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GIS-BASED LANDSLIDE SUSCEPTIBILITY MAPPING USING MULTI-CRITERIA METHODS: A CASE STUDY IN MAHABALESHWAR TEHSIL OF SATARA DISTRICT, MAHARASHTRA, INDIA

Subhash V. Karande

Dept. of Geography, Chhatrapati Shivaji College, Satara, Maharashtra- 415 001
Corresponding Email: karandesubhash@gmail.com

Abstract

Landslide is a natural disaster that causes many casualties and economic losses worldwide. As per report of GSI, Western Ghat, Eastern Ghat, Himalaya are more landslide susceptible areas and suffer numerous fatalities and financial damages. Therefore, the mapping of landslide vulnerable areas is essential for mitigation and preparedness. The purpose of this study is to evaluate the landslide susceptibility using Frequency Ratio, Analytical Hierarchy Process, Weighted overlay analysis methods in Mahabaleshwar tehsil of Satara district, Maharashtra, India. Sixteen landslide causing factors including slope, rainfall, relief, lithology, soil depth, soil erosion, soil texture, land use / land cover, road distance, drainage distance, drainage density, lineament distance, lineament density, aspect, temperature and seismology are analyzed. The weight and score assigned to each factor as per their importance and triggering intensity. All factors are merged into a single raster layer and the GIS multi-criteria model in ArcGIS 10.5 software used for the mapping of landslide susceptible zones. The landslide susceptibility map is classified into five classes: very high, high, moderate, low, very low. The final LSM shows that the relatively high susceptible (unsafe) area is 68.31%, moderately susceptible (slightly safe) area is 17.78 % and low to very low susceptible (safe) area is 13.91 %. 47 villages out of 113 and an important road of the study area is under high to very high risk. The developed landslide susceptibility map is very important for decision makers, planners, and engineers to prevent and mitigation measurements for reducing losses of life and properties.

Keywords: GIS, Landslide susceptibility, Weighted overlay analysis, Analytic hierarchy process, Frequency ratio

Introduction

Landslide are very destructive and fatal natural disasters among geological disasters (Tariq & Gomes, 2017). Landslides occur when the land slope is unstable due to natural or anthropogenic activities. The landslide causative factors are adverse climatic conditions, earthquakes, weathering, erosion, volcanoes, forest fires, relief, soil, gravity, agriculture, construction, mining, slope modification, overgrazing, drainage pattern, land-use/land cover etc. As per the report of Geological Survey of India (GSI), 12.6 % area of India comes under landslide susceptible zone and every year Himalayan region (Darjeeling, Sikkim, Himachal Pradesh, Uttarakhand, Jammu and Kashmir, Ladakh), the Western Ghat, and the Eastern Ghat, suffers heavy losses in terms of life and property (https://www.gsi.gov.in). Major landslide data in the last fifty years available on the website Geological Survey of India (https://www.gsi.gov.in) is presented in Table 1.

Table 1: Major Landslides in India

Date / Year	District / State	Effect
July 1975	North of West Bengal	45,000 people homeless in the areas of Teesta, Jaldhaka, and Diana.
October 1990	The Nilgiris, Tamil Nadu	36 people were killed and several injured. Several buildings and roads were damaged, and communications disrupted.
July 1991	Assam	300 people were killed, roads and buildings worth lakhs of rupees damaged.
August 1993	Kalimpong, West Bengal	40 people were killed, heavy loss of property.
August 1993	Kohima, Nagaland	200 houses were destroyed, 500 people killed, a 5 km stretch of road was damaged.
October 1993	Marapplam, the Nilgiris, T.N.	40 people were killed, property worth several lakhs of rupees damaged.
18 August 1998	Malpa, Kali river, Uttarakhand	210 people were killed. The village was wiped out in the event.
5 July 2004	Badrinath, Chamoli District, Uttarakhand	16 persons killed, 200 odd pilgrims stranded, 800 shopkeepers and 2,300 villagers trapped as cloudburst triggered massive landslides washed away nearly 200 metre of road on the Joshimath-Badrinath road cutting off Badrinath area.
16-20 February 2005	Anantnag, Doda, Poonch, Pulwama, and Udhampur Districts, Jammu & Kashmir	Over 300 people lost their lives.
July 2005	Raigad, Maharashtra	Places affected by landslides were at Dasgaon (36 deaths), Rohan (15 deaths), Jui (96 deaths), and Kondivate (34 deaths). Also, damage was caused to roads and other structures.
25 February 2010	Chimakurthi, Prakasam District, Andhra Pradesh	20 workers were feared killed
18 May 2010	Ladakh, Jammu & Kashmir	2 persons were killed and The Indian Army rescued 73 other persons
16 June 2013	Uttarakhand	Approximately 5700 peoples death in flood and landslide
30 July 2014	Malin Village, Pune	Around 151 peoples died and approximately 100 peoples were missing
1 July 2015	Mirik area of Darjeeling	Over 40 people had died

Source - https://www.gsi.gov.in.

The demarcation of the landslide-susceptible region is essential for reducing its intensity and saving lives and property. Various methods are used for the mapping of landslide susceptibility i.e., heuristic, qualitative, quantitative, semi-quantitative, probabilistic, geotechnical process model, on-ground monitoring, geomorphologic approach, factors overlay, remote sensing data etc. (Zink et al., 2001).

Geospatial technology is a powerful tool to analyse landslide-susceptibility (Karimi et al., 2010). In the recent decade Geographical Information System (GIS), Remote Sensing (RS) and Global Positioning System (GPS) based geospatial technology play a crucial role in the prediction and mapping of landslide-susceptible zones. It is a versatile time and cost saving technology handling a large and multiple data set. It is helpful in remote, mountain and forest areas for hazard mitigation and monitoring. The accuracy and efficiency of geospatial technology has led to much research and studies worldwide. This tool is used for the demarcation of landslide susceptibility. The main objective of this study is to prepare a landslide susceptibility map of Mahabaleshwar tehsil of Satara district based on the combination GIS and Analytical Hierarchical Process (AHP), Frequency ratio (FR) and Weighted overlay Method (WoM). Three different landslide mapping methods are used to create landslide susceptibility map in this study.

Study Area

The research area is located in the Mahabaleshwar tehsil of Satara district, Maharashtra. It lies between north latitude 17^{0}42’2” - 17^{0}58’55” and east longitude of 73^{o}32’14” - 73^{0}51’34”, with an area of 518 Km^2. According to the population census of 2011 the total population of tehsil was 72,830 persons (Census of India, 2011). The elevation of the tehsil is varied from 600 to 1440 m and average elevation is 1050 m, above mean sea level and 45 % area of the tehsil is dominated by the mountain range of Sahyadri. The climate of the tehsil is humid subtropical. The average amount of rainfall in the study area is 5805 mm, whereas 96 % rainfall is received only during the southwest monsoon. The mean temperature ranges between 16 ^{0}C and 26 ^{0}C (www.imd.gov.in, www.maharain.maharashtra.gov.in).

Mahabaleshwar tehsil has 113 villages. Mahabaleshwar tehsil is an important tourist destination in India, millions of tourists visit various places in this tehsil every year. The important tourist places are Mahabaleshwar, Tapola, Panchagani, Pratapgad etc. According to the civilians the landslide has become more common in the last few years in the tehsil. The landslide disrupted the life of tehsil and it also affected tourism on a large scale. The study is covered with basaltic lava and also called a Deccan trap. The thickness of these layers is from 4 to 66 m.

Geologically this is the most stable region but some natural and manmade reasons occur the instances of landslides in this area. Bhilar, Kaswand, Mahabaleshwar (Hotel Gautam), Panchgani, Metgulad, Gadalwadi, Tapola to Mahabaleshwar road landslide in 2005, Panchgani and Bhekawli landslide in 2015 and Umbari landslide in 2017 were major past landslide in the study area (www.satara.gov.in). In the year 2021, 1517 landslides[1] occurred during the monsoon season in the tehsil. Many villages were out of contact for a month. More than 100 landslides occurred on Ambenali ghat (Mahabaleshwar - Poladpur road) and it was closed for 45 days to all types’ transportation. Location map of the study area is shown in Fig. 1.

