GIS BASED RAINFALL INDUCED LANDSLIDE HAZARD MAPPING OF FAST TRACK ROAD USING INFORMATION VALUE METHOD

Supervisors

Prof. Dr. Hari Krishna Shrestha

Dr. Manita Timilsina

Co-ordinator

Asst. Prof. Manesh Malla

Group members

Prakriti Sharma (011-183)

Raju Banjade (011-192)

Nisha Dahal (011-179)

Suprita Deo (011-050)

Department of Civil Engineering
Nepal Engineering College

2015

ACKNOWLEDGEMENT

We would like to thank the Department of Civil Engineering, Nepal Engineering College for providing this opportunity to explore new ideas through this project. This project has really assisted us to broaden our knowledge in civil engineering. We take this opportunity to express our profound gratitude and deep regards to our supervisors Professor Dr. Hari Krishna Shrestha and Dr. Manita Timilsina Sharma for their exemplary guidance, monitoring and constant encouragement throughout the course of this project.

We would like to express our sincere gratitude towards Assoc. Prof. Dr. Ranjan Kumar Dahal, Department of Geology, Tribhuwan University, Mr. Nitesh Shrestha, Geotech Engineer, as well as all the staff members of Geotech solution International, for their cordial support, valuable information and guidance, which helped us in completing this task through various stages.

We are grateful towards the teachers and staff members of Nepal Engineering College for providing us with valuable suggestions and regular guidance during various stages of our work. Their cooperation during the period of our assignment, are appreciated.

We would like to thank our parents, brother, sisters and friends for their constant encouragement without which this assignment would not have been possible.

Abstract

The mountainous terrains of Nepal Himalaya are characterized by dynamic physical processes, and therefore, proper management and mitigation of geo-disaster is a big challenge. Landslide hazard mapping can be considered as a vital tool for disaster management and planning sustainable development activities in a country like ours where landslide poses problem in infrastructure development and livelihood. In this report, bivariate statistical technique, was applied, using a geographical information system (GIS), to prepare landslide hazard map of Kathmandu Terai Fast track (Kathmandu to Nijgadh), Nepal. The objective of this report is to prepare landslide hazard map of the study area so as to identify problematic sections along the proposed alignment which would be useful in planning and adopting necessary mitigation measures. For this, nine parameters including slope, aspect, relief, landuse, distance to stream, precipitation, geology, distance to road, and curvature were selected and their map was generated using GIS technique. Each causative factor was given a weight using the information value method where each of them was crossed with landslide inventory map. Weighted sum of these values were used to prepare final hazard map. The knowledge and skill acquired in this project can be valuable in assessing landslide hazard of any planned infrastructure development project site.

Table of Contents

1. INTRODUCTION

Background

The term "landslide" describes a wide variety of geological processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. Although the action of gravity is the primary driving force for a landslide to occur, there are other contributing factors affecting the original slope stability. Typically, pre-conditional factors build up specific sub-surface conditions that make the area/slope prone to failure, whereas the actual landslide often requires a trigger before being released. Landslide can be considered as natural process whose occurrence is frequent in the mountainous regions of the world. It would be of no harm if there were no people and infrastructure in the vicinity of its occurrence but most of the times it has taken the form of disaster causing tremendous impacts on the society. Globally, landslides cause hundreds of billions of dollars in damages and hundreds of thousands of deaths and injuries each year (USGS, 2015). In total, 2620 fatal landslides were recorded worldwide during 2004 to 2010, causing a total of 32,322 recorded fatalities. The majority of human losses occur in Asia, especially along the Himalayan Arc and in China (Petley, 2012).

Nepal is mainly characterized by rugged topography, very high relief, variable climatic conditions, complex geological structures affected by active tectonic process and seismic activities. Topographic elevation changes from 60 m in the southern plain to 8,848 m at the Mt Everest within a north–south horizontal distance of less than 200 km. This kind of topography is highly prone to geo-disaster. The seasonal monsoon rains, intense but improper landuse practices make the Nepalese Himalayas the most unstable landscapes in the world. (Dahal et al., 2010). Landslides may be regarded as one end of the spectrum of slope modification processes in the Nepal Himalaya (Waltham, 1996). Owing to its fragile geomorphological condition, Nepal suffers from tremendous landslide disaster problems every year and a great number of people are affected by large- and small-scale landslides throughout the country, especially during monsoon periods. Landslides and floods are most prominent geo-disasters in Nepal and on an average they kill 270 people per year. The records reveal that in South Asia, Nepal stands third in having highest number of average annual human deaths per million living population, behind Sri Lanka and Bangladesh (Upreti, 2010). Nepal lies in the seventh position for deaths resulting as consequences of floods, landslides and debris avalanches (Upreti, 2010). The Jure Landslide occurred on 2 August 2014 at Jure Village (which was located on top of a colluvial deposit) in the boarder of Mankha and Ramche VDC in Sindhupalchowk District killed 156, injured 27 and

displaced 436 people. 33 dead bodies have been pulled from the debris and 123 missing people buried in the debris were presumed dead (Shrestha, 2014).
Apart from natural phenomena, anthropogenic activities such as deforestation, unplanned human settlement, improper infrastructural development (e.g., highways, irrigation canals, and dams), overgrazing, etc., have also contributed in mass movements in Nepal (Shiwakoti, 2000) .All these facts clearly signifies requirement of proper planning before infrastructure development in Nepal so as to adopt relevant mitigation measures. In order to minimize the risk posed by Landslides, it is crucial to carry out study and research works on the landslide phenomena along with hazard mapping and risk assessment.

Landslide hazard can be assessed in terms of probability of occurrence of a potentially damaging landslide phenomenon within a specified period of time and within a given area (Varnes, 1984). Both intrinsic and extrinsic variables affect landslide hazards in an area (Siddle et al., 1991). The intrinsic variables determining landslides hazards include bedrock geology, geomorphology, soil depth, soil type, slope gradient, slope aspect, slope curvature, elevation, engineering properties of the slope material, landuse pattern, drainage patterns, and so on. Similarly, extrinsic variables include heavy rainfall, earthquakes, and volcanoes (Dahal et al, 2010). It has been observed that extrinsic variables are more site specific. In this report, we have used a number of intrinsic variables along with rainfall as extrinsic variable. Geographical information system (GIS) is an important tool for landslide hazard mapping which makes analysis of parameters or causative factors convenient.

Various modelling techniques such as heuristic model, physically based model and statistical model have been used for landslide susceptibility mapping (Ruff et al., 2008; Van Westen, 1993; Yalcin, 2008; Sorbino et al., 2010; Carrara et al., 1991). Statistical approach has been employed in this study. In statistical methods, landslide causal factors or parameters are derived and combined with landslide inventories to predict the future occurrence of landslides (Dai et al., 2001). Statistical methods can be further divided into multivariate and bivariate methods. In the former, all relevant landslide causative factors or parameters are treated together to obtain landslide hazard map. In bivariate statistical method, each landslide causative factor is combined with landslide inventory. The weights of each class within the factor maps are derived based on landslide densities in each attribute class. Weight estimation in bivariate statistical method has been done mainly by using three different techniques: Information value method (Sarkar et al.,2013), Weight of evidence method (Kayastha et al., 2012; Pradhan et al., 2010) and Landslide Nominal Susceptibility Factor (LNSF) method (Adhikari, 2011; Gupta et al., 1990).

In this study, bivariate statistical approach using information value method has been used to map landslide hazard of Fast track road.

Rationale of study

Landslides and floods during the monsoon season impact lives and livelihoods in Nepal every year. Floods and landslides have caused at least 8,400 deaths in Nepal between 1983 and 2013 (UN, 2015). The monsoon period represents 60–80% of the annual total precipitation, and in the past has accounted for around 90% of landslide fatalities (UN, 2015). Past events have caused significant loss of life and damage to vital infrastructure such as roads, hydropower, irrigation and drinking water facilities, agricultural land, and property. Additional landslides are expected due to the instability of the soil after the earthquake. Over 3,000 landslides were observed after the 25 April earthquake, higher than the number of landslides reported in the past five years combined. Approximately 40% of landslide dams break within a week of formation, and 80% break within 6 months, highlighting the need to monitor landslide occurrence closely and have mitigation measures in place (UN, 2015**).**

All the above facts clearly reveal that Nepal is highly prone to landslides. But geography and climatic conditions alone are not responsible for these disastrous situations. Lack of proper management has worsened the conditions. In recent days, risk of landslides has been raised by unmonitored expansion of rural transport network in hill regions, leading to terrain alterations and other negative impacts of environment (Petley, 2012).Nepal being highly vulnerable to landslide and related disasters, proper planning and implementation of appropriate mitigation measures prior to infrastructure development should to prioritized. Mitigation measures for risks associated with geohazards can broadly be classified in six categories: (1) landuse plans, (2) enforcement of building codes and good construction practice, (3) early warning systems, (4) construction of physical protection barriers, (5) network of escape routes and "safe" places and (6) community preparedness and awareness building (International Center For Geohazards, 2010). These measures can be adopted as per requirement only after proper assessment of hazard has been made. The results of hazard and risk mapping and analyses will be used to formulate mitigation strategies to assist decision-making on the need and cost-benefit of hazard mitigation works. However, very few attempts have been made so far by Nepal government and concerned authorities on hazard mitigation and to prepare map depicting hazard zones and risk associated with these events. If proper study, hazard mapping and restriction to habitat and developmental works in such zones are properly done then major of the destructions can be prevented. Concerned authorities should prioritize proper landslide and other hazard assessment in any location prior to developmental works. Especially in developing countries like ours, sustainable development should be given more emphasis which could lead to low maintenance and operating cost of the infrastructures along with decreased risk to the surrounding habitants. So this field of study still requires a lot of attention. According to Brabb (1993), at least 90% of landslide losses can be avoided if the problem is recognized before the landslide event. Hence, there is a direct need for landslide hazard assessment at various spatial scales.

Construction of roads in the mountains of Nepal is complicated because of steep slopes, thick soil profiles, weak rock mass and torrential rainfall due to the monsoon.

Our study area is Kathmandu Terai Fast track road which extends from Kathmandu to Nijgadh and it is under construction phase. This is most talked project as it carries lots of potential for further development of nation. This road will bring all people from the Eastern Development Region closer to Kathmandu by about 4 hours (Shrestha, 2014). This will push urbanization around Birgunj, Nijghad, Hetauda area counter balancing the excessive population growth in Kathmandu. Kathmandu Valley will have opportunity to develop itself as an administrative center, historical heritage site and academic center. A majority of export oriented industries can be shifted to Central East Terai as they will be closer to the international airport and also will be closer to the Kolkota port (Shrestha, 2014). So it needs a very detailed study regarding all the risks and probable management measures along the alignment and in the vicinity.

2. STUDY AREA

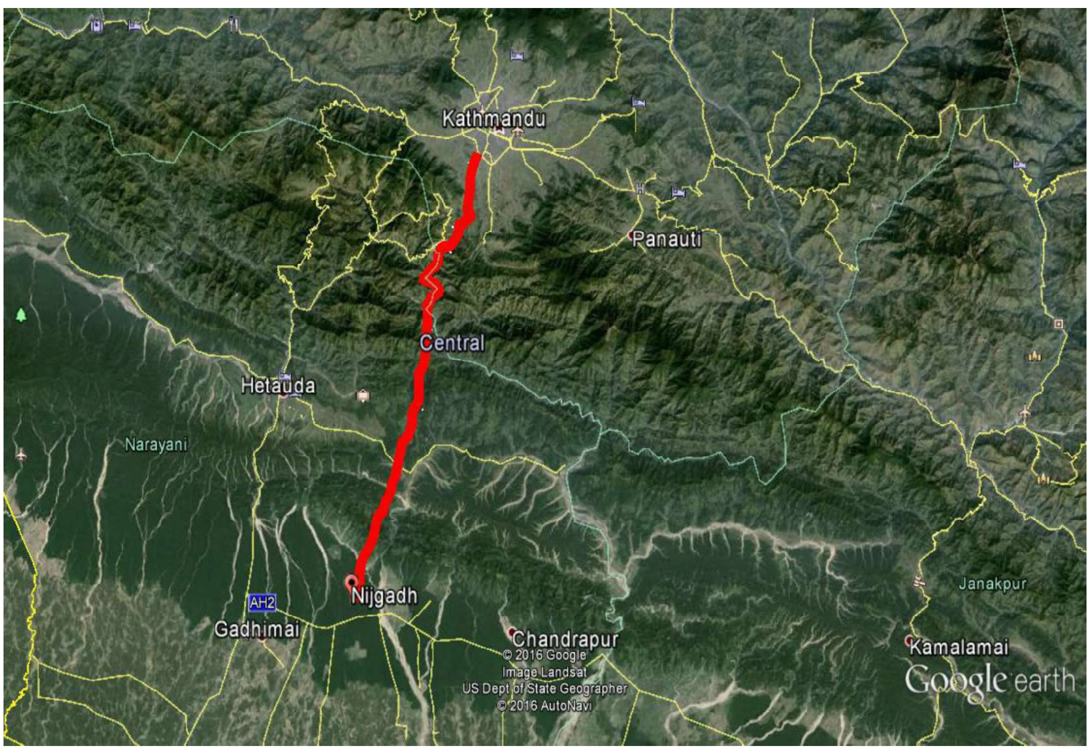


Figure 1: Alignment of Kathmandu Terai Fast track Road project (Kathmandu to Nijgadh)

Our study area is Kathmandu Terai Fast track which is under construction and it connects outskirts of Kathmandu with Nijgadh (Bara). The four-lane road extending from the outer ring road in Kathmandu to Nijgadh in the Terai region will be the shortest among half a dozen routes to Terai from Kathmandu and will only be 76 kilometers. The track will have a tunnel of 1.3 km at Thingana of Makawanpur. It has been under construction since 2008. The Fast Track is proposed along the Bagmati corridor which originates at Sano Khokana and travels through Chhaimale, Gausel, Malta, Thingen, Budune and Chhatiwan and reaches to Nijgdh at which it meets with the Mahendra Highway. The proposed project also intends to widen the 18 km stretch of Mahendra Highway between Nijghad to Pathalaiya Section. The study area lies in the sub-tropical region and the temperate climate prevails here i.e. 1.1°C – 31.5°C (DDC profile, 2005). Precipitation in the form of hail, dew is minimum whereas precipitation in the form of snow occurs rarely .The annual rainfall in this area is 1640 mm . Temperature decreases in winter whereas summer season is characterized by fine weather with sunny days (Dahal et al., 2014). There are various seasonal and perennial streams and rivers in the study area. The main river is Bagmati River which flows through the Kathmandu valley. Different seasonal springs (Khahare) serve as the part of drainage system in the study area. During rainy season the discharge of the rivers is high and cause flooding .Geologically the study area lies in the mid-hill region with rocky steps slope land structure .Sedimentary rocks like clay stone, sand stone, silt stone and igneous intrusive rocks are found. (Dahal et al., 2014)

3. OBJECTIVE

The objectives of this project are listed below as:

- To evaluate landslide hazard scenario along the Kathmandu Terai Fast track road (Kathmandu to Nijgadh) with classified zones i.e. low, medium and high hazard.
- To identify problematic sections along the proposed alignment of Fast track road so as to take necessary mitigation measures.

