# Chapter 17
# Village Level Landslide Probability Analysis Based on Weighted Sum Method of Multi-Criteria Decision-Making Process of Darjeeling Himalaya, West Bengal, India

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**Abstract** The Himalayan mountains are highly prone to landslides, and every year a multitude of slide events take place along its entire ranges. Darjeeling Himalayan region of West Bengal is not an exception and also highly prone to landslides. In the Darjeeling Himalayan extents, landslides are the major threat to the lives and properties of the people and also hamper the connectivity and commerce of the region aggravating lopsided development and poor economic condition. Considering the magnitude of landslide frequency and its extremities, this study aims to develop a landslide probability index (LPI) for the projection of landslide probabilities at the village level. The proposed methodology of the LPI is based on the weighted sum method of multi-criteria decision-making processes that involve eight explicitly localised proxy/indicator quantitative analysis, normalisation and weight assignment. The result of the derived LPI is divided into 4 distinct classes, viz. (a) very high landslide probability class comprising 45 villages, (b) high landslide probability class consists of 138 villages, (c) moderate landslide probability class includes 109 villages and (d) 56 villages are in low landslide probability class. It is evident from the study that the nature of landslide phenomenon is resulting from the interaction of contributing physical indicators, i.e. fragile lithology shares 34.58% in the radar diagram as the prime contributor of landslides in the DHR followed by drainage density at 17.91% and high degree of slope at 14.77%, and identification of such drivers of landslide probability can also be used in developing targeted adaptation planning and interventions.

**Key words** Darjeeling Himalayan region · Landslide probability index · Multi-criteria decision-making · Village level · Adaptation planning

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## 17.1 Introduction

The Himalayan mountains are highly prone to landslides. Landslides are simply defined as the movement of the mass of dislodged rock, debris or earth materials down a slope including a broad range of motions whereby falling, sliding and flowing under the influence of gravity (Mandal & Maiti, 2014). Basically, landslide is nothing but a complex and systematic interaction between sets of physical and manmade factors governed by geologic, hydrologic, climatic, geomorphic and land use attributes (Wilson & Keefer, 1985). Every year a multitude of slide events takes place along the entire Himalayan ranges. Darjeeling Himalayan region (DHR) of West Bengal is no exception and is also highly susceptible to landslides. Every consecutive year more than hundreds of new landslide events add to the region's landscape during the monsoon and immediate post-monsoon season (Mondal, 2016).

Regionally, the geomorphology of this terrain represents an intricate interplay of erosional and gravitational processes (e.g. mass wasting) aided by the active tectonic effects of the Himalayas due to proximity of regional tectonic plates (Ghosh et al., 2014). Mallet (1874) opined that in the Darjeeling territory the Gondwana rocks are overlain by metamorphic rocks, which are termed as Darjeeling gneiss (mainly mica-gneisses and schists) and Daling (mainly slates and phyllites). These two lithological units are highly fractured and have been weathered by rainwater to considerable depths below the surface. Thus, in the mountainous region, the ground behind the cliffs is highly decomposed vis-a-vis porous, and during the rains as saturation takes place, the rock face is gradually detached from the ground leading to small and large blocks of rock bodies to slide (Basu & Majumder, 2006). Alongside, the rainwater triggers landslides as it alters the pressure within the slope, which leads to slope instability. Consequently, the heavy water-laden slope materials (soil, rock, etc.) will succumb to the forces of gravity (Conners, 2017). Starkel (1972) for the first time observed the geomorphic effects of an extreme rainfall event in the eastern Himalaya (Darjeeling), India. Froehlich et al. (1990) investigated the same area and found that shallow slides and slumps on steep slope segments occur when 24 h rainfall reaches 130–150 mm or continuous 3 days rainfall totals 180–200 mm. Though the natural factors are very conducive to the occurrence of slides, owing to the regional instability, immature geology and meandering streams, the actual chaos on slopes came when the man entered the scene (Bhandari, 2006). Vast areas of the DHR hilly parts fell to his axe and were robbed of the protective vegetal cover in terms of lopping of trees for fuel or fodder, overgrazing, increased domestic and industrial consumptions of timber, which were chiefly responsible for deforestation. Nevertheless, the spurt of human settlements has increased the number and frequency of landslides, over the period of past few decades (Bhattacharya, 2012). Growing urbanisation and uncontrolled land use are increasing overwhelming pressure on immediately available sloppy mountainous land and making the ecosystem vulnerable with a rising trend of landslide hazards. These quasi-natural events are major

threat to the lives and properties of the people and also hamper the connectivity and commerce of the region aggravating lopsided development and poor economic condition.

Earlier studies have analysed landslides of the Darjeeling Himalayas from different perspectives. Many of them begin with geographical characteristics and climate that impacts the landslide configuration followed by some with unexpected consequences of the landslide. Contemporary research works have also tried to introduce new approaches to the landslide studies. Caine and Mool (1982) and Dhakal et al. (1999) focused on landslide risk assessment in Himalayan terrains by analysing physical properties of landslides and debris flows, effects of regional and local geological settings and recommendations for environmental-friendly preventive measures. Some studies attempt to establish the hazard mapping methods that consider natural terrain parameters which play a role in slope failure (Hays, 1981; Kitutu et al., 2009; Sarkar & Kanungo, 2010). Nevertheless, interesting works are also available in which the authors tried to apply intensive methods for landslide vulnerability zonation, and most of them include geologic and geomorphometric analysis of the study area to understand the various terrain parameters responsible for the different magnitudes of landslide susceptibility and field survey (Powde & Saha, 1976; Ghosh, 2011; Bhattacharya, 2014). Basically, the landslide vulnerability zonation contains two vital parts starting with the prediction of spatial probability of the occurrence of landslides in various magnitude zones over an area (Sharma et al., 2009, 2011; Luan et al., 2010; Mukhopadhyay et al., 2012) and ending with their use in the planning of risk mitigation as well as understanding their relation with the elements at risk, e.g. the population, buildings, civil engineering works, economic activities, public services, utilities, infrastructure, etc. (Govt. of India, 2009). Thus, it is quite clear that the landslide phenomenon of hilly regions has been examined from different viewpoints in the past, but this present study aims to develop a probability index of landslide occurrence at village level in the DHR. Based on the available data and geospatial techniques used, this particular study tries to identify possible sites of landslide occurrence on a microscale prior to the events within the selected geographical location.

The increasing trend of landslide events demands a better understanding of what causes landslides and how to mitigate future damage. The field of landslide risk assessment is growing rapidly, and many spatio-temporal modelling tools are addressing how to predict landslide frequency and severity. In this context, considering the magnitude of landslide frequency of the DHR and its extremities, the extended part of this study prepares a detailed inventory of landslide events with spatial information. The geoinformation technology played a formidable role in quantitative model building for village-wise landslide probability index (LPI) involving region-specific significant indicators and will empower us to identify villages with a higher probability of landslide occurrence as well as suggests strategic intervention mechanism. The outcomes of this study will enable the local administrators and stakeholders in proper decision-making and enforcement of better management strategies to combat with the recurring quasi-natural hazard owing to the regional settings within the concerned region and considered to be necessary input for effective area planning in near future.

