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Landslide Susceptibility Zonation Using Bivariate Models, Around Tehri Reservoir, Uttarakhand, India

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Abstract

Uttarakhand, the 27th state of India, is highly susceptible to landslides probably owing to its 86% area in Himalayan terrain. In recent times, however, the landslide incidents have increased leaps and bounds mainly due to unprecedented human interventions in the form of settlements, farming, road construction, myriad of hydroelectricity projects. One such case study is done in the current study around the Tehri Dam reservoir, Uttarakhand, India. Landslide causative factors such as slope, aspect, lithology, geology and geomorphology are derived using remote sensing techniques. Thereafter, two methods, Information Value (IV) and weight of evidence (WofE) model were applied and the output was reclassified into five zones *viz*. very low, low, moderate, high and very high. The validation of these models was performed using area under curve (AUC) analysis, which shows the accuracy of WofE model was 83% while that of IV model was 81%. Both WofE and IV susceptibility map shows 1.95% area under very high susceptibility zone which mostly covers the area bordering the reservoir hence implementing reservoir rim to be most prone for landslides.

Keywords: Landslide; Weight of Evidence (WofE); Information value (IV)

Introduction

Landslide is a result of a wide variety of geo-environmental processes which involves geological, meteorological as well as anthropogenic factors. Most inherent factors facilitating landslides could be bedrock geology (includes lithology, structure, permeability, porosity), geomorphology (includes slope, aspect, curvature and relative relief), soil, land use/land cover and hydrological conditions. The present study is trying to consider these characteristics using remote sensing and GIS to demarcate landslide zones around Tehri Dam reservoir. Tehri reservoir (surface area 52 km^2) was developed as a result of construction of an earth and rock fill dam (260.5 m high) at the confluence of two major glacial fed rivers named Bhagirathi and Bhilangna amidst of a highly rugged topography of Garhwal Himalayas. Many studies have indicated that impoundment of a reservoir has induced negative impact on the surrounding geo environmental system [1].

In 1984, Brabb [2] defined the term 'landslide susceptibility' as the spatial probability of occurrence of a landslide based on a set of geo environmental factors. In the same year Varnes [3] defined zonation (for landslide studies) as "division of the land surface into areas and ranking these areas according to the degree of actual or potential hazard from landslides or other mass movement on the slopes". Therefore, putting together both the definitions, Landslide Susceptibility Zonation (LSZ) can be defined as the identification of areas of landslide occurrences over a certain region based on set of internal landslide causative factors. Susceptibility maps derived through LSZ helps in identifying landslide prone areas thus dividing them into different zones based on their degree of susceptibility to landslides. This requires identification of those areas that are or could be affected by landslides, and the assessment of the probability of such landslides occurring within a specific period. Clerici et al. [4] identified three different categories of methods for landslide susceptibility mapping. First is the deterministic method which is based on stability models relying upon the understanding of physical laws controlling slope stability, it can be suitable for mapping hazards in smaller areas [5-8]. Second is the heuristic method which is based on knowledge based indexing where causative factors are ranked and weighed according to their assumed importance in causing a slope failure. The third and the final method is the statistical method based on landslide inventories.

In the present study, statistical approach involving landslide inventories is applied. In the case of large-scale mapping i.e., a small area, qualitative approaches are unreliable [9] hence, quantitative approaches such as deterministic and statistics are much feasible. Current methodology was preferred as the study area provides many sample points of landslides usually required and works best for a purely data-driven approach like WofE and it has been successfully implemented worldwide in diverse geological set up [10].

Study Area and Scope

The study areas lies in districts Tehri and Uttarkashi of Uttarakhand, India under 78°22'28" E to 78°32'05" E longitude and 30°21'49" to 30°28'05" latitudes. The prime focus of this study is in and around the Tehri reservoir and rim area. The area is in middle of an undulating topography represented by Lesser Himalaya with complex network of steams of dendritic pattern. Geologically, Tehri Dam and its reservoir lie in the main Himalayan block (MHB) in which the rocks of lesser Himalayan sequence are exposed.

As illustrated in Figure 1, the study area primarily comprises of Phyllites of Chandpur formation and Quartzites of Nagthat of Garhwal group. The phyllites which represent the central part of Tehri gorge are, in general, banded in appearance, the bands being constituted of variable proportions of argillaceous and arenaceous materials.

