GIS-Based Study To Develop Landslide Susceptibility Zonation Map Of District Mandi, Himachal Pradesh

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Abstract

Rising Incidents of landslide at district Mandi is issue of concern in Himachal Pradesh. Every year many people losses their life and property in these landslide event. This study is conducted with aim to preparation of landslide susceptibility zonation map of district Mandi using method of frequency ratio. Causative factor of landslide involved in preparation of Landslide susceptibility zonation map is Lithology, Slope, Drainage density, Aspect and Land use land cover. Slope, Drainage density, Aspect map are extracted through digital elevation model. Source of Digital elevation model used here is based on SRTM data whereas lithology map is based on data of geological survey of India. Land use land cover map is extracted by images of Landsat 8 satellite. Total of 52 existing landslides are used to model final map. LSZ map show 40.42% area is falling under medium susceptibility class, 34.5 % under low and 25.07% is under high susceptibility class which cover tehsils Mandi, Chachyot, Thunag and some part of Padhar, Aut and Bali Chowki. Further to validate these result areas under curve (AUC) method is use which give prediction rate of 76.06%.

Introduction

Event of landslide at mountain region of district Mandi, Himachal Pradesh causing high number of casualties every year. Prevention, Mitigation and Preparedness are the techniques advised to use by Himachal Pradesh state disaster management authority in case of any disaster. Role of vulnerability mapping is highly recommended to be used in mitigation process which is done by producing landslide vulnerability zonation map with help GIS software. Landslide hazard zonation is method of representing probability of future landslide in spatial format. Accuracy of landslide hazard zonation map depend on amount of data collected, quality of data and method of modelling(Guzzetti et al., 2005; Soeters & Westen, 1984). The preparation of landslide hazard zonation map is based on some assumptions as future landslide are more likely to occur at similar conditions which cause landslide at past, both remote sensing and field survey can be used to map landslides, It is possible to map causative factors with applications of remote sensing and GIS (Dai & Lee, 2002; Statistical et al., 1991; Varnes, 1958). P. Aleotti, R. Chowdhury has distinguished modelling method landslide susceptibility map broadly into two categories as qualitative and quantitative approach(Chowdhury, 1999). Individual judgement plays crucial role in qualitative approach which can be based on field survey or satellite images observation (Chowdhury, 1999; Paper, 2012). Quantitate approach is more of scientific and reliable method(Vakhshoori & Zare, 2016). Quantitative approach is distinguished further as Statistical Analysis, Geotechnical Engineering approaches, Neural network analysis(Chowdhury, 1999). Geotechnical engineering which is also termed as deterministic approach by some authors include preparation of mathematical model. Preparation of such model require different geotechnical properties of soil from specific location due to which this approach is not practical for large area (Paper, 2015). Statistical method on other hand is incredibly useful in large area mapping. Due to innovation in remote sensing technology large number of data is available from different satellite like landsat8, carto sat 2, TIROS, NOAA and SANTINEL satellite etc. as innovation in GIS technology occurred is last decade so the popularity of statistical approach in landslide hazard assessment (Paper, 2015). Statistical approach is further classified as Bivariate statistical analyses and

