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Research Article
GIS-Based MCDA Model to Assess Erosion Sensitivity in Gumara watershed, Blue Nile, Basin Ethiopia

Afera Halefom, Asirat Teshome and Ermias Sisay

Department of Hydraulic and Water Resourcing Engineering, Debre Tabor University, Debre Tabor, Ethiopia

Abstract
Background and Objectives: Soil erosion has become one of the main environmental problems in internationally, particularly in Ethiopia, where the topography is undulating and population pressure is high, steeplands are cultivated which is accelerating erosive in the study area. Soil and water conservation is critically required in these areas. The main objective of this study was to identify the most vulnerable areas to soil erosion in Gumara watershed, Blue Nile basin, Ethiopia by using the geographic information system based decision support system use that of multi-criteria evaluation (MCE). **Materials and Methods:** weighted overlay was used to combine a set of factors (land use, soil, slope, altitude and TWI) to make a decision according to the stated objective. Raster based pairwise comparison method considering five soil erosion-driving parameters have been done in Arc GIS and ERDAS 2014 environments. The MCE is used to quantify the raster based qualitative spatial erosion vulnerable model produced through pairwise comparison. **Results:** Raster based spatial model reveals that out of total watershed area, 6.45 km^2 (0.53%), 119.5 km^2 (9.73%), 1024.45 km^2 (83.45%), 75.3 km^2 (6.14%) and 1.92 km^2 (0.16%) areas are very high, high, medium, low and very low prone to soil erosion, respectively. **Conclusion:** It would be conclude that this research could help decision-makers and policy-makers to apply soil and water conservation techniques to minimize soil erosion in the study areas.

Key words: Ethiopia, gumara watershed, MCE, GIS, TWI, pairwise comparison

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Corresponding Author: Afera Halefom, Department of Hydraulic and Water Resourcing Engineering, Debre Tabor University, Debre Tabor, Ethiopia

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In the Ethiopian highlands, reduce the productivity of agricultural land through soil erosion. This problem occurs through both anthropogenic and natural activities, such as poor land-use practices, storm storms, particularly inadequate management systems, soil protection measures and steep slopes. As a result, the phenomenon causes land degradation problems in the highlands of Ethiopia[1]. About 1.3 billion t of fertile soil are lost each year and soil erosion and land degradation increase significantly due to the undulate and irregular topography of the area[2]. According to various specialists in the Ethiopian highlands, much of the lost land and heavily eroded land will make it economically inefficient in the near future[3,4]. As a result, it would cost $ 1.9 billion in land erosion between[5] 1985 and 2010. This requires immediate action to protect the country's water resources and physical quality. Spatial information exploration is a new approach that can identify, analyse and manage complex watersheds and catchment areas. Today, GIS is a good alternative tool for better decision support in the implementation, planning and management of land and water resources. The GIS is important for viewing, processing, manipulating and storing geodatabases. The Multi-Criteria Assessment (MCE) an instrument for improving GIS could help users to improve their decision-making processes. To explore a range of alternatives in terms of goal conflicts and multiple criteria, the MCE technique is used[6].

In order to achieve this, a ranking of alternatives and compromise alternatives according to their attractiveness must be produced[7]. In the last decade, MCE has received renewed attention in the context of a GIS-based decision making[8-10]. Numerous researchers have been study using MCE techniques in particular areas to conserve natural resources management[11-19]. In this outcome, MCE seems to be applicable to GIS-based spatial delineation of erosion exposure areas, which helps to carry out the delineation of the most erosion prone area in study watershed.

In general, this discovery explains the decision support system with STMs in the categorization of areas at risk of erosion in the Gumara watershed. The GIS combines land cover, TWI, slope, elevation and soil as impacts that contribute to the development of soil erosion. The main objective of this result was the delineation of vulnerable erosion areas by MCE in a Gumara GIS extension tool.

Multi-criteria assessment (MCE) often compares different alternatives based on specific criteria to identify sensitive areas of erosion. Various criteria were used to help identify the MCE hotspot area in the Gumara watershed. These are land use, TWI, slope, altitude and soil. The geographic information system (GIS) uses a specific map for each criterion. An effluent rate depends on topography and slope, which is one of the criteria for calculating the erosive potential. Satellite images were used for GIS land use classification to classify areas with good and low area coverage. Soil erodibility is also a factor in MCE, which influences soil erosion. Maps of land use, soil, soil, altitude and slope were ranked with different researchers. For each evaluation criteria, weight is assigned which indicates importance relative to the other criteria that were under consideration[20-22]. The main objectives of this paper was identifying of erosion hotspot area in the Gumara watershed to give priorities in ordered to apply biological and physical measurement of soil and water conservation techniques to reduce erosion hazards.

