Areal distribution of large-scale landslides along highway corridors in central Nepal

Netra Prakash Bhandary

Graduate School of Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama 790-8577, Japan

Ryuichi Yatabe

Graduate School of Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama 790-8577, Japan

Ranjan Kumar Dahal

Department of Geology, Tri-Chandra Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal

Graduate School of Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama 790-8577, Japan

Shuichi Hasegawa

Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu 761-0396, Japan

Hideki Inagaki

Kankyo-Chishitsu Company, 203 Kaizuka 1-4-15, Kawasaki-ku, Kawasaki 210-0014, Japan

Corresponding author

Netra Prakash Bhandary, Graduate School of Science and Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama 790-8577, Japan, Tel/Fax: +81-89-927-8566

E-mail: netra@ehime-u.ac.jp

Cite this article as:

Bhandary N.P., Yatabe R., Dahal R.K., Hasegawa S., Inagaki H., 2013, Areal distribution of large-scale landslides along highway corridors in central Nepal, Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, DOI:10.1080/17499518.2012.743377, iFirst version

Areal distribution of large-scale landslides along highway corridors in central Nepal

Abstract

Landslides are the most frequent natural disaster in Nepal. As such, the scientific study of the Nepal landslides has been in progress for several years, but no significant achievement has been made in preventing landslides and mitigating disaster damage yet. As one important aspect of dealing with landslides is understanding their distribution pattern based on geological and geomorphological formations, this paper addresses these issues, and attempts to present a scenario of large-scale landslide distribution along the road corridors of major highways in central Nepal. As a result of landslide mapping using aerial photographs, topographical maps, and field verification, the following points were understood: 1) the distribution of large-scale landslides is relatively dense over the area close to tectonic thrusts, 2) slate and phyllite zones have a greater ratio of landslide distribution, and 3) topographies with a mean slope angle of about 27 to 36 degrees have denser distribution of large-scale landslides.

Keywords: Large-scale landslide, Landslide distribution, Lesser Himalayan Zone, Nepal landslides, roadside landslides, Siwalik Zone

1. Introduction

The geology of Nepal, a mountainous country occupying an 800 km long central part of the Himalayan arc (Fig. 1), is characterized by tectonic movement of the Indian plate underneath the Eurasian plate and has resulted in folds and faults with extensive fracture zones. This particular tectonic effect in the region is the sole cause of dynamic mountain building process, which has resulted in highly elevated, rugged, and fragile mountains in the Himalaya. Combination of this dynamic mountain building process and monsoonal heavy precipitations causes hundreds of destructive landslides and roadside slope collapses every year. These disaster events often cause enormous loss of lives and properties and also destroy national infrastructure mainly over the middle east-west strip of hills and mountains in Nepal. The available data indicate that the annual rate of human deaths in landslides and related disaster events still stands at over 300 (Shrestha et al. 2004). One of the most devastating landslide-related disasters in the recent past killed more than 1500 people in central Nepal in 1993. According to Bhattarai et al. (2002), a total of about 12,000 small- and large-scale landslides occur in Nepal every year, most of which often remain unnoticed and unreported mainly because of an inadequate information system, little economic impact, or little harm to humans and national infrastructure.

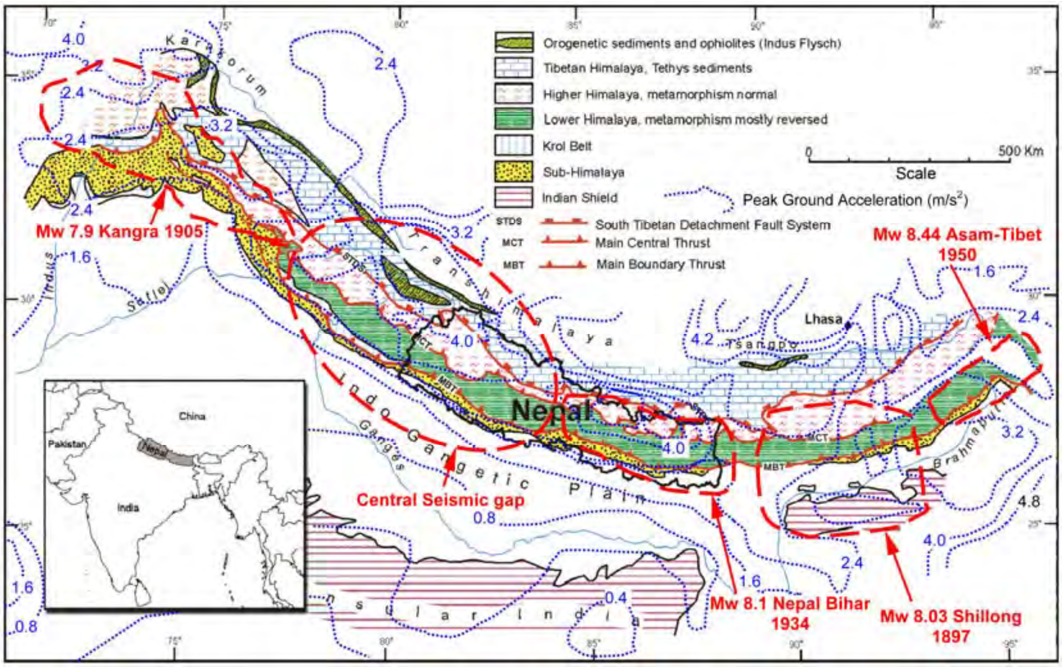

Figure1. Location of Nepal in the Himalaya along with major tectonic boundary and various longitudinal zones of the Himalaya (modified after Gansser 1964 and Upreti and Yoshida, 2005); Peak ground acceleration data adopted from Zhang et al. (1999). Seismicity of the region is also shown in the map and it shows that there is no great earthquake in central part since last 100 years, which is creating central seismic gap in the Himalayan region.

Despite having about 83% mountainous topography and failure-prone rugged and steep slopes, Nepal lacks a proper system to deal with landslide-related disasters. There also have been little efforts to identify landslide prone areas, and only a small area of the country has been mapped for landslide hazards.

Landslides in the Nepal Himalaya vary in size, from massive failures of whole mountain masses to very minor slope failures (Shroder and Bishop 1998; Higaki *et al.* 2000; Shang *et al*. 2003, Hasegawa *et al*. 2009). Several scientific studies have reported the basics of landslide mechanisms and processes in the Nepal Himalaya (e.g., Laban 1979, Selby 1988, Ives and Messerli 1981, Caine and Mool 1982, Wagner 1983, Heuberger *et al*. 1984, Keinholz *et al*. 1983, Keinholz *et al*. 1984, Dangol *et al*. 1993, Deoja *et al*. 1991, Dhital *et al*. 1991, Yagi and Nakamura 1995, Karmacharya *et al*. 1995; Burbank *et al*. 1996, Upreti and Dhital 1996, Wagner 1997, Sikrikar *et al*. 1998, Gerrard and Gardner 2000, Chalise and Khanal 2001, Yagi 2001; Dahal *et al*. 2006, Dahal and Hasegawa 2008, Dahal *et al*. 2008a, Dahal *et al*. 2008b. Poudyal *et al*. 2010, Ghimire *et al*. 2011). However, in most cases, they are found to have only addressed the issues of rain-induced, small-scale landslides and roadside slope collapses. There still is a great gap between the understandings of the mechanisms and processes of large-scale landslides and those of small-scale landslides in the Lesser Himalaya. By large-scale landslides, we refer in this paper to huge landmasses in natural slopes that might have moved long ago, in most cases from hundreds to thousands of years ago, and which still retain the original slope form without complete collapse as in ordinary rain-induced flow of soil mass. According to Varnes (1978) classification, the large-scale landslides we have considered here refer to rockmass creep, deep-seated soilmass creep, debris creep and all creep-related active landslides or relict landslide masses.

When landslides are talked of in Nepal, last three decades of landslide record reveals that road and human settlement slopes are more vulnerable to landslides than ordinary natural slopes. This suggests that there is significant influence of human intervention, particularly in terms of road slope cutting, land development, agricultural practices, etc., on the occurrence of landslides and related failures in Nepal. In most cases, the landslide events of remote areas remain unreported, whereas the landslides and slope collapses occurring alongside the important roads and highways have always drawn the greatest concern of the public as well as the government. There has been an average annual loss of about 788 million Nepalese rupees (equivalent to 11 million US dollars) in a period from 1983 to 2003 (DWIDP 2003), which primarily includes the cost of transport infrastructure (i.e., roads and bridges) destroyed in landslide and flood disasters (Note: the damage data only due to landslides are not available for this period in Nepal because the Nepal Government manages landslide and flood disaster data, especially the losses under the same category). This is a clear indication that the transport infrastructure in Nepal is heavily affected by landslide incidences every year. As a matter of fact, through a field survey conducted in 2003 in one of the arterial routes of Nepal (later in Section 5, referred to as Narayanghat-Mugling Highway), it was found that these small- to medium-scale roadside landslides very often occur as partial landslips within existing large-scale landslides in the area. Therefore, considering greater and effective serviceability of existing transport infrastructure, better planning of newer transportation routes, and safe land-use planning, it is very important to understand the distribution pattern of large-scale landslides so as to mitigate the risk of future infrastructure damage and economic losses. At the same time, it is also of significant importance to investigate the causal factors and characteristics of landslide failures in the Himalaya as one of the hotspots of landslide-related disasters.

In this context, this paper presents comprehensive information about the areal distribution of the large-scale landslides identified in the major highways running through river valleys of central Nepal. The main objectives of this study are: (1) exploring the distribution of active and relict landslides in failure-prone mountain slopes, (2) mapping of the large-scale landslides along the major highways, (3) evaluating distribution characteristics of the large-scale landslides along the highways and roads in central Nepal.

2. Study area

Three national highway routes of central Nepal were selected for this study (Fig. 2), namely, Prithivi Highway (H4), Tribhuvan Highway (H2) and Narayanghat-Mugling Road (H5), which are the busiest routes linking the capital city of Kathmandu with other national business and industrial centres. The present trend of prioritizing natural disasters in Nepal indicates that landslide occurrences along these highways are given extra importance due to greater economic loss and human suffering due to the roadside failures. The efforts of landslide mapping and distribution analysis in this paper are thus expected to help better plan the maintenance work of highway routes in the selected study area.