[1] The data of the landslide were collected from the news in print and digital media, interaction with civilians, journalists, and administrative officers, Google earth image and during field visits.

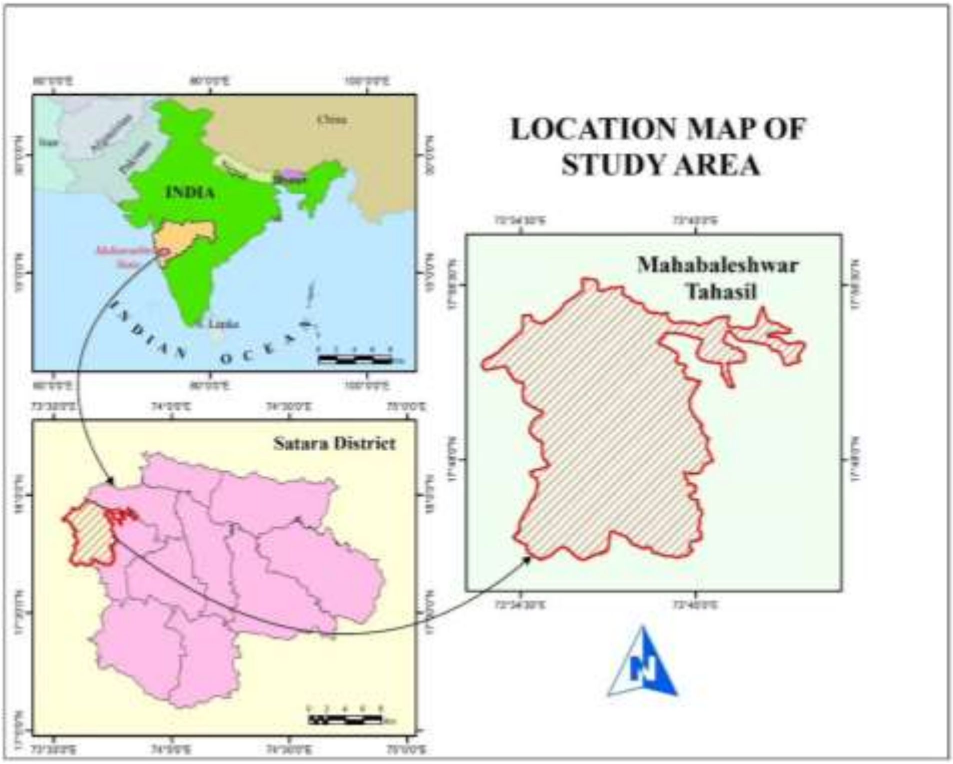

Fig. 1: Study Area

Material and Methods

For the present study, the methodology is involved in five steps: 1) selection of causative factors 2) database creation and generation 3) assign rank, weight and score for each causative factor 4) preparation of landslide susceptibility map 5) data validation and accuracy assessment. The workflow diagram of methodology adopted for this study is shown in Fig. 2.

Landslide inventory

Landslide inventory of the study area is developed based on the field visit and visual interpretation of high-resolution Google earth images. Total 1517 landslide locations are identified in the study area (Fig. 3).

Landslide causative factors

Sixteen causative factors of landslide (slope, rainfall, relief, lithology, soil depth, soil erosion, soil texture, land use/land cover, road distance, drainage distance, drainage density, lineament distance, lineament density, aspect, temperature, seismology) are selected for LSM based on literature review, field visit, and characteristics of study area. This database is collected from various sources and its specific use is presented in Table 2. Thematic layers of all these factors are prepared using ArcGIS 10.5 and ERDAS IMAGINE software.

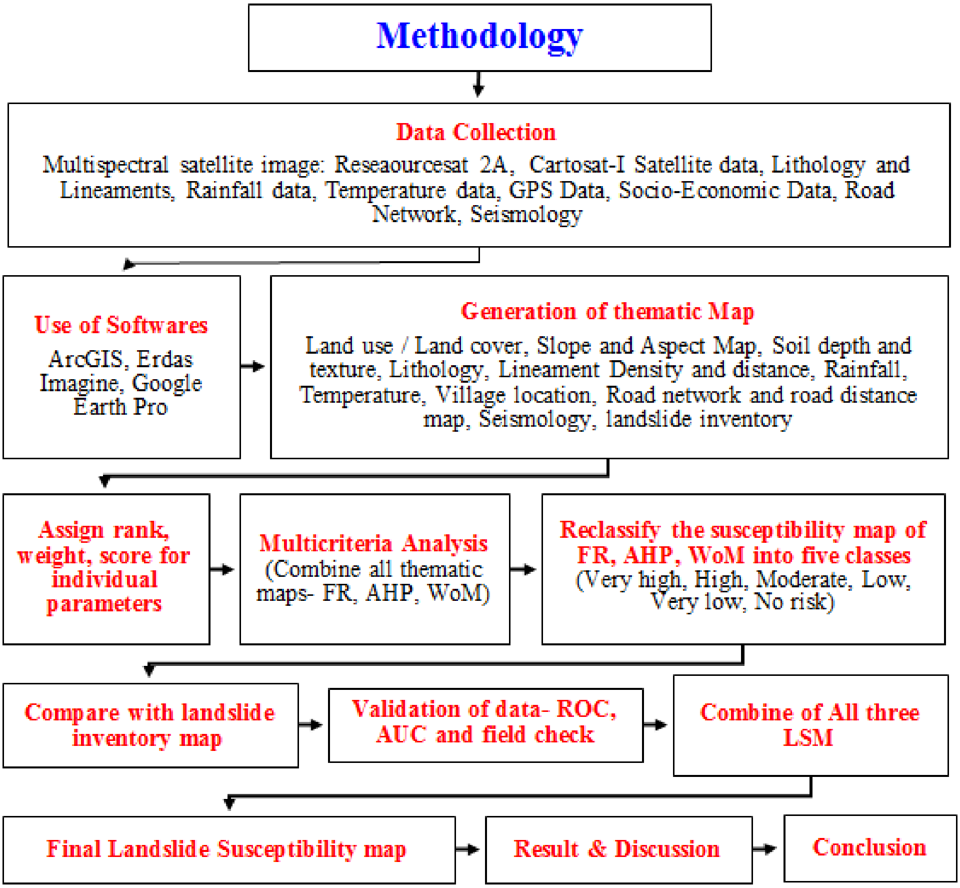

Fig. 2: Methodology

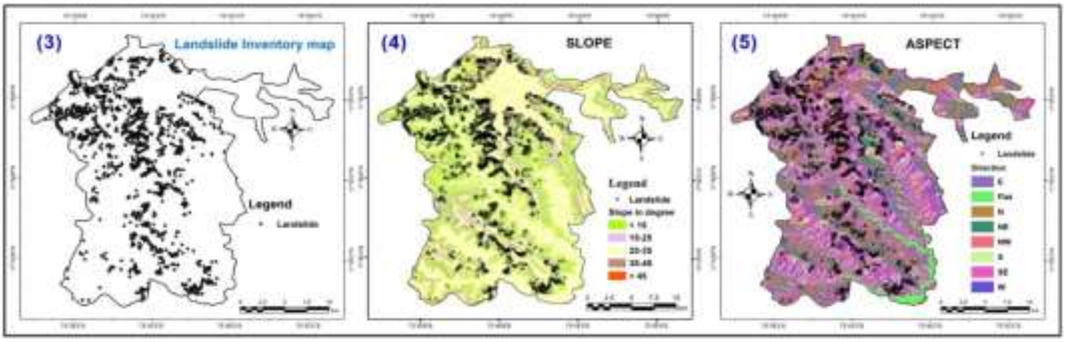

Fig. (3) Landslide Inventory, (4) Slope, (5) Aspect

Landslide susceptibility mapping (LSM)

Landslide susceptibility mapping is essential for identifying the spatial probability and intensity of landslides. Three methods (FR, AHP, WoM) are used to produce the LSM of the study area.

