Landslide susceptibility in Outer and Lesser Himalaya, parts of Solan, Shimla and Sirmur districts, Himachal Pradesh. - A case study.

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Abstract

The study area in parts of Outer and Lesser Himalayan tectonic milieu constitutes the most populous and important urban sector of Himachal Himalayas and is considered to be trunk corridor for accessibility to entire hill tracts of Himachal Pradesh. In recent years the area has also witnessed manifold increase in urban and infrastructure development due to its proximity to major foothill townships like Baddi, Kalka and Chandigarh. The extensive slope modification and / or slope instability are the common outcome of all kinds of anthropogenic activities. However, the problem of slope instability is vulnerable mainly in the proximity of major tectonic features like MBT, MBF and HFT. The Tertiary rocks are the worst affected and recorded more than 50 landslides between Parwanoo and Solan alone along (NH-22) owing to major road widening activities in the area. The study area exposes Proterozoic rocks of Jutogh, Jaunsar, Shimla and Baliana groups successively tectonically underlain by Palaeogene Sirmur and Siwalik Group of rocks. The structural elements have regional trend along NW-SE. These situations together pose severe landslide hazard problem in the area and were the basis of present study of Landslide Susceptibility mapping of the area on 1:50000 scale. The study provided a bird eye view of the distribution pattern of high, medium and low landslide susceptible area and understanding of combination of factors responsible for landslide hazards in the area that may provide a base map for elucidating risk mitigation options and long term land use planning for sustainable growth. The landslide susceptibility studies carried out using independent variables like Slope Morphometry, Geomorphology, Geology, Land use-Land cover, Structure and Drainage and Landslide Incidences as dependant variable. Using Multi class Index Overlay method in ArcGIS and Yule's Co-efficient of statistical method to determine the landslide favouring quotients and weightage for various geofactor class. The obtained score map in Arc GIS was finally classified into 'high', 'moderate' and 'low' susceptible sectors. The final susceptibility score map exhibited 'High', 'Moderate' and 'Low' susceptible zones as 20%, 22% and 58% in the study area encompassing 1176 sq km.

1. Introduction:

Problems of landslide and subsidence have been most widespread problem in hill tracts of Himachal Pradesh. The Geological Survey of India (GSI) has been studying landslide problems since 1951 in Himachal Pradesh that included mostly site specific landslide study and landslide susceptibility zonation on 1:50,000 scale in selected sectors. However, systematic studies only initiated through Pan-India National Landslide Susceptibility Mapping (NLSM) program on 1:50000 scale in 2014. The huge thematic and landslide database may provide the base for developing sustainable and long term land use zoning regulations and disaster management plans.

2. Physiography:

Study area spanning in parts of Shimla, Solan and Sirmur districts of Himachal Pradesh and bounded by longitudes E76º45' & E 77º00' and latitudes N30º45' & N31º 00' (Figure 1), constitutes parts of Lesser and Outer morpho-tectonic domain of Himalayas. The major ridges and valleys also follow to regional litho-structure trend along NW-SE with some cross interspersed valleys. The compactness and toughness of the rocks increases with age and resultantly the softer Tertiary rocks exhibit a highly rugged and fragile terrain as manifested around Kala Amb-Jamta-Morni-Pinjore-Parwanoo areas. In Precambrian belt of Lesser Himalayas with increased compactness of the rock mass, the relief of the terrain also rose manifold, thus exhibiting distinctive and characteristic geomorphological attributes.

These landforms facilitate to landslide when subjected to changed land use and land cover pattern in the form of road & building construction, deforestation and expansion of agricultural lands and improper or unsuitable irrigation practices. The approach to major townships like Parwanoo, Kumarhatti, Kandaghat, Chail, Solan, Kala Amb, Nahan, etc are worst affected due to landslides.