MATERIALS AND METHODS

Location of study area: The study area Gumera catchment area is located in the eastern part of Lake Tana, the altitude varies between 1796 and 3681 m above sea level. It is located in the northwestern highlands of the country. Coordinate location of the study area is 355745.7-411111 m length and 1279842.6-1316007 m width (Fig. 1). The main river Gumara drained the upper parts of the watershed to Tana Lake. The total area of the watershed is approximately 1227.7 km^2. The topography of the watershed can be divided into two main parts, the upper part of the watershed is mountainous and the lower part is relatively simple and gentle.

Description of MCDA model: The GIS approach with the integration of MCE techniques used to identified erosion hotspot areas to advance decision-making in operation and planning of water and soil conservation measures. The technique is able to analyse complex problems in the allocation and assessment of natural resources in ordered to address erosion hotspot areas. Consequently, the model is a decision support method that combines a number of different criteria to complete one or more goals[6]. Therefore, an objective is standpoint that serves to guide the structuring of decision rules, which is the procedure whereby criteria are combined and selected to arrive at a particular evaluation and evaluations are compared and acted upon. Many GIS software systems deliver the basic tools for estimating such a model. For this study, the GIS software MCE with IDRISI module was used. The major factors selected for this study based on its contribution for soil erosion were land use, soil, TWI altitude, and slope. The model includes a set of evaluation criteria and a set of geographically defined alternatives represented as

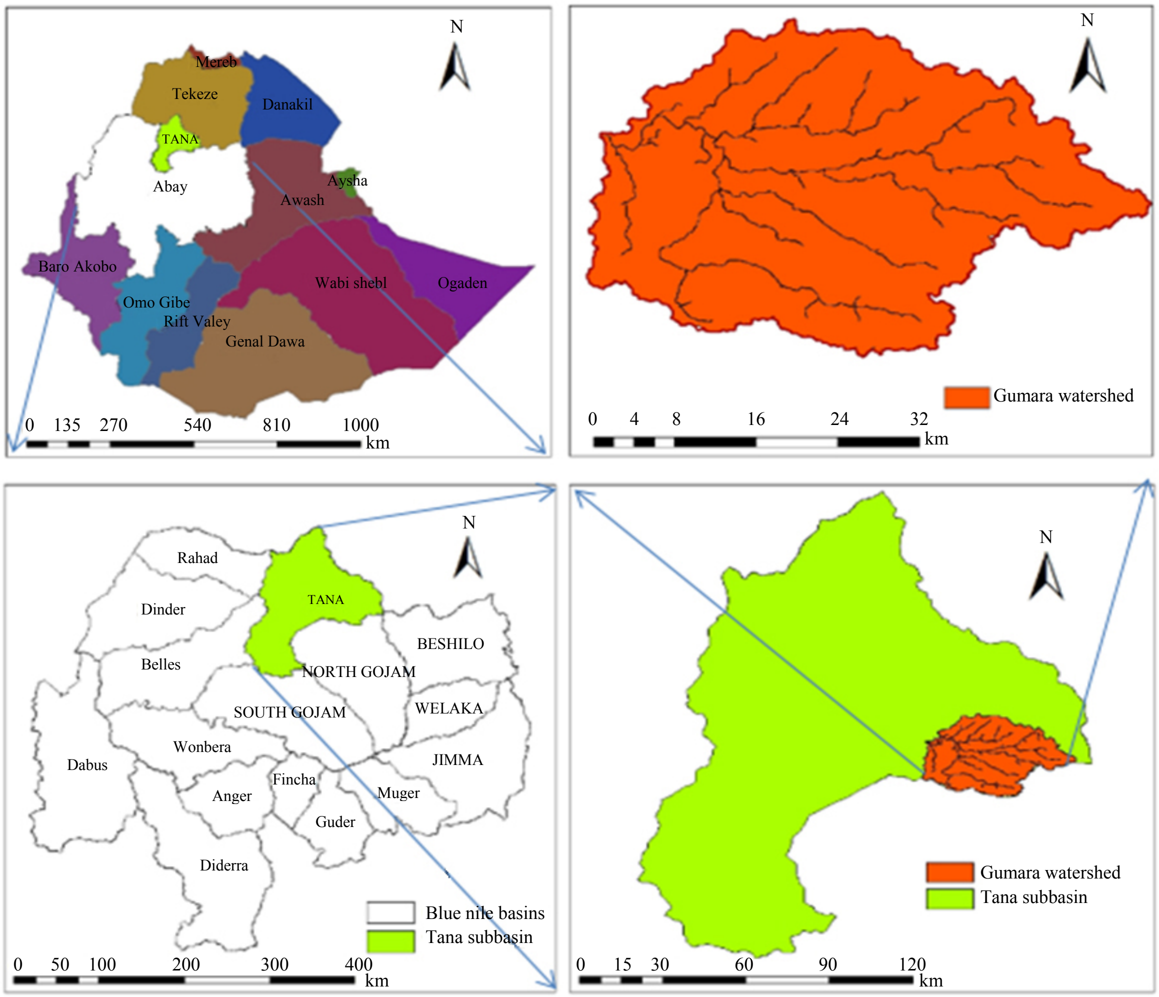

Fig. 1: Location of study area

map layers. The problem, which is to combine the criteria maps according to the preferences of the decision maker using a decision rule (combination rule) and the criteria values (attribute values). The main problem in MCE technique is the question of how to combine information from multiple criteria into a single rating index. As shown in (Fig. 2), the procedure for creating the final erosion hotspot map for the study area was presented.