The qualitative heuristic approach is used in this study and the weight and score for each thematic layer are assigned based on their relative contribution to landslide occurrence (Awawdeh et al., 2018), expert's opinion, literature review and field visit. The process adopted for LSM of all three methods is discussed below.

FR: The frequency ratio is a quantitative model used for landslides susceptibility mapping based on GIS techniques and spatial data (Lee and Talib; 2005). This model expresses the relationship between landslides inventory and landslide causative factors (Mandal et al., 2018). Frequency ratio of each class of the causative factors is calculated by using following formula (Mondal and Maiti, 2013):

$$Fr = \frac{b}{a} \quad (1)$$

Where,

$$a = \frac{NPix}{\sum NPix} X\ 100$$

Npix is the number of pixels in individual class of each factor and ∑ *NPix* is the total number of pixels of each class in the whole area

$$b = \frac{NPil}{\sum NPil} X\ 100$$

Npil is the number of landslides in individual class of each factor and ∑ *NPil* is the total number of landslides of each class in the whole area

Normalization frequency Index (FRn) = FRxi/Ln (2)

Where, FRxi is a frequency ratio of individual classes of each factor and Ln is a highest frequency ratio of each factor.

FRn values are assigned for individual classes of each thematic layer and landslide susceptibility is computed from the summing of the FRn of each thematic layer using the following formula in the ArcGIS 10.5 software (Lee and Talib, 2005).

$$LSI = \sum Fr_n \quad (3)$$

Where Frn is a normalized frequency Index and LSI is a landslide susceptibility index. Table 3 shows the Frequency ratio calculation of landslide influencing factors.

AHP: The Analytic hierarchy process (AHP) is a multi-criteria assessment decision-making tool developed by Saaty (Saaty, 2001). It is an effective tool to deal with complex and multi-attribute problems and widely used by the different scholars (Potekar et al., 2023; Bachri and Shresta, 2010). In this study, the score of each causative factor is assigned based on the expert's opinion and individual experience.

Table 2: Data sources and specific use

Sr. No.	Data Types	Source	Data/Layer Extracted
1	Multispectral LISS-IV satellite image: ResourceSat-2A Date: 31/01/2021 & 24/02/2021 Path: 95, Scene: 60 Spatial resolution - 5.8 M	NRSA, Hyderabad (https://bhoonidhi.nrsc.gov.in)	Land use / Land cover
2	DEM Satellite data: Cartosat-I Spatial resolution- 2.5 M	Bhuvan (*https://bhuvan-app3.nrsc.gov.in/data/download/index.php*)	Slope and Aspect Map
3	Soil Data Scale -1: 500000	European Soil Data Center (*https://esdac.jrc.ec.europa.eu/*)	Soil depth and texture map
4	Lithology and Lineaments Scale - 1:50000	Bhukosh website (*http://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx*)	Lithology map, Lineament Density and distance
5	Climatic data Rainfall data	India Meteorological Department of Pune (*https://imd.gov.in/*) and Maharashtra agriculture websites (*http://mahaagri.gov.in/*)	Rainfall and Temperature Map
6	Road Network	Google Earth Image and Satellite image	Road network and road distance map
7	Seismology	Bhukosh website (*http://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx*)	Seismology Map
8	Landslide location	GPS survey and Google earth satellite image	Landslide inventory map

Table 3: Frequency ratio calculation of landslide influencing factors

Factor	Class	Num. of Pixel in Class	Class Area % (a)	Num. of Landslide	Landslide % (b)	FR b/a	FRn
Slope (°)	< 150	160578	27.86	667	43.97	1.58	0.65
	16 to 250	81901	14.21	473	31.18	2.19	0.90
	25 to 350	309121	53.64	230	15.16	0.28	0.12
	35 to 450	20313	3.52	130	8.57	2.43	1.00
	> 450	4422	0.77	17	1.12	1.46	0.60

Aspect	Flat	14742	2.58	7	0.46	0.18	0.12
	N	35962	6.30	61	4.02	0.64	0.43
	NE	78519	13.75	157	10.35	0.75	0.51
	E	64633	11.32	174	11.47	1.01	0.68
	SE	70846	12.41	258	17.01	1.37	0.92
	S	78819	13.80	311	20.50	1.49	1.00
	SW	76935	13.47	221	14.57	1.08	0.73
	W	59705	10.46	133	8.77	0.84	0.56
	NW	60502	10.60	146	9.62	0.91	0.61
	N	30309	5.31	49	3.23	0.61	0.41
Relief (m)	0 to 600	72924	12.65	10	0.66	0.05	0.03
	600 to 800	238582	41.40	635	41.86	1.01	0.60
	800 to 1000	135750	23.55	598	39.42	1.67	1.00
	1000 to 1200	79571	13.81	253	16.68	1.21	0.72
	Above 1200	49508	8.59	21	1.38	0.16	0.10
Lithology	Laterite	39755	7.01	17	1.12	0.16	0.15
	Basalt	527169	92.99	1500	98.88	1.06	1.00
Lineament distance (m)	< 50	6949	1.21	21	1.38	1.15	0.62
	50 - 100	7790	1.35	23	1.52	1.12	0.61
	100- 150	7856	1.36	38	2.50	1.84	1.00
	150-200	6142	1.07	27	1.78	1.67	0.91
	>200	547588	95.01	1408	92.81	0.98	0.53
Lineament density (m/km^2)	Below 50	2833	0.49	34	2.24	4.56	1.00
	50 to 100	14142	2.45	88	5.80	2.36	0.52
	100 to 150	49653	8.62	266	17.53	2.04	0.45
	150 to 200	86623	15.03	259	17.07	1.14	0.25
	Above 200	423064	73.41	870	57.35	0.78	0.17
Drainage distance (m)	<50	184253	31.97	364	23.99	0.75	0.54
	50-100	153690	26.67	393	25.91	0.97	0.70
	100-150	109118	18.93	380	25.05	1.32	0.96
	150-200	57202	9.93	208	13.71	1.38	1.00
	> 200	72061	12.50	172	11.34	0.91	0.66
Drainage density in sq. km	Very low (< 2)	77306	13.41	73	4.81	0.36	0.25
	Low (2 to 3)	123860	21.49	300	19.78	0.92	0.65
	Medium (3-4)	255033	44.25	699	46.08	1.04	0.74
	High (> 4)	120124	20.84	445	29.33	1.41	1.00

