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Assessment of land degradation sensitivity in the Bilate river watershed, Ethiopia using the MEDALUS model and GIS Techniques

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Abstract

Mapping and quantifying land degradation status is a precondition to develop evidence-based and efficient sustainable land resource management planning. To meet this need, this study used the MEDALUS model, a multifactorial approach to evaluate the spatial distribution and severity of land degradation vulnerability in the Bilate River watershed, Ethiopia. To ascertain the sensitivity of land to degradation, the analysis included nine distinct parameters in addition to three im-portant quality indicators: soil, climate, and vegetation. According to the findings, 2.5 percent of the watershed has the potential of land degradation, and 83.1 percent is extremely vulnerable to it. Conversely, 14.4 percent of the watershed has low degradation susceptibility. The findings high-light the critical need for focused and effective land resource management techniques, with a focus on the most severely degraded areas, in order to promote sustainable land use practices and maintain long-term agricultural sustainability within the watershed.

Keywords: *Land degradation, MEDALUS model, environmental sensitivity, Bilate river watershed.*

Introduction

Land degradation is a leading driver of poverty, food insecurity, and environmental risk worldwide. It af-fects nearly 40 percent of the global population and almost one-third of Earth's terrestrial surface (Nkonya *et al.*, 2016). Drylands, including the East African highlands, are particularly vulnerable, where degradation reinforces a vicious cycle of reduced agricultural productivity, heightened disaster risk, and deepening rural poverty (UNCCD, 2017).

In Ethiopia, land degradation is among the most severe on the continent. Water-induced soil ero-sion, accelerated by deforestation, overgrazing, steep topography, and unsustainable farming practices, re-moves an estimated 42–300 t ha^{-1} yr^{-1} of topsoil from croplands (Hurni, 1993; Gebreselassie *et al.*, 2016). More than 40 million hectares—approximately 85 percent of the highland population—live on degraded land, with serious consequences for soil fertility, biodiversity, and national food security (Gebreselassie *et al.*, 2016; Ewunetu *et al.*, 2021).

Although several national and regional assessments have applied the widely used Mediterranean Desertification and Land Use

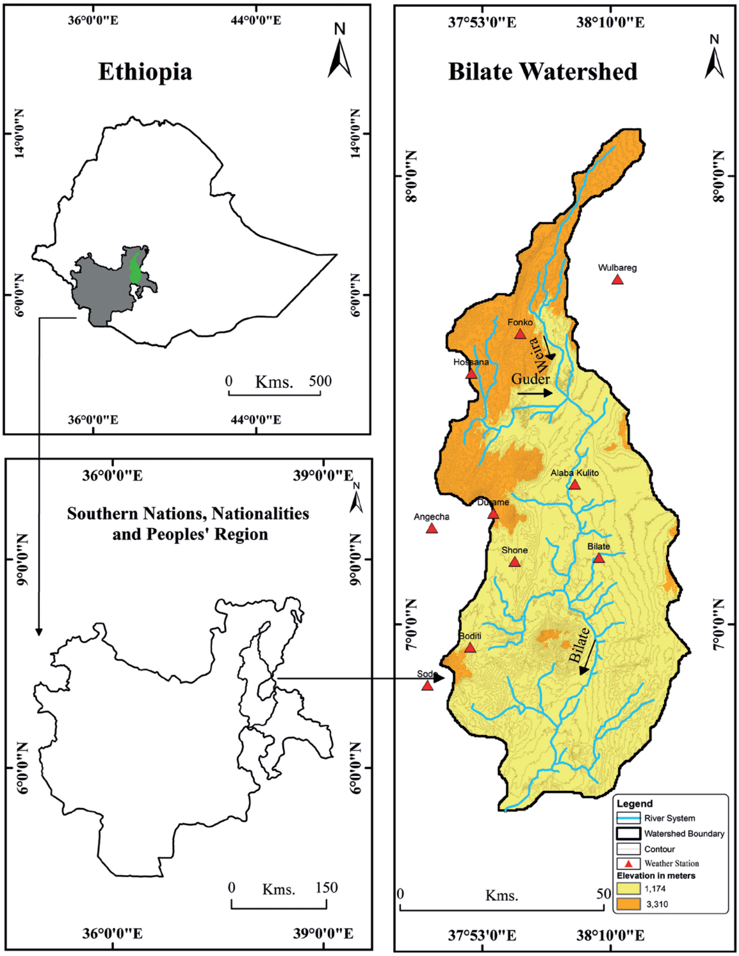

Fig. 1: Study area

(MEDALUS) framework in Ethiopia, most rely on coarse-resolution data or single-factor approaches and none have examined the Bilate watershed. This rapidly changing catchment in the Central Rift Valley is experiencing intense irrigation expansion, forest loss, overgrazing, and cultivation of steep slopes, yet lacks a spatially explicit, multi-indicator evaluation of degradation vulnerability.

