Chapter 18
Vulnerability Assessment of Landslide with the Help of Geospatial Approach in Western Himalayas, Upper Basin of River Sutlej, India

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Abstract Vulnerability assessment is an important part of environmental management, and this approach is used for the identification of hazards and its potential risk in the upper basin of the river Sutlej. The geospatial tool was used to analyse, monitor and map landslide vulnerability. Rockslide, rock fall, slump, earthflow, and subsidence types of landslides were identified in the field. High summital convexity (1), rectilinear (0.8), high relative relief (>1000 m), high dissection ratio (>0.97), less forest cover (8%), slope aspects; southeast (1), south (0.9), the fine texture of soil (1), subhumid region (1), limestone-based lithology (0.9), high earthquakes magnitudes (1), and hydropower construction (1) were the major factors that indicated a high degree of vulnerability (0.68) and a high weighted score (0.58). The major finding of the vulnerability assessment indicated that 27% (1812 km^2) area of the basin had a high vulnerability of landslide; however, 39% (2617 km^2) area of the basin exists with low vulnerability. In the future, if anthropogenic activities increase in this basin, then the impacts of landslides and their loss of physical environment shall be increased.

Keywords Landslide · Vulnerability assessment · Geospatial approach

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18.1 Introduction

Hazards are natural phenomena, which also include geological and meteorological hazards such as earthquakes, volcanic eruptions, wildfires, cyclones, floods, droughts, avalanches, and landslides. Landslide refers to the terms of a different form of mass wasting that include rock fall, deep-seated slope failures, mudflow, and debris flow (Rosi et al., 2018). Lithology, rainfall, nature of the slope, status of land use, land cover, snowfall, aquifer recharge, increasing hydrostatic pressure in rocks cracks, soil structure, and forest fire are all factors that control frequency and magnitude of the mass movement (Wei et al., 2018) Physical and chemical weathering also weaken the rocks and also increase the incidences of landslides (Di Maio et al., 2017). In recent times landslide incidences identification is a very simple method. Remote sensing and geographic information system are an applied science tool, which is used in many fields. It is more helpful in tuff terrain where field observation is not possible. The vulnerability assessment of hazards depends on the presence of threat and its impact factor. The Sutlej Basin of district Kinnaur is known for its geohazards such as landslides, cloud bursts, earthquakes, and avalanches. Landslide is one of the major responsible incidences for the loss of physical landscape in the basin (Jamwal et al., 2019). The anthropogenic activities such as hydropower construction are one major triggering factor for the loss of physical and social environment. Slope failure is very common in the basin because of construction activities (Blasting and mining) (Fan et al., 2019).

The climate of the Sutlej Basin is subhumid to temperate type. The lower region has high rainfall, and the upper region has maximum rainfall in the form of snowfall. The snowfall region has arid condition, and incidences of shooting stone are very common (IPCC, 2007a, 2007b). The lower region (Rampur, Noli) suffered very much because of its varied climatic condition. Debris flow, earthflow, debris slide, rock fall, rock slide, slump, and subsidence were some common types of mass movement. When the slope material becomes saturated with water, it becomes debris flow or mudflow (Di Maio et al., 2017). Very fine grain clay, fine sand silt, and fine-grained pyroclastic material were found in the basin areas like Karcham Wangtoo, Shuda Rang, Dhakhu, Barang, and Tapri. Earthflow incidences were recorded in the area of Tapri, Shongtong, and Powari during the rainy season from June to August. This also increased pour pressure and decreases the shared stress of material (David et al., 1984).

Debris slide incidences were commonly observed in the lower portion of the basin where rainfall intensity was high and soil texture was coarse. The debris includes the small fragments of rocks, trees, and coarse grain of soil. Doris slides also occurred in the upper region of the basin where the impact of snowfall was high. The fine particles of soil and small pieces of rock were common with the rolling snow (Hutchinson, 1968). Small and shallow landslides were observed in the area like Kasang, Barang, Apka, Sumdo, Khab, and Reckong Peo. High permeable soil was on the top, and low permeable soil was in the bottom. But road cutting, dam construction, and blasting caused deep-seated landslides. The Urni landslide occurred after the high-intensity rainfall of 2014. The recorded average debris flow was 23.5 m/s (Kumar et al., 2019). The Urni villages (elevation, 2300 m) agriculture and horticulture land was damage. This landslide was one of the deep-seated landslides that were associated with slope failure in the form of rock fall, rockslide, rotational, transitional, and complex movement. The Sutlej Basin River was highly affected under the incidences of landslides from Khab to Tapri. The natural setting and land use status of this basin indicate the vulnerability of the physical landscape. The study revealed that incidences of landslides were increased because of haphazard development of hydropower project in the basin (Kuniyal et al., 2019). The vulnerability assessment includes the phenomena identification, monitoring, mapping, buffering, risk, and threat. It could be highly valuable on ground level if the development process considers the vulnerability map. But in reality, the landslide safety majors are not considered in the Indian Himalayas region. Management information system (MIS) is more effective for the real time monitoring of hazards (Chen & Wang, 2007). The landslide vulnerability, susceptibility, and risk depend on the topographical characteristics and human activities in that region. The selected indicators such as anthropogenic activities, curvature, geological structure, slope, slope profile, relative relief, land use and land cover, lithology, soil texture, and precipitation were taken to complete this process (Jamwal et al., 2019).