4. LITERATURE REVIEW

A landslide is defined as "the movement of a mass of rock, debris, or earth down a slope" (Cruden, 1991). Landslides are a type of "mass wasting," which denotes any down-slope movement of soil and rock under the direct influence of gravity.

Types of landslides:

The landslide classification based on Varnes (1978) system has two terms:

- the first term describes the material type and
- the second term describes the type of movement.

Table 1: Types of landslides. Abbreviated version of Varnes' classification slope movements (Varnes, 1978).

TYPES OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			PREDOMINANTLY COARSE	PREDOMINANTLY FINE
FALLS		ROCK FALL	DEBRIS FALL	EARTH FALL
TOPPLES		ROCK TOPPLE	DEBRIS TOPPLE	EARTH TOPPLE
SLIDES	ROTATIONAL	ROCK SLIDE	DEBRIS SLIDE	EARTH SLIDE
	TRANSLATIONAL			
LATERAL SPREADS		ROCK SPREAD	DEBRIS SPREAD	EARTH SPREAD
FLOWS		ROCK FLOW (DEEP CREEP)	DEBRIS FLOW	EARTH FLOW
			(SOIL CREEP)	
COMPLEX		COMBINATION OF TWO OR MORE PRINCIPAL TYPES OF MOVEMENT		

Falls: They are abrupt movements of masses of geologic materials, such as rocks and boulders that become detached from steep slopes or cliffs.

Topple: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks.

Slides: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides.

- **Rotational slide** is a slide in which 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 across the slide)
- **Translational slide** is that type of slide in which the landslide mass moves along a roughly planar surface with little rotation or backward tilting.

Lateral spreads: They usually occur on very gentle slopes or flat terrain. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state.

Flows: There are 5 basic categories of flows that differ from one another in fundamental ways.

- **Debris flow**: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as slurry that flows downslope. Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snow melt that erodes and mobilizes loose soil or rock on steep slopes.
- **Debris avalanche**: This is a variety of very rapid to extremely rapid debris flow.
- **Earth flow**: Earth flows have a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions.
- **Mud flow**: A mudflow is an earth flow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles.
- **Creep**: Creep is the imperceptibly slow, steady, downward movement of slope forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure.

Complex: Combination of two or more of the above types is known as complex landslides. (Novotný, 2013)

Causes of landslides:

Many factors contribute to landslides, including geology, gravity, weather, groundwater, wave action, and human actions. Typically, a number of elements will contribute to a landslide, but often there is one which triggers the movement of material. Some of the major causes of landslides:

1. Geological causes
a. Weak or sensitive materials
b. Weathered materials
c. Sheared, jointed, or fissured materials
d. Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)
e. Contrast in permeability and/or stiffness of materials

2. Morphological causes
a. Tectonic or volcanic uplift
b. Glacial rebound
c. Fluvial, wave, or glacial erosion of slope toe or lateral margins
d. Subterranean erosion (solution, piping)
e. Deposition loading slope or its crest
f. Vegetation removal (by fire, drought)
g. Thawing

h. Freeze-and-thaw weathering
i. Shrink-and-swell weathering

3. Human causes
a. Excavation of slope or its toe
b. Loading of slope or its crest
c. Drawdown (of reservoirs)
d. Deforestation
e. Irrigation
f. Mining
g. Artificial vibration
h. Water leakage from utilities
(United States Geological Survey, 2004)

Landslide Hazard mapping:

The susceptibility of a given area to landslides can be determined and depicted using hazard zonation. Landslide hazard zonation is an important step in landslide investigation and landslide risk management. Varnes and IAEG (1984) defines the term 'zonation' as 'the process of division of land surface into areas and ranking of these areas according to the degree of actual or potential hazard from landslides or other mass movements'. Courture R (2011) explained the concept of landslide hazard as 'division of land into somewhat homogeneous areas or domain and their ranking according to the degrees of actual or potential landslide susceptibility, hazard or risk or applicability of certain landslide related regulations'.
Many landslide hazard assessment methods have been proposed to evaluate the landslide hazard and produce maps portraying its spatial distribution .Some of the widely used methods of landslide hazard mapping are as follows:

Heuristic method: In this method, causative factors of mass movement in the study area are considered as parameter maps. The different parameters maps are assigned a weighing value based on their relative importance. These weight values are assigned on the basis of the previous studies, empirical generalization, and nature and physical properties of each parameter (Deoja et al., 1991).

Statistical method: In last few years the approach towards Landslide hazard mapping has been changed from heuristic (knowledge based) approach to data driven approach (statistical approach) to minimize subjectivity in weightage assignment procedure and produce more objective and reproducible results(Kanungo et al., 2009). The statistical methods for landslide Hazard mapping can be grouped into two viz. bivariate and multivariate statistical analysis.

In the bivariate statistical method, a weight value for a parameter class is defined as the natural algorithm of the landslide density in the class divided by the landslide density in the entire map (Van Westen, 1997). This method compares each data layer of causative factor to the existing landslide distribution (Kanungo et al., 2009). Frequency Analysis approach, Information Value Model (IVM), Weights of Evidence Model, Weighted overlay model are some of the important bivariate statistical methods (Pradeshi et al, 2013).

Multivariate approach to landslide susceptibility zonation has widely been used since past few years and proved to be more objective method for assessing landslide hazards in complex geo-environmental settings (Conoscenti et al, 2008; Eckhaut et al, 2009; Ercanglu et al., 2003; Ayalew and Yamagishi, 2005). These methods allow assessing comparative contribution of each causative factor in landslide occurrence (Pradeshi et al, 2013).

Information Value (Info Val) method: Information Value Model (IVM) is a bivariate statistical method for spatial prediction of landslides based on relationships between landslide occurrence and related parameters (Sarkar et al., 2006). Information Value Model has proved useful method in determining the degree of influence of individual causative factor responsible for landslide occurrence (Kanungo et al., 2009; Champatiary, 2000; Champatiary et al., 2007; Arora et al, 2004). This method was originally suggested by Yin and Yan in 1988 (Yin et al., 1988). The information value I_i, for a parameter i is:

$$Ii = ln\ \frac{density\ of\ a\ landslide\ within\ a\ class\ of\ a\ parameter}{density\ of\ landslide\ within\ a\ study\ area}$$

$$= \frac{\frac{Npix(si)}{Npix(Ni)}}{\frac{\Sigma Npix(si)}{\Sigma Npix(Ni)}}$$

Where, Ii = information value for a parameter;
Npix (Si) = Number of pixel of landslide within class i;
Npix (Ni) = Number of pixel of class i;
ΣNpix (Si) =Number of Pixel of landslide within the whole study area;
ΣNpix (Ni) = Number of pixel of the whole study area.

Now, the total information value in a pixel j is:

$$Ij = \sum_{i=1}^{M} Xji \times Ii$$

Where, Xji is value of parameter i, j = 1, 2, ..., N; and i = 1, 2, ...M; = 1, if parameter i exists in grid cell j and = 0, if parameter i does not exist in grid cell j; M=number of parameters considered. And N is total number of pixel. (Sarkar et al., 2006)

Deterministic Method: The deterministic or physically based models are based on the physical laws of conservation of mass, energy and momentum (Westen and Terlien, 1996). Many deterministic models are site-specific and do not consider the spatial distribution of the input parameters. (Dahal et al., 2010).

5. METHODOLOGY:

We adopted following methods to achieve our objectives:

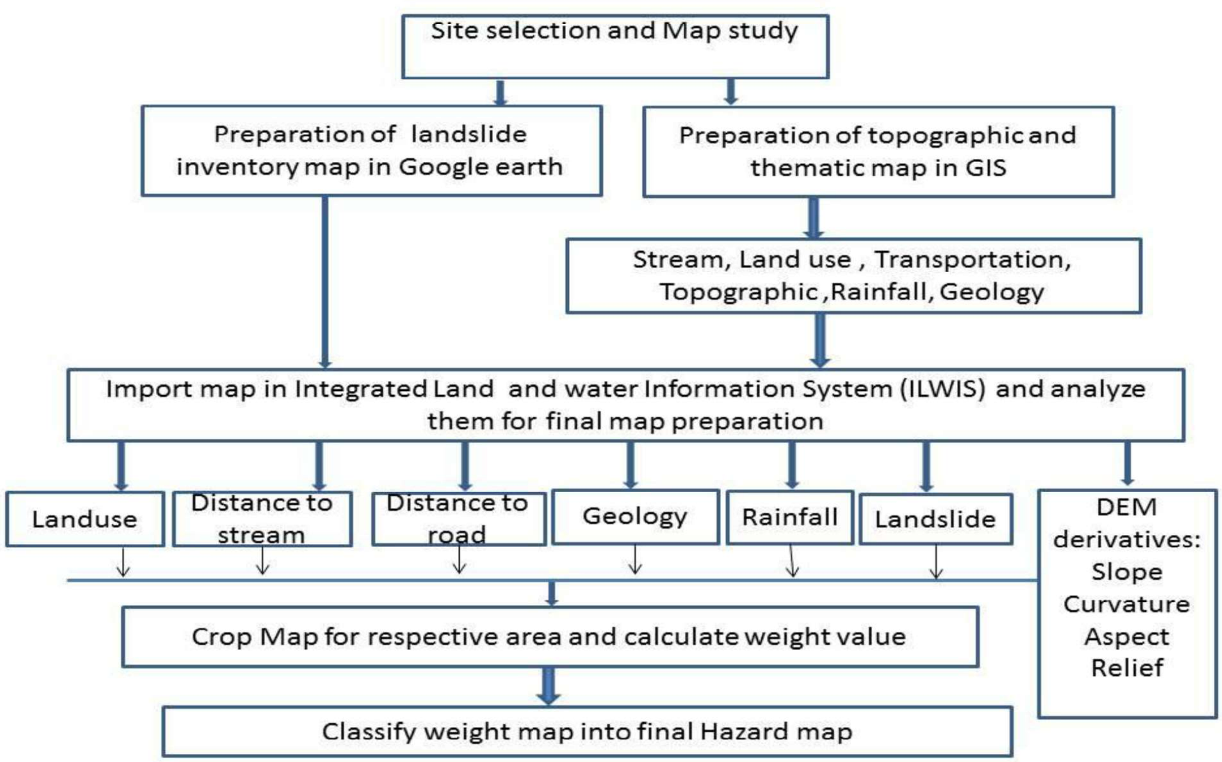
Data collection

We used secondary data provided by Survey Department of Nepal in the form of digital map sheets. Similarly, rainfall data was obtained from Department of Hydrology and Meteorology (DHM) and geological data was obtained from Department of geology. We relied on various research papers, books and geomorphology of the selected location to identify the relevant parameters affecting occurrence of landslide in our study location.

Data analysis

We analyzed thus obtained data to prepare various thematic maps. Analysis was done on GIS based software ARC GIS and ILWIS.

General steps or methods followed are shown below in flow chart as:



Before preparing final hazard map, we prepared different causative factor maps and landslide inventory maps so as to combine these parameters with landslide. Arc GIS and ILWIS were utilized to prepare data layers from the data sources. Following are the description of parameters used:

Landslide inventory map

Landslide inventory map shows the location of occurrence of landslides. Cruden (1991) defined landslide inventory as 'the simplest form of landslide information which records the location and where known, the date of occurrence, type of landslides that have left identifiable traces in the area'. Landslide inventory play significant role in landslide hazard assessment in weight of evidence model as overlay analysis requires an inventory map. The quality and completeness of landslide inventory influences reliability of landslide investigation. For our study, landslide inventory map was prepared through map study. Google earth was used to view and trace the location of landslides in our study area in recent years (from 2010 to 2015).Thus traced locations of landslides were used to prepare landslide inventory map in GIS. Our landslide inventory map traces total 84 locations of landslides which are shown in fig. 2

DEM based derivative

A Digital Elevation Model (DEM) representing the terrain is a key to generate various topographic parameters, which influence the landslide activity in an area. To prepare DEM from the contour map, contour interpolation was performed. Contour interpolation is an operation which first rasterizes the contour lines in a segment map with a value covered by segments. The contours were interpolated and resampled to 20×20 m^2 pixel size .Now with domain, and then calculates values by means of a linear interpolation for pixels that are not the help of DEM slope, aspect, relief and curvature map were prepared.

Slope

Slope is the measure of steepness or the degree of inclination of a feature relative to the horizontal plane. Gradient, grade, incline and pitch are used interchangeably with slope. Slope is typically expressed as a percentage, an angle, or a ratio. The average slope of a terrain feature can conveniently be calculated from contour lines on a topo map. Slope data layer, an important parameter in slope stability considerations, comprises of different eight classes. We created total 6 classes i.e. $<10^0$,10^0-20^0,20^0-30^0,30^0-40^0,40^0-50^0 and $>50^0$ on the basis of histogram obtained from our slope map. Slope map has been given below in fig 3.

Aspect

Aspect (also called as slope orientation) is defined as the directional component of the gradient (slope) vector and is the direction of maximum gradient of the surface at a given point. It is also called as the compass direction that a topographic slope faces, usually measured in degrees from north. Aspect can be generated from continuous elevation surfaces. It can be considered as landslide conditioning factor and this parameter has been considered in several other studies (Westen and Bonilla, 1990; Gokceoglu and Aksoy, 1996; Saha et al, 2005; Yalcin, 2005). Some of the meteorological events such as the direction of rainfall, amount of sunshine, the morphological structure of the area affect the slope stability (Mohammadi, 2008). The aspect of a slope can influence landslide initiation. Moisture retention and vegetation is reflected by slope aspect, which in turn may affect soil strength and susceptibility to landslides. If rainfall has a pronounced directional component by influence of a prevailing wind, the amount of rainfall falling on a slope may vary depending on its aspect (Wieczorek et al., 1997). For our selected catchments, we divided aspect into nine classes, namely, N, NE, E, SE, S, SW, W, NW and Flat. DEM was used to calculate the aspect of a slope within the study area. Aspect map has been shown in fig.4.

Relief

A Relief map is another DEM based derivative that shows the configuration and height of the land surface, usually by means of contours. Relief is also an important landslide conditioning factor because it is controlled by several geological and geomorphological processes. (Gritzener et al.2001, Dai and Lee, 2002). Relative relief data layer was prepared from the difference in maximum and minimum elevation and was sliced into 5 classes at 500 m elevation difference i.e.0-500m, 500m-1000m, 1000m-1500m, 1500m-2000m, 2000m-2500m. Relief map has been shown in fig.5

Curvature

The term curvature is theoretically defined as the rate of change of slope gradient or aspect, usually in a particular direction (Wilson and Gallant, 2000).It represents the convex and concave topography found in the mountain system. The influence of plan curvature on the slope erosion processes is the convergence or divergence of water during downhill flow. For this reason, this parameter constitutes one of the conditioning factors controlling landslide occurrence (Nefeslioglu et al., 2008).Curvature map was produced from ILWIS 3.3.And we have classified it on two classes; concave and convex with values in -0.9-0 and 0-0.9 respectively. Concave map has been shown in fig. 6.

