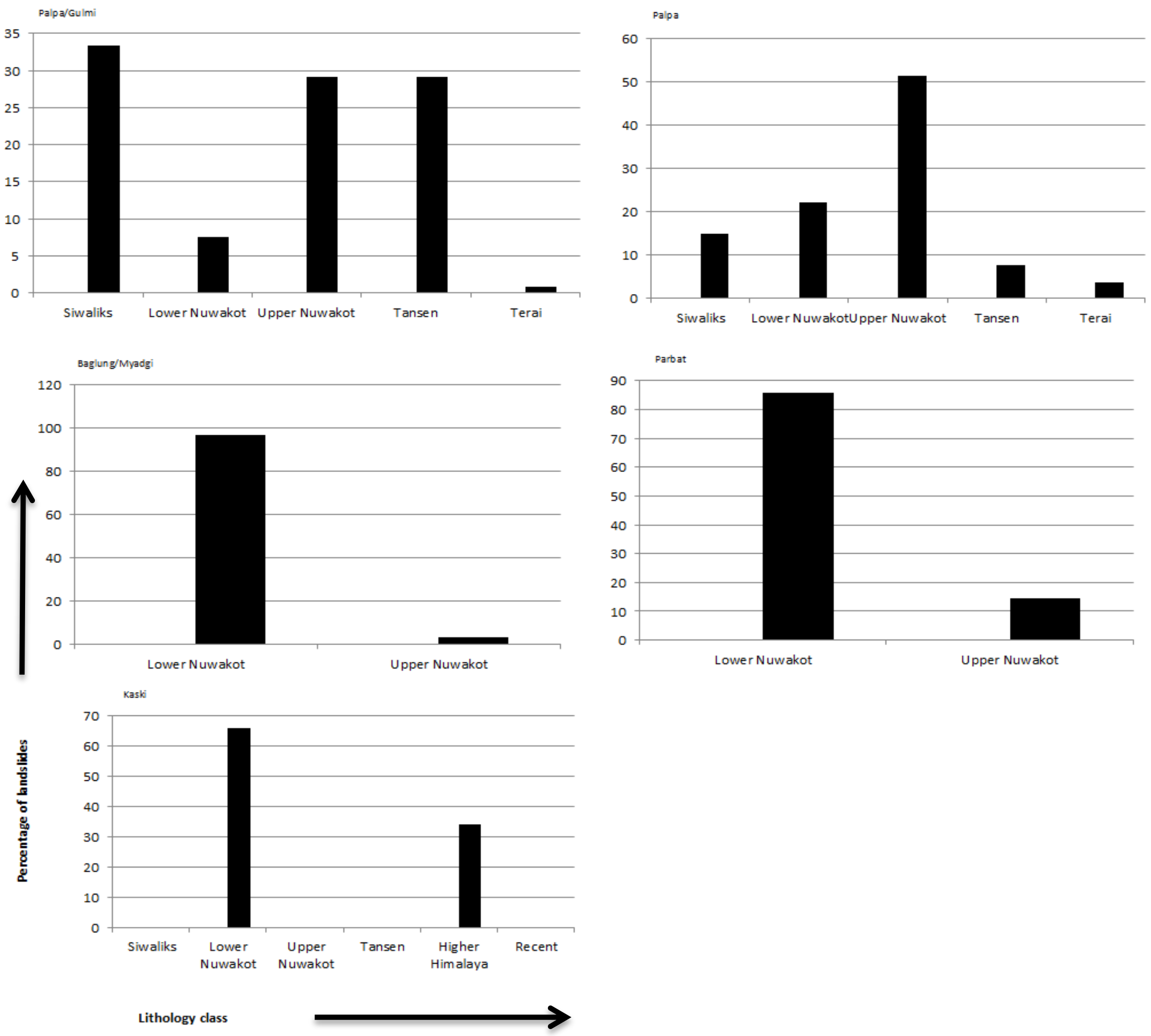

Figure 13 Landslide distribution according to lithology class

Palpa/Gulmi and Palpa contained five lithology classes while Baglung/Myadgi, Parbat and Kaski owned two lithology classes in each (Figure 8). Palpa/Gulmi, and Palpa have similar lithology and landslides are concentrated in Silwaliks, Upper Nuwakot and Tansen. The distribution of landslides in Siwaliks and Tansen was reduced in the Palpa compared to Palpa/Gulmi.

Lower Nuwakot hosted highest proportion of the landslides in Baglung/Myadgi, and Parbat while it occupied small proportion of landslides in Palpa/Gulmi and Palpa. This might be due to large proportion of area covered by Lower Nuwakot in Baglung/Myadgi and Parbat (Figure 8).

The lithologies that are susceptible to slope instability were Terai, Siwaliks, Lower Nuwakot, Upper Nuwakot and Tansen except the Higher Himalayan zone. Terai constitutes recent deposits of alluvial soil, sand and boulders which are very highly prone to landslides. Siwaliks are composed of sedimentary rocks and are highly prone to landslides.

In Lower Nuwakot sensitivity of rock materials to landslide varies from high to low. It consists of white massive quartzites, shales, green phyllites, carbonaceous slates and green slates. In addition it also has augen gneisses and muscovite biotite gneiss in very small areas. These rock minerals are less prone to landslides.

Upper Nuwakot is medium prone to landslides. The lithology composition of Upper Nuwakot included sedimentary and metamorphic rocks. This lithology unit has grey shales with intercalation of limestones and quartzite, calcareous quartzite and quartzitic limestone intercalated with shales. Shales and limestones are sedimentary rocks while quartzites are mixed with sedimentary rocks.

Tansen is composed of sedimentary rocks which are highly prone to landslides. The rock materials of this lithology unit are sandstone and shales with fine grained fossiliferous limestones.

Higher Himalayan zone consists of relative stable rock masses. But the high slope gradients with bare rocks induce landslide process in this zone. This lithology zone has garnet biotite gneiss, biotite and quartzitic mica schists, thin bands of marbles.

9.1.3 Landslide distributions in land cover class

Land use maps of the study areas were derived from the GLOBCOVER v2.v map. The land use of the study areas were classified into eight classes. Landslide distribution map was compared with the land cover map and a percentage of landslides within each land use class were calculated (Figure 14).

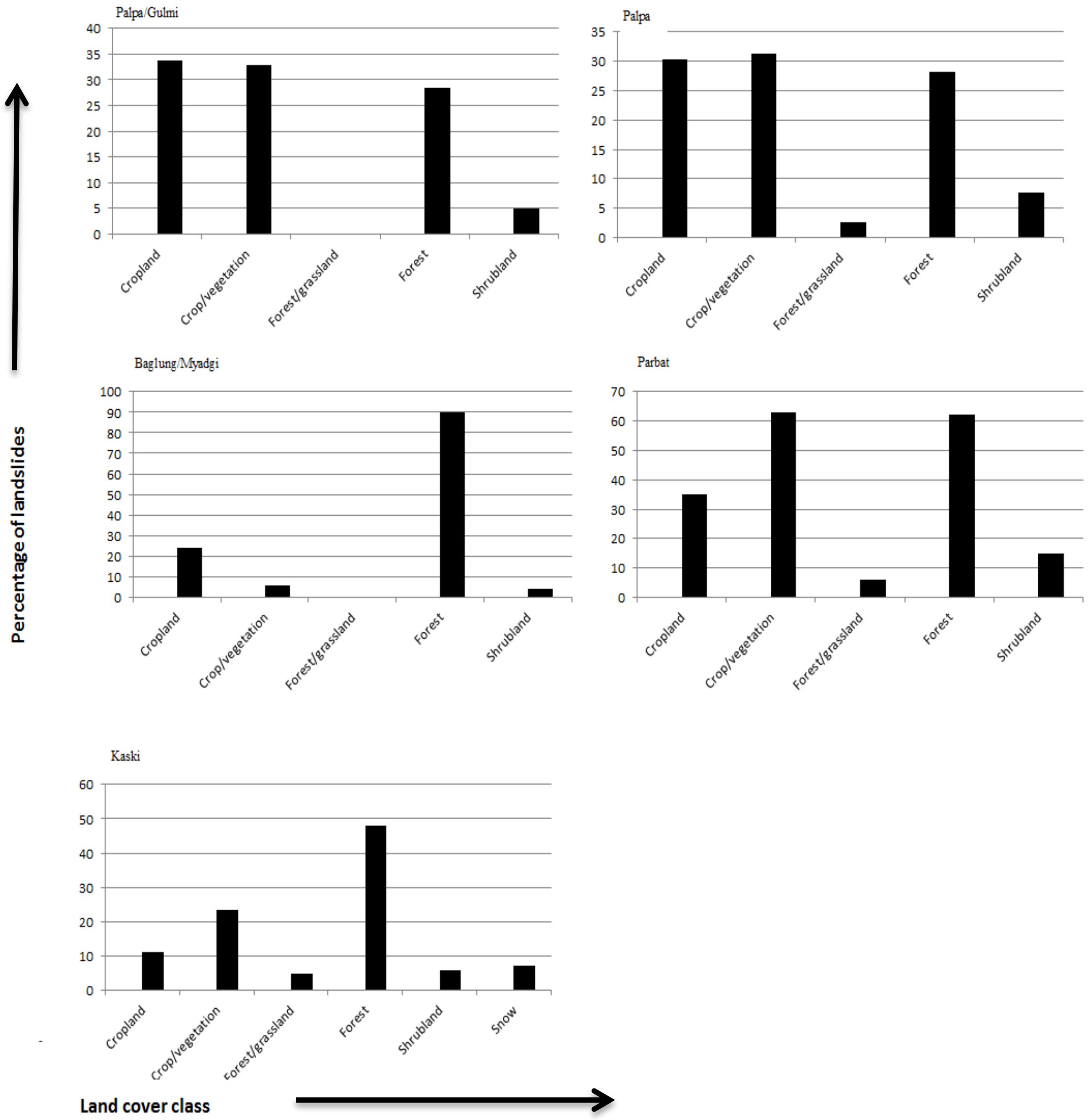

Figure 14 Landslide distribution according to lithology class

The land use pattern influence the landslide susceptibility of an area. The areas with thick vegetation are usually less prone to slope failure than areas devoid of vegetation. Presence of vegetation on the ground decreases quick over land flow by gradual infiltration of water through soil down to bedrock. This prevents buildup of pore water pressure in the soil, thereby reducing the risk of slope failure. The root of the plants increases the shear strength of the soil.

In contrast, agricultural fields and forests were the most susceptible areas in the study areas (Figure 14). In Palpa/Gulmi and Palpa, cropland and forests were most sensitive to landslides. Cultivated land covered approximately 65% of the total area and grassland and Shrubland occupied around around 8% area. Forests covered remaining 27% of the area. In Baglung/Myadgi around 70% of landslides were distributed in forests. This area included around 70% of forests, around 10% of grass and shrubland and 20% of cropland. In Parbat and Kaski also cultivated land and forests were most susceptible to landslides. The forests in these areas are intensively used as a result forests are degraded. The other most important aspect is that presence of forests in highly prone lithology might induce landslides due to added canopy and stem weights of trees during monsoons. Another reason is that the vegetated areas are steep slopes with little soil which affect the soil-root anchorage of the vegetation and consequently affect the landslide process.

9.2 LANDSLIDE SUSCEPTIBILITY MAPPING

The landslide susceptibility maps of the study areas were prepared in Arc GIS version 9.3. LNSF – a bivariate statistical method was employed to prepare the landslide susceptibility index (LSI) maps. LSI values were classified using mean standard deviation. The classified maps were grouped into five susceptibility classes as very low, low, medium, high and very high susceptibility class.

The maps of Baglung/Myagdi and Kaski produced six and seven classes by standard deviation. They were regrouped into five classes by summing up those classes that contained smallest number of pixels. The susceptibility classes with percentage of pixels closer to zero were added together to form a new class. The resulted susceptibility maps of the study areas are presented in figure (15 and 16).