The landslide hazard analysis was done with factors such as geomorphology, geology, land use, and hydrology. High-resolution satellite imageries were very helpful to study topography very precisely (De La Ville et al., 2002). Along the National Highway 5, a number of landslides incidences were observed. The incidences of slope failure were very common on the convexity of the basin such as Dublin landslide, Spillow landslide, Khadra Dhaank landslide, Lippa landslide, Pangi Nala landslide, Powari landslide, Sapni landslide, Brua landslide, Kuppa landslide, Urni landslides, Sholding landslide, and Nathpa landslide (Fig. 18.1).

Landslide analysis through the geospatial approach provides us a valuable strategy to control the potential risk. Geospatial technology is also suitable for the vulnerability assessment of the physical landscape, and low vulnerable areas can be considered for development. High vulnerable areas can be put under the management.

18.2 Study Area

The landslide vulnerability assessment was done in the upper basin of Sutlej River, Himachal Pradesh, India. Geographically this area was extended from 31°30′12”N to 32°22′16”N and 77°40′16″E to 79°13′16″E. The total area covered under this region was 6401 km^2 and elevated from 2320 m to 6816 m. This region was covered by Tibet and China in the east direction and Shimla in the west. This basin was known for its geographical complexities. The MCT passing through this basin and a number of faults were found in this area. Main central thrust (MCT) was defined as the boundary between quartzite and phyllite, from the Lesser Himalayan sequence, and the orthogenesis biotitic-rich schist, which belongs to the Greater Himalayan

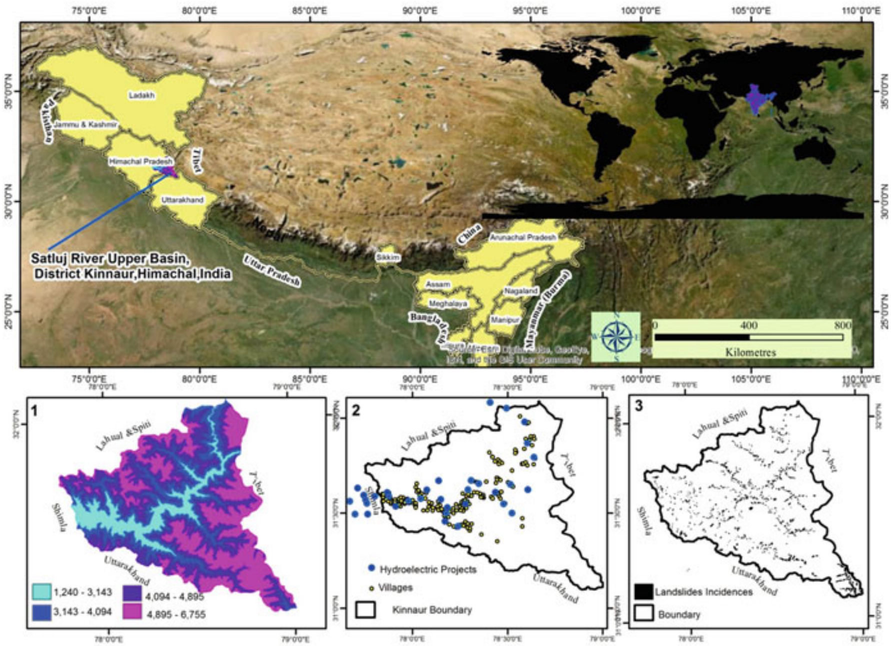

Fig. 18.1 Study area, upper basin, district Kinnaur, Himachal Pradesh. (1) Elevation status of upper basin. (2) Habitations and locations of HEPs. (3) Landslide incidences

crystalline complex (Daniel, 2003). The 80% (5483.92 km^2) basin area was found under the categories of high steep slope (>30°) and 74% area under the high altitude (>3000 m) (Jamwal et al., 2019). The basin had subhumid to arid temperate climate. This basin is known for its geohazards, and unique culture was related to tribal population of Mongoloid as well as Mediterranean. This region was known for its hydropower development and many social issues related to its development (Kuniyal et al., 2017). The upper basin of river Sutlej had the temperature type of subhumid temperate alpine highland and frigid aridic type. The low-altitude region of the basin had high rainfall during the monsoon season, and rainfall varies from 600 mm to 1400 mm. The average annual temperature of the basin was 13 °C. The total population (84,181) habituated in the 10% area of the basin and suffered huge losses during the incidences of hazards (Fig. 18.1).