## 17.2    Materials and Method

### *Study Area*

The Darjeeling Himalayas hilly parts are the portion of tertiary young fold mountain system, characterised by lofty ridges, numerous river valleys, mountain spurs and foothills (Terai) with its ramifications comprising a total area about 2390 km$^2$, extending from 27°13'N to 26°44'N latitude and 88°53'E to 87°59'E longitude, bordered by Mechi and Jaldhaka rivers in the western and eastern sides, respectively, and bounded by the state of Sikkim in the north, Nepal in the west, Bhutan on the north-east and Bangladesh in the south-east directions (Bhattacharya, 2017). More specifically the present study area deals with 6 hilly community development (C.D) blocks of Darjeeling district and 3 C.D blocks of Kalimpong district that includes 117 gram panchayats in which 348 villages/census and towns/municipalities have been well demarcated (Fig. 17.1).
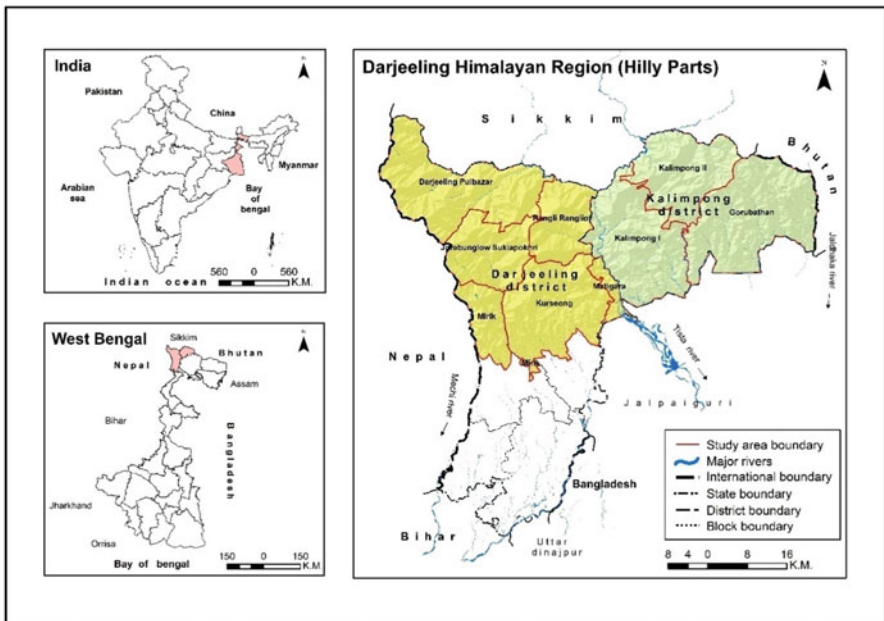


**Fig. 17.1**  Location map of the study area

## Collection of Dataset and Processing

To generate the base database for this study, topographical sheets bearing numbers 78A/4, 78A/8, 78A/12, 78A/16, 78B/1, 78B/2, 78B/3, 78B/5, 78B/6, 78B/7, 78B/9 and 78B/13 on 1:50,000, 1:63,360 and 1:2,50,000 have been collected earlier from Survey of India and National Atlas and Thematic Mapping Organisation Kolkata. Initially, toposheets have been geo-referenced using ESRI ArcGIS v10.3 software in Universal Traverse Mercator projection system. During the geo-referencing process, four ground control points were taken over the whole area from each topographical sheet whose latitude and longitude are identified. Afterwards, known coordinate values have been manually put to create the link, and a first-order transformation has been used for registration with root mean square error of 0.5 which is good. Resampling is performed by nearest neighbour technique to create a final geo-referenced map.

Pre-processed Linear Imaging Self Scanning-IV multispectral image (spatial resolution 5.8 m, path/row 584-587/272-273) of 2015–2016 fused with Cartosat-1 panchromatic data (spatial resolution 2.5 m) of 2015–2016 that were obtained from National Remote Sensing Centre, India, images and eventually exercised to obtain Standard False Colour Composite (SFCC) images in ERDAS Imagine v14 software. The Advanced Land Observing Satellite, PALSAR, orthorectified digital elevation model (DEM) data (spatial resolution 12.5 m) of 2015 were retrieved from the Alaska Satellite Facility repository to determine the spatial distribution of slope and aspects. Secondary data sources like geo-referenced digital lithology and mineral occurrence map on scale 1:2,50,000 have been collected from the Geological Survey of India.

## Inventorisation of Landslide Events

The most crucial step in this landslide probability study is to make a landslide inventory for past events. Geospatial inventory of landslides helps to draw the spatial relationship not only between landslides and biophysical factors, but it also enables us to enlighten the role of human interventions in the occurrence of the landslide. A landslide inventory is usually a collection of points and polygon shapes which represent the boundary of a single event or a complex landslide, generated by multiple events (van Westen, 1993; Guzzetti et al., 2012). Nowadays landslides are delineated digitally in a geographical information system environment (Carrara et al., 1991; Van Den Eeckhaut & Hervás, 2012) and even in several complex environments (forested areas with frequent debris or earth flows triggered by earthquakes) where certain geospatial data are available (high-resolution imagery, DEM) (Scaioni et al., 2014). Hence in this work, initially based on the SFCC images, landslides were marked in and around the study area by placing a single point on each landslide event that has occurred between 2005 and 2020. Consequently, the

village level spatial location of single landslide points has been precisely validated in the Google Earth Pro platform with limited field checks. For the sake of a detailed study, the derived landslide points are being analysed with every indicator data that are taken to develop the LPI to figure out the maximum correlation between them. Such case study approach that has been taken here for a transparent understanding in a substantial proportion for landslide inventories based on topographic maps and DEM could also be used for checking landslide probabilities in respect to the geomorphological-topological inconsistencies.

## *Development of LPI*

### **Selection of Region-Specific Indicators**

Landslide susceptibility mapping using digital spatial information has been conducted extensively since the early 1980s (van Westen et al., 2008). Most susceptibility mapping techniques in landslide study the potential use of previous landslide records in predicting future landslides with the reflection of certain regional factors (Abdulwahid & Pradhan, 2016). Therefore, in case of developing LPI for the projected landslide probabilities at the village level, a set of conditioning factors of the DHR have been taken into serious consideration. The proposed methodology of the village-wise LPI is based on the weighted sum method of multi-criteria decision-making (MCDM) processes involving eight explicitly localised proxy/indicators, namely, (a) fragile lithology (phyllite, schist, sandstone dominated), (b)more than 30° slope, (c) drainage density, (d) the number of landslide events that occurred, (e) forest cover, (f) pucca road density, (g) south and south-east aspect and (h) settlement.