Table 7 Susceptibility class and values

Susceptibility class	Value
Very Low	1
Low	2
Medium	3
High	4
Very High	5

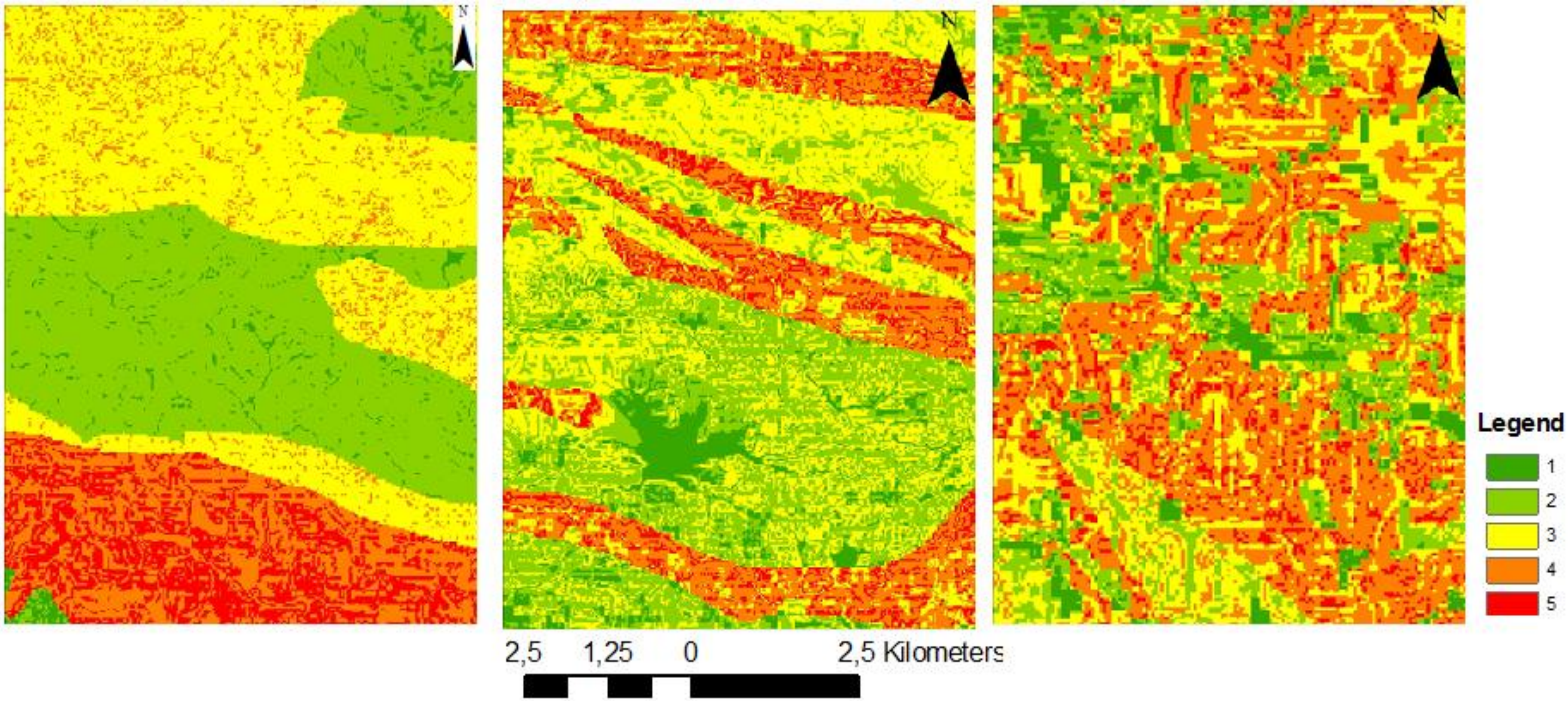

Figure 15 Susceptibility maps of Palpa/Gulmi, Palpa, Baglung/Myadgi

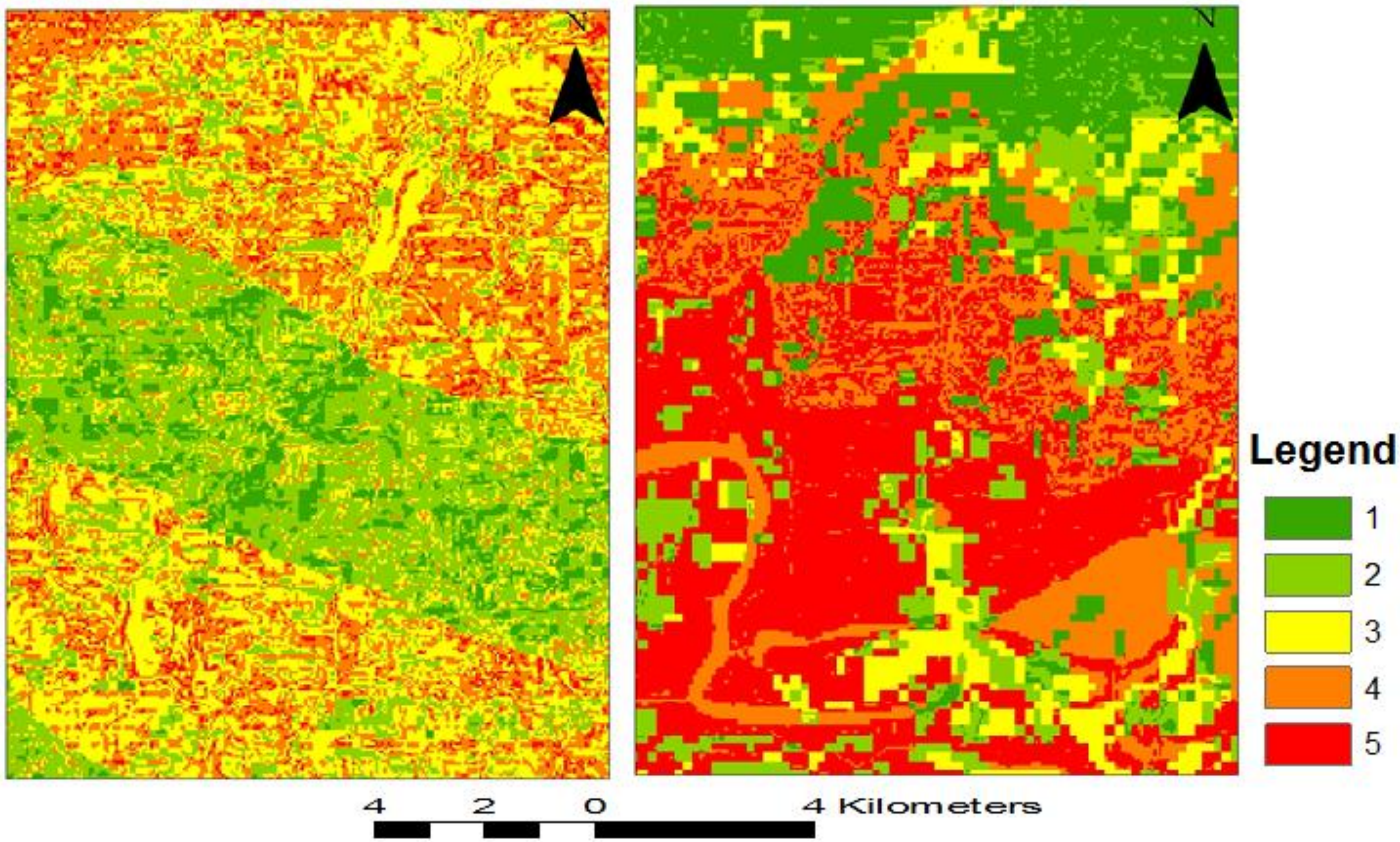

Figure 16 Susceptibility maps of Parbat and Kask

Landslide susceptibility maps of Palpa/Gulmi, Palpa and Parbat showed color transitions between lithology classes while Baglung/Myagdi and Kaski do not show any distinct transitions. There may be many reasons for this. But the main reason was theoretical basis of the analysis. The weights are assigned based on the abundance of the landslides in each attribute class of the thematic maps. The class in which the landslides are concentrated that class receives the highest weight. That particular class has influence over the parameter class with lower weights.

9.3 PARAMETRIC EFFECT ANALYSIS

Input parameters have effect on the susceptibility analysis. Effect analysis shows how susceptibility changes when the input factors are changed. If a selected factor results in a relatively large change in the outcome, then the outcome is said to be affected by that factor. Effect analysis quantifies the uncertainty of each factor. The factors that have the greatest impact on calculated landslide susceptibility map can, therefore, be identified using effect analysis (Lee 2007).

To estimate the effect of each factor on the susceptibility, landslide susceptibility for four combinations were calculated and plotted in graphs (rating curves) excluding each factor at a time. The exclusion of factors was conducted when summing up the weights using equation (2).

The contribution of three factors (slope, lithology and land cover) was evaluated by creating a rating curve. The rating curves represent the cumulative percentage of landslides with respect to susceptibility classes. To prepare the rating curves, the landslide susceptibility index maps were sorted in descending order and were sliced into100 equal-area classes. Similarly, the landslide database was also sliced into 100 equal-area classes. Then, the cumulative percentages of the susceptibility class corresponding to cumulative percentage of landslides were plotted in graphs (Figure 17-21).

Figures 17-21; show the rating curves obtained by plotting cumulative percentage of landslide susceptibility area and cumulative percentage of landslide occurrence. The curves for all (three) variables combination and two variables combination excluding each variable at a time are presented.

Influence of lithology on the landslide susceptibility is visible from rating curve. The curve except lithology is under estimated compared to the curve of the all variables (combined) for Palpa/Gulmi (Figure 17). Influence of lithology is visible in map with distinct color transition between susceptibility zones. Exclusion of slope and land cover did not show any changes in the rating curve. The curves excluding slope and land cover are aligned close to the curves of the all variables in all the study areas.

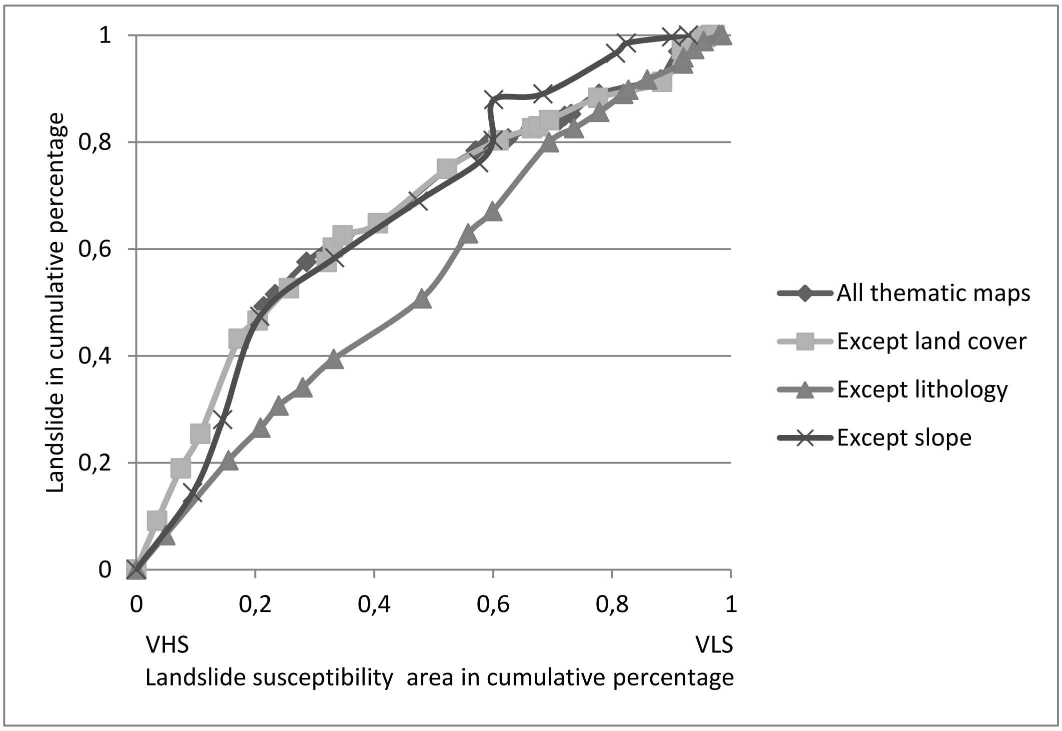

Figure 17 Landslide susceptibility index ranked (x-axis) and cumulative percentage of landslide occurrence (y-axis) of Palpa/Gulmi

Influence of slope, lithology and land cover on the landslide susceptibility is visible from rating curve. The curves produced with two parameters combination has better results compared to the curve of all variables for Palpa (Figure 18). But the difference between these curves is very small.