Soil depth	Very shallow	274525	47.69	618	40.74	0.85	0.42
	Shallow	54334	9.44	45	2.97	0.31	0.16
	Moderately deep	61936	10.76	47	3.10	0.29	0.14
	Very Deep	148781	25.85	789	52.01	2.01	1.00
	Water	36026	6.26	18	1.19	0.19	0.09
Soil texture	Clayey	253216	43.99	567	37.38	0.85	0.57
	Fine Loamy	210756	36.61	835	55.04	1.50	1.00
	Loamy	75603	13.13	95	6.26	0.48	0.32
	Water Body	36029	6.26	20	1.32	0.21	0.14
Soil erosion	Very Low	499105	86.71	1301	85.76	0.99	0.51
	Low	22668	3.94	116	7.65	1.94	1.00
	Medium	1632	0.28	5	0.33	1.16	0.60
	High	113	0.02	0	0.00	0.00	0.00
	Very High	15988	2.78	77	5.08	1.83	0.94
	Water	36103	6.27	18	1.19	0.19	0.10
Land use / Land cover	Agriculture	63392	11.00	6	0.40	0.04	0.02
	Dense Forest	200084	34.72	873	57.55	1.66	1.00
	Fallow land	71408	12.39	68	4.48	0.36	0.22
	Medium forest	141715	24.59	426	28.08	1.14	0.69
	Road	5195	0.90	9	0.59	0.66	0.40
	Settlement	1734	0.30	0	0.00	0.00	0.00
	Scrubland	65249	11.32	135	8.90	0.79	0.47
	Waterbody	27545	4.78	0	0.00	0.00	0.00
Rainfall (mm)	<2000	21221	3.68	0	0.00	0.00	0.00
	2000-3000	90635	15.73	34	2.24	0.14	0.10
	3000-4000	96787	16.79	215	14.17	0.84	0.62
	4000-5000	197317	34.24	657	43.31	1.26	0.93
	>5000	170363	29.56	611	40.28	1.36	1.00
Temperatur e ℃	<21.5	165137	28.65	605	39.88	1.39	1.00
	21.5-22.5	257613	44.70	813	53.59	1.20	0.86
	22.5-23.5	127383	22.10	99	6.53	0.30	0.21
	>23.5	26190	4.54	0	0.00	0.00	0.00
Road distance (m)	<100	102658	17.81	160	10.55	0.59	0.47
	100 - 200	72384	12.56	132	8.70	0.69	0.54
	200 - 300	65577	11.38	143	9.43	0.83	0.65
	300 - 400	50648	8.79	149	9.82	1.12	0.88
	400 - 500	46901	8.14	135	8.90	1.09	0.86
	> 500	238157	41.32	798	52.60	1.27	1.00
Seismology	Zone II	477111	82.79	1420	93.61	1.13	1.00
	Zone III	99212	17.21	97	6.39	0.37	0.33

The LSM based on the AHP method has been prepared in the following order.

1) Generation of the pairwise comparison matrix: The degree of the importance (1 to 9) of each causative factor for generation of pairwise comparison matrix is assigned based on Table 4 (Saaty, 2008). Table 5 shows the Pairwise Comparison Matrix of AHP weightage.
2) Computation of the criterion weights: The weight of each causative factor is divided by the sum of the column of the same causative factor and prepared by the normalized pairwise comparison matrix (Npcm). The row wise sum of each causative factor in the normalized pairwise comparison matrix is divided by the total number of the factors and prepared by the criteria weight. The criteria weight is multiplied with 100 and prepared the percentage of criteria weight (Table 6).
3) Estimation of the consistency ratio: Column wise original pairwise comparison matrix value of each class multiplies with criteria weight of same class and then row wise sum of each class and prepares the weighted sum value of consistency vector. Weighted sum value of the consistency vector of each class is multiplied with the criterion weight of the same class and prepared for the average value of the consistency vector. Consistency index is calculated using the following formula

$$CI = \frac{\lambda - n}{n-1} = 0.13 \quad (4)$$

Where, λ = average value of consistency vector and n=number of causative factors

$$CR = \frac{CI}{RI} = 0.08 \quad (5)$$

where CI = consistency index, RI= random index

The ideal CR values for a large matrix is 0.1, if it is more than 0.1 the pairwise matrix should be revised. For the generation of LSM, the weight for each causative factor and their subclasses is assigned and all thematic layers combined using an overlay analysis tool in the ArcGIS 10.5 environment. The final landslide susceptibility map is classified into five classes including very low, low, moderate, high, and very high.

Weighted Overlay Method (WoM): Weighted overlay method is also used in this study for landslide susceptibility mapping. Each causative factor classified into subclasses and heuristic technique based on the local information, prior knowledge of past landslide and their importance in causing or triggering landslide are used for the assign the scale (0 to 9) and weight (Gawali et al., 2017; Dai et al., 2002; Sarkar and Kanungo 2004). A detailed weightages is assigned to individual causative parameters as shown in Table 7.

Final LSM: LSM prepared using the all three methods are superimposed to each other and final LSM of the study area are prepared by addition of all the three classes (FR + AHP + WoM). The village and landslide inventory has been superimposed over the LSM and identifies landslide potential maps of villages.

Table 4: Degree of Importance in AHP

Numerical scale	Intensity of Importance
1	Equal importance - Two factors contribute equally
3	Moderate importance - slightly importance of one over another
5	High prevalence - Essential or strong importance
7	Very high prevalence - Demonstrated importance
9	Extremely high prevalence - Absolute importance
2, 4, 6, 8	Intermediate values - used when comprises is needed

Table 5: Pair-wise Comparison Matrix of AHP

F	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	2	2	3	3	4	4	5	5	5	6	6	4	4	7	7
2	1/2	1	2	7	2	2	4	5	3	3	7	7	3	2	7	3
3	1/2	1	1	2	3	3	4	4	4	4	5	5	5	6	7	7
4	1/3	1/7	1/2	1	2	2	3	3	3	3	4	4	4	5	6	6
5	1/3	1/2	1/3	1/2	1	2	3	3	3	3	4	4	4	5	6	7
6	1/4	1/2	1/3	1/2	1/2	1	2	2	3	3	4	4	4	5	7	7
7	1/4	1/4	1/4	1/3	1/3	1/2	1	2	2	2	3	3	3	4	5	5
8	1/5	0	1/4	1/3	1/3	1/2	1	1	2	2	3	3	3	4	5	5
9	1/5	1/3	1/4	1/3	1/3	1/3	1/2	1/2	1	2	3	3	3	4	5	5
10	1/5	1/3	1/4	1/3	1/3	1/3	1/2	1/2	1/2	1	2	2	2	3	5	5
11	1/6	1/7	1/5	1/4	1/4	1/4	1/3	1/3	1/3	1/2	1	2	2	3	5	5
12	1/6	0	1/5	1/4	1/4	1/4	0	0	0	1	1	1	2	3	5	5
13	1/4	1/3	1/5	1/4	1/4	1/4	1/3	1/3	1/3	1/2	1/2	1	1	2	5	5
14	1/4	1/2	1/6	1/5	1/5	1/5	1/4	1/4	1/4	1/3	1/3	1/3	1/2	1	3	3
15	1/7	1/7	1/7	1/6	1/6	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/3	1	3
16	1/7	1/3	1/7	1/6	1/7	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/3	1/3	1
Sum	4.89	7.35	8.22	16.62	14.09	16.90	24.15	27.65	28.15	30.23	43.73	45.23	40.90	51.67	79.33	79

1- Slope, 2- Rainfall, 3- Relief, 4- Lithology, 5- Soil Depth, 6- LULC, 7- Soil Texture, 8- Road Distance, 9- Drainage Distance, 10- Drainage Density, 11- Lineament Distance, 12- Lineament Density, 13- Soil Erosion, 14- Aspect, 15- Seismicity, 16- Temperature

Table 6: Relative Weight of Criteria of AHP

Factors	NPCM Sum	Weighted sum value (WSV)	Criteria Weight (CW)	WSV/CW	Weights
Slope	2.66	3.11	0.17	18.68	17
Rainfall	2.27	2.78	0.14	19.62	14
Relief	2.03	2.40	0.13	18.95	13
Lithology	1.43	1.69	0.09	18.91	9
Soil Depth	1.37	1.60	0.09	18.69	9
LULC	1.20	1.38	0.07	18.50	7
Soil Texture	0.85	0.98	0.05	18.42	5
Road Distance	0.78	0.89	0.05	18.30	5
Drainage Distance	0.73	0.83	0.05	18.05	5
Drainage Density	0.59	0.66	0.04	17.81	4
Lineament Distance	0.48	0.53	0.03	17.57	3
Lineament Density	0.45	0.47	0.03	16.72	3
Soil Erosion	0.43	0.45	0.03	16.39	3
Aspect	0.34	0.35	0.02	16.30	2
Seismicity	0.20	0.20	0.01	16.26	1
Temperature	0.19	0.21	0.01	18.13	1
	Total- 16		**Total- 1**	**λ - 17.96**	**100**

Accuracy: After the landslide susceptibility mapping (LSM) of all three methods, the accuracy of LSM is evaluated by using the receiver operating characteristic (ROC) and area under curve (AUC) in ArcGIS software. The AUC is a graphical representation of binary operating classes and it is a good method for the validation of models.

