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Soil erosion vulnerability in Umngot watershed using analytical hierarchy process in GIS

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Abstract

In this paper, soil erosion vulnerability mapping of the Umngot watershed has been done using Analytical Hierarchy Process (AHP) in Geographical Information System (GIS). Data used in the analysis includes CARTOSAT-1 DEM with a spatial resolution of 30 meter, LULC derived from LISS-IV satellite imagery of resolution of 5.8 meters, soil map at scale 1:50000. It also used rainfall data acquired in netCDF (network Common Data Form) files with a spatial resolution of 0.25o. The vulnerability mapping based on these tools and techniques clearly brings out the fact that a little over 8% of the watershed is extremely vulnerable to soil erosion while an additional 22% is highly vulnerable. The results have been validated using participatory research approach involving group discussion conducted among the villagers. A soil erosion map was sketched based on their perception that broadly corresponded to the map prepared by using AHP technique.

Keywords: *Umngot, soil erosion, AHP, erosion vulnerability, participatory research approach.*

Introduction

Soil erosion is considered as one among the most critical environmental hazards rendering vast cultivable land into unproductive barren land as well as contributing to its degradation. Majority of the population of the Northeastern region of India is directly or indirectly dependent on agriculture and soil loss is a major challenge for the agricultural community. The region receives heavy rainfall, with climate change, the number of rainy days have decreased whereas the rainfall intensity has increased (Bhagabati, *et al*., 2017). The increase in rainfall intensity have direct impact on increased soil erosion (Brandt, 1990; Das, *et al*. 2022). Assessing soil erosion is imperative for the sustainable development of the region. Assessment of soil erosion involves extensive field measurements and most of the watersheds in North Eastern India lack precise sediment load measurements due to a host of problems.

Meyer and Wischmeir (1969) proposed an erosion modelling approach that considers parameters like soil detachment by rainfall, transport by rainfall, detachment by runoff, transport by runoff as distinct but interconnected phases of soil erosion by water. In this line many models were derived such as Universal Soil Loss Equation (USLE) (Wischmeir and Smith, 1965), Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), Revised Universal Soil

Loss Equation (RUSLE) (Renard, *et al.*, 1997) and Morgan-Morgan-Finney Model (1984). Such empirical and conceptual methods required accurate and detailed spatio-temporal data. These models are based on quantifiable data and are structured around fixed empirical equations with little scope for modification in different spatial context. These models give good results when precise and reliable data are available pertaining to all parameters considered in the respective equations. However, in areas with highly variable condition and scarcity of data such Umngot, the efficacy of these models reduces.

When spatiotemporal data are limited, Analytical Hierarchy Process (AHP), a Multi-Criterial Decision Analysis (MCDA), allows integration of limited quantitative with qualitative criteria through expert judgment and give good results (Saaty, 1977). It is one of the best known and most widely used MCDA techniques, developed by Saaty in 1977 and popularized in 1980s. Soil erosion vulnerability mapping using AHP according to Saaty is a semi–quantitative decision-making value judgement approach that serves the decision maker's objectives to identify the most vulnerable areas. This method allows researchers to use their knowledge and experience to break down a problem into a hierarchy structure and solve it using AHP (Bagwan *et al.*, 2025). This method also makes it possible to normalize the weights of controlling factors. Saaty's method allowed for calculating needed weighting factors using a preference matrix in which all relevant criteria are compared against each other using reproducible preference factors. The researcher has the freedom to choose the best alternatives based on subjective and objective factors in AHP. It includes the creation of a pair-wise comparison matrix for the parameters used, calculation of their relative weights, assessing consistency ratios (CR), generation of soil erosion vulnerability maps, and validating the model (Vijith and Dodge-Wan, 2019). The pair-wise comparison matrix is a tool used to assess a set of decision criteria and rank them in terms of their relative importance (Saaty 1980; Saaty and Vargas 1984). AHP has been extensively used in analysing land degradation vulnerability (Yadav, *et al.*, 2022; Chatterjee, *et al.* 2023), flood hazard risk assessment (Mokhtari, *et al.*, 2023), ground water assessment (Gangadharan *et al.*, 2016) and others.