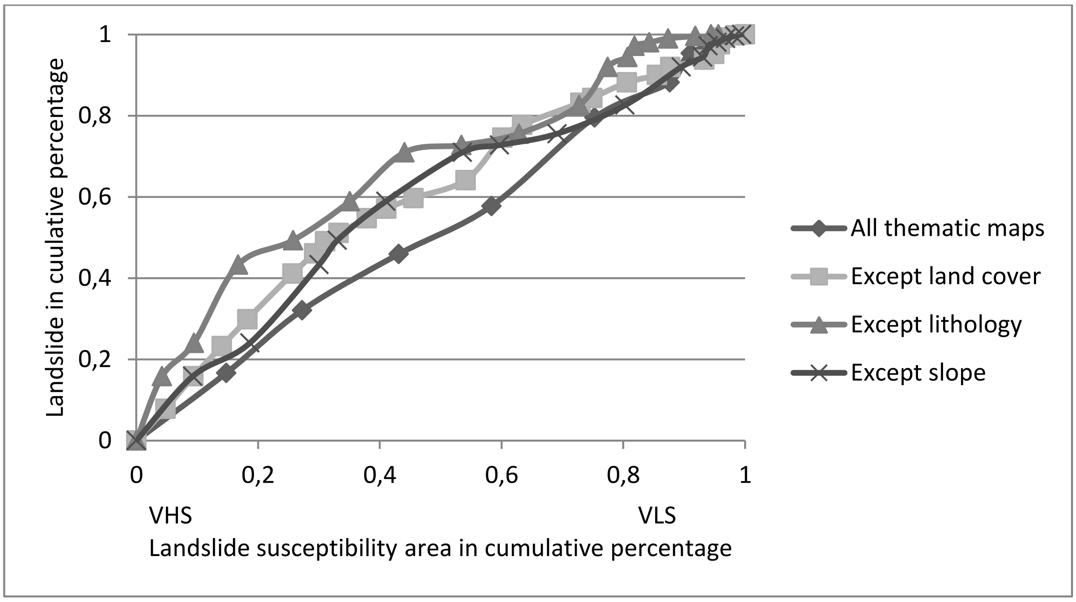

Figure 18 Landslide susceptibility index ranked (x-axis) and cumulative percentage of landslide occurrence (y-axis) of Palpa

Influence of lithology on the landslide susceptibility is visible from rating curve. The curve except lithology is under estimated compared to the curve of the all variables (combined) for Baglung/Myadgi (Figure 19). Exclusion of slope and land cover did not show any changes in the rating curve. The curves excluding slope and land cover are aligned close to the curves of the all variables.

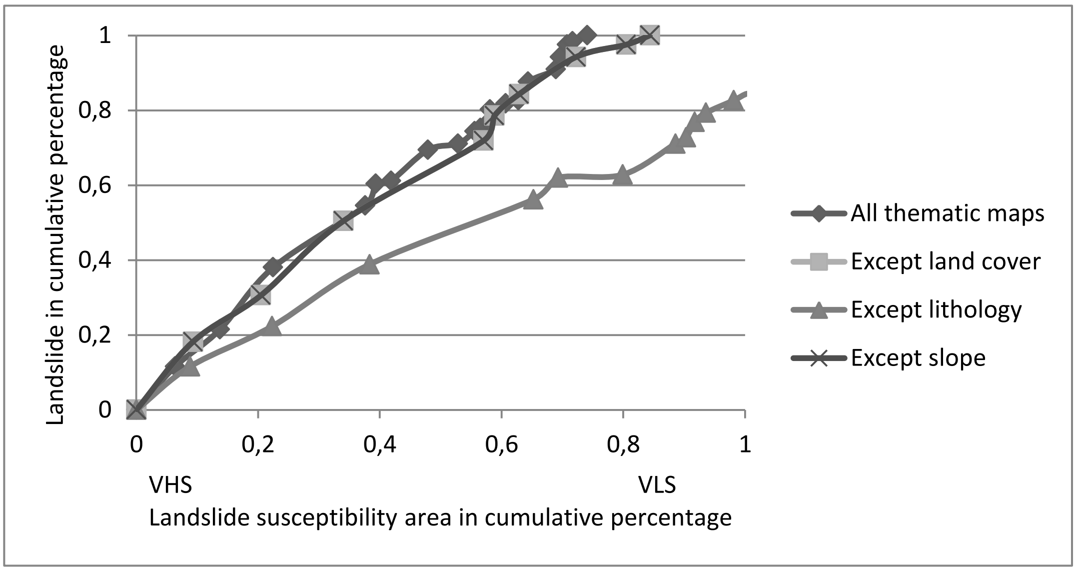

Figure 19 Landslide susceptibility index ranked (x-axis) and cumulative percentage of landslide occurrence (y-axis) of Baglung/Myadgi

Influence of slope, lithology and land cover on the landslide susceptibility is visible from rating curve. The curves produced with two parameters combination and curve with all variables combined has no difference for Parbat (Figure 20). This indicates that combination of any two parameters represent the susceptibility of the study area.

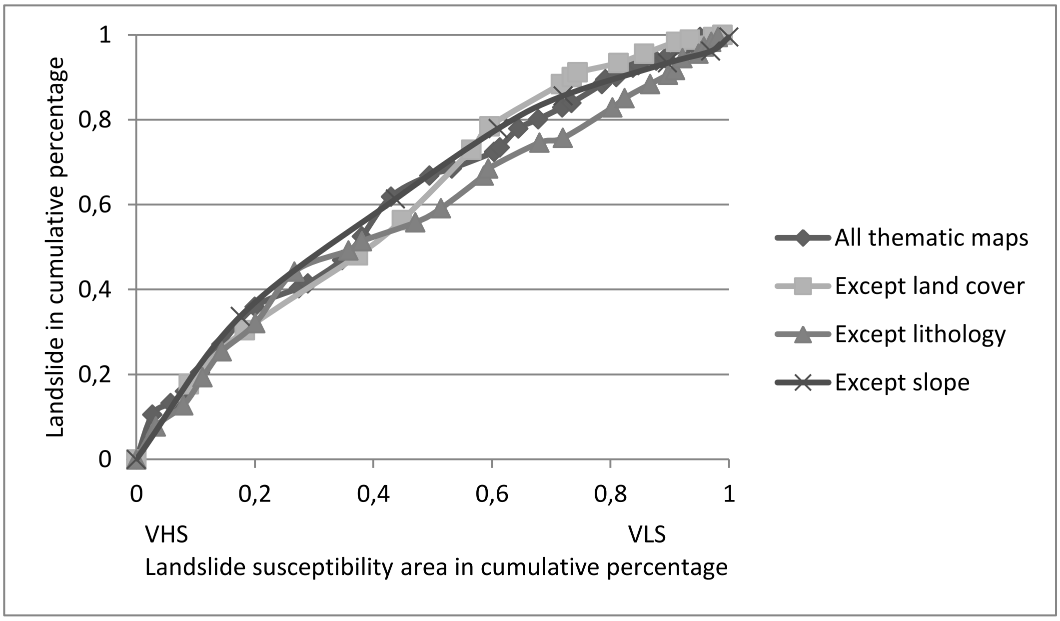

Figure 20 Landslide susceptibility index ranked (x-axis) and cumulative percentage of landslide occurrence (y-axis) of Parbat

Influence of slope, lithology and land cover on the landslide susceptibility is visible from rating curve. The curves produced with two parameters combination and curve with all variables combined has no difference for Parbat (Figure 15). This indicates that combination of any two parameters represent the susceptibility of the study area.

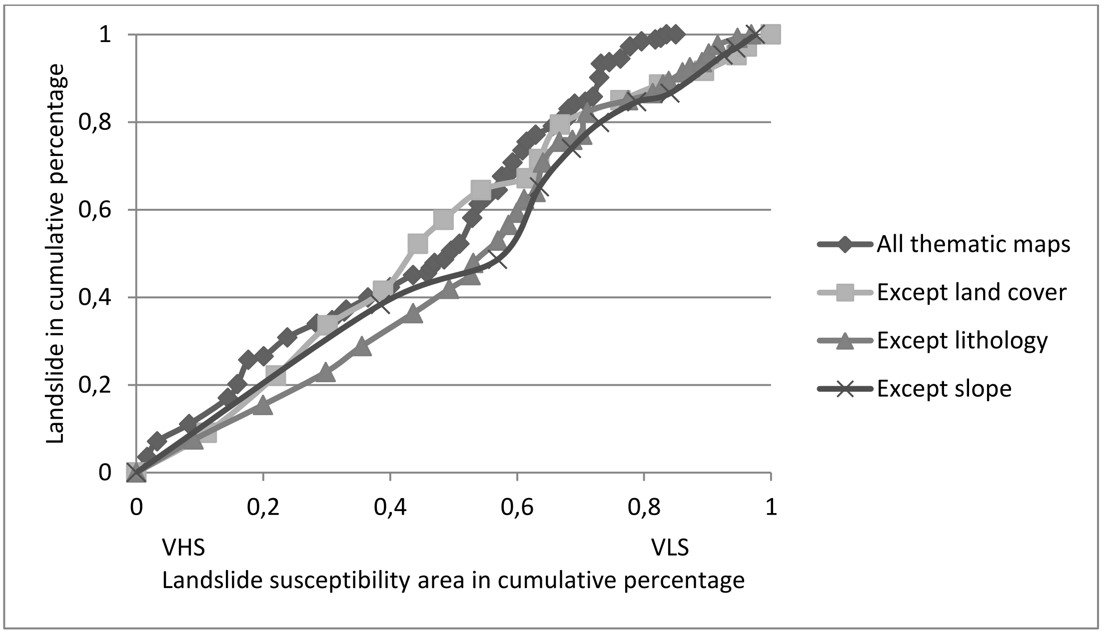

Figure 21 Landslide susceptibility index ranked (x-axis) and cumulative percentage of landslide occurrence (y-axis) of Kaski

Effect analysis results indicated that the effect of parameter on susceptibility is site specific. The effect of the same parameters changed with site. Lithology exerted influence on Palpa/Gulmi, and Baglung/Myadgi. In Palpa slight difference in the all variable combined curve and two variables curves was visible. In contrast, all four combinations yielded similar curves in case of Parbat and Kaski.

Including a number of input parameters does not necessarily improve model performance or produce better susceptibility maps. Therefore, identifying the major influential parameter is important to produce a better landslide susceptibility map.

9.4 MODEL REPLICATION TO TEST VALIDITY

Map validation is considered best when they are tested using independent population of landslides (Lee and Min 2001, Lee 2007, Pradhan and Buchroithner 2010). Model validation was conducted by model replication in which the analysis was done in one part of the study area (Palpa and Baglung/Myadgi) and the results obtained were replicated in other parts (Palpa/Gulmi and Parbat) with different landslides. The basic assumption underlying the goodness of fit test is that future landslides will occur in the same places as the past or existing movements in the study areas. If the susceptibility maps coincide well with the landslides then the maps are considered as satisfactory.

The model calibrated for Palpa and Baglung/Myadgi was replicated in Palpa/Gulmi and Parbat. The weights obtained for Palpa and Baglung/Myadgi were applied to thematic maps of Palpa/Gulmi and Parbat. The weighted thematic maps were summed up to produce the susceptibility maps using equation (2). Then the susceptibility maps were classified into very low, low, medium, high and very high susceptibility classes.

To test the goodness of fit of the replicated models; the cumulative percentage of landslide occurrence with respect to susceptibility class were plotted in a graph called as rating curve. The landslide susceptibility index maps were sorted in descending order and were sliced into100 equal-area classes. Similarly, the landslide database was also sliced into 100 equal-area classes. Then, the cumulative percentages of the susceptibility class corresponding to cumulative percentage of landslides were plotted in graphs.