All of these indicators were found to be an active contributor in the landsliding process specifically in the hilly terrain, and the rationales behind their involvement are well articulated in previous research studies. A vast amount of geotechnical information has been already collected as a result of demand-oriented studies. These studies reveal that the lithology of the DHR in most of the places is fragile in nature, and it is observed that phyllite-dominated Proterozoic litho-unit Reyang Formation of Daling group and another schist-dominated Proterozoic litho-unit Gorubathan Formation of the same group are highly weathered and foliated with maximum landslide probability (Basu, 1969–70). The slope is a constant influential acclimatising agent in landslide occurrence. This factor directly affects landslide occurrence and is typically considered in landslide susceptibility analysis (Alimohammadlou et al., 2013; Biswajit & Sameen, 2017). As the slope becomes steep, the vertical component of gravity increases; hence, most of the landslides occur on more than 30° slope (Tournadour et al., 2015; Abdulwahid & Pradhan, 2016). The slope aspect denotes downslope direction in respect to the alignment of slope facet, is an important casuative element for landslides. This factor stimulates weathering process by receiving direct hit of precipitation, wind and sunlight

(Budimir et al., 2015). In this study south and south-east aspects have been taken into account. Due to its windward face, south-west monsoon hits directly throughout the monsoon season resulting in the maximum number of landslide events. The drainage density is often used to estimate the surface flow and potential instability of fragile slope (Mondal & Maiti, 2013), along with higher drainage density of an area which indicates the higher magnitude of headward erosion on steep slope with fragile lithological ground results in slope failure-type landslide events (Roy & Sensharma, 1967). Among the selected indicators, only the forest cover maintains a negative functional relationship with the landslide, as the root system of forested vegetation stabilises hillslope by reinforcing soil shear strength. The more the roots penetrate a potential a shear plane, the greater is the chance that the vegetation will increase slope stability (Abe & Ziemer, 1990). However, changes in the forest landscape or large-scale logging can alter the soil infiltration and ground evapotranspiration rates, thus indirectly affecting the water contents in soil and reducing slope stability (Vanacker et al., 2005; van Noordwijk, 2005; Chuang & Shiu, 2017).

Anthropogenic interventions like the extensive spread of human habitation in form of settlement are highly site- and situation-oriented entity of land use practice, but the availability of suitable land for settlement in the mountains is quite challenging. At present, people of high mountains are living in risky and hazardous terrain and facing serious threats. The replacement of forests by agriculture and settlements is thought to cause severe erosion and landslides (Glade, 2003; Soini, 2005; Chuang & Shiu, 2017). The growing population of the hills demand better communication and mobility that in turn give rise to metalled road construction that are generally believed to compromise slope stability and trigger landslides as well as debris flows (Burton & Bathurst, 1998; Chuang & Shiu, 2017).

**Indicators Quantification**

Defined indicators are correlated with landslide by their functional relationship. It may be described in terms of *sensitivity* and *adaptive capacity*. Indicators for sensitivity reflect to what extent a system is sensitive or responding to the exposure from an external stress or hazard such landslide, whereas the adaptive capacity indicators represent the ability or capacity of systems, institutions and infrastructure to adjust to potential damage or change due to external stresses or hazards, including climate (Esteves et al., 2016; Sharma et al., 2019). In the case of LPI, the indicators having higher sensitivity will be of higher landslide probability and vice versa. Furthermore, to quantify all considered indicators in terms of numerical values and to fit them in the ultimate equation of LPI, mathematical operations have been performed accordingly (Table 17.1) (Fig. 17.2).
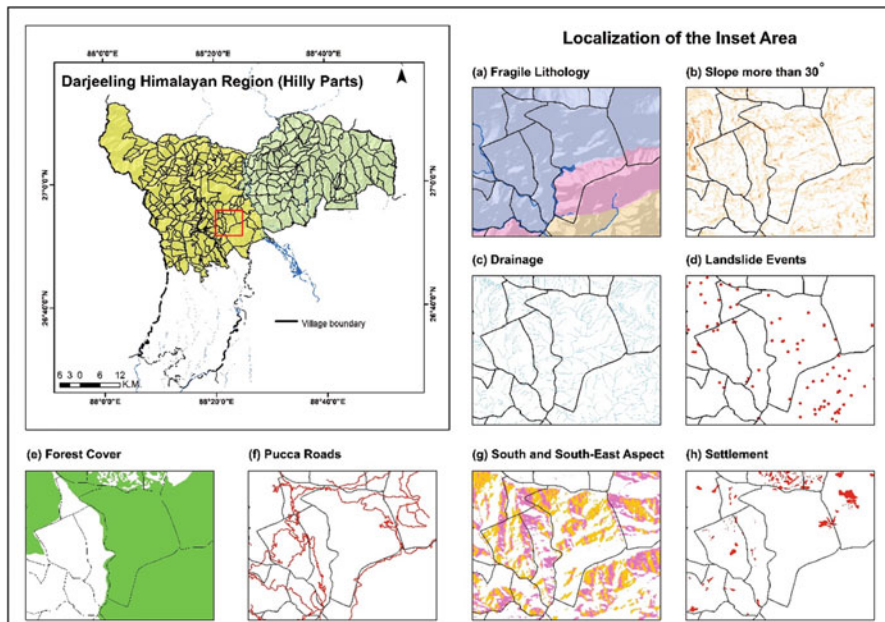
**Table 17.1** Village level selected indicators and their data extraction method for LPI development

| Village level indicators | Methods of data extraction |
|---|---|
| Percentage of area covered by the fragile lithological classes (phyllite, schist, sandstone dominated) | Geo-referenced lithology and mineral occurrence map that has been collected from geological survey of India vectorised precisely and intersected to village layer in GIS platform to determine spatial distribution |
| Area percentage of more than 30° slope | Using the slope algorithm of spatial analyst tool in ArcGIS, pixel-based calculation has been performed to figure out slope value as the maximum rate of change in value from that cell to its neighbours. After obtaining the downslope values, the output raster has been reclassified for vectorisation and spatially joined with the village layer |
| Percentage area under south and south-east aspect | Performed using spatial analyst aspect tool that identifies the downslope direction of the maximum rate of change in value from each cell to its neighbours. The values of each cell in the output raster indicate the compass direction that the surface faces at that location. Furthermore, spatially joined to villages to retrieve desired results |
| Drainage density in km/km$^2$ | Based on the SFCC images drainage, forest cover, settlement area and road network up to village level were extracted in and around the study area by on-screen digitisation on scale 1:10,000 |
| Percentage of area covered with forest | |
| Percentage of settlement area | |
| Pucca road density in km/km$^2$ | |
| Number of landslide events that occurred | Remote sensing methods based on image properties of both SFCC and high-resolution Google earth imageries were used to obtain historical records of the landslides over the past 15 (2005–2020) years. Field validations have been conducted using geographical positioning system device |

## Normalisation of Indicators

The normalisation of indicators is an essential part to compare among the indicators in which information can be combined in a logical way. Indicators are in different units, that is why it cannot be simply added to imply the index value (Esteves et al., 2016). The normalisation procedure enables aggregation of indicators with different units, by removing the units and converting all the values into dimensionless units. The normalised values of indicators lie between 0 and 1 and thus could be aggregated (Esteves et al., 2016; Sharma et al., 2019). Thus, in this study, normalisation has been done for landslide probability indexing and ranking that enable comparison and prioritisation among landslide-probable villages. Before starting the normalisation processes, it is essential to establish the functional relationship between the indicators and probability. There are basically two types of possible functional relationship: positive and negative relationship (Ravindranath et al., 2011).