This study adapts and refines the MEDALUS model for the Bilate watershed by integrating high-resolution open-source datasets (Sentinel-2 NDVI, CHIRPS precipitation, ISRIC SoilGrids, and 30-m SRTM DEM) to produce a detailed maps of soil, climate, vegetation, and management quality indices, culminating in an Environmental Sensitivity Area Index (ESAI). The work provides the first comprehensive, watershed-scale assessment of land degradation risk in this agro-ecologically diverse and data-scarce region, offering a replicable methodology for similar environments across the Ethiopian Rift Valley and beyond.

Materials and methods

Study area

Bilate River Watershed (BRW), is located in the southern Ethiopian rift valley and extends partially into the Western Ethiopian highlands. The Bilate River is a significant inland river in Ethiopia, serving as the primary drainage system for the northern portion of the Lake Abaya–Chamo basin which forms part of the main Ethiopian rift, which itself is a segment of the active East African Rift system (Sulamo *et al.*, 2021). The BRW lies between 7°0′ 00″ to 8°0′0″ N and 37° 53′0″ to 38° 10′0″ E (Fig. 1), covering an area of about 5606.7 km^2. The watershed exhibits pronounced topographic variation, with steep slopes dominating the northern and north eastern parts, while the central and the southern parts have gentler slopes (Burka *et al.* 2023). The highland and middle areas of the Bilate watershed are known for their intensive cultivation due to high population density. The land use system is dominated by rain-fed agriculture leading to subsist-ence agriculture. The highlands and middle areas are known for growing different crops such as wheat (Triticum Aestivum), barley (Hordeum vulgare), and Teff (Eragrostis Teff). Farmers have intensive home gardens, where they cultivate enset (Ensete ventricosum) and coffee.

Data sources and pre-processing

Land degradation assessment and mapping are fundamental components of effective land management, particularly for developing strategies aimed at prevention, restoration, and protection. This study employed comprehensive geospatial datasets that capture various biophysical and climatic factors influencing land degradation in BRW (Table 1). A total of nine geographically explicit datasets with varying spatial resolu-tions were obtained from different sources, including the International Soil Reference and Information Centre (ISRIC), the United States Geological Survey (USGS), and the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS). These datasets encompass essential environmental variables such as land use, digital elevation

Table 1: Key characteristics of parameters and associated indicators

Indicators	Parameters/ Data type	Spatial resolution	Period	Data source
Soil Quality Index (SQI)	Soil Texture	250 m	2024	Soil Grids (ISRIC)
	Slope Gradient (%)	20m	2024	Derived from a Digital Eleva-tion Model (DEM) obtained from (USGS)
	Soil acidity (pH)	250 m	2024	Soil Grids (ISRIC)
	Soil depth (cm)	250 m	2024	Soil Grids (ISRIC)
	Soil Organic Carbon (%)	250m	2024	Soil Grids (ISRIC)
Climate Quali-ty Index (CQI)	Rainfall data/(mm/yr)	250m	30 years	CHIRPS
Vegetation Quality Index (VQI)	Percent vegetation cover (Pv)(NDVI)	10m	2024	Sentinel-2A
	Erosion protection	10m	2024	Sentinel-2A

model (DEM), climate, and soil parameters. Specifically, soil-related data including texture, depth, acidity (pH), and soil organic carbon (SOC) were acquired from the ISRIC Soil Grids database at a spatial resolution of 250 m, while the slope gradient was derived from the DEM at 20m resolution. The datasets, originating from diverse sources and spatial resolutions, were pre-processed to ensure consistency and compatibility prior to analysis. All raster layers were projected to the WGS 1984 UTM Zone 37N coordinate system using the project raster tool in ArcGIS 10.8, and the slope raster was resampled from 20 m to 250 m using bilinear interpolation to align with other soil parameters. Subsequently, all raster were clipped to the Bilate watershed boundary using the clip tool to maintain a uniform spatial extent. After harmonization, each raster was reclassified according to MEDALUS criteria to assign sensitivity scores, and the reclassified layers were combined using the raster calculator to compute the Soil Quality Index (SQI) through the geometric mean of all soil indicators, ensuring spatially consistent and integrated representation of soil degradation sensitivity.