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Weathered quartzites of Nagthat formation, western part of study area, is characterized by white, purple, cherry-red and green colour. These rocks are separated by a predominant tectonic plane namely Srinagar Thrust also locally known as Pratapnagar fault, it runs in between the Garhwal Lesser Himalayan Zone delineating two different litho-tectonic segments i.e., Jaunsar Group and the Garhwal Group in its south and north direction respectively.

Data Used and Methodology

Remote Sensing and GIS based investigations require large volumes of data primarily from remote sensing platforms along with ground truth data which is gathered from field investigation. First of all various causative factors are identified in the area of interest and then the thematic maps of these factors are prepared using different multispectral, panchromatic as well as stereo images. Multispectral data used in current study was LISS-IV obtained from IRS- Indian Remote Sensing Satellite, Panchromatic and stereoscopic images were CartoSat-1, also obtained from IRS, some thematic maps were also created from previously published maps and Survey of India toposheets. Software such as ESRI ArcMap 10.1, 10.3, Arc View were used for GIS based requirements while ERDAS IMAGINE 2014 was used for most of the remote sensing work (Figure 2). Detail of these materials used are given in Table 1.

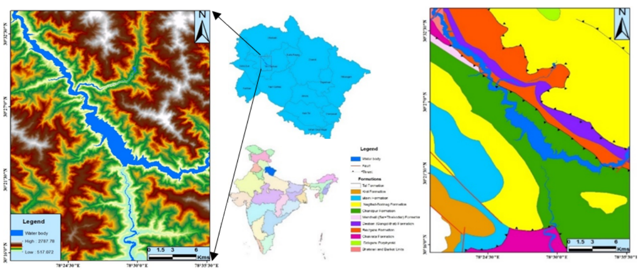

Figure 1: Study area map along with a geological map (Modified after K.S. Valdiya).

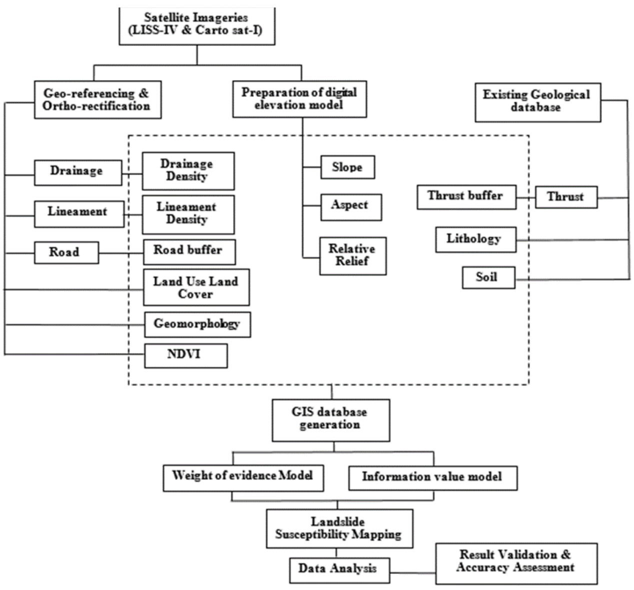

Figure 2: Methodology.

Thematic maps

Landslide inventory: Landslide inventory is the first and for most part in damage assessment and is essentially required for any kind of susceptible model [11-15]. "The distribution of landslides, the types of mass movements, the areas where landslides have occurred, the date of incidence, the past and present movement of slides can all be inferred from the landslide inventory map" [16-20]. "Preparing landslide inventories is very important for documenting the extent of landslide phenomena in a region, investigating the distribution, types, pattern, recurrence and statistics of slope failures, determining landslide susceptibility, vulnerability and risk, and studying the evolution of landscapes dominated by mass-wasting processes" [21].

Landslide inventory was prepared on 1:25,000 scales (Figure 3) from the high resolution RESOURCESAT LISS-IV (5.8 m) multispectral images acquired up to 2017. Generally, two sets of data are required for any statistical modeling, one for developing the model while other for validation. It is often seen that studies have been carried out using the same inventory, 70% for determining the model while 30% for validating, but here in this study two different landslide inventories are prepared.

A LISS-IV multispectral image of year 2012 (Figure 3a) was used to develop the models. A total 85 landslides covering an area of 3.79 km^2, were identified based on their tone, texture, size and shape. Another inventory was prepared using another LISS-IV imagery of the year 2017 (Figure 3b) for the purpose of validation of the models. It covered an area of 3.83 km^2 which included some of the new landslides as well as some still active old landslides.

Topographic factors: Topographic parameters, i.e., aspect and slope (Figures 4a-4g) of the area are generated from the digital elevation model (DEM) which was derived from the high resolution Cartosat-1 panchromatic stereoscopic imageries (2.5 m).

