Integrated Analytical Hierarchy Process (AHP) and GIS techniques based Soil Erosion Susceptibility Mapping in Chite Watershed, Mizoram, India

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Abstract
Soil erosion is a significant form of land degradation that profoundly affects agricultural and ecosystem sustainability. The present study aimed at addressing this issue by developing precise and feasible erosion susceptibility map in Chite watershed, India, using integrated approach combining the Analytical Hierarchy Process (AHP) with Geographic Information System (GIS). To evaluate erosion susceptibility conditions, multiple causative factors including elevation, slope, drainage density, distance from streams, land use / land cover, rainfall intensity, normalized difference vegetation index, lithology, soil texture and lineament density were selected. These factors and their sub-classes were prioritized by AHP method based on their relative influence on soil erosion.

Subsequently, the calculated AHP weights were utilized for generating a spatial dataset of soil erosion susceptibility through GIS technology. Accuracy assessment by the area under the ROC curve (AUC) reveals considerably acceptable results for the predicted map when compared to erosion inventory, producing an accuracy level of 0.812 (81%) and 0.922 (92%) for erosion and non-erosion points respectively. Thus, the present study manifests the efficiency of integrating the AHP and GIS techniques for erosion susceptibility mapping in the Chite watershed and this may serve as a valuable tool for sustainable land management and erosion control.

Keywords: Soil erosion, Erosion susceptibility mapping, Analytical Hierarchy Process (AHP), Geographic Information System (GIS), Chite watershed.

Introduction

Globally, soil erosion is a critical issue for agriculture and the environment[22]. It is a crucial obstacle to adequate and sustainable food supply and will persist as the main attribute of land degradation throughout the 21st century[19].

Soil erosion is, therefore, a significant challenge to human welfare as most of the essential food consumptions (99.7%) are obtained from the land[23]. Owing to its humid sub-tropical and tropical location, agriculturally dependent countries like India are more subjected to the influence of water-induced soil erosion[16].

As per recent reports, water erosion has been the paramount cause of land degradation which affects 29.77% of the total geographical area (TGA) in India i.e. approximately 97.85 M ha (million hectares)[30]. In the mountainous regions of northeast India, water erosion is more significantly noticeable in the form of sheet, rill and sporadic gully. It has dominantly influenced land degradation on 4.60 M ha of land area, constituting 18.2% of the region[4]. As soil erosion is a dynamic process, a comprehensive erosion assessment is challenging. It requires an in-depth understanding of complex interrelationships among various conditioning factors.

Different models have been developed using the multi-criteria decision making (MCDM) procedures to address such complicated problems influenced by multifarious variables. Among them, the analytical hierarchy process (AHP) is one of the most significant methods applied for evaluating environmental susceptibility due to (i) its clarity and flexibility to handle multiple criteria with precise output, (ii) its ability to consider both qualitative and quantitative variables; (iii) its capacity to check inconsistency for bias decision etc.[12,13] Moreover, the AHP integrated with a Geographic Information System (GIS) can produce a decision assistance framework through competent spatial data with effective visual representations[18]. Hence, modeling approaches based on AHP and the technological advancements of GIS have proved to be an effective tool for soil erosion susceptibility mapping with rapid and accurate results[10].

Among the rugged hilly terrain of northeastern India, Mizoram has experienced the most severe water erosion-induced land degradation which affects 12.6% of the TGA[4]. The predisposition of the region has been the collective influence of unsustainable land use, extensive deforestation, traditional practice of shifting cultivation etc. on the weak geo-environmental conditions characterized by rolling terrain, steep gradient slopes, fragile geological structure and copious rainfall[17]. Besides the region's sensitivity coupled with haphazard anthropogenic activities reflected on land degradation, the region still lacks comprehensive studies related to erosion susceptibility mapping. Therefore, the present study aims to generate a soil erosion susceptibility map by integrating AHP and GIS technology in Chite Watershed, Mizoram.

As most areas of the State's capital, Aizawl, comprising more than one-third of its population, fall within its ambit, it is one of the most urbanized and seriously degraded watersheds. Hence, the validated results will provide a valuable tool for researchers, decision-makers and stakeholders to derive site-specific development programmes for controlling soil erosion and land conservation.

Study Area

Chite watershed is geographically located between 23°38.29' to 23°45.24' N latitude and 92°42.54' to 92°47.15' E longitude, extending for about 52.16 km^2 (Fig. 1). Young landforms with rugged hilly terrain and steep slopes characterize the watershed. Elevation of the study area ranges from 172 to 1239 metres above mean sea level, with a maximum slope of about 59.61°. Geologically, the region is part of the middle and upper Bhuban formation of the Surma group, which predominantly consists of rocks such as sandstone, shale and siltstone[15]. The climate can be classified as a sub-tropical humid type that receives abundant rainfall, approximately 2086.59 mm, through southwest monsoon.