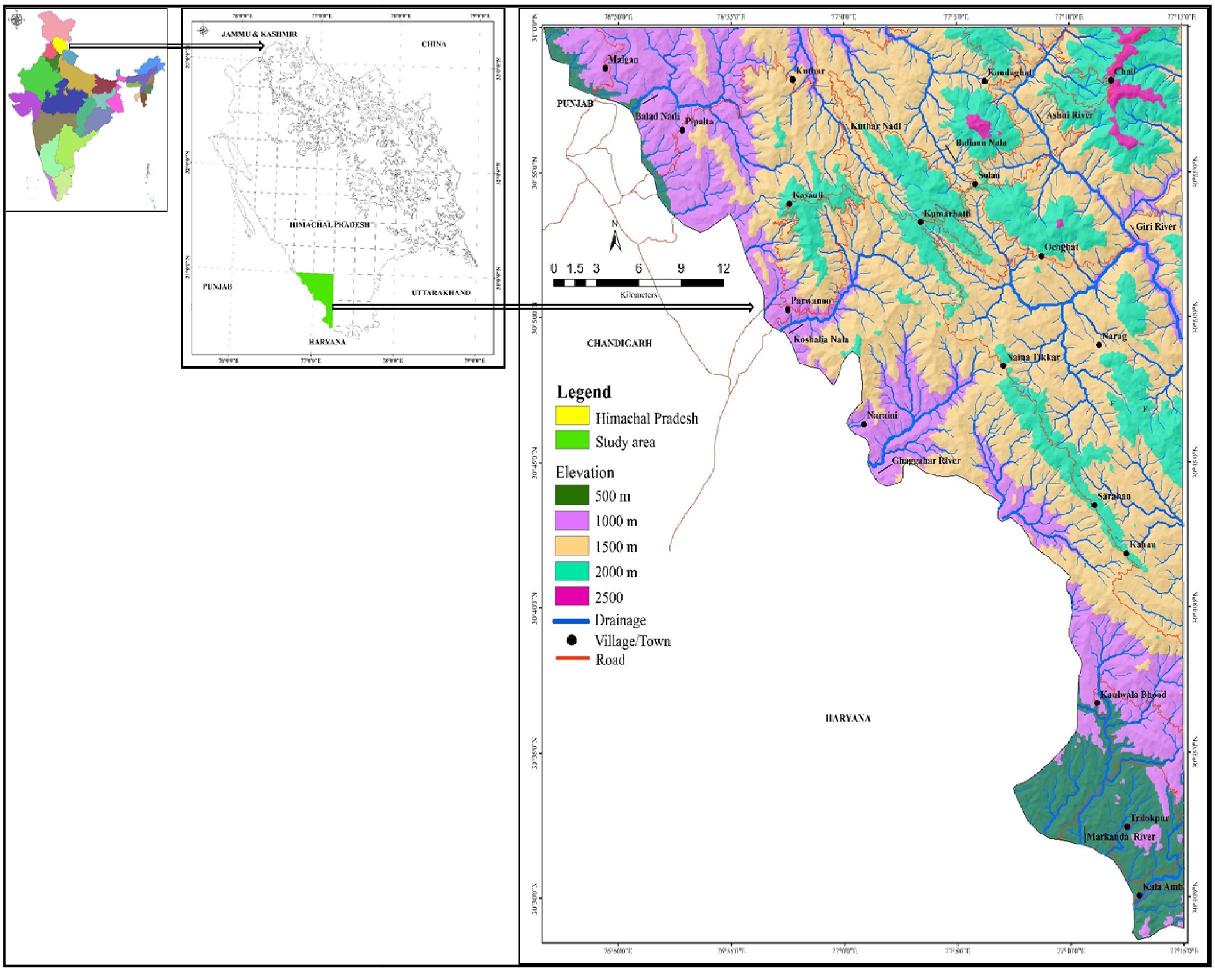

Figure 1 Location map of study area covering parts of Shimla, Solan and Sirmur districts of Himachal Pradesh.

The ground elevation of study area ranges from 500 metres in southwest to 2500 metres above msl towards north-east. The Pinjor Dun separates Frontal (Outer) Himalaya with Punjab plain. Outer Himalaya exhibits low denudated hill ranges whereas Lesser Himalaya comprises intricate mosaic of dissected hills ranges with steep slope rendering higher relief and rugged ranges trending along N-S and NW-SE directions. The area is mainly drained by Ashni River, Kuthar *Nadi* and Baliana *Nala*, Giri River, Markanda River, Kaushalya River and Ghagghar River which exhibits sub-dendritic to dendritic and sub-trellis drainage pattern. Giri and Ghagghar rivers flow SE and SW direction respectively and belong to Ganga catchment system. River valleys in Lesser Himalaya with 20°-30° slope is dominantly covered by colluvial footslope, colluvial cone, transportational mid slope and terraces whereas 30°-50° slope exhibits steep rocky and barren land. The Outer Himalaya river valley with slope of 5°-20° comprises huge alluvial flood plain, alluvial terraces and colluvial plain.

3. Geology and tectonics:

The Lesser Himalayan sector of the study area is occupied by the rocks of Proterozoic represented by Jutogh, Jaunsar, Shimla and Baliana group of rocks whereas the Outer one comprising Sirmur and Siwalik group of rocks exposes mostly sandstone-mudstone/shale sequence (Figure 2). The rock succession have undergone polyphase deformation during Himalayan orogeny resulting in to development of several NW-SE trending regional thrusts [(Jutogh Thrust, Krol Thrust, Chail Thrust, Main Boundary Thrust, Main Boundary Fault, Nahan Thrust and Himalayan Frontal Thrust (HFT)] and faults (Kandaghat Fault, Surajpur Fault etc).