18.3 Methodology

The vulnerability assessment of landslide was done on the basis of the selected parameters. All parameters were elected on the basis of geophysical aspects such as relative relief, anthropogenic activities, curvature, geological structure, slope aspect, slope profile, land use and land cover, lithology, precipitation, and soil texture. The slope, slope aspect, relative relief, and curvature were generated from the ASTER DEM (USGS, 2004) of 30 m resolution. The geological map was prepared on the basis of the Geological Survey of India (GSI). The soil texture map was prepared with the help of a second map of the National Bureau of Soil Science (NBSS). The slope profile map was prepared on the basis of the geomorphological map, and later it was corrected and analysed through a field survey (SOI). The precipitation map of the study area was prepared by using weather station data. The landslide points (GPS) were collected from the field along the Sutlej Valley, Tapri to Khab, and also along the Baspa Valley. The terrain was very complex, and it was difficult to collect all landslide incidences, so these landslide points were extracted from Google Earth. Google Earth images of WGS84 were used to extract the affected area under the landslides at the resolution of 15 m. Then, the shape files of landslide area were overlapped on the raster data set with other parameters. The extracted area was calculated on every subclass of parameters. The selected parameters were classified, and the affected areas were identified on these subclasses. The highest affected area was scored with the highest number from the total number of subclasses. The values were normalized from 0 to 1 to check the impacts on parameter classes.

The formula was used to normalized the value:

$$P_{\mathrm{N}}\ (\text{parameters normalized}) = P_{\mathrm{s}}\ (\text{Parameters Score}) \,/ N_{\mathrm{p}}\ (\text{Total the number of parameters}) \tag{18.1}$$

Then vulnerability was also identified in every subclass. The vulnerability scored on the basis of impact factors such as 0 for no vulnerability and 1 for vulnerability.

The risk was also identified on the basis of normalizing value and impact (threat value), and the formula is as follows:

$$\text{Risk} = \text{Impacts (Threat area)} \times \text{weight rank}\ (W_n) \tag{18.2}$$

Equation (18.2) was used to analyse the risk on every parameter. Then the average vulnerability and risk score were calculated. The vulnerability and risk score index was generated. Finally, the overlay analysis was done, and one vulnerability score map was prepared. This indicated the region with the high, medium, and low vulnerability of landslides.

18.4 Types of Landslides

Landslides were classified on the basis of its nature of occurrences and its geometrical shape. Rock fall, rock slide, debris slide, complex slide, and transitional debris were noticed as mass movement in the field. Crown cracks slide and transitional debris slide were commonly noticed in the field. Minor scarps were observed on the rectilinear section of the slope profile. Debris fall was noticed where soil structure belongs to coarse grain soil. Earthflow incidences were highly noticed in the upper region of Sutlej like that Akpa, Spillow, Khas, Pangi, and Kwangi. Debris flow was noticed in the upper basin of Sutlej and known for its devastating impact. Pagal Nall received a huge amount of rocks, fine soil, and clay with water with rapid movement (Varnes, 1978). During the rainfall in the basin, the incidences of debris were very commonly found in the place of Akpa, Ribba, Purbani, Powari, Shongtong, Karcham, and Ghanvi (Jamwal et al., 2019). Geological elements had the dominant impact on such types of landslides which include rotational failure, flow, falls, and debris slides. The basin was also known for its earthquake incidences. The vibration-based landslides occurred in places like Shoultu, Pangi, Kang, Purbani, Sudharang Dhaku, and Malling. The human-induced landslides were noticed in and around of hydroelectric project affected area of Khab, Jangi-Thopan-Powari, Shongtong Karcham, and Karcham Wangtoo. These landslides were caused due to the slope excavation, mining, and blasting (Fig. 18.2).

Fig. 18.2 Landslides incidences; (**a**) Tapri, (**b**) Near Pangi, (**c**) Near Powari, and (**d**) Near Barang

18.5 Result and Discussion

Identification and Status of Landslides as per the Selected Parameters

The Sutlej Basin in district Kinnaur is known for its complex topography. The basin had received a number of landslides of different scale; some were very large, and some were very small. The triggering factors were such as relative relief, slope, slope aspect, lithology, curvature, soil texture, lithology, effective land use, and anthropogenic activities. Geographic information system indicated that the landslide's occurrence value was higher in and around of hydroelectric project affected area of Khab, Jangi-Thopan-Powari, Shongtong Karcham, and Karcham Wangtoo.

Relative Relief (R_R)

Relative relief is one of the important topographic factors for the analysis of the landscape. The high degree of relative relief (R_R = 1244–6755 m) and high dissection indicate the high vulnerability of landslide and soil erosion (Singh, 2004a). In the Sutlej upper basin, maximum landslides occurred under the high relative relief (Muthukumar et al., 2009). The human activities in this elevation were the major cause of this environmental loss. The whole basin had high relative relief >3000 m which had high vulnerability (1) and risk and for agriculture and horticulture. Human properties and lives lost were observed along the river Sutlej Rampur to Khab with a risk score of 1 (Table 18.1).