3. Geology, geomorphology and rainfall

Geologically and tectonically, Nepal is divided into five major tectonic zones, namely, Terai, Sub-Himalayan Zone (Siwaliks), Lesser Himalayan Zone, Higher Himalayan Zone, and Tibetan-Tethys Zone (Ganser 1964, Upreti 1999). These tectonic zones are separated by major thrusts and faults of the Himalaya, namely from north to south (Fig. 2), South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT). Brief information about the main rock types and geological age of each geological units of Nepal are provided in

Table 1.

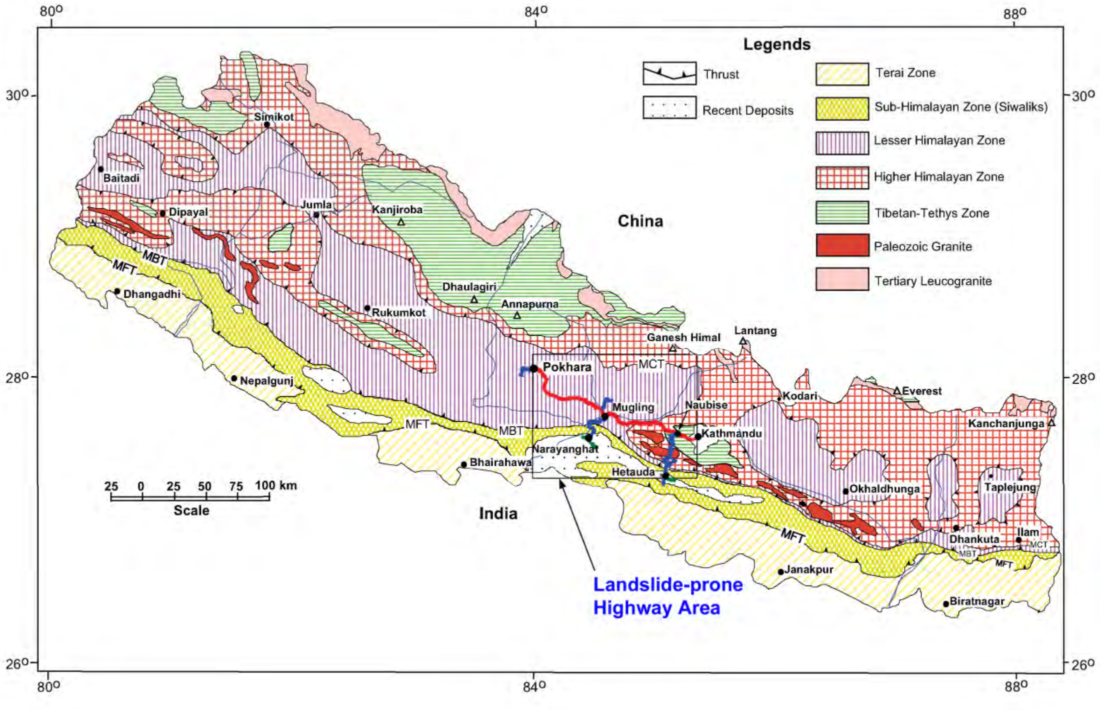

Figure 2. Selected road network for study and generalized geological map of Nepal (modified after Dahal 2006)

Geomorphologically, Nepal is divided into eight units running east-west (Table 1 and Fig. 3), namely, Terai, Churia Range, Dun Valleys, Mahabharat Range, Midland, Fore Himalaya, Higher Himalaya, Inner and Trans Himalaya (Hagen 1969, Upreti 1999). Basically, units such as Churia Range, Dun Valleys, Mahabharat Range, Midland, Fore Himalaya, Higher Himalaya, Inner and Trans Himalaya are characterized by the development of steep and rugged mountains due to very dynamic geological environment of the Himalaya. The topography of these units contributes significantly to the landslide disasters in Nepal and other parts of the Himalayas. The effective width of the mountainous part of Nepal is about 150 km while the difference in elevation between the highest and the lowest points is nearly 9 km. Owing to this extremely steep average gradient of the mountain lands, the rivers through mountains and hills in Nepal tend to flow much faster, which erode riverbeds and riverbanks at a greater rate and make the mountain slopes fail under comparatively less favourable conditions, such as even during less amount of rainfall or inadequate influence of intrinsic parameters. In addition, as the land gradient is high, the surface runoff following rainfall events flows faster and causes excessive gully formations , particularly over highly erosion-prone, exposed soft rock masses and soil deposits on the barren and rugged mountain slopes. These gullies, in a very short span of time, turn into deeper channels, which eventually aid to instability of the slope soil mass often leading to massive landslides.

Table 1. Geomorphologic units of Nepal and major geomorphologic evolution (modified after Dahal, 2006 and Hasegawa *et al*. 2009)

Geomorphic Units	Terai	Churia Range	Dun Valleys	Mahabharat Range	Midlands	Fore Himalaya	Higher Himalaya	Inner and Trans Himalaya
Width (km)	20-50	10-50	5-30	10-35	40-60	20-70	10-60	5-50
Altitudes (m)	100-200	200-1300	200-300	1000-3000	300-2000	2000-5000	>5000	2500-4500
Main Rock Types	Alluvium composed of coarse gravels in the north near the foot of the hills gradually fine sand and silt in south	Sandstone, mudstone, shale and conglomerate.	Valleys within the Churia Hills filled up by coarse to fine alluvial sediments	Schist, phyllite, gneiss, quartzite, granite and limestone belonging to the Lesser Himalayan Zone	Schist, phyllite, gneiss, quartzite, granite, limestone belonging to the Lesser Himalayan Zone	Gneisses, schists, phyllites and marbles belonging to the Lesser Himalayan Zone	Gneisses, schists, migmatites and marbles belonging to the Higher Himalayan Zone	Gneisses, schists and marbles of the Higher Himalayan Zone and limestone, shale and sandstone of the Tibetan-Tethyan Zone
Geological Age	Recent	Mid-Miocene to Pleistocene	Recent	Precambrian and Paleozoic and some Cenozoic	Precambrian and Paleozoic to Mesozoic	Precambrian	Precambrian	Precambrian and Cambrian to Cretaceous
Geomorphological processes	Deposition and erosion by rivers and tectonic upliftment	Tectonic upliftment, erosion, and small-scale landslides	River deposition, erosion and tectonic upliftment	Tectonic upliftment, weathering, erosion, and large-scale and small-scale landslides	Tectonic upliftment, weathering, erosion, and small-scale landslides	Tectonic upliftment, weathering, erosion, and large-scale and small-scale landslides	Tectonic upliftment, weathering, erosion (rivers and glaciers), and large-scale landslidese	Tectonic upliftment, wind and glacial erosion, and slope degradation by rock disintegrations, large-scale and small-scale landslides

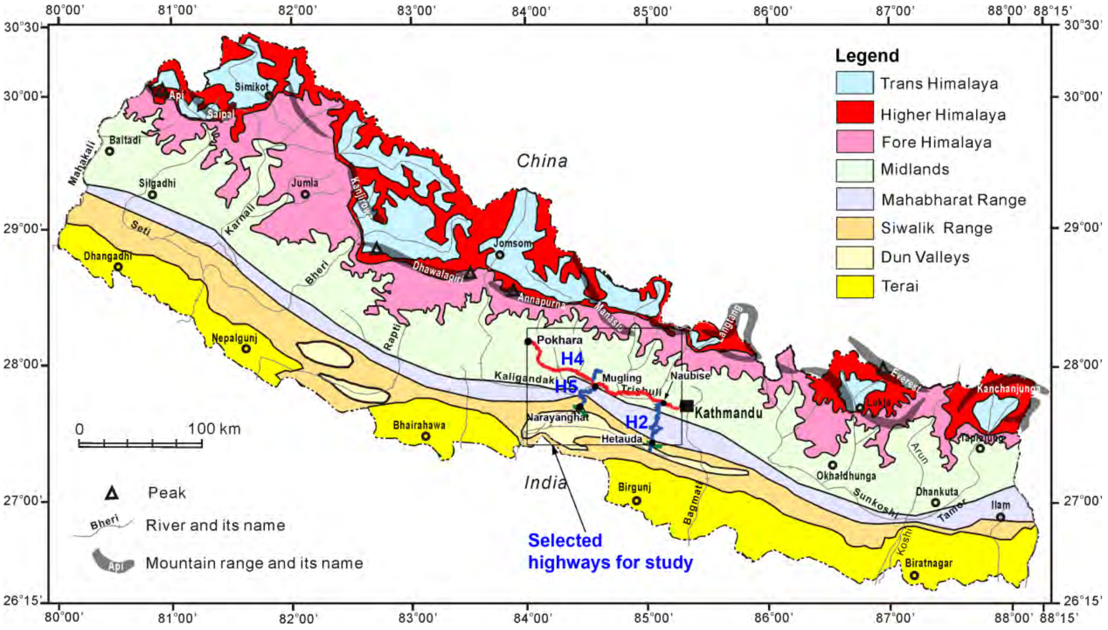

Figure 3. Geomorphological map of Nepal (modified after Dahal 2006 and Hasegawa *et al*. 2009)

The geomorphic and tectonic history of the Nepal Himalaya largely supports the occurrence of deep and steep river valleys in central Nepal (*Hasegawa et al*. 2009). These valleys consist of many large-scale landslides, but without adequate geological survey, they have been extensively used to build roads over to connect the capital city of Kathmandu with other important places such as by constructing the national highway routes H2, H4 and H5 and.

The extremely non-uniform rainfall pattern is also considered one of the major triggering agents of landslide-related disasters in Nepal. The rainfall pattern is highly heterogeneous, temporally as well as spatially. The annual amount of precipitation, 80% of which takes place in a period of about four months from mid May to mid September, varies from less than 250 mm in the north of the Himalayan Range to around 6,000 mm at Lumle in central Nepal. From the map of distribution of maximum 24-hour precipitation in Nepal (Fig 4), it is clear that the areas of highway routes H2, H4 and H5 receive 200 mm to 300 mm of maximum daily precipitation. Karmacharya (1989) studiedthe relationship between total annual precipitation and the frequency of landslide events in Nepal during a period between 1971 and 1980 through a spatial distribution analysis, and found that the landslide frequency is high in high annual precipitation zones . Mainly in central Nepal, the area between Okhaldhunga (in east) and Pokhara (in west) is having higher amount of rainfall-induced landslides than other part of country. The maximum 24-hour daily rainfall map (Fig 4) also suggests higher concentration of rainfall in that area. Dahal and Hasegawa (2008) have established an empirical rainfall threshold of landslides for the Nepal Himalaya and found that if daily rainfall exceeds 144 mm, small-scale or shallow-seated landslides, which generally refer to failure of weathered slope material over hard or soft bedrock mass, may occur in the Nepal Himalaya.