Material and Methods

Data acquisition: Different data used in the present study were acquired from several authenticated sources and through extensive field surveys. The "Shuttle Radar Topography Mission Digital Elevation Model" (SRTM-DEM) with 30 m spatial resolution was downloaded from Earth Explorer, U.S. Geological Survey (https://earthexplorer.usgs.gov/). Lithological map was derived from Geological Survey of India online data portal "Bhukosh GSI" (https://bhukosh.gsi.gov.in/). Sentinel-2 image (10 m resolution) was obtained from "Copernicus European Union (EU) and European Space Agency (ESA)" (https://scihub.copernicus.eu/).

Rainfall data were acquired from 3 stations viz. State Meteorological Centre, Directorate of Sience and Technology, Govt. of Mizoram (SMC), HQ CE (P) Pushpak, Aizawl (HQP) and Thungsulthliah BDO Office (TBDO), Mizoram, covering a period of 12 years (2010-2021). Soil samples were collected from 90 sites within and around the study area using a systematic sampling procedure as shown in fig. 2(b).

Erosion inventory mapping: Erosion inventory is required to validate the erosion susceptibility model and was undertaken in the initial stage through extensive field surveys. The location of 133 erosional sites and 90 non-erosion sites was collected from the study area using handheld GPS (Fig. 2a and fig. 4).

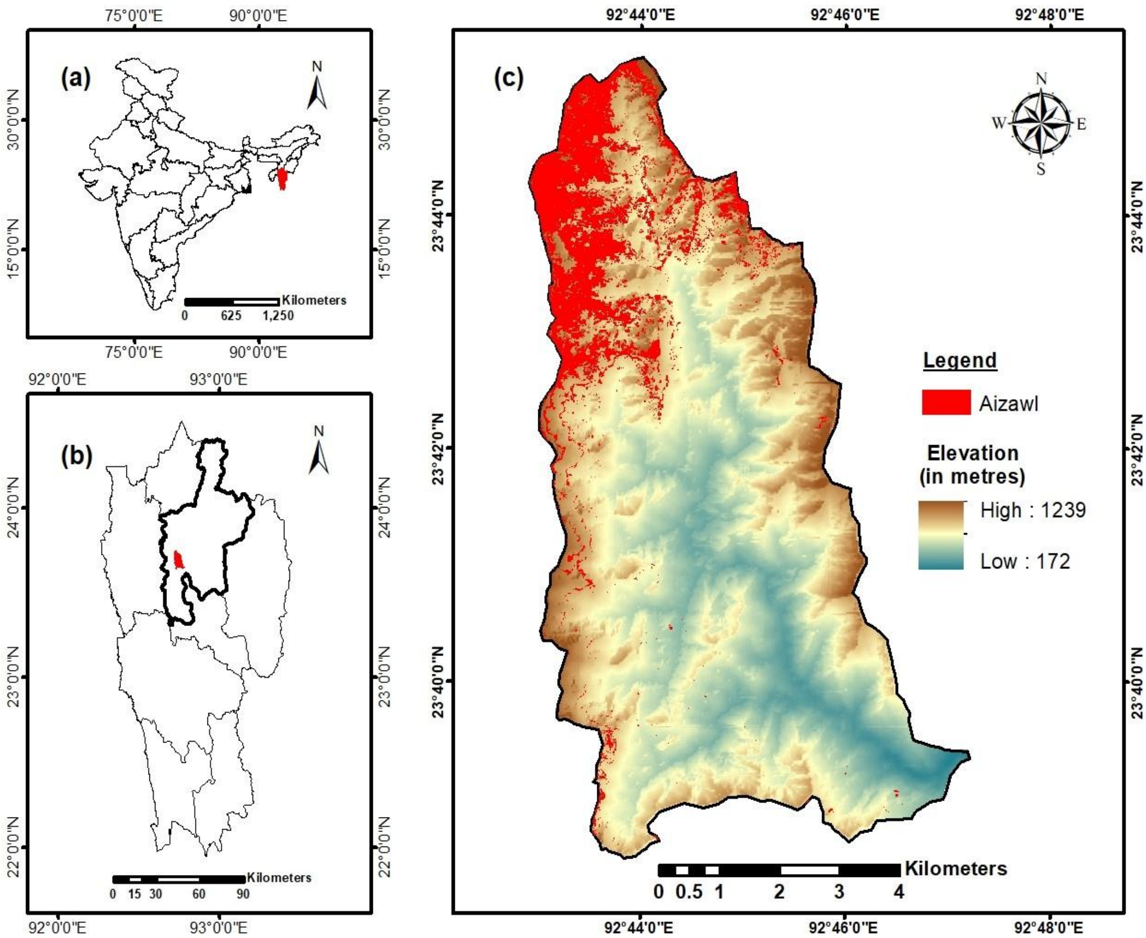

Fig. 1: Location map of the Study Area (a) India, (b) Mizoram and (c) Chite watershed.

