

# Landslide occurrence and its relation with terrain factors in the Siwalik Hills, Nepal: case study of susceptibility assessment in three basins

Motilal Ghimire

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**Abstract** Landslides in the three studied basins of the Siwalik Hills are not random in distribution; they tend to cluster in certain areas implying the control of certain in situ factors or their combination. Landslide controlling in situ factors were reviewed and analyzed from maps, aerial photos and imageries using GIS. Chi square analysis was carried out to test the significance of landslide distribution vis-à-vis in situ factors. Slope gradient and relative relief were consistently significant in landslide distribution. Geology, dip-topography relation, land use and land cover, and vegetation conditions appeared important in landslide occurrence in all three basins either in terms of area or count in any two basins. Slope aspect and altitude tested significant for landslide occurrence in at least two basins. However, upslope flow contributing area, drainage density and distance to lineament were found insignificant in all three basins. In situ factors that tested significant in any two basins were used for landslide susceptibility analysis using a bivariate statistical approach. The distribution of landslides strongly correlates with susceptibility indices. With in situ factors, landslide susceptibility had good correlation with slope gradient and relative relief. Incorporating calculated factor weight values from one basin to the other two basins, proxy susceptibility index maps were also prepared. A moderate to good positive correlation appeared between them implying certain range of confidence for replicating the result for whole of the Siwalik Hills. Slope gradient and relative relief can be used as proxy indicators of landslide susceptible areas in the Siwalik Hills.

**Keywords** Landslide · Siwalik Hills · In situ factors · Landslide susceptibility

## 1 Introduction

Landslide refers to the movement of a mass of rock, debris, or earth down a slope (Cruden 1991). They become hazardous when they interfere with human activity. Huge loss of human life and property and a great amount of money spent on relief and recovery has been

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M. Ghimire (✉)  
Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan  
e-mail: gmotilal@wwwgeo.ees.hokudai.ac.jp; motighimire@gmail.com

experienced in recent years due to increased landslide disaster in many parts of the world. Heavily populated hills of Nepal are no exception. This has necessitated the identification of landslide susceptible areas for the mitigation of landslide hazard.

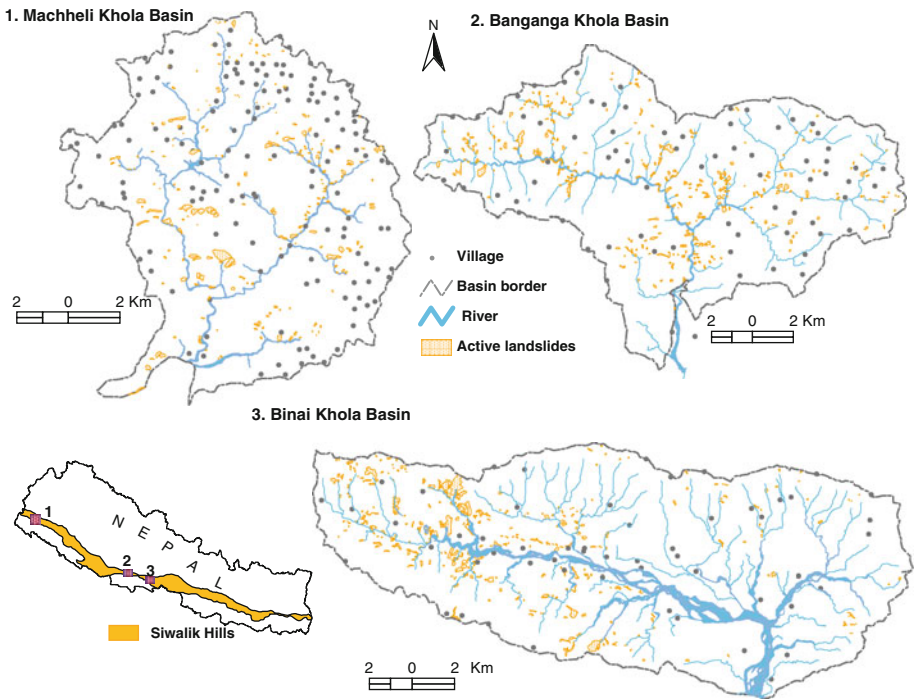
Landslides are the product of a complex interplay of various triggering and conditioning in situ factors. In-depth understanding of landslide relation to terrain and susceptibility thereby requires various methods, tools and techniques developed in the geomorphology, geology and engineering. Quite a number of published literature about landslides in the Nepal Himalaya are available that significantly contribute to the knowledge of landslide's causes, locations, forms, processes and mechanisms as well as degradation, hazards and risks (Laban 1979; Ives and Messerli 1981; Selby 1988; Caine and Mool 1982; Wagner 1983; Heuberger et al. 1984; Dhital et al. 1993; Gerrard and Gardner 2000; Hasegawa et al. 2008). More specifically, a few studies pertaining to landslide and gully erosion processes and associated hazards covering parts of the Siwalik Hills can be mentioned (Brunsdon et al. 1981; Tamrakar et al. 2002; Rautela and Lakhera 2000; Ghimire et al. 2006).

The role of in situ terrain factors for landslide susceptibility assessment have been considered, and a large number of them are applied in most studies using GIS and remote sensing for susceptibility assessment (e.g., Anbalagan 1992; Brabb 1995; van Westen 1997; Guzzetti et al. 1999; Dahal et al. 2008). But few studies (e.g., Gritzner et al. 2001) have statistically tested the significance of these factors in relation with landslide occurrence before using them as input parameters for susceptibility assessment in meso-scale watershed unit. The significance of the method and result of the study can be judged if they are replicable and the methodology adaptable in a similar geophysical region. The studies of various areas belonging to a similar geophysical region using comparable method and parameter are needed to assess consistency and conformity of the findings, which can be extended or replicated to a greater region such as the Siwalik Hills. The present study evaluates terrain of the selected three basins and analyzes the landslide relations to in situ factors. The landslide–terrain relation was further applied to assess the landslide susceptibility of the basins. The study also evaluates whether the method and the obtained result can be validated and if they are replicable between the basins and finally to the greater Siwalik region for susceptibility assessment. The study assumes the dominant triggering factors like rainfall and seismicity in these basins of the same geo-physical region.

## 2 General description of the selected basins

The selected basins for the study: the Machheli Khola Basin (179 km<sup>2</sup>), the Banganga Khola Basin (179 km<sup>2</sup>) the Binai Khola Basin (216 km<sup>2</sup>) are considerably the large basins of the Siwalik Hills of Nepal (Fig. 1). The Machheli Khola Basin and the Binai Khola Basin have developed on the Siwaliks rocks, whereas the northern part of the Banganga Khola Basin is formed on the Lesser Himalayan rocks of Cambrian to Precambrian era (DMG 2007) (Fig. 2).

The sedimentary sequence of the Siwalik Group can be classified into three major groups: (1) the Lower Siwaliks (fine-grained sandstone with interbeds of mudstone, shale, siltstone and occasional marl; proportion of mudstone is comparatively high), (2) the Middle Siwaliks (medium- to coarse-grained sandstone, pebbly sandstone with interbeds of siltstone and mudstone, with some content of coaly materials and plant fossil; proportion of sandstone is high as compared to mudstone), (3) the Upper Siwaliks (boulder, cobble and conglomerate with mud and silts and sand lenses (DMG 2007). These rocks were formed