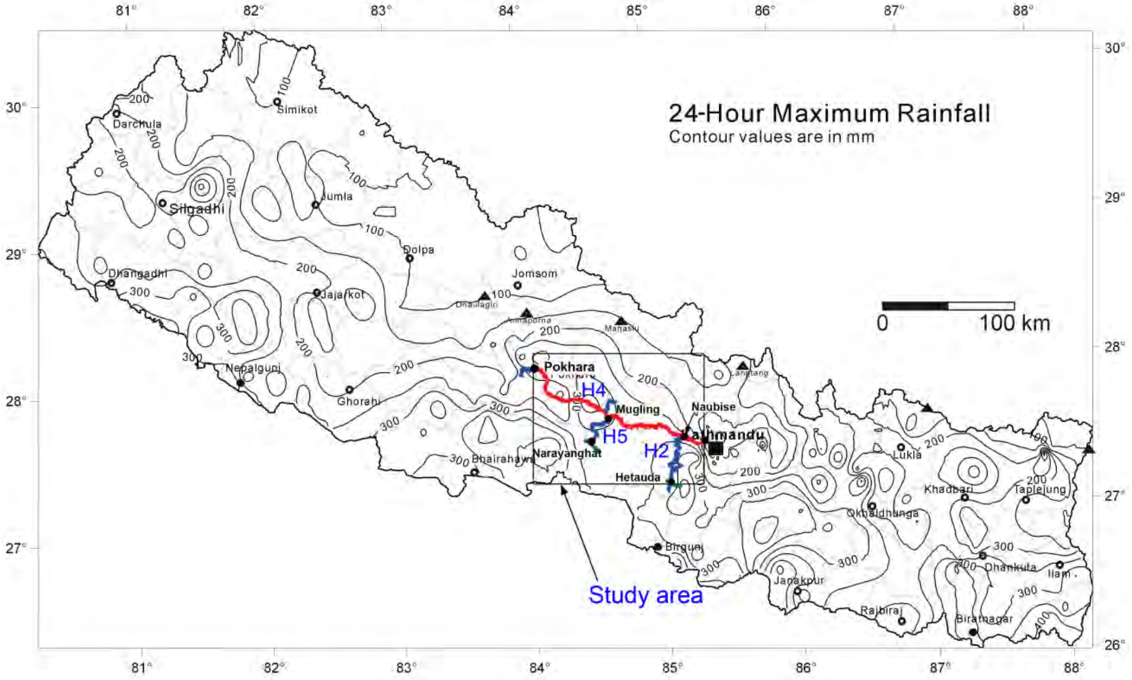

Figure 4. 24-hour maximum rainfall map of Nepal (Data source: Department of hydrology and Meteorology, Government of Nepal).

4. Large-scale landslides in Nepal

Landslides are not only a significant natural disaster but they also contribute to the geomorphic reshaping of the mountain landscape. There are various definitions of landslides, but in general, a landslide is the movement of rock, detritus, or soils caused by the action of gravity. Most frequent landslides are small in size and the failure surface is usually shallow. However, when large mountain slopes are investigated, slow-moving creep-like landslide masses can be found very commonly, which we refer to here in this paper as large-scale landslides. Such landslides have a long history of occurrence, and they generally affect the river courses and influence the activity and livelihood of local communities. A large-scale landslide may potentially provoke terrible disasters, and also change the geomorphologic setting of several square kilometres of mountains. In many cases, large-scale landslides possess very slow movements (e.g., a few to few tens of centimetres a year), and specialised instruments, such as inclinometers, extensometers, GPS installations, etc. may be necessary to understand that they are in fact moving.

When discussing large-scale landslides in the Nepal Himalaya, we come across steep slopes as the key features of the Himalayan geomorphology. Rapid upliftment from Miocene, which continues even today, has created local relief measurable in kilometres from river valleys to mountain peaks. As a result, large-scale valley slope creeping (i.e., large-scale landslides) have been ongoing probably since the early upliftment of the mountains, which is a common process in the Nepal Himalaya. In fact, large-scale landslides are one end of the spectrum of slope modification processes in the Himalayan region (Hasegawa *et al.* 2009). In the Nepal Himalaya also, landslides contribute significantly to the geomorphic evolution of the natural environment over a long time span, as a slope is further steepened by tectonic upliftment or river and glacial erosion, the resulting instability will lead to gravitational redistribution of rock or soil mass in the form of a large-scale landslide to form a gentler terrain. A typical view of large-scale landslide terrain alongside a road or river in the Nepal Himalaya is illustrated in Fig. 5. As seen in this figure, most roads in Nepal that run through river valleys are built frequently over the large-scale landslide toes, which sometimes have also reactivated some relict large-scale landslide masses. It is however important to understand here that the road building process as a human intervention is not supposed to induce these types of landslides. In fact, the large-scale landslides in Nepal can be found to have gone through various stages of geomorphological evolution. A large-scale landslide mass usually has small-scale slope failures and incised drainages near the toe where road construction is practiced without adequately considering the consequences of possible reactivation of the relict landslide mass or the possibility of frequent slope collapses, as shown in Fig 5. These roads usually have low-cost mitigation measures on the cut slopes, such as vegetation with surface drainage system (i.e., bio-engineering), stone masonry retaining walls, gabion walls, etc., which prove to be very ineffective mainly due to the creeping displacement of large-scale landslide masses.

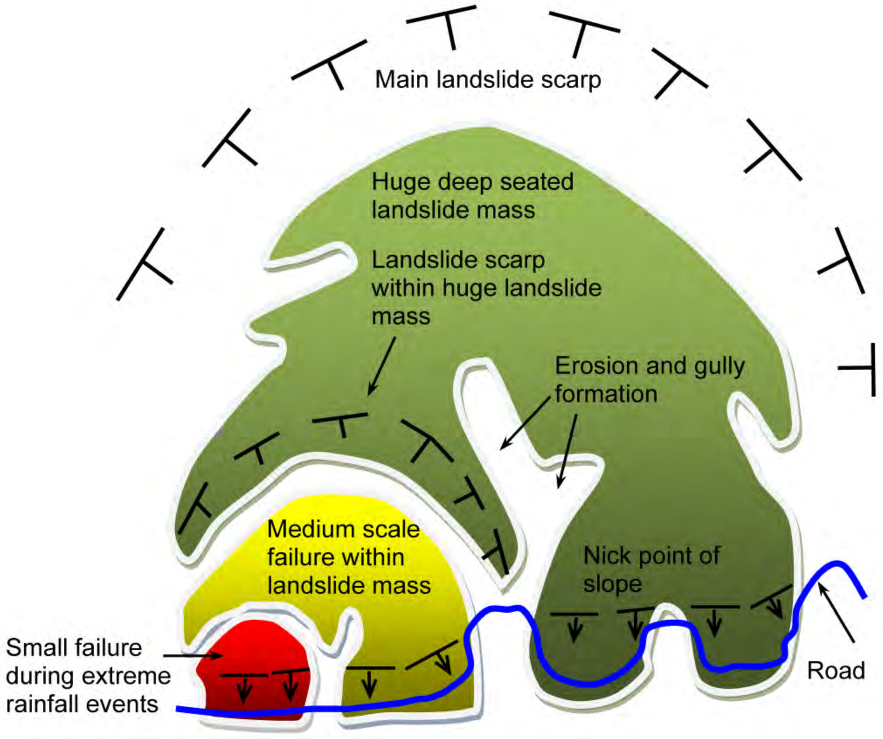

Figure 5. Model of large-scale landslide terrain in the Nepal Himalaya. The major highways, H2, H4 and H5 are constructed on the toe part (modified after *Hasegawa et al*. 2009).

Yagi and Nakamura (1995), upon analyzing large-scale landslides in an 85×75 km area peripheral to Kathmandu valley mainly on the west in the Lesser Himalayan Zone using aerial photographs taken in 1954 (1:30,000 and 1:60,000), have found the effects of relief and rock types on the process of landslide occurrence. They have calculated the mean landslide area ratio to be 6.61% of the total area mapped with greater values over phyllitic and faulted quartzite zones and smaller values over granitic and quartzite zones. They conclude that the landslide distribution ratios are relatively low in granite, quartzite, and limestone zones but high in pelitic rock zones such as phyllite, slate, metasandstone, and gneissose rock. Occurrence of large-scale landslides is particularly associated with clay mineralization in the slip surfaces, and pelitic rocks, due to their foliated structures, have a greater tendency to decompose through the foliation planes, especially when they are in a fault zone leading to accelerated clay mineralization. Hence, the finding of Yagi and Nakamura (1995) also reveals the importance of studying the large-scale landslides in central Nepal.

5. Methodology

With an aim to explore the distribution of large-scale landslides along the major highways in central Nepal, the following methods were adopted in obtaining necessary data and their analysis.

5.1 Landslide mapping

As stated in the previous section, this study was carried out over the road corridor sections of Prithvi Highway, Narayanghat-Mugling Road, and Tribhuvan Highway in central Nepal. Almost all sections of the Prithivi Highway and the Narayanghat-Mugling Road run parallel with the rivers, whereas a greater part of the Tribhuvan Highway runs through mountain ridges making the roadside slopes comparatively small.

An index map of the landslide study area through the highways of interest is shown in Fig. 6. The study area was demarcated as a 3-km strip along the highways, mainly on the highway side of the mountains (2 km on the highway side and 1 km on the riverside for Prithvi Highway and Narayanghat-Mugling Highway; 1.5 km on either side for Tribhuvan Highway). The total length of the Prithvi Highway covered in this study is about 95 km, which extends from Naubise to just beyond Mugling (Fig. 6). The portion covered of the Narayanghat-Mugling Highway is from Mugling to about 9 km ahead of Narayanghat measuring 27 km, and that covered of the Tribhuvan Highway is from Kathmandu to Hetauda measuring 111 km (Fig. 6).