Slopes

The slope was classified on the basis of A. Young classification (Young, 1964). The sloping nature of the region decided the vulnerability of landslide and erosion (Webb et al., 2011). The region had a high degree of slope, and maximum degraded area was observed under the vertical slope (17.01 km^2) and under the moderately steep slope (6.42 km^2). The vertical slope had a high degree of risk (17.01 km^2) and vulnerability scored as 1. The risk factor was increased on the steep slope (Table 18.1).

Slope Profile

The slope profiles were one of the deciding factors for the acceleration of eroded material and slope segments classified on the basis of geometrical shape (Singh, 2004b). Summit convexity, rectilinear section, free face, and basal connectivity were the main identified slope profiles in the basin. About 8.1 km^2 area was degraded

Table 18.1 Landslide impacts and status on different parameters. (W_n) *W*, Weighted; *n*, number of classes of parameter

S. No. parameters (Weight)	Classification	Area degradation (mass movements) Identification and weight rank (W_n)		Vulnerability	Risk
1. Anthropogenic (W_4)	Under construction	5.47	1	1	5.47
	Commissioned	2.41	0.7	1	1.687
	Obtaining clearance	1.14	0.2	0	0.228
	Under investigation	2.03	0.5	0	1.015
2. Curvature (W_2)	Concavity	7.3 to −7.3	1	1	1
	Convexity	8.12 to −8.12	0.5	0	0.5
3. Geological aspects (W_2)	Geological structure	2 fault 1 thrust	1	1	1
	Magnitudes	5.5	0.5	1	2.75
4. Slope (W_6)	Gentle slope (0°–5°)	0.31	0.1	0	0.031
	Moderate slope (5°–10°)	3.31	0.3	0	0.993
	Moderate steep slope (10°–18°)	6.42	0.8	0	5.136
	Steep slope (18°–30°)	6.12	0.6	1	3.672
	Very steep slope (30°–45°)	4.45	0.5	1	2.225
	Vertical slope (45°–90°)	17.01	1	1	17.01
5. Slope profile (W_4)	Summital convexity	4.6	1	1	4.6
	Rectilinear section	1.9	0.7	1	1.33
	Free face	1.8	0.5	1	0.9
	Basal concavity	0.1	0.2	0	0.02
6. Relative relief W_2	R_R 1244–3000	D_I (0.93)	0.5	0	0.5
	R_R > 3000	D_I (0.97)	1	1	1
7. Land use and land cover (LULC) (W_8)	Settlements	0.15	0.2	1	0.03
	Agricultural	0.7	0.3	1	0.21
	Forest cover	0.8	0.5	0	0.4
	Wasteland	8.46	1	1	8.46
	Grass/grazing	8.39	0.8	1	6.712
	Scrubland	1.97	0.7	1	1.379
	Water bodies	1.17	0.6	0	0.702
	Snow/glacier	–	0.1	0	0
8. Slope aspect	Flat	0.85	0.2	0	0.17
	North	1	0.5	0	0.5
	North-east	0.71	0.3	1	0.213
	East	3.24	0.7	1	2.268
	South-east	9.47	0.8	1	7.576

(continued)

Table 18.1 (continued)

S. No. parameters (Weight)	Classification	Area degradation (mass movements) Identification and weight rank (W_n)		Vulnerability	Risk
	South	**14.12**	**1**	**1**	**14.12**
	South-west	2.93	0.6	1	1.758
	West	0.22	0.1	0	0.022
	North-west	0.91	0.4	1	0.364
9. Lithology	P_{t1} regionally metamorphosed	11.46	1	0	11.46
	P_{t3e} greenish grey sandstone	5.7	0.8	1	4.56
	Y granite and granitoid	0.91	0.2	1	0.182
	P_{g3o} Boulder conglomerate, sandstone, shale, clay	4.24	0.7	1	2.968
	OC limestone, siltstone, shale	2.31	0.4	1	0.924
	P_{t23} slate, phyllite, quartzite, grey shale	3.28	0.5	1	1.64
	P_{t2} Ortho-quartzite, basic volcanic	0	0.1	1	0
10. Soil texture	Coarse texture	4.3	0.5	1 0.5	2.15
	Fine texture	15.1	1	1	15.1
	Medium texture	3.8	0.2	1	0.76
	Rocky/badland	4.5	0.7	1	3.15
11. Precipitation	Subhumid	16.1	1	1	16.1
	Subtropical	4.9	1	1	4.9
	Subhumid temperate	8.9	0.5	1	4.45
			0.58	0.7	164.2

under all different segments. The summital convexity had high vulnerability (1) and high risk (4.6). The free face segments of the slope were highly affected due to construction activities (Table 18.1). Rock fall incidences were highly noticed under this section of the slope. The basal concavity segments of the slope profile were highly affected due to flood and soil erosion (Fig. 18.3).