Input for the model: To carry out this study a 30 m by 30 m resolution Digital Elevation Model (DEM) for Gumara watershed (Fig. 3) was downloaded from Shuttle Radar Topography Mission http://earthexplorer.usgs.gov website for creating aspect, Slope, Area description and altitude map analysis using Arc GIS 10.3 version.

Multi criteria decision analysis evaluation: Assigning weight to each selected parameter involves a multi-criteria function. To assign a weight to the parameters, the logical and well-structured decision processes were followed to ignore the possible confusion. There are many MCDA methodologies available to solve complex decision problem with multiple criteria[23-25]. This study used the Analytical Hierarchy Process (AHP) according to Chankong and Haims[25]. This process uses simple and straight forward postulates in analysing multi criteria decision problems. However, the AHP always allows for some level of variations which should not exceed a certain threshold[25]. The weights of each parameter were determined using the pairwise analysis of the parameter, based on the scale of relative importance[25]. The scale of 1 signifying equal value to 9 signifying extreme different was allocated to the pairwise parameter (Table 1). The pairwise matrix was then normalized and the eigenvalues of the normalized matrix representing the parameter weights were calculated. The consistency of the assessment for this study was evaluated and confirmed using the Consistency Ratio (CR)

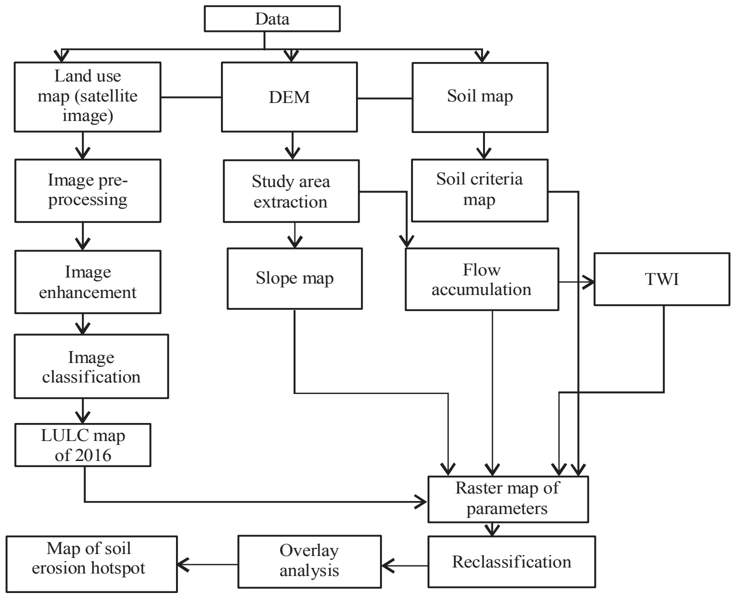

Fig. 2: Workflow of the analysis method

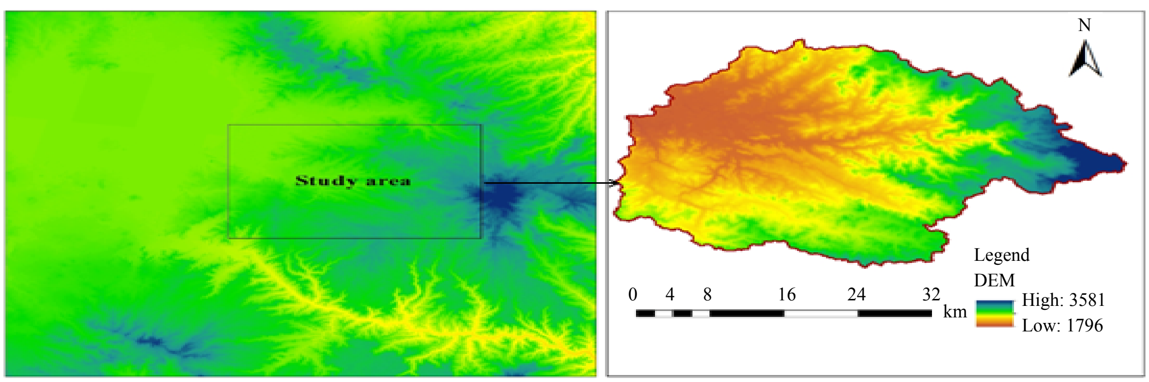

Fig. 3: Digital elevation model (DEM) of Gumara (from http://earthexplorer.usgs.gov)