Assessing soil erosion vulnerability is essential for implementing soil conservation measures on a priority basis. This research aims to find out various soil erosion vulnerability zones in Umngot watershed using AHP on GIS environment. Six parameters affecting soil erosion have been used to construct vulnerability zones and results are verified by using participatory research approach for more effective implementation and sustainability. The parameters selected in this study are grounded on the established soil erosion models.

Materials and methodology

Study area

Umngot watershed (Fig. 1) is located in Cherrapunjee, Meghalaya, India. It has an undulating topography consisting of steep slopes and rocky terrain. The soil thickness is less and vegetation cover is very poor (Starkel & Singh, 2004; Upadhaya *et al.* 2014). Soil erosion in this area has the potential to severely hit agrarian population due to prevailing thin layer of soil.

The basin lies between 25° 33' 24" N to 25° 11' 24" N latitude and 91° 50' 21" E to 92° 8' 60" E longitude. The river Umngot which originates from the southern slope of Khasi hills is one of the major watersheds of Meghalaya and elevation changes are common

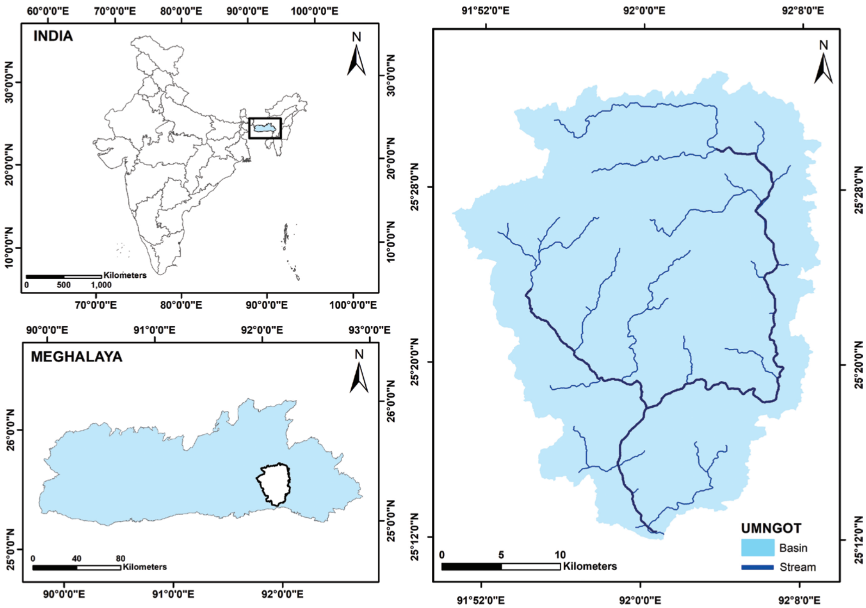

Fig. 1: Location of Umngot river basin

throughout the region. It has an average altitude of 1140 m above the mean sea level. The total area of the basin is 829.4534 km^2. The mean annual precipitation during 2012 to 2022 is 3047.03 mm in the upstream and 2261.74 mm in the downstream areas, with an average of 2654.39 mm for the watershed. The soil types are varied; including the most common sandy clay loam soil occupying 58.54% of the total area followed by clay soil covering 21.9%, clay loam soil covering 11.89% and loamy skeletal soil accounting for 7.65% of the area under the watershed (Fig. 2e).