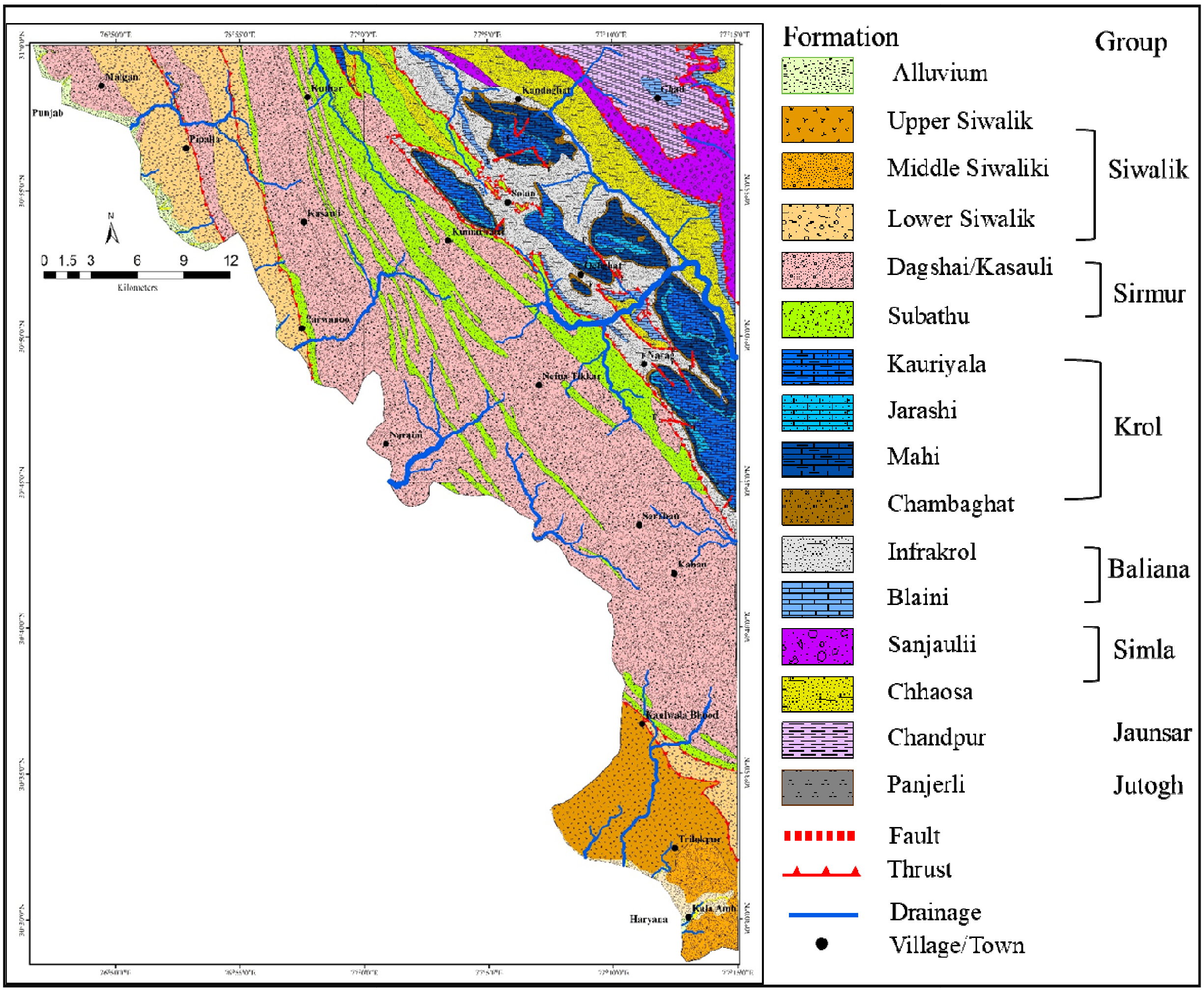

Figure 2 Geological map of study area *(Source: Geological Survey of India, Chandigarh).*

Siwalik Group divisible into Lower, Middle and Upper Siwalik Sub Groups thrust over Alluvium along HFT and also having faulted contact along Surajpur Fault. Lower Siwalik Group tectonically rests over the Upper Siwalik Group along the Nahan Thrust which in turn is thrust over by Sirmur rocks along Main Boundary Fault. Sirmur Group is divided in Kasuali, Dagshai and Subathu formations comprising shale and sandstone sequence with subordinate limestone. The flysh sequence of Shimla Group overrides Subathu Formation along Krol Thrust also popularly known as Main Boundary Thrust. The Krol Group is divisible into the arenaceous Chambaghat, calcareous Mahi, argillaceous Jarasi and calcareous Kauriyala Formations in ascending stratigraphic order (Srikantia et al. 1998). The Baliana Group in the area is represented by Blaini and Infrakrol formation and unconformably lies over Simla Group. The Jutogh Group is represented in the area only by the Panjerli Formation, thrust over the Chandpur Formation of Jaunsar Group.