Multivariate statistical analyses. Bivariate statistical analyses are much related with comparing every causative factor with past landslides with aim to give individual weightage to each class of factor (Paper, 2015). Some common method used and compared by method of AUC by different researcher in this category are logistic regression(Paper, 2010; Rasyid et al., 2016; Vakhshoori & Zare, 2016), frequency ratio (Anbalagan et al., 2015; Estate, 2014; Paper, 2015; B. Pradhan & Lee, 2010; Rasyid et al., 2016; S. Sharma & Mahajan, 2018; K. Singh & Kumar, 2017; Talib, 2005; Vakhshoori & Zare, 2016), analytical hierarchy process method(Article, 2006; Paper, 2014; Vakhshoori & Zare, 2016), fuzzy logic approach(Anbalagan et al., 2015; Paper, 2015; Vakhshoori & Zare, 2016), Information Value method (Articles, 2005; Mahajan, 2019; Pareek et al., 2013; K. Singh & Kumar, 2017). State of Himachal Pradesh fall under Himalayan mountain belt. Petley in his work on 2012 found that maximum number worldwide fatalities due to landslide is found to be occurring along Himalayan arc and china (Petley & Petley, 2012) whereas work done by Surya Prakash in India has shown that west and North West area of Himalayas suffer more landslide compare to northeast and south India(Parkash, 2015). This west and northwest part include states Himachal Pradesh, Uttarakhand, Jammu and Kashmir. Due to increase in event of landslide and effect to social and economic condition several researchers inspired to conduct case studies and assessing landslide event is these region (Bhardwaj et al., 2019; A. Kumar et al., 2017; Parkash, 2016; Sundaram, n.d.). Few work is done on some part of Himachal Pradesh for preparation of landslide hazard zonation is observed at district of Kullu(Bandhu & Chandel, 2016; S. Sharma & Mahajan, 2018; Versain, 2019), Kangra(S. Sharma & Mahajan, 2018), Dharamshala(Mahajan, 2019), Chamba (K. Singh & Kumar, 2017), highway from Nahan to Rajgarh(V. Kumar et al., 2019) and region of Sirmur district(Rautelal, 2000). Some massive landslides in district of Mandi was observed on past like Kotropi landslide which cause death of 46 people (S. P. Pradhan et al., 2019; Verma et al., 2020). This massive landslide event attracted some researcher for conducting case study and providing remedial measure (P. Sharma et al., 2018; Verma et al., 2020) and work to improve risk communication and early warning system (Fennessy & Mikolajczak, 2016). Although all these efforts are made but future possible landslide event still possess threat to new and existing settlements in this region. GIS bases study and landslide hazard zonation provide scientific base for decision maker. Therefore, work to prepare landslide susceptibility zonation map of this region become most crucial requirement for ensuring safe development of this region. Aim of this study is to prepare landslide susceptibility zonation map of district Mandi, Himachal Pradesh using frequency ration approach.to achieve this objective list causative factor for landslide is identified and region is distinguished into different classes of each factor. Frequency ratio of each class is calculated so that final map can be prepared. aim of this landslide susceptibility zonation map is to help decision maker to identify locations with most requirement of landslide mitigation measure and this study will also help future planning for land use pattern.

Material And Method

Study Area

Study area covered is district Mandi of state Himachal Pradesh, India. Himachal Pradesh is hill state of India which entirely fall on Himalayan mountain range. Himachal Pradesh is located at northen part of

country whereas Mandi is situated at centre of Himachal Pradesh as in Fig. 1 (a) District of Mandi rests between $31^{\circ}13'50''\text{N}$ to $32^{\circ}04'30''\text{N}$ latitude and $76^{\circ}37'20''\text{E}$ to $77^{\circ}23'15''\text{E}$ longitude. Lesser Himalayan range cover maximum part of district. During months from July to September Heavy rainfall is observed in maximum are and medium snowfall during months October to march at higher elevation. Elevation show variation from 478m to 3346m as shown in Fig. 1(b). Jogindernagar and Sarkaghat tehsils witness maximum rainfall in district (P. Singh et al., 2008). Major type of rocks present in district are Shah, Tertiary, Jutog and Chail group of rocks were each group having number of Formation and Lithology, which distinguish it in total of 32 lithology class. Beas and the Satluj are two main rivers in district which are having number of tributaries locally known as khad. Topography of region is rugged and having steep slope. Water holding capacity of soil is poor as maximum soil is of argillaceous origin. Further detailed information on method used for preparation of LSZ map and collection of material (different thematic and landslide map) is provides in following subsections.