Inclination angle of a slope plays a critical role in determining the shear stress of a slope, higher the slope angle greater will be the shear stress hence greater will be the probability of slope failure. Hence, knowing the slope angle is very essential in considering the causes of a landslide. It is very well known that in hilly terrain such as the Himalaya, most of the landslide occurs at slope ranging between 30°-60° and it is rightfully seen in current study too where most of the landslides are concentrated in areas with a slope angle between 40°-80°. However, slope failures are also witnessed in areas with gentle slopes which may be caused due to other factors.

Aspect is another parameter which plays a crucial role in slope failures as it indicates the direction of the slope. In current study the slope aspect is classified into the following classes: Flat, North, North-east, South, South-east, South-west, West and North-west.

Vegetation and land use and land cover: The NDVI map (Figure 4h) stands for normalized difference vegetative index, calculated by band ration using the formula (Near Infrared-Red)/(Near Infrared+Red). This index indicates the type of vegetation, for example evergreen forests have a higher vegetative index compared to deciduous forests. Hence it signifies the higher the NDVI values the denser the vegetation. Further it is well established that vegetation binds and holds the soil, hence the areas having high NDVI are less prone to slope failures.

Second crucial factor is LULC (Figure 4f) which may be drastically varied by human interventions. Clearing forest lands for farming, grazing and settlements and all make the slope more precarious and hence lead to slope failures more frequently.

Type of Data	Causative Factors	Resolution/scale	Source of Data	Significance
Anthropogenic	Road	2.5 m	Cartosat-1 (mono)	Slope modernization by cutting and fill
Geology	Lithology	1:2,50,000	Valdiya 1980	Characteristic of hill slope material/strength of rocks
Geomorphology	Geomorphology	1:25,000	IRS- LISS IV	Landforms associated with landslides
Hydrogeology	Drainage	1:25,000	IRS- LISS IV	Toe and under cutting by flowing water
Land cover	LULC	1:25,000	IRS- LISS IV	Landforms associated with landslides
	NDVI	1:25,000	IRS- LISS IV	Higher NDVI signifies higher vegetation, vegetation prevents mass wasting
	Soil	1:2,50,000	National Bureau of Soil Survey (NBSS)	Type and depth of soil influence the mass movement
Topography	Aspect	10 m	Cartosat-1 (Stereo) DEM	Aspect of the area indicates the direction of the slope
	Relative Relief	10 m	Cartosat-1 DEM	
	Slope	10 m	Cartosat-1 DEM	Steeper slopes are more pronounced to landslide activity
Tectonics	Thrust & Faults	1:2,50,000	Valdiya 1980	Identification of the weak zones
	Lineaments	10 m	Cartosat-1 (mono)	
Landslide Inventory	Landslide	1:25000	IRS- LISS IV	Spatio-temporal pattern of unstable zone

Table 1: Causative factors, sources and their significance.

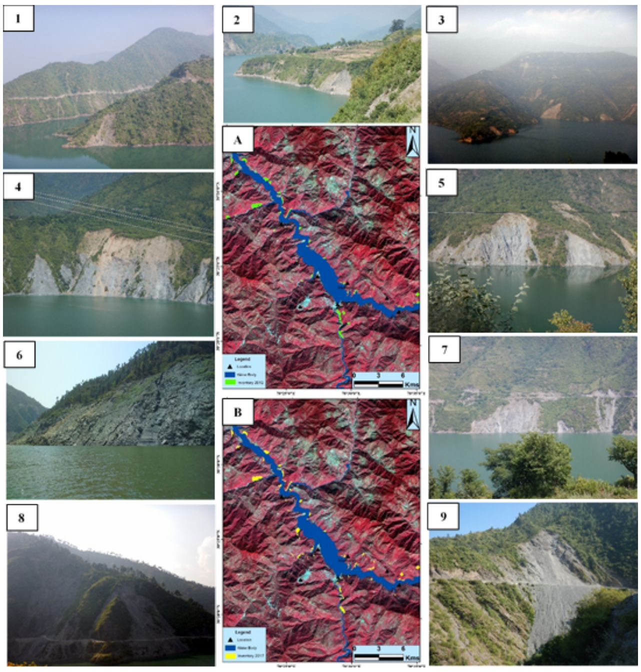

Figure 3: Landslide inventory map along with field photographs of landslides all around the reservoir. (A) Landslide inventory map of 2012. (B) Landslide inventory map of 2017. 1-7, slope failure due to reservoir fluctuation between full reservoir level (FRL) and dead storage level (DSL) 8-9, slope failure due to road cutting.