Data

The six geo-environmental parameters used in deriving the soil erosion vulnerability map of are derived from the four basic spatial data base. The first important data used in this paper is the Digital Elevation Model (DEM) derived from the CARTOSAT -1 with a spatial resolution of 30 meters (Fig. 2a) and LISS-IV satellite images, with three spectral bands in a resolution of 5.8m and swath of 23 km from https://bhunidhi.nrsc.gov.in. The soil map of the study area is sourced at the Northeastern spatial data repository form https://nesdr.gov.in. This map was prepared at 1: 50,000 scale based on the published reports and maps of National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) in 1: 125,000 scale and verified by collecting soil sample by Northeast Space Application Centre (NESAC). The gridded average annual rainfall data in 0.25-degree resolution is collected from https://www.imdpune.gov.in. The Normalized Difference Vegetation Index (NDVI) map is generated in Google Earth Engine platform using Landsat 8 data for the year 2022.

Analytical hierarchy approach (AHP)

The AHP is used for soil erosion vulnerability mapping as it is one of the most efficient methods for integrating the parameters considered in the conventional models, without using rigid empirical equations. This approach gives more flexibility in integrating influencing parameters and provide ample

Table 1: Scale for pair-wise comparison

Scale of importance	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
Intermediate (2, 4, 6, 8)	Intermediate values between adjacent scale values
Reciprocals (1\2, 1\3, 1\4, 1\5, 1\6, 1\7, 1\8, 1\9)	Values for inverse comparison

scope to include qualitative input such as expert judgement- the intellectual assessment of the relative influence of one parameter over others grounded in existing realities. The reliability of this judgment is checked by using consistency ratio. In this paper, six parameters- LULC, NDVI, R factor, K factor, slope, and drainage density- are selected to estimate soil erosion vulnerability. The hierarchical structure of the criteria is based on the relative importance of the parameter in the estimation of soil erosion vulnerability. A paired comparison matrix with all six parameters against other in terms of their relative importance is constructed using the Saaty's scale and presented in table 1.

Relative importance is assigned to the parameters based on expert judgement in terms of their relative influence on soil erosion. Based on this a 6 X 6 pairwise comparison matrix is created; the entries in the row represent its relative importance of the factor given in column. Normalization of the matrix is done by dividing the entry in each cell with the respective column total. The normalized principal eigen vectors for each of the parameter are derived by calculating the average of each entry in the rows in the normalized matrix. These values also represent the weights to be assigned to the parameters. The acceptance of the assigned weightage depends on the value of consistency ratio, CR. If the CR value exceeds 0.1, the judgment is considered inconsistent and unreliable.

Consistency ratio (CR)

The consistency of the weights assigned to all six parameters are tested using consistency ratio (CR), calculated using Saaty's formula (1977). An acceptable CR value is less than or equal to 0.1. It is calculated by the following formula:

Consistency ratio, $CR = (\frac{CI}{RI})$

Here, CI = Consistency Index

RI = Random Consistency Index value given by Saaty in 1980 (given in Table 1).

The formula to calculate the Consistency Index (CI) is:

$CI = (\lambda max - n) / (n - 1)$

Here, n = Size of the comparison matrix and λmax refers to average eigen value of the matrix derived by multiplying the normalised principle eigen vectors with the paired comparison matrix and subsequent division of the row total for each entry with the normalised principle eigen vectors.

The soil erosion vulnerability is determined by conducting weighted overlay analysis of all six parameters, here the respective weightage of each parameter is derived from AHP. The raster data are fixed

Table 2: Random consistency index (RI) values (Saaty, 1980)

Matrix Size (n)	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

at a consistent spatial resolution of 30 x 30 meters for each of the six parameters. This uniform cell size was chosen to ensure both consistency and accuracy in the analysis.

The soil erosion vulnerability model can be represented as the summation of the product of all six parameters with their respective weightage assigned by AHP:

$$V = \sum_{i=1}^{6} Pi \times Wi$$

Here, P is the parameter and W is their assigned weightage

The validation of the results derived from AHP was done with the help of PRA. The approach ensures greater reliability and contextual relevance of the soil erosion vulnerability pattern as it incorporates and integrates local knowledge and community perception, grounded in long term interaction of people with the land.