**Fig. 17.2** Example of the village level selected indicators data extraction method to develop partial and full landslide probability indices. (**a**) Percentage of area covered by the fragile lithological units (phyllite, schist, sandstone) represented by different colours, (**b**) area percentage of more than 30° slope, (**c**) estimation of drainage density (length of drainage/unit area), (**d**) number of landslide events that occurred, (**e**) percentage of area covered with forest, (**f**) measurement of pucca road density in km/unit area, (**g**) percentage area under south and south-east aspect and (**h**) percentage of settlement area

## Normalisation Method for Indicators of Positive Relationship with Landslide Probability

In positive relationship cases, the higher the value of the indicator, the higher will be the probability. As the values of these indicators increase, greater will be the vulnerability of the community. In such cases the variables have direct and positive functional relationship with probability, and normalisation is done using Eq. (17.1):

$$X_{ij}^p = \frac{X_{ij} - Min_i\{X_{ij}\}}{Max_i\{X_{ij}\} - Min_i\{X_{ij}\}} \qquad (17.1)$$

where $X_{ij}$ is the variable that is being normalised, i.e. in this case $X_{ij}$ is the value of $j$th indicator for the $i$th region and $X_{ij}^p$ is the normalised value. Normalised value of $X_{ij}^p$ scores will lie between 0 and 1. The value 1 will correspond to that village with maximum value, and 0 will correspond to the village with minimum value (Esteves et al., 2016; Sharma et al., 2019).

Normalisation Method for Indicators of Negative Relationship with Landslide
Probability

For indicators where the probability increases with decrease in the value of the
indicator, the following normalisation equation (Eq. (17.2)) needs to be adopted, and
the normalised score of the indicator can be computed accordingly:

$$X_{ij}^n = \frac{Max_i\{X_{ij}\} - X_{ij}}{Max_i\{X_{ij}\} - Min_i\{X_{ij}\}} \quad\quad (17.2)$$

In the above Eq. (17.2), $X_{ij}$ is the variable that is being normalised, i.e. in this case
$X_{ij}$ is the value of the $j$th indicator for the $i$th region and $X_{ij}^n$ is the normalised value.
Normalised value of $X_{ij}^n$ scores will lie between 0 and 1. The value 1 will correspond
with that village with maximum value, and 0 will correspond to the village with
minimum value (Ravindranath et al., 2011; Esteves et al., 2016; Sharma et al., 2019).

### Assigning Weights of Indicators

Assignment of proper weights to indicators is practically crucial job to imply reliable
results. The problem of choosing an appropriate method of determining weights in
MCDM process is very important which complies with the decision-making process
(Pamučar et al., 2018). There are different methods of weight assignment, but in this
specific study, expert judgement method was adopted, and the opinion of experts
was considered to attribute weights for an individual indicator on 0 to 1 rating scale.
Regarding the set of experts, who are knowledgeable about the region, their views on
selected factors responsible for landslides and relationship with the process in the
DHR are seriously taken into account for arranging indicator's weight (Table 17.2).

### Aggregation of Indicators and Indexing

Aggregation of different indicators with appropriate weights is necessary to obtain a
composite index or aggregated value (Esteves et al., 2016, Sharma et al., 2019). The
weights are multiplied with the normalised indicator value and aggregated to obtain
the LPI or the ranking of the systems. Probability index is normally developed to
assist the policymakers, development administrators, NGOs and planners in
prioritising the villages. It may also suggest (a) a comparative index value of
different villages, (b) the spatial distribution of the high or low probability units
and (c) helps to identify the drivers of landslide hazard, so that adaptation invest-
ments can be focused on dominant drivers (Sharma et al., 2015; Sharma et al., 2019).
The result of the probability assessment can be classified on a scale of very high to
very low vulnerability and represented spatially through profile maps. The results
indicate the vulnerability ranking of landslide-prone villages on the basis of LPI

**Table 17.2** Village level selected indicators and their functional relationship with landslide and assignment of weights to develop LPI

| Sl No. | Village level indicators | Functional relationship with landslide (positive/negative) | Weights |
|---|---|---|---|
| a | Percentage of area covered by the fragile lithological classes (phyllite, schist, sandstone dominated) | Positive | 0.21 |
| b | Area percentage of more than 30° slope | Positive | 0.17 |
| c | Drainage density in km/km$^2$ | Positive | 0.14 |
| d | Number of landslide events that occurred | Positive | 0.12 |
| e | Percentage of area covered with forest | Negative | 0.12 |
| f | Pucca road density in km/km$^2$ | Positive | 0.10 |
| g | Percentage area under south and south-east aspect | Positive | 0.08 |
| h | Percentage of settlement area | Positive | 0.06 |
| Total | | | **1** |

values, and a critical utility of this probability assessment is the identification of the drivers of landslides along with their proportional contribution. Information about the indicators or factors that contribute most to the aggregate probability is useful in prioritising development and implementation of adaptation interventions.

## 17.3 Results and Discussion

### Quantitative Analysis of the Regional Indicators

This part of the study is categorised into some major dimensions, as the exploration of diversified region-specific varied indicators data and their spatial components that provide efficient support for intensive landscape hazard analysis. The combination of lithology and slope involving primary rock strata and structural control of lithology on the fluvial characteristics influences the local terrain as well as climatic characteristics and impacts the micro-level land use planning, whereas the drainage is similarly one of the most important factors that contribute to the landslide mechanism. Other influencing regional characteristics that are basically a result of modern-day man-environment interaction are also considered here for landslide probability assessment.