Preparation of erosion conditioning factors: In this study, ten erosion causative factors that encompass several geo-environmental conditions like elevation (ELE), slope (SLP), drainage density (DD), distance from streams (DFS), land use / land cover (LULC), rainfall intensity (RI), normalized difference vegetation index (NDVI), lithology (LIT), soil texture (ST) and lineament density (LD) were selected based on published literatures[1-3,6,21,31]. Thematic layers were prepared for all these selected factors under the ArcGIS environment (Fig. 3a to j). The inherent susceptibility within each element was represented by dividing each parameter into sub-classes based on their erosion potential. Subsequently, the layers were projected under a similar coordinate system i.e. WGS1984 UTM Zone 46 and each layer was resampled to a standard cell size (30 x 30 m) to maintain accurate raster analysis.

As landform stability is influenced by changes in elevation which affect both runoff and infiltration rate, higher elevations have more erosion potential[34]. Varying elevations of the study area were extracted from SRTM DEM. Slope is the primary factor that influences erosion susceptibility and tends to increase with increasing slope inclination[8]. For determining different slope values in the study area, a filled SRTM DEM was used under 3D Analyst Tools. In this research, the aggressiveness of rainfall was represented by rainfall intensity which was calculated based on the Modified Fournier Index (MFI) made for Indian conditions[32]:

$$RI = \sum_{i=1}^{12} \frac{P_i^2}{P} \quad (1)$$

where RI refers to rainfall intensity, P_i is the monthly average rainfall (mm) for the i^{th} month and P is the average annual rainfall (mm).

The particle size distribution of the collected soil samples was analysed using the Bouyoucos hydrometer method for generating soil texture[20]. Textural classification was based on the percentage of sand, silt and clay particles[33]. Erosion processes are more prevalent in medium and fine textured soils, marked by low water infiltration[34], resulting in increased run-off. The spatial distributions of rainfall intensity and soil texture were then represented by using the Inverse Distance Weighted (IDW) Interpolation method. Rocks of different lithological groups have distinct physical characteristics which manifest a varying degree of erodibility[9]. Hence, rocks of varying lithological groups are extracted from Bhukosh GSI, including sandstone with subordinate siltstone, mudstone and shale as well as grey sandy splintery shale, siltstone and mudstone.

Considering their relative potential erosion susceptibility, they were assigned a specific numerical code: 1 and 2 respectively. Lineament features of the study area were extracted through visual interpretation using a DEM image and a lineament density map was subsequently generated using Line Density Tools. Lineament portrays a weaker zone in the low-resistant landform and is usually affected by soil erosion[31]. Areas with more stream channels have a higher drainage density, indicating higher chances of soil erosion[6]. Extracted drainage network from DEM image was used to prepare drainage density map using line density tools. Soil erosions are more dominant along the adjoining areas of streams due to the force generated by running water[23].