Slope Aspects

Solar energy is the main driving force that affects the slope aspects (Dearman, 1974). In general, the slope aspect can influence the distribution and density of mass

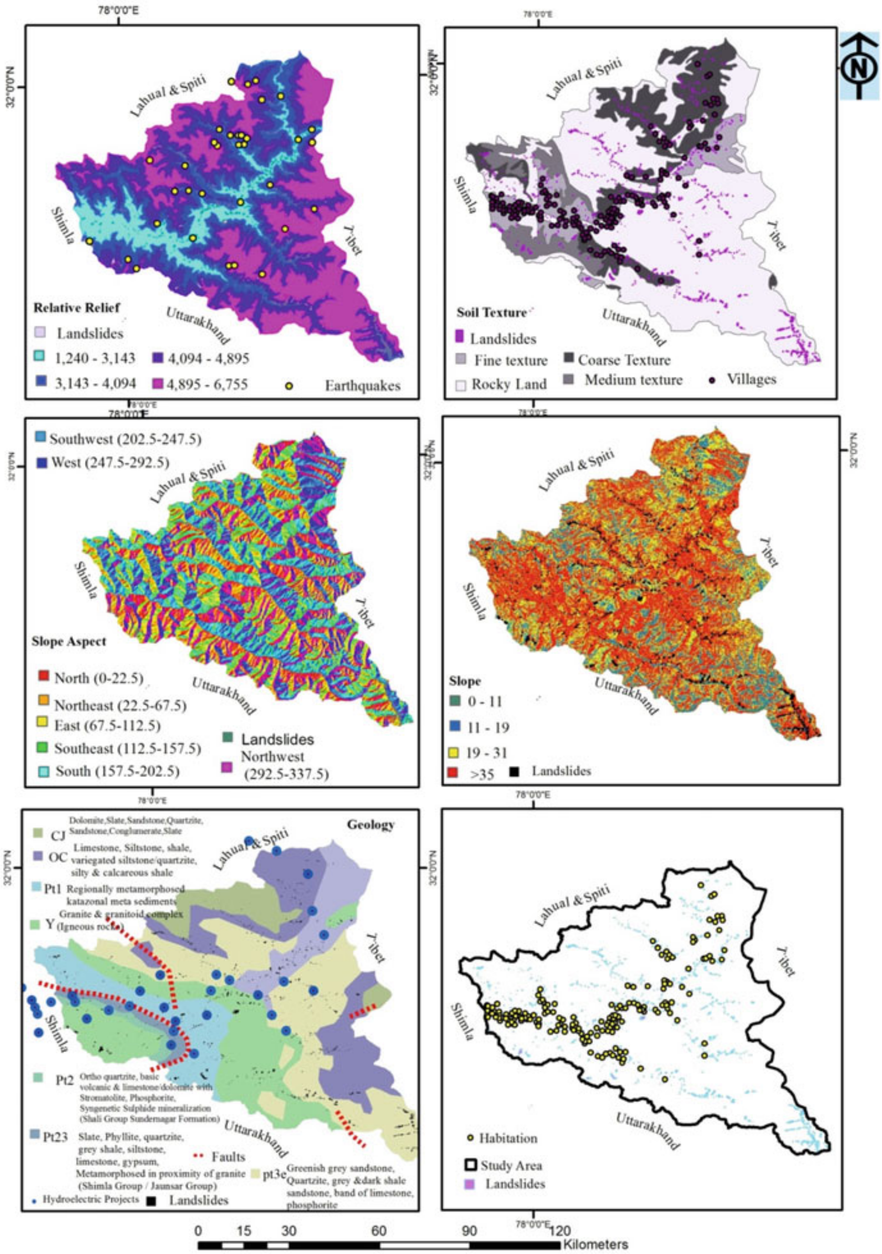

Fig. 18.3 Parameter-based analysis

movement by controlling the concentration of soil moisture or orientation of tectonic fracture (Wieczorek et al., 1997). In the northern hemisphere above the 33° latitudes, the maximum sunny area was found under the south, south-west, and south-east aspect of a slope. The high risk was found on the south (1), south-east (0.8), east (0.7), and south-west (0.6) aspect of slope. High vulnerability (1) and high risk (14.2 km^2) were observed under the slope aspect of the south.

Curvatures

The acceleration and deceleration of flow across on earth's surface depend on the concavity and convexity of a slope. A negative value (−10.4) indicates that the surface is upwardly convex at that cell, and flow will be decelerated. A positive profile (10.4) indicates that the surface is upwardly concave at that cell, and the flow will be accelerated (Rautelal & Lakhera, 2000). The incidences of soil erosion and landslide were noticed both curvatures of the slope. But affected pixels had a high value on the concavity of slope. The vulnerability (1) and risk (1) were high on the concavity of slope. The risk factors of human settlements were very high at the convexity segments of the slope, and the concave segments of the slope were highly affected due to anthropogenic activities (road and dam construction). The convexities of slopes were highly scored as 1, and concavities of the slope were scored as 0.5 (Table 18.1).