4. Landslide Incidences and mapping:

Himachal Himalaya is geodynamically active and is affected by thrusts and faults where weathering and erosion of such fragile bed rock and overburden have caused natural landslides. These are further aggravated by anthropogenic activities which caused numerous loss to life, property and state exchequer. Study area has also experienced major landslide incidences at Jabli village, Salogra village, Garkhal village, Parwanoo village, Shamlech village, Chakki Mor etc. Several landslide incidences were aggravated and triggered due to unscientific slope cutting for road construction (along National Highway-22, State Highway-02, State Highway-06, Kalka-Dharampur road, Solan-Kumarhatti bypass road, Kandaghat-Chail and other state roads). Heavy rainfall in the region has triggered numerous landslides in recent years interrupting the surface communication and occasional loss of lives. The landslides were mapped with the help of available archives as well as field observations.

5. Methodology:

The landslide susceptibility mapping is based on knowledge driven integration technique known as the weighted Multi Class Index Overlay method, (Guzzetti et al., 1999) is an improved bivariate statistical technique which uses landslide as a dependent variable to estimate the landslide susceptibility of an area. The method derives the weightages of geofactor maps taking into considering the landslide association and frequency with respective classes and using Yule's coefficients (Yc) the degree of association of landslides with each geofactor class are determined. From this the Landslide Occurrence Favourability Score (LOFS) is obtained. For a particular mapping unit, the susceptibility score is calculated after adding the LOFS values of geofactor maps and normalizing it by its weight. Further Success rate curve (Chung and Fabbri, 2003), is used to subdivide the susceptibility scores into three classes of landslide susceptibility i.e. high, moderate and low. The cut-off boundaries are taken based on cumulative distribution of landslide percentage such that 70% landslides are contained within high susceptibility and 80% in moderate susceptibility. If the success rate curve is steeper at lower cumulative map area than those of higher cumulative values, then the landslide susceptibility map has strong ability to predict areas that are most susceptible to sliding.

For the susceptibility study of the area, a total of nine factor maps, viz., slope, aspect, curvature and drainage (derived from 30m Aster DEM), geomorphology and land use/land cover (prepared from toposheets and Google Earth images as base maps in ESRI Arc GIS 10.2), slope forming material (field based and GSI Geology map), and landslide inventory (from imagery, archival data and field observations) using toposheets and Google Earth images as base map have been prepared. LOFS for each sub-class of nine thematic maps was obtained by using Yule's coefficient and susceptibility score was calculated after adding the LOFS values of all nine factor maps and normalizing it by its weight. This has been illustrated as below in (Figure 3, Table 1).

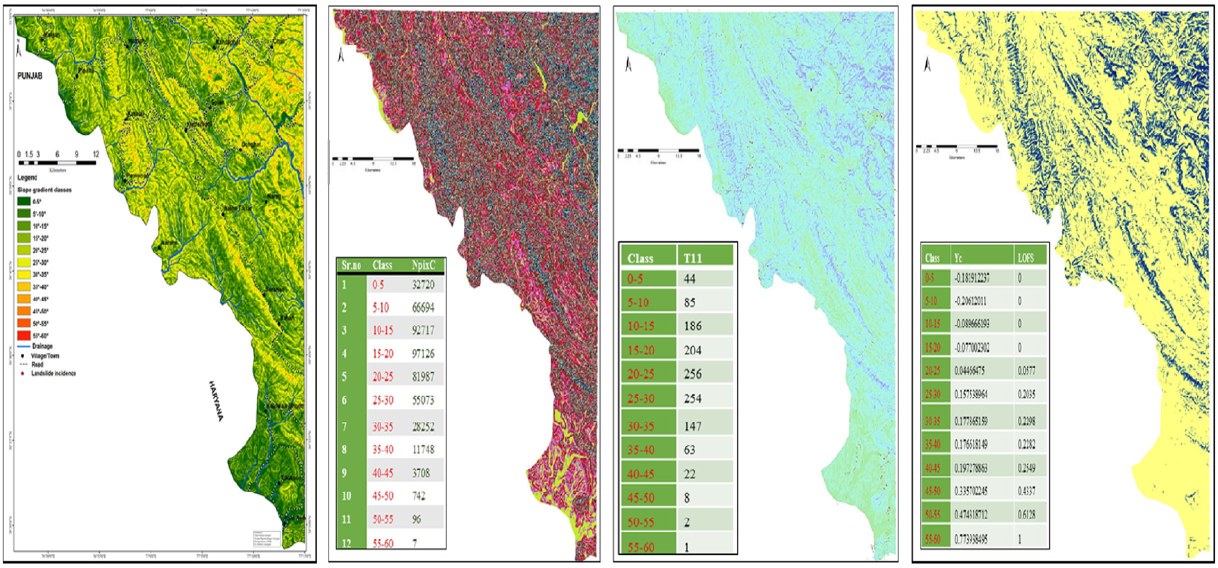

Figure 3 Process of thematic map (slope) integration with landslide and LOFS value.