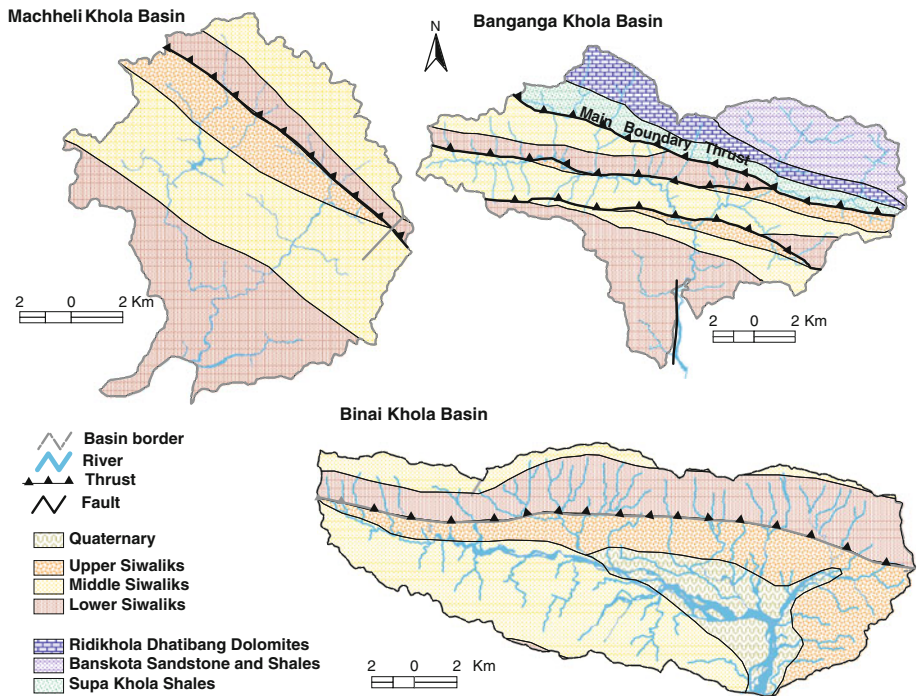
**Fig. 1** Study areas: the selected basins of the Siwalik Hills

from sediments deposited in foreland basin deformed by thin skinned tectonics between Middle Miocene to Middle Pleistocene (Tokuoka et al. 1986; Lavé and Avouac 2001).

Several north dipping thrusts delineate the tectonic boundary in the Siwalik Group. The northern border of the Siwalik Group is the Main Boundary Thrust (MBT) consisting of medium-grade metasediments. Along this zone, the Lesser Himalaya is thrust onto the Siwalik units (Molnar 1990). Active tectonics along this zone is evidenced by geomorphic features such as wide valleys, uplifts and offsets of unpaired terraces and sharp scarps and warping and fitting of rocks (Valdiya 1992). The MBT traverses the north part of the Banganga Khola Basin, while subsidiary thrust faults of the MBT are observed in the other two basins.

The Main Frontal Thrust (MFT) (Nakata 1989) forms the southern boundary of the Siwaliks. This zone characterizes the Indian plate thrusting beneath the Himalayan plate. It is a frontal fault in the Himalayas and is tectonically and seismically most active (Molnar 1990; Lavé and Avouac 2000), which makes the terrain susceptible to slope failure. Predominantly homoclinal bedding structure prevails in the studied basins, where bedrock dips toward north. Some syncline and anticline folds are also observed in the Banganga Khola Basin and the Binai Khola Basin.

The local relief of the Machheli Khola Basin (250–1,972 m) and the Banganga Khola Basin (200–2,260 m) is high compared to the Binai Khola Basin (181–1,560 m). In general, all basins characterize steep topography with an average basin slope of 21° for the Binai Khola Basin and 24° and 27° for the Machheli Khola Basin and the Banganga Khola Basin, respectively. Valleys with river terraces along the trunk stream are found in the former basin, whereas the latter two basins feature narrow valleys and steep foot slopes.



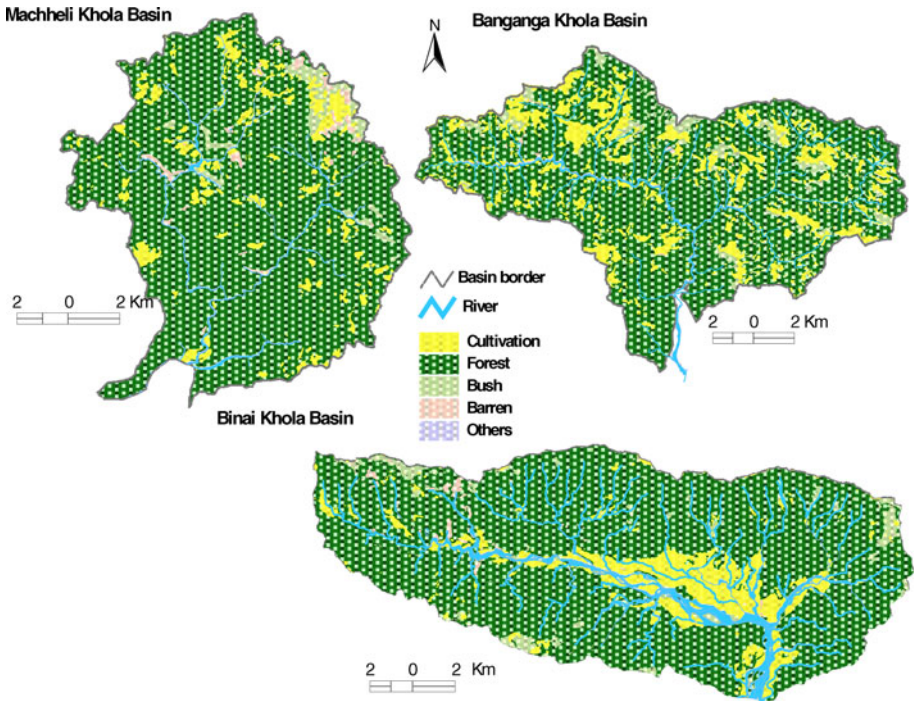
**Fig. 2** Geology and structure

Incised valleys in the upper Machheli Khola catchments are very evident. Complex deformation of the crust is demonstrated by the irregular or twisted pattern of steep slopes and scarps mostly closed to the major thrust and faults. The Binai Khola Basin exhibits gently to steeply dipping folded structure and several escarpments on the steep dip slopes at the north facing slope are observed.

Hot wet summers and cool dry winters prevail in all three basins. Mean annual temperature is around 23–30°C with summer maximum of 26–35°C and winter minimum of around 4–10°C. The mean annual rainfall is about 1,600 mm, about 80% of which occurs in summer as a result of the monsoon. A large part of the area of all three basins is under forest, i.e., about 81–71% in total. Correspondingly, cultivated terraces constitute about 11–23% of the total area (Fig. 3).

Population of the Machheli Khola Basin, the Banganga Khola Basin and the Binai Khola Basin is estimated to be around 9,400, 16,600 and 13,400, which is spread over 144, 74 and 54 villages, respectively (CBS 2002). Villages in the Maccheli Khola Basin are smaller in size and are distributed in smaller patches of moderately sloping to steep arable slopes (<25°) across the basin. In the Banganga Khola Basin, villages are relatively bigger in size; most of the villages are located on ridges and gentler slopes. In the Binai Khola basin, about 79% of the population lives in the valleys and river terraces. The other people live on the settlements (about 27) located on scattered small patches of arable land on moderately steep slopes. Relatively stabilized old landslide topographies on the hill slopes have become abode for many settlements in all three basins.

In all three basins, more than 85% of households (CBS 2002) are involved in agriculture as their main occupation. Agricultural land, livestock and poultry are the major livelihood



**Fig. 3** Land use and land cover

assets. A large part of agricultural land was damaged and many houses and livestock sheds were swept away by the landslides and floods in the Machheli Khola and Banganga Khola Basin in the last decade.

### 3 Methodology

#### 3.1 Review of the methods adapted in earlier studies

Susceptibility of a given area to landslides has been determined or depicted by hazard zonation, with geomorphic features (Waters 1958; Brunsden and Jones 1972; Carrara and Meranda 1976). In the Himalayas, the works of Ives and Messerli (1981), Kienholz et al. (1983), Zimmermann et al. (1986) and Yagi and Oi (1993) are some good examples of geomorphic approach to hazard mapping. This approach of mapping relies on the investigator’s understanding of geomorphological processes acting upon the terrain and his ability to estimate actual and potential slope failures (Guzzetti et al. 1999). Hence, the consistency in landslide predictability and reproducibility of such maps can be questioned. Qualitative to semi-qualitative approaches of susceptibility assessment for landslides considering the sites’ geology, geomorphology, soil and hydrology along corridors for purpose of road alignment in the Nepal Himalaya have been in practice (Brunsden et al. 1975; Wagner 1981; Deoja et al. 1991; Dhital et al. 1991).