**Lithological Setup and Landslides Occurrences: An Association**

The DHR can be subdivided laterally from south to north as (a) the sub-Himalaya or the Siwalik belt composed of Upper Tertiary Siwalik sediments; (b) the lower or lesser Himalayas composed of Gondwana, Lower Tertiaries and Achaean rocks
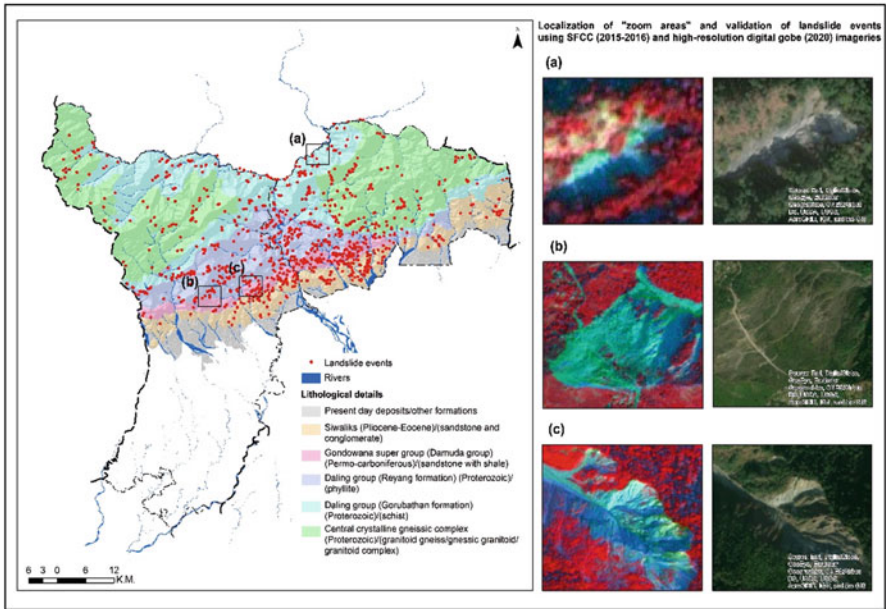
**Fig. 17.3** Fragile lithological details and its association with landslides. As demonstrated in (**a**) landslide over Daling group (Gorubathan Formation) in Sangser village of Kalimpong II block, (**b**) landslide of the South Shibkhola Tea Garden village of Kurseong block on Daling group (Reyang Formation) and (**c**) another landslide located on Gondwana supergroup (Damuda group) in Latpanchar forest village

along with some intrusive; and (c) the higher Himalayas, composed of intrusive Tertiary granites and other igneous and metamorphic rocks. The Siwalik belt is subdivided into an upper pebbly sandstone/conglomerate facies and lower sandstone facies, and it comprises of soft greyish sandstone, mudstone, shales and conglomerates that cover about 209.18 km$^2$ area in the studied region. During the monsoon season, a high amount of rainfall seeping through the pore spaces of these coarse-textured sandstone decomposed the feldspar to form kaolin which acts as a lubricant for sliding of rock materials. Hence, an amalgamation of this triggering factor makes the Siwalik a landslide regime of the region; a total of 196 landslide events have been identified here, and these are concentrated mainly in deforested Lish and Gish basin area of the Kalimpong district. Subsequently, upper Carboniferous to Permian feldspathic and micaceous quartzite, sandstone and carbonaceous slates with thin seams of crushed coal contain the Damuda group of Gondwana supergroup, which is highly landslide prone, as 149 past landslide events have been demarcated within 114.63 km$^2$ area of this group (Fig. 17.3).

Further to the north, low-grade meta-psammopelitic sequence of Precambrian Daling group's Gorubathan and Reyang formations cover 16% area of the study area, are taken into account due to its extensive geographical coverage with the selected studied reach. The Gorubathan Formation comprises green slate, phyllite,

phyllonite, cherty chlorite quartzite and green tuffaceous wake with basic metavolcanic materials, while the Reyang Formation consists of variegated slates, phyllite and low-graded schists. Highly metamorphosed argillaceous rocks in both the formations of the Daling group, where 136 landslides in Gorubathan and 261 landslides in Reyang formation have occurred respectively, are extremely fragile and most landslide prone litho-units of this region.

On the other hand, the Central Crystalline Gneissic Complex (CCGC) is dominantly present in the DHR. Fundamentally this group is made up with schists and Darjeeling gneisses of higher rank with subordinate quartzites and lenticular isolated bodies of calcsilicate rocks. It is spatially distributed over the entire north-western part of Darjeeling and north-eastern corner of the Kalimpong district with an area coverage about 28% comprising 163 landslide events. Considering the geographical area of this group of formation, the number of landslide events that occurred is inconsequential to contribute sensitivity, as the rock types of this formation are harder in nature and make it less vulnerable to landslide. Although variability in precipitation, altitudinal effects and aspects are all responsible for a landslide, the diversified lithological characteristics, as slight recrystallised and coarse-grained sandstone, are characterised by cataclastic deformation which destroy the clastic texture with intense granulation along ramifying narrow zones of fractures, which initiate landslide hazards (Basu & Sarkar, 1985; Basu & Ghosh, 1993). Furthermore, intense metamorphism of Daling is referred to as the classical ground of the low-grade metamorphosed rocks, influencing landslides (Acharya, 1972).

## Characterisation of Slope and Aspect with Landslides

The high degrees of slope, specifically more than 30° with fragile lithology, are the most favourable element of slope failure in the selected region. This category of slopes covers 27.05% area to the total area of the study. More than 30° slopes are often regarded as steep slopes, mainly concentrated on escarpments, and the source region of first-order streams and coupled with the fragile lithology range is witnessing greater percentage of landslide events. A total of 498 out of 1045 number of landslide events have occurred in this slope category which is 47.66% of total observed landslides and the rest of landslide events under other lower degree of slopes, which covers 72.95% of the total study area. The south- and south-east-facing slopes are in windward direction and get a high amount of sunlight, respectively, compared to north-facing slopes, which have steeper inclinations and receive a higher amount of rainfall as the branch of south-west monsoon hits directly from the south during monsoons. This group of aspects covers 652.22 km$^2$ area that denotes only 27.29%, but 503 out of the total number of landslide events are accountable over it (Fig. 17.4a, b).

Owing to the unique tectonic setting of the Himalayan thrust front failures, earth materials along the slope are common. The strength of hillslope materials is a function of geologic composition and stress state and is modified by past movement,
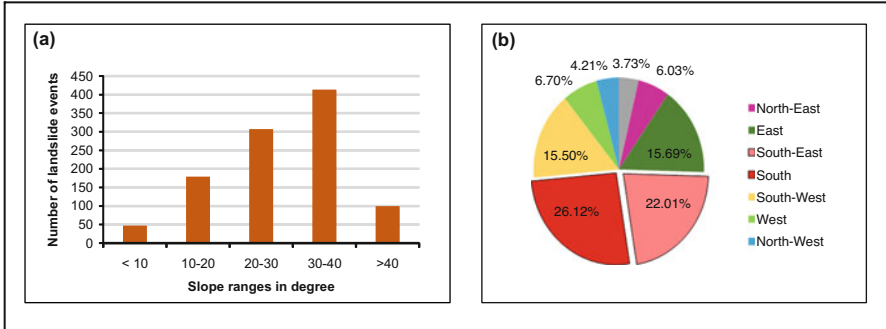
**Fig. 17.4** Characterisation of slope and aspect with landslides as stated in (**a**) slope ranges and corresponding landslides events that occurred on it and (**b**) percentage of landslide occurrences in different aspects

weathering, vegetation and hydrologic processes (Lu & Godt, 2008), and here south-facing slopes exhibit more landslide activity and are thus an important predictor of susceptibility to translational landslide (Ghosh et al., 2011).