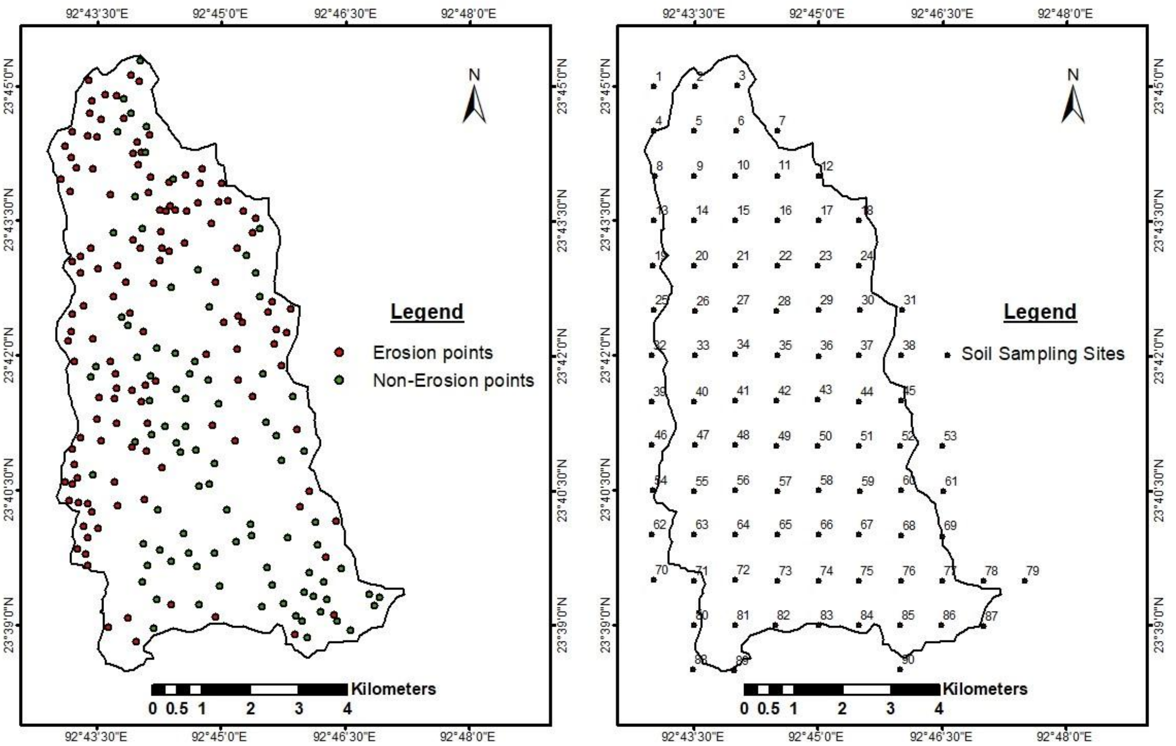

Fig. 2: (a) Erosion Inventory and (b)Soil sampling sites.