In recent times, the use of computer-based GIS technology has enabled production of landslide susceptibility maps by integrating various causative map layers (factors)

employing bivariate and multivariate statistical methods and knowledge-based approach (Brabb 1995; van Westen 1997; Guzzetti et al. 1999, Ayalew and Yamagishi, 2005, Dahal et al. 2008). These statistical methods simply rely on the association of landslides occurrence with causal factors that are chosen without understanding the actual nature of causes, modes and mechanisms and role of environmental change behind the slope failure on the site, and often termed as “black-box” approaches (Guzzetti et al. 1999; van Westen et al. 2006).

Various computer-assisted physical base models, i.e., SHALSTAB (Montgomery and Dietrich 1994) and SINMAP (Pack et al. 2005) are also available for predicting slope instability using engineering principles and DEM derivatives as major input data. But such deterministic models are based upon the understanding of few physical laws controlling slope instability (Montgomery and Dietrich 1994; Guzzetti et al. 1999), and the results are often slope gradient biased in the absence of appropriate data about slope material and conditions, and high-resolution DEM (Paulin and Bursik 2009).

The present study is not going to address abovementioned methodological issues. It will only focus on the statistical significance of the relationship between landslides and some available in situ causal factors in the three Siwalik basins. Second, it will examine the validity of landslide susceptibility patterns and compare the result between the basins.

### 3.2 Data sources and development

Landslide inventories for the three basins were completed using 1:50,000 aerial photographs taken in 1990 and 1996; and stereo capable IRS-1D and ALOS (PRISM) Pan imageries acquired in 2003 and 2007, respectively. The term *landslide map* (or landslide inventory map) is used here to indicate a map portraying the distribution of deposition and depletion areas of mass movements, which vary in type and age (Guzzetti et al. 1999). Landslides in the stereoscopic vision appear as gray to light gray tone, with lenticular, spoon-like, tree-like or triangular shape, which are mainly located near ridges, cutoff slopes of riverbanks, gully heads or are frequent on topographic concavities and have their long axis along the direction of gravity. The scar is sharp, fresh and unvegetated, the displaced mass is represented by hummocky topography, and the tension cracks are fresh/identifiable (Mather et al. 2003).

The aerial photographs and imageries were orthorectified in ILWIS 3.3 software using Ground Control Points collected from the topographic map (scale: 1:25,000) vis-à-vis ellipsoid heights from Digital Elevation Model (DEM). The anaglyph image was produced using the stereo-pair orthorectified imageries. The digitization of landslides and other features was all performed by virtual 3D viewing of anaglyph image on a planimetric scale. Field work was carried out on a few sites in the basins for verifying the landslides interpreted from the aerial photographs and imageries, and to cross-check the lithology, structure, landform and land use and land cover type described in the maps. Because of similar geophysical setting, the photo/imagery ground relation of landslide, landform and land use land cover established from the visited field sites was extended to the data verification of the uncovered parts of the basins.

GIS map layers showing factors commonly attributed to landslide occurrence were developed from the various data sources. Map layers depicting lithology and major structures (thrust, fault, dip amount and direction) were derived from the geological maps prepared by DMG (2007). Predicted geological lineaments were incorporated from the imageries and aerial photographs through visual interpretation. A dip-topography relation map was developed by relating the rock bedding structure, i.e., dip direction and amount

(slope) to slope aspect and angle by map overlay in GIS. This layer depicted the surface characterizing dip, overdip, underdip, escarpment, steep escarpment, subdued escarpment and the orthoclinal slopes (Meentemeyer and Moody (2000)). The topographic layers representing slope angle, slope aspect, relief and relative relief (m/ha) were produced from the DEM derived from digitized contours (20 m interval) and spot height from the topographic maps. The concept of specific catchment area (defined as upslope area per unit contour length) introduced by Beven and Kirkby (1979) was incorporated in this paper for calculating topographic convergent and divergent areas using grid-based DEM (Montgomery and Dietrich 1994; Tarboton 1997) in ArcView 3.2. Drainage density maps, i.e., drainage length/250 × 250 m, were calculated in GIS from the drainage lines interpreted from the topographic maps. Land use and land cover layers were digitized from the published topographic maps based on 1990 (Banganga Khola and Binai Khola Basin) and 1996 (Machheli Khola Basin) aerial photographs. Cross checking and corrections of land use and land cover information were also done referring the same aerial photographs and imageries as well as ground-truthing of the visited sites. A Normalized Difference Vegetation Index map showing vegetation condition was calculated using the Landsat imageries recorded on red and infrared wavelength regions of electromagnetic energy in 1989–1990. Consideration of the time of the imageries acquired was done in order to represent the vegetation conditions before the occurrence of most landslides depicted in the inventory.

### 3.3 Chi square and correlation analysis

A Chi-square analysis was first completed in order to determine which above-mentioned in situ factors are related to landslide occurrence. In order to satisfy the requirements for the Chi-square test, the values in continuous series for distance to lineaments, slope, altitude, relative relief and vegetation index maps were converted into the integer classes at natural breaks or appropriate intervals representing the range of values for each grid cell. The number of classes was determined so as to retain maximum amount of information possible. The statistical hypothesis for chi-square test states that there are no differences between observed and expected landslide distribution as area or count in different classes of a factor considered in this study. The level of significance for accepting or rejecting the null hypothesis was fixed at 0.1. Factor types not significant at the 0.1 level for any of three basins were eliminated in the landslide susceptibility mapping.

### 3.4 Landslide susceptibility mapping

For landslide susceptibility mapping, bivariate statistical index method was employed under a GIS environment. In this method, a weight value for each factor class is calculated. Weight value is defined as the natural logarithm of the landslide density in the class, divided by the landslide density in the entire map (van Westen 1997). All the weight values for each factor's class are added to form a total weight map, which is then normalized into the appropriate range of integers representing the landslide susceptibility index. This is widely used statistical method with apparent predictability rate curve (Brenning 2005). It offers a flexible way of testing the importance of input factors for landslide susceptibility and can be used as a supporting tool in expert-based mapping (Lee et al. 2002; van Westen et al. 2006).

### 3.5 Assessment of validity and replicability

A rule of thumb criterion of at least 75% of landslide grids or counts should occur in 25% of grids under highest susceptibility index was set up for accepting the validity of susceptibility assessment. In case, the susceptibility maps of each basin proved valid, the weight calculated for each factor class of one basin was applied to the corresponding factor class of other basins to calculate similar landslide susceptibility index maps. These maps for each basin were correlated to assess the replicability of the result.

## 4 Results and discussions

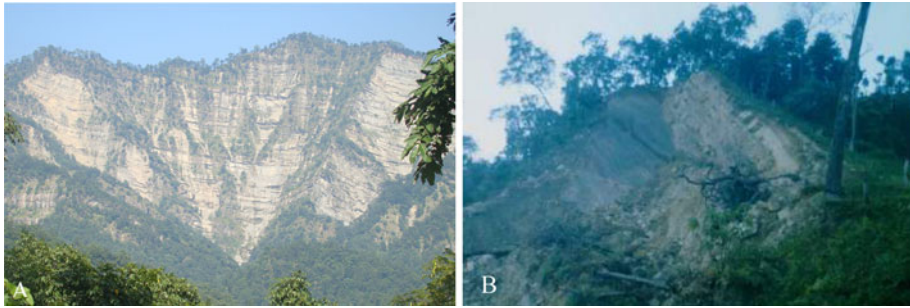
### 4.1 Landslide inventory, types and spatial pattern

An inventory of 225, 336 and 373 active/fresh landslides were made in the Maccheli Khola Basin, Banganga Khola Basin and Binai Khola Basin, which covered 1.51 (271 hectare: ha), 1.34 (239 ha) and 1.86 (403 ha) % of the total area, respectively. The average size of the landslides in all three basins is around one hectare, i.e., (0.84–1.2 ha) with a standard deviation of 1.34 to 2.34. These inventories include landslides of various forms, size, material content and mechanism as classified by Varnes (1978). Landslides in the studied basins reflect the role of the structure and the rock strength. Control of bedding structure and the role of a well-defined system of prominent joints (3–4 sets of joints including varying spacing interval) and differential rates of weathering and erosion of the sedimentary rocks of the Siwaliks and meta-sedimentary and metamorphic rocks of the Lesser Himalaya (northern part of the Banganga River Basin) are evidenced by the landslide types and processes. Physical and chemical action of water in the major joints or hair cracks and solution pores of the calcareous or matrix-supported sediments plays a crucial role in slope failures (Tamrakar et al. 2002).