Lineament density: Lineaments (Figure 4d) are linear features indicative of zones which are weak and hence these features tend to have a probability towards failure. Tectonic features such as thrust, faults comes under linear features, sometimes a drainage may also be associated with a lineament as it is easier for water bodies to run down an already weakened track. In this study lineaments were mapped using Cartosat-1 (mono) and classified into 5 classes based on the density.

Geomorphology: Geomorphological landforms like dissected hills are more susceptible to landslides while others like piedmont zones are less susceptible. The study area in the current work comprises highly dissected hills (covering about 80% of the area) and valleys, moderately dissected hills and valleys, piedmont alluvial plain, active flood plain, and younger flood plain, thereby making it highly susceptible to landslides (Figure 4c).

Drainage: Drainage Network has a prominent relation with the landslides. In mountainous terrain, streams play a major role in creating steep sided slopes by continuously eroding its banks. Such slopes are always more prone to failures resulting into landslides. For current work, Drainage map (Figure 4b) have been derived from Survey of India toposheets.

Lithology: Lithology in this work refers to the parent material which plays a significant role in slope movement as by providing slip surfaces, several lithological units are more prone to landslides than others. The hard and massive rocks are generally resistant to erosion, e.g., granite and limestone. Apart from that, rock composed by sandstone is more vulnerable to erosion so that it is more susceptible to a landslide (Figures 4i-4k).

Soil type: Soil is the topmost layer present in any terrain. Thus, the

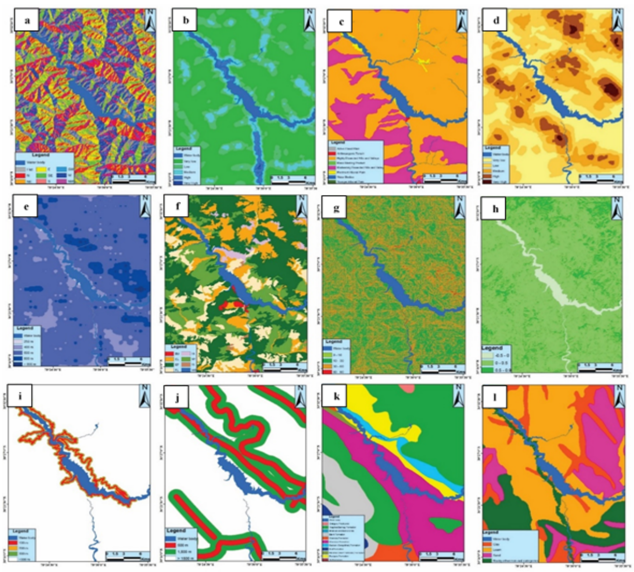

Figure 4: Showing different thematic layers used in both the models (a) aspect map, (b) drainage density map, (c) geomorphology map, (d) lineament density map, (e) relative relief map, (f) Land use land cover map, (g) slope map, (h) NDVI map, (i) road buffer map, (j) thrust buffer map (k) lithology map, (l) soil map.

type of soil governs the movement of rocks or sediments. It has been observed that the loamy silty soil is more prone to landslide movement as compare to a clay rich soil which actually remain more intact (Figure 4l).

Road buffer: Roads are an important key to development but as for the benefits it serves, it equally acts as one of the prime causative factors for slope instability in hilly terrain. Improper cutting of road may expose the bedding or foliation planes making it vulnerable, which result in sliding. Dumping of road cut material/overburden in downslope also results in instability hence a buffer zones was created around the road layer of 100 m difference up to 400 m. It was observed that 100 m buffer showed positive relation with the susceptibility while above 400 m was having a negative weight (Figure 4i).

Landslide susceptibility analysis

As mentioned earlier, there are two approaches used in this study, weight of evidence (WofE) and information value (IV). Both of these methods are closely related to concepts from information theory where one of the goals is to understand the ambiguity involved in calculating the outcome of arbitrary events given varying degrees of knowledge of other variables. Thus, this is a perfect framework for variable screening and exploratory analysis for predictive modeling.