Results and Discussion

Slope: The slope is an important parameter for stability assessment (Kannan et al., 2015), as the slope angle controls the slope stability and driving force intensity of unstable moving material. According to Dai & Lee (2002), the highest landslide occurs when the slope angle is between 25° to 35° degree and it decreases when slope is above 35°. The slope map of the study area is derived from DEM data of Cartosat-1 using spatial analyst tool in ArcGIS (Fig. 4). On the basis of angle, slope data classified into five classes as per Bureau of Indian Standards (BIS) such as <15^0 (Very gentle slope), 15 - 25^0 (Gentle slope), 25 - 35^0 (Moderate slope), 35 - 45^0 (Steep slope) and above 45^0 (Very steep slope) (Fig. 4). Most of the landslide (1370) was reported in areas where slope is between 5° to 35°. These classes are rated with the highest weight. About 43.97% of landslide events occurred in class I (< 15°), whereas the least landslide events (1.12 %) occurred in class V (> 45° %).

Aspect: Aspect map shows the directions of the ground slope, it is one of the most important predisposing factors of landslides. Mostly the aspects control the microclimatic factors such as rainfall intensity, soil moisture, sunlight exposure, wind intensity, intensity of evapotranspiration and ground temperature etc. (Dai et al., 2002; Cevik and Topal, 2003). Aspect map of the study region is generated from DEM data Cartosat - 1 using spatial analyst tool in ArcGIS 10.5. The aspect map of the study area is divided into nine classes on the basis of slope directions viz., north, northeast, east, southeast, south, southwest, west, northwest and flat (Fig. 5). The last ninth class represents the flat area and remaining eights are representing the slope angle. Most of the landslide (790) was reported in S, SW and SE direction, whereas it is monsoon facing.

Relief: Relief is related to the elevation of the terrain. Fig. 6 shows the relief map of the study area which is derived from DEM data of Cartosat-1 using spatial analyst tool in ArcGIS 10.5. It is divided into five relief zones such as a very low relief zone (< 600 m), low relief zone (600 - 800 m), medium relief zone (700 - 1000 m), high relief zone (1000 - 1200 m) and very high relief zone (> 1200 m). Highest landslide was observed in 600 to 800 (635) and 800 to 1000 (598) classes. Highest rating allotted to these classes.

Lithology: Lithology refers to all physical characteristics of a rock and it controls slope stability. (Sarkar and Kanungo, 2004). The lithological map of the area has been prepared by using the data of “Bhukosh GeoPortal” of Geological Survey of India. Major lithological characters of the study area are divided into two classes viz. Basalt and Laterite (Fig. 7). The most dominant lithology class is Basalt and they cover 93 % of the study area and the highest 1500 landslide incidence was observed in this class. Therefore, the highest rating value is assigned to this class.

Lineament Density and Lineament Distance: Active faults are more susceptible to the landslide (Mehmood et al., 2022). Lineament data is downloaded from "Bhukosh GeoPortal" of Geological Survey of India. Lineament density and distance map generated from this lineament data. The lineament density map is divided in five classes viz., very low (< 50 m/km^2), low (50 to 100 m/km^2), medium (100 to 150 m/km^2), high (150 to 200 m/km^2) and very high (more than 200 m/km^2) density zone (Fig. 8). The highest landslide (870) event is observed in the lineament density above 200 m/km^2. Therefore, the highest rating value is assigned to this class. The distance from lineament is generated using the Euclidean distance tool of ArcGIS 10.5. The lineament distance map is classified into eight classes viz. <20 m, 20 to 40 m, 40 to 60 m, 60 to 80 m, 80 to 100 m, 100 to 120 m and >120 m (Fig. 9). The highest landslide (1408) event is observed in the lineament distance above 200 m. Therefore, there is no correlation of the lineament distance with landslide incidence.

Table 7: Rating and Weightage to landslide responsible layers

Parameter	Class	Rating	Weightage
Slope	0-15	5	20
	15-25	4	
	25-35	3	
	35-45	2	
	Above 45	1	
Rainfall	<2000	1	15
	2000-3000	2	
	3000-4000	3	
	4000-5000	5	
	>5000	4	
Relief	0 to 600 m	1	12
	600 to 800	5	
	800 to 1000	4	
	1000 to 1200	3	
	Above 1200	2	
Lithology	Laterite	1	12
	Basalt	2	
Soil depth	Very shallow	4	5
	Shallow	2	
	Moderately deep to Deep	3	
	Very Deep	5	
	Water	1	
Land use / Land cover	Agriculture	3	5
	Dense Forest	8	
	Fallow land	5	
	Medium forest	7	
	Road	4	
	Settlement	1	
	Scrub land	6	
	Waterbody	2	
Soil texture	Clayey	3	4
	Fine Loamy	4	
	Loamy	2	
	Water Body	1	

Road Distance	<100 m	5	4
	100 - 200	1	
	200 - 300	3	
	300 - 400	4	
	400 - 500	2	
	> 500	6	
Drainage distance	<50	4	4
	50-100	6	
	100-150	5	
	150-200	3	
	200-250	2	
	>250	1	
Drainage density	Very low (below 2 Km)	1	4
	Low (2 to 3 sq km)	2	
	Medium (3 - 4 sq km)	4	
	High (above 4 sq km)	3	
Lineament distance	< 50	1	3
	50 - 100	2	
	100- 150	4	
	150-200	3	
	>200	5	
Lineament density	Below 50 m/Km2	1	3
	50 to 100 m/Km2	2	
	100 to 150 m/Km2	4	
	150 to 200 m/Km2	3	
	Above 200 m/Km2	5	
Soil erosion	Very Low	6	3
	Low	5	
	Medium	2	
	High	1	
	Very High	4	
	Water	3	
Aspect	Flat	1	2
	N	2	
	NE	5	
	E	6	
	SE	8	
	S	9	
	SW	7	
	W	3	
	NW	4	
Seismology	Zone II	2	2
	Zone III	1	
Temperature	<21.5	3	2
	21.5-22.5	4	2
	22.5-23.5	2	2
	>23.5	1	

Soil: The different characteristics of soil and its parameters play an important role in the study of soil stability and landslide susceptibility mapping. On the basis of observational study different soil characteristics affected slope stability (Sidle et al., 2006).

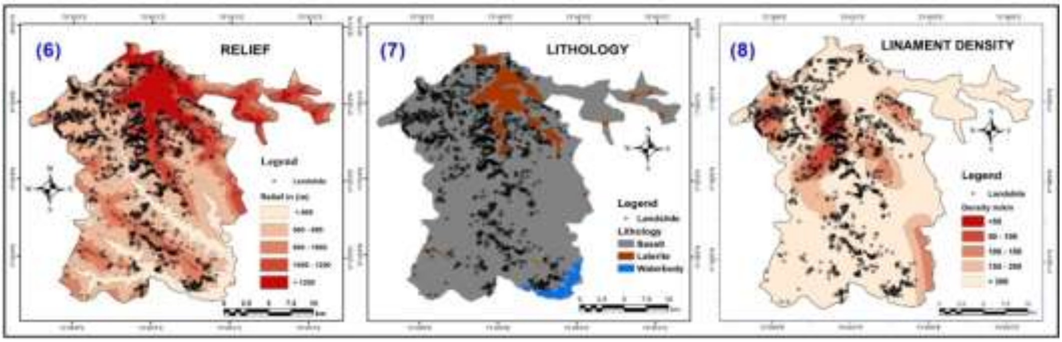

Fig. (6) Relief, (7) Lithology, (8) Lineament Density

The soil data is prepared from the map published by the European Soil Data Center on the website and used for preparation of soil depth, soil texture and soil erosion map. Field check is carried out to verify the characteristics of soil data. The study area is dominated by three soil types: clayey (43.99%), fine loamy (36.61 %) and loamy (13.13 %) (Fig. 10). The majority of landslide events (835) happened in the fine loamy soil and shallow black soil (567). Therefore, the highest rating values are assigned to these classes. The soil depth map is classified in four classes: very shallow, shallow, moderately deep to deep, and very deep (Fig. 11). Most of the landslide was observed in very shallow (618) and very deep soil depth (789). Therefore, the highest rating values are assigned to these classes. The soil erosion map is generated using a RUSLE model (Renard et al., 1997). The soil erosion map is divided into five classes which are Very low, Low, Medium, High, very high (Fig. 12). The highest landslide (1301) event was observed in the area of very low soil erosion and very low were observed in the High (0) and medium (05) soil erosion area. Therefore, there is no correlation of the soil erosion with landslide incidence.