Table 1
Slope gradient classes, distribution and LOFS rating

Sr.no	Class	NpixC	NpixT	T11	NpixLS	T12	T21	T22	Yc	LOFS
1	0-5	32720	470870	44	1272	1228	32676	436922	-0.181912237	0
2	5-10	66694	470870	85	1272	1187	66609	402989	-0.20612011	0
3	10-15	92717	470870	186	1272	1086	92531	377067	-0.089666193	0
4	15-20	97126	470870	204	1272	1068	96922	372676	-0.077002302	0
5	20-25	81987	470870	256	1272	1016	81731	387867	0.04466475	0.0577
6	25-30	55073	470870	254	1272	1018	54819	414779	0.157538964	0.2035
7	30-35	28252	470870	147	1272	1125	28105	441493	0.177865159	0.2298
8	35-40	11748	470870	63	1272	1209	11685	457913	0.176618149	0.2282
9	40-45	3708	470870	22	1272	1250	3686	465912	0.197278863	0.2549
10	45-50	742	470870	8	1272	1264	734	468864	0.335702245	0.4337
11	50-55	96	470870	2	1272	1270	94	469504	0.474318712	0.6128
12	55-60	7	470870	1	1272	1271	6	469592	0.773938495	1

Where: -
NpixC=No of pixels in class
NpixT=Total no of pixels
T11=Landslide pixel count in class
NpixLS=Total no of pixels of landslides
T12=NpixLS-T11 i.e. where landslide is present and class is absent
T21=NpixC-T11 i.e. where class is present and landslide is absent
T22=NpixT-T11-T12-T21 i.e. where no class, no landslide and no intersection
Yc=(SQRT(T11/T21)-SQRT(T12/T22))/(SQRT(T11/T21) +SQRT(T12/T22))
LOFS= IF(Yc<0,0,Yc/Yc max)

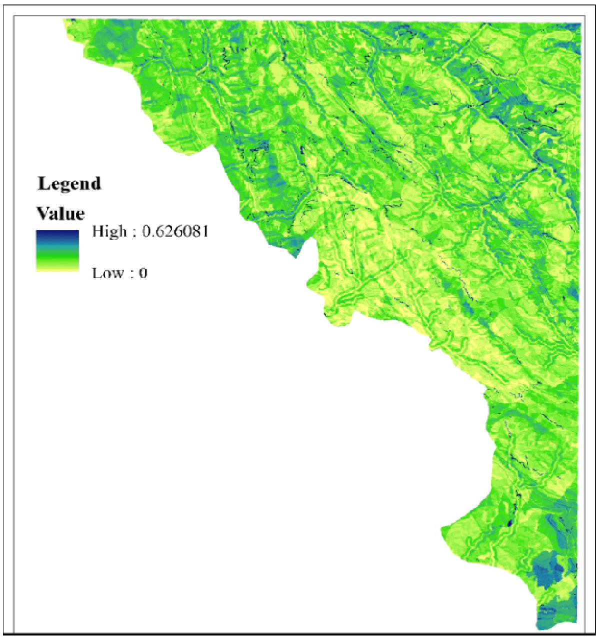

Figure 4 Landslide score map of study area.

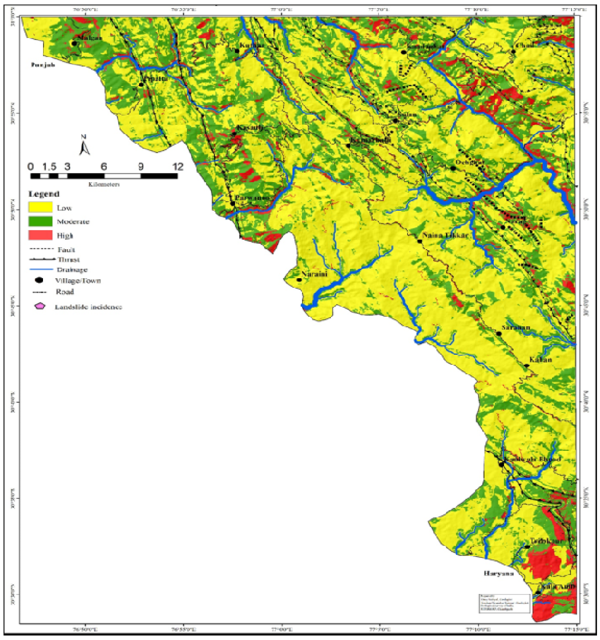

Figure 5 Landslide susceptibility map showing 'High, Moderate and Low zone.

Similarly, the Susceptibility Score Map (Figure 4) was obtained by integration of LOFS for all thematic map and combined with landslide inventory map to generate Success Rate Curve in ILWIS 3.2 where the same was classified in to high, moderate and low classes accordingly to procedure. As result 20%, 22% and 58% area is respectively under high, moderate and low zone (Figure 5).

6. Landslide inventory mapping:

The zone of depletion of landslides were digitized as polygons using Google Earth and archival data and then exported to a GIS platform to prepare the imagery based landslide inventory map followed by field validation and updation. Landslide present in the study area indicates, the rockslide, debris slide and rock fall comprises nearly 82.3%, 9.2% and 8.4% respectively.