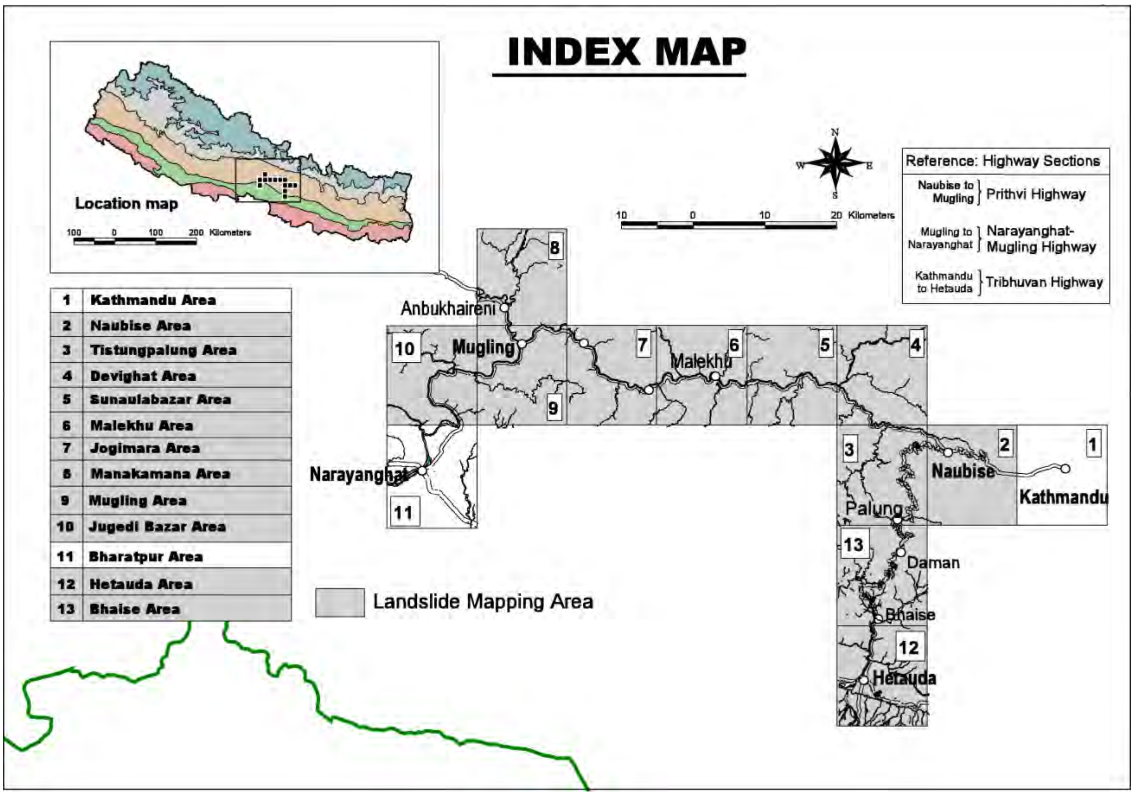

Figure 6. Index map of the investigation area (Highway sections).

The landslide mapping area was divided into several sections along the highways, based on the available topographic maps, for the purpose of making the mapping reference easy, as indicated in Fig. 6. One divided section approximately measures 12.5 ×14 km, and there are altogether 11 sections, of which two sections are common to Prithvi Highway and Tribhuvan Highway and one is common to Prithvi Highway and Narayanghat-Mugling Highway. The Prithvi Highway was divided into 8 mapping sections, while the Tribhuvan Highway and the Narayanghat-Mugling Road were divided into 4 and 2 mapping sections respectively.

In this particular study, the term ‘landslide mapping’ is referred to as being location-based, indicating that it only considers the location of large-scale landslides, which are identified by the conventional method of reading stereo-pairs of aerial photographs and marking the landslide areas on topographic maps involving mainly the following steps.

(1) Reading stereo pairs of aerial maps (with the help of stereoscopes).

(2) Identifying large-scale landslide topographies by 3-D viewing of aerial photographs, especially for landslides larger than 0.01 km^2, which was restricted

by the scale of aerial photographs(1:50,000). This is based on expert decision, in which the landslides are identified on the aerial photos through the observed difference in topographic features of landslides and adjacent area, particularly the change in gradient of slope.

(3) Identifying the state of other hazardous areas, such as old landslide deposits, talus deposits, terrace deposits, colluvial deposits, alluvial fans, etc. although these areas were not considered in the landslide distribution analysis.

(4) Plotting the landslide size and shape on topographic maps based on the aerial photograph interpretation.

(5) Field verification of the landslides.

(6) Field-based mapping, especially for small-scale failure sites and unprotected slopes including locations at the risk of rockfall

(7) Digitizing the landslide map using ArcGIS, a commercially available software, together with estimating the landslide area and slope properties.

There are various methods of presenting landslide distribution data, which may include 1) number of landslides per unit mapping area, 2) number of landslides per unit length of road or stream/river, 3) ratio of landslide area to the watershed area, 4) ratio of landslide area to the mapping area, etc. As the work in this paper focuses on landslide mapping and areal distribution analysis (Westen *et al.* 2010, Hasi *et al*. 2010, Xu *et al*. 2011) along the highway corridors, the landslide distribution data has been presented in terms of the ratio of landslide area to the highway corridor area. Analysis in terms of the number of landslides per unit area also helps to quickly and easily understand the distribution pattern. However, the difficulty in judging the number of large-scale landslides, particularly because in most cases, they may or may not be the combination of different stages of landslidings has led to areal distribution analysis being adopted in this paper.

5.2 Geological and geomorphological study

The geological field study was conducted from 2003 to 2006, and all geology- and geomorphology-related information along the highway corridors were collected in the field. Available geological and topographical maps (modified after Stöcklin and Bhattarai 1982) were also extensively referred to in the study.

6. Findings of field and desk studies

6.1 Landslide mapping and field status

The landslide maps produced from the desk and field studies are shown in Fig. 7, Fig. 8, Fig. 9 and Fig. 10. Fig. 7 presents an overall pictorial distribution of landslides along the highway corridors in discussion, while Fig. 8 through Fig. 10 present the enlarged views of the landslide maps over the highway sections. The active and relict landslides (indicated by red ovules) and the debris deposits, terrace deposits, and talus deposits (indicated by red-spotted ovules/areas) along the Prithvi Highway corridor are shown in Fig. 8. Similarly, these marked areas along the Narayanghat-Mugling Road corridor and the Tribhuvan Highway corridor are shown in Fig. 9 and Fig. 10, respectively.

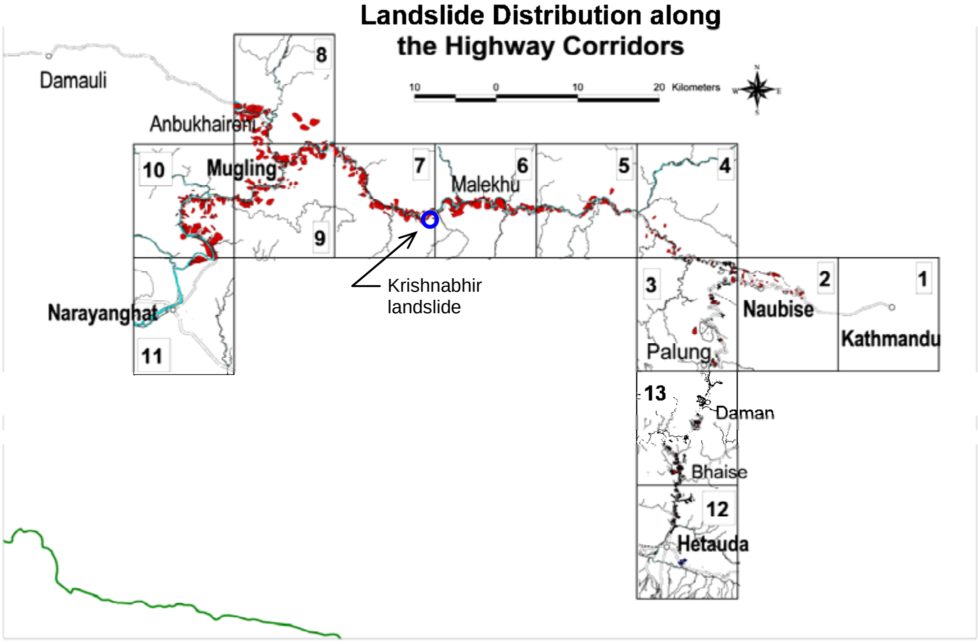

Figure 7. Index map of the investigation area (Highway sections).

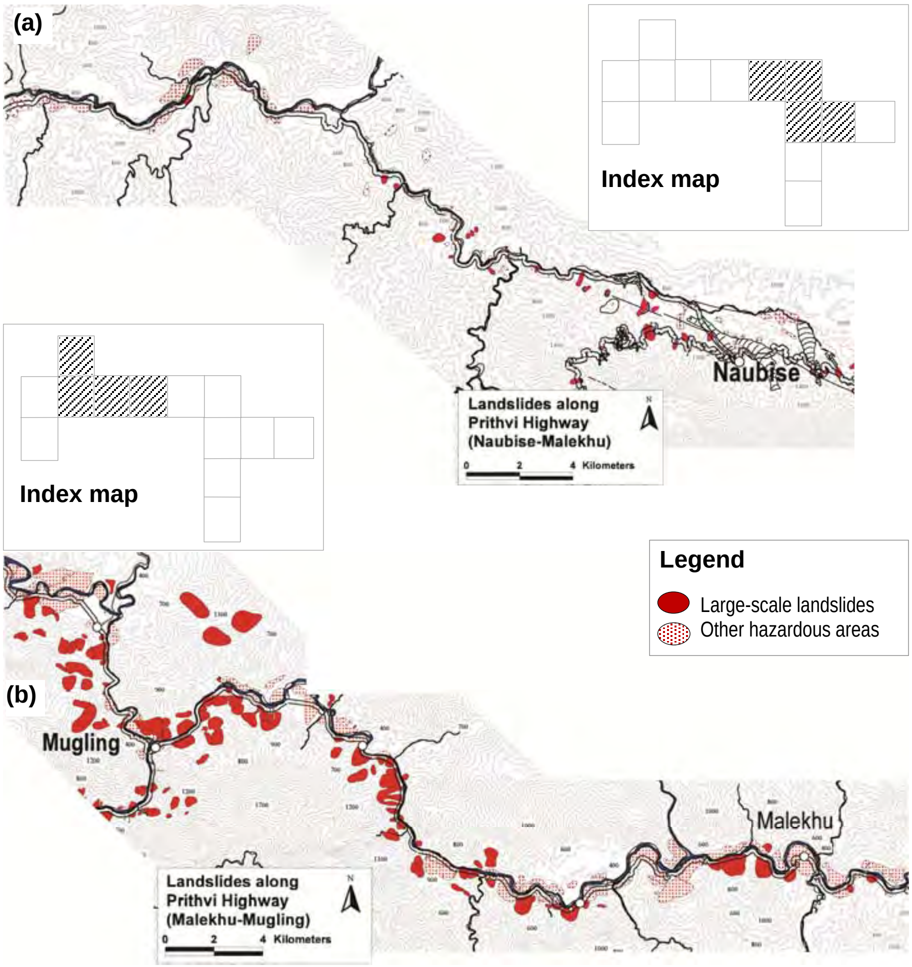

Figure 8. Landslide mapping of Prithvi Highway corridor in (a) Naubise-Malekhu section and (b) Malekhu-Mugling section