As a part of PRA exercise, group discussion sessions were conducted with the villagers form the study area. This discussion facilitated exchange of individual observation and experiences related to soil erosion. During the sessions, the participants were asked to identify and mark areas that they perceived as severely affected by soil erosion. Based on the community input, a sketch map was prepared highlighting the severely soil erosion affected areas of the basin.

Analysis and discussion

Deriving the parameters for AHP

The LULC map of the study area is prepared by supervised classification of the LISS-IV satellite imagery for the month of November 2022, using random forest algorithm in GIS platform (Fig. 2d). It is found that the most extensive land cover in the watershed is forests- both dense and open- making up approximately 52.25% of the total area. The second most common category is scrubland, encompassing roughly 20.73% of the area followed by cropland covering 15.49% area. The built-up areas are limited to 3.30% and water bodies cover only 1.95% area. Remaining areas are covered with barren land.

The NDVI map (Fig. 2i) is created in Google Earth engine platform using the average annual values of Landsat 8 Collection 2 Level 2 Surface Reflectance (SR) data for the year 2022. The formula used in creating NDVI is NDVI = (NIR - R) / (NIR + R) where, NIR = Near-Infrared and R= Red.

NDVI values range from -1 to +1, indicating the health and density of vegetation cover. In this study, the NDVI values ranged between -0.09 and 0.5 classified into five classes such as very low, low, moderate, high and very high NDVI values. Higher values of NDVI corresponds to high vegetation areas with lower vulnerability to soil erosion and lower values of NDVI correspond to low or no vegetation with higher vulnerability to soil erosion.

R-Factor represents the erosive force of rainfall. It combines total energy and intensity of storms to detach and transport soil particles. It quantifies the ability of rain to cause erosion. R Factor is calculated by multiplying the kinetic energy of rainfall by maximum rainfall intensity during a period of 30 minutes. However, this method can only be applied in areas equipped with autographic recorders which are absent in the watershed under investigation. In order to overcome this problem, an alternative