Weight of Evidence (WofE) model: Weight of evidence model is a bivariate model based on Bayesian Bayes theorem and on the prior and posterior probability for determining the relation between the distribution of an area affected by landslides and the distribution of analyzed landslide susceptibility factors. Following are the formulas to calculate the WofE model.

$$W^{+} = \ln\left(\frac{P\{B \mid L\}}{\{B \mid \bar{L}\}}\right) \quad \text{eq. (1)}$$

$$W^{-} = \ln\left(\frac{P\{\bar{B} \mid L\}}{\{\bar{B} \mid \bar{L}\}}\right) \quad \text{eq. (2)}$$

Where, W^{+}=positive weight

W^{-}=negative weight

P=conditional probability

B=Presence of a potential LCF

$\bar{B}$=absence of a potential LCF

L=Presence of a landslide

$\bar{L}$=Absence of a landslide

$$C=(W^{+})-(W^{-}) \quad \text{eq. (3)}$$

Where, C stands for contrast in both the weights and the final weight is derived from eq. (3), which is assigned to each class of every landslide causative factor to produce a multiclass weighted map.

Information value method: The information value method involves finding the probability of Landslides within each class of landslide causative factors [22-26]. The final weight assigned to each class of the landslide causative factors is determine by the formula in eq. (4).

$$Wi = ln\left(\frac{\dfrac{Npix_{(Si)}}{Npix_{(Ni)}}}{\dfrac{\sum Npix_{(Si)}}{\sum Npix_{(Si)}}}\right) \quad \text{eq. (4)}$$

Where, W_i=Weight of a factor class;

$Npix_{(Si)}$=Number of pixel of landslide within class i;

$Npix_{(Ni)}$=Number of pixel of class i;

$\Sigma Npix_{(Si)}$=Number of Pixel of landslide within the whole study area;

$\Sigma Npix_{(Ni)}$=Number of pixel of the whole study area.

Weights were calculated using above mentioned equations (eq.1, eq.2, eq.3, eq.4) and the values for each class of each factor is mentioned in the following Table 2.

Results and Discussion

A comparative graph was plotted between the calculated weights of both WofE and IV for each class of the causative factors and we can see in Figure 5, the trend for every class is almost similar.

The graph also shows that geomorphology, lithology, LULC and road network has a positive effect on causing landslide while greater NDVI regions, grasslands, forestlands have a negative weight. This confirms that areas with a better vegetal cover is supposed to be less

Factors	Class	Class%	Slide%	W+	W-	C	W_i
Aspect	Flat	0.29	0.00	-0.29	0.00	-0.29	0.00
	N	13.47	13.93	0.01	0.00	0.01	0.03
	NE	10.31	2.16	-0.68	0.04	-0.72	-1.56
	E	14.03	1.61	-0.94	0.06	-1.00	-2.17
	SE	10.83	20.19	0.27	-0.05	0.32	0.62
	SE	15.81	24.67	0.20	-0.05	0.24	0.44
	SW	11.85	17.46	0.17	-0.03	0.20	0.39
	W	14.06	16.40	0.07	-0.01	0.08	0.15
	NW	9.35	3.58	-0.42	0.03	-0.44	-0.96
Geomorphology	Mass Wasting Product	0.06	2.69	1.73	-0.01	1.74	3.77
	Piedmont Alluvial Plain	1.04	1.02	-0.01	0.00	-0.01	-0.02
	Active Flood Plain	0.07	7.07	2.24	-0.03	2.27	4.60
	Moderately Dissected Hills and Valley	24.27	23.38	-0.01	0.00	-0.02	-0.04
	Highly Dissected Hills and Valleys	73.75	65.79	-0.05	0.11	-0.16	-0.11
	Younger Alluvial Plain	0.04	0.00	0.00	0.00	0.00	0.00
	Anthropogenic Terrain	0.08	0.05	-0.22	0.00	-0.22	-0.52
	Water Bodies	0.67	0.00	0.00	0.00	0.00	0.00