Landuse

Landuse data documents how much of a region is covered by forests, wetlands, impervious surfaces, agriculture, and other land and water types as well how people are using the land. A map that shows the types and intensities of different land uses in a particular area is landuse map. It is also considered as one of the important factors responsible for landslide occurrence. Barren slopes are more prone to landslides. In contrast, vegetative areas tend to reduce the action of climatic agents such as rain etc. thereby preventing the erosion due to the natural anchorage provided by the tree roots and, thus, are less prone to landslides (Gray and Leiser, 1982; Styczen and Morgan, 1995; Greenway, 1987). As per the digital map provided by Nepal Department of Survey, we have classified landuse map into different classes namely building, forest, agriculture, bush, bamboo, barren land, scattered tree, pond or lake, nursery, sand, topography, water body and grass .The landuse data layer were generated in Arc GIS and were imported in ILWIS in the term of polygon map. Domain of different classes of landuse created was defined to thus imported polygon map and then it was converted into raster landuse map by employing rasterize operation in IlWIS 3.3.It has been shown in fig 7.

Distance to Stream

An important parameter that controls the stability of a slope is the saturation degree of the material on the slope. Streams may adversely affect stability by eroding the slopes or by saturating the lower part of material until resulting in water level increases (Gokceoglu and Aksoy, 1996). It has been found that slide along stream is usually more. This can be attributed to the fact that terrain modification caused by gully erosion may influence the initiation of landslides. Hence, with an assumption that landslides may be more frequent towards streams due to groundwater movement towards stream and toe undercutting, distance to stream map was generated. For this, first of all we created stream map on Arc GIS using digital database provided by Survey Department of Nepal. This map was imported to ILWIS 3.3 for further analysis where thus imported segment map of stream was rasterized by employing raster operation. Again thus formed raster map was employed for raster operation where distance to stream was calculated to generate distance to stream map .According to histogram generated through distance to stream map, domain was created with seven classes i.e. 0-100m, 100-200m, 200-300m, 300-500m, 500-700m, 700-1000m and >1000m. After classification, slicing operation was done on the distance to stream map to define domain classification on it. Distance to stream map has been shown in fig 8.

Distance to Road

During landslide inventory map preparation, we found out that there were more slides in the locations near to roads. Besides many previous studies have used distance to road as causative factor for landslide (Pourghasemi, et al., 2012; Tazik et al., 2014 and many other such research papers). The distance to road parameter reflects human activities (Pourghasemi et al., 2009). In other words, landslides may occur on the slopes intersected by roads (Nielsen et al., 1979). According to recent studies, cutting slopes for highway construction and frequency vibrations caused by cars would induce landslides (Mittal et al., 2008). It has been observed at many places that a slope balanced before the road construction may be disturbed afterwards due to excavation. Hence we have created 10 different classes to determine the effect of the road on the stability of slope namely 0-100m, 100-200m, 200-500m, 500-800m, 800-1200m, 1200-1500m, and 1500-2000m. Like distance to stream map it was also created from transportation line map. Segment map of transportation was converted to raster and then raster operation was employed to calculate distance to road and thus form map. Finally slicing operation was done on thus formed distance to road map to classify it on the basis of domain which is shown in fig.9.

Geology

The science of geology includes the study of the earth as a whole, its origin, structure, composition, history and nature of processes which have given rise to its present state. Geology of any location can be considered as one of the very important parameters affecting occurrence of landslides. Distribution of landslide is largely controlled by bedrock geology (Kawabata et al., 2002).We obtained geological map of our study area from Department of Geology, Nepal and digitized it using Arc GIS so as to obtain our final Geology map. Our study area was found to pass through different geological formations like chandragiri formation, Chitlang formation, Galyang formation, Ghanapokhara formation, Lower Siwalik, upper Siwalik, Middle Siwalik, Tawa Khola formation, Tistung formation, Udaypur formation and so on. Bedrock geology; its types and strength play a very important role in landslide occurrence. It has been shown in fig 11.

Rainfall

Rainfall is one of the triggering factors of landslide. High intensity and long duration rainfall events are the most frequent triggers for rapid shallow landslides in mountainous regions (Caine, 1980; Guzzetti et al., 2008). Infiltrating rainfall water adds load to the soil mantle (Chigira and Yokoyama, 2005) and concurrently reduces internal soil strength (Mitchell and Saga, 2005; Lu et al., 2010), and may induce positive pore pressure destabilizing and soil mass (Iverson,2000). In the Himalayan context, shallow landslides are associated with torrential rainfall brought by the monsoon (Dahal & Hasegawa, 2008). A large and well known landslide of the Prithivi Highway, named the Krishnabhir landslide, occurred after some days of intense precipitation, in the Trishuli River valley (Lesser Himalaya) at the beginning of mid of August 2000 and blocked the Prithivi Highway, the main entry route of Kathmandu, for 11 days (Dahal et al., 2010). This signifies rainfall as triggering factor of landslide. We prepared rainfall map in ILWIS 3.3 by employing secondary data of annual rainfall of the surrounding gauge stations obtained from Department of Hydrology and Meteorology (DHM).Interpolation method was employed for raster map preparation in ILWIS 3.3. On the basis of annual rainfall of different locations within our study area rainfall map has been classified into 5 classes ie.1400 mm-1600 mm, 1600 mm-1800 mm, 1800 mm-2000 mm, 2000 mm-2200 mm. Rainfall map has been shown in fig. 10. Respective maps are shown below as:

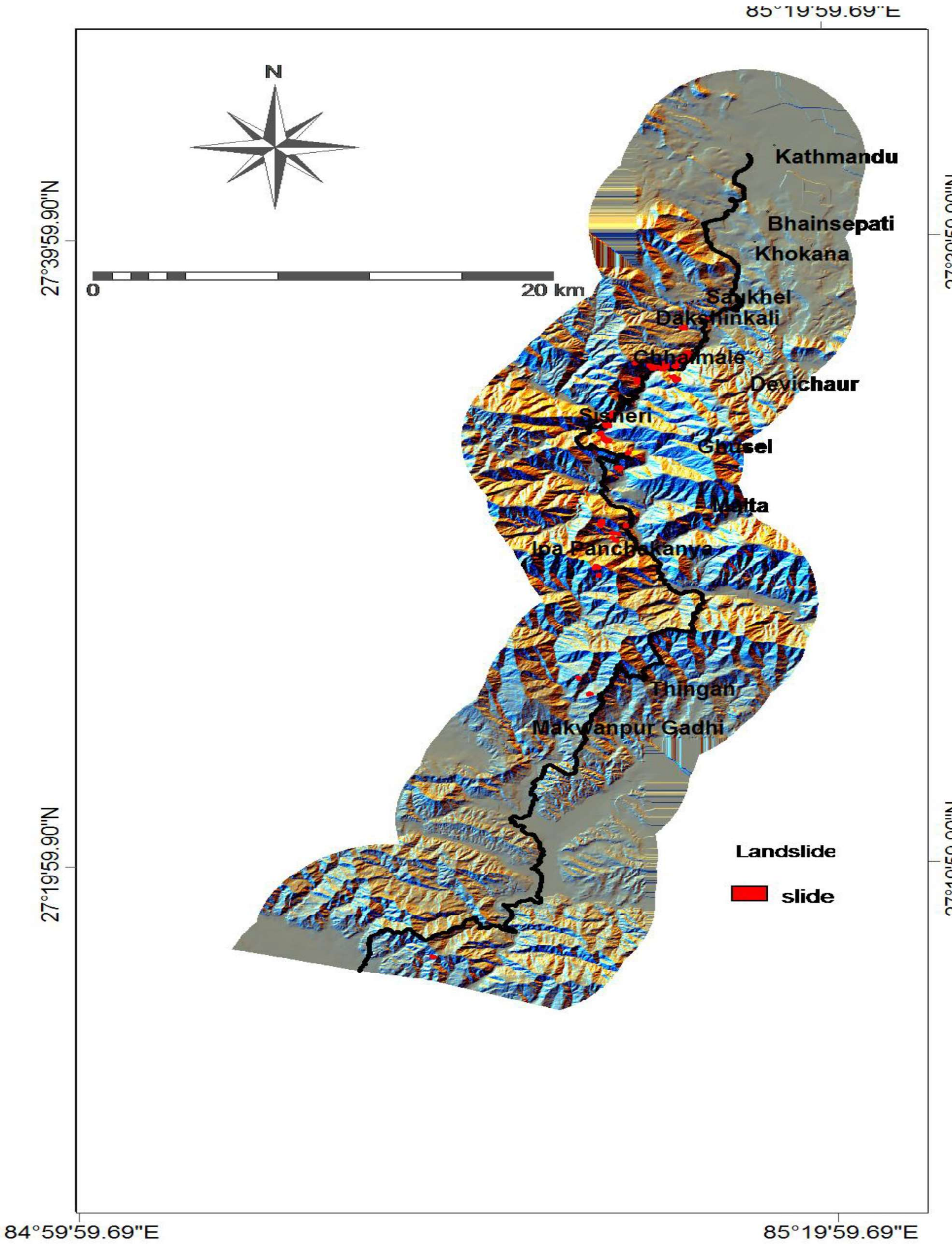


Figure 2: Landslide inventory map

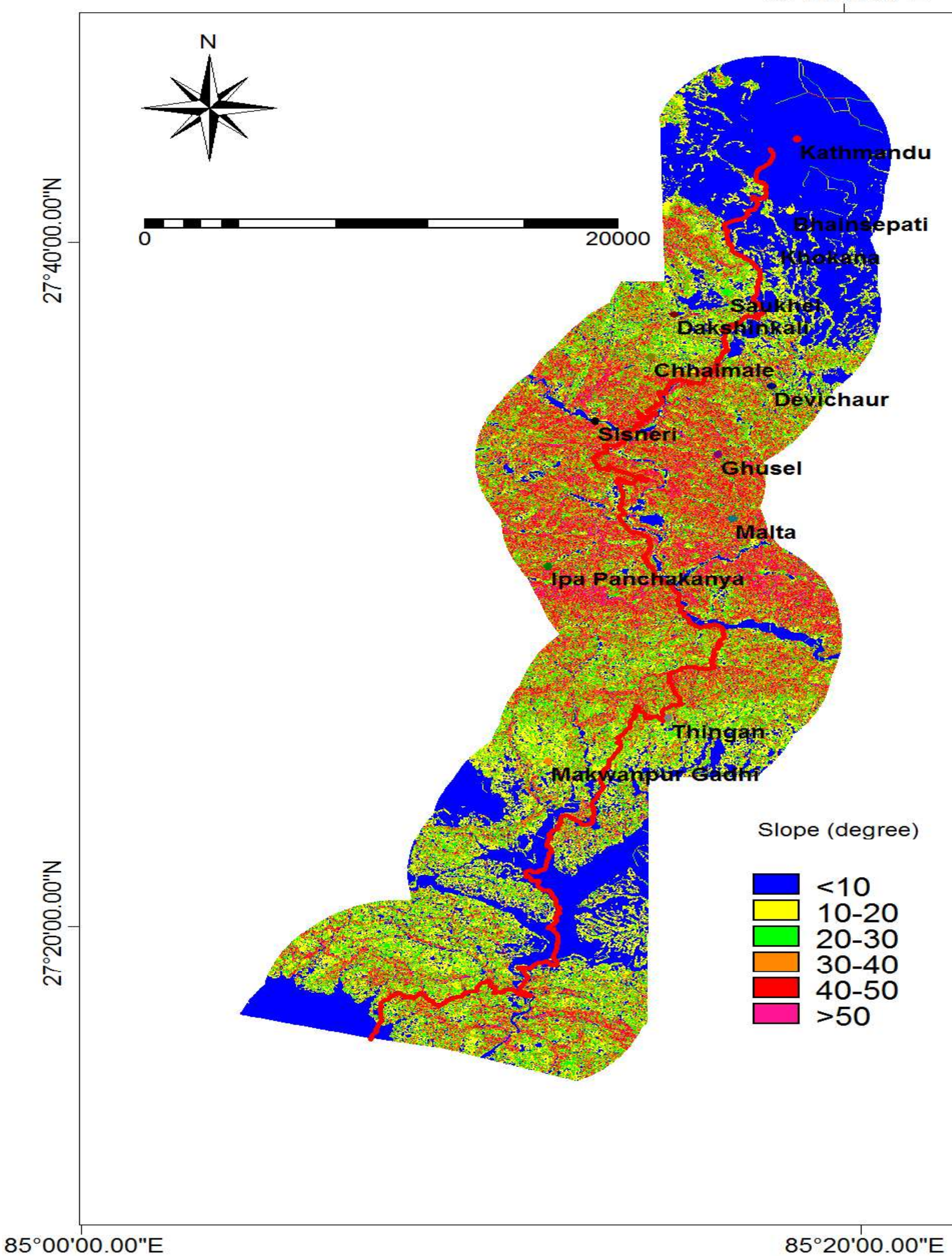


Figure 3: Slope map

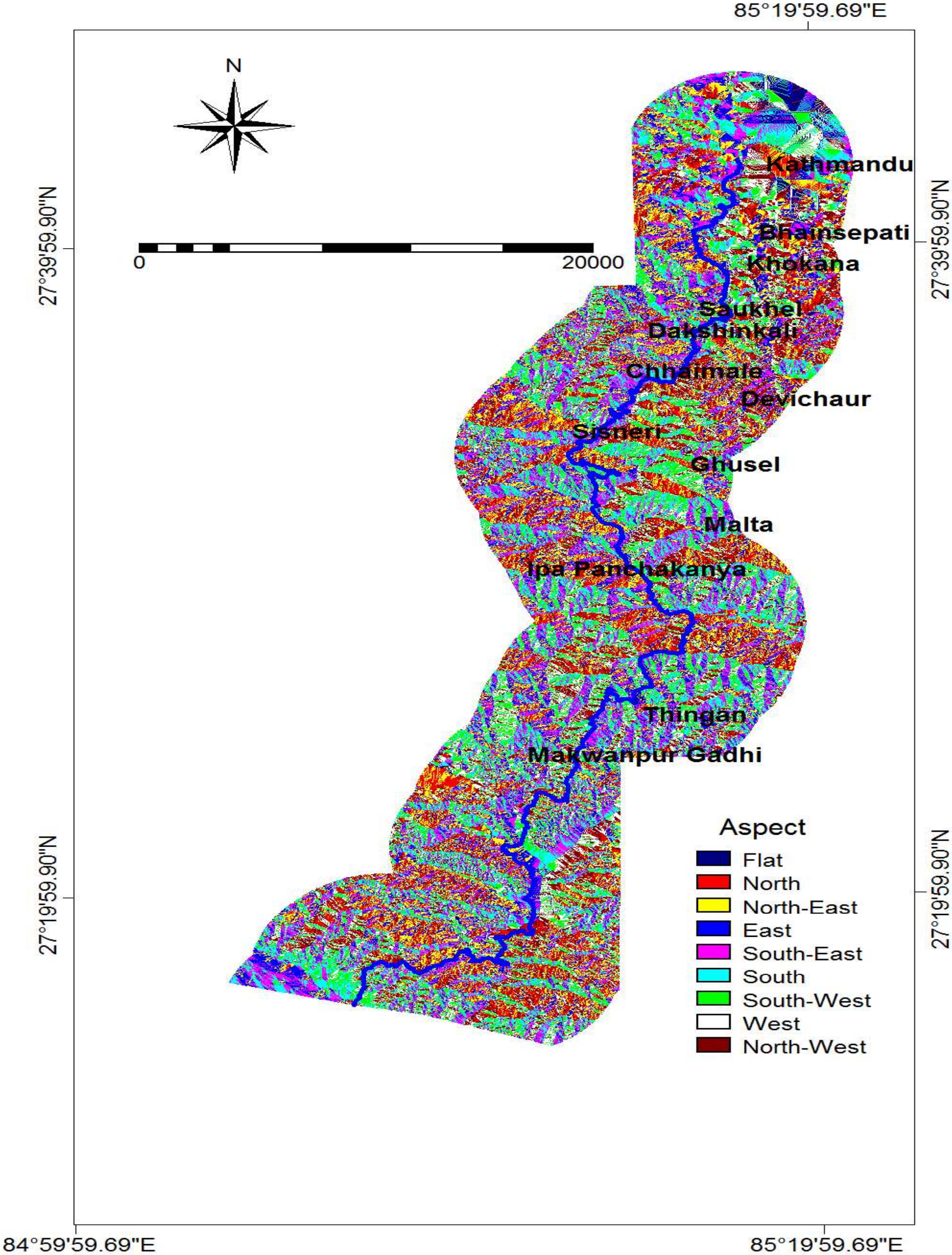


Figure 4: Aspect map

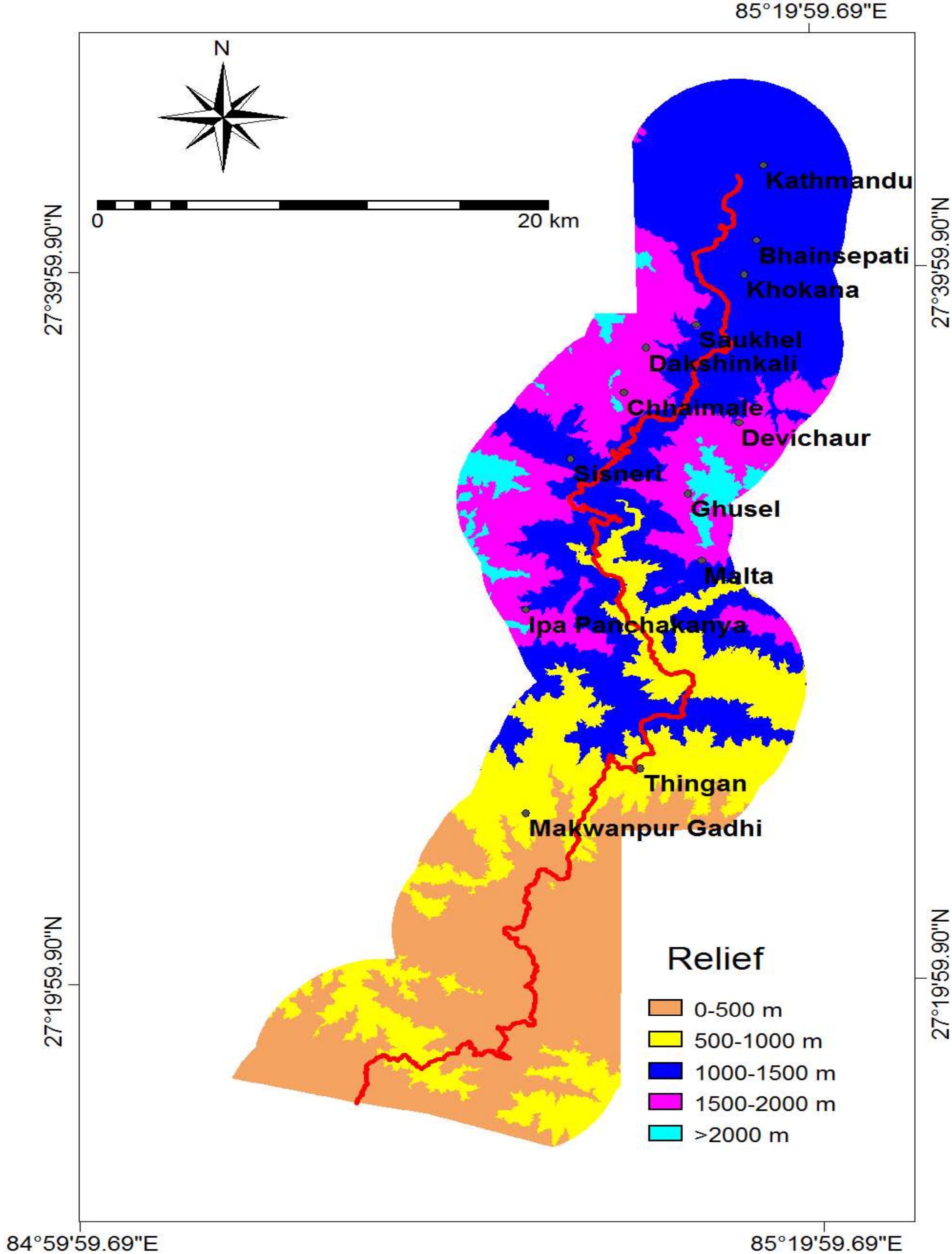


Figure 5: Relief map

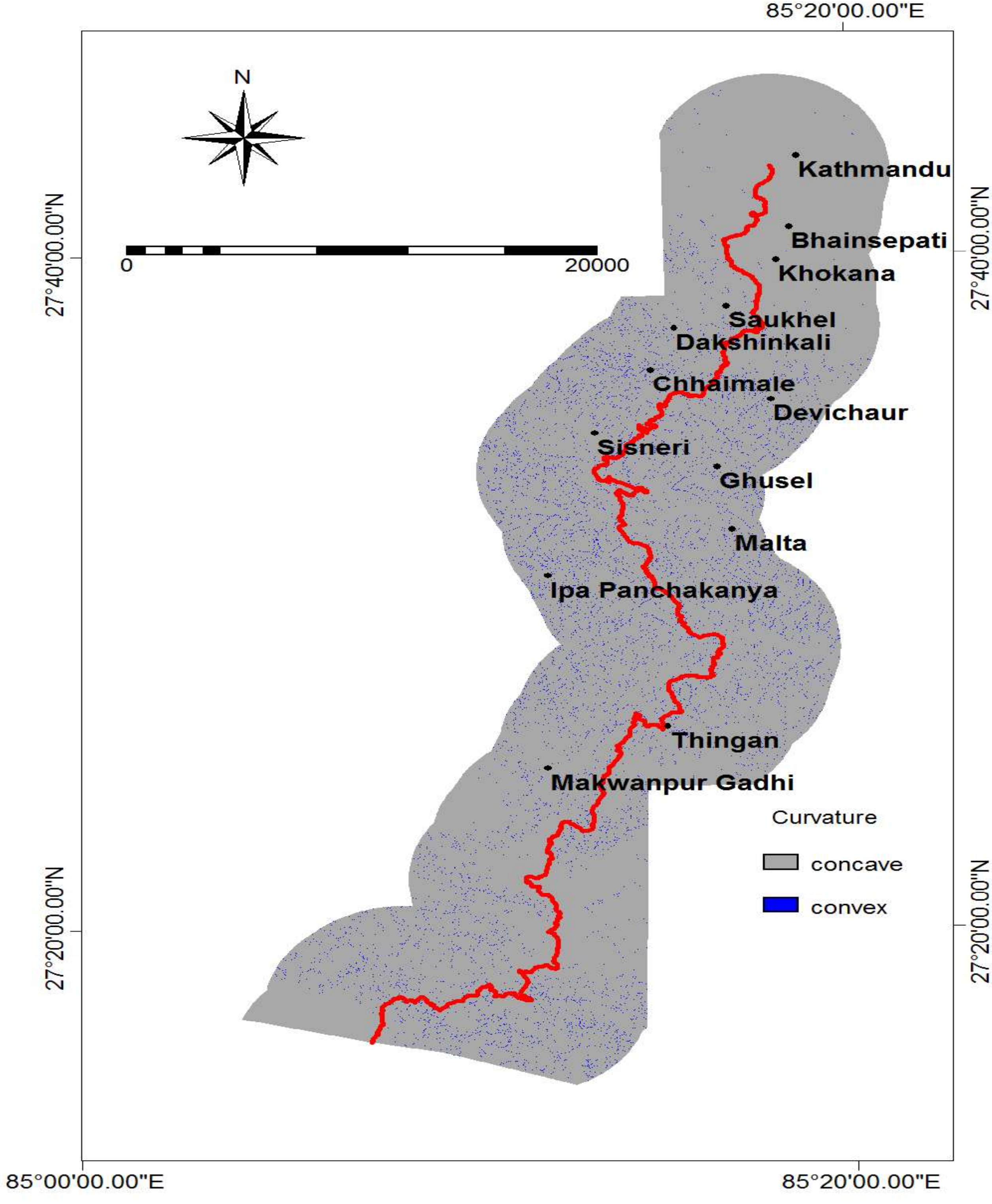


Figure 6: Curvature map

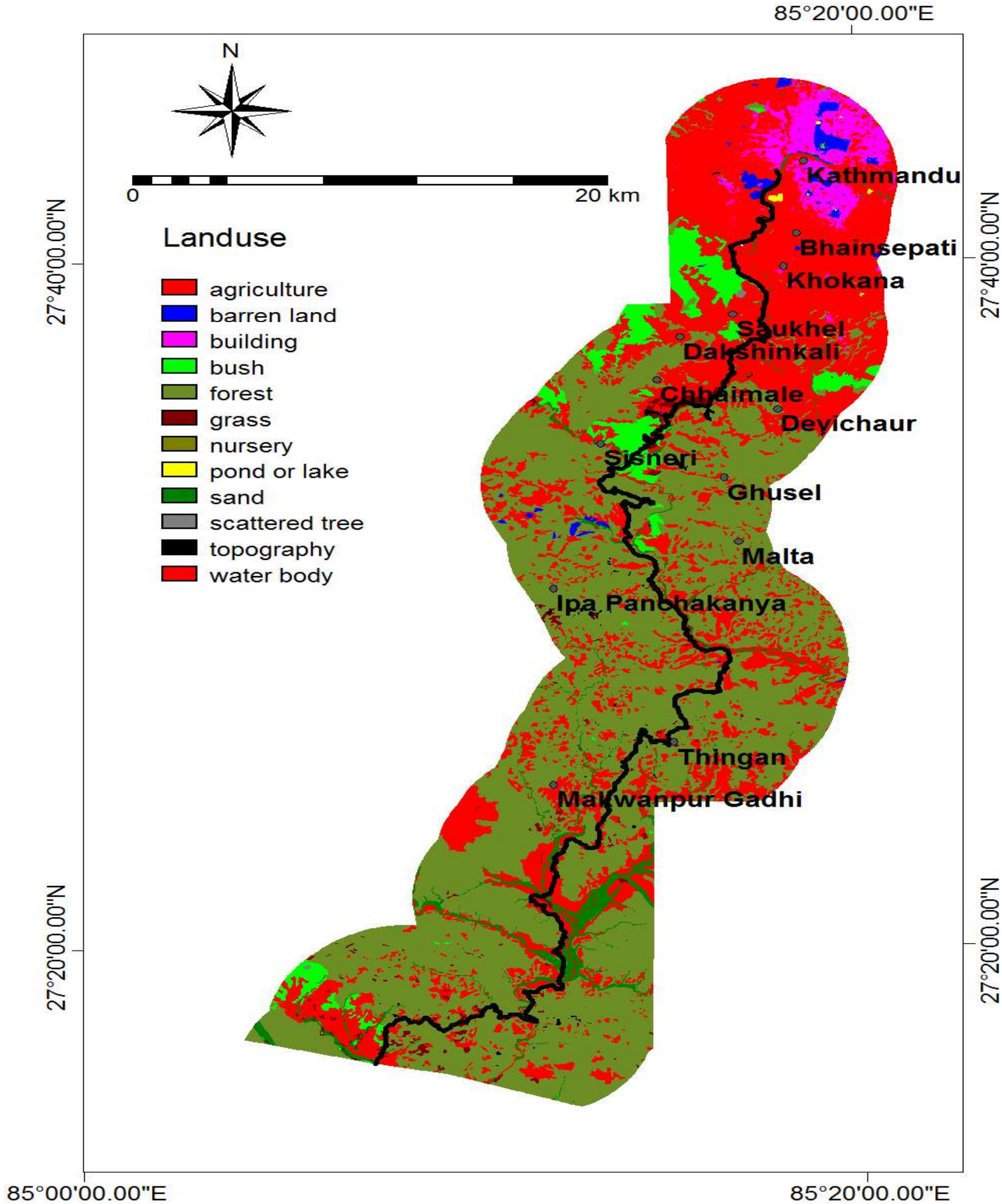


Figure 7: Landuse map

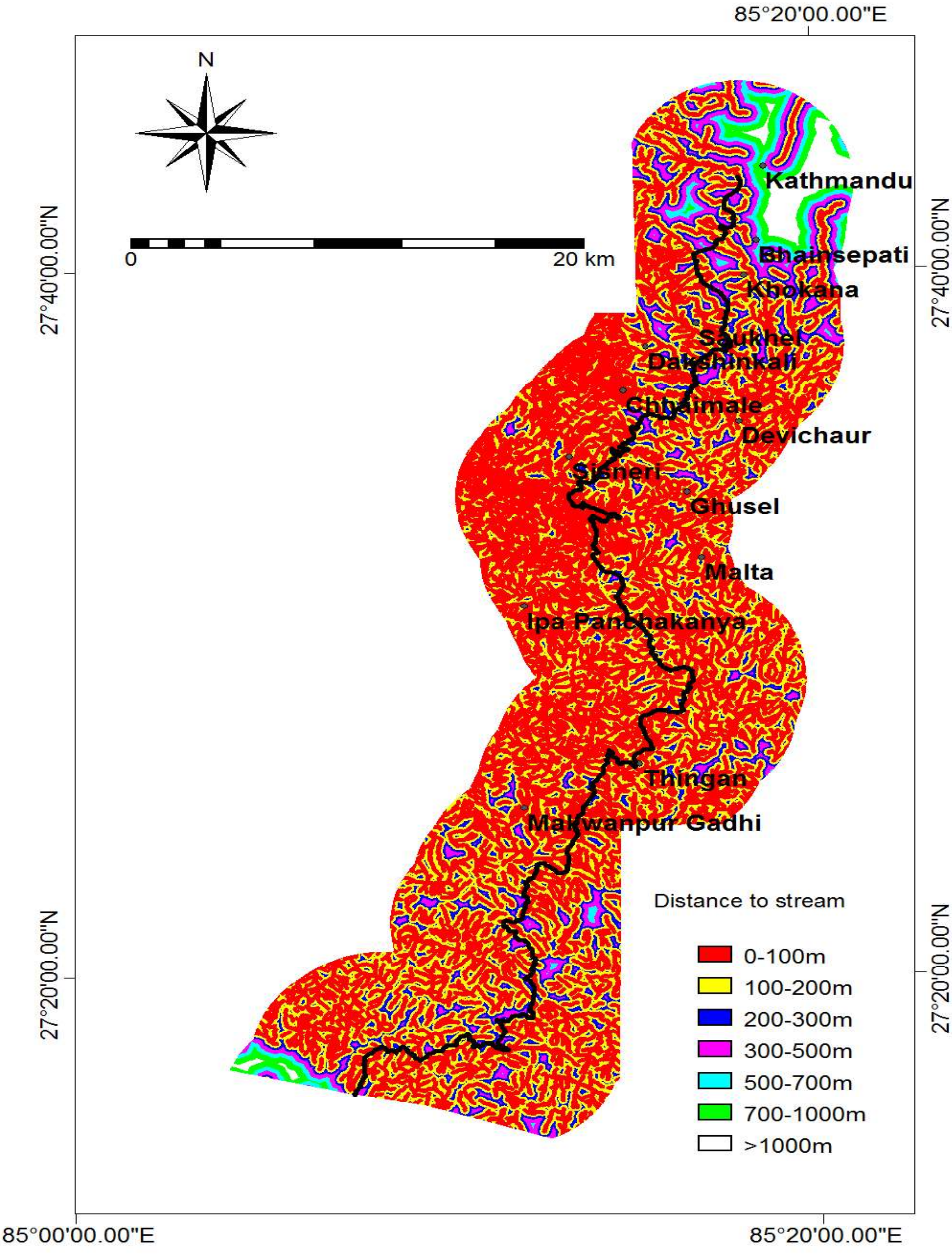


Figure 8: Distance to stream map

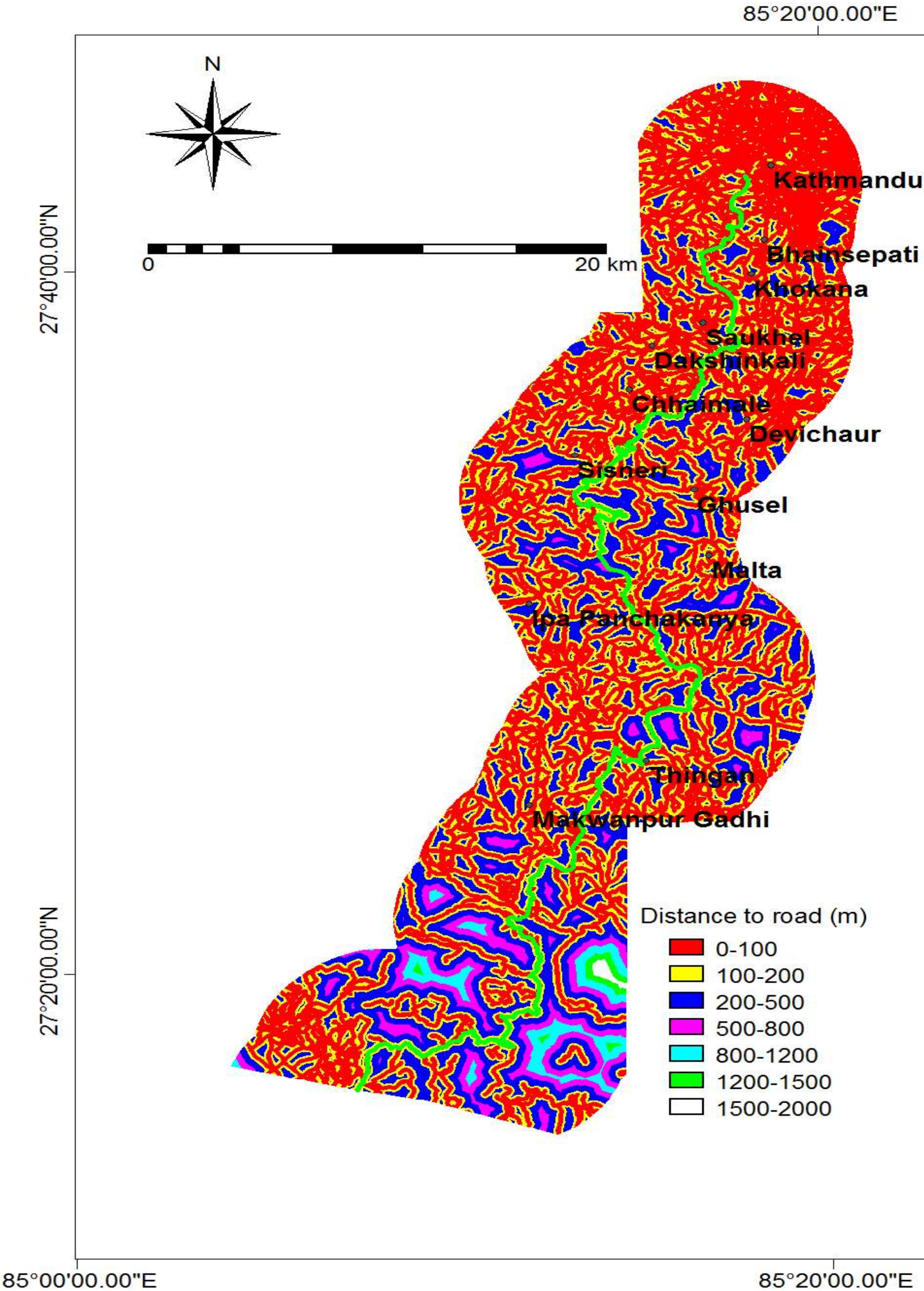


Figure 9: Distance to road map

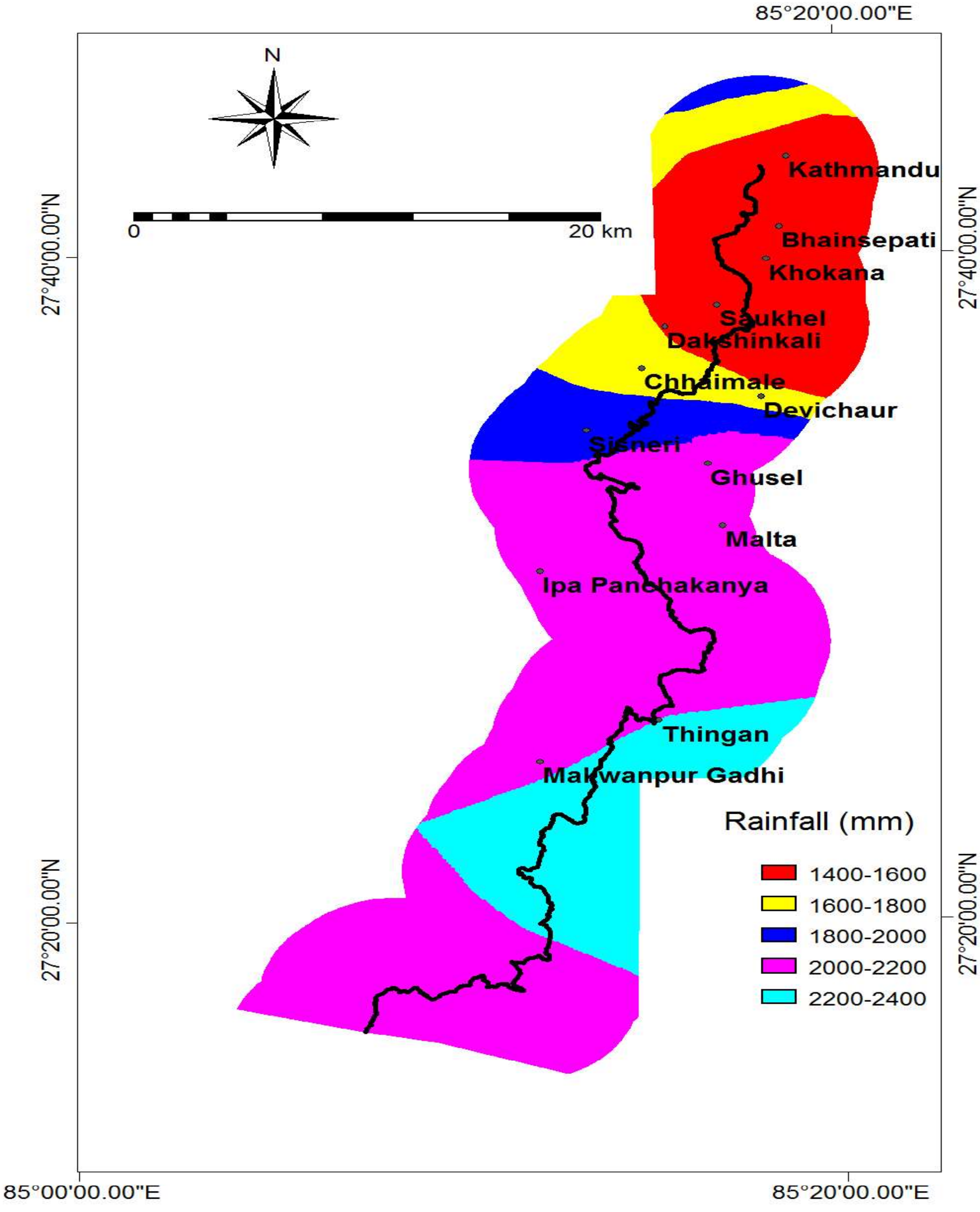


Figure 10: Rainfall map

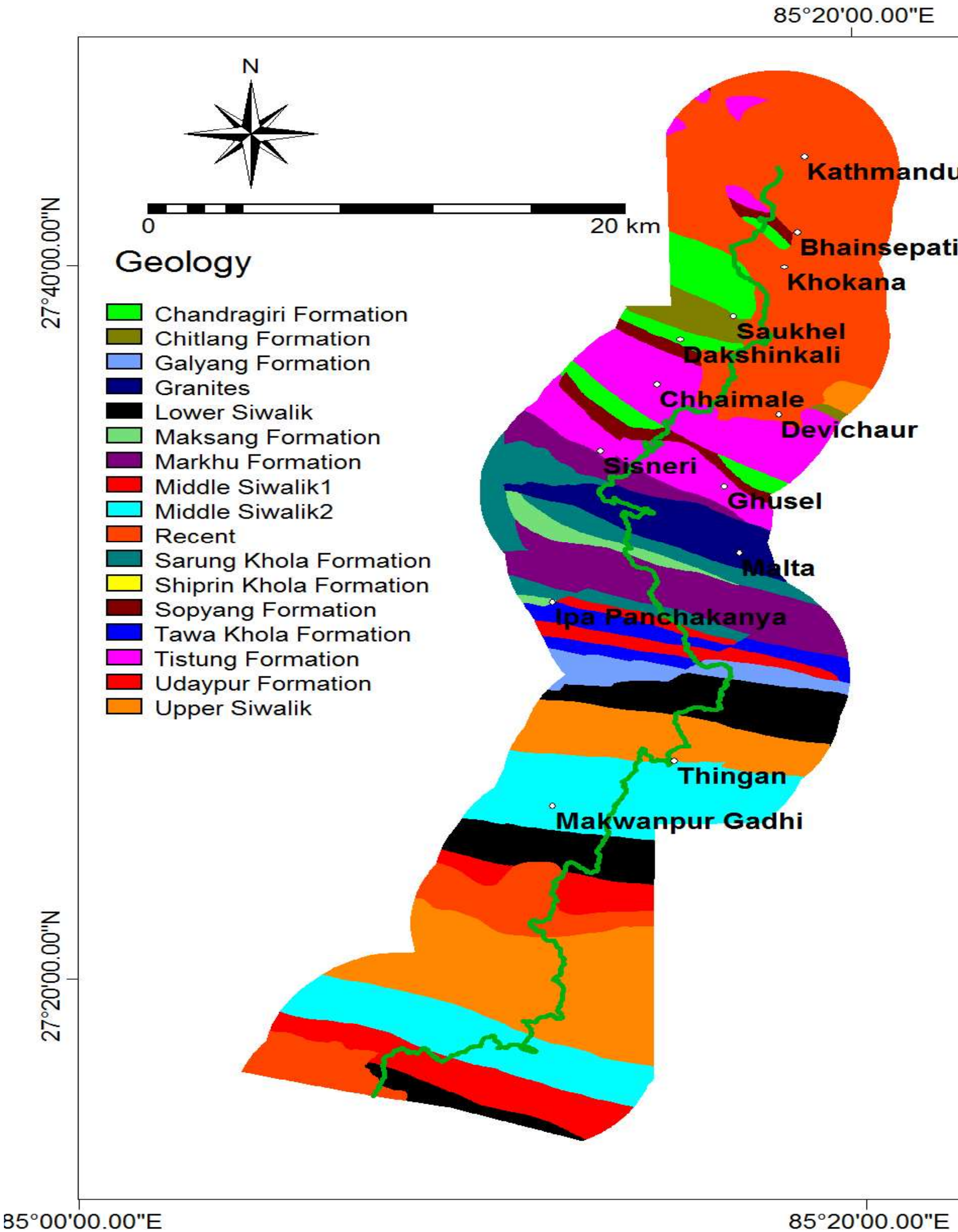


Figure 11: Geology map

6. RESULTS AND DISCUSSIONS

For landslide hazard mapping, the main steps were site selection and map study of the selected location, preparation of relevant causative factor maps (thematic maps and topography related feature maps) using database provided by Survey Department Nepal in digital map sheets. Similarly landslide inventory map or the map showing the places of occurrence of landslide was prepared from Google Earth. The relationship between these landslide predictive factors and landslide was shown so as to prepare final hazard map. Arc GIS and ILWIS were utilized to prepare data layers from the data sources.

Crossing of each parameter map with landslide map was done so as to find out the total area occupied by landslides in different classes of the parameter map .Crossing operation was performed in ILWIS 3.3.Area has been calculated in the term of pixel. Each parameter with different classes and total pixels in those classes and the pixels where there is presence of landslide has been shown below in respective tables. Similarly it has been represented in bar graph.