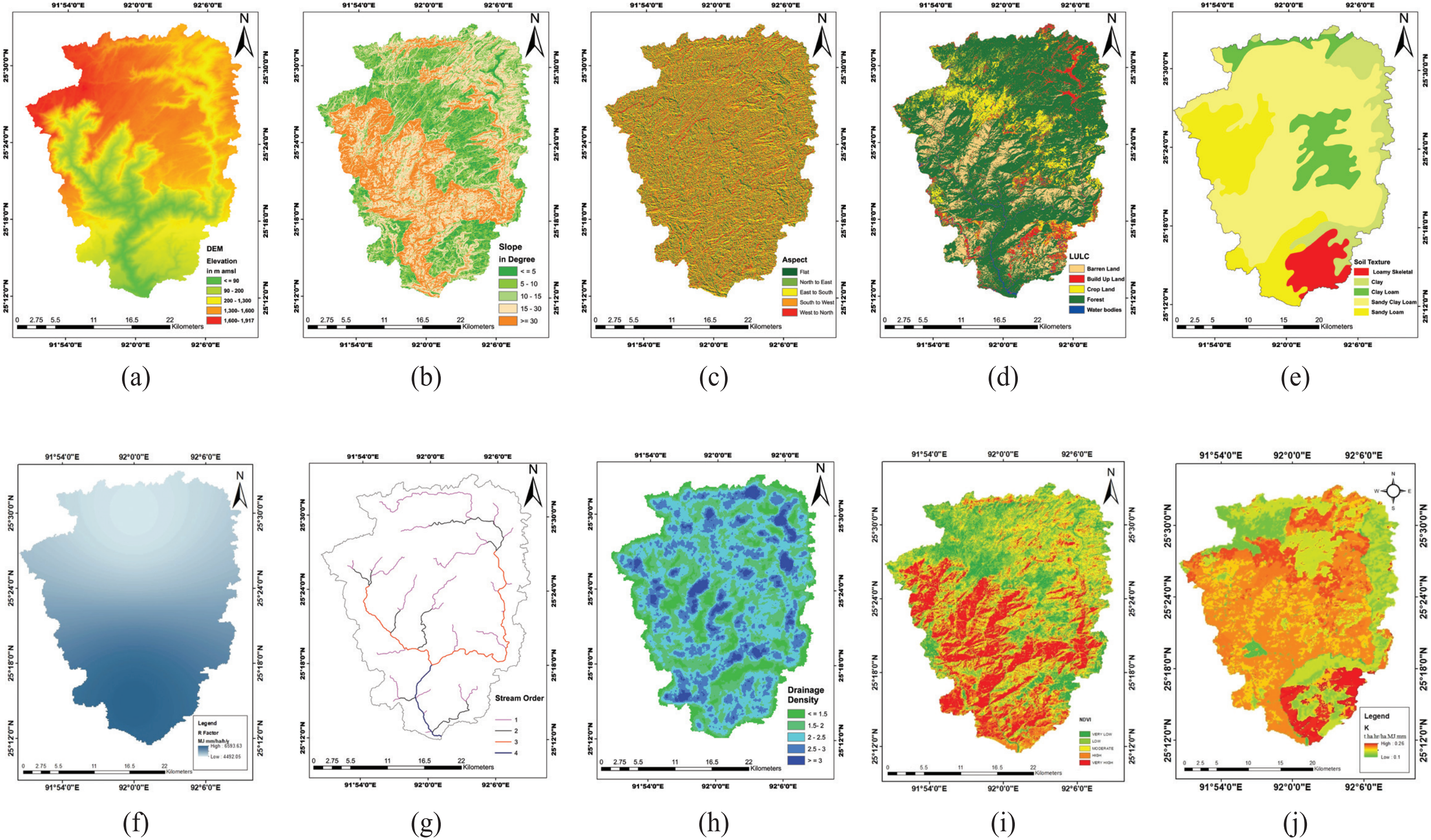

Fig. 2: (a) DEM, (b) Slope (c) Aspect (d) Land Use Land Cover (e) Soil (f) Rainfall Erosivity (g) Stream Order (h) Drainage Density (i) Normalized Differential Vegetation Index Map (j) Soil Erodibility.

formula was developed by Wischmeier and Smith (1978) and modified by Arnoldus (1980) that involves only annual and monthly rainfall which has been used in this paper to determine the R factor calculated by the following formula:

$$R = \sum_{1}^{12} 1.735 \text{ X } 10^{1.5 \log_{10}(P/Pi) - 0.818}$$

where,

R = rainfall erosivity factor in Mega Joules × millimeters per hectare per hour per year

P_i = monthly rainfall in millimeters

P = annual rainfall in millimeters.

The interpolation technique (IDW) is used in GIS platform to show the spatial variation of the R factors in the study area (Fig. 2f).

The soil erodibility factor (K-Factor) is influenced by soil and geological characteristics of the area. K-factor represents the intrinsic susceptibility of soil particles to get detached and transported by rainfall and runoff. It includes factors like parent material, texture, structure, organic matter content, and porosity. It is measured in tonnes of soil loss per hectare per hour per mega joule of energy per millimeter of rainfall. In this paper, the K factor values are assigned to the soil types as per the NBSS&LUP, ICAR, as given in table 3. Spatial distribution of K factor of Umngot basin is shown in Fig. 2(j), generated in GIS environment from the soil data collected from NESDR, NESAC.