NDVI	(-0.5-0)	0.18	2.52	1.17	-0.01	1.18	2.62
	0-0.5	86.94	94.60	0.04	-0.38	0.42	0.08
	0.5-1	12.88	2.89	-0.65	0.05	-0.70	-1.49
Lithology	Tal Formation	1.51	0.00	0.00	0.01	-0.01	0.00
	Krol Formation	4.35	0.00	0.00	0.02	-0.02	0.00
	Blaini Formation	10.64	0.00	0.00	0.05	0.00	0.00
	Rautgara Formation	9.88	8.94	-0.04	0.00	-0.05	-0.10
	Chakrata Formation	3.45	5.61	0.21	-0.01	0.22	0.49
	Deoban (Gangolithat) Formation	4.37	17.99	0.62	-0.07	0.69	1.41
	Mandhali (Sar+Thalkedar) Formation	0.70	4.15	0.78	-0.02	0.80	1.78
	Nagthat-Berinag Formation	39.51	6.07	-0.81	0.19	-1.00	-1.87
	Debguru Porphyroid	0.50	0.00	0.00	0.00	0.00	0.00
	Bhatwari and Barkot Units	0.41	0.59	0.16	0.00	0.16	0.36
	Chandpur Formation	24.68	56.65	0.36	-0.24	0.61	0.83
LULC	GL	2.21	0.03	-1.92	0.01	-1.93	-4.43
	WB	0.14	0.00	0.00	0.00	0.00	0.00
	FL	14.60	24.69	0.23	-0.06	0.29	0.53
	MF	18.45	20.64	0.05	-0.01	0.06	0.11
	BU	0.56	4.47	0.91	-0.02	0.93	2.07
	SL	0.66	0.00	0.00	0.00	0.00	0.00
	CL	18.68	39.44	0.33	-0.13	0.46	0.75
	EF	44.69	10.74	-0.62	0.21	-0.83	-1.43
Lineament Density	Very low	30.40	45.06	0.17	-0.10	0.28	0.39
	Low	35.47	29.59	-0.08	0.04	-0.12	-0.18
	Medium	24.84	12.96	-0.28	0.06	-0.35	-0.65
	High	8.43	9.73	0.06	-0.01	0.07	0.14
	Very high	0.86	2.66	0.50	-0.01	0.50	1.13
Relative relief	250 m	0.16	0.19	0.07	0.00	0.07	0.16
	400 m	11.24	27.53	0.39	-0.09	0.48	0.90
	600 m	77.86	63.81	-0.09	0.21	-0.30	-0.20
	800 m	10.42	8.47	-0.09	0.01	-0.10	-0.21
	993.2 m	0.32	0.00	0.00	0.00	0.00	0.00
Soil	Rocky,other non-soil categories	24.14	13.53	-0.25	0.06	-0.31	-0.58
	Clay	16.85	8.91	-0.28	0.04	-0.32	-0.64
	Loamy sand,sand	20.54	6.31	-0.51	0.07	-0.58	-1.18
	Loam, silt loam,sandy loam	38.48	71.25	0.27	-0.33	0.60	0.62
Distance from Road	100	3.38	29.58	0.96	-0.14	1.10	2.17
	200	2.50	14.47	0.77	-0.06	0.83	1.76
	300	1.96	7.84	0.61	-0.03	0.64	1.39
	>400	92.17	48.12	-0.28	0.82	-1.10	-0.65
Slope	0-10	0.00	0.01	0.27	0.00	0.27	0.62
	10 to 30	56.54	44.08	-0.11	0.11	-0.22	-0.25
	30 to 60	42.90	54.91	0.11	-0.10	0.21	0.25
	60 to 90	0.56	1.00	0.25	0.00	0.25	0.57
Drainage Density	Very low	63.56	31.37	-0.75	0.41	-1.16	-0.71
	Low	22.56	23.87	0.12	-0.04	0.16	0.06
	Medium	10.90	34.12	0.68	-0.22	0.90	1.14
	High	2.92	10.42	0.87	-0.06	0.93	1.27
	Very high	0.06	0.22	0.00	0.00	0.00	1.26
Distance from Thrust	<500 m	14.67	18.65	-0.06	0.08	-0.15	0.35
	500-1500 m	24.91	25.97	0.13	-0.03	0.16	0.15
	>1500 m	60.42	55.38	0.06	-0.02	0.08	0.02

Table 2: Weights calculated for different classes of causative factors.

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susceptible to landslides. Both WofE and IV models were applied with different combinations of thematic layers out of which the combination of 11 layers was the best fit. The output was then reclassified into five zones *viz.* very low, low, moderate, high and very high. The output is shown in Figure 6.

The final WofE susceptibility map indicate that about 1.95% area comes under very high susceptible zone, 10.4% of the area comes under high susceptible zone, 35.2% under moderate susceptible zone, 40.5% has low susceptibility and 11.7% area has very low susceptibility to landslides. The final IV model showed 1.95% area under very high susceptibility, 14.6% area under high susceptibility, 38.4 under moderate and 30.04%, 14.9% under low and very low susceptibility zones respectively. Both WofE and IV models identified 1.95% of the total area to fall under very high susceptible zones and as we can in Figure 6, this highly landslide susceptible zone mostly lies around the reservoir rim and also follows the road network. Therefore it is quite clear that the landslide in this region is mostly affected by the reservoir water level fluctuations as well as improper road cutting (Table 3).