Frequency ratio method for landslide susceptibility zonation

Landslide susceptibility zonation map is developed using frequency ratio method. Aim where is to develop model showing likelihood of landslide occurrence at Mandi district using current occurred landslide data. Frequency ratio is obtained by ratio of percentage landslide area in each factor class to percentage area of each class in factor itself (Prakash & Chandong, 2010; Rasyid et al., 2016; K. Singh & Kumar, 2017; Talib, 2005; Vakhshoori & Zare, 2016), this frequency ratio represent correlation of each class to landslide hazard (Lee, 2009; Talib, 2005; Vakhshoori & Zare, 2016) High value of FR represent higher contribution of that class in future possible landslide. Value of FR of each class is used to give perdition value in order to give individual weightage to each parameter. Mathematically, FR of each desired class may be represented as

$$FR_d = (\%L_d) / (\%C_d)$$

FR_d Frequency ratio of desired class

$\%L_d$ is percentage of landslides in a desired class,

$\%C_d$ is percentage area in desired class

Final landslide susceptibility index is calculated using raster calculator in ArcGIS 10.3 toolbox, which can be represented mathematically as.

$$LSI = \sum_{d=1}^n FR_d$$

Data sources and layer preparation

To prepare LSZ map it was important to find exact location of landslide occurrence which was possible by using GPS system and google earth software. journey was made at different location of Mandi to know exact location of landslide two of which is shown in Fig. 2 and validated by using google earth software.

Location which was not assessable only remote sensing data was used. To understand factor of landslide repeated field visit was made. Different factors responsible for landslide at district was selected based on previous work and field observation. Factor which we used in our study was Slope, Aspect, Lithology, land use land cover and Drainage density. Map of different influencing factors has been downloaded and used for further process on ArcMap 10.3. SRTM data was used for extracting DEM tiles of study area which is made available by USGS shown in Table 1. Mosaic tool was used for combining all available tiles of and prepare one common tile. From where DEM data for study area was extracted using clip function of ArcGIS. Slope, aspect drainage density data was extracted using DEM map while using different tools on ArcGIS 10.3. Lithological map of area is obtained from GSI. All the raster was resized to same cell size by using resample tool. Every raster was classified into different class. Pixel count for different classes in each factor and pixel count of landslide in each class is obtained. Which was further used to obtain RF, RF and PR values. Main objective of finding Frequency ratio is to give weightage to each class and use prediction rate to give individual weightage to each factor. All the raster layers are submerged together by using raster calculator tool and LSZ map is obtained at last. Final map obtained divide area into three different classes of susceptibility of landslide as low, medium, high class. This obtained map is verified by observing landslide location and obtained zones. Total of 52 landslides were observed and considered in our study which is having 17.73 km² area whereas total study area is 3666.5 km².

Table 1
Data source and use

Data type	Source	Sensor	Spatial Resolution	Data derivative
Satellite images	Landsat 8	OLI and TIRS	30m	Land use and land cover
	Google earth			Landslide inventory
				Landslide distribution
DEM	SRTM	c-band x-band	30m	Slope Aspect Drainage density
Geological map	GSI			Lithology
Field Survey	GPS			Location and feature of landslide

DEM-based derivatives

When terrain of area is represented in digital format is known as Digital elevation model of that area. DEM help to generate various maps which may influence occurrence of landslide in area like slope, aspect, drainage density. Slopes show how steep is the area which can be major influencing factor for landslide. Slope map is extracted from DEM by using slope tool. It is reclassified in five classes as 0°-6°, 6°-16°, 16°-26°, 26°-36°, 36°-46°. most of area is observes as steep terrains having slope more than 36° as shown in

Fig. 3 (b). Aspect term in GIS is generally used to show orientation of slope face which may be start from north and further follow all compass directions. Aspect of slope generally influence factors like sunlight strike in slope, growth of vegetation, soil moisture in indirectly effect occurrence of landslide. Aspect of Mandi district is obtained from DEM by using aspect tool and reclassified into nine classes as north, northeast, south, southwest, east, southeast, west, northwest and flat see Fig. 3(a). Drainage density is perimeter which show weather area is draining water efficiently or not. It can be found by dividing total stream length to total area is that particular drainage basin. It is reclassified into three classes low medium and high.it is generally extracted by application of line density tool as in Fig. 3 (c)

Lithology and LULC

Lithological area of Mandi is divided into 32 classes by geological survey of India, all of these classes has been used in our work as shown in Fig. 4. Data for lithology is obtained from Bhukosh which is well established portal by government of India to download geoscientific data of geological survey of India. Lithology of district consist of Sillimanite - kyanite bearing schist, quartzite, leucocratic granite, aplite, quartz veins Bed rock classification which are also most effected due to landslide. Land use land cover of area is distinguished as five different classes as water body, vegetation, settlement, forest, barren land as shown Fig. 3 (d). To prepare this map firstly images of landsat8 satellite are downloads. although number of images of different satellite is available now days but images of Landsat 8 is used due to its compatible spatial resolution for our area, high number of bands used.