Land Use / Land Cover: Land use and land cover map of the study area generated from multispectral ResourceSat-2A (LISS-IV) satellite image with 5.8 m spatial resolution acquired on 31/01/2021 & 24/02/2021 after digital image processing in ERDAS imagine software (Fig. 13). It is classified into 8 classes: Dense Forest (34.72 %), Medium Forest (24.59 %), Fallow land (12.39 %), Scrubland (11.32 %), Agriculture (11 %), Waterbody (4.78 %), Road (0.9 %) and Settlement (0.3 %). The roots of the trees hold the soil firmly in place and slope more stable and less prone to slipping (Nohani et al., 2019). However, in this study area the highest (1299) landslide is observed in the forest area.

Distance from road: The road network in the mountainous area poses a threat to slope stability (Nohani et al., 2019). The road network in the area is digitized from ResourceSat-2A (LISS-IV) satellite image and Google earth satellite data. The distance from the road map is prepared by using the Euclidean distance and it is classified into six classes viz. <100 m, 100 – 200 m, 200 – 300 m,300 – 400 m,400 – 500 m and > 500 m. In the area under study, 10.55 % landslide events occurred within 100 m distance from any given road and the highest (72 %) landslide was observed away from the road (Fig. 14). This may be because most of the part of the study area is mountain and occupied with dense vegetation cover, however the road network is not dense.

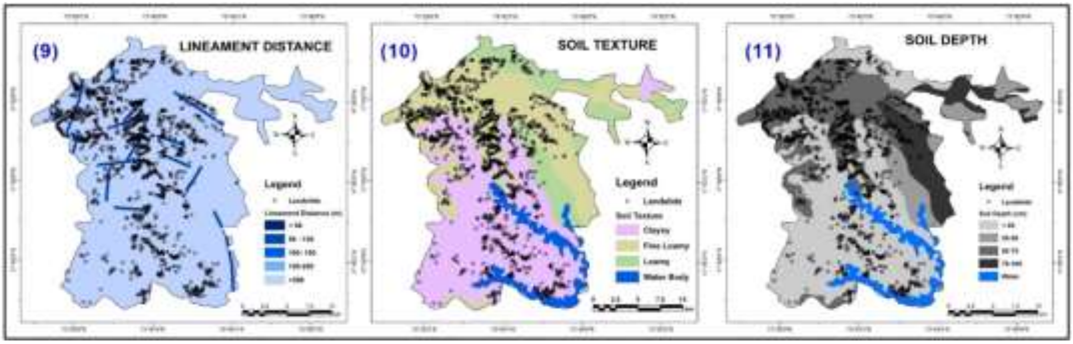

Fig. (9) Lineament Distance, (10) Soil Texture, (11) Soil Depth

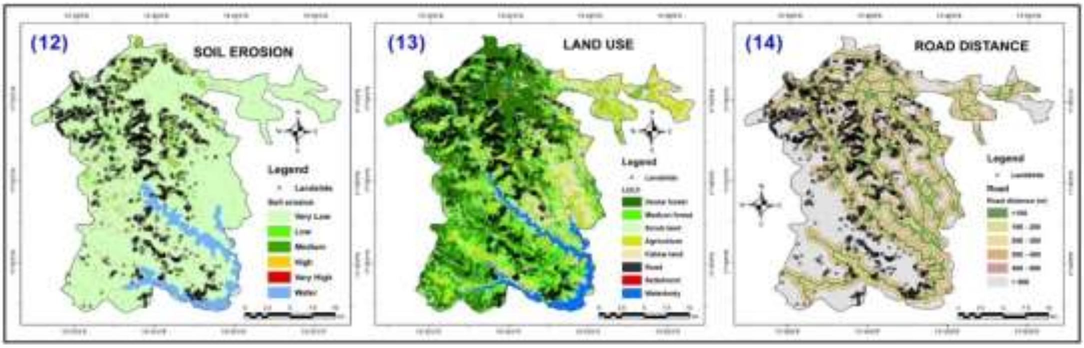

Fig. (12) Soil erosion, (13) Land Use / Land Cover, (14) Road Distance

Drainage distance and Drainage density: Drainage is an important aspect to determine the landslide probability. Drainage density and drainage distance influencing the occurrence of the landslide. Pham et al. (2018) stated that 65% of landslides occurred within 50 meter distance from drainage. The drainage network is generated from DEM data of Cartosat-I using the spatial analyst tool of ArcGIS 10.5 software. Using the drainage network two thematic maps are prepared viz., drainage density and drainage distance. The distance from drainage is prepared from the drainage network by using the Euclidean distance approach. The map is categorized into five classes as follows below: 50 m, 50 - 100 m, 100 - 150 m, 150 - 200 m and above 200 m. (Fig. 15). In the study area, distanced 0-100 m from the stream is a high potential of landslide (757) occurrence. The density is calculated as the length of streams in Km^2 (Fig. 16). These are classified into three classes' viz., very low (below 2 km^2), low (2 to 3 km$^{2)}$, medium (3 to 4 km^2) and high (> 4 km^2). The highest landslide occurred in the medium to high drainage density area.

Rainfall: Rainfall is the most landslide triggering factor (Tesic et al., 2020). The study area experiences heavy rainfall during monsoon season and most of the landslides have occurred in this season. The heavy rainfall in the year 2021 initiated more than 1500 landslides in the study area. The rainfall map (Fig. 17) is generated using the IDW interpolation method and the entire study area is divided into five classes: <2000 mm, 2000 to 3000 mm, 3000 to 4000 mm, 4000 to 5000 mm and >5000 mm.

The highest rainfall values are observed in the western part of the study area and the lowest values in the eastern part (Fig. 17). The rainfall data showed that the frequency of landslide events increases with increased rainfall intensity. The highest weightage is assigned to these classes.

Temperature: Temperature is a passive cause of landslides. It regulates the amount of runoff and evaporation and the increase in air temperature can have contrasting consequences on slope stability. A higher air temperature will expand evapotranspiration on vegetated slopes (Gariano and Guzzetti, 2016). The temperature map is generated in the IDW interpolation method of ArcGIS 10.5 with the help of temperature data (Fig. 18).