The rating curves were analyzed based on two assumptions: a) a hypothetical validation curve coinciding with a diagonal of 0 to 1 would be equivalent to total random prediction. The further up and away the validation curve from the diagonal the better the predictability of the model and susceptibility map (Remondo et al. 2003, Lee 2007). And b) The higher the proportion of landslides in most susceptible zones the better the predictability of the model (Remondo et al. 2003).

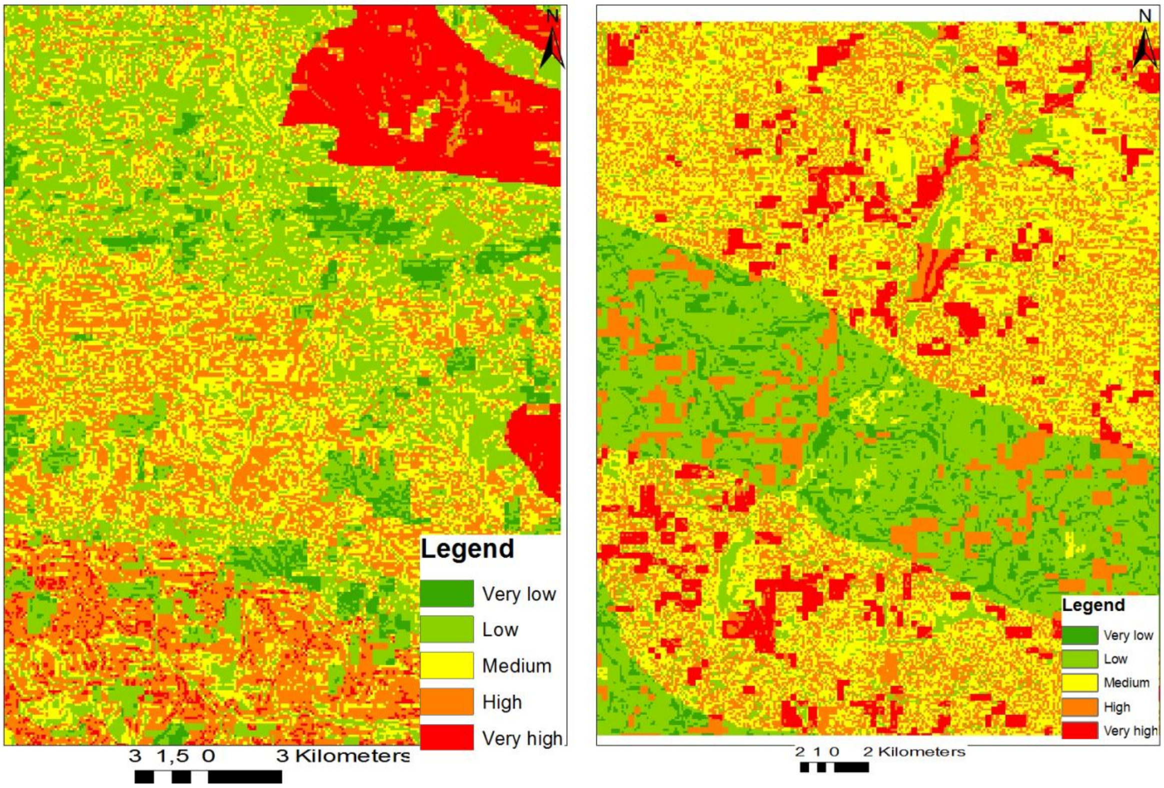

Figure 22 Landslide susceptibility maps of Palpa/Gulmi and Parbat

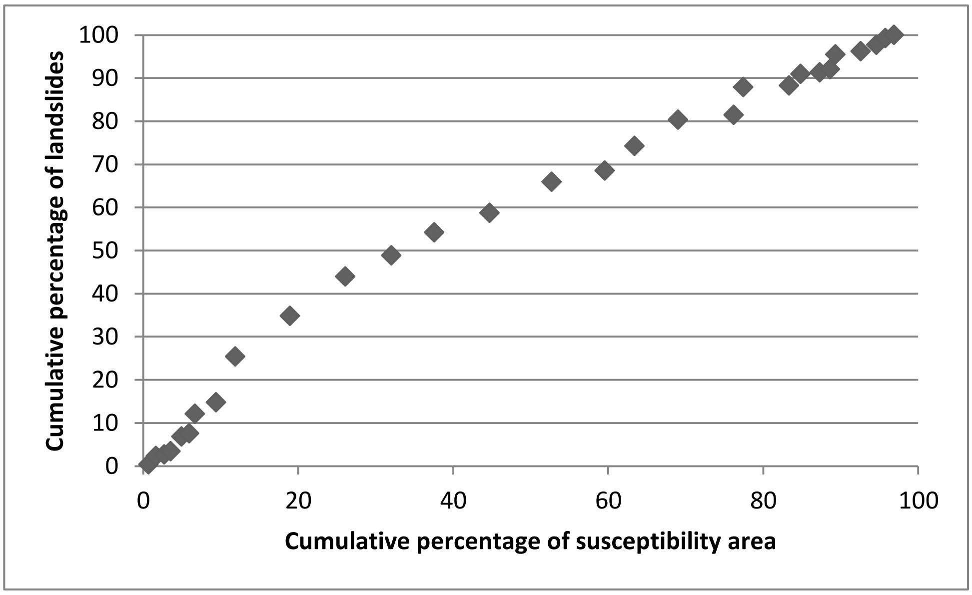

Figure 23 Cumulative frequency of susceptibility area and landslide occurrence of Palpa/Gulmi

The first 20% high susceptibility zone occupied around 38% of the landslides in Palpa/Gulmi (Figure 23). This indicates that the model performed moderately well when replicated. The curve is slightly higher than the hypothetical diagonal curve of 0 to1.

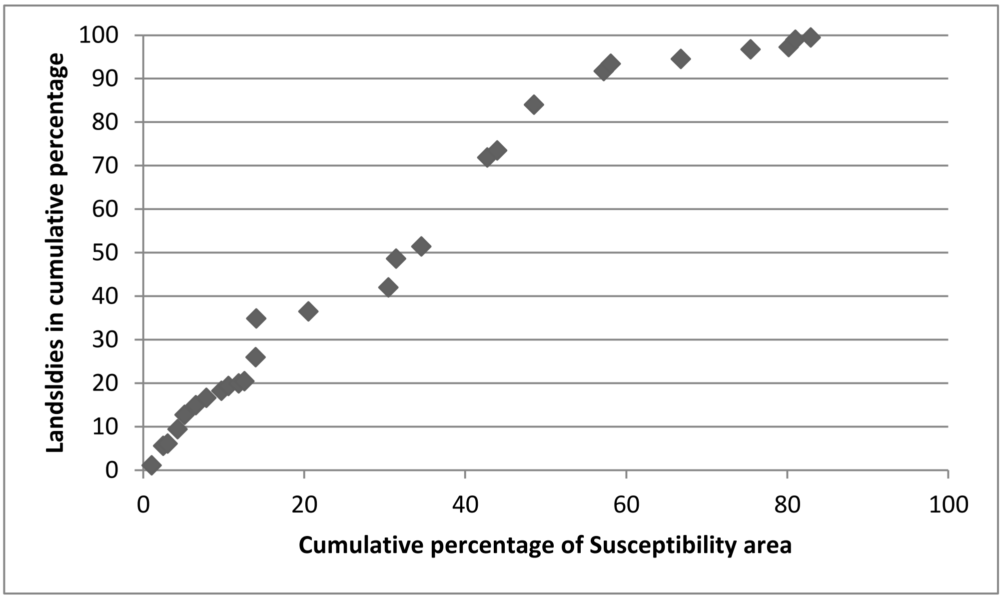

Figure 24 Cumulative frequency of susceptibility area and landslide occurrence of Parbat

The first 20% high susceptibility zone hosted around 39% of the landslides (Figure 24). This indicates that the model performed moderately well. The curve is slightly higher than the hypothetical diagonal curve of 0 to1.

Table 8 Landslide susceptibility zones and percentage of area in calibrated and model replicated map of Palpa/Gulmi

Landslide susceptibility zone	Calibrated map area percent	Percentage of area in map (model replication)
Very low	4	5
Low	29	32
Medium	39	26
High	20	28
Very High	7	9

In Palpa/Gulmi area distribution by susceptibility class varied in calibrated and model replicated map (Table 8). In model replicated map, very low and low susceptibility zone occupied 37% of the total susceptibility while medium susceptibility zone hosted around 32% of the total area. High and very high susceptibility zone contained 37% of the total area. Similarly, in calibrated map the very low and low susceptibility zones included 33% of the total area while medium class had 32% of the area. High and very high zones occupied 27% of the total area.

Table 9 Landslide susceptibility zones and percentage of area in calibrated and model replicated map of Parbat

Landslide susceptibility zone	Calibrated map area in percent	Model replicated map area in percent
Very low	1	6
Low	5	27
Medium	28	32
High	36	27
Very High	31	8

In Parbat, area distribution by susceptibility class in calibrated and model replicated map had huge variations. The area in very high and high susceptibility zones differed by 32%. These zones hosted around 67% of the total area in calibrated map while model replicated map occupied only 35% of the total area. In model replicated map, very low and susceptibility zone occupied 33% of the total susceptibility while these zones in original maps occupied around 6% area. The medium susceptibility zone hosted around 32% of the total area in model replicated map and 28% in calibrated map (Table 9).

Comparison between calibrated and model replicated maps in terms of area distribution in susceptibility classes depicted better results of model replicated maps. Tables 8 and 9 showed an increase in percentage of area in very low and low susceptibility classes in both replications. In Palpa/Gulmi, calibrated map occupied 33% of the total area while model replicated map yielded 37% of the total area. In Parbat, calibrated map hosted 6% of the total whereas model replicated map owned 36% of the total area. Larger areas in lower susceptibility zones have implications over land use management. Larger area in lower susceptibility zones means large proportion of area is usable.

10 CONCLUSIONS

Nepal is one of the landslide prone countries of the World. Very high relief, steep slopes, complex geology and diverse vegetation cover has made Nepal vulnerable to landslides. Landslide susceptibility mapping is very crucial for planning and development in a disaster prone region of Nepal. Some national level and individual research initiatives have been published about landslide process, mechanisms and hazard zonation. But there are a few studies carried out in the Western region of Nepal which is one of the landslide affected regions of the country.

The main aim of the study was to prepare landslide susceptibility maps of five sample sites (Palpa/Gulmi, Palpa, Baglung/Myagdi, Parbat and Kaski) of Western Nepal and test the validity of the model. Landslide Nominal Susceptibility Factor (LNSF)-a bivariate statistical method was employed to analyze the data in Arc GIS version 9.3. The main reason for choosing these sites was availability of landslide inventory database. The results obtained were validated by sample split and model replication.

A total of 787 landslides were recorded in these five study sites with an area of approximately 10.7 km^2. The study sites covered an area of approximately 838.7 km^2 (Palpa/Gulmi), 865.03 km^2 (Palpa), 636.4 km^2 (Baglung/Myagdi), 824.6 km^2 (Parbat) and 881.4 km^2 (Kaski). Similarly, these sites occupied around 2.1 km^2 (Palpa/Gulmi), 4 km^2 (Palpa), 1 km^2 (Baglung/Myagdi), 1.5 km^2 (Parbat) and 2 km^2 (Kaski) of landslide area.

Landslide susceptibility maps of the Palpa/Gulmi, Palpa, Baglung/Myagdi, Parbat and Kaski were made by establishing the relationship between landslides and each casual factor in Arc GIS environment. For this, the database of landslide inventory and slope, lithology and land cover were collected and preprocessed. The preprocessing steps included data conversion to raster format, resampling to 90mx90m resolution and projection in WGS_84 coordinate system. Resampling of landslide inventory resulted in loss of 3 landslide points in Baglung/Myagdi and one in each of Palpa/Gulmi and Palpa. The size of the landslide was small.

The relationship between landslide distribution and the thematic factors was compared by estimating percentage of landslides within each class of the slope, lithology and land cover map. Percentage of landslides increased with increased slope gradient. But the range of slope gradient from where the landslide distribution fell varied between study areas. . The landslides in sedimentary rocks failed in lower angles. The intensive land use in fragile geology also contributed positively for landslide failure in lower slope angles.

