Invited Commentary

Rainfall-induced Landslides in Nepal

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The rainfall-induced landslides in the Nepal Himalaya extend tremendous damage to lives, property, infrastructure, and environment, particularly in the monsoon season. This paper particularly discusses the issues related to the rainfall-induced landslides in the Nepal Himalaya. All geological zones of Nepal were evaluated from the landslide occurrence perspective. To evaluate the landslide processes and associated hazards in Nepal, the rainfall-induced landslides were assessed from three perspectives: hydrological and slope stability modelling, rainfall threshold of landslides, and landslide hazard. This paper is an outcome of these evaluations and exclusively covers the major issues of rainfall-induced landslides in the Nepal Himalaya.

Key words: rainfall-induced landslide, Nepal, Himalaya, rainfall threshold, landslide hazard

1. INTRODUCTION

Approximately 2,400 km long Himalayan mountain chain is tectonically one of the most active mountain ranges on the earth. These mountainous terrains of the Himalaya are home to millions of people in northern India, northern Pakistan, Nepal, Bhutan, and parts of other Asian nations. Rugged topography, unstable geological structures, soft and fragile rocks, along with heavy and concentrated rainfalls during monsoon periods collectively cause severe land sliding problems and related phenomena in the Himalayan region. The annual economic loss due to landslide damages alone in this region is estimated to exceed one billion US dollars, including hundreds of human fatalities. Studies indicate that the loss due to landslides and related problems in the Himalayan region alone constitutes about 30 percent of the world's total landslide-related damage value [*Li*, 1990]. A large number of human settlements on the Himalayas are situated either on old landslide masses or on landslide-prone areas (**Fig. 1**). As a result, a great number of people are affected by large- and small-scale landslides all over the Himalayas especially during monsoon periods. For example, only in the half monsoon period of 2009 (June 10 to August 15), 50 people were killed by landslides in Nepal. Similarly, in 1988, a huge landslide at Darbang, about 200 km west of Kathmandu, killed 109 people and temporarily blocked the Myagdi River. About 62 years before this incident, the same landslide had buried Darbang area killing about 500 people [*Yagi*, 1990]. This was the worst landslide disaster in the history of the Himalayan landslides. Likewise, another worst landslide tragedy took place at Malpa Uttarakhand, India on 11 and 17 August 1998 resulting in death of 380 people when massive landslides washed away the entire village. Apart from such huge landslides, many small-scale landslides go unreported when they occur in remote areas of Himalaya. More than that, the loss of productive lands in the hills due to landslides and related mass erosion phenomena during every rainy season, which are seldom reported unless they involve the loss of life, seems to be so great that the economic loss if quantified will be no less than that during any other big event of natural disaster.

National infrastructures such as roads, bridges, dams, hydropower stations, canals, buildings repeatedly suffer landslide and flood damages. A rapid rise in construction of infrastructures including roads, hydropower, and dams with inadequate or little consideration against the natural hazards has considerably contributed to triggering of landslides in the mountains of the Himalaya. Similarly, due to a rapid increase in population over the Himalayan hills in the last three decades, the trend of settling over comparatively hazardous areas is in rise. Thus, the increasing levels of risk from the landslides triggered by hydro-meteorological variability perpetually entail considerable loss of life and property losses and inflict significant damage on the vital economic system of the nations in the Himalayan Region. Landslides in the Himalaya are size-dependent, from massive extent of whole mountain ranges through failure of single peaks to very minor slope failures [*Shroder and Bishop*, 1998].