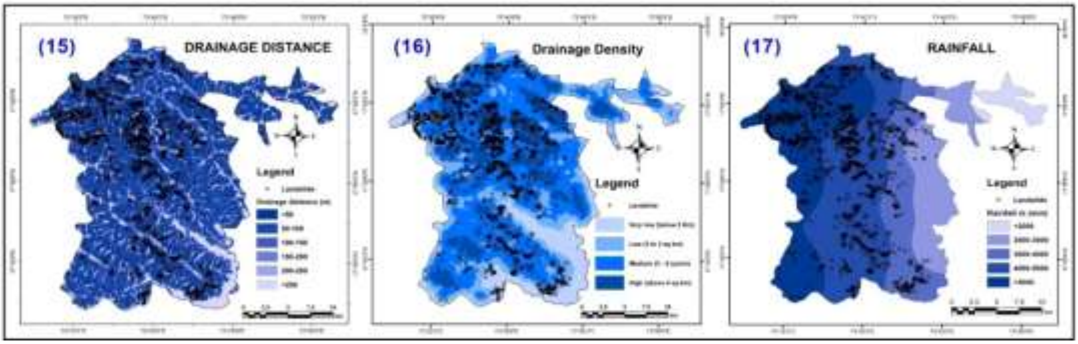

Fig. (15) Drainage distance map, (16) Drainage density map, (17) Rainfall map

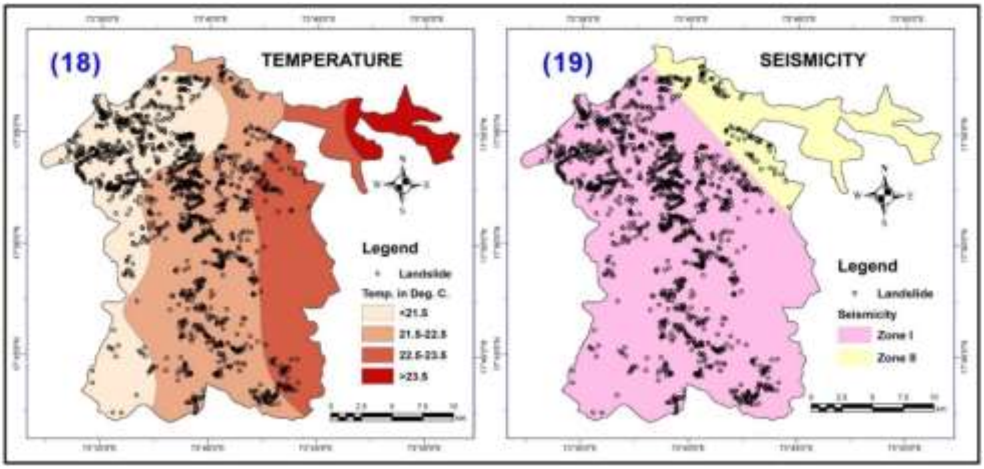

Fig. (18) Temperature map, (19) Seismology map

Seismology: Earthquake data is downloaded from “Bhukosh GeoPortal” of Geological Survey of India. Seismology map generated from earthquake data. The study area is distributed in two seismic zones (Fig. 19). Highest landslide occurred in the seismic zone –I.

Landslide Susceptibility Map using FR

In this study, sixteen causative factors are used for preparation of potential landslide susceptibility in Mahabaleshwar tehsil using the frequency ratio (FR). Fig. 20a shows the LSM using FR and Table 8 shows the class wise landslide susceptibility. The results indicate that 34.80% area falls in the very high class followed by high susceptibility class 24.40% while 16.70% area is recognized as moderate class, 13.41 is under very low and low susceptibility class is 10.69 %. The landslide inventory indicates that 1122 (73%) landslides are under the very high susceptibility class, 315 landslides under the high susceptibility class, 66 landslides are under the moderate susceptibility class and only 14 landslides are under the low and very low susceptibility class.

Table 8: Landslide susceptibility based on FR

Sr. No.	Susceptibility Class	Area (km^2)	% of Area	Landslide	% of landslide
1	Very high	180.28	34.80	1122	73.96
2	High	126.39	24.40	315	20.76
3	Moderate	86.48	16.70	66	4.35
4	Low	55.40	10.69	11	0.73
5	Very low	69.45	13.41	3	0.20
Total		**518**	**100**	**1517**	**100**

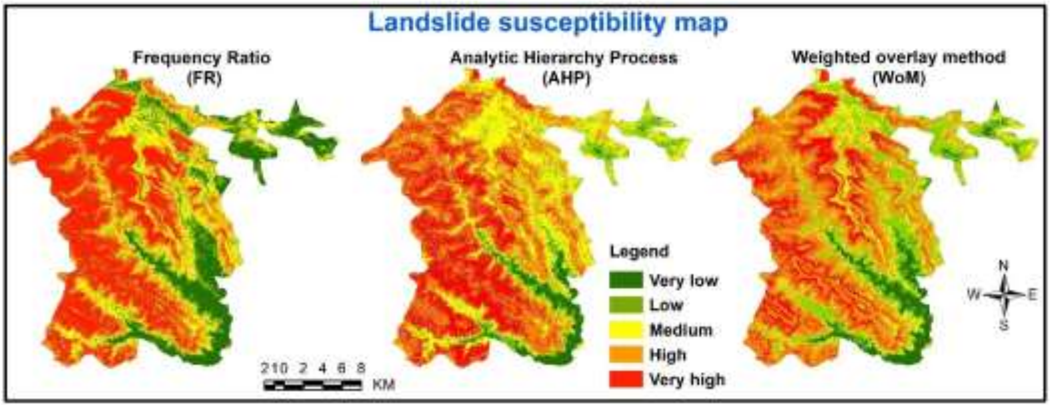

Fig. 20: (a) Landslide susceptibility map of FR, (b) Landslide susceptibility map of AHP and (c) Landslide susceptibility map of WoM

Landslide Susceptibility Map using AHP

The Landslide susceptibility map generated by the AHP methods is shown in Fig. 20b and Table 9 shows the class wise landslide susceptibility. The results shows that 61.76 % of the study area was categorized as high (39.96) to very high (21.80) landslide susceptibility class and 24.43% falls on moderate susceptibility class, while the rest 13.81 % is categorized as low to very low susceptibility class. The landslide inventory indicates that 637 landslides are under the very high susceptibility class, 745 landslides under the high susceptibility class, 128 landslides are under the moderate susceptibility class and only 7 landslides are under the low susceptibility class.

Landslide Susceptibility Map using Weighted Overlay Method

For the generation of LSM, each causative factor is evaluated independently and assigned weight based on their importance. The highest weight assigned to slope (20), rainfall (15), relief (12) and lithology (12) based on their highest influence on slope instability.

Table 9: Landslide susceptibility based on AHP

Sr. No.	Susceptibility Class	Area (km^2)	% of Area	Landslide	% of landslide
1	Very high	112.94	21.80	637	41.99
2	High	206.98	39.96	745	49.11
3	Moderate	126.57	24.43	128	8.44
4	Low	43.49	8.40	7	0.46
5	Very low	28.02	5.41	0	0.00
Total		**518**	**100**	**1517**	**100**

The Landslide susceptibility map generated by the WoM is shown in Fig. 20c and Table 10 shows the class wise landslide susceptibility. It can be concluded that a total of 24.28 % of the area is not susceptible (low and very low susceptibility), 18.10 % area is moderate susceptible and 57.62 % of the area is susceptible (high and very high susceptibility) to a landslide occurrence (Fig. 20c). About 1431 landslides are observed in high (796) and very high (635) susceptible areas.

Table 10: Landslide susceptibility based on WoM

Sr. No.	Susceptibility Class	Area (km^2)	% of Area	Landslide	% of landslide
1	Very high	71.22	13.75	635	41.86
2	High	227.23	43.87	796	52.47
3	Moderate	93.76	18.10	74	4.88
4	Low	89.29	17.24	12	0.79
5	Very low	36.50	7.05	0	0.00
Total		**518**	**100**	**1517**	**100**

Data validation

The classified landslide susceptibility map of three methods is validated using the ROC and AUC (Metz, 1978). The accuracy is evaluated by comparing 1517 the landslide locations with the LSM in the ROC tool of Arc-SDM in ArcGIS 10.5. (Fig. 21) The area under the curve of FR and WOM shows the accuracy value of 0.813 (81.3%) and 0.806 (80.6 %) respectively; it is above 0.8 and shows very good test quality of the model. The area under the curve of AHP and final LSM shows the accuracy value of 0.754 (75.4 %) and 0.752 (75.2%) respectively, it is above 0.7 and shows good test quality of the model. The validation results showed that all three models are correctly classified and test quality good and acceptable.

Final Landslide Susceptibility Map

All three methods are combined and final LSM of the study area (Fig. 22) has been prepared (Table 11). The landslide susceptibility map shows, very high susceptibility zone occupies about 224.15 km^2 (43.27 %) of the total area. 1190 landslides (78.44 %) landslide and 13 villages are followed in this class.