Soil Texture

Soil texture and rainfall are two important factors which affect the movement of landslides. Coarse texture, fine texture, medium texture, and very fine texture were classified categories of soil in the study region. Very fine textures were commonly observed in the upper basin and coarse texture in the lower basin. In the lower basin of the study region, the coarse texture gives birth to debris slides and debris fall. The very fine texture of soil generates the mudflow with tiny particles in the presence of rainfall. This was very common in the upper region of district Kinnaur, where climate types are arid and very cold (subhumid temperate). Here maximum rainfall in the form of snowfall and vegetation belongs to alpine type. The rocky surface of the region was not very much affected but un-stabilized by haphazard human activities.

High vulnerability and risk were found under the fine texture of the soil (1). This indicates a high risk (15.1 km^2) of the physical landscape. Fine textures were scored as 1, the coarse texture was scored as 0.5, a medium-fine was scored as 0.2, and rocky badland was scored as 0.7 (Table 18.1). The soil textures of the region were also determined by the climatic condition of the region. But it's very fine, and the fine texture of the region had sparse vegetation, which was more susceptible to landslides and soil erosion (Jenny, 1941; NRSC, 2010).

Lithology

The lithology of the study region is a type of sandstone, shale, clay, limestone, siltstone, and regionally metamorphism. The lithology is one of the dominant factors which control the rate of surface erosion. Lithology consist the rock types such as alluvial, sedimentry, limestone, siltstone, shale, and dolomite in the lower regions, were affected with mass movement during the season of rainfall. Below the Shongtong and Tapri area region, most of the rock strata were loosed because of the high rainfall intensity. The highest affected area was found under the categories of regionally metamorphosed rocks type Pt1 and Pg3o and scored as 1 with high risk and a high risk of 11.46 km^2. Boulder conglomerate, sandstone, shale, and clay were scored as 0.7, P_{t23} is scored as 0.8, limestone, siltstone, and shale OC were scored as 0.4, greenish grey sandstone p_{t3e} was scored as 0.8, granite granitoid base was scored as 0.2, and orthoquartzite basic volcanic rocks were scored with the lowest 0.1 (Gupta, 2003).

The average magnitude of the basin varies from M5.5 to 6.0, and this magnitude was sufficient to generate small- and large-scale landslides (Fig. 18.4). The slopes cutting process were including the vibration of slopes area which later becomes the causes of slopes failure. These continuous vibrations of magnitude were generating a small number of landslides. The Sudharang Dakhu landslide occurred due to high rainfall in June 2014 but still continuous sliding one of possible causes was earthquakes vibrations (Keefer, 1994). Shallow-focus earthquakes were crustal earthquakes, and they existed in the crustal layer. Deep-focus earthquakes were generated because of the collision of two plates and generated from the depth 300–700 km. Deep-focus earthquakes generate high energy, which had a high vulnerability of destruction (Meunier et al., 2013).

Land Use and Land Cover (LULC)

The study region has covered only 8% forest cover, the maximum area of the study region falls under snow-covered 2490 km^2 (39%), and the wasteland was 2030.63 km^2 (31%). Barren and sparsely vegetated areas were more prone to weathering and erosion (Majumder et al., 2019). According to forest policy, the minimum 33% area should be covered under the forest cover for a healthy landscape.

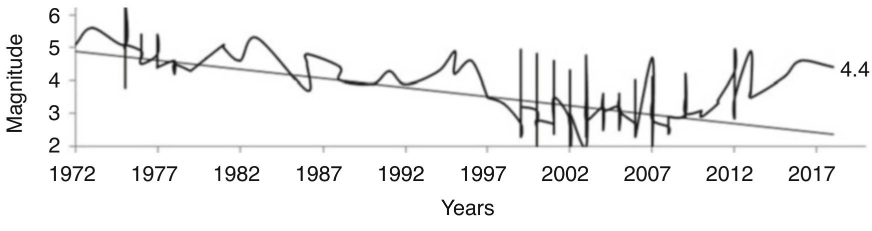

Fig. 18.4 Magnitude of earthquakes

The percentage of wasteland and snow-covered land was very high, which was 70%. The 1.89 km^2 of agriculture land was very low and is about 1.2%, which indicates the tuff terrain and low possibility of agriculture (0.7 km^2) and settlement (0.15 km^2) development in this region.

The increase of wasteland is a very serious problem in the basin, and wasteland has high vulnerability (1) and high risk of 8.46 km^2. It was evident from the field survey that the other land use type's agriculture (0.7 km^2), settlement (0.15 km^2) types were highly affected by mass movement and agriculture was scored as 0.7 and settlements were scored as 0.2. The scrubland (1.97 km^2) was scored as 0.7. A forest of the region was also affected (0.8 km^2) under the mass movement and scored as 0.5 (Table 18.1).