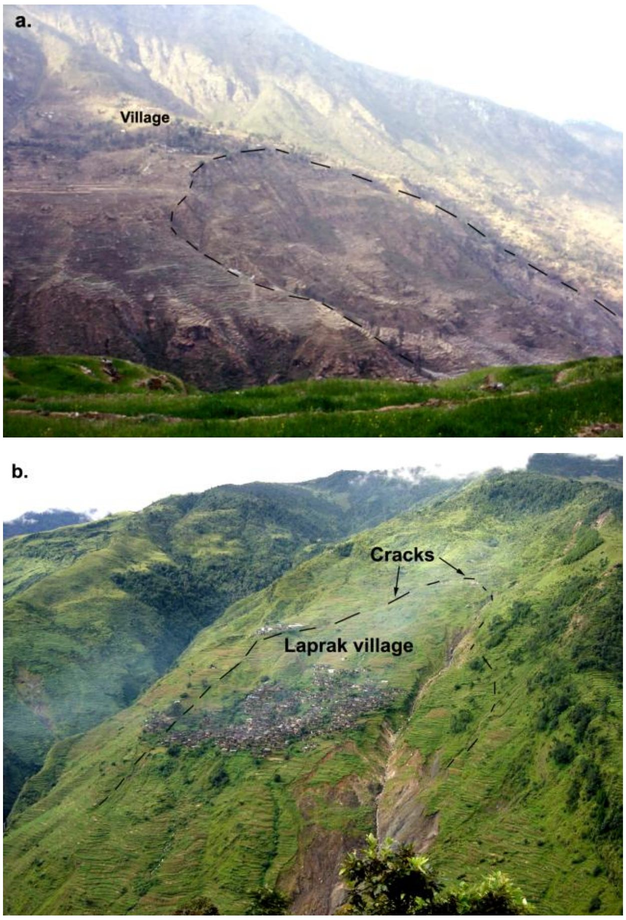

Fig. 1 Living with landslides in Nepal, two typical Himalayan landslides, **a.** Bhotekoshi River valley (north east of Kathmandu) of Sindhupalchowk district, near to the China border (photo courtesy B.N. Upreti) and **b.** Laprak village, a famous village near to the Mt Manaslu of Gorkha district (photo courtesy N. Gurung). See **Fig. 2** for location.

Processes and causes that contribute to landsliding in Nepal can be put in four categories: (i) geological causes (weak, weathered, sheared materials, and contrast in permeability of materials); (ii) morphological causes (fluvial, erosion of slope toe, tectonic uplift, erosion of marginal sides; (iii) physical causes (intense rainfall, prolonged or exceptional precipitation, earthquake, and snowmelt); and (iv) human causes (deforestation, irrigation, mining, road construction, water leakage, land use changes).

In Nepal, intense rainfall may be regarded as the main triggering factor of landslides because most landslide disasters in the region occur in monsoon period every year making a great number of people suffer heavily in large- and small-scale landslides throughout the country. With all this in the background, this paper highlights monsoon rainfall and landslides in the Nepal Himalaya.

2. GEOLOGY AND GEOMORPHOLOGY IN BRIEF

Geomorphology, geology, and climate play the most important role in preparatory process of landslide initiation in any region. With 83% low to high mountainous area, Nepal covers approximately one third of the Himalayan mountain ranges (800 km) in the central Himalaya.

The Nepal Himalaya has eight well-defined regional geomorphologic zones in north–south direction: 1) Terai (the northern edge of the Indo-Gangetic plain), 2) Siwalik (Churia) Range, 3) Dun Valleys, 4) Mahabharat Range, 5) Midlands, 6) Fore Himalaya, 7) Higher Himalaya, and 8) Inner and Trans Himalayan Valleys [*Hagen*, 1969]. Each of these zones has unique altitudinal variation, slope and relief characteristics, and climatic pattern. A digital elevation model (DEM)-based regional geomorphologic map of Nepal is shown in **Fig. 2**. The structural framework of the Himalaya is characterized by three northerly inclined major breaks in the upper crust of the Indian Plate namely, the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT).

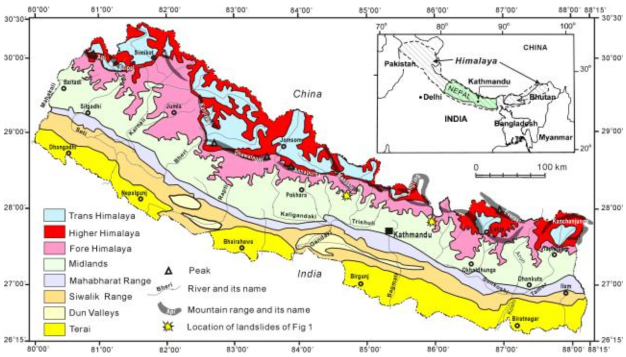

Fig. 2 Regional geomorphological map of Nepal (modified after *Dahal and Hasegawa*, 2008). Inset shows location of Nepal in the Himalaya.

These thrust faults distinctly separate the tectonic zones in the Nepal Himalaya, which include the Higher Himalayan Zone, Lesser Himalayan Zone, Siwalik Zone, and Terai Zone (**Fig. 3**). The MFT on the south separates the sedimentary sequence of the Sub-Himalayan (Siwalik) Zone and the alluvial deposits of Gangetic Plains. The MBT separates the low grade metamorphic rocks of the Lesser Himalayan Zone and the Siwalik Zone. Likewise, the MCT is a boundary between the high grade metamorphic rocks of the Higher Himalayan Zone and the Lesser Himalayan Zone [*Schelling*, 1992]. Moreover, the South Tibetan Detachment System (STDS) marks the boundary between the Higher Himalayan Zone and the overlying sedimentary sequence of the Tibetan-Tethys Himalayan Zone.