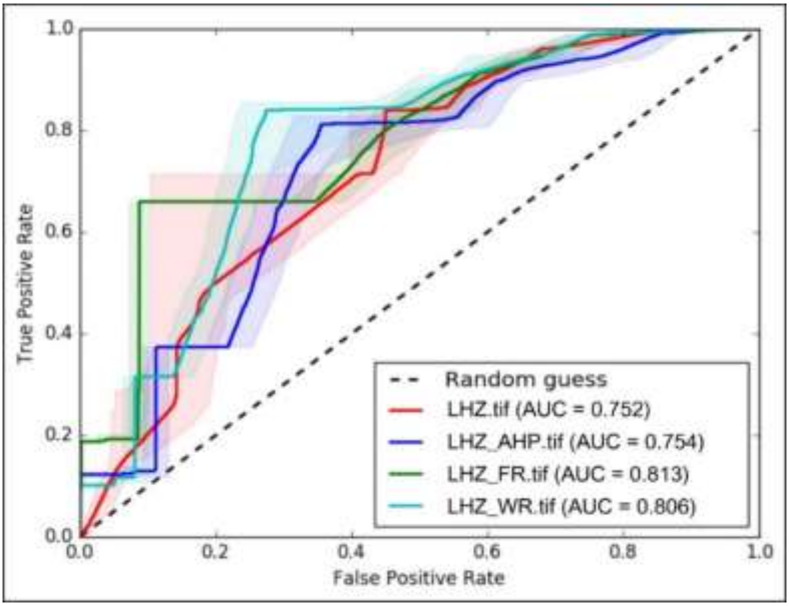

Fig. 21: ROC and AUC Curve of Landslide susceptibility map of FR, AHP, WoM and final LSM

High susceptibility zone covered 129.71 km^2 (25.04 %) area and about 286 landslides and 34 villages are under this class. Moderate susceptibility zones covered 92.1 km^2 (17.7 %) area and 37 landslides and 45 villages are under this category. Low and very low susceptibility zone covered 72.03 km^2 area and only 4 landslides and 21 villages are under this category. It is notable that most of the high and very high potential zones are located in the central and western part of this study area due to the presence of lower slope, high drainage distance, shallow soil density, and heavy rainfall. The medium potential zone is found in the surroundings of high and very high potential zones. The low and very low potential zones are found in alluvial plains and along the Koyna dam.

Table 11: LSM based on the combination of three methods

Sr. No.	Class	Landslides	% of Landslides	Villages	% of Villages	Area
1	**Very low**	0	0.00	10	8.85	35.40
2	**Low**	4	0.26	11	9.73	36.63
3	**Moderate**	37	2.44	45	39.82	92.10
4	**High**	286	18.85	34	30.09	129.71
5	**Very high**	1190	78.44	13	11.50	224.15
Total		**1517**	**100**	**113**	**100**	**518**

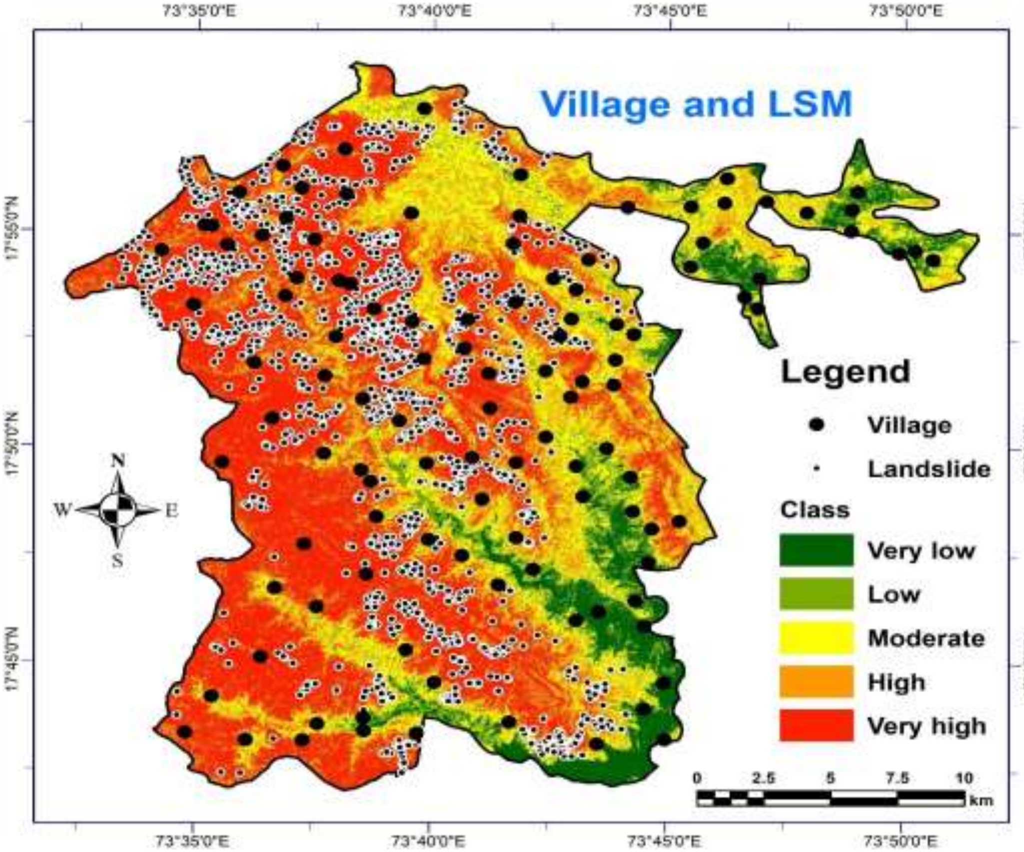

Fig. 22: Village and Landslide susceptibility map

Conclusion

Geospatial technology (RS, GIS and GPS) is an effective tool for landslide susceptibility mapping. In this study, FR, AHP and WoM methods were used to map the landslide susceptibility of the study area. The derived landslide susceptibility map through FR, shows that 59.2 % of the study area is identified as high to very high susceptible; AHP methods indicate 61.76 % of the overall area is under high to very high susceptibility zone, whereas the LSM generated with the WoM shows that 57.62 % of the total area is under high to very high susceptibility. It showed that FR (Frequency Ratio) methods are considerably better to predict the landslide susceptibility as compared to the AHP and WoM. The comparative study of all these methods are ideal for the correct mapping of the landslide susceptibility. The intergrated analysis of three methods shows that the relatively very high to high susceptible (unsafe) area is 68.31%, moderately susceptible (slightly safe) area is 17.78 % and safe (low to very low) area is 13.91 %. 47 villages along with Ambenali Ghat, Pasarni Ghat, Kelghar Ghat and Mahabaleshwar-Tapola road are identified to be in high to very high landslide susceptible zones and more than 3000 populations of these areas under the threat of landslides.

The comparison of the landslide inventory with the landslide causative factors shows that the physiographic condition (slope, relief, aspect, soil, drainage and lithology) and anthropogenic activities like, cutting of mountain for road network, construction work on the slope side, agriculture, and deforestation are the most influential and controlling factors of the landslide. It is noticed that, most of the landslides occurred during the monsoon rainfall and heavy rainfall is the triggering factor of the occurrence of landslides. Every year millions of tourists visit the different places in the Mahabaleshwar tehsil. A partial or complete rehabilitation is required of some villages to avoid all types of future development in the high to very high susceptible zones. The retaining wall and proper drainage control along the roadside will be helpful in reducing the landslide intensity in the high susceptable areas. In addition, awareness campgain of landslide causes and effects among the residents of high susceptable villages is also required. Hence, the developed landslide susceptibility map is very important for decision makers, planners, and engineers to prevent and mitigation measurements for reducing losses of life and properties.

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