Result And Discussion

Extracting slope from DEM model shown that slop in area show variation from 0° to 45° although maximum of area is highly inclined between 36° - 46° slope. From table 2 Frequency ratio of slope ranging 36° - 46° is observed to be 1.000527 which show high probability of landslide occurrence. Aspect term in GIS is generally used to show orientation of slope face. Aspect class of Northeast, South, Southwest West is showing high correlation with landslide as they are having FR value as 1.160062, 1.464596, 1.8702,1.195669 respectively. Reason for their high probability can be due to lack of sunlight and low vegetation growth in these directions. lithology spatial relation of each class is identified. It is observed that out of 32 classes as given by geological survey of India as in table 2. Salt Grit, Purple Grit, "Lokhan" have highest value of frequency ratio which is 24.75594. Beside this Tholeiitic Basalt Minor Quartzarenite, Shale having FR 5.547095 and Micaceous Sandstone, Purple clay, Mudstone having FR 8.336085 also show high spatial relation with landslide. Note that among 32 classes maximum area is covered by class Brown Sandstone, Red clay, Purple Chocolate Shale which is 15.53% of total area in term of drainage density. In term of drainage density maximum frequency ratio is observed at Medium class which is 1.197418 whereas FR at low and high DD is 0.996376, 0.805864 respectively. It is worth observing that maximum area falls under low class observed 44% that of total area. Causative factor LULC is classified into five different classes namely Water bodies, Vegetation, barren land, Forest, Settlement. Among all these maxima of area is covered by forest (41.346 % of total area) and minimum area is covered by water bodies (0.913 % of total area). High correlation of landslide is observed with barren land, Vegetation, Settlement

which have FR value as 2.015722, 1.139227, 1.492711 respectively. least influencing class observed was Forest having FR as 0.273637 which also have maximum area among all classes.

Table 2. Frequency ratio value of every class of each causative factor.

Factors	Class	Area Covered by class	Ni (total pixels in class)	Area (%)	Si (land slide pixel per class)	Land slides Area%	FR
slope	0-6	0.79	768	0.021	0	0	0
	6-16	0.25	245	0.006	0	0	0
	16- 26	0.36	350	0.009	0	0	0
	26-36	0.54	524	0.0146	0	0	0
	36-46	3664.5	3578688	99.94	17324	100	1.000527
Aspect	Flat	1.24	1209	0.034	0	0	0
	North	247.98	242171	6.763	809	4.669	0.690437
	Northeast	273.66	267244	7.464	1500	8.658	1.160062
	East	367.71	359096	10.029	1260	7.273	0.7252
	Southeast	409.85	400248	11.178	1763	10.177	0.910377
	South	419.21	409381	11.43	2901	16.745	1.464596
	Southwest	426.06	416078	11.62	3765	21.733	1.8702
	West	446.94	436464	12.19	2525	14.575	1.195669
	Northwest	522.10	509868	14.24	1864	10.759	0.75559
	North	551.69	538761	15.047	937	5.409	0.359452
Drainage Density	Low	1593.05	155578	44.04	7602	43.881	0.996376
	Medium	1018.34	994474	28.153	5840	33.71	1.197418
	High	1005.81	982245	27.806	3882	22.40	0.805864
Lithology	Shale, Siltstone, Quartzite and Greywacke	0.18	176	0.004	0	0	0
	Quartzite, Shale,Slate, A few basic flows.	40.32	39380	1.099	469	2.707	2.461515
	Streaky and Banded Gneiss.	82.83	80890	2.259	151	0.872	0.385822
	Sillimanite – Kyanie Bearing Schist,	546.78	533963	14.91	3657	21.109	1.41553