Terai, Siwaliks, Lower Nuwakot, Upper Nuwakot and Tansen except the Higher Himalayan zone were susceptible to landslides. These lithological zones are composed of rock materials such as alluvial soils, sedimentary rocks (sandstone and shales with fine grained fossiliferous limestones, shales etc) and metamorphic rocks (white massive quartzites, carbonaceous slates and green slates, green phyllites etc). Higher Himalayan zone consists of relative stable rock masses such as garnet biotite gneiss, biotite and quartzitic mica schists, thin bands of marbles. But high slope gradients with bare limestone and metamorphic rocks induce landslide process in this zone.

In Palpa/Gulmi and Palpa, Parbat and Kaski cropland and forests were most sensitive to landslides. Large proportions of landslides were confined to cropland and forests. These areas have intensive land use for agriculture. For example, cultivated land covered approximately 65% of the total area and grassland and Shrubland occupied around 8% of the total area while forests occupied remaining 27% of the area in Palpa/Gulmi. In Baglung/Myadgi around 70% of landslides were distributed in forests. This area included around 70% of forests, 10% of grass and shrubland and 20% of cropland. The forests in these areas are intensively used as a result forests are degraded. The other most important aspect is that presence of forests in highly prone lithology might induce landslides due to added canopy and stem weights of trees during monsoons. Another reason could be vegetated areas in steep slopes with little soil also affects the soil-root anchorage of the vegetation and consequently affect the landslide process.

To evaluate the contribution of each factor towards landslide susceptibility, each thematic factor map was separately overlayed with landslide inventory map of respective area. Then a weightage for each thematic class was estimated using equation (1). The estimated weights were directly assigned to the respective thematic layers to produce the weighted thematic maps. The weighted thematic maps were summed up to produce a landslide susceptibility index (LSI) map according to equation (2). The LSI values were classified into five susceptibility classes using mean standard deviation.

Distinct color variations between lithological boundaries were visible in the maps. The reason for this was the weighting process. The effect of each parameter on landslide susceptibility was analyzed by creating rating curves. Parametric effect analysis indicated that the effect of susceptibility parameters is site specific. The effect of lithology was distinct in Palpa/Gulmi, Palpa and Baglung/Myadgi where the abrupt changes in color between lithology boundaries were seen in the maps. There was very slight difference between rating curves excluding slope, lithology and land cover in Parbat and Kaski.

Including an input parameter in susceptibility analysis does change the output. The exclusion of land cover did not show any changes in the rating curves in all cases. Therefore, identifying the most influential parameter is important.

Model validation was performed by model replication. The goodness of fit of the replicated model was evaluated with rating curves. The rating curves were analyzed based on two assumptions: a) a hypothetical validation curve coinciding with a diagonal of 0 to 1 would be equivalent to total random prediction. The further up and away the validation curve from the diagonal the better the predictability of the model and susceptibility map (Remondo et al. 2003, Lee 2007). And b) The higher the proportion of landslides in most susceptible zones the better the predictability of the model (Remondo et al. 2003).

Model replication proved moderately successful for areas of similar lithology conditions. The rating curves were slightly higher than the hypothetical diagonal curve of 0 to1. The first 20% high susceptibility zone occupied around 38% and 39% of the landslides in Palpa/Gulmi and Parbat respectively.

Comparison between calibrated and replicated models by area in susceptibility class showed better results of model replication. An increase in percentage of area in very low and low susceptibility classes was observed in both replications. In Palpa/Gulmi, calibrated map occupied 33% of the total area while model replicated map yielded 37% of the total area. In Parbat, calibrated map hosted 6% of the total whereas model replicated map owned 36% of the total area. Larger areas in lower susceptibility zones have implications over land use management. Larger area in lower susceptibility zones means large proportion of area is usable. The model replication strategy proved better for Parbat as it improved the predictive capacity of the model by reducing the area of most susceptible zones by 32% compared to the area predicted in the original map (susceptibility map developed using the landslides of the same area).

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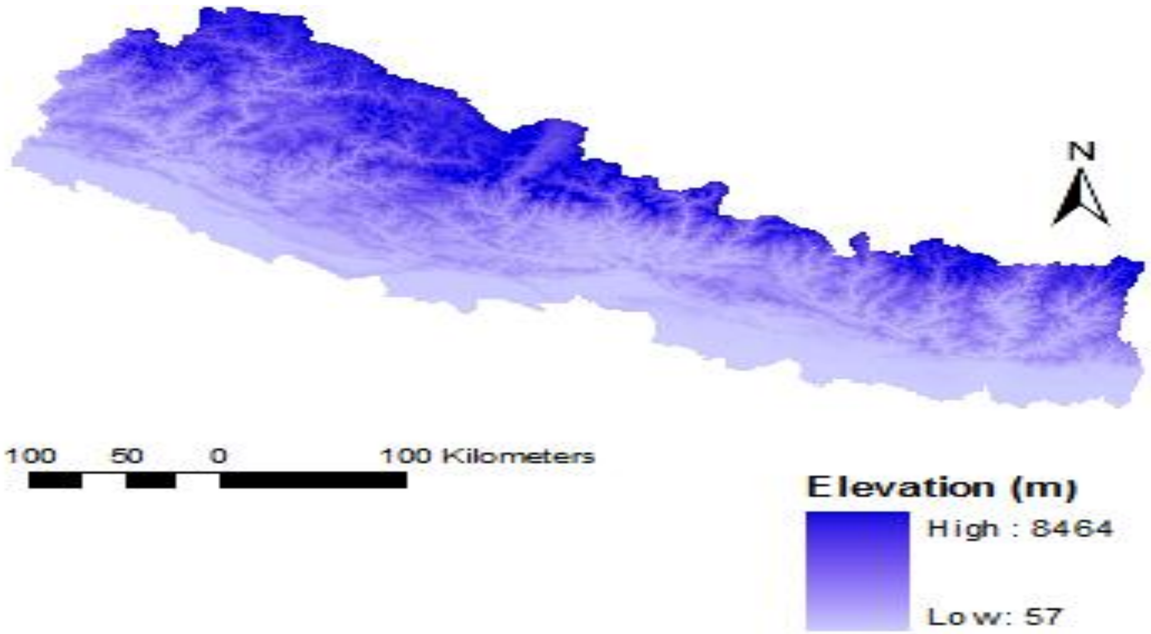
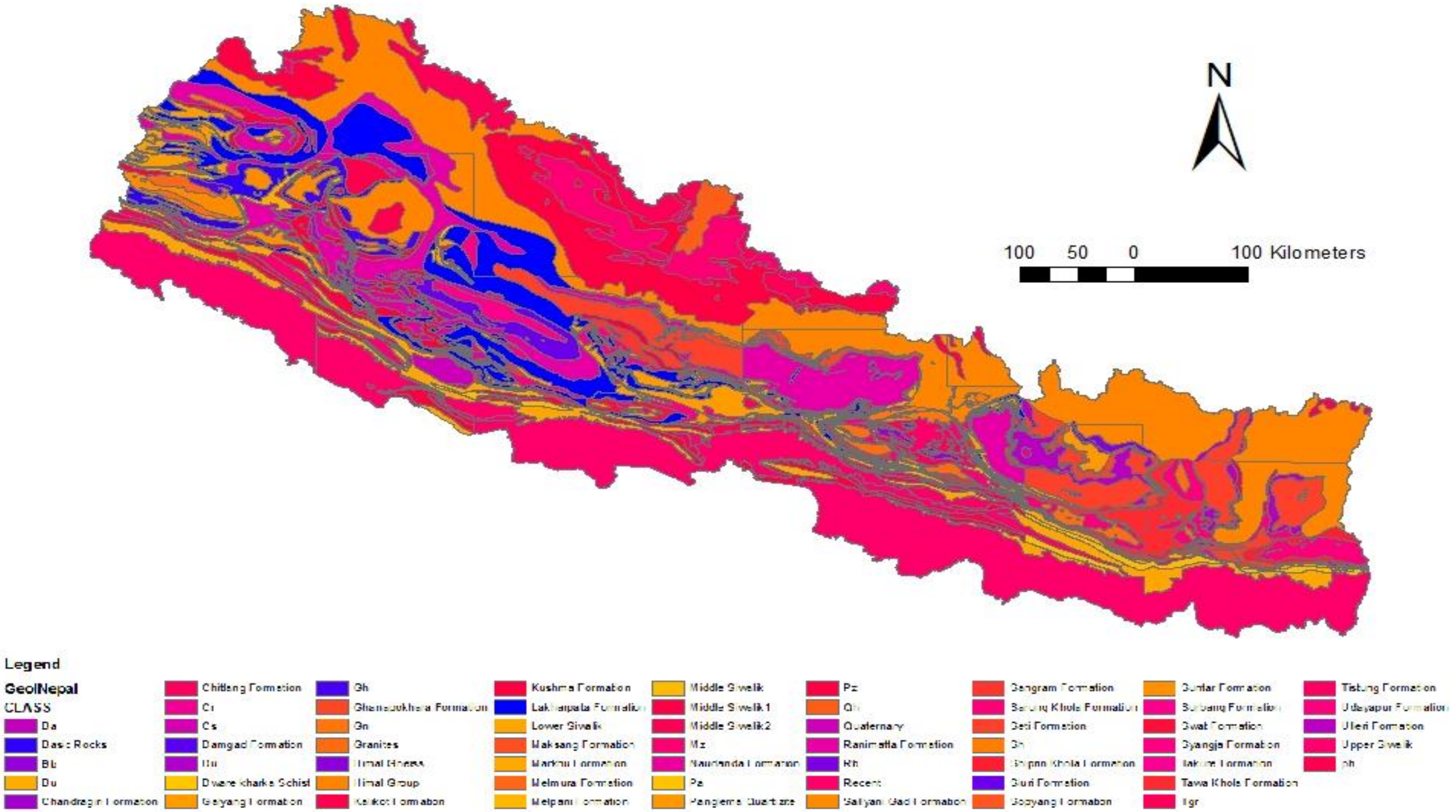
APPENDICES