The slope map of Umngot watershed is derived from CARTOSAT DEM, with a spatial resolution of 30 meters (Fig. 2b). Five slope classes are classified such as gently sloping with a slope ranging from 0 to 5%, moderately sloping with 5 to 10% slope, strongly sloping with 10-15% slope, steeply sloping with slopes between 15-30% and very steep sloping with slopes greater than 30% (Fig. 2c). Similarly, the stream order map of Umngot basin (Fig. 2g) and drainage density map (Fig. 2h) are derived from the same DEM using the spatial analyst hydrologic toolset in GIS software. According to Leopold *et al.* (1964), the drainage density value above the critical value of 0.90 km/km^2 has a higher vulnerability to soil erosion.

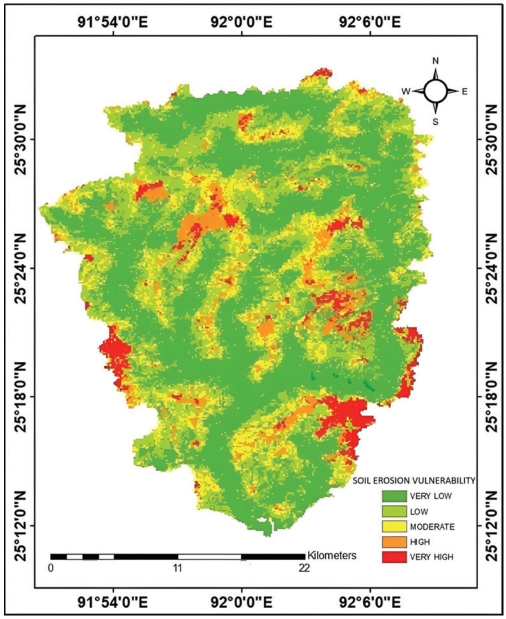

Fig. 3: Soil erosion vulnerability mapping of Umngot watershed using AHP

Table 3: K-Factor as per the soil type with its susceptibility to soil erosion

Soil Type	K- Factor	Erodability
Clay	0.05	Low
Clay Loam	0.10	Medium
Loamy Skeletal	0.28	More
Sandy Clay Loam	0.15	Medium

Source: Das et al., 2022; Ghosh & Guchhait, 2012

Analytical hierarchy process (AHP)

AHP is a structured decision-making method used to prioritize and select the best option when we have multiple, often conflicting, criteria. The raster layer of all six parameters is configured with a consistent spatial resolution of 30x30 meters in GIS, this uniform cell size is chosen to ensure both consistency and accuracy in the analysis.

The relative importance of the six parameters used here are established using pair wise comparison matrix, derived by intellectually assessing the relative influence of one parameter upon others, on occurrence of soil erosion in the study area. Repeated trial and error method has been used to assign the final relative importance in order to get consistency ratio less than 0.1. In this paper, a total of 4 sets of importance were assigned to the six parameters. The first three trials result into consistency ratio value more than 0.1 and are rejected, however, the fourth set gave consistency ratio of 0.019, so, acceptable.

The fourth pair-wise comparison matrix is shown in this paper (Table 4). Here, λmax equals to 6.123 (Table 6) and n is 6.

The Consistency Index (CI) for the matrix is given by:

$$CI = (\lambda max - n) / (n - 1)$$
$$= (6.123-6) / 5$$
$$= 0.0246$$

The Random Consistency Index, RI = 1.24 (see Table 2, for n=6)

Thus, the Consistency ratio, $CR = (\frac{CI}{RI})$

$$= 0.0246/1.24$$
$$= 0.019$$

CR value of 0.019 is within acceptable value i.e. < 0.1, so, the pair-wise comparison is acceptable and the weightage thus derived from AHP are also acceptable. The weightage of each parameter is given by the corresponding normalized Eigen vectors calculated in the table 5.