## Drainage Density Estimation

The complex interplay of rock types and its structure in the Himalaya produces varied hydrogeological environments that often lie in proximity to each other. Further, variability in precipitation, altitudinal effects and aspects are all responsible for the formation of intricate drainage network in the DHR. The hilly Darjeeling Himalaya gave rise to unaccountable streams and numerous rivers and have been divided into two parts by the Tista River. In this work, village level drainage density has been calculated and used as a significant proxy that alone could address the litho-structural effect active on the region participating in the landsliding process. Village-wise drainage density of the DHR shows a diverse characteristic as the values range from 0 to 12.75 km/km$^2$, and the maximum density was observed in the north-western part which is composed of central crystalline rock group as well as in parts of Kalimpong districts where the CCGC and Daling rock groups are prevalent (Fig. 17.5a, b). Here, high densities can also indicate a greater probability of landslide (Mandal & Mandal, 2016). Drainage density is also determined as a good susceptibility index for rainfall-induced landslides, and study of drainage density is a practical approach for disaster management (Hasegawa et al., 2009).

## Forest Cover Depletion and Spread of Settlement and Transport Network

The forest cover of the study area is considered as an adaptive proxy in the LPI study. Usually, the preventive nature of forest vegetation root system helps to arrest soil erosion and slope failures in a hillslope. From the historical perspective, the
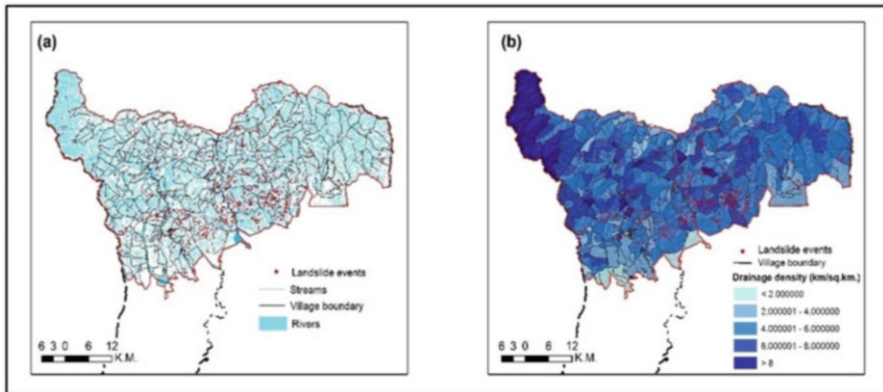
**Fig. 17.5** Village level drainage density assessment. (**a**) Drainage network and landslides events of the study area and (**b**) computed drainage density of villages that ranges from 0 to 12.75 km/km$^2$
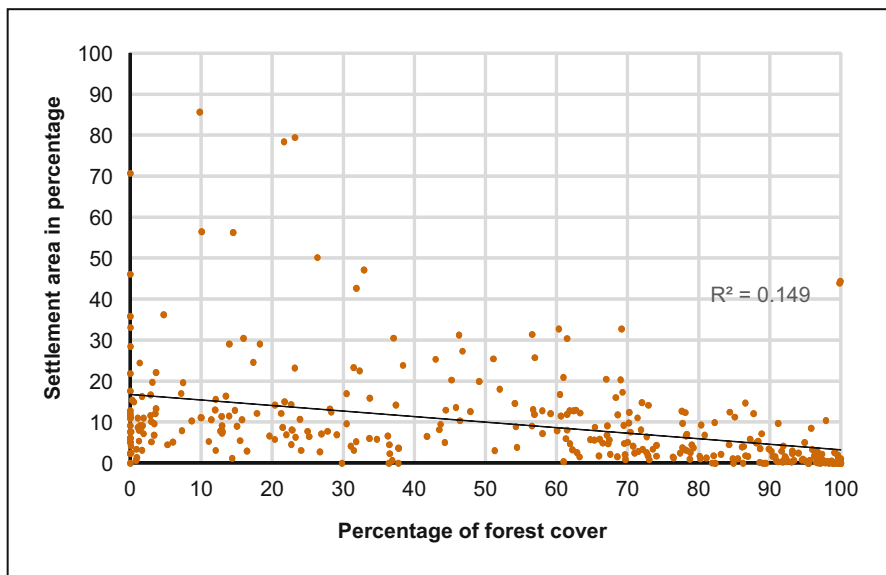


**Fig. 17.6** Bivariate analysis shows correlation between percentage forest cover and settlement areas percentage at village level of the study area

entire hilly tract of Darjeeling Himalaya was completely clothed with dense forests from the top of the hills to the very bottom of the valleys, but timely demand of land for settlements, cultivation, tea (*Cinchona*) plantation and road constructions leads to deforestation activities. Figure 17.6 establishes this fact, as it shows there is a negative correlation between the percentage of forest cover and settlement areas in villages within the defined study area.
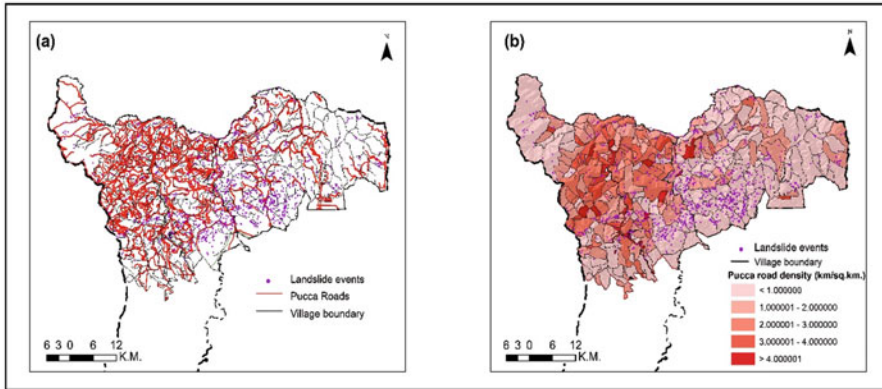
**Fig. 17.7** Village level pucca road density analysis. (**a**) Landslides events located along the pucca road corridor in the study area and (**b**) calculated pucca road density of villages that ranges from 0 to 18.395 km/km$^2$