Quartzite						
Schist and Quartzite	206.53	201689	5.633	8	0.046	0.008198
Pink, Grey Limestone, Sporadic Shale.	149.25	145755	4.07	84	0.485	0.119114
Pink, Grey Dolomite, Phyllite, Shale.	122.53	119656	3.342	0	0	0
Brown Sandstone, Red clay, Purple Chocolate Shale	569.71	556356	15.53	911	5.259	0.338432
Dolomite, Brick Red Shale.	13.52	13205	0.369	6	0.0346	0.093911
Dolomite, Sporadic Quartzite.	111.03	108433	3.028	622	3.59	1.185589
Grey Sand, Silt and Clay	26.29	25671	0.716	182	1.05	1.465325
Grey Phyllite, Schist and Quartzite	8.98	8767	0.245	156	0.9	3.677722
Pink, White Quartzite, Thin Beds of red Shale.	50.15	48975	1.367	41	0.237	0.173027
Limestone, Shale, Quartzite, Sporadic Conglomerate	95.63	93392	2.608	0	0	0
Grey, Purple, Red Sandstone, Shale, Limestone	231.7	225953	6.310	1686	9.73	1.542215
Quartzite, Slate, Basic Flows.	24.12	23551	0.657	0	0	0
Cherty Dolomite, Quartzite, Limestone.	13.09	12786	0.357	0	0	0
Shale, Siltstone & Limestone	5.07	4957	0.138	0	0	0
Diamictite, Shale, Slate, Sandstone, Limestone	57.15	55809	1.559	303	1.749	1.122131
Gravel, Pebble, Sand, Silt and Clay	97.09	94823	2.648	0	0	0
Tholeiitic Basalt Minor Quartzarenite, Shale	62.72	61255	1.71	1644	9.489	5.547095
Salt Grit, Purple	2.94	2872	0.08	344	1.986	24.75594

Grit, "Lokhan"							
	Leucocratic Granite, Aplite, Quartz Veins.	365.28	356721	9.963	1336	7.712	0.774075
	Carbonaceous Slate, Phyllite, Quartzite	147.20	143753	4.015	190	1.097	0.273176
	Micaceous Sandstone, Purple clay, Mudstone	108.23	105696	2.952	4263	24.607	8.336085
	Shale, Quartzite with Basal Laterite	0.17	165	0.004	0	0	0
	Grey Micaceous Sandstone, Gravel Beds, Shale, Clay	47.68	46563	1.30	98	0.565	0.435001
	Slate, Phyllite, Quartzarenite, Limestone, Metabasics.	286.75	280028	7.821	1150	6.638	0.848793
	Coarse Sandstone, Boulder Conglomerate, Clay & Grit	180.59	176359	4.925	0	0	0
	Shale, Slate, Quartzite, Cherty Dolomite	1.50	1467	0.041	23	0.133	3.240433
	Carbonaceous Slate, Phyllite, Limestone, Quartzite	3.95	3867	0.108	0	0	0
	Green, Carbonaceous Shale, Limestone, Quartzite.	7.83	7648	0.213	0	0	0
Land Use Land Cover	Water bodies	33.46	32681	0.913	54	0.312	0.34151
	Vegetation	798.84	780124	21.788	4300	24.821	1.139227
	barren land	692.97	676735	18.90	6600	38.097	2.015722
	Forest	1515.9	1480425	41.346	1960	11.3137	0.273637
	Settlement	625.27	610616	17.053	4410	25.456	1.492711

Landslide susceptibility zonation map

All the raster layers are submerged together by using raster calculator tool and LSZ map is obtained at last. Final map obtained divide area into four different classes of susceptibility of landslide as low, medium,

high, very high classes as shown in fig 5 (a). Thorough investigation of final map show that south-east part of district is falling under high susceptibility class which mainly consist part of tehsil Mandi, Chachyot, Thunag and some part of Padhar, Aut and Bali Chowki. Other tehsils of district are falling under medium to low susceptibility class. With help of pixel count in different class is observed that maximum number of are is falling medium susceptibility class which is 40.42% area. 34.5 % area is observed under low susceptibility class whereas only 25.07% area is observed under high susceptibility class as shown in table3.