The Climate Quality Index (CQI) was developed using long-term rainfall data obtained from the CHIRPS dataset covering a 30-year period (1994–2024) at 250 m resolution. The CHIRPS dataset was selected for its temporal stability and suitability for regional environmental analyses in data-scarce regions. Mean annual rainfall was calculated to represent long-term climatic conditions of the watershed, projected to the same coordinate system, and clipped to the watershed boundary for spatial consistency. The rainfall and erosivity layers were reclassified into sensitivity classes based on MEDALUS criteria, and their geometric mean produced the CQI, reflecting the climatic contribution to land degradation.

Vegetation indicators, including percent vegetation cover and erosion protection, were generated from Sentinel-2 imagery at a 10m spatial resolution. Both vegetation raster was projected to WGS 1984 UTM Zone 37N, resampled to 250 m to align with other datasets, and clipped to the watershed boundary. The NDVI-based layers were reclassified following MEDALUS standards, where dense vegetation and strong erosion protection were assigned low sensitivity scores, while sparsely vegetated and exposed areas received higher scores. The reclassified vegetation layers were then combined using the raster calculator to produce the Vegetation Quality Index (VQI), indicating vegetation-related degradation vulnerability. Since the datasets had varying spatial resolutions (10m, 20m, and 250m), all layers were harmonized to a common grid size of 250m for integration within the MEDALUS framework.

Methodology

Environmental Sensitivity Area Index (ESAI)

The ESAI is a multidimensional indicator that integrates partial indices representing climate, soil, vegetation, and management quality, forming a distinctive component of the MEDALUS framework. In this study, the MEDALUS was adopted with minor modifications to align it with the environmental and socio-ecological conditions of the BRW. Originally developed and validated under Mediterranean conditions (Salvati & Bajocco, 2011), the methodology has since been successfully applied in non-Mediterranean regions too,

Table 2: Soil quality indicators, parameters, descriptions, and assigned weight

Quality indicators	Parameters/factors	Class	Description	Index
Soil Quality (SQI)	Soil texture class	L, SCL, SL, LS, CL	Good	1
		SC, SiL, SiCL	Moderate	1.2
		Si, C, SiC	Poor	1.6
		S	Very poor	2
	Soil depth (cm)	>75	Deep	1
		75-30	Moderate	1.6
		15-30	Shallow	1.8
		<15	Very shallow	2
	Slope (%)	<6	Very gentle to flat	1
		6-18	Gentle	1.2
		18-35	Steep	1.5
		>35	Very steep	2
	Soil pH value	< 5.5	Extremely acidic	2
		5.6-6.5	Moderately acidic	1.6
		6.6-7.4	Neutral	1.2
		>7.5	Alkaline	1
	Soil organic carbon (%)	>6	High	1
		2.1-6.0	Medium	1.2
		1.1-2.0	Low	1.4
		<1.0	Very low	2

Note: L = loam, SCL = sandy clay loam, SL = sandy loam, LS = loamy sand, CL = clay loam, SC = sandy clay, SiL = silty loam, SiCL = silty clay loam, Si = silt, C = clay, SiC = silty clay, and S = sand.

including Cabo Verde (De Pina Tavares *et al.*, 2015), the Brazilian Northeast (Vieira *et al.*, 2015), Serbia (Momirović *et al.*, 2019), and southwestern Romania (Prăvălie *et al.*, 2020). In the present study, the model was utilized to identify areas within the Bilate watershed that are particularly sensitive to land degradation, marking its first application in this watershed. The MEDALUS method quantifies land sensitivity through ESAI, calculated as the geometric mean of four component indices: SQI, CQI, VQI, and Management Quality Index (MQI), which incorporates human influence (Kosmas *et al.*, 1999). In this study, the three environmental indices (SQI, CQI, and VQI) were employed due to a lack of available data on anthropogenic factors required for calculating the MQI. This limitation is due to the vast spatial extent of the study area, which hindered the acquisition of consistent socio-economic and land management data. The ESAI for land degradation has been therefore determined by merging the three environmental quality layers, with indices calculated individually for each component. Similar methodological adjustments are seen in other studies. For instance, Dagne *et al.* (2023) excluded the MQI in case of Omo-Gibe River basin, South-Western Ethiopia. Likewise, Teferi