Broadly these landslides can be classified as rockfall, wedge failure, complex, rotational and translation slides and shallow scar type slope failures based on conventionally accepted morphologic characteristics (Varnes 1978; Cruden and Varnes 1996).

Rockfalls and slides were common in the anti-dip slopes of cuesta topography of the Machheli Khola Basin and on the steep slopes of the Lesser Himalaya in the Banganga Khola Basin in meta-sedimentary rocks, i.e., sandstone and shale inter-bedding (Fig. 4a). Wedge failures (sliding along the line of intersection of two planar discontinuities) were observed on slopes perpendicular or oblique to bedding orientation (Fig. 4b). The dip of the line of intersection associated with the potentially unstable wedge is less than the dip of the slope (Hudson and Harrison 1997). Such failures comparable to deep seated bedrock failures were detected on the orthoclinal slopes of the Middle Siwaliks and Lower Siwaliks of all three basins. Complex to rotational bedrock landslides without a distinct plane of failure are very widespread in the Banganga Khola and Binai Khola Basin. Weathering of mudstone and the disintegration of the sandstone through joints and crack networks may have caused large-scale bedrock slumps (Fig. 5a). Planar failures were observed in the gentler dip slopes. Such planar failures were numerous on dip slopes of gently inclined homoclinal structures (less than 40°) of the Machheli Khola Basin (Fig. 5b). In the Banganga Khola Basin, due to very steep bedding plane of rock strata, i.e., more than 50° in most cases, the dipslopes were not encountered, and therefore planar failures were not apparent. Shallow landslides were common in the highly weathered slopes and on the Upper Siwaliks (Fig. 6a) and parts of the Siwaliks in the Maccheli Khola Basin overlain by the quaternary sediments, and within old





**Fig. 4** **a** Rockfall areas in the anti-dip slopes of the Machheli Khola Basin; **b** Wedge failure at orthoclinal slope in the Banganga Khola Basin

landslide topographies, in the form of regressive or multiple activities. In these areas, shallow slump failures were also noticed. And on the very steep slopes also, such shallow landslide scars with long axis appearing like debris flow were detected (Fig. 6b).

The pattern analysis (Boots and Gettis 1988; ILWIS 3.3 2007) shows that landslides in all three basins are not random in distribution and but they tend to cluster. This clustering pattern may indicate that the landsliding activity is localized to a specific set of controlling and triggering factors. Every next landslide has more than 50% probability of occurrence within a 270, 220 and 180 m for the Machheli Khola Basin, the Banganga Khola Basin and the Binai Khola Basin, respectively. There is 75 to 85% probability of landslide occurrence within 400 m in these basins. This may suggest that landslides are frequent in space and their significance in contribution to landform assemblage can be acknowledged.

Distribution patterns of the active landslides show that the few largest landslides occupy the large proportion of the areas, i.e., 20% largest landslide occupies about 60 to 75% of the total landslide area (Fig. 7). This implies that they are rare in space (as defined by their probability density function (Fig. 8) and are less frequent in time, but their contribution in total volume displaced by mass wasting and accompanied change in landform is high.

## 4.2 Relation with in situ factors

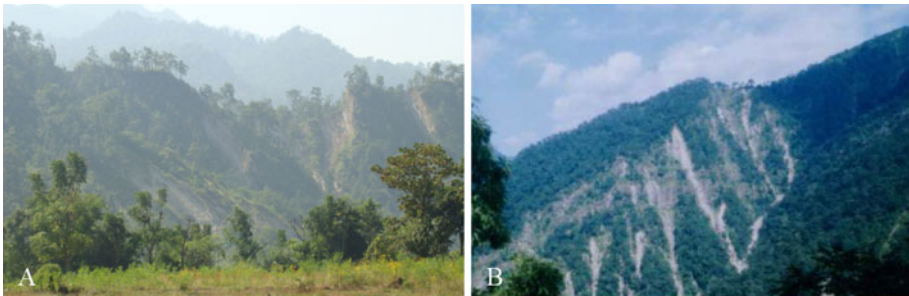
### 4.2.1 Geology and structure

Lithological and structural variations often lead to a difference in strength and permeability of rocks and soils (Pachauri and Pant 1992; Roering et al. 2005), which greatly influences landslide occurrence. Chi-square analysis (Fig. 9 Table 1) reveals that the landslide area in relation to lithology was significant in all basins whereas that for landslide point frequency was contrastingly insignificant in all basins. This implies that the size of the landslides plays an important role in determining the significance of the terrain. Remarkably, the pattern of the curve for expected landslide and observed landslide area did not appear consistent for the Lower and the Middle Siwaliks between basins. Both formations characterize inter-bedding of alternate sequence of hard (sandstone) and soft rock (shale and siltstone and mudstone), and they differ in proportion of grain size composition. Intricate network of joints and fractures on these rocks makes the terrain highly susceptible to bedrock slope failure during high rainfall, and to seismic events or any extrinsic stress.

The observed landslide frequency was comparatively low in the Upper Siwaliks. Nevertheless, loosely packed unconsolidated coarse and fine sediments of this sedimentary

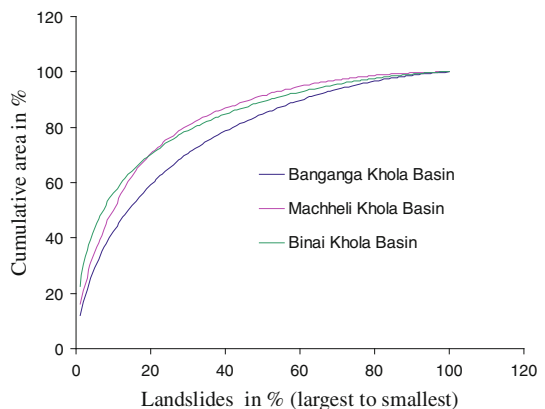


**Fig. 5** **a** Landslides in the mudstone and sandstone sequence of the Lower Siwaliks; **b** Complex translational slides on the dipslopes of the Middle Siwaliks in the Machheli Khola Basin

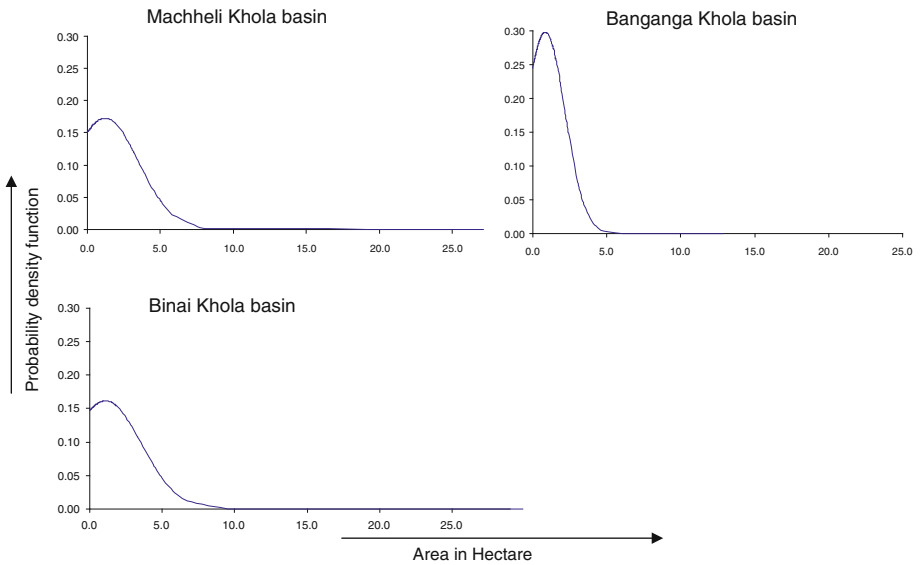


**Fig. 6** *Shallow landslides*. **a** the south facing slopes of Upper Siwaliks in the Binai Khola Basin, and **b** the steep south facing slopes of the Middle Siwaliks in the Banganga River Basin