Soil erosion vulnerability mapping using AHP

The obtained weights for the six geo-environmental parameters were employed in the computation of the soil erosion vulnerability model. This was accomplished using a straightforward method known as the weighted linear sum approach, as demonstrated below:

V=LULC (37%)+RF (6%)+KF (16%)+DD (24%)+NDVI (10%)+Slope (4%)

All six geo-environmental parameters are resampled to a pixel size of 30 x 30 m and weightage are given based on their influence on occurrence of soil erosion. These are subsequently reclassified into five classes using the natural break method, and ranks are assigned as per their direct (positive) of indirect (negative) influence on soil erosion. High ranks are given to classes that have higher influence and lower ranks are given to those which do not have any influence in soil erosion. The soil erosion vulnerability map of Umngot basin is prepared using GIS software and weightage derived from AHP method and is presented in fig. 3.

The figure shows that the moderate to very high soil vulnerability zone lies in the dissected patches in the higher elevated areas of the basin. Two distinct patches of very high soil erosion vulnerability are located along the south east and south west part of the basin. In the study area, 8.08% of the watershed is subject to very high vulnerability of soil erosion, 21.98% has high soil erosion vulnerability and 31.57% has moderate soil erosion vulnerability. About 38.37% of the total area is under low to very low soil erosion vulnerability (Table 7).

Table 4: The pair-wise comparison matrix for soil erosion vulnerability in AHP

Criteria	LULC	DD	K factor	NDVI	R factor	Slope
LULC	1	2	3	4	5	6
DD	0.50	1	2	3	4	5
K factor	0.33	0.50	1	2	3	4
NDVI	0.25	0.33	0.50	1	2	3
R factor	0.20	0.25	0.33	0.50	1	2
Slope	0.17	0.20	0.25	0.33	0.50	1.0
Total	2.45	4.28	7.08	10.83	15.50	21.00

Table 5: Normalized pair-wise comparison matrix and weights of the geo-environmental parameters

Criteria	LULC	DD	K Factor	NDVI	R Factor	SLOPE	Total weight, T	Normalized eigenvector, E=(T/n)x 100
LULC	0.40816	0.46692	0.42352	0.36923	0.32258	0.28571	2.27614	37.93574
DD	0.20408	0.23346	0.28235	0.27692	0.25806	0.23809	1.49298	24.88301
K factor	0.13605	0.11673	0.14117	0.18461	0.19354	0.19047	0.96260	16.04337
NDVI	0.10204	0.07782	0.07058	0.09230	0.12903	0.14285	0.61464	10.24412
R factor	0.08163	0.05836	0.04705	0.04615	0.06451	0.09523	0.39296	6.549422
Slope	0.06802	0.04669	0.03529	0.03076	0.03225	0.04761	0.26066	4.344338

Table 6: Matrix multiplication of pair-wise comparison matrix with the normalized eigenvector calculated in Table 5 parameters

Criteria	LULC	DD	K Factor	NDVI	R Factor	SLOPE	SUM	SUM / E
LULC	37.94	49.77	48.13	40.98	32.75	26.07	235.62	6.21
DD	18.97	24.88	32.09	30.73	26.20	21.72	154.59	6.21
K Factor	12.65	12.44	16.04	20.49	19.65	17.38	98.64	6.15
NDVI	9.48	8.29	8.02	10.24	13.10	13.03	62.18	6.07
R Factor	7.59	6.22	5.35	5.12	6.55	8.69	39.52	6.03
SLOPE	6.32	4.98	4.01	3.41	3.27	4.34	26.34	6.06
				λ max is the average value of the last column				6.123

Table 7: Soil erosion vulnerability zones in Umngot Basin

Zones	**Area (km2)**	**% of to tal area**
Very low	183.511505	22.12439
Low	134.766188	16.24759
Moderate	261.845084	31.56839
High	182.302328	21.97861
Very high	67.0282869	8.081019

Validation by PRA

The results of the AHP generated soil erosion vulnerability zones is validated using a PRA integrating the local knowledge with the scientific analysis. It involves structured group discussion with local villagers around Dawki Kali Mandir area and local market areas along the NH 209 in the Umngot river basin. As part of the PRA exercise, community members collaboratively sketched a soil erosion affected areas on the Umngot basin base map provided to them, based on their perception, observation, traditional knowledge and lived experience on soil erosion over time. Local people were able to identify four erosion prone areas in the provided base map (Fig. 4). The PRA exercise reveals that the areas identified by the villagers are actually the area delineated as high to very high soil erosion vulnerable areas derived from AHP. This alignment between local knowledge base and the scientific analysis strengthens the credibility of the results and confirms the practical relevance of the AHP method in mapping soil erosion vulnerability in Umngot basin.