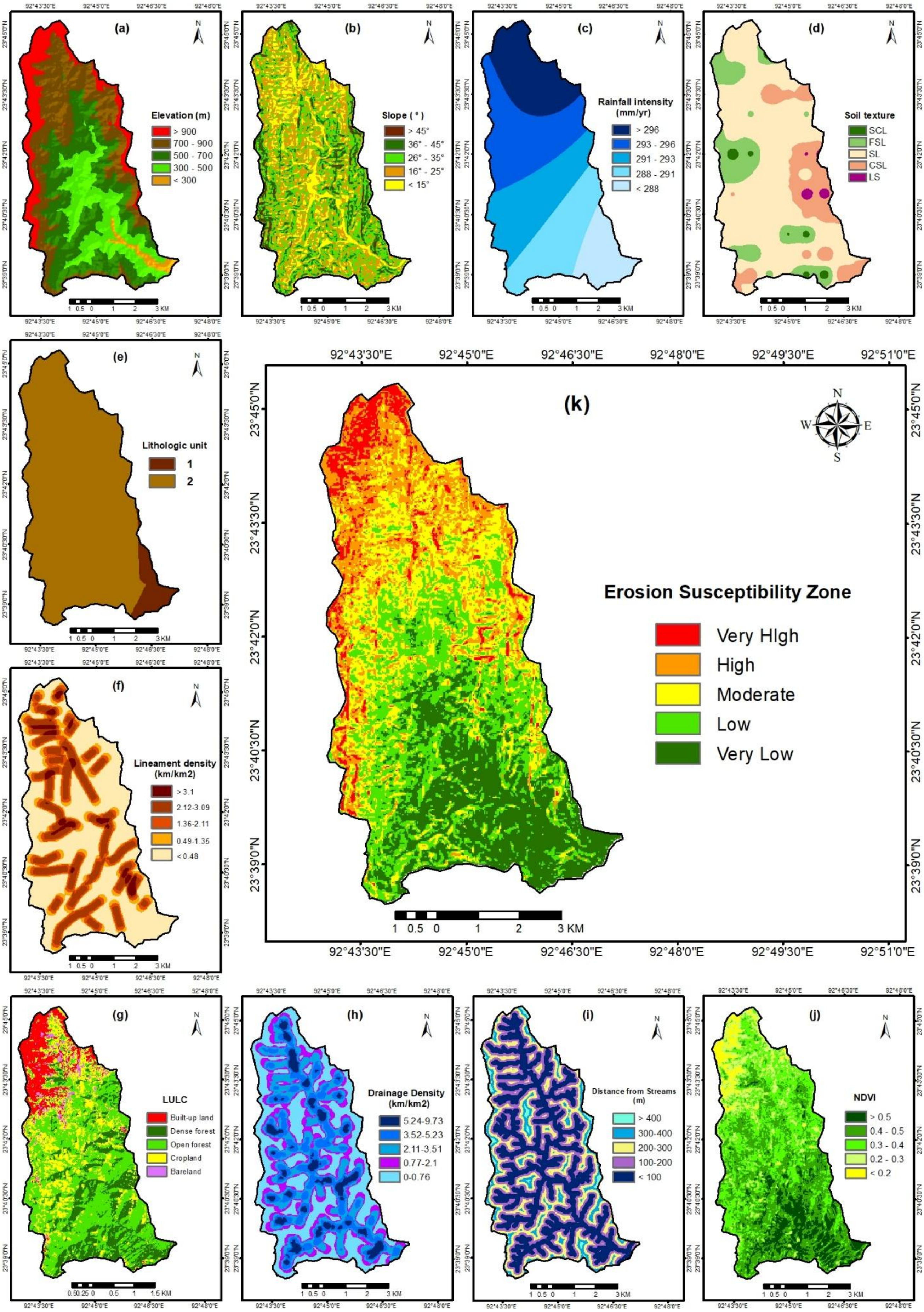

Fig. 3: (a) to (j) Erosion conditioning factors and (k) Erosion Susceptibility Map.

Hence, proximity to streams indicates more likelihood of soil erosion and distance from the stream layer was attained by Euclidean Distance buffer using the extracted drainage networks. Radiometrically corrected Sentinel-2 satellite imagery was used for sorting different LULC types based on the Supervised - Maximum Likelihood Classification method (MLC), which produced an overall accuracy of 87% and Kappa coefficient of 0.89. Generally, LULC classes that represent cultural landscapes with lesser vegetative covers are more inclined to the direct impact of soil erosion. Vegetation reduces erosion susceptibility by protecting the land surface and supporting soil structure[11]. Thus, NDVI was calculated for estimating vegetation cover and health based on Sentinel-2 imagery using the following formula in raster calculator[26]:

$$NDVI = (NIR-R) / (NIR+R) \quad (2)$$

where NIR is the near-infrared band of Sentinel-2 image and R denotes the red band.

Multicollinearity analysis: In the present study, multicollinearity analysis has been performed for the ten selected erosion conditioning factors using the multicollinearity diagnostic tools- Tolerances (TOL) and Variance Inflation Factors (VIF). To assess multicollinearity issues, 700 random points were selected using the “Create Random Points” tool in ArcGIS software. Subsequently, the randomly selected points were taken out by the “Extract Multi Values to Points” tool in Spatial Analyst Tools and the multicollinearity test was performed using IBM SPSS Statistics 25.

Prioritization with AHP: The present study employed the AHP techniques for decomposing and synthesizing various selected parameters that influence erosion susceptibility. Weights were assigned to the subjective and objective criteria through a pairwise comparison based on a dimensionless ratio scale ranging from 1 to 9 to show their relative preferences[29]. Comparative ranks were allocated based on regionally acquired knowledge through field observation and experts’ judgement derived from literatures[2,3,6,21,25,31]. The parameter’s weights or normalized weights were then computed through the comparison matrix.

To check inconsistency or bias judgement in the matrix, the consistency ratio (CR) value should be determined. It has been suggested that an acceptable CR value should be ≤ 0.1[28]. CR value can be calculated by using the given equation:

$$CR = CI/RI \quad (3)$$

where RI indicates random consistency index and it represents the mean value for observed consistency index (CI) in accordance with comparison matrix forwarded by Saaty et al[27] (Table 1). CI can be computed using the formula:

$$CI = \lambda\_max – n / n-1 \quad (4)$$

where λ_max refers to the principal Eigen value obtained from the normalized matrix and n indicates the number of conditioning factors or criteria.

Erosion susceptibility mapping: The spatial distribution of erosion susceptibility was determined through soil erosion susceptibility index (SESI) which was computed by the following expression:

$$SESI = \sum_{i=1}^{n} W_i^s \text{ x } S_i^s \quad (5)$$

where SESI indicates soil erosion susceptibility index, W_i^s refers to the weights of parameters/criteria and S_i^s is the weights of the sub-parameters/sub-criteria.

Fig. 4: Photographs of active erosional features in the study area.

Validation of model: A model's accuracy must be validated to determine its reliability[1]. The "Receiver operating characteristics (ROC) curves" or "area under the ROC curves (AUC)" were applied to validate the erosion susceptibility model using the ArcSDM tool. The ROC curves graphically represent the possibility of acquiring an accurate prediction of an event against an erroneous predicted reaction with the change in the threshold values. At the same time, the AUC produces numerical indicators for accuracy assessment[7].

Results and Discussion

Multicollinearity analysis: Multicollinearity refers to a strong correlation among the selected independent variables in a modeling. As it can create a problem within a regression model, multicollinearity is a serious issue in statistical analysis[5]. It is said to exist when the values of the TOL and VIF are > 5 to 10 and < 0.1 to 0.2 respectively[14]. The analysis results showed no collinearity among the ten factors and hence, all the parameters are considered eligible for modeling soil erosion susceptibility (Table 2).