AUC is very popular method used to calculate prediction rate of model(Mahajan, 2019; K. Singh & Kumar, 2017)where simple trapezium method is used to find area under curve (AUC) value. To fulfil this purpose, it is important to calculate cumulative landslide area percentage which can be calculated with help of landslide area. This cumulative landslide area percentage is then plotted against landslide susceptibility index percentage to find area under curve. Valve between 0.5 to 1 of AUC is considered of effective model. fig 5 (b) show 0.76 value of AUC for landslide susceptibility zonation map of district Mandi.

Table 3. Different characteristics of each class of LSZ map of district

Susceptibility Class	Area	Pixel of Class	%Area Covered by Class
Low	1243.957	1214802	34.50378
Medium	1457.28	1423125	40.42074
High	904.0404	882852	25.07547

Conclusion

Landslide susceptibility mapping play major role in prevention and mitigation part of disaster management cycle. Distinguishing the area into different susceptibility zones give opportunity to decision and policy maker to spend their resources in intelligent way. In this study landslide susceptibility zonation map of district Mandi, Himachal Pradesh was developed with use of five different causative factors namely drainage density, slope, lithology, aspect and land use land cover. Drainage density, aspect and slope, is based on DEM obtained from SRTM. Where lithology data is obtained by geological survey of India. Landsat 8 satellite images was used to make Land use land cover map. Total of 52 landslides were used for model zonation map. From DEM it was observed variation in elevation from 450m to 3400m. Slope in the area is seems to be very steep with deep valleys maximum of which are above 36°. Salt Grit, Purple Grit, "Lokhan" class of lithology is seems highly correlated with landslide occurrence. In LULC forest cover is seems to have maximum share in area which is 41% of total area. Barren land cover shows highest correlation whereas forest cover shows lowest correlation in LULC factor. After developing and analysing LSZ map 40.42% is observed under medium susceptibility class, 34.5 % area is observed under low susceptibility class whereas 25.07% area is observed under high susceptibility class which contain tehsils Mandi, Chachyot, Thunag and some part of Padhar, Aut and Bali Chowki. 0.76 (76.06%) value of AUC is

obtained for landslide susceptibility zonation map of district Mandi which is considered well considering total area of study.

Abbreviations

LSZ: Landslide Susceptibility Zonation, DEM: Digital Elevation Model, SRTM: Shuttle Radar Topography Mission, AUC: Areas Under Curve, GIS: Geographical Information System, TIROS: Television Infrared Observation Satellite, NOAA: National Oceanic and Atmospheric Administration, LSI: Landslide Susceptibility Index, USGS: United States Geological Survey, OLI: Operational Land Imager, TIRS: Thermal Infrared Sensor, GSI: Geological Survey of India, GPS: Global Positioning System, FR: Frequency Ratio, RF: Relative Frequency, PR: Prediction Rate, LULC: Land Use Land Cover

Declarations

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Authors' Contributions Sachin Verma was major contributor in every step. He was involved in field survey, collection of dataset and various map, preparation of susceptibility zonation map using FR approach and writing of manuscript. Vidya Sagar Khanduri play major contribution in testing model using AUC and approved final the manuscript.

Availability of data and material

Dataset used in this study for analysis purpose can be provided if asked by author.

Competing interests

The authors declare that they have no competing interests.

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References

1. Anbalagan, R., Kumar, R., Lakshmanan, K., Parida, S., & Neethu, S. (2015). *Landslide hazard zonation mapping using frequency ratio and fuzzy logic approach , a case study of Lachung Valley , Sikkim.* <https://doi.org/10.1186/s40677-014-0009-y>
2. Article, O. (2006). *A review of landslide hazards in Japan and assessment of their susceptibility using an analytical hierarchic process (AHP) method.* March 2005, 149–158. <https://doi.org/10.1007/s10346-005-0031-y>
3. Articles, O. (2005). *An approach for GIS-based statistical landslide susceptibility zonation – with a case study in the Himalayas.* October 2004, 61–69. <https://doi.org/10.1007/s10346-004-0039-8>