APPENDIX 1 DIGITAL ELEVATION MODEL, GEOLOGY AND LAND COVER MAPS OF NEPAL



DEM of Nepal


N
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Legend
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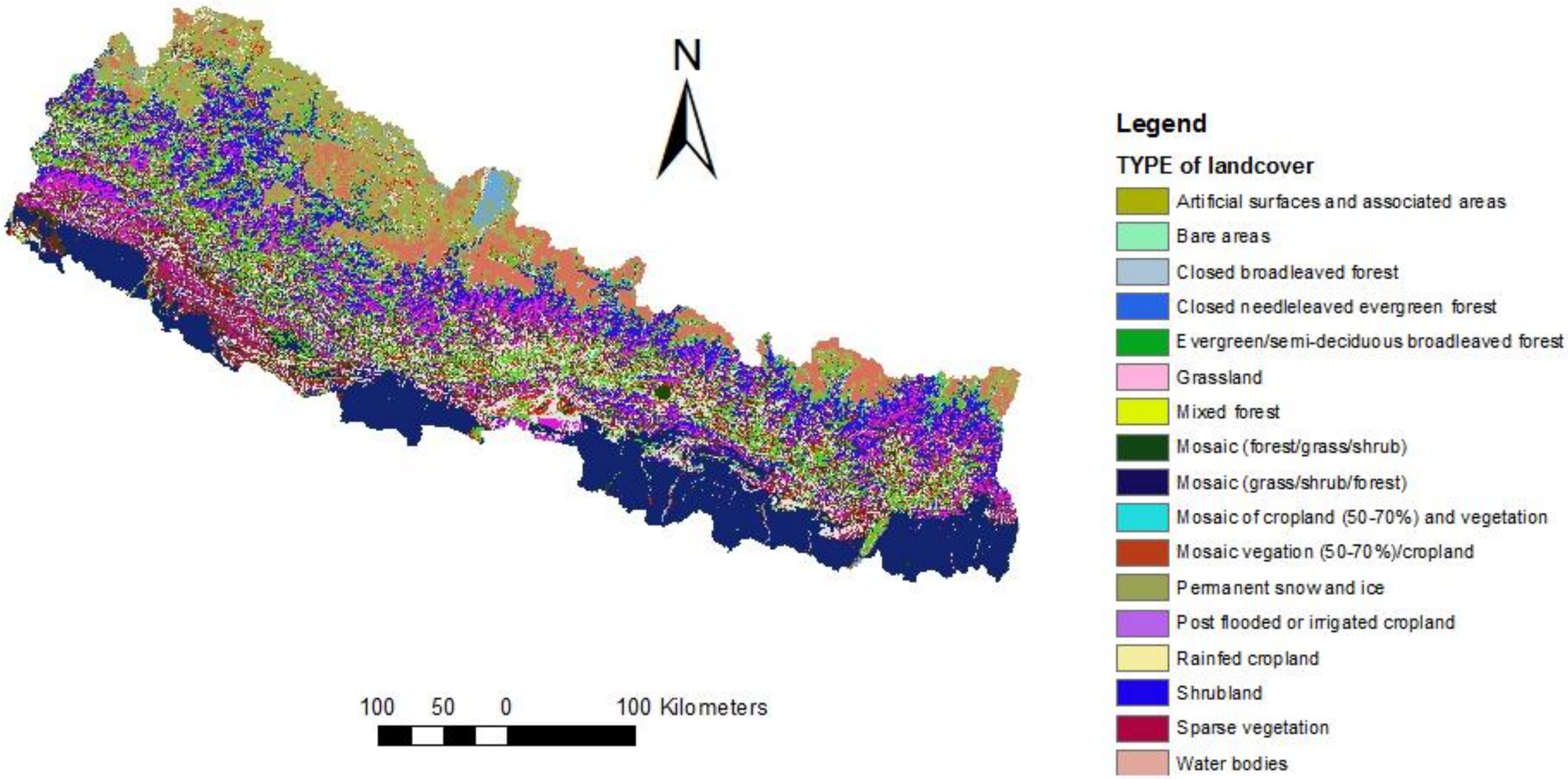
CLASS
Da
Basic Rocks
Bb
Du
Chitlang Formation
Cr
Cs
Damgad Formation
Dwarekharka Schist
Gh
Ghanapokhara Formation
Gn
Granites
Himal Group
Kushma Formation
Lakharpata Formation
Lower Siwalik
Maksang Formation
Melmura Formation
Middle Siwalik
Middle Siwalik 1
Middle Siwalik2
Mz
Pa
Pz
Qh
Quaternary
Ranimatta Formation
Rh
Recent
Sangram Formation
Seti Formation
Sh
Suri Formation
Sundar Formation
Swat Formation
Syangja Formation
Tawa Khola Formation
Tistung Formation
Udayapur Formation
Ulleri Formation
Upper Siwalik
ph

Geological Map of Nepal



Land cover map of Nepal

APPENDIX 2 Lithology classification of Nepal

OBJECT ID	Class	Symbol	Name	Group	Sub_ Group	Age	Description of the geological unit
1	(blank)						
2	Ba	Ba	Baitadi Beds	Midland Group	Lakharpat a	Upper pre cambrian - Late Paleozoic	Thick beds of grey siliceous dolomites
3	Basic Rocks	Bs					"perhaps basalt and extrusive rocks from sea origin
4	Bb	Bb	Balbang schists	Midland Group	Jal Jala	Pre Cambrian	Schist quartz mica schist interbedded with calcareous quartzites and thinly laminated crystalline limestones
5	Bh	Bh	Bhimphedi Group	Bhimphedi		Precambrian	Green schists metamorphosed rocks. Schists, quartzites and few marble horizons. Locally migmatized and gneissified. Granite intrusions present. Equivalent to Precambrian rocks of the Higher Himalayan Crystallines
6	Bu	Bu	Budhi Ganga Gneiss	Dadelhura		Pre Cambrian	Augen gneisses, granitic gneisses, and feldsphatic schists
7	Chandragir i Formation	Ca	Chandragir i Formation	Kathmand u	Phulcoki	Pre Cambiran - Devonian	Light fine grained cyrstalline limestones partly siliceous thick to massively bedded quartzites in upper parts. Wavy limestones contain late ordovician schinoderms
8	Chitlang Formation	Ch	Chitlang Formation	Kathmand u	Phulcoki	Pre Cambiran - Devonian	Dark slates with white quartzites at the base impure limestones and two ferrugenous beds containing trilobites
9	Cr	Cr	Chour-	Midland	Dailekh	Upper pre cambrian -	Chour carbonates white to gray compact dolomite and

			Ghanapokhara Formation	Group		Late Paleozoic	dolomitic limestones interbedded with shales beds
10	Cs	Cs	Calc. Silicate rocks (member of Sarung Khola)	Kathmandu	Bimphedi	Pre Cambiran - Devonian	Calcareous silicate rocks and marble bands
11	Damgad Formation	Da	Damgad Formation	Dadelhura		Pre Cambrian	Grey to greenish grey quartzites, calcareous quartzites, and crystalline limestones
12	Du	Du	Dunga Quartzites beds	Midland Group	Lakharpata	Upper pre cambrian - Late Paleozoic	Quartzites
13	Dware kharka Schist	Dk	Dware kharka Schists	Himal		Pre Cambrian	Medium to coarse grained quartz muscovite biotite schists garnetiferous schistose gneisses and kyanite schists
14	Galyang Formation	Gl	Galyang Formation	Midland Group	Lakharpata	Upper pre cambrian - Late Paleozoic	Dark gray slates intercalated with thin grey calcareous slates and lamillae of carbonates
15	Gh	Gh	Ghatte Gad Carbonates	Dadelhura		Pre Cambrian	Bluish crystalline limestones, calcareous schists, and quartz biotite schists
16	Ghanapokhara Formation	Gp	Ghanapokhara Formation	Midland Group	Dailekh	Upper pre cambrian - Late Paleozoic	Black to gray carbonaceous slates and green shales
17	Gn	Gn	Augen gneisses				Augen gneisses, banded gneisses
18	Granites	Gr	Granites				
19	Himal	Hg	Himal	Himal		Pre Cambrian	Two mica gneisses, granitic gneisses, banded gneisses,

	Gneiss		gneisses				kyanite bearing gneisses, migmatites, and thin bands of marbles
20	Himal Group	Hm	Himal Group	Himal		Pre Cambrian	Garnet biotite gneisses, kyanite biotite gneisses, garnetiferous mica schists augen gneisses, micaceous quatzites, and thin bands of marbles
21	Kalikot Formation	Kk	Kalikot Formation				Garnetiferous biotite schists and micaceous quartzites with gneisses
22	Kushma Formation	Ks	Kushma Formation	Midland Group	Dailekh	Upper pre cambrian - Late Paleozoic	Greenish grey, White fine to medium grained at places ripple marked massive quartzite intercalated with green phyllites. Basic intrusions are abundant
23	Lakharpata Formation	Lk	Lakharpata Formation	Midland Group	Lakharpat a	Upper pre cambrian - Late Paleozoic	Fine grained, light blue, grey limestones and dolomites with thin intercalations of grey shales, White, pink dolomitic limestones, purple quartzites and green shales at the top. Algal structure and stromatolites are present
24	Lower Siwalik	Ls	Lower Siwalik	Siwalik		Mid Miocene - Pleistocene	Fine grained, hard, grey sandstones interbedded with purple and chocolate coloured shales, nodular maroon clays and pseudo conglomerates
25	Maksang Formation	Mk	Maksang Formation	Kathmand u	Bimphedi	Pre Cambiran - Devonian	White fine grained quartzites cross bedded
26	Markhu Formation	Mr	Markhu Formation	Kathmand u	Bimphedi	Pre Cambiran - Devonian	Massive coarse to medium grained crystalline marble changin northward to dark fine biotites schists interbedded with impur marbles and quartzites. Stromatolites are found
27	Melmura Formation	Me	Melmura Formation	Dadelhura		Pre Cambrian	Grey to dark grey phyllites quartzites and phyllitic schists
28	Melpani Formation	Mp	Melpani Formation	Surkhet		Cretaceous - Eocene	White, grey, ferruginous well bedded massive or the quartzites interbedded with grey carbonaceous crumpled and reddish brown shales and occasional conglomerates and fossiliferous limestones gastropodes (Promothilida),

							pelecypods (Modiolo, Peuromya, Homom
29	Middle Siwalik	Ms	Middle Siwalik	Siwalik		Mid Miocene - Pleistocene	Fine to medium grained arkosic pebbly sandstones with rare to dark grey clays, siltstones and conglomerates and coarse grained friable arkosic sandstones hard massive grey sandstones, interbedded with green to greenish grey shales and mudstones. Plant an
30	Middle Siwalik1	Ms1	Middle Siwalik1	Siwalik		Mid Miocene - Pleistocene	Fine to medium grained friable arkosic sandstones and hard compact massive sandstones intercalated with green to greenish grey clays, thin bands of pseudo-conglomerates and mudstones. Plant and animal fossils are present in clays
31	Middle Siwalik2	Ms2	Middle Siwalik2	Siwalik		Mid Miocene - Pleistocene	Medium to coarse grained, arkosic, pebbly sandstones with rare grey to dark greys clays and occassionally silty sandstones and conglomerates
32	Mz	Mz	Sandstone Tibetan			Triassic to Lower Cretaceous	Mainly sahllow continental plateform sediments with local pro-delta facies in the Early Cretacious. Sandstones, slates, shales with glauconite. Mainly ammonites and belemnites in Jurrassic limestone
33	Naudanda Formation	Nd	Naudanda Formation	Midland Group	Dailekh	Upper pre cambrian - Late Paleozoic	White massive fine to medium grained quartzites with ripple marks interbedded with shales beds
34	Pa	Pa	Pandrang (member of Tawa Khola Fm.)	Kathmand u	Bimphedi	Pre Cambrian - Devonian	light green quartzites
35	Panglema Quartizite	Pg	Panglema Quartzite	Himal		Pre Cambrian	Fine grained compact quartzitic schists and quartzites occassionally cyrstalline limestones
36	ph	ph	Phulchauki Group	Phulchauki		Early to Middle Paleozoic	Fossiliferous (crinoids and trilobites) calcareous rocks with subordinate siliceous and argilaceous sediments in the upper part. Lower part consists of clastic and feebly

							metamorphosed rocks (phyllites, quartzites and siltstones)
37	Phulchowki Formation	Ph	Phulchowki Formation	Kathmandu	Phulcoki	Pre Cambrian - Devonian	Light brown dolomite underlain by crinoidal limestones
38	Pz	Pz	Limestone Tibetan			Cambrian to Permian	Lower part mainly calcareous, middle part pelagic and upper part is rich in detrital sediments. Limestone, sandstone and shale. Early Permian tilloid beds with platn fossils and focal spilitic lava flows.
39	Qh	Qh	Quaternary Himalaya			Plio-Pleistocene	Mainly fluvial and fluvio terrential sediments with local lacustrine clays and marlstones
40	Quaternary	Q	Quaternary			Quatenary	Alluvium, boulders, gravels, sands and clays
41	Ranimatta Formation	Rm	Ranimatta Formation	Midland Group	Dailekh	Upper pre cambrian - Late Paleozoic	Grey greenish grey gritty phyllites grilstones with conglomerates and white massive quartzites. In the upper parts basic instrusion are noted
42	Rb	Rb	Robang Formation	Midland Group	Lakharpata	Upper pre cambrian - Late Paleozoic	Green chlorotic phyllites layers of basic rocks
43	Recent	Rec	Recent			Recent	Alluvium, boulders, gravels, sands and clays
44	Sallyani Gad Formation	Sl	Salyani Gad	Dadelhura		Pre Cambrian	Aplites granite gneisses, augen gneisses, and biotite gneisses
45	Sangram Formation	Sg	Sangram Formation	Midland Group	Lakharpata	Upper pre cambrian - Late Paleozoic	Black, dark gray to greenish grey shales with intercalation of limestones and quartzites
46	Sarung Khola Formation	Sk	Sarung Khola Formation	Kathmandu	Bimphedi	Pre Cambiran - Devonian	Fine grained dark green grey biotite and quartzitic mica schists occassionally garnetiferous interbedded with impure strongly micaceous quartzites
47	Seti	St	Seti	Midland	Pokhara	Upper pre cambrian -	Grey to greenish grey phyllites, gritty phyllites and