Especially in the east of the Tista River, hilly tracts of Kalimpong district have been highly altered from dense forest land to Khasmahal or government estates to fulfil the demand of the land. In the areas of Khasmahal like Pabringtar, Yangmakum, Nobgaon, Samether and Suruk, landslides are quite frequent, and some of the past landslides were also reactivated within the last few decades. It is observed that 415 out of 1045 landslide events have been marked in the Kalimpong I block of Kalimpong district, and most of them are associated with deforested Khasmahal areas. Moreover, increasing pressure of population, heavy inflow of tourist and other livelihood activities are transforming rural areas of the hills into urban centres. Based on the tourist demand, multistoried buildings and homestays are continuously built on unstable slopes underlying with fragile lithology. Road construction similarly alters the terrain characteristics, as slope modification at the toe of a slope compromises the continuity of water flow and reduces the ability of the slope to drain, in turn reducing its stability (Fig. 17.7a, b). It is observed that the major roads of the DHR are familiar to the renowned landslides, e.g. Tindharia, Gayabari 14th Mile and Khairekhola landslides are on Hill Cart Road and National Highway 10 and Sevok-Teesta Bazaar sector, the famous Setijhora and 29th Mile landslides are on State Highway 12 (SH 12) and Algarah-Gorubathan sector and the Chibo, Bong, Chisopani, Bhameygaon and Kolbong landslides of the Kalimpong district are located nearby SH 12.

Khasmahals are severely affected by extensive deforestation, tremendous agricultural pressure and overgrazing; as a result, most of the precipitated water goes down the deforested slopes causing soil erosion and sliding (Basu & Ghosh, 1993). Besides, the vulnerability of roads is not only delaying overall development by impacting the livelihood of the people and delaying administrative activities and accessibility to daily needs of goods and medicine, but also heavy vehicular congestion along the narrow passage of hilly road increases expenses from longer

driving distances due to road blockages (Zeˆzere et al., 2007; Chuang & Shiu, 2017). This indirect damage entails the effects on society from disruptions to utility services and local businesses, which result in a loss of revenue and tourism (van Westen et al., 2008).

## *Interpretation of LPI*

Village level quantification of differential contributing data in a precise manner further leads to normalisation of indicators in accordance with the stated methodology. Therefore, functional relationships of the selected proxies have been rationally attributed to indicators in compliance with weight assignment to them, and finally, aggregation was done for different indicator value to obtain the LPI. The prepared LPI is divided into four distinct classes by maintaining equal intervals of LPI values. The (a) very high landslide probability class comprises 45 villages with LPI value more than 4.33, (b) high landslide probability consists of 138 villages having the LPI range from 4.32 to 3.03, (c) moderate landslide probability zone includes 109 villages where the values LPI ranging between 3.03 and 1.73, and 56 villages are in (d) low landslide probability zone of LPI value less than 1.73 (Fig. 17.8).
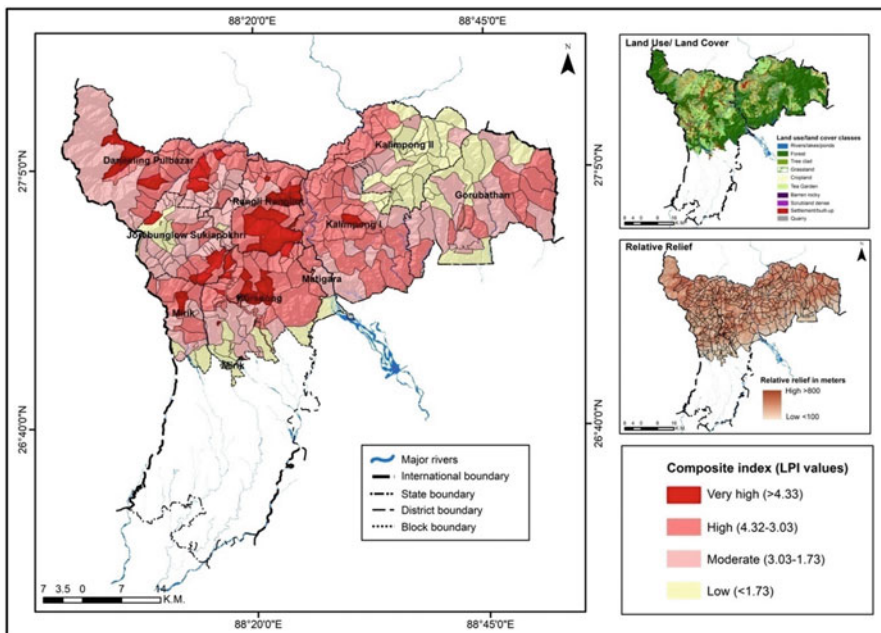


**Fig. 17.8** Landslide probability map showing landslide-prone villages of different categories, e.g. very high landslide probability, high landslide probability, moderate landslide probability and low landslide probability villages
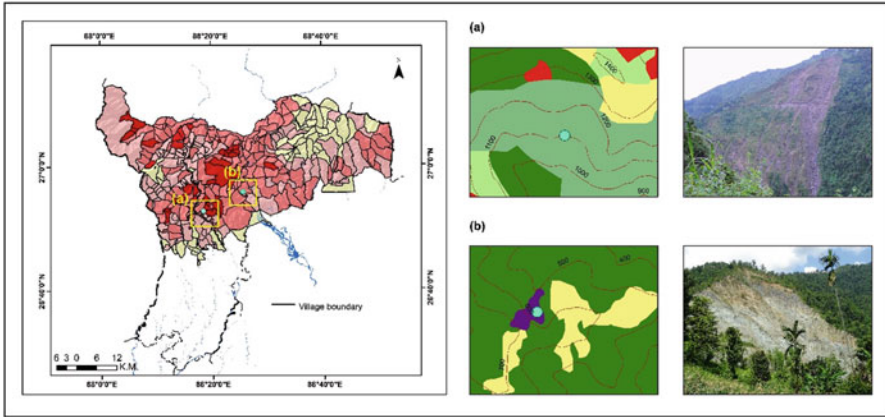
**Fig. 17.9** Validation of LPI results as with limited field checks as exemplified in (**a**) the Paglajhora, one of the famous landslides of the DHR falls in the very high landslide probability class and (**b**) the devastating lower Karmat landslide is under the high landslide probability class

Village-wise lithological configuration shows that very high and high probability of landslide occurrence villages like Kolbong Khasmahal, Lingding Khasmahal, Chegra Khasmahal, Hum Tukdah Khasmahal, Labda Khasmahal, etc. of Rangli Rangliot block and Mangpu Cinchona Plantation, Malotar Tea Garden, Lizziepur Tea Garden, Majua Tea Garden, Mahal Diram Tea Garden, etc. of Kurseong block are lying over landslide-prone Daling group. On the other hand, villages having certain percentage area covered by high degree of slope, e.g. Rambi Bazar D.I.F. (97.84%), Singi Khasmahal (40.61%) of Kalimpong I block, North Shibkhola Tea Garden (44.23%) of Kurseong block, Kolbong Khasmahal (34.97%) of Rangli Rangliot block, and villages, namely, Phuguri Forest (82.58%) of Mirik block, Chegra Khasmahal (75.96%), Hum Tukdah Khasmahal (74.39%) of Rangli Rangliot block, Turzam Forest (65.67%) of Kalimpong I block, Lodhama (61.49%) of Darjeeling Pulbazar block, Majua Tea Garden (57.92%) and Jungpana Tea Garden (57.35%) of Kurseong block covered with by certain percentage of area of a specified slope aspects, are in very high to high probability of landslide category (Fig. 17.9a, b).