Slope:

Table 2 and Figure 12 indicate higher landslides in the locations with slope 40-50 degree in our study area. As expected, the number of landslides increased with increase in slope, which is due to lower resisting force in sloped land; various other studies show similar relationship between slope and landslide occurrence (Dahal et al, 2008; Pourghasemi et al., 2012; Nepal et al., 2015). Gravity acting on steep slope can be considered as the main reason of landslide though there are other triggering factors. Besides, it can be seen from the diagram that there is decrease in landslide at slope class more than 50^0. It could be due to decrease in soil depth at higher slope. Most of the rocks lie in higher slope.

Table 2: slope classification showing total pixel and slide pixel in each class.

Class	slide pixel	class pixel	% slide
<10	26	10400	4.99%
10-20	20	8000	3.84%
20-30	62	24800	11.90%
30-40	128	51200	24.57%
40-50	177	70800	33.97%
>50	108	43200	20.73%

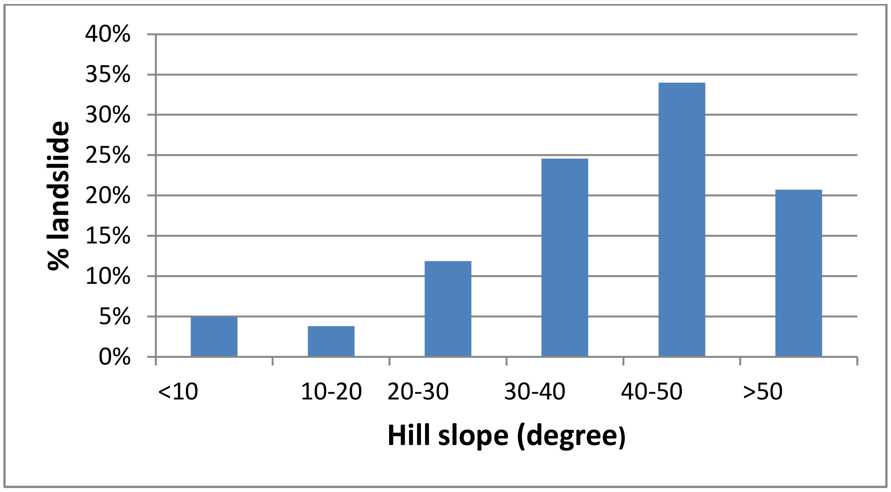


Figure 12: Bar diagram showing percentage of slides in different slope class

Relief:

Table 3 and Figure 13 indicates there is higher landslide in the relief class 1000-1500m.This could be due to more depth of soil in this class of relief. At higher relief, depth of soil decreases which might lead to less landslide occurrence.

Table 3: Relief classification showing total pixel and slide pixel in the classes.

Class	slide pixel	class pixel	% slide
500-1000 m	46	18400	8.83%
1000-1500 m	427	170800	81.96%
1500-2000 m	48	19200	9.21%

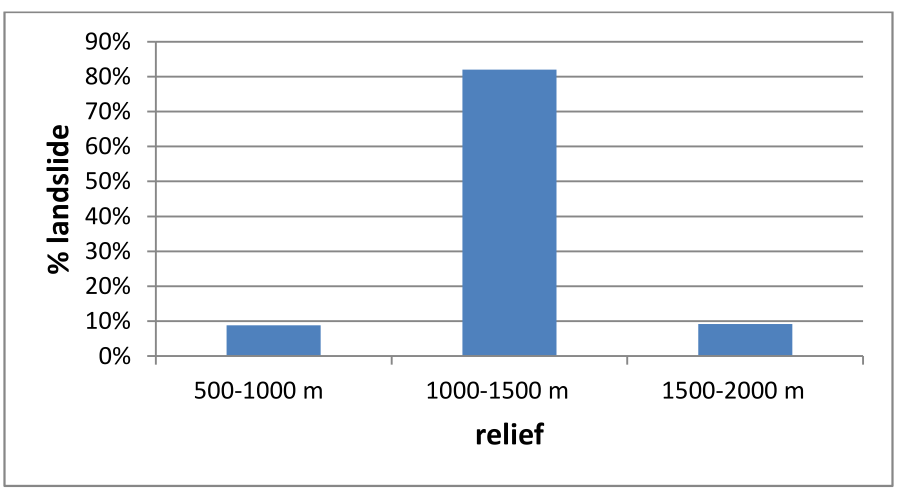


Figure 13 : Bar diagram showing percentage of landslides in different relief classes

Aspect:

Table 4 and Figure 14 reveals higher landslide occurrence in South East aspect. Though aspect is one of the parameters of landslides, it cannot be solely given high weightage in landslide hazad mapping. In those classes of aspects with higher landslide occurrence, the presence of other causative factors there plays greater role in causing landslide. If rainfall has a pronounced directional component by influence of a prevailing wind, the amount of rainfall falling on a slope may vary depending on its aspect (Wieczorek et al., 1997).

Table 4: Aspect classification showing total pixel and slide pixel in the classes.

Class	slide pixel	class pixel	% slide
North	38	15200	7.31%
North-East	78	31200	15.00%
East	72	28800	13.85%
South-East	144	57600	27.69%
South	91	36400	17.50%
South-West	55	22000	10.58%
West	14	5600	2.69%
North-West	28	11200	5.38%

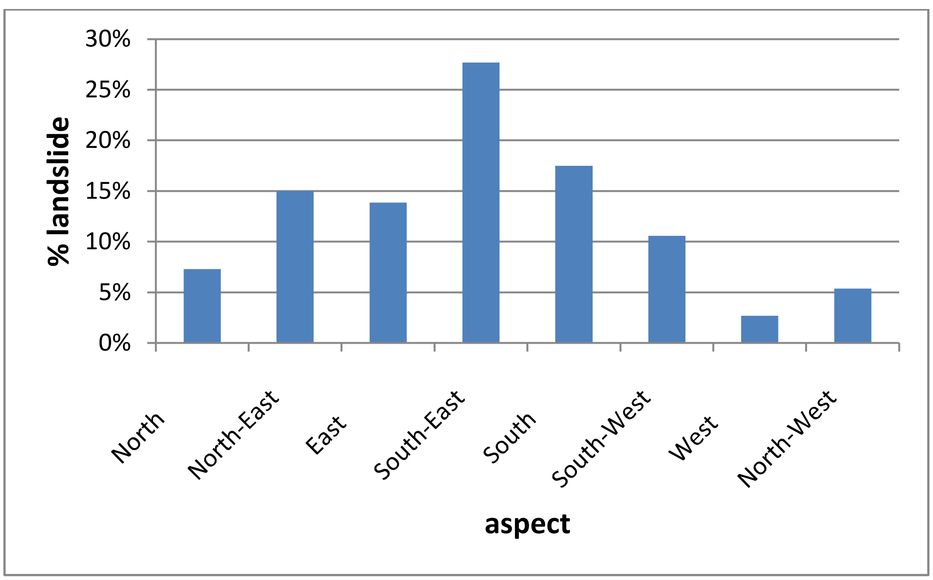


Figure 14: Bar diagram showing percentage of landslides in different aspect classes

Distance to Road:

From Table 5 and Figure 15, we can clearly see that lesser is the distance from the road higher is the landslide occurrence. It could be due to many reasons. Blasting and excavation during road construction disturb the balance of the slope which could lead to landslide in that location. Similarly, it is a well-known fact that road increases access to many places. Deforestation could be the result of increased access of people to forest thereby causing increase in landslide. Besides, cutting of slopes along dip angle during road construction could favor landslide occurrence. Debris flows and other landslides onto roadway are common during rainstorms and often occur during milder rainfall conditions than those needed for debris flow on natural slope.

Table 5: Distance to road classification showing total pixel and slide pixel in each class.

class	slide pixel	class pixel	% slide
0-100	222	88800	42.61%
100-200	193	77200	37.04%
200-500	106	42400	20.35%

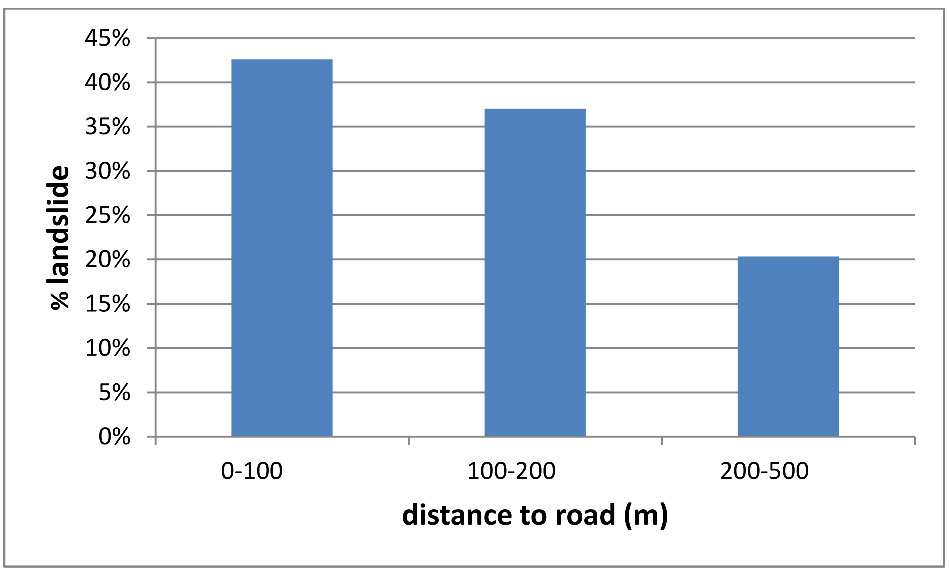


Figure 15: Bar diagram showing percentage of landslides in different classes of distance to road

Distance to stream:

From Table 6 and Figure 16, it has been clearly shown that more closer the stream more is the occurrence of landslide. It is maximum in the class 0 to 100m.It could be due to saturation of slope materials due to water in the stream, resulting in loss of cohesion thereby flowing downward easily. Continual erosion along the base of slopes due to wave action and scouring may lead to more landslides along the stream channels.

Table 6: Distance to stream classification showing total pixel and slide pixel in each class.

class	slide pixel	class pixel	% slide
0-100m	241	96400	46.26%
100-200m	212	84800	40.69%
200-300m	61	24400	11.71%
300-500m	7	2800	1.34%

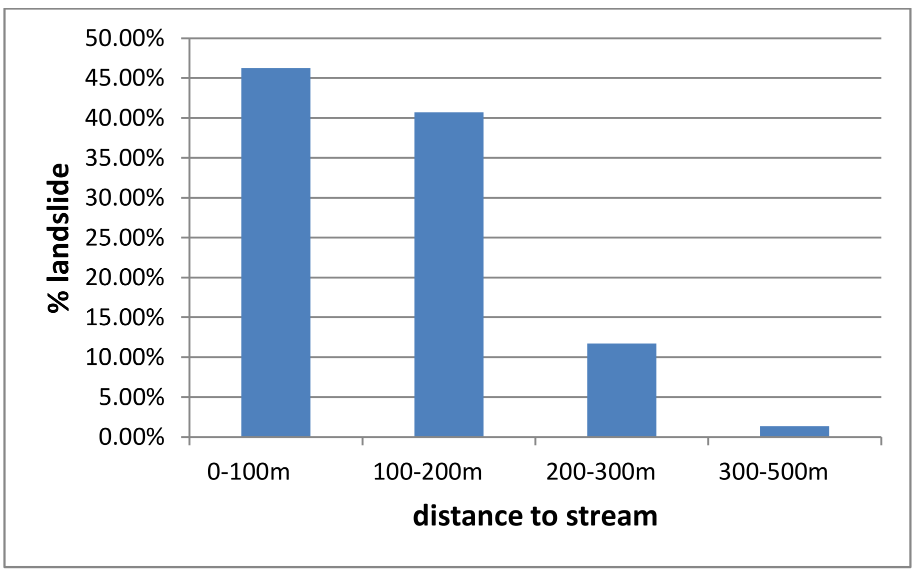


Figure 16: Bar diagram representing percentage of slides in different distance to stream classes

Rainfall:

From Table 7 and Figure 17, it has been known that there is higher rainfall in the class of rainfall 2000-2200mm and this is the class of maximum rainfall. Rainfall is one of the important triggering factors of landslide. If other conditions are favorable for the landslide occurrence, then rainfall assists in initiating the slide.

Table 7: Rainfall classification showing total pixel and slide pixel in different class.

Class	slide pixel	class pixel	% slide
1400-1600	19	7600	3.65%
1600-1800	145	58000	27.83%
1800-2000	105	42000	20.15%
2000-2200	252	100800	48.37%

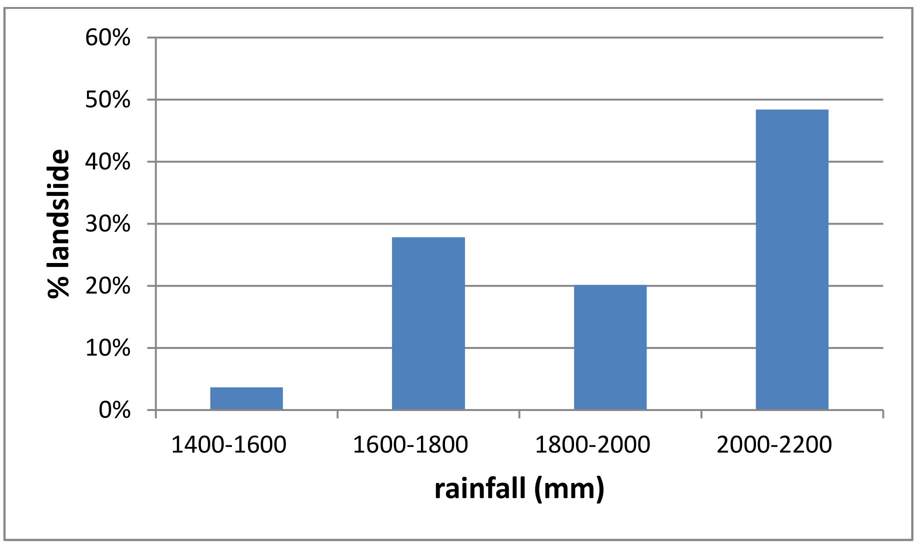


Figure 17: Bar diagram showing percentage of landslides in different rainfall classes

Landuse:

Table 8 and Figure 18 shows higher landslides occurrence in the forest landuse. This could be due to forest encroachment or increased deforestation leading to higher landslide. Besides, significant landslides in agriculture landuse may be due to practice of flood irrigation. This can act as a favorable condition to trigger landslide.

Table 8: landuse classes showing total pixel and landslide pixel in the classes

class	% slide	slide pixel	class pixel
agriculture	13.94%	70	28000
bush	16.14%	81	32400
forest	46.22%	232	92800
grass	23.11%	116	46400
topography	0.60%	3	1200

.