As one can see in Figure 7, the high correlation in the scatter plot (R^2=0.9) between both the models, WofE model still have better success as well as prediction rate than IV model. Validation of these models were carried out using the area under curve analysis (AUC). The success rate for WofE model was obtained 82.18% while its prediction rate was 83% where else in IV model, success rate was 78.1% and prediction rate was 81.1% (Figure 8). This proves that the WofE model correlates more with landslides but since both the models has a prediction rate greater than 80% hence we can say both the models have done a very good work in determining the relationship with the landslides in the current study area.

Conclusion

The susceptibility map reflects that left bank of Bhagirathi is more susceptible to mass wasting activities than rest of the area but is mostly influenced by road cutting. The current work not only presents one such case example where landslides occurs due to infrastructure development, but also the efficacy of remote sensing and GIS tools in mapping the landslide hazards and risks at regional scale. The current work enumerates and depicts the potentiality of each causative factor *viz.* drainage, NDVI, geomorphology, slope, aspect, land use/land

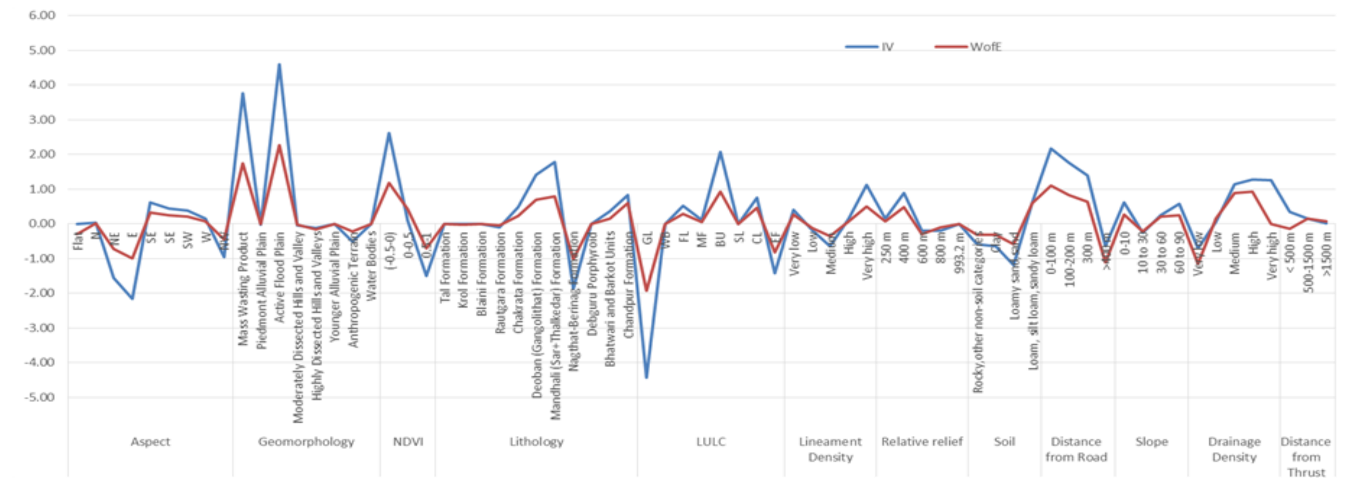

Figure 5: Comparison between weights calculated for WofE and IV for each landslide causative factors.

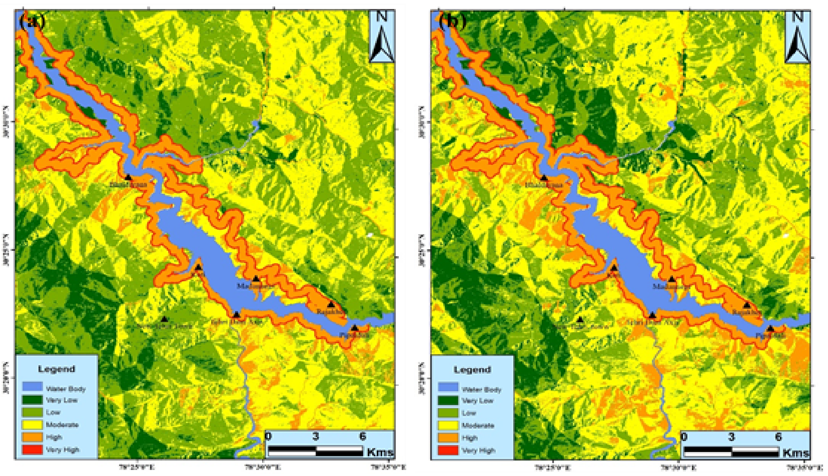

Figure 6: Susceptibility maps with different classes using (a) Weight of Evidence (WofE) and (b) Information Value Method (IV).