Table 1: Continuous rating scale

Rating scale								
1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely Less important	Very strongly	Strongly	Moderately	Equally	Moderately More important	Strongly	Very strongly	Extremely

Source: Chankong and Haims[25]

and Consistency Index (CI) (Eq. 1 and 2)[25]. This measure examines the extent to which the submitted finding is consistent. The CI is zero if all the judgments are completely consistent:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

$$CR\ (\%) = \frac{CI}{RI} \times 100 \quad (2)$$

$$\lambda_{max} = \sum_{i=1}^{n} X_{i,j} * W_{i,j} \quad (3)$$

Where:
CI = Consistency index
n = Number of parameters
RI = Random index using the Chankong and Haims[25] scale (Table 2)
λ_{max} = Average of the eigenvalues of the normalized comparison matrix computed using Eq. 3

Table 2: Value of RI for the corresponding number of criteria/alternatives

Size	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

Table 3: Weights of paired factors concerning hotspot area

Criteria	LCT	Altitude	Soil	Slope	TWI	Row total
LCT	1.00	8.00	5.00	3.00	4.00	21.00
Altitude	0.13	1.00	0.125	0.25	0.33	1.83
Soil	0.20	8.00	1.00	7.00	1.00	17.20
Slope	0.33	4.00	0.14	1.00	0.50	5.98
TWI	0.25	3.03	1.00	2.00	1.00	7.28
Column total	1.91	24.03	7.27	13.25	6.83	53.29

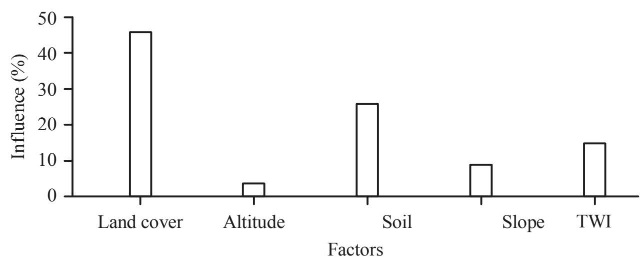

Fig. 4: Overall contribution of parameters for soil erosion

Pairwise analysis of the parameters: The hierarchy in Table 3 shows the relative impact of each factor to soil erosion. In allocating soil erosion hotspot areas, land use was considered as the most influential factor and it come on top of the hierarchy while altitude was considered to have the least influential factor. The values in each cell represent the scale of relative importance for the given paired factors. The diagonal has the value of 1 throughout because the diagonal represent factors being compared to itself and the scale equal importance "1" is assigned. In the lower diagonal the values of the scale are in fractions because the factors are being paired in the reverse order and the scale of relative importance is given as the reciprocal of the upper diagonal pairwise comparisons. From Fig. 4 land use was ranked the 1st, soil is ranked the 2nd, TWI the 3rd, slope the 4th and altitude the 5th most important parameters in identifying erosion hotspot area in Gumara watershed.

Description of input parameters

Land cover factor map: Based on the landsat image downloaded from http://earthexplorer.usgs.gov by analyzing in ERDAS 2014 then export to GIS environment, the land cover map was created in raster format. Depending on the specific cover type, the most important land cover types were classified into 5 land cover types as Urban, Plantation, Water body, Agricultural land and Pasture land. The five classes of cover types were reclassified according to their susceptibility to erosion (Fig. 5, 6). Based on the knowledge of researchers and experts the priority prone to soil erosion has given to urban areas then agricultural land, pasture land, plantation and water body.

Soil factor map: The soil types in the study area also considered as a major factors contributing for soil erosion. There were six major soil types incorporated in the study area. These important soil types were reclassified depending on their sensitivity to soil erosion (Fig. 7).

Slope factor map: The slope is one of the most significant topographical features that impact degradation and production. Each slope category was given an index for their prone to erosion (Fig. 8, 9).

Topographic wetness index (TWI) factor: Another important element considered for identification of erosion hotspot area was TWI and also called Compound Topographic Index (CTI). In addition, it is important for soil/land evaluation for sustainable use[26], watershed management and hydrologic modelling, land use planning and management[27]. In this study the TWI was extracted from Digital Elevation Model (DEM) and it was calculated[28] using the Eq.:

$$\text{TWI} = \ln \frac{\alpha}{\tan \beta}$$

where, α is the contributing area in m^2 and β is the slope in degree calculated from the DEM. The TWI was calculated using raster calculator from Arc GIS 10.3 version.

All criteria layers were obtained from MCE factor generation and reclassification and multiplied by applicable weight derived from pairwise comparison of criteria. In pairwise comparison technique, each factor was in line head-to-head (one-to-one) with each other and a comparison matrix was arranged to express the relative importance[29]. A scale of significance was broken down from a value of 1-9. The highest value 9 links to absolute importance and reciprocal of all scaled ratios are entered in the transpose position[30] (1/9 shows an absolute triviality) (Table 1).