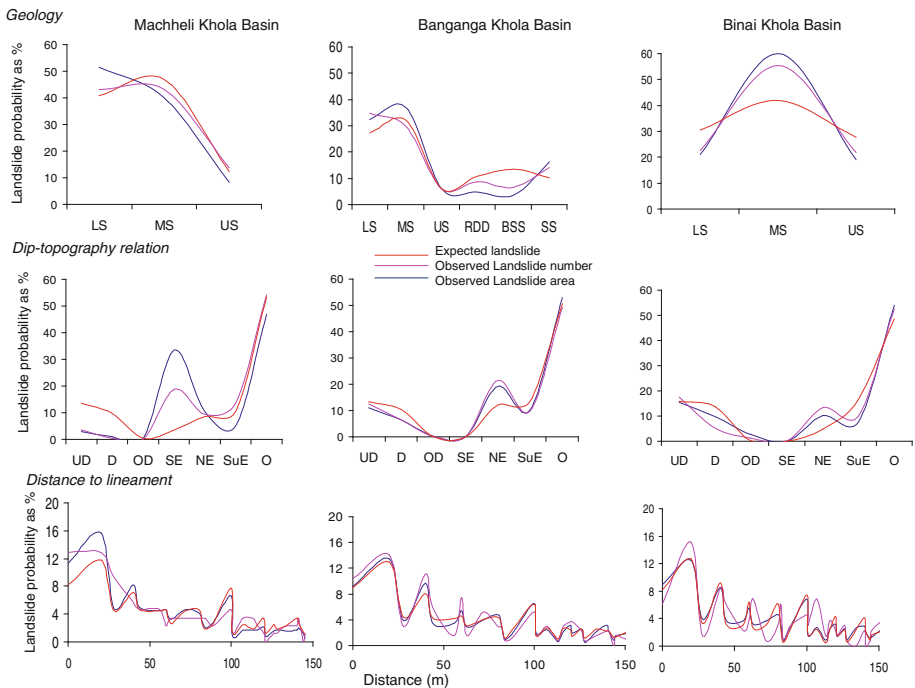
**Fig. 7** Active landslides distribution and area



sequence are highly erodible and the sediments are easily plucked or reworked by the fluvial agents (Dhital et al. 1993). Any scars made by a mass movement in these rocks could easily be modified to oblivion by water erosion. In the Lesser Himalayan part of the Banganga Khola Basin, more landslides were observed in areas of brittle shale rock while those of dolomite and limestone, fewer landslides were observed than expected.



**Fig. 8** Active landslides distribution with respect to area



**Fig. 9** Observed and expected landslides in geology (*LS* Lower Siwaliks, *MS* Middle Siwaliks, *US* Upper Siwaliks, *RDD* Ridi Khola Dhatibang Dolomite, *BSS* Banskota Sandstone and Shales, *SS* Supa Khola Shales); dip-topography relation (*UD* underdip slope, *D* dip slope, *OD* overdip slope, *SE* steep escarpment, *NE* normal escarpment, *SuE* subdued escarpment, *O* orthoclinal slope); and distance to fault or lineament

**Table 1** Calculated  $\chi^2$  value for landslide distribution in various in situ terrain factors

In situ factors	Basins	Degree of freedom ( $n-1$ )	Calculated $\chi^2$ value for landslide		Critical values at 0.1 significance level
			Area	Number	
Geology	Ma. Kh	2	5.01	0.64	4.605
	Ba. Kh	4	15.84	7.64	7.779
	Bi. Kh	2	13.35	7.37	4.605
Dip-topography relation	Ma. Kh	6	266.91	80.28	10.645
	Ba. Kh	6	8.03	15.07	10.645
	Bi. Kh	6	41.39	39.89	10.645
Distance to lineament	Ma. Kh	26	6	20.19	35.563
	Ba. Kh	27	2.77	15.92	36.741
	Bi. Kh	27	2.92	41.59	36.741
Slope gradient	Ma. Kh	17	390.28	187.53	24.769
	Ba. Kh	17	30.95	57.09	24.769
	Bi. Kh	17	103.85	96.76	24.769
Relative relief	Ma. Kh	15	498.32	211.86	22.307
	Ba. Kh	15	32.97	52.02	22.307
	Bi. Kh	15	132.41	101.22	22.307
Altitude	Ma. Kh	15	16.48	15.62	22.307
	Ba. Kh	15	39.22	28.47	22.307
	Bi. Kh	15	42.84	42.12	22.307
Slope aspect	Ma. Kh	8	129.47	101.23	13.362
	Ba. Kh	8	10.72	17.82	13.362
	Bi. Kh	8	12.84	11.23	13.362
Contributing upslope area	Ma. Kh	11	3.79	10.54	17.275
	Ba. Kh	11	5.04	5.89	17.275
	Bi. Kh	11	8.06	11.47	17.275
Drainage density	Ma. Kh	17	13.75	8.28	24.769
	Ba. Kh	17	10.66	6.3	24.769
	Bi. Kh	17	8.58	6.84	24.769
Land use and land cover	Ma. Kh	4	16.94	5.09	7.779
	Ba. Kh	3	703.7	795	6.251
	Bi. Kh	4	374.58	151.67	7.779
Vegetation density	Ma. Kh	17	44.93	28.63	24.769
	Ba. Kh	17	61.89	26.77	24.769
	Bi. Kh	17	42.07	11.3	24.769

(*Ma. Kh.* Machheli Khola Basin; *Ba. Kh.* Banganga Khola Basin; *Bi. Kh.* Binai Khola Basin). The shaded cells indicate the relationship is significant because calculated  $\chi^2$  value for landslide is greater than the critical value

A significant relationship between dip-topography and landslide area and count was analyzed in all three basins (Fig. 9 and Table 1). The pattern of the observed landslides with respect to expected landslides is more or less consistent between the basins. Generally, underdip and dip slopes were found less vulnerable to landslides as compared to escarpments or orthoclinal slopes. This result is quite contrary to the findings of Roering et al. (2005) and Guzzetti et al. (2008). Dip slopes are generally considered as potential zones of weakness, and failure surface is ready made and the condition of the groundwater

flow in dip slopes are favorable for slope failure (Cruden 1988). The abundance of landslides in anti-dip and orthoclinal slopes is probably related to the presence of prominent joints in the direction perpendicular or oblique to the bedding and the steep topography.

Many active faults of local and regional scale in the Siwaliks have been identified in association with the thrusting activity of the earth crust along the thrust zone (Nakata 1989; Lavé and Avouac 2000). Several straight to slightly curved linear topographic features (lineaments) have been traced from imageries and aerial photos that represent fractures, fault traces and topographic breaks. The slopes traversed by faults or lineaments are regarded as potentially unstable.

The chi-square analysis showed no apparent significance of faults and lineaments on the distribution of landslides both in area and counts within the buffered zone of 150 m (Fig. 9 and Table 1). This threshold was considered on the basis of the extent of slope failures from mountain scarps, topographic breaks, identified faults and the distance between local crest line and foot-slope. The reason may be that landslides are perhaps controlled by an intricate system of widespread minor and major joints, superimposed over the sedimentary bedding structure irrespective of the proximity to faults or major lineaments.