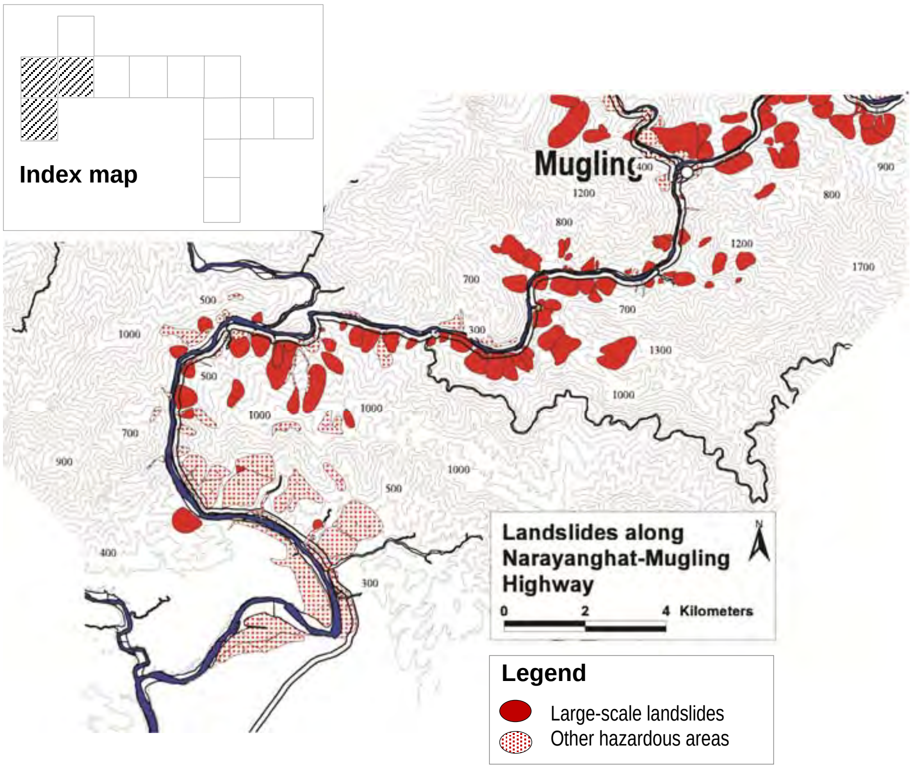

Figure 9. Landslide mapping of Narayanghat-Mugling Highway corridor (27 km section from Mugling)

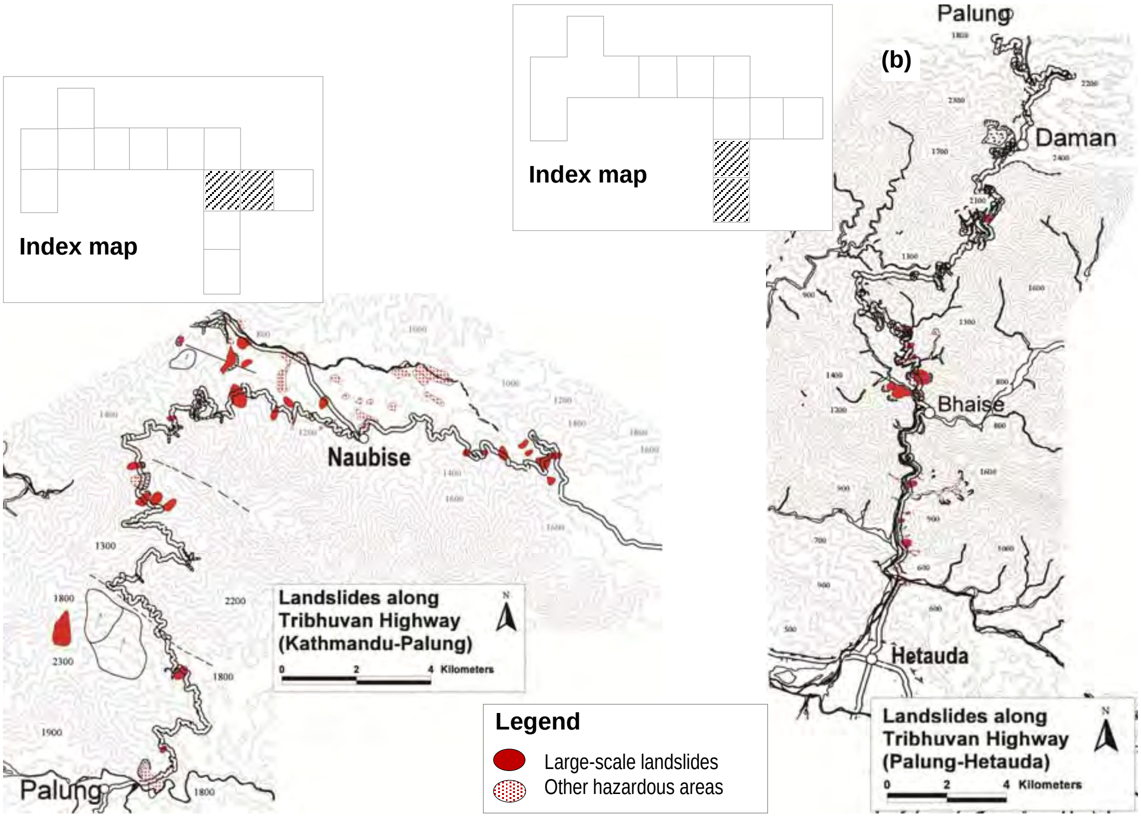

Figure 10. Landslide mapping of Tribhuvan Highway corridor in (a) Kathmandu-Palung section and (b) Palung-Hetauda section

After the reconstruction of Prithvi Highway in 1992, the continuous heavy monsoonal rainfalls of 1993 caused tremendous landsliding at several locations in the highway corridor, severely damaging the highway and closing it for several days. In 2003, nearly 40% length of the Narayanghat-Mugling Highway was damaged by debris flows (i.e., slope collapses occurred away from the road, but the debris mass damaged the road and bridges) and landslides (i.e., roadside slope collapses) induced by heavily concentrated rainfall exceeding 400 mm a day. Likewise, the Tribhuvan Highway mostly because of little maintenance and repair work extensively suffers every year from slope and rockmass failures at many locations.

As of November 2004, the condition of Prithvi Highway and Narayanghat-Mugling Highway had been very poor due to a number of slope failure sites and landslide deposits. The problem of Krishnabhir landslide (Fig. 11), which has been reported several times in various national and international publications, has remained almost unaltered except for the reduction in the amount of new debris deposits due mainly to natural stabilization of the failed debris and complete failure of all unstable slope masses. Efforts of the Department of Roads, particularly by applying vegetation and surface drainage system, however, have reduced the chance of its further failure. A number of other places along the highway can also be observed to have been hazardous due to unprotected rockmass failures, creeping landslide-caused road level subsidence, river cutting failures, etc.

Figure 11. Krishnabhir landslide in 2004

Similarly, the Narayanghat-Mugling Road was completely damaged as of the end of 2004. The highway sections at different locations were destroyed by the slope collapses, and at many locations the road surface was covered by landslide deposits and a number of road sections were also bottlenecked by riverside slope failures.

The condition of Tribhuvan Highway as of the same period was the worst with many sections narrowed and covered by landslide masses from the roadside slopes including a few sections of landslide deposit and complete failure of the road sections and retaining structures.

6.2 Geological and geomorphological findings

A geological map of central Nepal with superimposed sections of Prithvi Highway, Narayanghat-Mugling Highway, and Tribhuvan Highway is presented in Fig. 12. The entire length of the Prithvi Highway runs over hills, valleys, and alluvial deposits in the midlands of the Lesser Himalayan Zone, which vary in altitude from 200 to 2000 m and have an average width of 60 km. Main rock types found in this area are schist, phyllite, gneiss, quartzite, granite, and limestone. In most instances, these rocks, particularly schist, phyllite, and quartzite are found to have been heavily decomposed on the surface forming thick layers of soil material on the hill slopes, which are particularly prone to shallow landslide failures, especially in deforested areas. Moreover, the tectonic activity and its consequences in upliftment and mountain building process have largely given rise to a fractured state of bedrock in the hill slopes in proximity to thrust faults, which is likely to be the most important factor for the aggravated state of weathering in the Lesser Himalayan mountains.

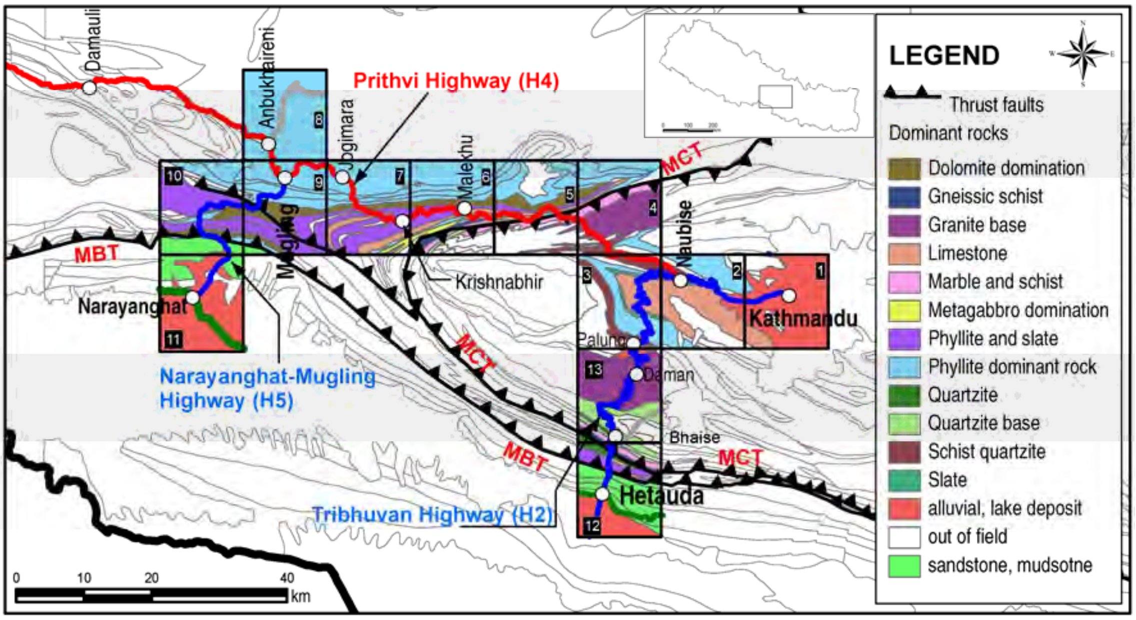

Figure 12. Geological map of the highway areas (modified after Stöcklin and Bhattarai 1982)

Similarly, the Narayanghat-Mugling Highway runs across the Siwalik Zone and Mahabharat Range in the Lesser Himalayan Zone to meet the Prithvi Highway at Mugling and intercepts one of the major tectonic thrusts, the MBT, at about 22 km south of Mugling. The Siwalik Zone is made up of geologically young sedimentary rocks including mudstones, siltstones, sandstones, shale, and conglomerates, which in general are soft and loosely packed having greater tendency for rapid disintegration. The conglomerates in the Siwalik Range are particularly loose and fragile because of low extent of consolidation. Likewise, the mudstones are often expansive in nature and behave plastically when saturated, and the sandstones are poorly compacted and weakly cemented, thus being prone to rapid weathering. In addition, these formations are often jointed, faulted, and folded, and consist of a number of east-west active faults locally.