4. Bandhu, V., & Chandel, S. (2016). *Geo-Physical Disasters in Himachal Pradesh: A Spatial Perspective*. November 2015.
5. Bhardwaj, A., Wasson, R. J., Ziegler, A. D., Chow, W. T. L., & Pal, Y. (2019). Geomorphology Characteristics of rain-induced landslides in the Indian Himalaya : A case study of the Mandakini Catchment during the 2013 flood. *Geomorphology*, 330, 100–115. <https://doi.org/10.1016/j.geomorph.2019.01.010>
6. Chowdhury, P. A. R. (1999). *Landslide hazard assessment: summary review and new perspectives*. 21–44.
7. Dai, F. C., & Lee, C. F. (2002). *Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong*. 42, 213–228.
8. Estate, R. (2014). *Using Frequency Ratio Method for Spatial Landslide Prediction*. 7(15), 3174–3180. <https://doi.org/10.19026/rjaset.7.658>
9. Fennessy, N. A., & Mikolajczak, N. A. (2016). *Improving Landslide Risk Communication in Mandi District*. May.
10. Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., & Ardizzone, F. (2005). *Probabilistic landslide hazard assessment at the basin scale*. 72, 272–299. <https://doi.org/10.1016/j.geomorph.2005.06.002>
11. Kumar, A., Asthana, A. K. L., & Priyanka, R. S. (2017). PT. *Geomorphology*. <https://doi.org/10.1016/j.geomorph.2017.01.003>
12. Kumar, V., Kumar, K., & Reza, H. (2019). Catena Sedimentological characteristics and application of machine learning techniques for landslide susceptibility modelling along the highway corridor Nahan to Rajgarh (Himachal Pradesh), India. *Catena*, 182(December 2018), 104150. <https://doi.org/10.1016/j.catena.2019.104150>
13. Lee, S. (2009). *Delineation of landslide hazard areas using frequency ratio, logistic regression and artificial neural network model at ...* December 2016. <https://doi.org/10.1007/s12665-009-0245-8>
14. Mahajan, S. S. A. K. (2019). Information value based landslide susceptibility zonation of Dharamshala region, northwestern Himalaya, India. *Spatial Information Research*. <https://doi.org/10.1007/s41324-019-00259-z>
15. Paper, O. (2010). *Landslide susceptibility zonation of the Chamoli region, Garhwal Himalayas, using logistic regression model*. February, 411–423. <https://doi.org/10.1007/s10346-010-0202-3>
16. Paper, O. (2012). *A comparison of landslide susceptibility maps produced by logistic regression, multi-criteria decision, and likelihood ratio methods: a case study at Izmir, Turkey*. July 2011, 93–106. <https://doi.org/10.1007/s10346-011-0283-7>
17. Paper, O. (2014). *Landslide susceptibility zonation using analytical hierarchy process and GIS for the Bojnurd region, northeast of Iran*. December 2013. <https://doi.org/10.1007/s10346-013-0458-5>
18. Paper, O. (2015). *Assessment of rainfall-generated shallow landslide / debris-flow susceptibility and runout using a GIS-based approach: application to western Southern Alps of New Zealand*. February 2014, 1051–1075. <https://doi.org/10.1007/s10346-014-0533-6>