Table 3: Climate quality indicators, parameters, descriptions, and assigned weight

Quality indicators	Parameters	Class	Description	Index
Climatic quality index (CQI)	Rf (mm/yr)	>1200	High	1
		900-1200	Medium	1.2
		350-900	Low	1.6
		<350	Very low	2
	Rainfall erosivity (MJ mm ha^{-1} yr^{-1})	< 150	Very low	1
		151-350	Low	1.2
		351-700	Medium	1.6
		>700	High	2

Table 4: Vegetation quality indicators, parameters, descriptions, and assigned weight

Quality indicators	Parameters	Class	Description	Index
Vegetation Quality Index (VQI)	Percent vegetation cover (Pv) (NDVI)	<10 (%)	Very low	2
		10-30 (%)	Low	1.6
		30-50 (%)	moderate	1.4
		50-70 (%)	High	1
	Erosion protection (LULC)	Agricultural lands, bare land	Low	1.6
		Marshland, Settlement area	Moderate	1.4
		Forest, Shrub-land, Woodland, Grassland	High	1.2

et al. (2023) in case of Ethiopia and Hamad *et al.* (2021) adopted the same approach for assessment of environmental sensitivity to desertification in Maymona project, south of Iraq. In all cases, these modifications were necessitated due to the absence of reliable spatial data on human factors, highlighting the flexibility of the MEDALUS model in regions where such data are scarce.

The method incorporates six soil-related parameters (Table 2), three climate-related parameters (Table 3), and two vegetation-related parameters (Table 4) to derive the SQI, CQI, and VQI, respectively. According to the original methodology developed by Kosmas *et al.* (1999), the Quality Indices assume values ranging between 1 (lowest sensitivity to degradation) and 2 (highest sensitivity to degradation). Once the three quality indices are calculated, the final step comprises computing ESAI as the geometric mean of the three quality indices in identifying critical and fragile areas. The Environmental sensitivity areas index is calculated with the help of the following equation:

$$ESAI = \sqrt[3]{SQI * CQI * VQI}$$

1. **Soil quality Index (SQI)** is closely linked to factors such as available moisture and erosion tolerance. In this study, several key soil parameters are used to assess soil quality in the watershed. These parameters include soil texture, soil depth, soil organic carbon (SOC), soil acidity (pH), and slope gradient, as outlined in table 2. The soil quality indicator for each area was derived by grading the soil according to the ranges