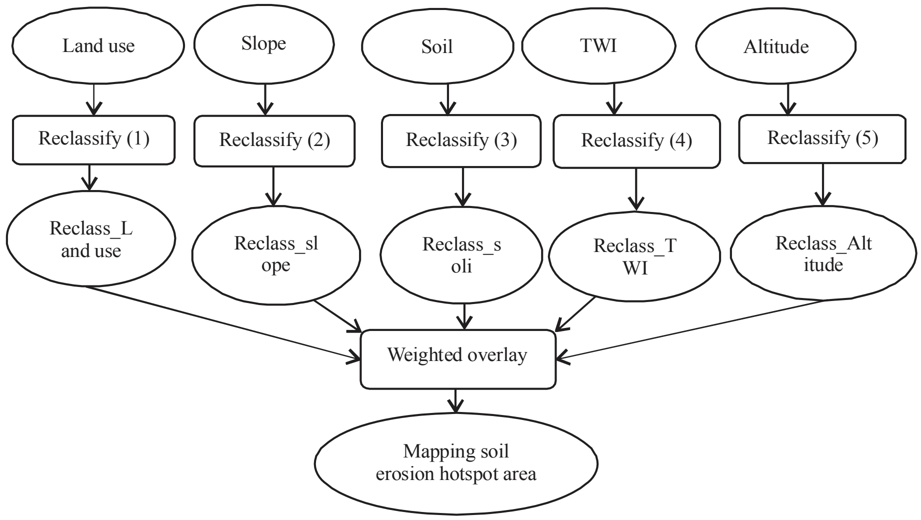

Fig. 5: Workflow of the criteria weighting using MCE in Arc GIS 10.3

Table 4: FAO slope categories and related susceptibility to soil erosion

New class	Slope category	Characteristics	Area (km^2)	Area (%)	Susceptibility
1	0-5	Flat to gently undulating	401.07	32.67	Very low
2	5-10	Undulating	401.58	32.71	Low
3	10-15	Rolling	264.48	21.54	Medium
4	15-30	Moderately steep	128.54	10.47	High
5	>30	Steep	32.06	2.61	Very high

Table 5: Land cover type in the gumara catchment area

Land use	Area (km^2)	Area (%)	Susceptibility
Urban	4.85	0.39	Very high
Plantation	116.49	9.49	Low
Water body	2.11	0.17	Very low
Agriculture land	1059.24	86.27	High
Pastureland	45.06	3.67	Medium

Table 6: Soil type and distribution (%)

Major soil	Area (km^2)	Area (%)	Susceptibility to erosion
Chromic luvisols	1.38	0.11	Very high
Eutric fluvisols	297.87	24.28	Low
Eutric leptosols	114.43	9.33	High
Eutric vertisols	793.08	64.59	Medium
Haplic luvisols	18.02	1.47	Very high
Urban	3.01	0.25	Very high

RESULTS AND DISCUSSION

The result of this study presents the selection of potential soil erosion hotspot areas by integrating multiple GIS layers, spatial analysis and multi-criteria assessment.

Impact of land use on soil erosion: Percentage distribution of land use/cover and susceptible to erosion classes in Gumara Watershed presented in Table 5. As noted above the agricultural lands comprises about 86.27% of the entire area of the watershed. The re-classified land use map (Fig. 6b) indicated that 4.85 km^2 (0.39%) of the land use is very high susceptible; 1059.24 km^2 (86.27%) highly susceptible; 45.06 km^2 (3.67%) medium susceptible; 116.49 km^2 (9.49%) low susceptible and 2.11 km^2 (0.17%) very low susceptible to soil erosion.

Soil type impact on erosion: Soil texture is an important property, which contributes to soil erodibility. The study watershed is dominated by haplic fluvisols with an area of 793.08 km^2 (64.59%), followed by Chromic luvisols 297.87 km^2 (24.26%), which are normally influenced by some form of water control and mainly by their topographic/physiographic location (Table 6). Figure 7a presented soil types in Gumara Watershed. The reclassified soil map (Fig. 7b) indicated that 22.41 km^2 (1.83%) of the land use is very high susceptible; 114.43 km^2 (9.33%) highly susceptible; 792.08 km^2 (64.57%) medium susceptible and 297.87 km^2 (24.28%) low susceptible to soil erosion.