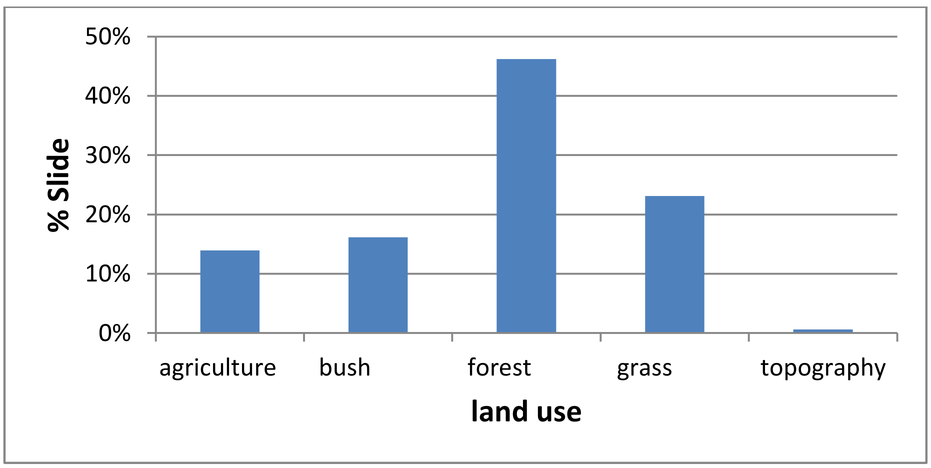


Figure 18: Bar diagram representing percentage of slides in different landuse classes

Geology:

Table 9 and Figure 19 indicate landslide occurrence in different geology classes namely Udaypur Formation, Tistung Formation, Middle Siwalik2, Chandragiri Formation, Granites, Markhu Formation, Sarung Khola Formation. Higher percentage of landslides is in Tistung Formation, granites exposure area and Markhu Formation. Metasandstones, siltstones, phyllites, Slates and calc-phyllites which are considered to be the weak rocks are the main lithology of Tistung formation. Similarly, Markhu Formation consists of marble and schist which are also weak rocks and favours slides in geologically active zones. Granite is a light-colored igneous rock and is composed mainly of quartz and feldspar with minor amounts of mica, amphiboles and other minerals. Though granite is considered as a strong rock, our results show higher landslide occurrence in granites. This could be due to weathered action or due to presence of fragmented granites rock. This might be an implication that presence of strong rock does not always favor stability.

Table 9: Geology classification showing total pixel and slide pixel in different classes.

class	slide pixel	class pixel	% landslide
Udaypur Formation	35	14000	7.69%
Tistung Formation	162	64800	35.60%
Middle Siwalik2	12	4800	2.20%
Chandragiri Formation	10	4000	2.20%
Granites	100	40000	21.98%
Markhu Formation	134	53600	29.45%
Sarung Khola Formation	2	800	0.44%

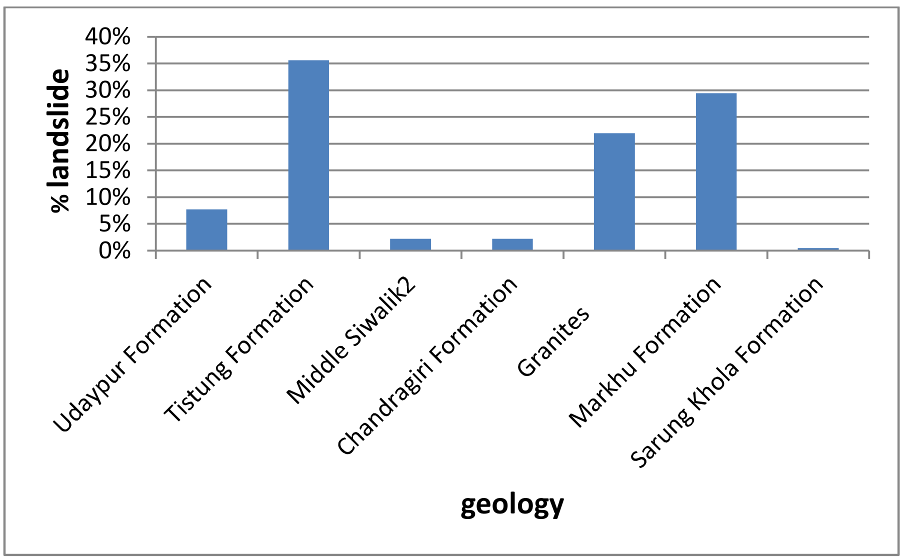


Figure 19: Bar diagram representing landslides percentage in different Geology classes

Final Hazard Map

To evaluate the contribution of each factor towards landslide hazard, the existing landslide distribution data layer has been compared with various thematic data layers separately. For this purpose, we have,

$$W_i = \log_e \left\{ \frac{D_{clas}}{D_{map}} \right\}$$

$$W_i = \mathrm{Log}_e \left(\frac{Npix_a}{Npix_b} \Big/ \frac{\sum Npix_a}{\sum Npix_b} \right)$$

where, Wi=weight value of any class of a parameter,
Npixa=slide pixel in the class,
Npixb=total pixel in the class,
ΣNpixa =total number of slide pixel in the map,
ΣNpixb=total number of pixel in map.
(Dahal and Timilsina, 2015)

The factor maps were all combined with the landslide inventory map for the calculation of the positive and negative weights. The calculation procedure was written in the form of a script file in ILWIS 3.3, consisting of a series of GIS command to support above equations. Since all of the maps are multi-class maps, containing several classes, the presence of one factor, such as agriculture implies the absence of the other factors of the same landuse map. Therefore in order to obtain the final weight of each factor, the positive weight of the factor itself was added to the negative weight of the other factors in the same map (Van Westen et al., 2003). After running the script, we obtained various weights for different classes in different parameters.

Parameter	**weight value ranges from**
Slope	-1.80707 to 1.44746
Aspect	-1.62167 to 0.70072
Relief	-3.493470 to 0.843820
Distance to road	-3.493470 to 0.47680
Distance to stream	-3.493470 to 0.48059
Geology	-3.49347 to 1.758800
Rain	-3.493470 to 1.24798
Landuse	-3.49370 to 3.203070

Weight value of each class of different parameters has been calculated and tabulated below. The classes with very low weight have been included in the same class with nominal weight value.

Table 10: Parameter classes and their respective weight values

Parameter class	Weight Value
Relief class	
0-500	-3.49347
500-1000	-0.8473
1000-1500	0.84382
1500-2000	-0.56495
>2000	-3.49347
Aspect class	
flat	-1.62167
west	-1.43935
North West	-0.69011
North	-0.45852
South west	-0.20135
East	0.08448
North east	0.1282
South	0.30426
South east	0.70072
Distance to stream class	
0-100	-0.2239
100-200	0.48059
200-300	0.42652
300-500	-1.09558
>500 m	-3.49347
Geology class	
Chandragiri Formation	-0.51794
Granites	1.7588
Markhu Formation	1.33003
Middle siwalik1	-0.92852
Middle siwalik2	-1.68518
Recent	-0.8688
Sarung Khola Formation	-2.39486
Tistung Formation	1.3436
Udaypur Formation	1.72958
others	-3.49347

Parameter class	Weight value
Distance to road class	
0-100	-0.18659
100-200	0.47682
200-500	0.05327
>500	-3.49347
Landuse class	
agriculture	-0.92086
Bush	1.35856
Forest	-0.19394
Grass	3.20307
topography	0.9884
water body	1.79832
Others	-3.49347
Slope class	
<10	-1.80707
10-20	-1.57655
20-30	-0.3979
30-40	0.40039
40-50	1.04449
>50	1.44746
Rainfall class	
2200-2400	-3.49347
1400-1600	-1.65292
2000-2200	-0.04349
1800-2000	1.04449
1600-1800	1.24798

From Table 10, it has been known that parameters slope, rainfall, landuse and Geology have relatively higher weight value.

Weights of all the parameters were added by running the following command in ILWIS 3.3:

Hweight=Waspect+Wrelief+Wslope+Wlanduse+Wdisstream+Wdisroad+Wgeology+Wrain

The histogram of thus obtained Hweight map was calculated which showed boundary values ranging from -21.1199 to 9.74406. And each boundary or weight values has respective number of pixels.40, 80, 60 and 90 percentile boundary values were calculated. These respective boundary values were selected to classify the Hweight map into very low, low, moderate, high and very high hazard. Boundary value below 40 percentile were classified as very low hazard, between 40 to 60 percentile were classified as low hazard ,between 60 to 80 percentile were classified as moderate, and 80 to 90 percentile as high hazard while above 90 percentile as very high hazard. After that, slicing operation was performed in the hazard map and thus final classified hazard map was obtained.

Thus obtained map contains classified hazard zones from very low to very high represented by different colors. This map clearly reveals different sections which are under the threat of landslide along the Fast track road section. It has been shown in fig. 20.

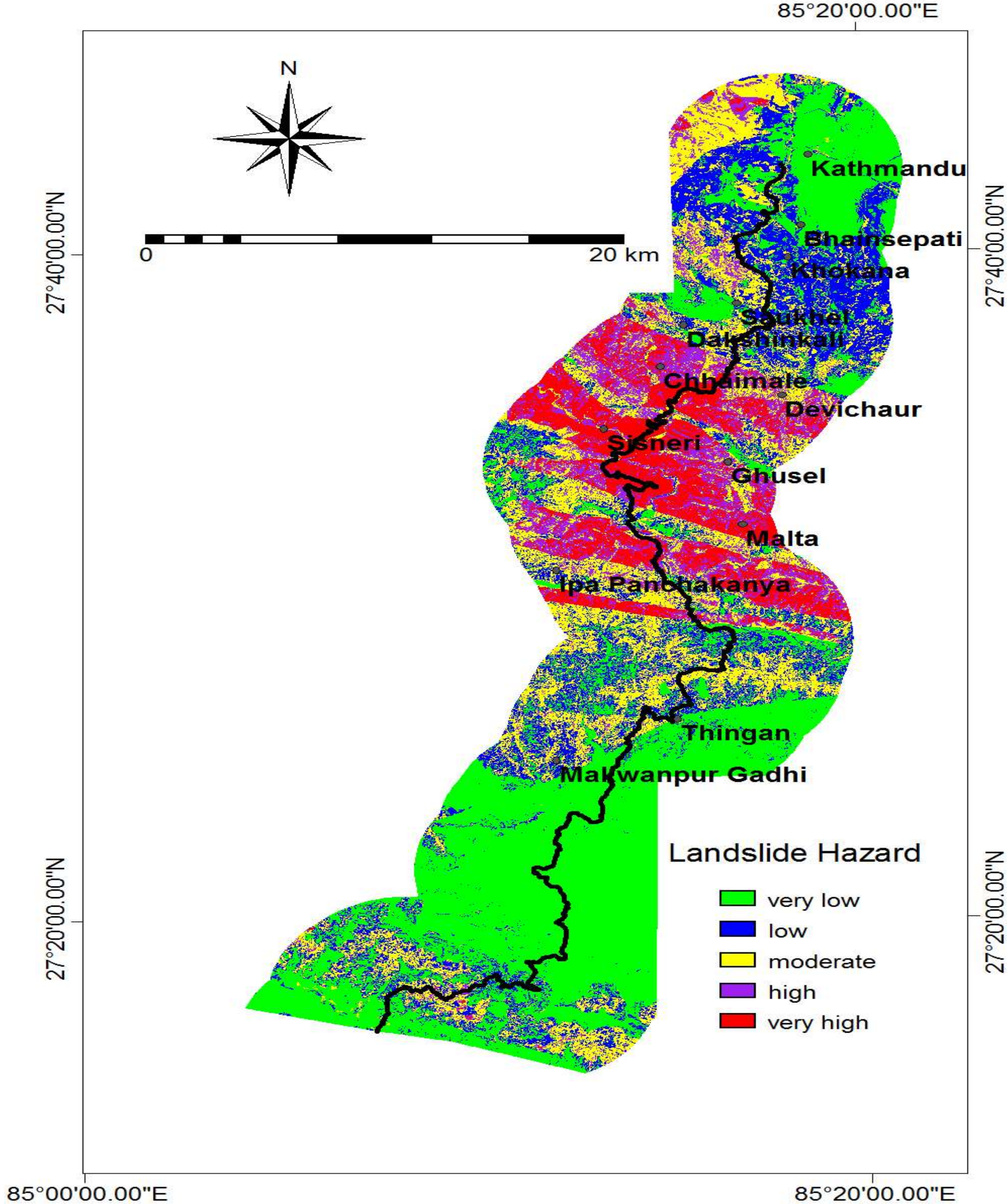


Figure 20: Classified landslide hazard map

Above hazard map was again crossed with landslide inventory map which revealed the following information.

Table 11: Hazard classes with landslide pixel and total pixel in each classes.

class	class pixel	Slide pixel	%slide
low	1600	4	0.77%
moderate	15200	38	7.29%
high	23600	59	11.32%
very high	168000	420	80.61%

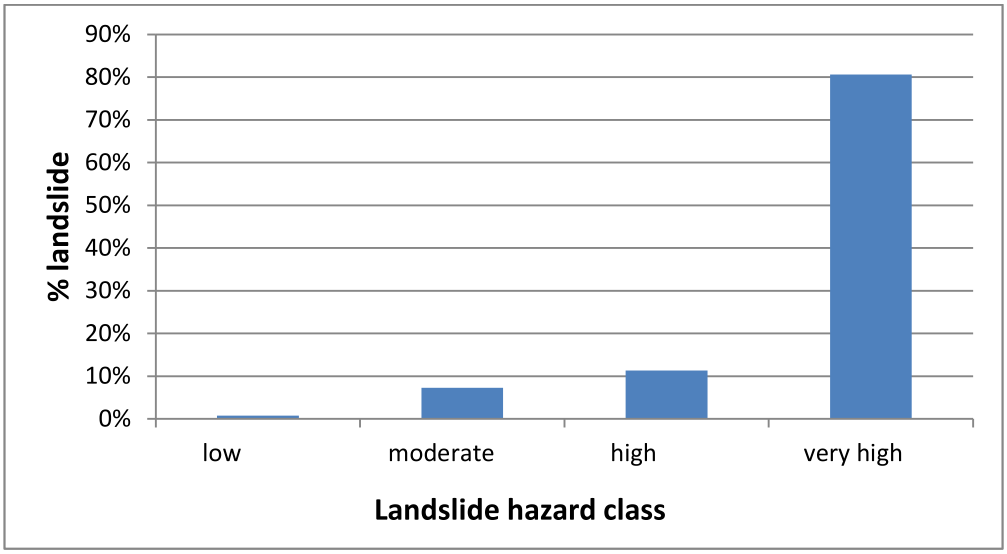


Figure 21: Bar diagram showing percentage landslides in different hazard classes

Table 11 and Figure 21 indicates occurrence of higher percentage of landslide in the very high hazard class which is obvious. It indicated there has been lot of landslide occurrence in those locations of our study area which falls under high hazard zone.