Prioritized factors: The normalized weights and CR value were calculated for all erosion conditioning factors (Table 3) based on the relative preference assigned to each element. Subsequently, the ranks and ratings of the parameter's sub-classes were calculated along with their spatial extent (Table 4).

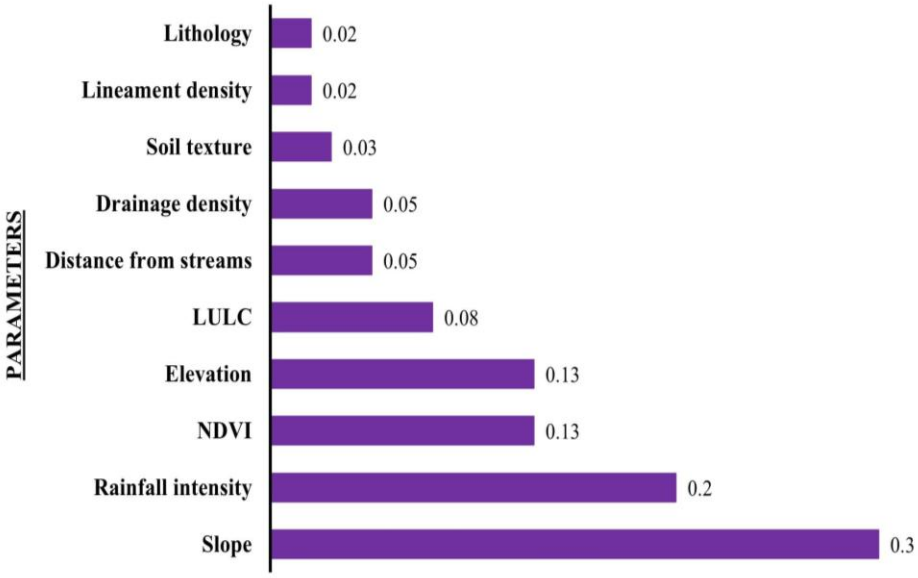

Fig. 5: Normalized weights for erosion conditioning factors.

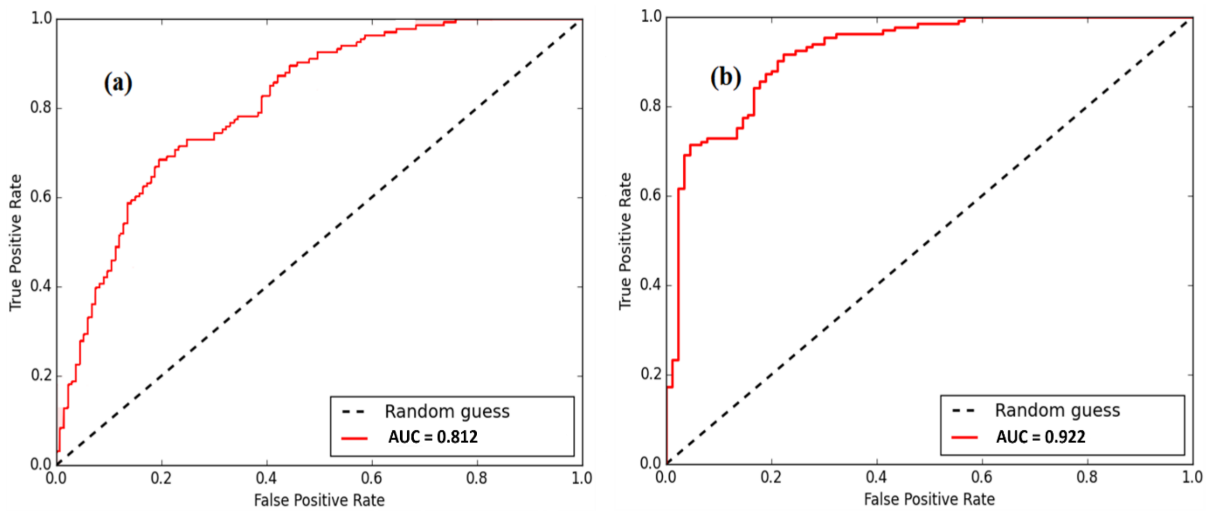

Fig. 6: ROC-AUC for (a) Erosional points and (b) Non-Erosional points.

Table 1
Random Index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty and Vargas[27].

Table 2
Collinearity statistics for erosion susceptibility parameters.

S.N.	Parameters	Collinearity Statistics	
		Tolerance	VIF
1	Elevation	0.37	2.71
2	Lithology	0.56	1.77
3	Soil Texture	0.92	1.09
4	Land use / Land cover	0.91	1.09
5	Distance from streams	0.33	2.99
6	Drainage Density	0.34	2.96
7	Rainfall Intensity	0.36	2.80
8	Slope	0.89	1.12
9	Lineament Density	0.95	1.06
10	Normalized Difference Vegetation Index	0.52	1.93

Table 3
Normalized matrix and CR value.