Susceptibility Zones	Percentage of Slides	
	WofE	IV
Very Low	11.72%	14.92%
Low	40.57%	30.04%
Moderate	35.27%	38.44%
High	10.47%	14.63%
Very High	1.95%	1.95%

Table 3: Distribution of landslides in classified susceptibility zonation map.

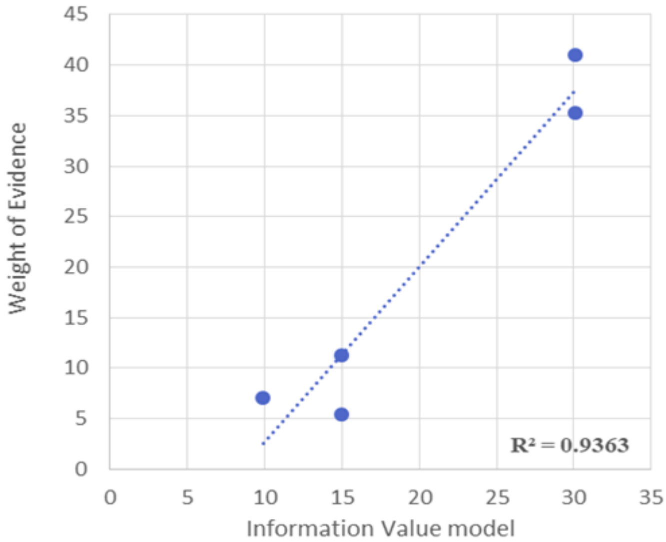

Figure 7: Scatter plot between different classes of Weight of Evidence and Information Value Model.

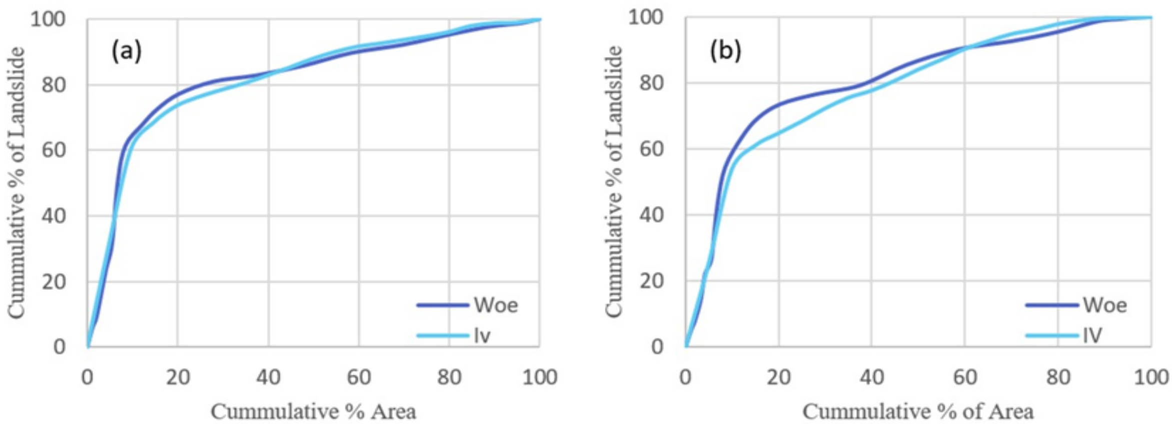

Figure 8: (a) Success rate curve, (b) Prediction rate curve.

cover, soil, thrust, lineament density, lithology, relief and integrates them in GIS environ to demarcate landslide prone areas. The similar kind of maps can be utilized by the concerned government authorities in formulating disaster management and preparedness plan, executing a rehabilitation programme, carrying out environment planning and framing other future development policies. Identifying susceptible areas at regional scale shall facilitate the preparedness well in advance in case of any infortune and may minimize the damage to life and property. There are many measures to check and prevent landslides. However, when the entire terrain is susceptible, some common measures may be adopted to stabilize the slopes which includes plantation of shrubs, bushes and other trees. Further, depending upon the vulnerability and risk, some specialized measures like grouting may also be taken.

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