The Tribhuvan Highway passes across Mahabharat Mountains in the Lesser Himalayan Zone and the Siwalik Mountains. It transects nearly 14 geological formations, dominantly represented by dark argillaceous, marly slates, metasandstones, siltstones, phyllites, granites, limestones, fine-crystalline, quartzite in the Lesser Himalayan Zone including molassic sandstones, mudstones, and conglomerates of the Siwalik group

(Stöcklin and Bhattarai, 1982). This highway intercepts both main boundary thrust (MBT) and main central thrust (MCT) that run almost parallel to each other with a close separation of about 4 km and are situated about 5 km north of Hetauda (Fig. 12). All this has resulted in weak geological condition, mainly because of closely running thrust lines, which has made the Tribhuvan Highway slopes near the thrust lines comparatively vulnerable to landslide problems.

7. Areal distribution of landslides

Fig. 7 reveals that the density of identified landslides in the highway corridors is much higher for the sections 6 through 10 than the sections 2 through 5, 12, and 13. Particularly, the sections 7, 9, and 10 appear to have greater landslide susceptibility, whereas the sections 2, 3, 4, and 5 possess the least number of landslides, and the average size is much smaller than the landslide size in the sections 7 to 10. A similar comparison can be also made in Fig. 8 through Fig. 10 and the difference can be clearly observed. These differences in distribution patterns and landslide scales can be attributed mainly to dissimilar geological and geomorphological features of the areas considered

Table 2 summarizes the results of landslide mapping in terms of projected landslide area ratio (i.e., the total area of landslides divided by the highway corridor area in a particular mapping section) in each highway corridor section considered and slope property analysis .

Table 2. Landslide distribution in the highway corridor sections along with geological and geomorphological information .

Highway	Section	Dominant Rock Types	Section Length (m)	Area Considered* (km^2)	Total Landslide Area (km^2)	Projected Areal Ratio (%)	Slope Inclination Properties (Based on 50x50m mesh calculations)				
							Minimum (degrees)	Maximum (degrees)	Mean (degrees)	Standard Deviation	% Error of Mean**
Prithvi Highway	2	quartzite schist, micaceous quartz	4070.06	12.210	0.060	0.49	0.00	78.81	21.43	14.64	68.32
	3	quartzite schist, micaceous quartz	7230.28	21.691	0.487	2.24	0.00	75.40	23.91	15.64	65.41
	4	granitic gneiss, schist quartzite	10993.16	32.979	0.346	1.05	0.00	70.51	25.56	13.15	51.45
	5	phyllite, tuffaceous, marble, limestone	15522.95	46.569	0.073	0.16	0.00	75.73	24.73	15.49	62.64
	6	slate, phyllite, tuffaceous, limestone	17263.34	51.790	1.888	3.65	0.00	79.49	27.08	15.99	59.05
	7	slate, phyllite, phyllitic quartzite, conglomerate	18329.86	54.990	4.064	7.39	0.00	79.18	31.20	15.01	48.11
	8	phyllite, quartzite, conglomerate	10224.47	30.673	3.429	11.18	0.00	76.57	27.45	15.45	56.28
	9	phyllite, quartzite, conglomerate	10693.54	32.081	5.518	17.20	0.00	83.27	32.77	15.42	47.06
		Total	94327.66	282.983	15.864	5.61					
Narayanghat-Mugling Highway	9	phyllite, limestone, quartzite, dolomite	10275.21	30.826	5.364	17.40	0.00	82.10	35.98	15.38	42.75
	10	slate, phyllite, quartzite, dolomite, sandstone, mudstone	16758.25	50.275	3.954	7.86	0.00	78.71	30.50	15.95	52.30
		Total	27033.46	81.100	9.318	11.49					
Tribhuvan Highway	2	metasandstone, siltstone, phyllite	22290.48	66.871	0.461	0.69	0.00	78.81	21.43	14.64	68.32
	3	limestone, metasandstone, argillaceous, slate, phyllite, schist-quartzite	33981.49	101.944	1.018	1.00	0.00	79.18	27.74	15.55	56.06
	13	tourmaline granite, micaceous quartzite	46306.62	138.920	0.737	0.53	0.00	82.10	30.65	14.96	48.81
	12	marble, schist, quartzite, slate, phyllite, sandstone, mudstone	8448.00	25.344	0.179	0.71	0.00	72.71	26.82	16.14	60.18
		Total	111026.59	333.080	2.395	0.719					
High landslide density area (overall)	7	slate, phyllite, phyllitic quartzite, conglomerate	-	172.360	9.210	5.343	0.00	89.98	31.89	14.93	46.82
	9	phyllite, limestone, quartzite, dolomite	-	172.360	21.281	12.347	0.00	89.85	33.73	15.94	47.26
	10	slate, phyllite, quartzite, dolomite, sandstone, mudstone	-	172.360	6.681	3.876	0.00	86.66	28.41	17.01	59.87
		Total		517.080	37.172	7.189					
High landslide density area (excluding road corridor)	7	slate, phyllite, phyllitic quartzite, conglomerate	-	117.370	5.146	4.385	0.00	81.24	33.92	14.56	42.92
	9	phyllite, limestone, quartzite, dolomite	-	109.454	10.399	9.501	0.00	83.10	32.87	16.34	49.71
	10	slate, phyllite, quartzite, dolomite, sandstone, mudstone	-	122.085	2.727	2.234	0.00	88.31	27.24	17.43	63.99
		Total		348.909	18.273	5.237					

*Highway Corridor Area = Section Length x Average Corridor Width (i.e., 3 km)

**% Error of Mean = 100x(Standard Deviation/Mean)

The landslide area ratio (i.e., projected areal ratio) in Table 2 only includes large-scale landslides as identified in Fig. 8 through Fig 10. In order to investigate the influence of topographical features on the landslide distribution, a simple GIS technique was applied for extracting mean slope angle and its correlation with the landslide distribution ratio in the study area considering a pixel size of 50x50m. The results obtained out of this are summarized in Table 2 in terms of minimum, maximum, and mean slope angles together with the standard deviation and percent error of mean (i.e., percentage of standard deviation with respect to the mean). A greater value of standard deviation refers to greater deviation of most slope angles from the mean value, while a lower percentage of error of mean indicates that most slope angles in the area considered are closely clustered around the mean value. As the standard deviation for all sections is between 13.1 and 17.4, the mean slope angle in all sections is considered to be representative of the dominant slope angle in the area considered.

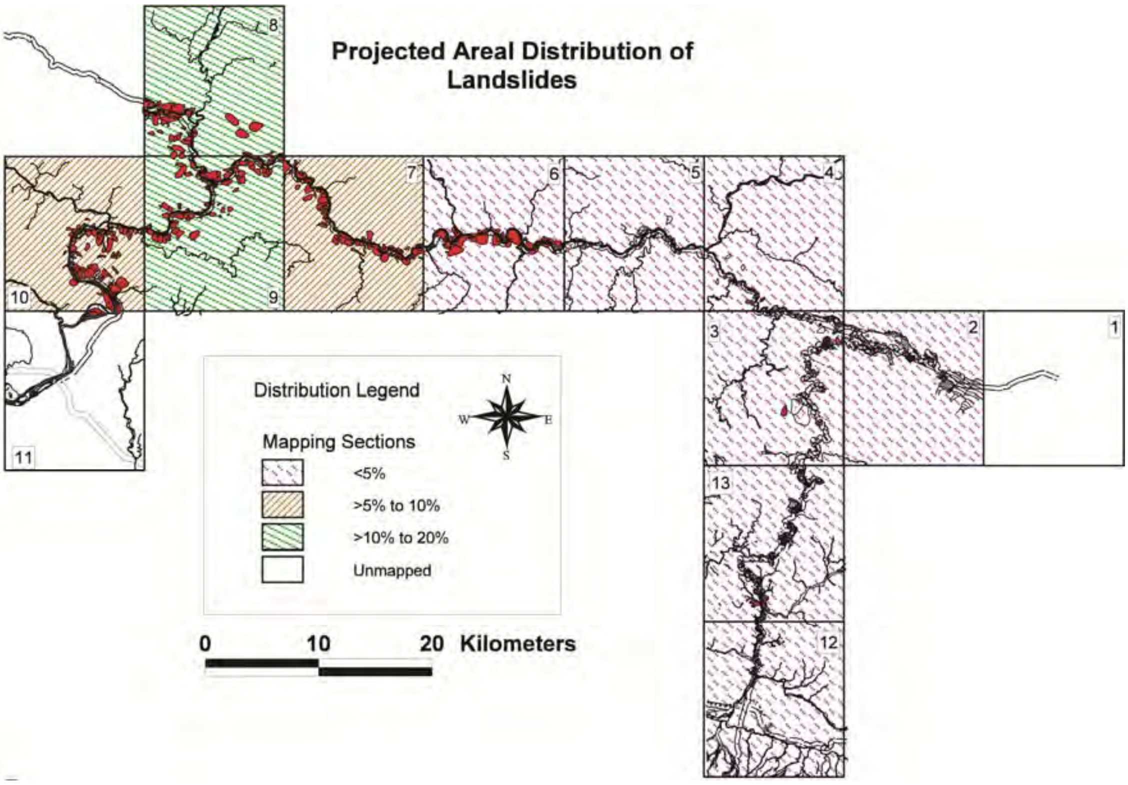

Figure 13. Areal distribution of landslides over the highway sections

Fig. 13 is prepared from the values of landslide area ratio in each section considered, as listed in Table 2. For a categorical perception, the distribution pattern is divided into three classes: less than 5%, 5% to 10%, and 10% to 20%. As seen in the figure, the Naubise-Malekhu section (i.e., section 2 through 6) of the Prithvi Highway and Naubise-Hetauda section (i.e., sections 2, 3, 13, and 12) of the Tribhuvan Highway have less than 5% areal distribution of landslides. Section 7 in the Malekhu-Mugling stretch (Fig. 8) of the Prithvi Highway, however, exceeds 5% areal distribution, and sections 8 and 9 in the same stretch exceed 10%. Similarly, section 9 of the Narayanghat-Mugling Highway reaches nearly 20%, while section 10 remains below 10%. Analysis of such a landslide distribution pattern in geologically and geomorphologically different areas may reveal the causal factors of large-scale landslides in the Lesser Himalayan Zone and the Siwalik Mountains of Nepal.