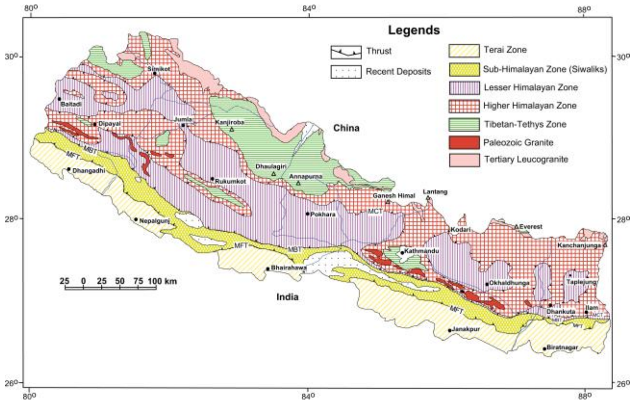

Fig. 3 Geological map of Nepal (modified after *Dahal* 2006)

3. CLIMATE AND MONSOON RAINFALL

Climate of Nepal is extremely varied and controlled by the monsoonal winds and the regional geomorphology. It ranges from seasonably humid subtropical to semiarid alpine. In Nepal, monsoon is the major source of rainfall in summer and approximately 80% of the total annual precipitation takes place in June to September, whereas western winds are responsible for limited precipitation in winter beginning November until February. Topography and aspect of mountain slope also make local change in rainfall, wind and temperature. The south facing slopes of Nepal Himalaya have a higher rate of insolation and usually have higher evaporation rates [*Upreti and Dhital*, 1996]. As a result, such slopes always have less vegetation in comparison with north facing slopes. In Nepal, elevation is the most leading factor for climatic changes. Travelling from south towards North, variation in the climate can be experienced as being hot, warm, cool, cold, and very cold. Based on this climatic variation, Nepal can be divided into six climatic zones: tropical, subtropical, warm temperate, cool temperate, alpine, arctic or tundra.

In global sense, the climate of Nepal is tropical monsoon, except for parts of the north of the country, which are in the rain shadow of the Himalayas and have a cold semi desert climate. The wet monsoon is responsible for almost 90% of the south Asian water demand.

The monsoon enters Nepal during the first week of June and it brings extreme rain until September. The duration of the monsoon and amount of rain varies across Nepal, the western one third of the country being drier than the east. Monsoon depressions move from southeast to northwest, on average at the rate of two per month, bringing heavier bursts of rain. The monsoon is longest and wettest in the eastern part of the country. Conversely, winter monsoon due to frontal system, generates more concentrated rainfalls in western part of Nepal and very low in eastern part. These rainfalls contribute to one fifth of the total annual rainfall. Similarly, heavy rainfall in November and December is rare. The Nepalese climate therefore shows a very marked dry season lasting from mid October until May, and during this period, many locations experience severe drought.

The measured values of mean annual precipitation in Nepal range from a low of approximately 250 mm at a few areas on the north of the Himalaya to many areas exceeding 6,000 mm especially in an around Pokhara area. The annual rainfall in the capital city of Kathmandu (central Nepal) generally exceeds 1,350 mm. The mean annual rainfall varying between 1,500 mm and 2,500 mm predominate over most of the country. Daily distribution of precipitation during the rainy season is also uneven. Sometimes, 10% of the total annual precipitation can occur in a single day while 50% of the total annual rainfall can also occur within 10 days of the summer. This type of uneven distribution of precipitation plays an important role in triggering landslides in Nepal.

The orographic effect of the mountains is the main cause of extreme rainfall in Nepal during monsoon. The prevailing winds (moisture-laden vapor) from the Arabian Sea and the Bay of Bengal get intercepted by the mountains. As the air hits a higher land, it is forced to rise. When the air rises above the dew point, it can no longer hold all its water, and it starts to condense. This results in high rainfall across the southern flanks of the Himalayan range (windward face) and low rainfall behind Himalaya (leeward face). The orographic effect of the Mahabharat Range is also significant in whole Nepal and windward face of the range usually suffers much rainfall in monsoon. The orographic effect of the Fore Himalaya is responsible for extreme monsoon rainfall in Midland. The topographic profiles of eastern, central and western

Nepal clearly suggest this phenomenon (**Fig. 4**). Moreover, in the southern part of central Nepal, the elevation is relatively lower than other parts of the country (**Fig. 5**) but abruptly rises in the north as Dhaulagiri, Annapurna and Manaslu ranges. As a result, Pokhara area generally gets much more rainfall than other parts of Nepal because of strong orographic effect of Annapurna and Dhaulagiri ranges (**Fig. 5b**). Likewise, central Nepal always has high values of both mean annual rainfall and extreme 24-hour rainfall (**Fig. 6**).