19. Pareek, N., Pal, S., Sharma, M. L., & Arora, M. K. (2013). Computers & Geosciences Study of effect of seismic displacements on landslide susceptibility zonation (LSZ) in Garhwal Himalayan region of India using GIS and remote sensing techniques. *Computers and Geosciences*, 61, 50–63.
<https://doi.org/10.1016/j.cageo.2013.07.018>
20. Parkash, S. (2015). *Some Socio-Economically Significant Landslides in Uttarakhand Himalaya : Events , Consequences and Lessons Learnt*. 211–232. <https://doi.org/10.1007/978-4-431-55242-0>
21. Parkash, S. (2016). *Historical Records of Socio-economically Significant Landslides in India*. December.
22. Petley, D., & Petley, D. (2012). *Global patterns of loss of life from landslides*.
<https://doi.org/10.1130/G33217.1>
23. Pradhan, B., & Lee, S. (2010). Environmental Modelling & Software Landslide susceptibility assessment and factor effect analysis: backpropagation artificial neural networks and their comparison with frequency ratio and bivariate logistic regression modelling. *Environmental Modelling and Software*, 25(6), 747–759. <https://doi.org/10.1016/j.envsoft.2009.10.016>
24. Pradhan, S. P., Panda, S. D., Roul, A. R., & Thakur, M. (2019). Insights into the recent Kotropi landslide of August 2017, India: a geological investigation and slope stability analysis. *Landslides*, 16(8), 1529–1537. <https://doi.org/10.1007/s10346-019-01186-8>
25. Prakash, C., & Chandong, P. (2010). *Landslide susceptibility maps comparing frequency ratio and artificial neural networks: a case study from the Nepal Himalaya*. 1049–1064.
<https://doi.org/10.1007/s12665-009-0426-5>
26. Rasyid, A. R., Bhandary, N. P., & Yatabe, R. (2016). Performance of frequency ratio and logistic regression model in creating GIS based landslides susceptibility map at Lompobattang Mountain , Indonesia. *Geoenvironmental Disasters*. <https://doi.org/10.1186/s40677-016-0053-x>
27. Rautelal, P. (2000). *Landslide risk analysis between Himachal Himalaya (India) Piyoosh Rautelal and Ramesh Chandra Giri and Tons Rivers in*. 2(3), 153–160.
28. Sharma, P., Rawat, S., & Kumar, A. (2018). Study and Remedy of Kotropi Landslide in Himachal Pradesh ,. *Indian Geotechnical Journal*. <https://doi.org/10.1007/s40098-018-0343-1>
29. Sharma, S., & Mahajan, A. K. (2018). *Comparative evaluation of GIS-based landslide susceptibility mapping using statistical and heuristic approach for Dharamshala region of Kangra Valley , India*. 1–16.
30. Singh, K., & Kumar, V. (2017). *Landslide hazard mapping along national highway-154A in Himachal Pradesh , India using information value and frequency ratio*.
31. Singh, P., Kumar, V., Thomas, T., & Arora, M. (2008). *Changes in rainfall and relative humidity in river basins in northwest and central India*. 2992(October 2007), 2982–2992. <https://doi.org/10.1002/hyp>
32. Soeters, R., & Westen, V. A. N. (1984). *SLOPE INSTABILITY RECOGNITION F ANALYSIS , AND ZONATION*.
33. Statistical, G. I. S. T. A. N. D., Evaluating, I. N., & Hazard, L. (1991). *GIS TECHNIQUES A N D STATISTICAL MODELS I N EVALUATING*. 1.

34. Sundaram, R. (n.d.). *Lecture Notes in Civil Engineering Geotechnics for Transportation Infrastructure* (Vol. 1).
35. Talib, J. A. (2005). *Probabilistic landslide susceptibility and factor effect analysis*. 982–990.
<https://doi.org/10.1007/s00254-005-1228-z>
36. Vakhshoori, V., & Zare, M. (2016). *Landslide susceptibility mapping by comparing weight of evidence , fuzzy logic , and frequency ratio methods*. 5705(February).
<https://doi.org/10.1080/19475705.2016.1144655>
37. Varnes, D. (1958). *Slope Movement Types and Processes*.
38. Verma, S., Sagar, V., & Mittal, A. (2020). Materials Today : Proceedings Stabilization of colluvial soil using rice husk ash and micro silica powder. *Materials Today: Proceedings*, xxxx.
<https://doi.org/10.1016/j.matpr.2020.04.019>
39. Versain, L. D. (2019). *Bi-variate Statistical Approach in Landslide Hazard Zonation: Central Himalayas of Himachal Pradesh , India*. 14(2), 415–428.

Figures

Figure 1

(a) location map of study area (b) DEM image of study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Field observation of landslide at Kotropi on district Mandi, Himachal Pradesh.

Figure 3

Thematic maps of district Mandi showing (a) aspect, (b) slope, (c) drainage density, (d) land use land cover

Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Thematic maps of district Mandi showing lithology. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

(a) LSZ map of district Mandi, Himachal Pradesh (b) prediction rate curve for landslide susceptibility model using frequency ratio approach Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.