Conclusion

Umngot watershed receiving heavy rainfall throughout the year is prone to soil erosion. The analysis of soil erosion vulnerability in the Umngot watershed using AHP in GIS revealed that over 61% of the watershed is vulnerable to moderate to very high soil erosion. Only the valley areas have low to very low soil erosion vulnerability. The PRA confirms the finding of the AHP method in terms of locating the erosion affected areas. However, it does not empirically confirm the accuracy of the AHP generated vulnerability map. PRA being a valuable tool for effectively integrating complex hydro-physical analysis with the simple community perception on the problem and subsequently problem solving, has made the analysis more acceptable to the community. This is expected to help the local community in the long run to target

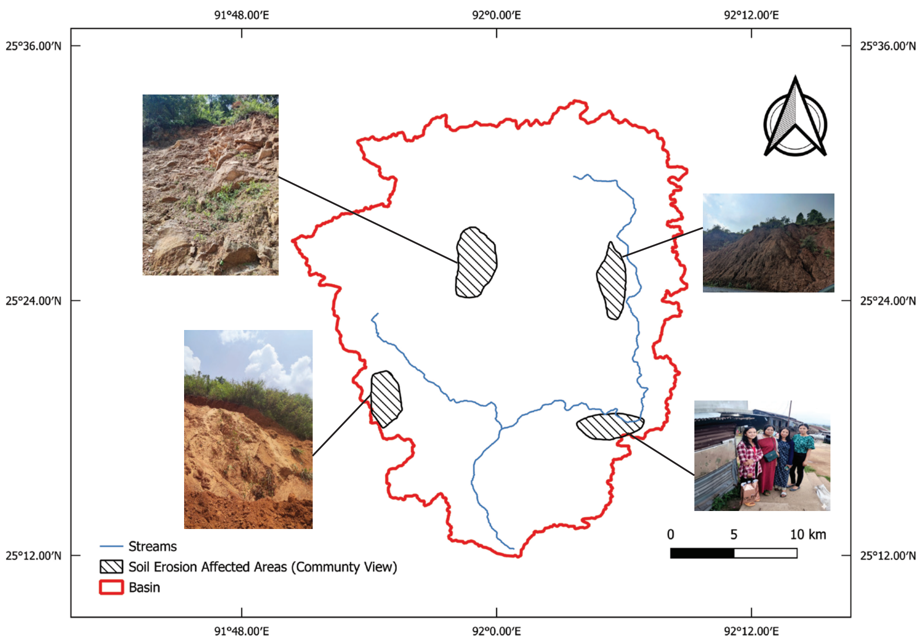

Fig. 4: Soil erosion affected area identified by villagers

soil conservation measures in the high soil erosion vulnerable areas of the basin.

One of the limitations of the study is the use of the modified Arnoldus (1980) formula for estimation of erosivity, as according to some literatures this method is not suitable in high-intensity rainfall areas, as it may underestimate actual soil loss due to the omission of rainfall intensity (Dabral *et al*., 2008). However, this method has been used in this research due to lack of relevant data. Another limitation pertains to considering soil erodability as directly related to the soil type without taking any other underlying factors. It would have been better if the actual spatial variation of soil erodability in Umngot basin has been derived from the field and used here. The use of PRA for validation is also questionable for some as even though the areas sketched by the local villagers qualitatively align with the generated map, it cannot be statistically correlated or validated with the AHP generated soil erosion vulnerability map.

Competing interest

The corresponding author declares that they have no conflict of interest.

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