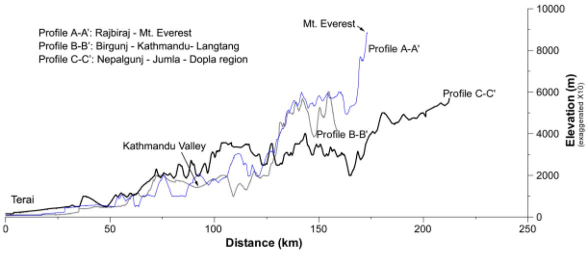

Fig. 4 Topographic profile of eastern, central and western Nepal. The location of profile lines are given in **Fig. 7a**.

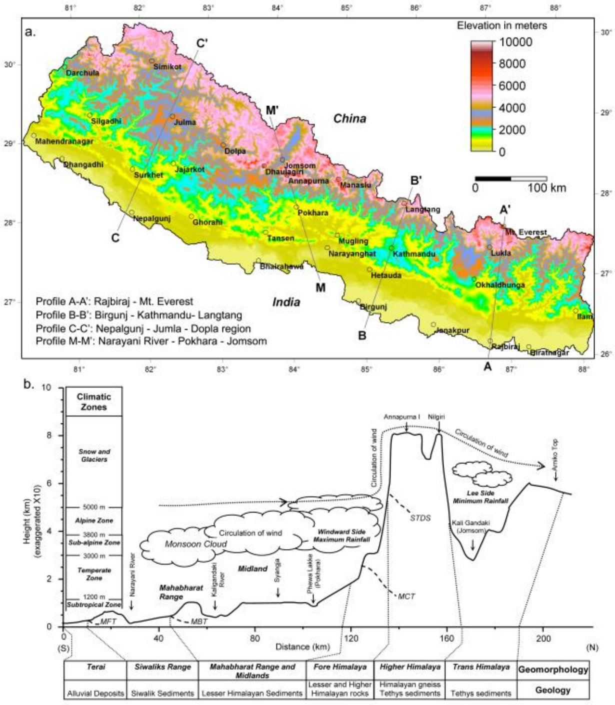

Fig. 5 a. Relief map of Nepal, a lower altitude area is situated inthe area between west of Kathmandu and Pokhara. The topographical profile of line AA', BB' and CC' already given in **Fig. 4**. **b.** Topographical profile (through line MM' in **Fig. 5a** of Nepal Himalaya with illustration of climatic zones, main geology and geomorphology.

4. LANDSLIDES IN NEPAL

Brief scenario of landslide occurrences in various geomorphic provinces are described below.

The Siwalik (Churia) Range is made up of geologically very young sedimentary rocks such as mudstones, shale, sandstones, siltstones and conglomerates. These rocks are soft, unconsolidated and easily disintegrable. The Upper Siwalik contains thick beds of conglomerates and they are loose and fragile. Similarly, Lower Siwalik and Middle Siwalik have problem from alternating beds of mudstones and sandstone.

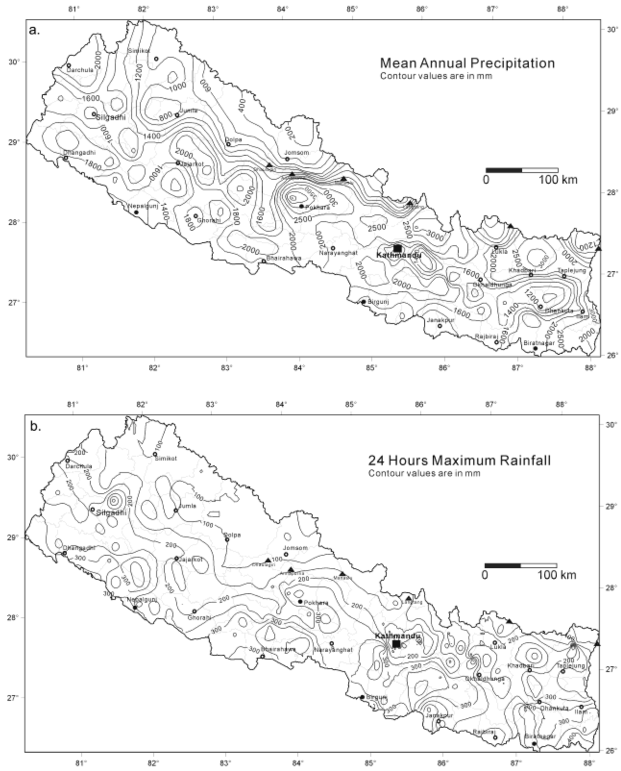

Fig. 6 Rainfall distribution in Nepal. **a.** Mean annual precipitation; **b.** Maximum rainfall of 24 hours.