By reviewing the geological formations corresponding to higher values of landslide distribution ratio in Table 2, it is noted that most of these sections are dominated by slates and phyllites with occasional presence of schist and gneiss, particularly through the sections of Prithvi Highway and Narayanghat-Mugling Highway. Likewise, the rock types corresponding to a lower value of landslide distribution ratio are quartzites and granites. For instance, section 4 of Prithvi Highway and section 13 of Tribhuvan Highway mainly consist of granitic formations, and the areal distribution of landslides in these sections is well below 1%. Similarly, the areas of quartzitic schist, phyllitic quartz, metasandstone, marble, schist, etc., such as sections 2, and 3 of Prithvi Highway and sections 2, 3, and 12 of Tribhuvan Highway, have less than 3% landslide area ratio. There is however a slight variation of landslide distribution pattern even in slate and phyllitic zones, such as sections 5 and 6 of Prithvi Highway, which may be due to greater influence of other factors, such as geomorphological conditions and orientation of schistocity, which when in critical state, i.e., critical slope inclination or orientation of schistocity towards the direction of slope, may be more dominant.

Slates and phyllites as such are from the same sedimentary origin but differ in degree of metamorphism. The origin of both these rock types including other similar metamorphic rocks such as schist and gneiss is shale (mudstone as sedimentary deposit), and the change according to the extent of metamorphic process takes place in an order of shale-slate-phyllite-schist-gneiss from comparatively stable to comparatively unstable chemical structure . Slates and phyllites fall under foliated structure of metamorphic rocks with fine-grained slaty cleavage, which upon undergoing chemical weathering exhibit little resistance to shear stresses. This particular process through a certain span of time may lead to landsliding in slate and phyllite zones. So, like other previous investigations, such as Yagi and Nakamura (1995), this study also leads to a conclusion that most landslides in Lesser Himalayan Zone, particularly in the highway corridors of central Nepal, have occurred in phyllite and slate zones with comparatively less occurrence in the areas of schist. The quartzitic and granitic zones also have landslides but there is a marked noticeable difference in the scale and number of landslides, which is probably due to the difference in mineralogical composition and lack of schistocity. However, depending upon many other factors, such as the passage of thrust faults, presence of local faults, orientation of schistocity, etc., the landslide distribution pattern may be different. For example, in areas close to thrust-faults zones, such as sections 9, 10 (Fig. 7, Fig. 12, Table 2), the landslide distribution ratio is high. As also mentioned in Hasegawa *et al.* (2008), the rocks in close proximity of thrusts and faults and particularly along the axis of folds are weak and prone to weathering. On the other hand, despite lying in the interception zone of the major thrusts, sections 5, 6, and 12 have significantly small values of landslide distribution ratio. This indicates that thrust-fault proximity and rock type (i.e., phyllite and slate in this study) cannot always be dominant as landslide causal factors. A close look at the photogeological map (scale 1:100,000) of central Nepal (Stöcklin and Bhattarai 1982) reveals that the rockmass discontinuities in sections 5 and 6 dip into the slope, making the slopes comparatively stable , while in sections 9 and 10, they dip more or less towards the direction of slope (i.e., kinematic instability condition), making the slopes comparatively unstable . In case of section 12, the highway mostly intersects the discontinuity planes in perpendicular direction, which means that the roadside slopes in this section of the highway are stable.

The common geological information and the landslide distribution ratio in Table 2 are graphically presented in Fig. 14, which also indicates that areas with domination of slate-phyllite and phyllite-quartzite have greater ratio of areal distribution of landslides. The average value of distribution ratio in other zones is below 2%.

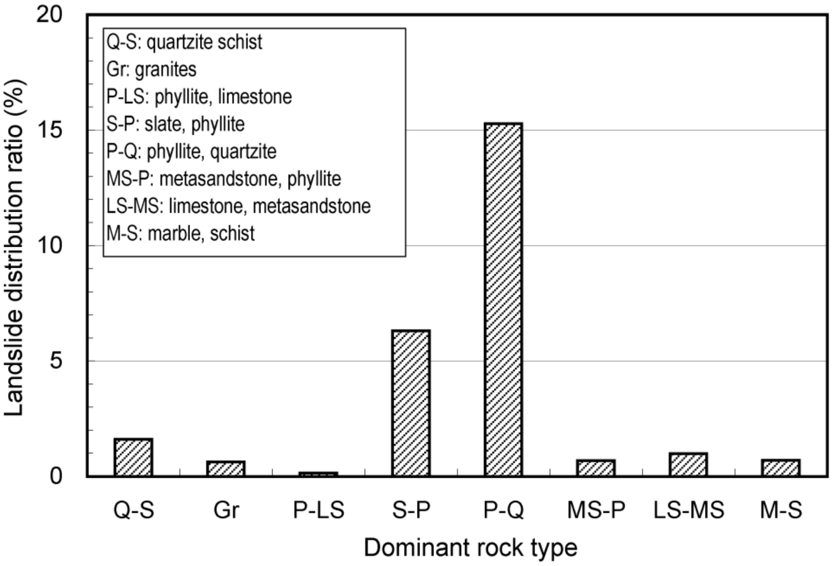

Figure 14. Areal distribution of landslides over the highway sections

When the landslide distribution ratio is plotted against the mean slope angle, as shown in Fig. 15, a clear trend of linear rise but with certain range of scatteredness, probably due to influence of other factors, can be confirmed. As the standard deviations of the slope angles in all sections vary within a range of 2 to 3 degrees (Table 2), it is ascertained that a higher value of mean slope angle represents steeper topography. Fig. 15 indicates that the mean slope angles for the areas considered along the highways vary from about 21 to 36 degrees, and a higher ratio of landslide distribution can be confirmed in areas with 27 to 36 degrees of mean slope angle. Although one section with mean slope angle greater than 30 degrees is seen to have less than 1% landslide distribution ratio, the data in Table 1 makes it clear that this section belongs to tourmaline granite zone (i.e., section 13, Fig. 12), where chances of large-scale landslide failures are less mainly because the absence of clearly defined foliation in the granitic mass leads to slow rate of inner mass decomposition and clay mineralization.

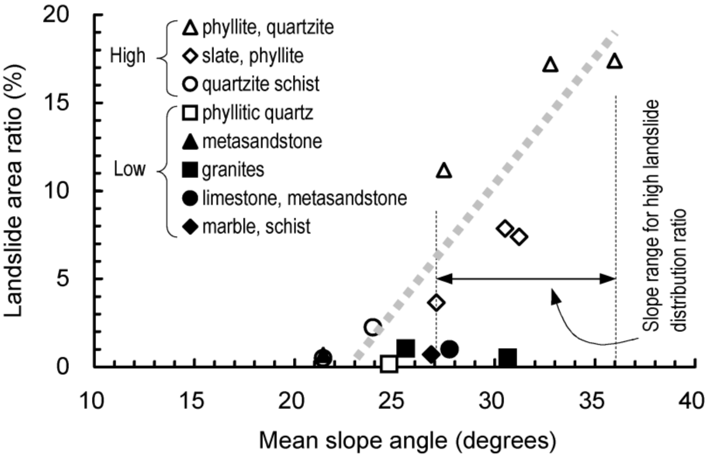

Figure 15. Areal distribution of landslides over the highway sections

8. Concluding remarks

In Nepal, geological and geomorphological constraints are always a major hurdle to development activities including road network development. Steep and rugged mountain topographies over tectonically folded and faulted rock masses, especially near the thrust faults are the root cause of landslides and roadside slope collapses in the Nepal Himalaya. Various researchers have already investigated a large part of the geological and geomorphological factors including concentrated precipitation behaviour in relation to the frequent landslide occurrences in the Lesser Himalayan and Siwalik Zones of Nepal, but what has been achieved so far is still inadequate to deal with disaster prevention and damage reduction. The nation suffers from an unaffordable economic loss due to landslide-related disasters every year. Despite the need for landslide management in Nepal for the last several years, the lack of a proper methodology to deal with these disasters has resulted in an ever increasing number of roadside landslides.

- A preliminary attempt has been made in this paper to look into the problem of large-scale landslides along the major highway corridors in central Nepal that probably have the highest areal distribution of landslides in the state road network. As a result of large-scale landslide (larger than 0.1 km^2) mapping in about 3-km wide corridors of the Naubise-Mugling section of Prithvi Highway, about 27 km section of Narayanghat-Mugling Road, and the Kathmandu-Hetauda section of Tribhuvan Highway, and analysis of the landslide distribution pattern, the following conclusion are drawn. The distribution of landslides is denser over the areas close to thrust faults, but factors like rock type, adversely oriented discontinuities, etc. also play an influential role in causing large-scale landslides.

- The thrust movement and occurrence of large-scale landslides in Nepal are closely related. Hasegawa et al. (2009) has suggested that the large-scale landslides near to the major thrust have significant clay mineralization in sliding zones due to substantial hydrothermal alteration in the Lesser Himalaya during and after the advancement of the thrusts. This clearly suggests that large-scale landslide activity is always high near to the trust zone and the highways passing through it are always facing troubles.
- Slate and phyllite zones are found to have a greater ratio of landslide distribution. However when there is coexistence of other rock types such as quartzite, and limestone, the areal ratio of large-scale landslides is found to be less. Moreover, the schist and gneiss areas have comparatively less distribution. In contrast, granite zones and the Siwalik mountains have very little distribution of large-scale landslides.
- Topographies with about 27 to 36 degrees of mean slope angle in the study area are found to have a nearly linear increase in landslide area ratio. The phyllite and slate zones were found to have exhibited this trend, but , in most other zones,

the mean slope angle was found to range from 22 to 31 degrees with no definite change in landslide area ratio

Finally, the analysis performed in this paper is based on readily available geological and geomorphological data, and it only gives a regional-scale perspective of large-scale landslide distribution in central Nepal. A number of issues are still unaddressed, but a broader assessment of the effect of geology and geomorphology on large-scale landslide distribution in central Nepal Himalaya is expected to aid to future specific studies..