Villages of the high landslide probability class correspondingly display high values of drainage density, as identical in Singi Khasmahal (8.10 km/km$^2$) of Kalimpong I block, Dayal Thong (D.R.) Tea Garden (8.08 km/km$^2$), Edenvale Tea Garden (7.51 km/km$^2$) of Kurseong block, Parmaguri Khasmahal (7.92 km/km$^2$) of Jorebunglow Sukhiapokhri, Hum Tukdah Khasmahal (7.89 km/km2), Kolbong Khasmahal (7.80 km/km$^2$) and Rayak Khasmahal (7.40 km/km$^2$) of Rangli Rangliot block. The LPI result also reveals villages, viz. Lapchu Khasmahal (36.19%), Soriang Khasmahal (35.85%) of Rangli Rangliot block, Saurinibasti (29.05%) of Mirik block, North Shibkhola Tea Garden (25.44%) of Kurseong block, Patliabas Forest (27.33%) and Lodhama (25.75%) of Darjeeling Pulbazar block having maximum settlement covers, are also included very high to high chances of landslide occurrence.

In contrast, villages characterised by harder rocks type of CCGC, a lesser area covered with high degree of slope and determinant aspect, low drainage density along with the high percentage of forest cover and insignificant settlement transport distribution are in moderate to low landslide probability category. Most of the villages of these classes are sporadically distributed over the concerned study area; the majority of them are situated near Neora Valley National Park of Kalimpong II block, while others are close to the foothills zone. So the weakest lithologies with cohesion, consolidation or interlayering of materials having highly varied permeabilities can lead to high degrees of fracturing, jointing or erosional dissection (Cruden & Varnes, 1996). As landslide risk is fundamentally a product of hazard and vulnerability; these two phenomena can be managed in mutually varying proportions (Alexander, 2012), and, thus, the assessment of landslide probability is very essential as it predicts the places associated with hazard at a microscale prior to its occurrence.

## *Identification of Drivers of Landslide Probability for Adaptation Planning*

The LPI assessments are often designed to support and improve adaptation planning, with the overall objective of reducing vulnerability in the region under consideration. It can also help to substantiate decision-making when it comes to selecting adaptation measures, based on the assessment of drivers of landslide occurrences with their index value. Thus, this LPI can be designated to assess the drivers of probability for developing targeted adaptation planning. Here in this study, the contribution of a single indicator to the LPI was obtained as a product of its weight and measured value. In this study, the different drivers of landslides and their contribution to it are shown in the radar diagram (Fig. 17.10) which depicts the



**Fig. 17.10** Drivers of landslide probability and their contribution in the LPI
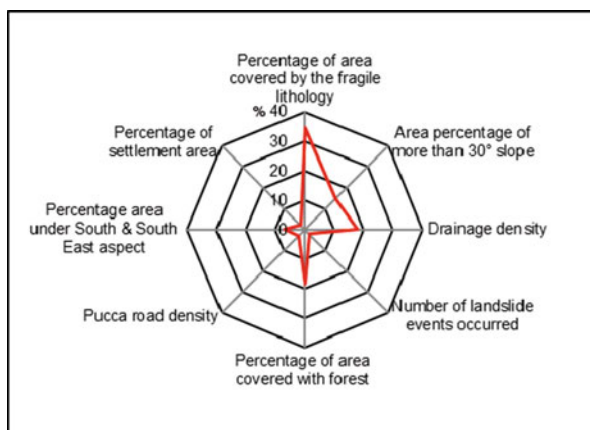
fragile lithology shares 34.58% as the prime contributor of landslides in the DHR followed by drainage density (17.91%) and high degree of slope (14.77%). The study reveals that the physical indicators like fragile lithology, drainage density and high degree of slope are main causative factors to the occurrence of landslide events of the region, but most significantly the forest cover holds 18.39% in the radar plot and that stands for the adaptive capacity measures to minimise landslide hazards.

Contrastingly, indicators like south and south-east aspects and the number of landslide events contribute 6.92% and 1.98%, respectively, in the landslide probability. Landslide events identified on south and south-east aspects are mainly monsoon driven in nature. In case of the proportional contribution of landslide events, it is necessary here to mention that this particular proxy is result oriented while others are causative. Eventually, reactivation nature of previously occurred major landslides locally increases high chances of slope failure which is not reflected throughout the region. It is also observed from the present study that the frequency of landslides under forested area is less, while other parts of the study area are highly infested with such hazards as the percentage of settlement area and road density share 2.18% and 3.25% correspondingly. Here, the contemporary ground scenario is an evidence that reveals that the combination of anthropogenic activities like deforestation, slope cutting, digging for settlements and road construction is highly impacting the recurring hazard phenomenon in the entire DHR. As the Himalaya represents one of the most fragile mountain ecosystems of the world, systematic planning is a must for successful implementation of developmental schemes (Anbalagan et al., 2008); thereafter, the LPI and its results are truly a practical approach that might be taken into account for both the inherent and external parameters responsible for slope instability and future landslides.

## 17.4   Conclusion

The proposed index has analysed all the significant indicators that are actively taking part in the landslide mechanism and represents the vulnerable state of the DHR. With the advancement of time, the exposure to landslide hazards may increase to both people and places as the elements may intensify depending on situations. It is also evident from the study that the nature of landslide phenomenon results from the interaction of contributing physical indicators, i.e. fragile lithology, high degree of slope, high drainage density over the studied region, which are considered to be the active agents working in 183 villages of very high to high landslide probability categories.

Through geospatial technology, the adopted methodology can be applicable to all territorial systems, and this will allow to visualise the results, through maps, as a realistic representation and to identify and manage the process through an easily comprehensible flow chart programming in form of spatial decision support system. In this way, this study may prove to be adequate in the integration of climate, landscape and social dynamics data that will enable us not only in developing

landslide early warning system but also considered as the base input to the planners and policymakers for strategic intervention and good governance approach to minimise the landslide vulnerability, which is directly related to the human life and livelihood of the region.

### Declaration

**Compliance with Ethical Standards**   This research work is carried out in compliance with transparency, moral values, honesty and hard work. No human or animal experiments are involved in this research work.

**Conflict of Interest**   There is no question of conflicts of interest for any co-authors of this work directly or indirectly.

**Ethical Approval**   The methodology, findings and conclusions made here belong to original research work as per our knowledge and belief.

**Informed Consent**   Everything is carried out with collective decision and consent.

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