In such alternating bands, mudstone can flow when saturated with water which results in overhanging sandstone beds. Such overhang jointed sandstone beds easily disintegrate into blocks. Similarly, throughout Nepal, the rainfall within Churia Range is normally in the range of 2,000 to 2,500 mm per year. As a result, geological conditions and the climate render the Churia Range highly susceptible to landslides processes.

The Mahabharat Range belongs to the Lesser Himalayan Zone. It is the most important barrier of the monsoon clouds and it greatly influences the rainfall distribution pattern in Nepal. Almost in whole Nepal, the southern face of Mahabharat Range gets extensive rainfall in comparison to Midland. The annual rainfall in Mahabharat Range area is comparatively higher and the frequency of high intensity rainfall is also high. Thus, these areas get extensive problem of floods, debris flows and shallow landslides. These events periodically cause big disaster events. The disaster of south and southeast Kathmandu in 1993 and the disaster of Mugling-Narayanghat Road of central Nepal in 2003 are a few examples of such problems. Not only rainfall but geological condition and very steep slopes also play a major role in causing soil slips and debris flows in the Mahabharat Range. From field observation, it is noticed that in the area made up of rocks such as limestone, dolomite marble and granites, the slopes are comparatively stable in the Mahabharat Range, whereas the area consisting of rocks such as phyllites, slates, intercalation of phyllites and quartzites render the terrain to be heavily prone to landslides.

The Midlands also belongs to the Lesser Himalayan Zone and is situated at the north of the Mahabharat Range. It has a gentle topography compared to Churia and Mahabharat ranges. The slopes are also comparatively gentler than in other zones of Himalaya. Thick soil formations are found in slopes of the Midlands because of deeply weathered rocks. As a result, the slopes are very prone to landslides, especially after an intense rainfall. Usually, Midlands is considered as rain shadow zone of the Mahabharat Range, which only receives a total annual rainfall of 1,000 to 2,000 mm. Most of the population of Nepal lives in the Midlands, and for this reason, this zone is intensively cultivated. Irrigation system can be found in every terrace on slope as well as on old landslide debris, and mismanagement of irrigation canals can be noticed everywhere. These improper agricultural practices generally contribute to land sliding or reactivate old landslides and usually damage whole settlement on the slope.

The Fore Himalaya is a northern part of Midlands and it is the frontal portion of the Higher Himalaya. Geologically, it ~~is~~ generally belongs to the Lesser Himalayan Zone in many places but in some places it is the Higher Himalayan Zone. Thus, main rock types of this province are phyllites, schists, marble, quartzites, and gneisses. Tectonically, this zone is very active and uplifting at a high rate, and the topography is steep and rugged (Upreti 2001). Similarly, like the south faced slope of the Mahabharat Range, the Fore Himalaya also gets high rainfall in the range between 2,000 and 3,500 mm. This province is also another vulnerable area for landslide occurrence, but because of less soil on steep slope, mainly rock related failure problems are very frequent. Some landslide dams are also noticed in narrow river valleys of this province.

The Higher Himalaya province covers the highest area of Himalaya. It includes all elevated peaks and their slope exceeding 5,000 m in altitude. Geologically, this province belongs to the Higher Himalayan Zone and the Tibetan-Tethys Himalayan Zone in some extent and main rock types of this zone are gneiss, schist, marble and quartzite. Vertical or steep rocky slopes are very common in this province. Usually, the southern face of the province generally receives high precipitation. Mainly, in this province, there is no or little soil cover on slopes and rock related failure phenomena are very common, but because of very low population and non-existent infrastructure development, the degradations of the Higher Himalaya are not attentive for planners and researchers.

The province behind (north) the Higher Himalaya is called Trans Himalaya. Geologically, this province belongs to the Tibetan-Tethys Himalayan Zone. This area is situated in the rain shadow zone of the greater Himalayan Range. This zone has very low average annual rainfall in comparison to the Midlands and the Fore Himalaya. Thus, soil related landslides are less frequent but debris flow in a snow-fed stream is quite common. River banks made of alluvial and glacial moraine possess bank failure problem.