9. Acknowledgements

The financial support received from the Government of Japan under the program 'Grant-in-Aid for Overseas Scientific Research and Investigation (2009-2012: Team Leader, R. Yatabe, Ehime University)' for this study is sincerely acknowledged. The paper-based as well as digital data availed by the Department of Survey of Nepal and the digital geological map of Nepal provided by ICIMOD, Nepal have been the primary base for this study.

10. References

Bhattarai D., Tsunaki R., and Mishra A.N., 2002. Water and Risk. In: *Proceedings of Asia High Summit, 6-10 May 2002, ICIMOD, Nepal*

Burbank D.W., Leland, J., Brozovic, E.N., Reid, M.R., and Duncan, C., 1996. Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas, *Nature,* 379 (6565), 505–510

Caine, N., Mool, P.K., 1982. Landslides in the Kolpu Khola Drainage, Middle Mountain, Nepal. *Mountain Research and Development* 2, 157–173.

Chalise S.R., Khanal, N.R., 2001. Rainfall and related natural disasters in Nepal. In: *Tianchi, Li., Chalise, S.R., and Upreti, B.N. (Eds.), Landslide hazards, mitigation to the Hindukush-Himalayas, ICIMOD, Kathmandu,* 63–70.

Dahal R.K., 2006. Geology for Technical Students, Bhrikuti Academic Publications, Exhibition Road, Kathmandu, Nepal, 756p.

Dahal R.K., Hasegawa S., Masuda T., and Yamanaka M., 2006. Roadside Slope Failures in Nepal during Torrential Rainfall and their Mitigation. *Universal Academy Press, Inc. / Tokyo, Japan*, 503–514.

Dahal R.K., Hasegawa S., 2008. Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology* 100, 429-443.

Dahal R.K., Hasegawa S., Nonomura A., Yamanaka M., Dhakal S., and Paudyal P., 2008a. Predictive modelling of rainfall-induced landslide hazard in the Lesser Himalaya of Nepal based on weights-of-evidence. *Geomorphology* 102, 496–510.

Dahal R.K., Hasegawa S., Nonomura A., Yamanaka M., Dhakal S., 2008b. DEM-based deterministic landslide hazard analysis in the Lesser Himalaya of Nepal, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 2(3), 161-178.

Dangol V., Upreti B.N., Dhital M.R., Wagner A., Bhattarai T.N., Bhandari A.N., Pant S.R., and Sharma, M.P. 1993, Engineering geological study of a proposed road corridor in eastern Nepal. *Bulletin of the Department of Geology, Tribhuvan University, Nepal, Special Issue*, 3(1), 91-107.

Deoja B., Dhital M.R., Thapa B., and Wagner A. 1991. Mountain risk engineering handbook, ICIMOD, Kathmandu, 875p.

Dhital M.R., Upreti B.N., Dangol V., Bhandari A.N., and Bhattarai T.N., 1991, Geological engineering methods applied in mountain road survey: an example from Baitadi-Darchula Road Project, Nepal. *Journal of Nepal Geological Society*, 7, 49-67.

DWIDP, 2003. Disaster Review 2003, an annual publication of the Department of Water Induced Disaster Prevention, Nepal.

Gansser A., 1964. Geology of the Himalayas, Inter Sciences Publishers, London, 39-229.

Gerrard, J., Gardner, R.A.M., 2000. Relationships between rainfall and landsliding in the Middle Hills, Nepal. Norsk geogr. Tidsskr. 54, 74–81.

Ghimire M., 2011. Landslide occurrence and its relation with terrain factors in the Siwalik Hills, Nepal: case study of susceptibility assessment in three basins, *Natural Hazards*, 56(1), 299-320.

Hagen, T., 1969. Report on the geological survey of Nepal preliminary reconnaissance. *Zürich Mémoires de la soc. Helvétique des sci. naturelles*, 185 p.

Hasegawa, S., Dahal, R.K., Yamanaka, M., Bhandary N. P., Yatabe R., and Inagaki H., 2008. Causes of large-scale landslides in the Lesser Himalaya of central Nepal, Environmental Geology, 57(6), 1423-1434.

Hasi B., Ishii Y., Maruyama K., and Terada, H. (2010) Controls on distribution and scale of earthquake-induced landslides caused by the Iwate-Miyagi Inland earthquake in 2008, Japan. *European Geosciences Union (EGU) General Assembly 2010, held 2-7 May, 2010 in Vienna, Austria*, 382p

Heuberger, H., Masch, L., Preuss, E., and Schrocker, A., 1984. Quaternary landslides and rock fusion in central Nepal and in the Tyrolean Alps. Mountain Res. Dev. 4:345–362

Higaki D., Yagi H., Asahi K., and Miyake N., 2000. Landslides on the late quaternary deposits in the Bhotekoshi area, Central Nepal. *Journal of Nepal Geological Society, Special Issue,* 22, 505-512.

Ives, J.D., Messerli, B., 1981. Mountain hazards mapping in Nepal; introduction to an applied mountain research project. *Mountain Research and Development*, 1, 223–230.

Karmacharya S.L., Koirala A., and Shrestha V.B., 1995, Landslide Characteristics in some parts of Nepal. *Proceedings of international seminar on water induced disasters, DPTC-JICA, 1995 Kathmandu, Nepal,* 172-176.

Karmacharya, M., 1989. Landslide in Nepal in the period 1970-1980. *M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished*, 55p.

Kienholz H., Hafner H., Schneider G., and Tamrakar R., 1983. Mountain hazards mapping in Nepal's middle mountains, maps of land use and geomorphic damage (Kathmandu-Kakani area). *Mountain Research and Development*. 3(3), 195-220.

Kienholz H., Schneider G., Bichsel M., Grunder M., and Mool P., 1984, Mapping of mountain hazards and slope stability. *Mountain Research and Development*. 4(3), 247-266.

Laban, P., 1979. Landslide occurrence in Nepal. *HMG/FAO and UNDP, Ministry of Forest, Department of Soil Conservation, Integrated Watershed Management, Kathmandu*, 27p.

Poudyal, C.P., Chang, C., Oh. H-J. and Lee, S., 2010. Landslide susceptibility maps comparing frequency ratio and artificial neural networks: a case study from the Nepal Himalaya. *Environmental Earth Science* 61, 1049–1064.

Selby, M.J., 1988. Landforms and denudation of the High Himalaya of Nepal: results of continental collision. *Z. Geomorphol., Neue Folge* 69, 133–152.

Shang, Y., Yang, Z., Li, L., Liu, D., Liao, Q., and Wang, Y., 2003. A super large landslide in Tibet in 2000: background, occurrence, disaster, and origin. *Engineering Geology*, 54, 225-243.

Shrestha H.K., Bhandary N.P., and Yatabe R., 2004, Trends in human life and economic losses from landslides and floods in Nepal. *Proceedings of 2nd international seminar on disaster mitigation in Nepal, 8 November 2004, Kathmandu*, 103-110.

Shroder, J. F., Bishop, M.P., 1998. Mass movement in the Himalaya: new insights and research directions. *Geomorphology* 26, 13–35.

Sikrikar S.M., Rimal L.N., Jäger S., 1998, Landslide hazard zonation mapping in the Phewa Lake catchment area, Pokhara, Nepal. *an unpublished report (final) under technical cooperation project 'Environmental Geology' submitted to Department of Mines and Geology, Nepal*

Stöcklin J., Bhattarai K.D., 1982, Photogeological map of part of central Nepal (scale 1:100,000). *Department of Mines and Geology, Nepal.*

Upreti, B.N., 1999. An overview of the stratigraphy and tectonics of the Nepal Himalaya. *Journal of Asian Earth Sciences* 17, 577–606.

Upreti B.N., Dhital M.R. 1996. Landslide studies and management in Nepal. *A publication of ICIMOD 1996, Kathmandu, Nepal,* 1-34.

Upreti B.N., 2001, The physiography and geology of Nepal and their bearing on the landslide problem. *Tianchi L., Chalise S.R., and Upreti B.N. (eds) Landslide hazard mitigation in the Hindu-Kush Himalayas, ICIMOD, Nepal,* 31-49.

Upreti, B. N., Yoshida, M., 2005. Guidebook for Himalayan Trekkers, Series No. 1, Geology and Natural Hazards along the Kaligandai Vallley, Nepal, *Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal*, 165p.

Varnes, D. J., 1978. Slope movement types and processes, landslide analysis and control, Special Report 176, Transportation Research Board, National Academy of Sciences, pp.11-33.

Wagner A., 1997. Hazard mapping and geophysics applied to landslide study in the Himalayas and Hindukush. *An unpublished brochure submitted to ITECO Nepal*

Wagner, A., 1983. The principal geological factors leading to landslides in the foothills of Nepal: A statistical study of 100 landslides - steps for mapping the risk of landslides. *HELVETAS–Swiss Technical Cooperation and ITECO–Company for International Cooperation and Development, unpublished*, 58p.

Westen CV, Gorum T, Fan XM et al., 2010. Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan Earthquake. *Geophysical Research Abstracts* 12.(EGU2010-4437)

Xu Q., Zhnag S., and Li W., 2011. Spatial Distribution of Large-scale Landslides Induced by the 5.12 Wenchuan Earthquake. *Journal of Mountain Science* 8, 246–260.

Yagi H (2001) Landslide study using aerial photographs, Landslide Hazard Mitigation in the Hindu Kush-Himalayas. In: *Tianchi L, Chalise SR, and Upreti BN (eds) Landslide hazard mitigation in the Hindu-Kush Himalayas, ICIMOD, Nepal*, 79-88.

Yagi H., Nakamura S., 1995. Hazard mapping on large scale landslides in the lower Nepal Himalayas. In: *Proceedings of international seminar on water induced disasters (ISWID-1995), DPTC-JICA, Kathmandu, Nepal*, 162-168.

Zhang P., Yang Z., Gupta H. K., Bhatia S.C. , Shedlock K.M., 1999, Global Seismic Hazard Assessment Program (GSHAP) in Continental Asia, ANNALI DI GEOFISICA, 42 (6): 1167-1190.