	SLP	RI	NDVI	ELE	LULC	DFS	DD	ST	LD	LIT	Normalized Weights	CR Value
SLP	0.37	0.52	0.39	0.39	0.29	0.24	0.24	0.21	0.18	0.18	0.30	**0.06**
RI	0.12	0.17	0.29	0.29	0.23	0.20	0.20	0.18	0.16	0.16	0.20	
NDVI	0.09	0.06	0.10	0.10	0.17	0.16	0.16	0.15	0.14	0.14	0.13	
ELE	0.09	0.06	0.10	0.10	0.17	0.16	0.16	0.15	0.14	0.14	0.13	
LULC	0.07	0.04	0.03	0.03	0.06	0.12	0.12	0.12	0.12	0.12	0.08	
DFS	0.06	0.03	0.02	0.02	0.02	0.04	0.04	0.06	0.08	0.08	0.05	
DD	0.06	0.03	0.02	0.02	0.02	0.04	0.04	0.06	0.08	0.08	0.05	
ST	0.05	0.03	0.02	0.02	0.01	0.02	0.02	0.03	0.06	0.06	0.03	
LD	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	
LIT	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

From AHP analysis, slope has the highest normalized weight of 0.30, indicating its dominant influence on erosion susceptibility, followed by rainfall intensity (0.20), NDVI (0.13) and elevation (0.13) while the LULC (0.08), distance from streams (0.05), drainage density (0.05), soil texture (0.03), lineament density (0.02) and lithology (0.02) have shown a decreasing order of relative influence on soil erosion (Fig. 5). Despite the varying weights, the obtained CR value is 0.06 which implies that all selected erosion conditioning factors have produced a consistent result, considering the consistency threshold of ≤ 0.1[28].

Hence, no biased decisions are made in choosing the factors and in the ranks and weights allocation. Therefore, the calculated AHP results are considered as reliable for soil erosion susceptibility modeling in the study area.

Soil Erosion Susceptibility Map: The soil erosion susceptibility map for the Chite watershed was generated by classifying soil erosion susceptibility index (SESI) values into five categories using the natural breaks method: "Very low, Low, Moderate, High and Very high" (Fig. 3k). The high and very high susceptible zones represent the most critical areas of potential soil erosion covering 13.56 km^2 (26.04 %) of the TGA (Table 5). They are mostly restricted to the upper catchment in the northern parts of the watershed and adjacent to the watershed divide that constitutes the eastern and western margins. The higher susceptibility of these areas is mainly attributed to various anthropogenic activities persisting on the relatively fragile landscape.

The moderate susceptibility zone covers approximately 13.25 km^2, constituting 25.40% of the study area (Table 5). This zone also conforms to regions with high human interference and associated environmental modification. However, a decreasing severity of erosion susceptibility can be attributed to the declining influence imposed by various inherent geo-environmental factors.

Moreover, a moderately improved vegetation cover may also be held accountable for minimizing the likelihood of soil erosion occurrences.

The low and very low zones of erosion susceptibility covered an area of about 25.33 km^2, constituting 48.56% of the total geographical area (Table 5). These zones with comparatively lower chances of soil erosion are generally contained within the middle and southern parts of the watershed where human interventions are least significant or even absent in some cases. Hence, the areas exhibit a secure zone where vegetation's protective function is considered the sole factor[11].

Table 4
Parameter's sub-classes (sub-criteria) results.