5. EVALUATION OF LANDSLIDE PROCESSES AND HAZARDS

To understand landslide processes, mechanism and associated hazard, rainfall-induced landslides of the Nepal Himalaya are evaluated from three perspectives: hydrological and slope stability modeling, rainfall threshold of landslides, and landslide hazard study. The findings of the research are briefly described in following paragraphs.

The hydrological and slope stability study was performed with the help of physically-based models as per the physico-mechanical law of conservation of mass, energy, momentum and the equilibrium of forces. GeoSlope software package and self-developed heuristic approach were used for hydrological and slope stability modelling. For the rainfall threshold for the landslides in the Nepal Himalaya, empirical relationships were developed and they were correlated with global rainfall threshold for land sliding. Statistical and deterministic hazard modelling has been done to perform rainfall-induced landslides hazard evaluation in the Nepal Himalaya.

When spatial distribution of landslides was evaluated from a historical landslide record at 677 locations, it was found that greater number of landslide events were concentrated (**Fig. 7**) in central Nepal, in the area of high mean annual rainfall between Pokhara and Kathmandu. The small-scale rainfall-triggered landslides in Nepal are generally shallow (about 0.5 to 2.5 m thick) and are triggered by changes in physical properties of slope materials during rainfall. Relatively large-scale and deep-seated landslides, on the other hand, are affected by long-term variation in rainfall.

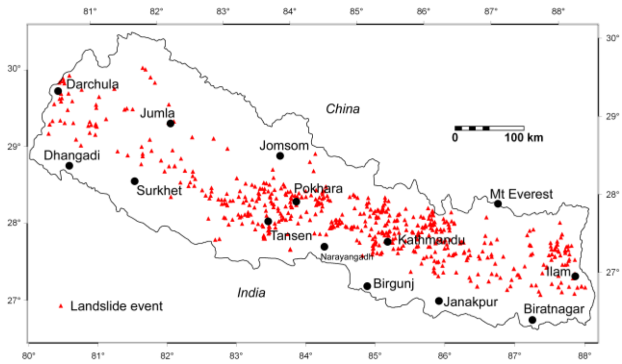

Fig. 7 Landslide distribution in Nepal. This map was preparedusing more than 677 landslide events. The map does not represent total landslides events in Nepal.

When monsoon rainfall and landslide relationship was taken into consideration, it was noticed that a considerable number of landslides were triggered in the Himalaya by continuous rainfall of 3 to 90 days. It has been noticed that continuous rainfall of 5 days or 7 days or 10 days are usually responsible for landsliding in the Nepal Himalaya. **Fig. 8** shows some examples of rainfall and landslide occurrence time during monsoon period in eastern Nepal. It clearly demonstrates the relationship of progressive monsoon rainfall and frequency of land sliding. Monsoon rains usually fall with interruptions of 2–3 days and are generally characterized by low intensity and long duration. Thus, there is a strong role of antecedent rainfall in triggering landslides. It is suggested that a moderate correlation exists between the antecedent rainfalls of 3 to 10 days and the daily rainfall at failure in the Nepal Himalaya [*Dahal and Hasegawa*, 2008]. When rainfall threshold of landslides is considered for research, in total, 677 landslides occurring from 1951 to 2006 were studied to analyze rainfall thresholds of landslide in the Nepal Himalaya (Fig 7). Out of the 677 landslides, however, only 193 associated with rainfall data were analyzed to yield a threshold relationship between rainfall intensity, rainfall duration, and landslide initiation. The threshold relationship fitted to the lower boundary of the field defined by landslide-triggering rainfall events is $I = 73.90\ D^{-0.79}$ (I = rainfall intensity in mm/hr and D = duration in hours), revealed that when the daily precipitation exceeds 144 mm, the risk of landslides on Himalayan mountain slopes is high. Normalized rainfall intensity–duration relationships and landslide initiation-thresholds were also established from the data after normalizing rainfall-intensity data with respect to mean annual precipitation (MAP) as an index in which $NI = 1.10\ D^{-0.59}$ (NI = normalized intensity (h^{-1}) and D = duration in hours).