Discussions

Application in Civil Engineering

Landslide is not a new hazard to our country. We have been facing a lot of problems every year due to landslides. Loss of lives, destruction of houses, roads, irrigation canal, hydropower and many such infrastructures due to landslides are in news every now and then, especially during monsoon seasons. This has signified the need of proper planning and adoption of relevant mitigation measures. For this, identification and assessment of landslide prone zones is very important. Landslide hazard mapping is one of the effective methods for this purpose. It must be considered as an integral part of the infrastructure development so as to make any development project sustainable. Landslide hazard mapping is one of the means of landslide disaster management. Similar hazard map of different other disasters (eg. earthquake, flood) are very crucial in disaster management. Landslide hazard map shows different zones of high, low and moderate hazards which can be useful in restricting habitats in such zones. It helps in preparedness during any project planning. If any infrastructure has to be developed along the landslide risk zones then possible mitigation measures and suitable codes for building and structures can be adopted and implemented effectively. This will lead to highly sustainable development consequently preventing the possible chances of damage and reducing the maintenance and operation cost in long term. It has very important application in road alignment, settlement planning, and Hydropower components like intake, powerhouse, dam etc. site location and design. Roads are most affected infrastructure due to landslides. So it must be considered as an integral part in transportation planning.

Mitigation Measures:

In Nepal, river training and management of landslides are two major works in engineering approach of geo-disaster mitigation (Dahal and Bhandary, 2013). For landslide prevention, different mitigation measures are in common practice in Nepal. Bioengineering, drainage measures and structural support measures are some of the most accepted and widely employed practices.

Drainage Measures

The management of drainage is often very important for the control of landslide. Both surface (for removal of surface runoff) and subsurface (for controlling excess of subsurface water) drainage measures have been used. East-West Highway have relatively good management of surface runoff at cut slopes and a reduced landslide frequency in comparison with low cost rural roads (Dahal et. al, 2010). In these roads, surface runoff of up to 1 m^3/s has been drained out with lined catch drains and riprap channels designed to cope with storms of a minimum 25 years return period whereas drainage of subsurface water has been managed using French drains (depth 1.5 m to 2.5 m) (Dahal et al, 2010). After deterministic slope stability analysis at different landslide sections along the Fast track road, suitable drainage measure can be adopted. Drainage condition and patterns should be properly studied before installing any surface or sub surface drainage measures. When installing subsurface drains, filter protection such as a geotextile or properly sized sand or gravel should be used to prevent migration of fine soil particles into underdrains, thereby allowing groundwater to drain from the soil without building up pore pressure (Transportation Research Board, 2012).

Structural support measures:
In roadside slopes of Nepal, structural support measures are also applied in combination with drainage and bioengineering measures (Dahal et al, 2010). Most commonly used structures for landslide mitigation in Nepal are retaining walls such as gabion wall, stone masonry and composite masonry wall. Support structures such as rock bolts, earth anchors and soil anchors have been installed at locations where the slopes could not be made safe enough through drainage measures and building of retaining wall alone (Adhikari, 1997). Proper geotechnical study is required for designing of such structures. Calculations of safety factor against overturning, base sliding, structural adequacy and overall stability should be made. Attention should be paid to provide adequate drainage so as to ensure safety to the roads. Rock bolt with bars are particularly useful where plane failures and wedge failures are likely to occur (Adhikari, 1997).

Bioengineering:
It is a technique that employs plants to stabilize the slopes. They are most common in roads of Nepal and one of the cheapest techniques of slope stabilization. In Nepal, comprehensive bioengineering works have been carried out and large experience has been collected in slope stabilization using vegetation (Howell 1999; Dahal 2001; Florineth et al. 2002). It has been proved to very useful method of landslide mitigation measures. Many of the roads of Nepal have adopted this measure. Some of the examples of bioengineered roads in Nepal are Koshi Highway, East-West Highway in the Siwalik, Prithvi Highway, Pokhara-Baglung roads (Dahal and Bhandary, 2013). Krishnabhir landslide (along Prithvi Highway) can be taken as a very good examples of such roads in which bioengineering along with civil structures stabilized the problematic section efficiently.

Limitations of the study:

- Dimensions of landslides are not mentioned. Different size landslides are used in the inventory map.
- In the Terai section, Kathmandu Terai Fast track road is affected by floods too. But this study does not show hazard of floods in those sections.

7. CONCLUSION AND RECOMMENDATIONS:

Nine maps showing different parameters were generated using GIS based softwares (Arc GIS and ILWIS). And crossing of 8 maps (curvature map was not used) with landslide map was done to obtain above tables and bar diagrams representing significance of each parameter in landslide occurrence. Script was run in Ilwis 3.3 and hence weight values of each causative factor were found which were added to obtain hazard map. Finally, classified hazard map was obtained. Thus obtained hazard map has shown Chhaimale, Devichaur, Sisneri, Ghusel and Malta as the most landslide hazard prone sections in the alignment. Deterministic approach can be adopted for slope stability analysis at specific landslides prone sections of the road so that relevant mitigation measures can be adopted. Many effective techniques such as retaining wall, soil nailing, reinforcement measures, bioengineering, draining technique etc. can be adopted after detailed study at specific landslide site locations.

REFERENCES

Adhikari TL, 1997, Landslide control and Stabilisation measures for Mountain Roads: A Case Study of Araniko Highway,Central Nepal, page 280-282

Ayalew L and Yamagishi H, 2005, The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahi

Caine N, 1980, The rainfall intensity-duration control of shallow landslides and debris flow, Geogr. Ann. A, 62, 23–27

Carrara A, Cardinali M., Detti R, Guzzetti F, Pasqui V and Reichenbach P, 1991, GIS techniques and statistical models in evaluating landslide hazard, Earth Surface Processes and Landforms, Vol.16, pp 427-445

Courture R, 2011, Landslide Terminology-National Technical Guidelines and Best Practices on Landslides. Geological Survey of Canada. p. 12.

Cruden D, 1991, A simple definition of a landslide. Bull-Int Assoc, Eng Geology; 43:27–29. doi: 10.1007/BF02590167

Champatiray P, 2000, Perationalization of cost-effective methodology for landslide hazard zonation using RS and GIS: IIRS initiative. In: Roy P, Van Westen C, Jha V, Lakhera R, editors. Natural Disasters and their mitigation; Remote Sensing and Geographical Information System Perspectives. Dehradun, India: Indian Institute of Remote Sensing; pp. 95–101

Champatiray P, Dimri S, Lakhera R, Sati S, 2007, Fuzzy based methods for landslide hazard assessment in active seismic zone of Himalaya. Landslides; 4:101–110. doi: 10.1007/s10346-006-0068-6

Conoscenti C, Di Maggio C, Rotigliano E., 2008, GIS analysis to assess landslide susceptibility in a fluvial basin of NW Sicily (Italy) Geophys J Roy Astron Soc.;94:325–339

Deoja BB, Dhital MR, Thapa B, Wagner A, 1999, Mountain risk engineering handbook. International Centre for Integrated Mountain Development (ICIMOD), Nepal, Kathmandu, p 875

Dahal PK, Dahal L, Khanal S, Poudel S, Khatiwada B, 2014, Environmental impact Assessment of Kathmandu Terai Fast-track, International Journal of Environment ISSN 2091-2854Volume-3, Issue-4, 2014, ISSN 2091-2854

Dahal RK, 2001, Use of Bioengineering in watershed management, Bulletin of Nepal Geological Society 19: 68–72.

Dahal RK , Hasegawa S, Nonomura A, Yamanaka M, Masuda T. , Nishino K, 2008, GIS-based weight-of-evidence modeling of rainfall induced landslides in small catchments for landslide susceptibility mapping, Environmental Geology 54 (2): 314-324, DOI: 10.1007/s00254-007-0818-3.

Dahal RK, Timilsina M, 2015, ILWIS Guidebook for Landslide Hazard Mapping

Dahal RK and Bhandary NP, 2013, Geo-Disaster and Its Mitigation in Nepal, F. Wang et al. (eds.), Progress of Geo-Disaster Mitigation Technology in Asia, Environmental Science and Engineering, DOI: 10.1007/978-3-642-29107-4_6

Dai FC, Lee CF, 2002, Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. Geomorphology 42:213–228

Eckhaut M, Reichenbach P, Guzzetti F, Rossi M, Poesen J, 2009, Combined landslide inventory and susceptibility assessment based on different mapping units: an example from the Flemi Ardennes, Belgium. Nat Hazards Earth Syst Sci. 9:507–521. doi: 10.5194/nhess-9-507-2009.

Ercanglu M, 2005, Landslide susceptibility assessment of SE Bartin (West Black Sea region, Turkey) by artificial neural networks. Nat Hazard Earth Syst Sci.;5:979–992. doi: 10.5194/nhess-5-979-2005

Florineth F, Rauch HP and Staffler HP, 2000, Stabilization of landslides with bio-engineering measures in South Tyrol/Italy and Thankot/Nepal. In: INTERPRAEVENT 2002 in the Pacific Rim, 2002, Matsumoto/Japan; Congress publication 2: 827–837.

Gokceoglu C, Aksoy H, 1996, Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques. Eng Geol 44:147–161

Gray DH, Leiser AT, 1982, Biotechnical slope protection and erosion control. Van Nostrand Reinhold, New York

Greenway DR, 1987, Vegetation and slope stability. In: Anderson MG, Richards KS (eds) Slope stability.Wiley, New York, pp 187–230

Gritzner ML, Marcus WA, Aspinall R, Custer SG, 2001, Assessing landslide potential using GIS, soil wetness modeling and topographic attributes, Payette River, Idaho. Geomorphology37:149–165

Guzzetti, F, Peruccacci S, Rossi M, and Stark CP, 2008, The rainfall intensity-duration control of shallow landslides and debris flows: an update, Landslides, 5(1), 3–17

Howell J, 1999. Roadside Bio-engineering, HMG Nepal, Department of Roads, Babar Mahal, Kathmandu, Nepal, Reference Manual 216p and Site Handbook 160p.

Himalayan Havoc, 2014, Sunkoshi landslide, Vol: 08 No. 5

International center for geohazards, 2010, Prevention and Mitigation, http://www.ngi.no/en/Geohazards/Research/Prevention-and-mitigation/

Iverson RM, 2000, Landslide triggering by rain infiltration, Water Resource. Res., 36(7), 1897–1910

Kanungo D, Arrora M, Sarkar S, Gupta R., 2009, Landslide Susceptibility Zonation (LSZ) mapping-a review. J South Asia Disaster Stud. 2:81–105.

Mann U, Pradhan B, Prechtel N, Buchroithner MF, 2012, Terrigenous Mass Movements Detection, Modelling, Early Warning and Mitigation Using Geoinformation Technology

Mohammadi M, 2008, Mass movement hazard analysis and presentation of suitable regional model using GIS (Case Study: A part of Haraz Watershed), M.Sc. Thesis, Tarbiat Modarres University International Campus, Iran, p 80

Mittal SK, Singh M, Kapur P, Sharma BK, Shamshi MA, 2008. Design and development of instrument network for landslide monitoring, an issue an early warning. Journal of Scientific &Industrial research 67,361–365.

Nefeslioglu HA, Duman TY, Durmaz S, 2008, Landslide susceptibility mapping for a part of tectonic Kelkit Valley (Eastern Black Sea region of Turkey). Geomorphology 94:401–418

Nepal B, Rao PJ, and Ho TV, 2015, Geographic information systems based landslide susceptibility index mapping using information value method – a case study of Sindhupalchok district, Nepal

Novotný J., 1978, VARNES LANDSLIDE CLASSIFICATION, Charles University in Prague, Faculty of Science, Czech Republic ARCADIS CZ a.s., division Geotechnika, Czech Republic

Pardeshi SD, Autade SE, and Pardeshi SS, 2013, Landslide hazard assessment: recent trends and techniques, Springerplus ; 2: 523. Published online 2013 October 17. doi: 10.1186/2193-1801-2-523

Petley D, 2012, Global patterns of loss of life from landslides, Geology, Vol. 40, No. 10, 927-930

Pourghasemi HR, Morad HR, Fatemi Aghda SM, Mahdavifar MR, Mohammdi M, 2009, Landslide Hazard Assessment Using Fuzzy Multi Criteria Decision- Making Method; Iranian Jornal of Watershed Management Science & Engineering, 3(8): 51-62

Pourghasemi HR, Pradhan B, Gokceoglu C and Moezzi KD, 2012, Landslide Susceptibility Mapping Using a Spatial Multi Criteria Evaluation Model at Haraz Watershed, Iran. In B. Pradhan and M. Buchroithner (eds.), Terrigenous Mass Movements, pp 23-49, Springer-Verla, Berlin Heidelberg

Sarkar S, Kanungo D, Patra A, Kumar P, 2006, Disaster mitigation of debris flows, slope failures and landslides. GIS based landslide susceptibility mapping- a case study in Indian Himalaya. Tokyo, Japan: Universal Academy Press; pp. 617–624

Shiwakoti DR, 2000, An assessment of soil loss and natural hazards in Nepal. J Nepal Geol Soc 21:41 – 48

Shrestha C.B., 2014, Kathmandu – Terai Fast Track: From Non-Starter To National Project, 25 January 2016, <http://www.spotlightnepal.com/News/Article/Kathmandu-Terai-Fast-Track>

Shrestha HK, 2014, Jure Landslide power point presentation, Nepal Engineering College

Transportation Research Board, 2012, Cost Effective and sustainable Road slope stabilization and Erosion Control, NCHRP synthesis 430

UN Office for the Coordination of Humanitarian Affairs, 2015, Landslides and Flash Floods in the Monsoon.

Upreti BN, 2010, Impact of natural disaster on development of Nepal, in Bhandary NP. Disasters and development, investing in sustainable development in Nepal, Ehime University, Japanand Bajra Publication Kathmandu, Nepal, Subedi JK (ed), pp 11–33

U.S. Geological Survey (USGS), 2004, Landslides Types and Processes, Fact sheet 2004-3072, U.S. Department of the Interior.

U.S. Geological Survey, 2015, Landslide 101, 9 February 2016, <http://landslides.usgs.gov/learn/ls101.php>

Van Western CJ, 1993, Application of geographic Information Systems to landslide hazard zonation, ITC publication, Vol. 15, Enschede, The Netherlands

Varnes, DJ, 1984, Landslide Hazard Zonation: A Review of Principles and Practice. Unesco, Paris.

Waltham T, 1996, Very large landslides in the Himalayas, Geol Today (Sep–Oct):181–185

Wieczorek GF., Mandrone G, DeCola L, 1997, The influence of hillslope shape on debris-flow initiation. In: Chen, C.L. (Ed.), Debris-flow hazards mitigation: mechanics, prediction, and assessment. American Society of Civil Engineers, New York, pp. 21 – 31.

Wilson JP, Gallant JC, 2000, Terrain analysis principles and applications. Wiley, New York