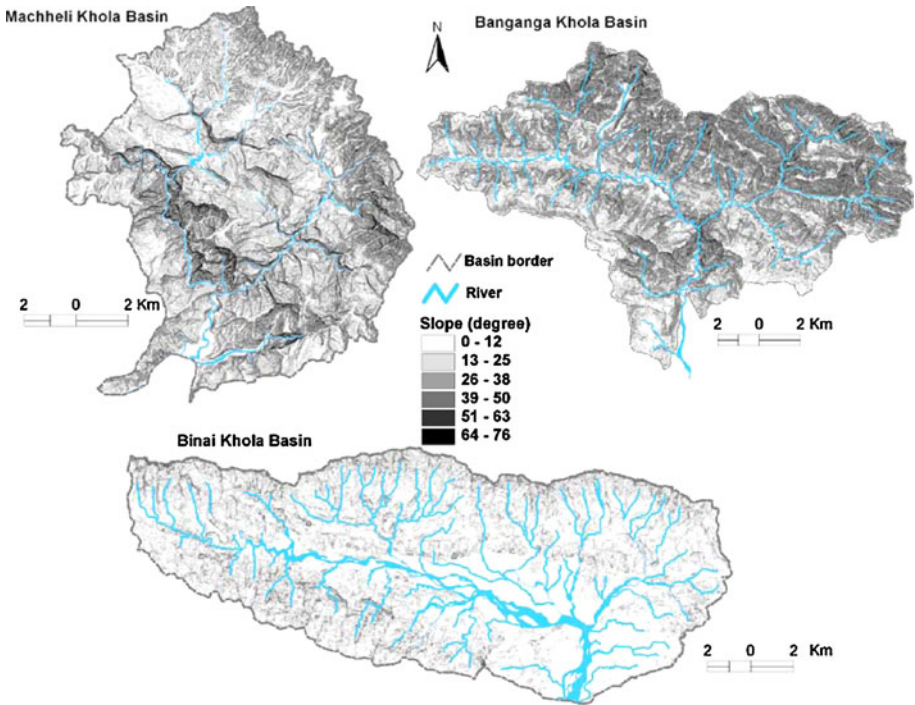
#### 4.2.2 Topographic factors and drainage density

In all three basins, the landslides are mostly distributed on the slopes between 20 and 40 degree (Fig. 10). The chi-square analysis shown in the figure also establishes the fact that steep slopes are related to landslide occurrence both in terms of landslide area and frequency (Fig. 11 and Table 1). Hence, this relation accords with the theory that the downhill component of force is high on the steeper slopes, which induces gravitational shear stress on slope materials to induce slope failure (Dai et al. 2001; Chapin et al. 2002). However, since slope gradient in combination with the slope material cohesion, angle of repose and moisture conditions normally determine slope stability conditions; gentler slopes may also render the landslides, particularly in colluvial or deeply weathered slopes (Selby 1993).

Relative relief, i.e., local difference in height within a unit area (hectare) also shows a significant association with landslide area and count as well (Fig. 11 and Table 1). The threshold local height is between 50 and 55 m/ha beyond where the observed landslide probability increases for the both cases compared to the expected probability in all three basins. Potential energy required for erosion and mass movement in general increases with increased local elevation. High relative relief can be both cause and consequence of the landslides in the susceptible sedimentary Siwaliks where bedrock slides as are common.

The aspect of the slope reflects the moisture retention, and vegetation and its relation to rain-bearing wind and the attitude of rock bedding, which in turn influence the physical properties of slope material and its susceptibility to failure (Dai et al. 2001). The chi-square test verifies the significance of the landslides relation to slope aspects for two basins only (Fig. 11 and Table 1). However, the abundance of landslide areas and numbers on south facing slopes is quite evident when compared to other slope aspects. The south facing slopes of the basins are generally steep and anti-dipping slopes (where rockfall and incessant fall of thin weathered debris is common); and many south facing facets are on the windward side of the summer monsoon rain. This result agrees with that of Marston et al. (1998) and Dai et al. (2001)'s study. However, the topography in these basins is not so high to produce pronounced orographic effect as in the High Himalaya (Marston et al. 1998).

Chi-square analysis does not reveal defendable relation between altitude and landslides both in areas or frequency in all three basins (Fig. 12 and Table 1). However, the

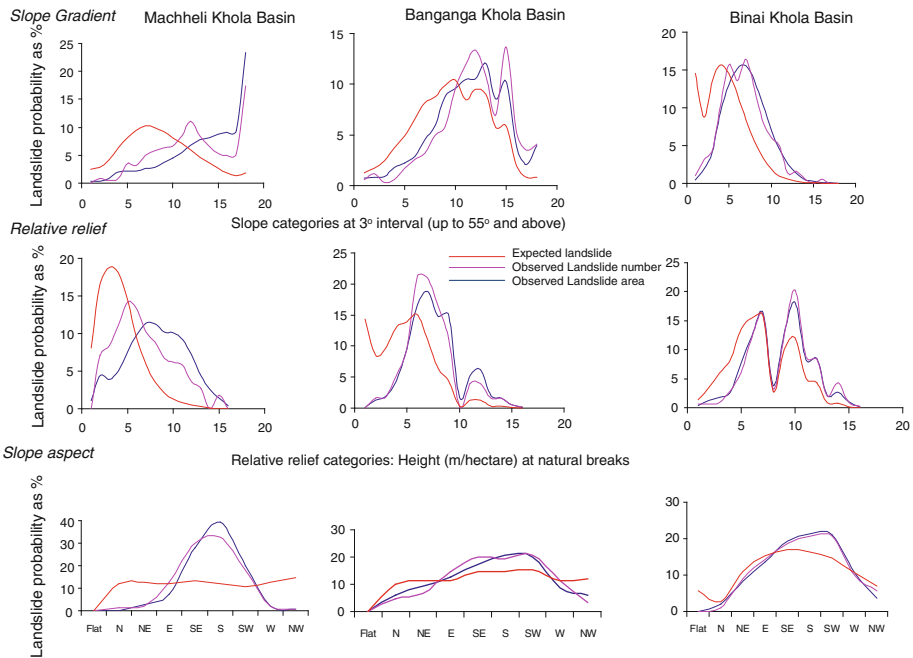


**Fig. 10** Slope map

proportion of landslides progressively rises with relief up to the middle altitude. Then after the proportion tend to decline toward high altitudes. Generally, in hill summits, the rock mass strength is normally high and usually consists of weathered rocks or whose shear strength is much higher (Dai et al. 2001). The intermediate elevation in the study basins tend to be generally steep and convergent terrain, and the role of pore water pressure in the joint planes and on the thin veneer of colluviums probably make the terrain prone to both bedrock and shallow landslide activity.

The upslope contributing area, which is calculated from the DEM can be a proxy expression of ridge line, site of residual soil, colluvium concentration and moisture availability and drainage flow line (Beven and Kirkby 1979; Dietrich et al. 1995; Pack et al. 2005). It determines where the slope materials and water is dispersed and where the flow of both water and slope materials tend to concentrate. The later one is known as convergent slopes, which can be potential areas of colluviums, saturation and landslides. The chi-square analysis shows no apparent relation with landslides for both area and count in all three basins (Fig. 12 and Table 1). However, the observed frequency for landslides is high on the mid-slopes of the Machheli Khola Basin and the Binai Khola Basin, where the mass wasting processes, particularly soil covered failures are usually high.