6.1. Geofactor classes and association of landslide:

Landslide is related to terrain attributes such as slope geometry, geomorphology and land use/land cover (LULC) and slope forming material etc. In geomorphology the main factor is attributed to slope because most of geomorphological features are associated with slope morphometry. Land use and land cover are also important factors because they affect the stable slope. Modification of stable slope is generally done by unscientific cutting of bottom of the slope or upper part will be cut as small benches for agriculture leading to instability of slope on heavy downpour of rain or snowfall. Thickness of overburden is one of the important factors for assessing the stability of the debris and landslide susceptibility of the slope with the increase of soil depth, the tendency of soil to absorb runoff is increased thereby resulting in increased tendency of slope failure. It is the outcome of many factors in combination that may include the intensity of snow fall, rains, porosity of soil and physical as well as chemical properties of underlying rock. Drainage is very important in prospecting of landslide occurrences because of their toe cutting action. Geological structures also play vital role as they affect the physical nature of the rock mass. In study area slope morphometry shows that maximum distribution of landslide is within 20 º-30º followed by 15º and 35º slope classes, however, the 60º class constitutes the most vulnerable slope class. Landslide occurrences are mostly associated with SW, SSW and WSW slope directions and more frequently in those areas where the slopes are convex. Geomorphological feature indicate that denudation hill slope followed by and highly dissected hill slope constitute vulnerable geofactor sub-classes. Landslide vulnerability is mainly associated with extensive slope cut followed by barren rocky slope. The maximum numbers of landslide is associated with bedrock followed by colluvium and slope wash. The fault/fracture analysis revealed presence of landslide is up to 50m and 300-400m distance interval that gradual increases to maximum distance interval at 5km. The drainage analysis revealed that most vulnerable buffer zone is the 150-200 m and gradually increases to maximum distance at 5 km. (Figure 6).

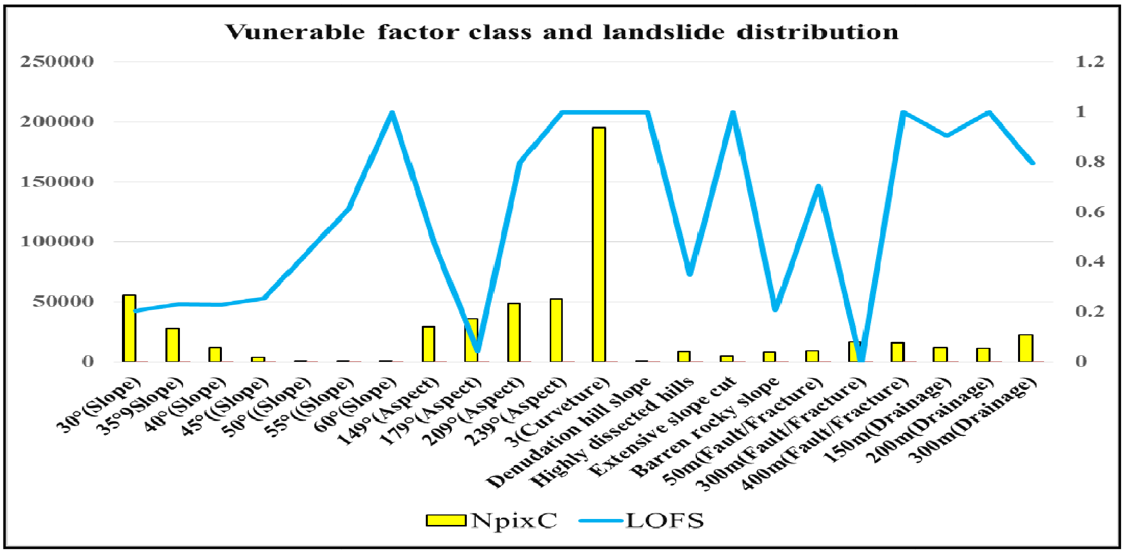

Figure 6 Vulnerable factor class and landslide distribution (LOFS) (where, NpixC-Area coverage).

Generally, 2nd to 4th order perennial streams are most relevant to land sliding. This indicates that maximum landslide occurrences are governed by geomorphic processes like toe erosion and denudation.

6.2. Landslide Occurrence Favourability Score (LOFS):

LOFS for various class of individual geofactor gives the idea about the probability of the occurrence of slide and the responsible class of the particular geo-factor. It is derived by using the Weighted Multiclass Index Overlay method.

For preparation of landslide susceptibility mapping in study area nine geo-factor maps were prepared and Yule's coefficients (Yc) used for determining the degree of association of landslides with each factor class and the respective LOFS was obtained. Following table show the maximum Yc_{max} and LOFS value associated with particular geofactor class (Table 2).