Impact of topography on erosion: Topography is the major surface parameter for soil erosion assessment. The Topographic Wetness Index (TWI) also called compound topographic index (CTI), is a steady-state wetness index. In

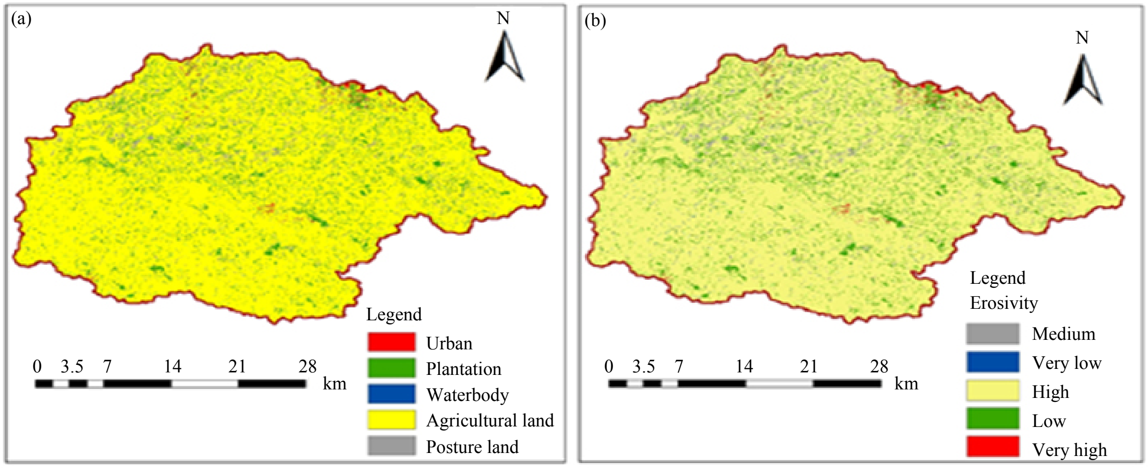

Fig. 6(a-b): (a) Land use map and (b) Re-classified land use map

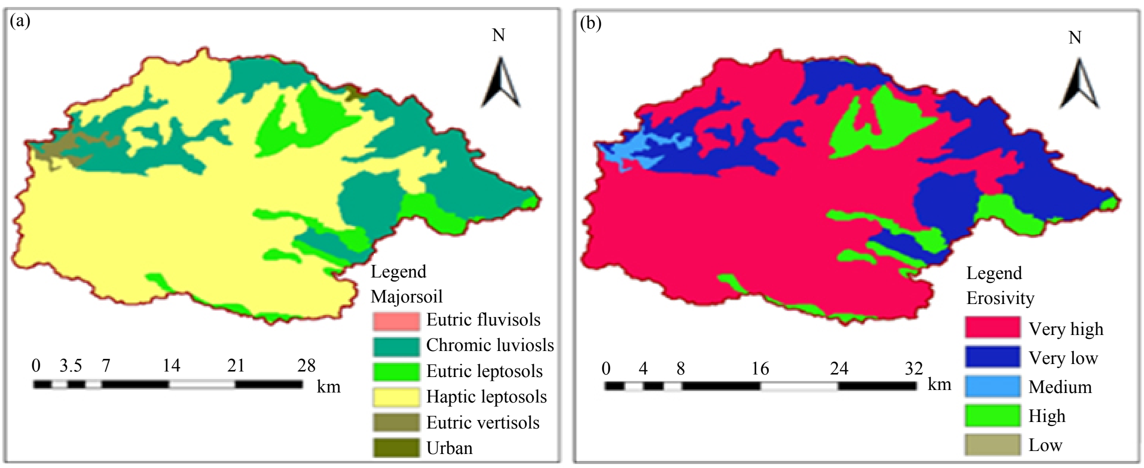

Fig. 7(a-b): (a) Soil map and (b) Re-classified soil map

Table 7: Topographic wetness index susceptibility class

TWI	Area (km^2)	Area (%)	Erosivity group
3-4.06	453.28	36.92	Very low
4.06-5.19	364.02	29.65	Low
5.19-6.43	270.41	22.03	Medium
6.46-8.26	102.08	8.31	High
8.26-12.71	37.94	3.09	Very high

some areas, TWI has been shown in some study areas to predict solum depth[31]. It involves the upslope contributing area (a), a slope raster and a couple of geometric functions. The value of each cell in the output raster (the CTI raster) is the value in a flow accumulation raster for the corresponding DEM. The re-classified TWI map (Fig. 8b, Table 7) indicated that 37.94 km^2 (3.09%) of the land use is very high susceptible; 102.08 km^2 (8.31%) highly susceptible; 270.41 km^2 (22.03%) medium susceptible; 364.02 km^2 (29.65%) low susceptible and 453.28 km^2 (36.92%) very low susceptible to soil erosion.

Impact of slope on erosion: The slope gradient is one of the most vital factors affecting the surface flow erosion. The re-classified Slope map (Fig. 9b, Table 4) indicated that 37.94 km^2 (3.09%) of the land use is very high susceptible; 102.08 km^2 (8.31%) highly susceptible; 270.41 km^2 (22.03%) medium susceptible; 364.02 km^2 (29.65%) low susceptible and 453.28 km^2 (36.92%) very low susceptible to soil erosion.