Drainage density indicates run-off conditions as well as the degree of dissection of the landscape. The dense network of drainage line indicates high runoff and low infiltration and vice versa. Some research shows that pore pressure develops due to high infiltration of rainwater and makes the slope potentially unstable (Selby 1993). On the contrary, one theory states that channel heads can be the initiator of landslides, particularly on the deeply

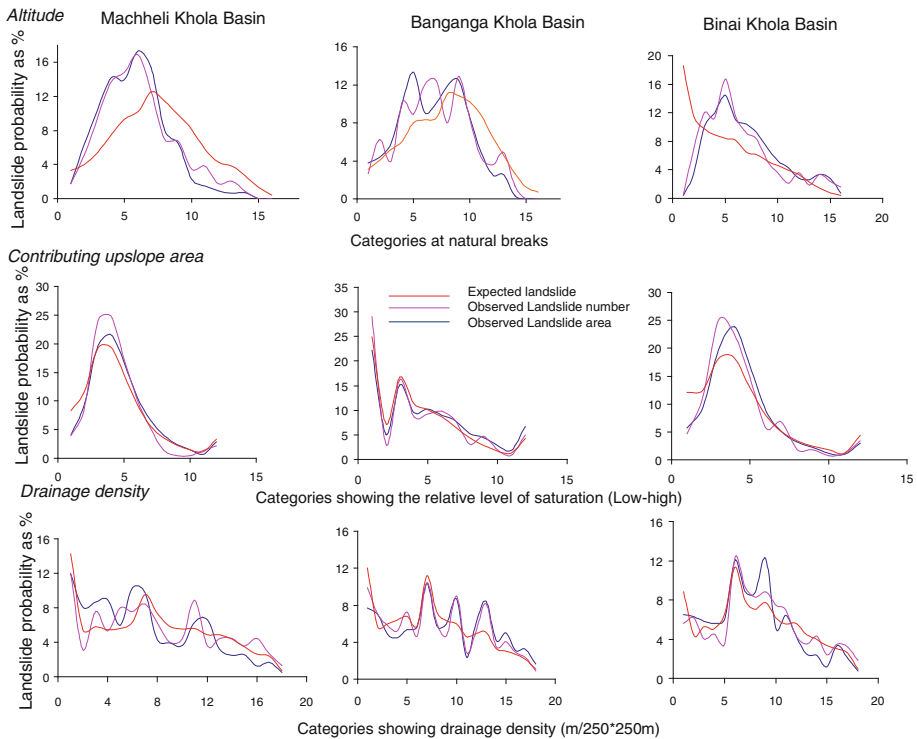


**Fig. 11** Observed and expected landslides in categories of slope gradient, relative relief and slope aspect

weathered and thick colluvium mantle slopes (Dietrich and Dunne 1978). In such cases, high incidences of landslides are expected on high drainage density. No significant relation between drainage densities and landslides were qualified by chi-square test (Fig. 12 and Table 1). In the study area, both shallow and bedrock landslides were common, which might be the result of abovementioned phenomenon.

4.2.3 Land use and land cover and vegetation density

Land use and land cover in the Siwalik basins reflects the terracing of slopes for cultivation or forestry. The chi square test shows landslide occurrence (both in area and number) on land use and land cover type in all three basins is very significant (Fig. 13 and Table 1), which implies that it could be an important conditioning factor. This relation is mainly controlled by the barren land, which is attributed to landslide and erosion scars as revealed by the aerial photographs. Pre-landslide conditions on the slopes are likely to be forest or shrub-land by virtue of landslide location. The normalized difference vegetation index map showing vegetation condition of 1989–90 also depicts a significant relation (Chi square) to landslide occurrence, except for the Binai Khola Basin in regards to landslide frequency (Fig. 13 and Table 1). Landslide incidences are high in the degraded area. The widely held view is that the vegetation can protect slopes by reducing erosion, strengthening soil and inhibiting landslides, which increase general slope stability. (Greenway 1987; Bell 1998). However, tall hardwood trees in the Siwaliks exposed to wind may transmit the forces into the slope and cause slope failure by increasing the lateral load in fragile terrain. Weight of such trees surcharges the slope, increasing normal and downhill force components and may cause failure (Bell 1998) during the monsoon.



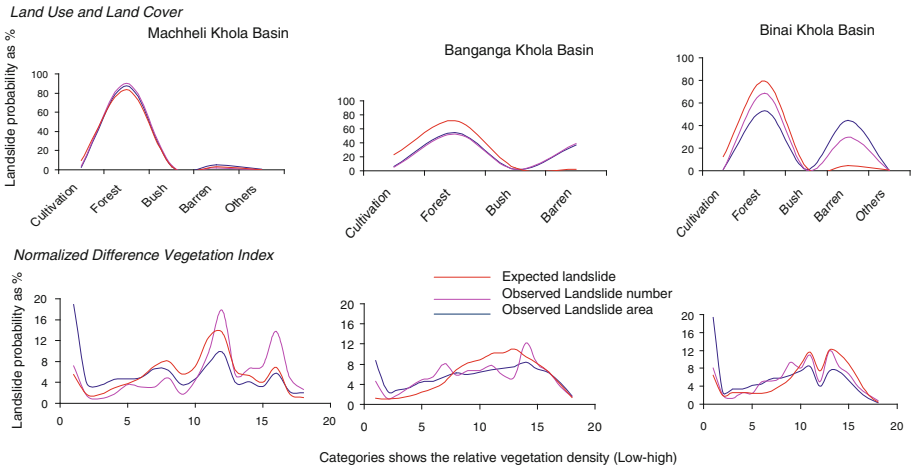
**Fig. 12** Observed and expected landslides in categories of altitude, contributing upslope area and drainage density

### 4.3 Landslide susceptibility mapping and validation

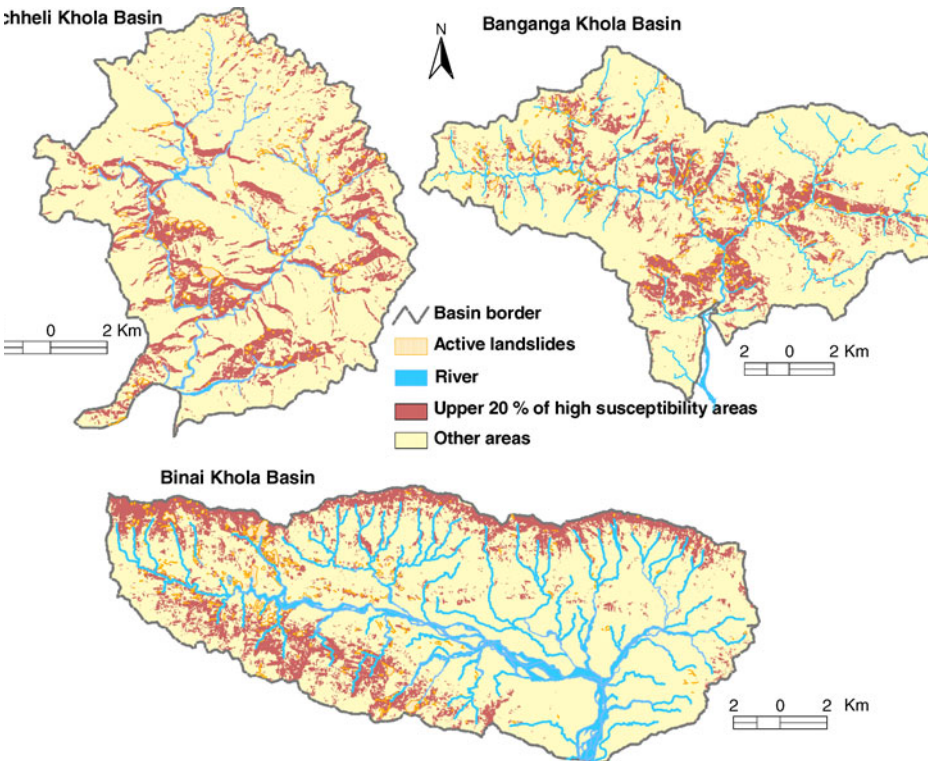
Landslide susceptibility is measured in terms of the susceptibility index, which is the sum total of the weight of various classes of in situ factors. As mentioned earlier, about 8 in situ factors (Table 1) have tested significant association with landslide areas or number in at least two basins in chi-square analysis. These factor maps were chosen for susceptibility analysis for each basin. As a result, landslide susceptibility maps were produced for each basin (Fig. 14). About 74–86% of landslide areas and above 71% of landslide numbers were concentrated in areas showing upper 20% of the susceptible index in all three basins (Fig. 15). There is a clear positive S-shaped trend between the susceptibility index and landslide density in all three basins (Fig. 16).