Anthropogenic Activities

The Sutlej Basin of district Kinnaur is known for its development of hydroelectric projects. Different types of hydroelectric projects such as under construction, commissioned, obtaining clearance and under investigation were identified in study region. Under construction types, hydroelectric projects have a number of landslide incidences. Tunnelling and blasting had adverse impacts on human settlements and the physical landscape (Kuniyal et al., 2015; Kuniyal et al., 2017). Slope instability is found under the surrounding area of hydropower projects (CEIA, 2014). Increased landslide incidences, flash floods, river morphological changes, water quality deterioration, reduction in agricultural/horticultural production, forest degradation, land degradations, inadequate compensation due to construction activities, damage to human health due to dust, and cracks in houses are major adverse impacts noticed within the project-affected area (Lata et al., 2017) (Fig. 18.5). The impact value was high under the construction types of HEPs, which have a threat of mass movement and scored with high vulnerability and risk (1). The susceptibility score (21.88 km^2) was high under these categories. But the other categories of the hydroelectric projects have a low vulnerability and less susceptibility. Land degradation and loss of agricultural land are found under the construction hydroelectric projects. A high vulnerability is found within the buffer of under-construction hydroelectric projects.

Precipitation

Precipitation is one of the dominant factors for the generation of landslides. About 80% of landslide is related to rainfall, and the remaining 20% belongs to the other responsible factors. According to the intergovermental panel of climate change (IPCC) 2014 model projection relative to 1986–2005, RCP2.6 (left) and RCP8.5 (right), the dotted pattern shows the projected change and variability in rainfall. This IPCC model also indicated the sign of the change (IPCC, 2014) (Fig. 18.6). The precipitation pattern was different in the study region which was influenced by

Fig. 18.5 Glimpse of study area; (**a**) degraded river valley, (**b**) landslides at Sudharang Dakhu, (**c**) interaction with respondent, (**d**) River valley at Powari

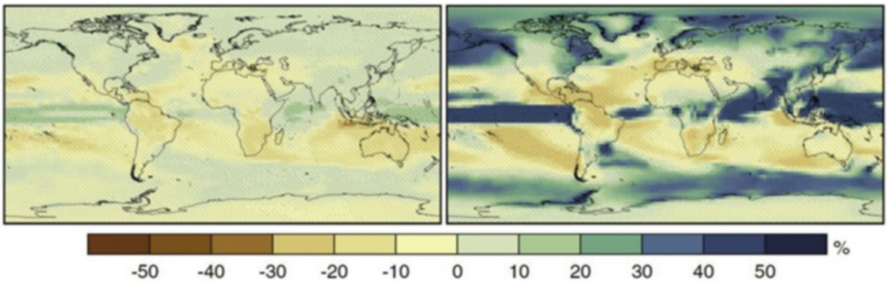

Fig. 18.6 Change in average precipitation (1986–2005 to 2081–2100) after: IPCC, 2014

topographic variance (434–6448 m). Isohyets study made it clear that the annual isohyets varied from 100 to 1400 mm. Annual rainfall in this basin was decreased from the Lesser to the Greater Himalayan range. Subhumid subtropical region (below Tapri) received maximum incidences of the landslide which was scored as

1, and above Tapri, the region was found under the sub-temperate which received fewer incidences of landslides which were scored as 0.5 (Table 18.1).

18.6 Comprehensive Vulnerability

No vulnerability region had no any anthropogenic activities and highly covered with forest. The low vulnerability region had a vulnerability score of 0.3–0.5 and sparsely covered with the vegetation. The incidences of landslides were also recorded in this region. Moderate vulnerability score was varies from 0.5 to 0.7, and human settlements were also recorded in this region. The incidences if earthquakes were also recorded in this zone. This zone was not much affected by hydropower development but highly affected by the incidences of slope failures because of road cutting. The region of high vulnerability had most incidences of landslides, floods, and earthquakes. The region of high vulnerability had a high vulnerability score >9 with high losses of the landscape. High incidences of landslides were also recorded in this region (Fig. 18.7). This region recorded along the river Sutlej from Tapir to Khab. The numbers of under-construction hydroelectric projects were developed in this