Table 2
Yc max and LOFS value associated with particular geofactor class

Serial numbe	Geofactor class	Yc_{max}	LOFS
(1)	55°-60 ° (Slope)	0.773938495	1
(2)	209°-239° (Aspect)	0.121724 1	1
(3)	3 (Convex curvature)	0.09142	1
(4)	Denudation hill slope	0.71037	1
(5)	Extensive slope cut	0.83509	1
(6)	Young loose debris	0.710368115	1
(7)	300-400 m (Fault and Fracture)	0.11935	1
(8)	150-200 m (Drainage)	0.17410	1

6.3. Interpredictor weights:

Individual spatial factors can have different degrees of spatial associations with landslides. Therefore, calculation of inter-predictor weights is important in predictive modelling. The analysis can benefit from expert/generic knowledge of causal factors of landslides. However, expert knowledge is subjective and landslide experts are likely to assign different weights. Predictor rating (PR) for every spatial factor based on their degree of spatial association with landslides and it has been determined by calculation. Below table is showing PR in decreasing order (Table. 3).

Table 3
Predictor rating (PR) or weight of factor map

Sr.no.	Factors	Min Yc	Max Yc	Abs. Diff.	Int. Wt.
1	Slope forming material	-1.00000	0.71037	1.71	7
2	Land use and land cover	-1.00	0.8351	1.84	7
3	Geomorphology	-1.00	0.7104	1.71	7
4	Curvature	-1.00000	0.21277	1.21	5
5	Slope	-0.21	0.77394	0.98	4
6	Fault and Fracture	-0.390140	0.147232	0.54	2
7	Drainage	-0.2162757	0.20126395	0.42	2
8	Aspect	-0.052940	0.19863	0.25	1

The output map is a predictive model of landslide susceptibility to occurrence of landslides under examination in the area. The Landslide Susceptibility Map (LSM) was prepared in raster format, using pixel of 50m x 50m grid as a mapping unit and by calculating the Landslide Occurrence Favourability Score (LOFS) for all factor classes of each geo-factor theme in ArcGIS.

6.4. Validation and Success Rate Curve:

Validating the landslide susceptibility maps by mere physically overlapping the landslide incidence map over landslide susceptibility map is only trivial and cannot provide quantitative assessment of the actual performance of any predictive model. There are several methods for validation, but two most common methods are (i) validation by using landslide density or area percentage value and (ii) Validation using success/prediction rate curves.

Validation using success/prediction rate curves method is used for the susceptibility modelling.

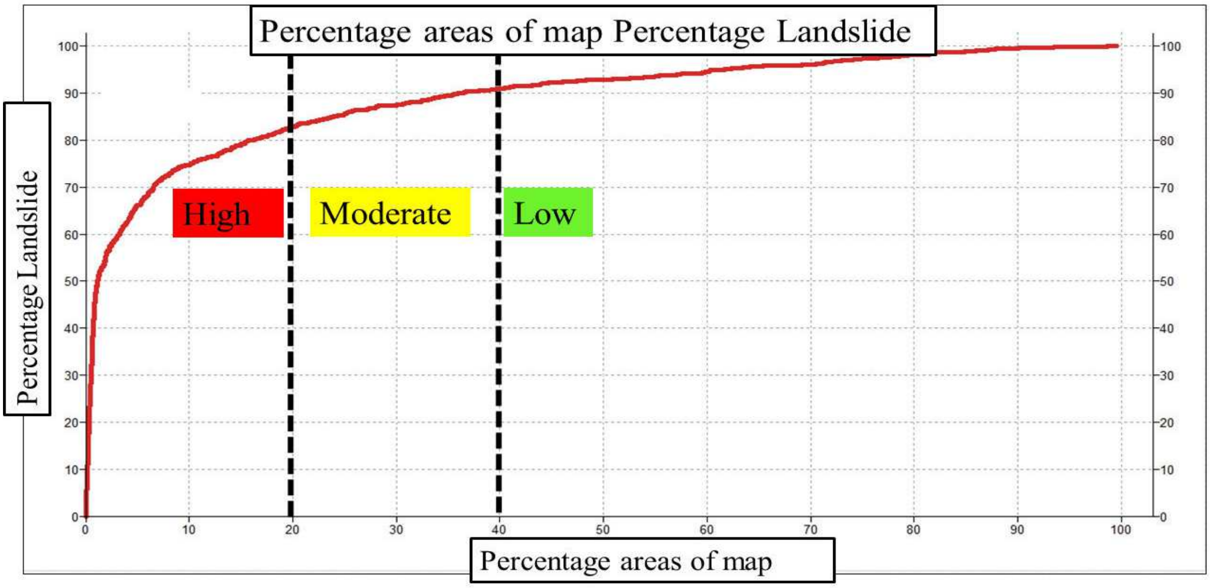

Figure 7 Success rate curve of the study area (After Chung and Fabbri, 2003)

The obtained success rate curve is about 82% cumulative distribution of all landslide source areas is contained within 20% of the study area having higher susceptibility scores. The next 10% landslides or 18% of cumulative landslides are contained within 20% or 80% of the study area, respectively. The susceptibility score values at the cut off boundary of cumulative 82% and 92% landslides are taken for defining the boundary limit of high and moderate susceptibility class (Figure 7).