This reasonably verifies the validity of method adapted for susceptibility mapping. A correlation between susceptibility index and slope gradient and relative relief was calculated as 0.66 and 0.69 for the Machheli Khola Basin; 0.46 and 0.45 for the Banganga Khola Basin; and 0.75 and 0.81 for the Binai Khola Basin, respectively. Between slope and relative relief, the correlation was 0.60 for the Banganga Khola Basin, and it was 0.8 for the Machheli Khola Basin and 0.88 for the Binai Khola Basin, implying a certain degree of colinearity between them. Other value maps representing altitude and vegetation density also showed considerably good correlation with the landslide susceptibility index, i.e., 0.61 and 0.62 in that order for the Binai Khola Basin only. These parameters were not significant for the other two watersheds. The steep terrain formed at anti-dip slopes and on the



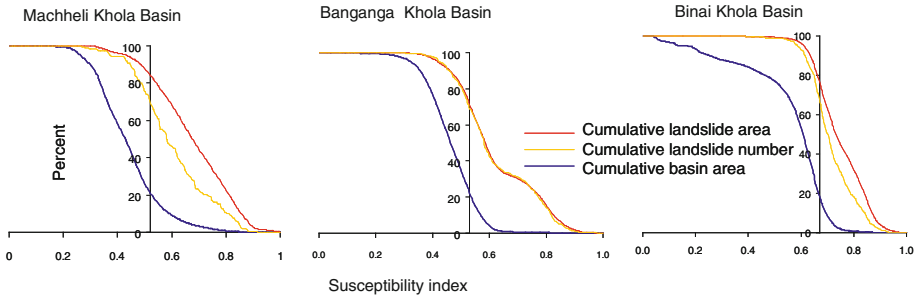


**Fig. 13** Observed and expected landslides in categories of land use and land cover and vegetation density

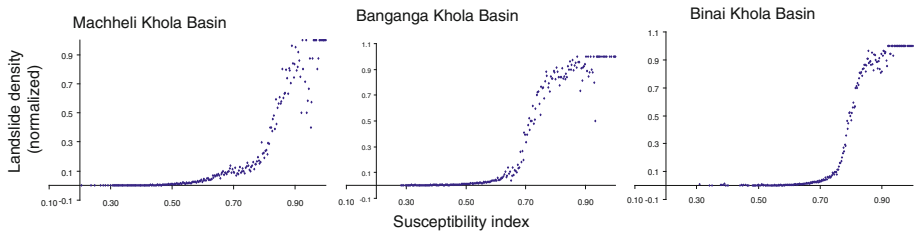


**Fig. 14** Landslide susceptibility maps

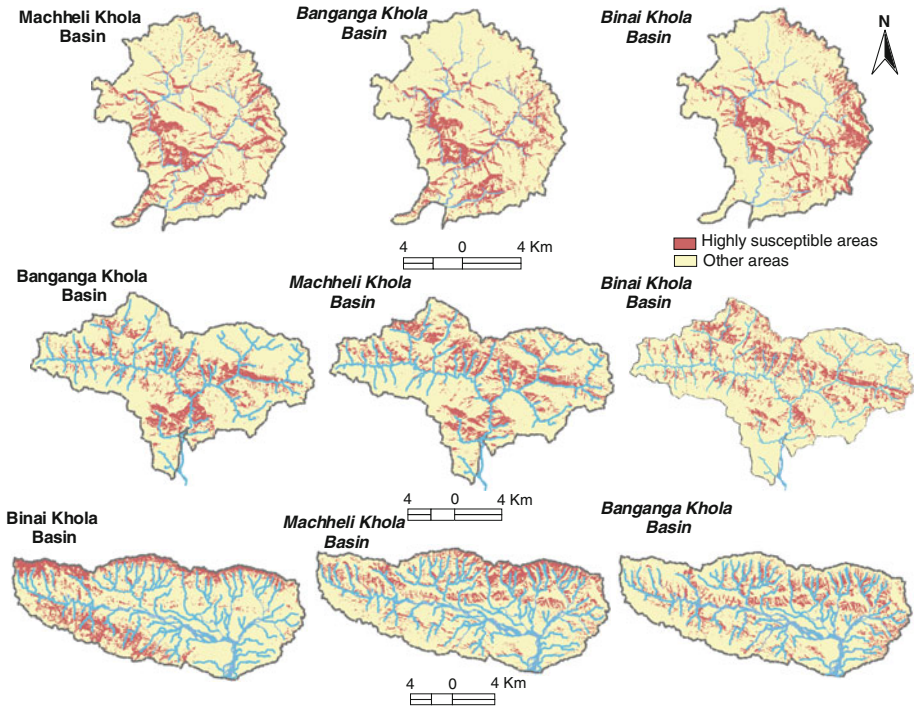
south aspects also characterized the landslide susceptible areas in all the three basins. Noticeably, the highly susceptible areas seem aligned to the Main Boundary Thrust and imbricate faults in the Banganga Khola Basin.



**Fig. 15** Distribution of cumulative percent of susceptible index area, landslide area and number



**Fig. 16** Relation between susceptibility index and landslide density



**Fig. 17** Landslide susceptibility index maps calculated from inter-basin weight values (in situ factor) incorporated from the different basins. The name in italics denotes the source basin

**Table 2** Correlation matrix of the susceptibility index maps produced from the in situ factor classes' weight calculated for three different basins

		Weight source			
		Basin	Machheli Khola	Banganga Khola	Binai Khola
Machheli Khola	Machheli Khola		1	0.78	0.57
	Banganga Khola		0.78	1	0.56
	Binai Khola		0.57	0.56	1
		Weight source			
		Basin	Banganga Khola	Machheli Khola	Binai Khola
Banganga Khola	Banganga Khola		1	0.78	0.73
	Machheli Khola		0.78	1	0.58
	Binai Khola		0.73	0.58	1
		Weight source			
		Basin	Binai Khola	Machheli Khola	Banganga Khola
Binai Khola	Binai Khola		1	0.61	0.42
	Machheli Khola		0.61	1	0.71
	Banganga Khola		0.42	0.71	1

By incorporating the in situ factors' class weight values calculated for one basin to other two basins, proxy susceptibility maps were also calculated for each basin (Fig. 17). The correlation matrix shows that the susceptibility maps (both main and proxy) have a certain range of positive correlation between them (Table 2). Comparatively, susceptibility maps prepared from the weight scores of the Machheli Khola Basin and the Banganga Khola Basin were better correlated than that of the Binai Khola Basin.

Landslide susceptibility seems to be dominantly controlled by the slope gradient and relative relief. Hence, these two parameters possibly can be used as proxy indicators for landslide susceptibility in the entire Siwalik Hills.

### 5 Conclusion

A combination of several in situ terrain factors on a location offer different degrees of susceptibility to terrain for slope failure. As a result, landslides tend to cluster in distribution. This statistical black-box approach study does not explain the true nature of the relationship of terrain factors to landslide activity in the Siwaliks; nevertheless, the statistical relation that this study has exposed is important to identify and map the susceptible areas. The GIS-based bivariate mapping approach was successfully applied for susceptibility mapping and verifying the reliability at the present scale of analysis. A certain degree of replicability of the result to a greater region of similar geo-environmental setting was found among the studied basins. For this reason, at least, landslide numbers in the range of around 200–400 can be explained for the calculated susceptibility maps of any basin. By assessing the landslide relationship, and analyzing the result, I found that the role of steep and rugged topography and steep anti dip slopes of the Lower Siwaliks and the Middle

Siwaliks sedimentary sequence can be used as proxy indicators of landslide prone areas in the Siwalik Hills. To a greater extent, steepness of the terrain can be a surrogate for landslide susceptibility of the Siwalik Hills. In the absence of detailed information about terrain factors pertaining to geological structure, underground hydrology and soil on a larger map scale and the identification of critical parameters that cause slope failure, this approach of landslide-terrain relation investigation and susceptible assessment can be one of the alternatives in the Siwalik Hills.

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