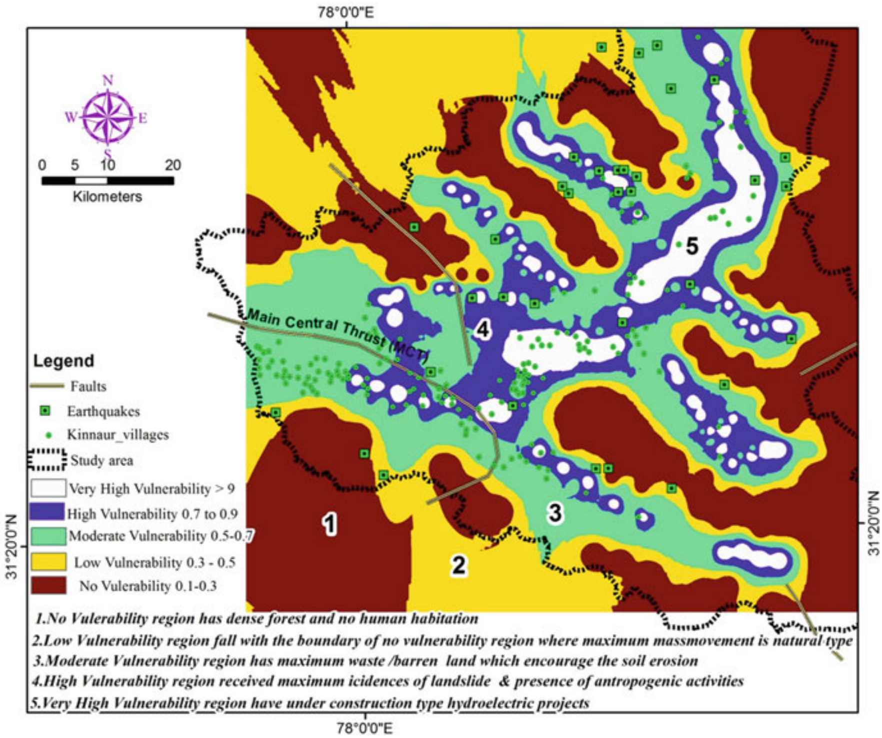

Fig. 18.7 Landslides incidence identification in Sutlej Basin

region. Constructed hydroelectric projects were more responsible for the number of landslides. The development of hydroelectric projects and any other developmental activities should be a sustainable way, and all suggestive approaches and methods should be adopted to control the incidences of landslides.

18.7 Suggestive Approach to Control the Incidences of Landslides

- In the Sutlej Basin, structural managements were very poor and not properly followed. Channel linings are another method for stabilizing a stream. The boulders could be deposited near the bank of the river. It could be helpful to protect the riverbank and settlements/road near the river. This can be used near the riverbank of Karcham Wangtoo. Linings are not costly like the check dam.
- Basically check dams are small, sediment storage dams which are made of dressed and undressed stone. This can be implemented in the upper Sutlej Basin from Khab to Rampur. In Himachal Pradesh the check dam formation process was completed under the forest department. This technique reduces the soil erosion, reduces the steep gradient of the river, and offers toe support to small stream slopes.
- Ditches and drains method could be implemented in the convex types of slopes, where the soil of the lower slope segment has a fine to medium texture. The lower trench could be little excavated to the base of the shallow soil. The eroded material will be deposited on the lower section of the slope. The stability of the concave slope could be attained. The ditches and drains methods could be implemented in Pangi and Powari villages.
- Horizontal drain piping is a commonly used method to reduce the risk of landslide. In this method, PVC pipes were installed in the wall. This hydraulic method reduces the water table and also reduces the risk of slope failure. This method will be very effective near the Powari region where the soil is fine and sandy and the water table fluctuates with rainfall. In the rainfall, the water table raises, and vulnerability of landslide is increased. The drain pipes reduce the intensity of storing water in sandy soil and reduce the risk of landslides.
- The gabion wall-based wire mesh technique is widely used in the basin because this technique required less engineering knowledge. Most of constructed works of gabion walls in Tapri, Kwangi, Karcham, Powari, Brang, Shongtong, Sudharang Dhaku, Khab, Sangla, and Chitkul were done by local labourers. This technique became helpful to cut soil erosion and landslide incidences but not very much effective. There is a need to strengthen the base foundation of gabion walls. Large and long gabion walls were constructed on the left bank of river Sutlej in Shongtong. The army settlements were protected by this gabion wall from a massive flood in 2014. This wall can be constructed in the Powari village on the left bank of river Sutlej.

- It is a very serious matter that in the Sutlej Basin 8% area covers green cover and 36% falls under barren or wasteland. The slope stabilized through the growth of vegetation. The shrub is enough to control soil erosion and landslide incidences. The shrub-covered area was less prone to landslides and reduces the surface runoff. Bioengineering techniques can be used to stabilize the slope in the area of Urni and Apka landslides. But here slope was very steep, and hydraulic seedling can be used for the reduction of slope failure incidences. However, this region was very complex but not impossible.
- In the valley along the roadside, >65% area had the steep slope, and the problem of rock fall and shooting slope was very high from the Tapri to Khab road and another link road. Wire mesh can be placed on the rocky surface of the slope. It can be helpful to protect the people from the falling rocks. This mesh can be helpful to prevent small rocks less than 0.75 m from falling. The rock curtain can be used in and surrounding of highly vulnerable area (Apka) of the Sutlej Basin, where wind speed is very high and rolls out the rock fragment on the road. An open rock shed can be constructed where the slope was very steep and the problem of shooting stone was very high (Apka and Khab).
- This is best to avoid the blasting and mining, according to the people of the study region, as they are the most destructive of the region due to the anthropogenic activities. The blasting and mining activities lead to incidences of slope failures and landslide incidences. A hydraulic rock hammer could be used to down the rock from the slope.
- If we see the future perspective of this research, this validates the way for physical vulnerability. However when we go to resource management and their sustainable development, then we have to go through geospatial technology. The real implementation of vulnerability assessment required micro-level study and also requires a better budget.

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