7. Landslide susceptibility map and venerable zones:

Landslide Susceptibility assessment is based on spatial distribution and density of landslides in an area. The assessment of the susceptibility of a terrain for a slope failure expresses the likelihood that such a phenomenon may occur under the given terrain conditions or parameters. Although it is expected that landslide will occur more frequently in the most susceptible areas, however, in the susceptibility analysis no time frame and magnitude of the event can be predicted. The susceptibility is expressed in terms of the relative proneness to initiation of a landslide in a pixel under the given terrain conditions. Major landslides occurrences perceive in the study area during field work are at Garkhal village, along road stretches from Timber Trail to Solan town (NH-22) (Fig.12), Radiana village to Kharsipul along Kuthad road, Moginand village and Kala Amb village (NH -72), Kumarhatti to Paughat village (SH-02) (Fig.10 & 11), left bank of Kaushalya River (Fig.8), left bank of Giri River (Fig.9), Narag cut to Giripul village (SH-06), Ashni Khad section along Chail link road and left bank of Markanda River, etc.

Figure 8 Rockslide triggered due to toe erosion by Kaushalya Nala on its left bank, near Timber Trail

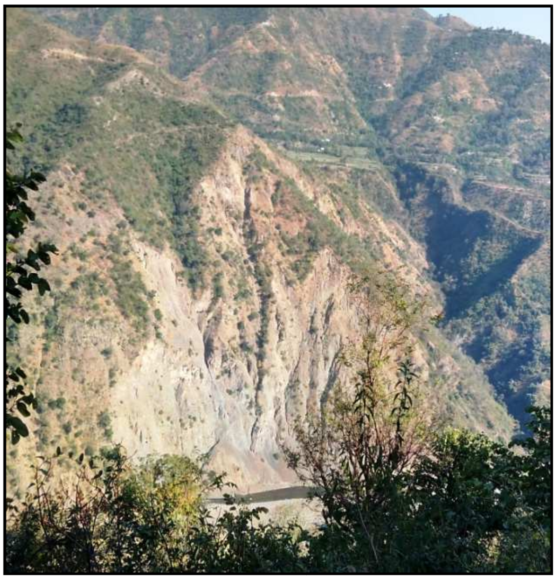

Figure 9 Rockslide on a major spur along the left bank of Giri River near Shalamun village

Figure 10 Rockslide on State Highway 02, due to heavy rainfall

Figure 11 Rockfall incidence on State Highway 02

Figure 12 Extensive slope cut during road widening leading to slope failure defined by crushed Dagshai shale of Sirmur Gp along NH-22 near Timber Trail

Landslide susceptibility map revealed that 235 sq km area are under high susceptibility zones associated with denudational hill slope, highly dissected hill slope and colluvial footslope of the hills.

Moderate susceptibility zone encompasses 259 sq km of the study area. Moderate susceptibility zone is manifested with moderately vegetated to agricultural land. Moderate susceptibility zones exhibit mostly rock fall and rockslide occurrences associated with lowly to moderately dissected hills where rocks are mostly fractured, sheared and crumbled.
Low susceptibility zone in remaining area of 682 sq km, where flat to gently sloping lands and mid transported slopes mostly covered by moderate to thick vegetation. The susceptibility map doesn't include temporal and magnitude prediction of landslide event. Prediction of landslide occurrence is difficult in Himalayan terrain because of wide variation in slope morphometry, geological, geomorphologic attributes coupled with varying degree of triggering factors like rainfall, seismic events and anthropogenic activities.

9. Recommendation :

The methodology involves an easy access to data source, simplified identification of landslide incidences and relevant geofactors and derivation of final susceptibility map of a large area which is close to the ground truth and in an effective manner in terms of time and economy involved. The landslide susceptibility map in 1:50,000 scale at a glance, gives an idea about the vulnerability of landslide particular areas as demarcated in 'High', 'Medium' and 'Low' zones and is meant for regional application. It is recommended that the development activities in the high susceptible zone may be avoided or be utilised for a purpose involving low risk only after execution of all control measures. Moderate Zone, also shows tendencies of mass wasting with varying magnitude and also include few major slides. Moreover, due to relatively moderate natural conditions these areas have also been encroached by various anthropogenic activities. In view of above such a terrain also warrants cautious dealing. It is recommended that existing or proposed areas for development and major urban pockets in high and moderate zone may be also subjected to detailed/landslide micro-zonation, hazard and risk analysis for sustainable and eco-friendly development. Low susceptibility zone in the study area is characterised by flattish slopes that can be utilised for various developmental activities. However, it is suggested that construction may be carried out in accordance with the building code as applicable. The structure/facility may be located at an adequate buffer distance from the river channel and major thrust/fault zone, slide zone, run-out zone and above the active flood plain.

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