	Formation		Formation	Group	(Dailekh?)	Late Paleozoic	quartzites with minor conglomeratic layers. Basic intrusions are also noted
48	Sh	Sh	Schists quartzites gneisses	Kathmand u	Bimphedi	Pre Cambiran - Devonian	Undeferentiated schists quartzites gneisses and calcareous silicate rocks (cs) of Bhimpedi sub group and Tistung Formation in rarious stages of migmatization
49	Shiprin Khola Formation	Sp	Siphirn Khola Formation	Kathmand u	Phulcoki	Pre Cambiran - Devonian	Coarse crystalline highly garnetiferous muscovite biotite quartz schists quartzites, green chlorites schists at the base
50	Siuri Formation	Sr	Siuri Formation	Midland Group	Jal Jala	Pre Cambrian	Garnetiferous quartz biotite schists, garnetiferous chlorite-quartz schists, muscovite biotite schists, calcareous schists, massive quartzites with rare graphitic schists. Intrusion of basic rocks and granites are found
51	Sopyang Formation	So	Sopyang Formation	Kathmand u	Phulcoki	Pre Cambiran - Devonian	Dark argillaceous and marly slates with thin limestones
52	Suntar Formation	Sn	Suntar Formation	Surkhet		Cretaceous - Eocene	Fine to medium grained, greenish grey sandstones and purple shales with intercalations of green splintary shales
53	Surbang Formation	Sb	Surbang	Midland Group	Jal Jala	Pre Cambrian	Grey to brown cherty crystalline limestones interbedded with calcareous schist, calcareous quartzites and biotite quartz schists
54	Swat Formation	Sw	Swat Formation	Surkhet		Cretaceous - Eocene	Grey to dary grey, carbonaceous, shales with lenses of fine grained fossiliferous limestones (Nummulites sp., Assilina sp., etc.)
55	Syangja Formation	Sy	Syanja Formation	Midland Group	Lakharpat a	Upper pre cambrian - Late Paleozoic	White pale orange pinkish or purplish calcareous quartzites and quartzitic limestones intercalated with dark grey purple and green shales strongly ripply marked quartzites at the base
56	Takure Formation	Tk	Takure Formation	Midland Group	Gondwana	Permo - Carboniferous	Sandstones, quartzitic sandstones, graphitic coals, chloritic phyllites, lamprophyre sills and at some places

							thin bands of dolomitic limestones
57	Tawa Khola Formation	Ta	Tawa Khola Formation	Kathmandu	Phulcoki	Pre Cambrian - Devonian	Coarse grained dark grey garnetiferous muscovite biotite quartz schists interbedded with greyish impure quartzites
58	Tgr	Tgr	granites Himalaya (Tert)			Miocene	Tow mica leucocratic grnites with tourmaline
59	Tistung Formation	Ti	Tistung Formation	Kathmandu	Bimphedi	Pre Cambrian - Devonian	Dull, green grey coloured phyllites pink purplish tinted sandstones with sandy limestones ripple marks, clay cracks, worm tracks are abundant. Pebbly beds near base
60	Udayapur Formation	Ud	Udayapur Formation	Kathmandu	Bimphedi	Pre Cambiran - Devonian	Coarse grained crystalline marbles with intercalations of schists
61	Ulleri Formation	Ul	Ulleri Formation	Midland Group	Dailekh	Upper pre cambrian - Late Paleozoic	Augen gneisses, muscovite biotite gneisses, feldsphatic schist
62	Upper Siwalik	Us	Upper Siwalik	Siwalik		Mid Miocene - Pleistocene	Coarse boulders, conglomerates with irregular beds and lenses of sandstones and thin intercalation of yellow, brown, grey sandy clays

Source: (DMG 1994)

APPENDIX 3 Slope, lithology and land cover classes and percent of total pixels, percent of landslide pixels and weights for five study areas by LNSF method

Palpa/Gulmi						**Palpa**					**Parbat**				
Slope class	No. Of	% to total	No of landslid	% to total	Weights	No. Of	% to total	No of landslid	% to total	Weights	No. Of	% to total	No of landslid	% to total	Weights

	total pixel s	pixel s	e pixels	pixel s		total pixel s	pixel s	e pixels	pixel s		total pixels	pixel s	e pixels	pixel s	
1	7544	7	8	3	0,30	10243	8	20	4	0,4	4496	6	3	2	0,24
2	12563	12	21	8	0,80	15932	12	43	9	0,9	9223	12	7	6	0,57
3	14859	14	47	18	1,78	19703	15	59	12	1,2	12992	16	10	8	0,81
4	17740	16	45	17	1,70	20487	16	69	14	1,4	13811	17	22	18	1,79
5	16372	15	35	13	1,33	19087	15	83	17	1,7	12745	16	16	13	1,30
6	13666	13	31	12	1,17	16088	12	77	15	1,5	10686	13	25	20	2,03
7	11013	10	32	12	1,21	12946	10	55	11	1,1	7619	10	11	9	0,89
8	7975	7	31	12	1,17	8963	7	54	11	1,1	4908	6	19	14	1,54
9	4663	4	12	5	0,45	4478	3	36	7	0,7	2677	3	3	2	0,24
10	1137	1	2	1	0,11	1273	1	3	1	0,1	559	1	8	7	0,57

Geology class

Siwaliks	25084	23	87	33	1,67	13548	10	75	15	1	0	0	0	0	0
Lower Nuwakot	8522	8	20	8	0,38	36116	28	111	22	2,3	50269	87	120	97	1,94
Upper Nuwakot	42162	39	77	29	1,46	43778	34	256	51	0,3	7236	13	4	3	0,06
Tansen	29944	28	77	29	1,46	33080	26	38	8	0,7	0	0	0	0	0
Higher Himalayan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recent deposits	1821	2	3	1	1,04	3019	2	19	4	0,16	0	0	0	0	0
Landcover class															
Cropland	3452	34	89	34	1,69	4315	36	151	30	1,51	902	12	24	19	0,95
Crop/vegetation	3108	31	87	33	1,65	3502	29	156	31	1,56	593	8	6	5	0,24
Forest/grassland	99	1	0	0	0,00	129	1	13	3	0,13	202	3	0	0	0,00
Forest	2697	27	75	28	1,42	3217	27	141	28	1,41	5443	72	90	73	3,65

Shrubland	714	7	13	5	0,25	785	7	38	8	0,38	420	6	4	3	0,16
Bareland	0	0	0	0	0,00	0	0	0	0	0,00	0	0	0	0	0,00
Grassland	0	0	0	0	0,00	0	0	0	0	0,00	0	0	0	0	0,00
Snow	0	0	0	0	0,00	0	0	0	0	0,00	0	0	0	0	0,00

	Kasi					Baglung/Myadgi				
Slope class	No. Of total pixels	% to total pixels	No of landslide pixels	% to total pixels	Weights	No. Of total pixels	% to total pixels	No of landslide pixels	% to total pixels	Weights
1	6578	6	10	6	0,55	6374	6	5	2	0,20
2	12108	11	20	11	1,10	11635	11	31	12	1,23
3	15660	15	45	25	2,49	16440	15	43	17	1,70
4	17442	16	32	18	1,77	18218	17	46	18	1,82
5	16266	15	26	14	1,44	16686	15	32	13	1,26
6	14053	13	17	9	0,94	14356	13	34	13	1,34
7	11530	11	12	7	0,66	11161	10	29	11	1,15
8	7989	7	10	6	0,55	7348	7	16	6	0,63
9	4530	4	6	3	0,33	4379	4	13	5	0,51
10	1376	1	3	2	0,17	1903	2	4	2	0,16
Geology class										
Siwaliks	0	0	0	0	0	0	0	0	0	0
Lower Nuwakot	72214	67	155	86	2,6	60052	56	166	66	1,06

Upper Nuwakot	35627	33	26	14	0,4	0	0	0	0	0
Tansen	0	0	0	0	0	0	0	0	0	0
Higher Himalayan	0	0	0	0	0	48098	44	87	34	0,94
Recent deposits	0	0	0	0	0	0	0	0	0	0
Landcover class										
Cropland	2470	25	35	19	0,97	968	10	28	11	0,89
Crop/vegetation	2315	23	63	35	1,75	1154	11	59	23	1,87
Forest/grassland	127	1	6	3	0,17	381	4	12	5	0,38
Forest	4345	43	62	34	1,72	5708	57	121	48	3,83
Shrubland	801	8	15	8	0,39	705	7	15	6	0,47
Bareland	0	0	0	0	0,00	6	0	0	0	0,00
Grassland	0	0	0	0	0,00	250	2	0	0	0,00
Snow	0	0	0	0	0,00	886	9	18	7	0,57

APPENDIX 4 STRATIGRAPHY OF THE WESTERN HIMALAYAN ADOPTED FROM UPRETI

Table 2
Stratigraphic correlation of the Lesser Himalayan formations of western Nepal

Unit	Stratigraphic subdivisions adopted in this work		Tansen Area (Sakai, 1983, 1985)		Piuthan-Sailyan-Jajrkot Area (Sharma et al., 1984)		Northern Dang (Piuthan-Sailyan Area) (Dhital and Kizaki, 1987 a,b)		Surkhet Area (Kayastha, 1979)	Geologic Age
Tansen Unit	Lower Tertiary Group	Dumri Formation	Tansen Group: Post-Gondwanas	Dumri Formation	Tansen Group	Dumri Formation	Tosh Group	Dubring Formation	Sumar Formation	Oligocene-Early Miocene
Tansen Unit	Lower Tertiary Group	Bhainskati Formation	Tansen Group: Post-Gondwanas	Bhainskati Formation	Tansen Group	Bhainskati Formation	Tosh Group	Dubring Formation	Swat Formation	Lower-Middle Eocene
Tansen Unit	Gondwanas	Upper Gondwanas	Tansen Group: Gondwanas, Upper	Amile Formation	Tansen Group	Amile Formation	Tosh Group; Sharda Gr (Klippe)	Satim Formation	Melpani Formation	Late Cretaceous-Paleocene
			Unconformity							
Tansen Unit	Gondwanas	Upper Gondwanas	Tansen Group: Gondwanas, Upper	Taltung Formation with Aulis Volcanics	Dubari Group; Gondwana Group	Goyaltham Formation; Taltung Fm	Tosh Group; Sharda Gr (Klippe)	Satim Formation		Late Jurassic-Early Cretaceous
			Unconformity							
Tansen Unit	Gondwanas	Lower Gondwanas	Tansen Group: Gondwanas, Lower	Sisne Formation	Dubari Group; Gondwana Group	Kochhap Formation; Phalabang Fm; Sallyan Fm	Tosh Group; Sharda Gr (Klippe)	Phalabang Fm; Sallyan Fm		Late Carboniferous-Permian
			Unconformity							
Nawakot Unit	Upper Nawakot Unit	Robang Formation	Kali Gandaki Supergroup	Kerabari Formation			Tosh Group	Rambas Formation	Lakharpata Formation	Early paleozoic ?
Nawakot Unit	Upper Nawakot Unit	Malekhu Limestone	Kali Gandaki Supergroup	Raundighat Formation			Tosh Group	Sirchaur Formation	Lakharpata Formation	Early paleozoic ?
Nawakot Unit	Upper Nawakot Unit	Benighat Slate	Kali Gandaki Supergroup	Raundighat Formation						
Nawakot Unit	Upper Nawakot Unit	Dhading Dolomite	Kali Gandaki Supergroup	Saidi Khola Formation	Nawakot Group	Sumbang Dolomite	Gwar Group	Dhorbang Khola Formation		Late Precambrian
Nawakot Unit	Upper Nawakot Unit	Dhading Dolomite	Kali Gandaki Supergroup	Khoraidi Formation	Nawakot Group	Sumbang Dolomite	Gwar Group	Dhorbang Khola Formation		Late Precambrian
Nawakot Unit	Upper Nawakot Unit	Dhading Dolomite	Kali Gandaki Supergroup	Chappani Formation	Nawakot Group	Variegated Formation	Gwar Group	Hapurkot Formation		Late Precambrian
Nawakot Unit	Upper Nawakot Unit	Nourpul Formation	Kali Gandaki Supergroup	Virkot Formation	Nawakot Group	Harichaur Formation	Gwar Group	Khaman Formation		Late Precambrian
Nawakot Unit	Lower Nawakot Unit	Dandagaon Phyllite	Kali Gandaki Supergroup	Heklang Formation	Nawakot Group	Hiuna Formation	Gwar Group	Ranagaon Formation		Late Precambrian
Nawakot Unit	Lower Nawakot Unit	Fagfog Quartzite	Kali Gandaki Supergroup	Naudanda Formation	Kuncha Group	Kuncha Formation	Sharda Group (Klippe)	Baile Quartzite		Late Precambrian
Nawakot Unit	Lower Nawakot Unit	Kuncha Formation		Kuncha Formation	Kuncha Group	Kuncha Formation	Sharda Group (Klippe)	Dangri Formation		Late Precambrian