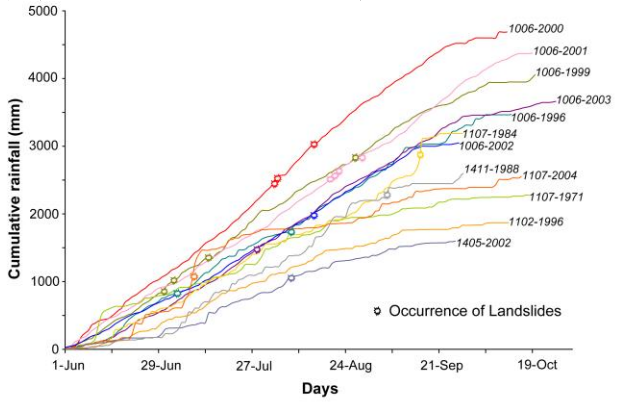

Fig 8. Illustration of cumulative rainfall and occurrence of landslides in eastern Nepal. Cumulative rainfall of station 1006, situated at about 60 km north east of Kathmandu, has a linear relationship with monsoon days.

When various threshold curves for rainfall-triggering landslides proposed by different researcher are compared with the curve of the Nepal Himalaya (**Fig. 9**), the curve proposed by *Larsen and Simon* (1993) for Puerto Rico (humid-tropical region) has greater similarity with the rainfall threshold of landslides in Nepal. Applications of hydrological and stability model in the ideal terrains of the Lesser Himalaya of Nepal suggested that soil characteristics, low internal friction angle of fines in soil, the presence of clay minerals, bedrock hydrology, and human intervention were the main contributing parameters for slope failures. The clay mineralogy of slope materials is also a contributing factor for rainfall-triggered landslides in the Nepal Himalaya.

By modelling pore water pressure and slope stability in the non landslide zone and the landslide prone zone, it was found that shallow and highly mobile landslides in zero order basins or topographic hollows of the Lesser Himalayan slopes are mainly triggered by transient positive pore water pressure in response to intense monsoon rainfall and bedrock seepage (**Fig. 10**). Antecedent rainfall affects landslide stability by reducing soil suction and increasing transient pore water pressure.

The study on landslide and monsoon rainfall concluded that there was a significant role of antecedent rainfall in the Nepal Himalaya especially in the northeastern part of central Nepal, and such rainfall was basically responsible for large-scale landsliding.

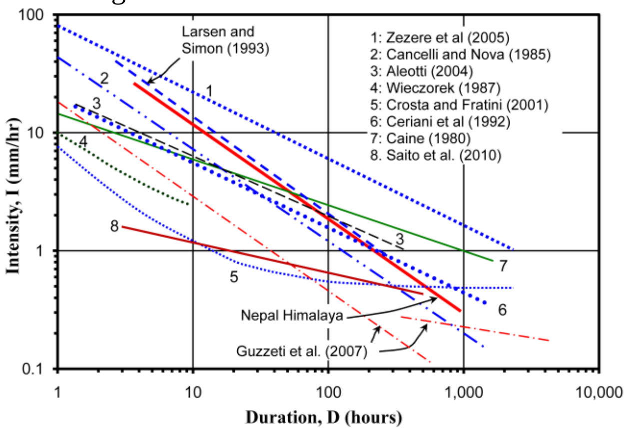

Fig. 9 Comparison of the landslide triggering; **a**. rainfall intensity–duration from various studies [modified after *Dahal*, 2009] for the Nepal Himalaya

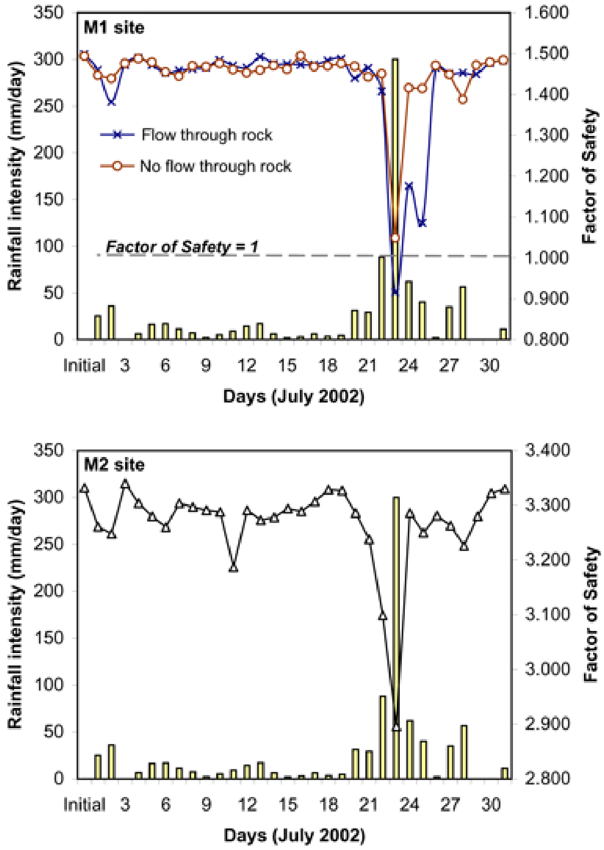

Fig. 10 Change of factor of safety with rainfall in ideal sites of the Lesser Himalaya in Nepal

Seepage analysis of antecedent rainfall in an area (middle part of central Nepal) has shown slight effects on build-up of pore water pressure on the slope. Thus, in the Lesser Himalaya of central Nepal, extreme rainfall of one or two days is usually responsible for shallow slope failures.