Impact of altitude on erosion: Altitude is one of the best important factors determining the conditions on the microsite that influence plant distribution, morphology, physiology and growth[32]. The altitude map generated from the DEM by raster format. The reclassified altitude map (Fig. 10b) indicated that 27.21 km^2 (2.22%) of the land use is Very high susceptible; 179.96 km^2 (14.66%) highly susceptible; 338.33 km^2 (27.56%) Medium susceptible; 362.01 km^2 (29.49%) low susceptible and 320.21 km^2 (26.08%) very low susceptible to soil erosion.

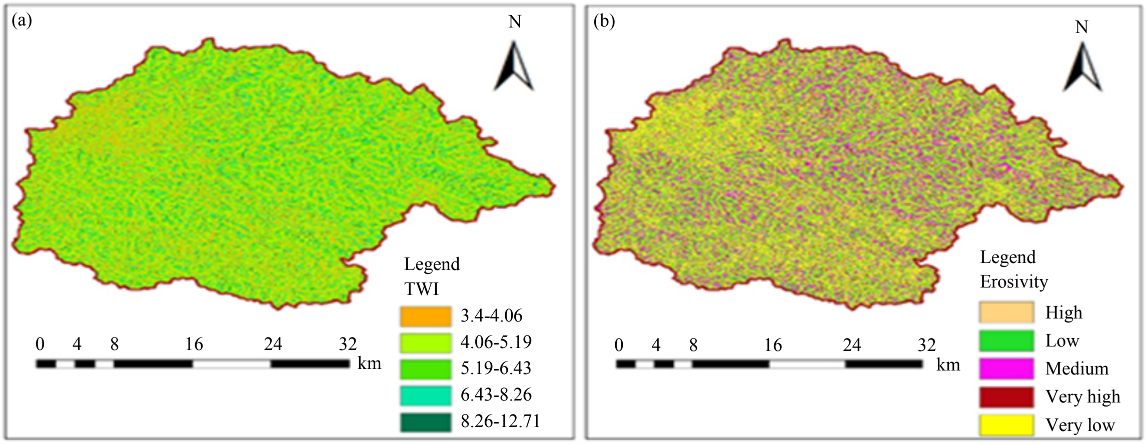

Fig. 8(a-b): (a) TWI map and (b) Re-classified TWI map

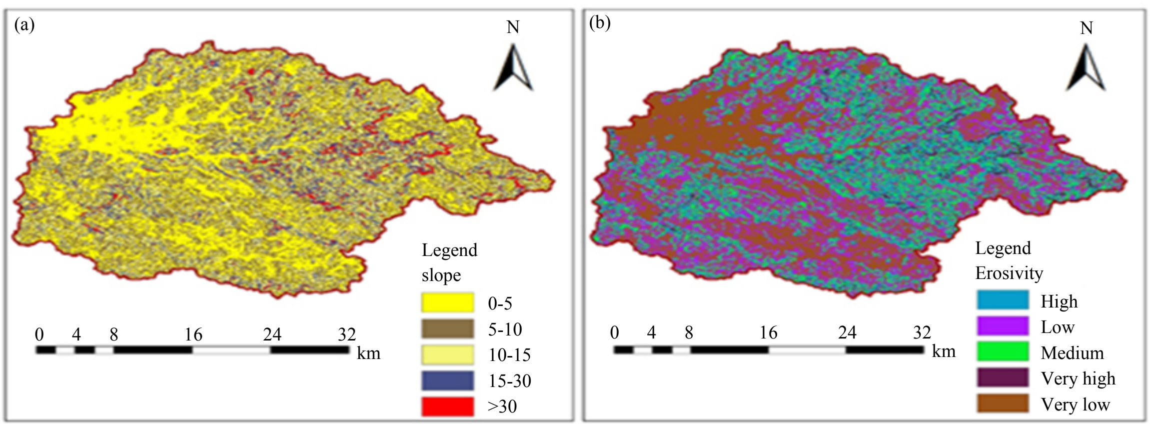

Fig. 9(a-b): (a) Slope map and (b) Re-classified slope map

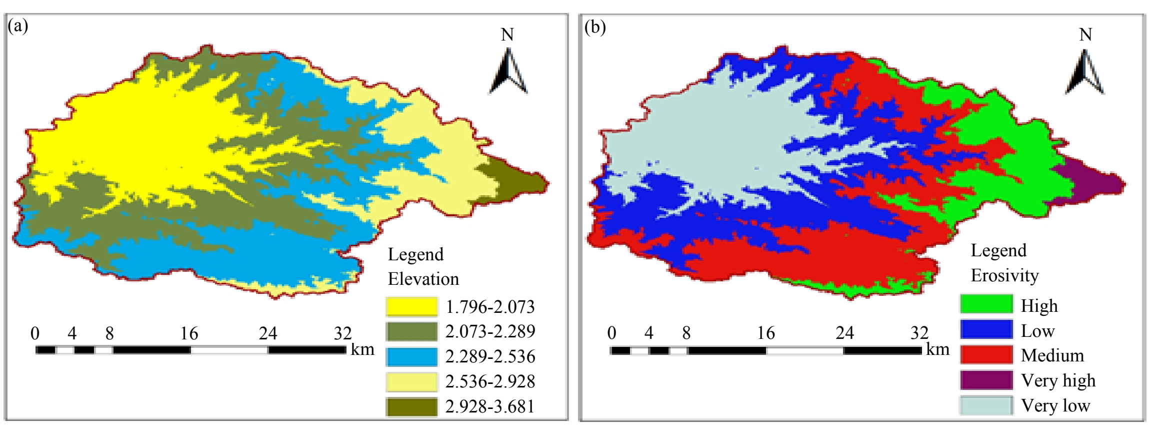

Fig. 10(a-b): (a) Altitude map and (b) Re-classified altitude map

Identification of soil erosion hotspot areas: Based on the methodology designed for identification of soil erosion hotspot area all selected factors were overlaid to identify the area susceptible to erosion as very high, high, medium, low

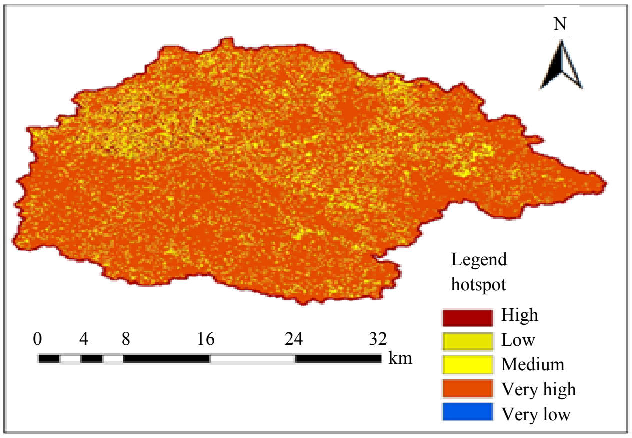

Fig. 11: Potential soil erosion vulnerable areas

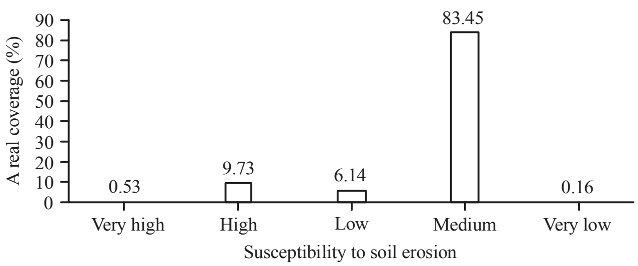

Fig. 12: Coverage of relative susceptibility (%) of soil erosion

Table 8: Areas under soil erosion

Susceptibility	Areal coverage (km^2)	Area (%)
Very high	6.45	0.53
High	119.50	9.73
Medium	1024.65	83.45
Low	75.30	6.14
Very low	1.92	0.16
Total	1227.82	100.00

and very low. The susceptibility map (Fig. 11) showed the relative ranking of the erosion potential sites, generated by weighted overlay mapping, according to the importance of concerned criteria. High susceptibility scores indicated that the site is highly susceptible for soil loss. According to the overall appropriateness score indicated as; 6.45 km^2 (0.53%), 119.5 km^2 (9.73%), 1024.45 km^2 (83.45%), 75.3 km^2 (6.14%) and 1.92 km^2 (0.16%) areas are very high, high, medium, low and very low prone to soil erosion respectively (Fig. 11, 12, Table 8). Very susceptible areas