APPENDIX 5 FLOW CHART OF LANDSLIDE SUSCEPTIBILITY PROCESS IN ARC GIS

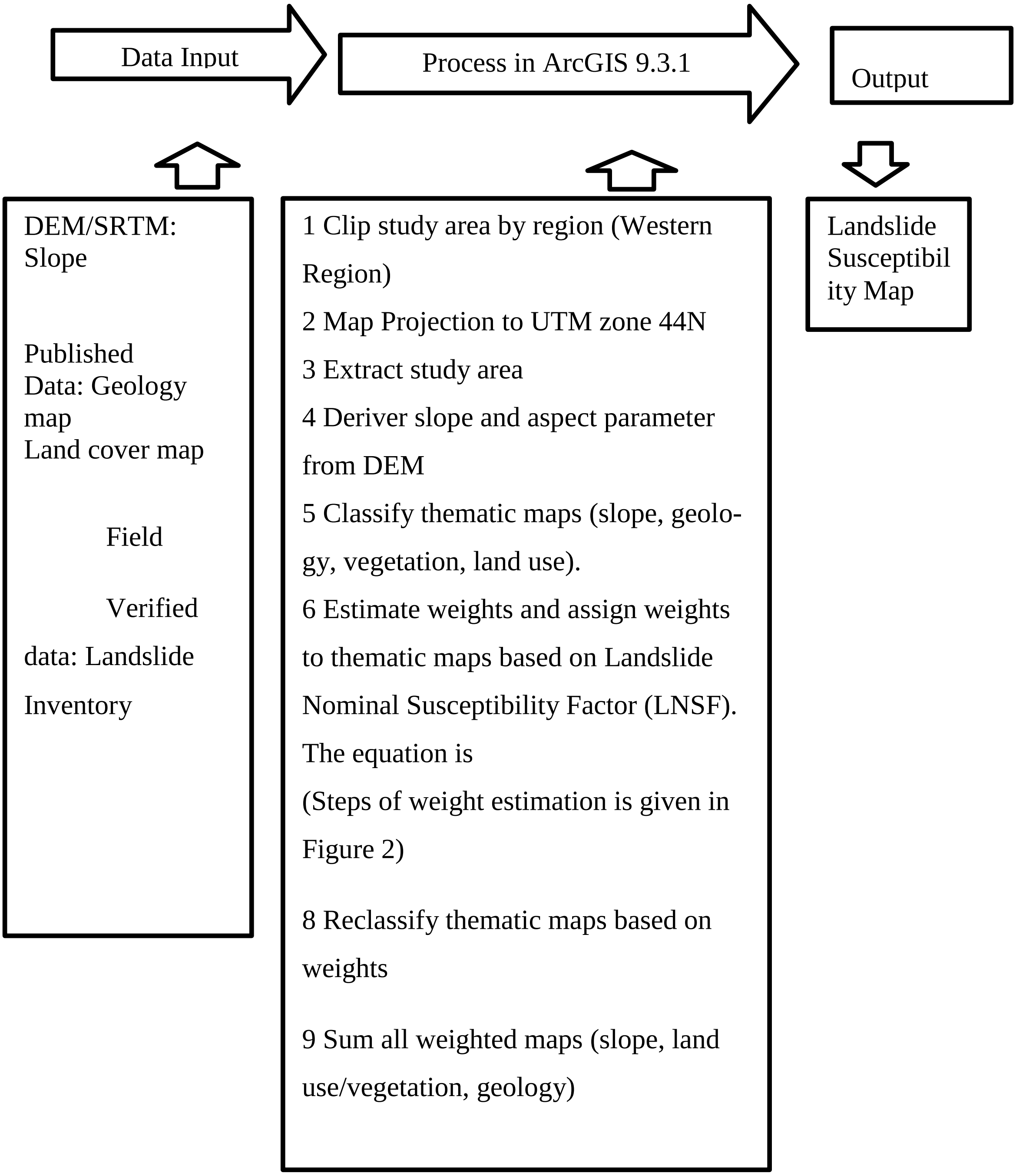
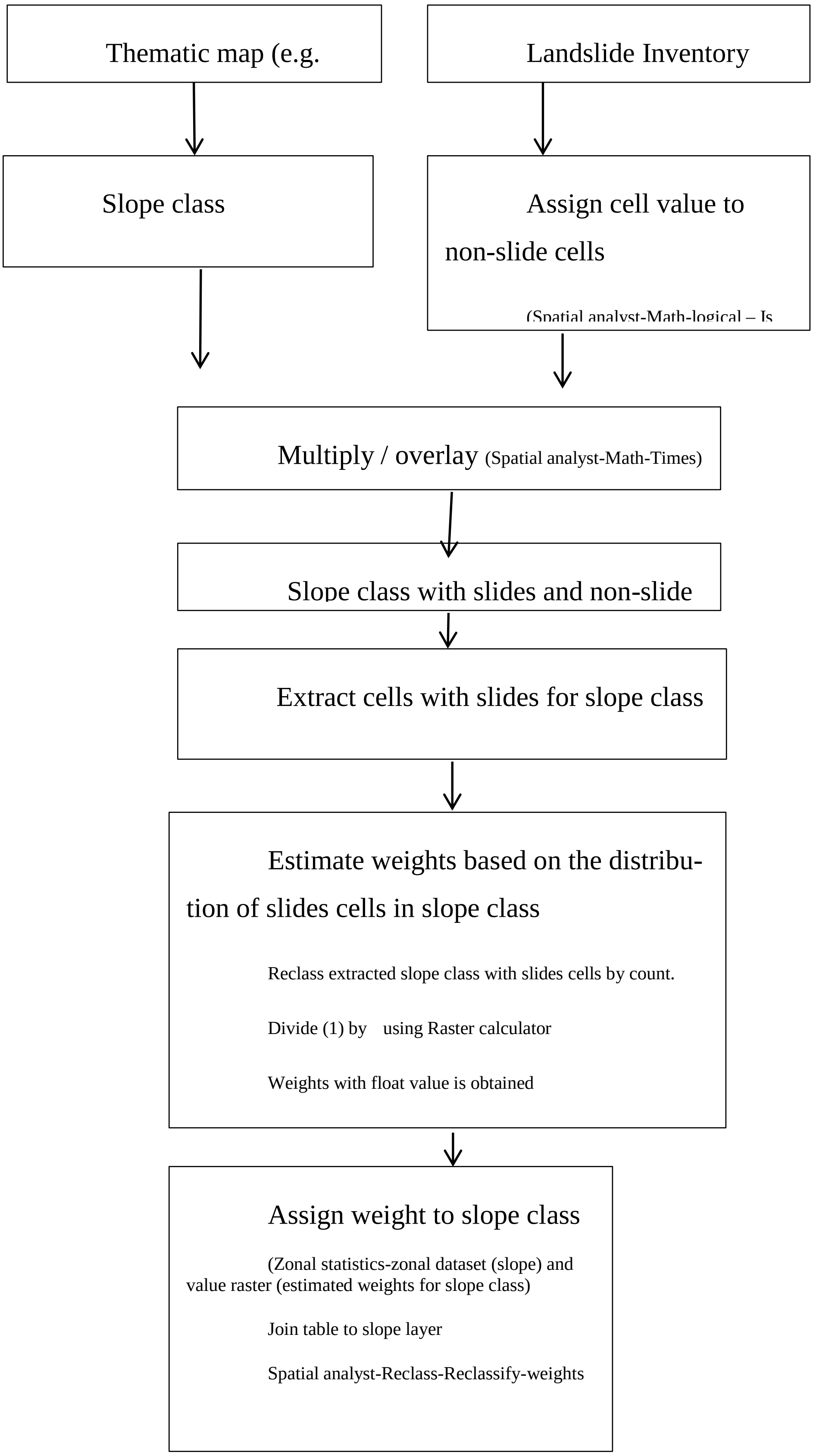


Figure 1 steps of landslide susceptibility analysis using bivariate statistics.

Step7 and step8 Flow chart of weight calculation



APPENDIX 6 LITHOLOGY CLASSIFICATION GIVEN BY NGI (ADOPTED FROM NGI REPORT)

Description of lithology and geologic units	Age	Sl
Quartzites Augen gneisses, banded gneisses Granites Tow mica leucocratic granites with tourmaline	Upper Pre Cambrian – Late Paleozoic - Devonian Miocene Grey siliceous dolomites Augen gneisses,	1
Grey siliceous dolomites Augen gneisses, granitic gneisses, and feldsphatic schists Crystalline limestones Grey to greenish grey quartzites, calcareous quartzites Gneisses and thin bands of marbles Quartzitic schists Dolomite underlain by crinoidal limestones Muscovite biotite quartz schists Crystalline marbles	Upper Pre Cambrian – Late Paleozoic Pre Cambrian Pre Cambrian - Devonian Pre Cambrian Pre Cambrian Pre Cambrian Pre Cambrian - Devonian Pre Cambrian - Devonian Pre Cambrian – Devonian	2
Quartz mica schist Schists metamorphosed rocks Dark slates with white	Pre Cambrian Pre Cambrian Pre Cambrian - De-	3

quartzites Calcareous silicate rocks and marble bands Dark gray slates Crystalline marble Phyllites quartzites and phyllitic schists Sandstones Limestone, sandstone and shale Phyllites grilstones with conglomerates and white massive quartzites. Biotite and quartzitic mica schists Schists quartzites gneisses and calcareous silicate rocks Muscovite biotite quartz schists quartzites Schists Crystalline limestones Sandstones, chloritic phyllites, lamprophyre sills Sandstones	vonian Pre Cambrian - Devonian Upper pre cambrian – Late Paleozoic Pre Cambrian - Devonian Pre Cambrian Mid Miocene - Pleistocene Cambrian to Permian Upper Pre Cambrian – Late Paleozoic Pre Cambiran - Devonian Pre Cambrian - Devonian Pre Cambrian - Devonian Pre Cambrian Pre Cambrian Permo - Carboniferous Pre Cambrian - Devonian	
Carbonates and dolomitic limestones Carbonaceous slates and green shales Sandstones	Upper pre cambrian – Late Paleozoic Upper pre cambrian –	4

Continental plateform sediments Quartzites with ripple marks interbedded with shales beds Calcareous rocks Grey shales with intercalation of limestones and quartzites Slates with thin limestones Sandstones Shales with lenses of fine grained fossiliferous limestones Calcareous quartzites and quartzitic limestones Coarse boulders, conglomerates	Late Paleozoic Mid Miocene – Pleistocene Triassic to Lower Cretaceous Upper pre cambrian – Late Paleozoic Early to Middle Paleozoic Upper pre cambrian – Late Paleozoic Pre Cambiran - Devonian Cretaceous - Eocene Cretaceous - Eocene Upper pre cambrian – Late Paleozoic Mid Miocene – Pleistocene	
Mainly fluvial and fluvio terrential sediments with local lacustrine clays and marlstones Alluvium, boulders, gravels, sands and clays Alluvium, boulders, gravels, sands and clays	Plio-Pleistocene Quaternary Recent	5