For hazard analysis, both statistical and deterministic landslide hazard modelling was employed in the Lesser Himalaya of Nepal. For statistical modelling, the weights-of-evidence modelling and information value method were applied, within a geographical information system (GIS), to derive landslide susceptibility maps of the ideal Lesser Himalayan terrain of Nepal (**Fig. 11**). Relevant thematic maps representing various factors (e.g. slope, aspect, relief, flow accumulation, soil depth, soil type, landuse and distance to road) that were related to landslide activity were generated using field data and landslide hazard were evaluated with GIS techniques. The success rates (**Fig. 12**) were estimated to evaluate the accuracy of landslide susceptibility and hazard maps, and it is found that the models are useful in landslide susceptibility and hazard mapping even in small catchment scale. The Digital Elevation Model (DEM)-based deterministic distributed analysis in GIS was carried out to calculate the probability of slope failure in an ideal terrain of the Nepal Himalaya. When normally distributed failure probability value were checked against existing landslides, it was found that more than 50% of the pixels of existing landslides coincided with a high calculated probability of failure. Although the deterministic distributed analysis has certain drawbacks, as described by previous researchers, this study concluded that the calculated failure probability could be utilized to predict the probability of slope failure in Himalayan terrain during extreme rainfall events.

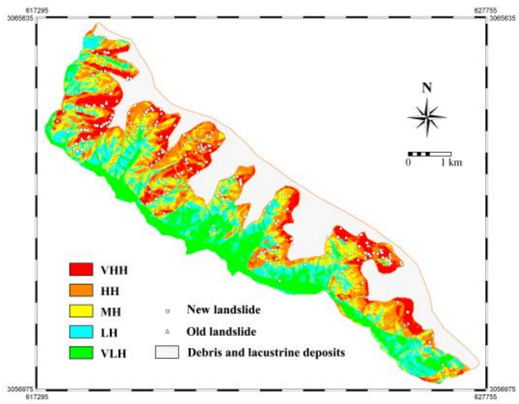

Fig. 11 Landslide hazard zonation map of the south-western hills of the Kathmandu Valley after weights-of-evidence modelling. VHH: very high hazard, HH: high hazard, MH: moderate hazard, LH: low hazard, VLH: very low hazard [modified after *Dahal*, 2009].

6. CONCLUDING REMARKS

An analysis of the 55-year record of landslides and rainfall events in the Himalaya has suggested that many landslides occurred under the influence of

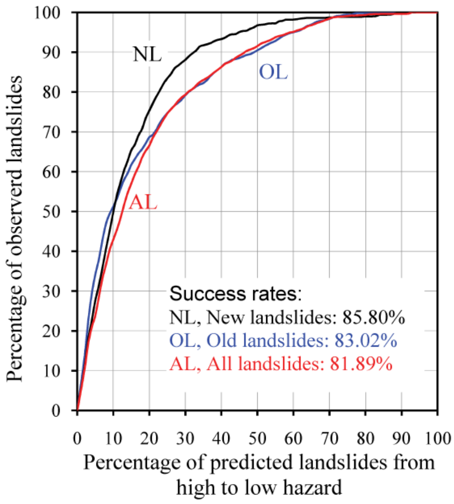

Fig. 12 Success rate curves of landslide hazard values alculated from three types of landslide inventory maps. [modified after *Dahal*, 2009].

a wide range of rainfall durations (5 hours to 90 days). Monsoon rains usually fall with interruptions and are generally characterized by low intensity and long duration. As a result, landslides are usually initiated only after few days of first monsoon rainfall and role of antecedent rainfall for landsliding in Nepal is bona fide. Orographic effect of Himalayan range is responsible for extreme rainfall in central and eastern Nepal. As a result, central Nepal usually faces many landslides related disaster than western Nepal.

Lastly, the findings of the research on rainfall-induced landslides in Nepal are very useful in reducing the loss of lives and properties due to landslides in the Nepal Himalaya.

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