are concentrated mainly in the upper and lower part of the watershed. On the basis of this result, it is therefore important to facilitate planning and involvements to reduce soil erosion problems in the watershed. Therefore, this study has designed a roadmap for multi-criteria decision-makers to bring sustainable development into the study area.

CONCLUSION

The erosion risk map has been generated by considering five important parameters namely, land use, soil, altitude, slope and Topographic Wetness Index (TWI). With the benefit of GIS and MCE, there are many ways to improve soil and water resource assessment. The main objective of this study was to identify erosion soil hotspot areas in the Gumara watershed. The MCE result showed that land cover and soil factor are given high priority, suggesting that 46 and 26%, respectively, of the land area is sensitive to soil erosion. The map created using this approach showed significant areas of potential erosion. The results show that land use plays an important role in soil erosion and degradation. The results of this study can help planners and policymakers to take appropriate soil and water conservation measures to reduce the alarming problems of soil loss and depletion in the catchment area.

SIGNIFICANCE STATEMENT

This study discover the integration application of GIS tool based Multi-criterial decision analysis techniques to identify erosion hotspot areas in Gumara watershed that can be beneficial for society to apply soil and water conservation techniques properly as Intensification of overgrazing, urbanization, agriculture and unwise utilization of natural resources, lead to the accelerating of the soil erosion. In addition to this, badly design of soil and water conservation structures intensifying these negative impacts in the study area. This study will help the researcher or scholars to uncover the critical areas of soil erosion that many researchers were not able to explore. Thus, a new theory in the study area may be arrived at.

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