Parameters	Range	Erosion Level (Ranks)	Area (km^2)	Area (%)	Ratings
Elevation	< 300	Very Low (5)	1.23	2.36	0.044
	300 – 500	Low (4)	10.15	19.46	0.076
	500 – 700	Medium (3)	16.68	31.98	0.144
	700 – 900	High (2)	16.48	31.60	0.268
	> 900	Very High (1)	7.62	14.61	0.468
Slope	< 15°	Very Low (5)	9.77	18.73	0.044
	15° – 25°	Low (4)	17.42	33.40	0.076
	25° – 35°	Medium (3)	17.37	33.30	0.144
	35° – 45°	High (2)	6.65	12.75	0.268
	> 45°	Very High (1)	0.95	1.82	0.468
Rainfall Intensity	< 288	Very Low (5)	4.91	9.41	0.095
	288 – 291	Low (4)	10.64	20.40	0.127
	291 – 293	Medium (3)	12.07	23.14	0.182
	293 – 296	High (2)	14.59	27.97	0.258
	> 296	Very High (1)	9.95	19.08	0.337
Drainage Density	0 - 0.76	Very Low (5)	17.94	34.39	0.055
	0.77 - 2.1	Low (4)	10.05	19.27	0.090
	2.11 - 3.51	Medium (3)	11.12	21.32	0.154
	3.52 - 5.23	High (2)	9.05	17.35	0.265
	5.24 - 9.73	Very High (1)	4.00	7.67	0.435
Distance from Streams	> 400	Very Low (5)	1.31	2.51	0.062
	300 – 400	Low (4)	4.32	8.28	0.099
	200 – 300	Medium (3)	10.67	20.46	0.161
	100 – 200	High (2)	14.52	27.84	0.262
	< 100	Very High (1)	21.34	40.91	0.416
Soil Texture	Loamy Sand (LS)	Very Low (5)	0.77	1.48	0.090
	Coarse sandy Loam (CSL)	Low (4)	8.72	16.72	0.126
	Sandy Loam (SL)	Medium (3)	33.74	64.69	0.180
	Fine Sandy Loam (FSL)	High (2)	7.87	15.09	0.254
	Sandy Clay Loam (SCL)	Very High (1)	1.06	2.03	0.349
Lithology	Sandstone with subordinate siltstone, mudstone, shale (1)	Low (2)	2.95	5.66	0.164
	Grey sandy splintery shale, siltstone and mudstone (2)	High (1)	49.21	94.34	0.252
Lineament Density	> 3.1	Very High (1)	27.22	52.19	0.044
	2.12 - 3.09	High (2)	5.63	10.79	0.076
	1.36 - 2.11	Medium (3)	7.21	13.82	0.144
	0.49 - 1.35	Low (4)	10.32	19.79	0.268
	< 0.48	Very Low (5)	1.78	3.41	0.468
Land use / Land cover	Dense Forest	Very Low (5)	10.10	19.36	0.053
	Open Forest	Low (4)	22.93	43.96	0.089
	Built-Up Land	Medium (3)	5.79	11.10	0.153
	Cropland	High (2)	11.70	22.43	0.262
	Bare Land	Very High (1)	1.64	3.14	0.444
Normalized Difference Vegetation Index	> 0.5	Very Low (5)	6.86	13.15	0.044
	0.4 - 0.5	Low (4)	19.12	36.66	0.076
	0.3 - 0.4	Medium (3)	17.21	32.99	0.144
	0.2 - 0.3	High (2)	6.39	12.25	0.268
	< 0.2	Very High (1)	2.58	4.95	0.468

Table 5
Soil erosion susceptibility zone of Chite Watershed.

Susceptibility Zone	Area	
	(Km^2)	(%)
Very High	4.08	7.83
High	9.50	18.21
Moderate	13.25	25.40
Low	13.67	26.21
Very Low	11.66	22.35
Total:	**52.16**	**100.00**

Model's Validation: In this research, the accuracy of the predicted map was assessed by comparing it with the erosion inventory map, comprising of 133 erosional and 90 non-erosional points.

As illustrated in fig. 6 (a) and (b), the verified model produced an AUC value of 0.812 (81%) for erosional points and 0.922 (92%) for non-erosional points. Accuracy level of 81% and 92% signifies a "Very Good" and "Excellent" modeling results respectively[24]. Hence, an integrated approach combining AHP and GIS techniques manifests a high level of precision for soil erosion susceptibility mapping in the Chite watershed.

Conclusion

The present study revealed the applicability of integrated AHP and GIS techniques for soil erosion susceptibility mapping in the Chite watershed, India. The AHP analysis produces a consistent judgement for parameters selection, weighting and ranking with CR value of 0.06 where slope (30%) and rainfall intensity (20%) are the most influential factors contributing to soil erosion susceptibility in the watershed. Above one-fourth of the study area, covering 26.04% of the watershed, is under critical condition. These relatively higher sensitive regions generally correspond to those areas where anthropogenic activities are prevalent upon the weaker environmental set-up. Furthermore, the presence or absence of vegetation cover has been observed to determine the area's susceptibility to soil erosion.

Model's validation has shown precise occurrences of ground-observed erosion and non-erosion points with accuracy levels of 81% and 92% respectively. Accordingly, the validated result has authenticated the competency of integrated AHP and GIS techniques based on soil erosion susceptibility mapping in the study area. Hence, the present research provides valuable insights into the spatially explicit pattern of soil erosion susceptibility within the Chite watershed which is essential information for researchers, stakeholders and decision-makers in formulating site-specific sustainable land management plans and practical measures for erosion control. This study may also serve as a foundation for addressing the severe challenges of soil erosion elsewhere in the region to ensure environmental and agricultural sustainability.

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