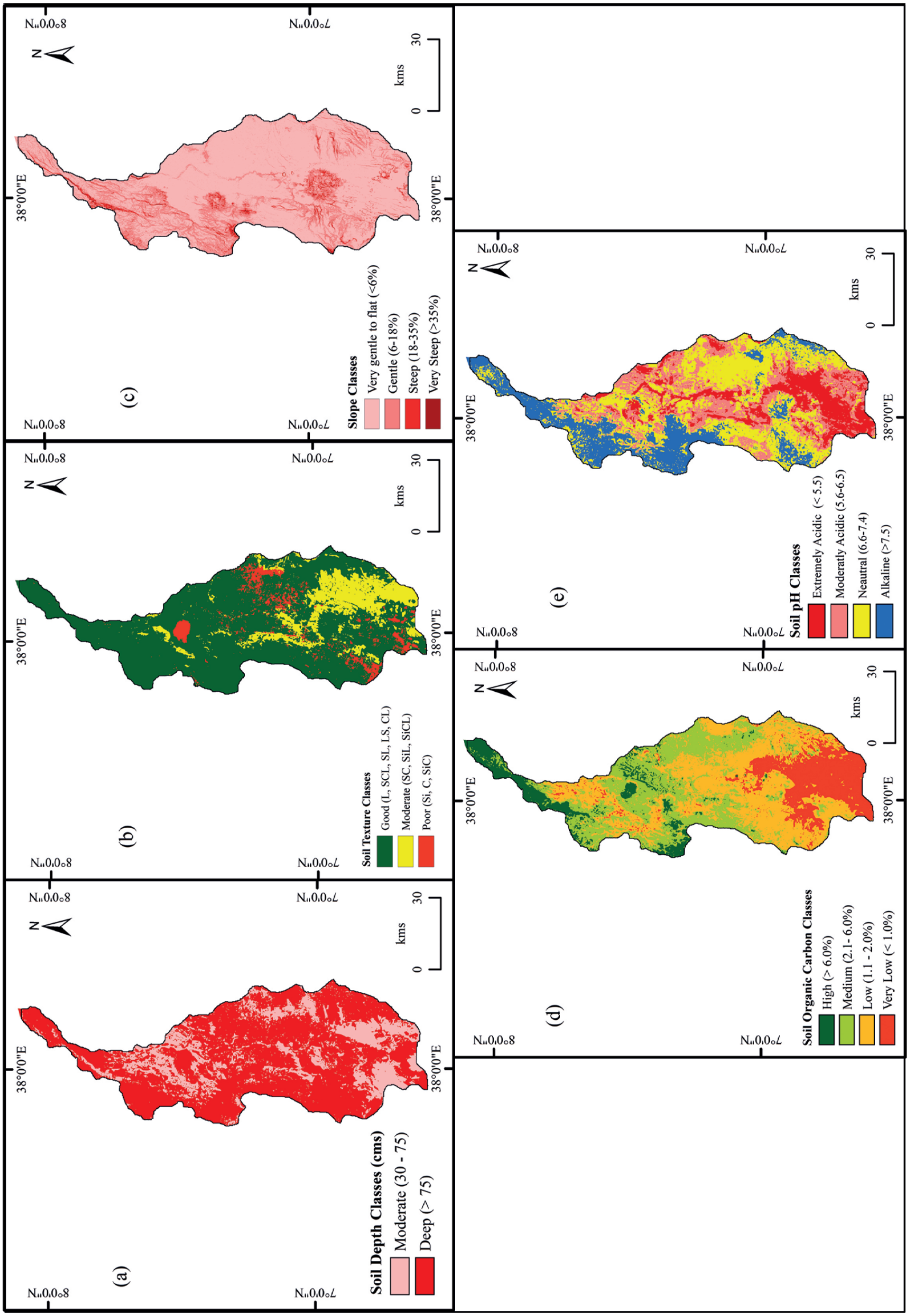

Fig. 2: Spatial distribution of soil quality sub-Indices in the Bilate watershed: (a) soil depth, (b) soil texture, (c) slope, (d) soil organic carbon, and (e) soil pH

provided by Kosmas et al. (1999) based on the selected soil attributes. The final soil quality indicator was calculated using the geometric mean of the sub-indicator scores, which integrates the individual scores into a single composite value, offering a comprehensive representation of soil quality in the study area. The calculation process is outlined as:

$$SQI \sqrt[5]{SoilTexture * Soil\ depth * Slope\ gradient * Soil\ organic\ carbon * Soil\ acidity}$$

2. **Climatic Quality Index (CQI)** focuses on parameters that affect the availability of water for plant growth. The CQI is composed of two key sub-indices: rainfall and rainfall erosivity, as detailed in table 3. To create the rainfall and erosivity maps, climate data from CHIRPS were used.

   For this study, the CQI was calculated based on long-term meteorological records spanning over 30 years (1994-2024) period collected from weather stations in Ethiopia and nearby watershed. This data was used to evaluate the climate's influence on land degradation,

Table 5: Influences of the sub-indexes and evaluation of the SQI in the watershed

Quality indicators	Parameters	Class	Description	Area (km^2)	Area (%)	Index
Soil Quality In-dex (SQI)	Soil depth(cm)	> 75	Deep	4170.0	74.4	1
		30 – 75	Moderate	1436.7	25.6	1.6
	Texture class	L, SCL, SL, LS, CL	Good	3828.8	68.3	1
		SiL, SiCL	Moderate	1440.4	25.7	1.2
		C, SiC	Poor	337.5	6.0	1.6
	Slope (%)	<6 (%)	Very gentle to flat	14127	73.6	1
		6-18 (%)	Gentle	324.0	23.6	1.2
		18-35 (%)	Steep	149.0	2.7	1.5
		>35(%)	Very steep	6.7	0.12	2
	Soil organic carbon (%)	>6 (%)	High	524.1	9.3	1
		2.1-6 (%)	Medium	1787.4	31.9	1.2
		1.1-2 (%)	Low	2292.1	40.9	1.4
		<1 (%)	Very low	1002.6	17.9	2
	pH value	< 5.5	Extremely acidic	884.2	16	2
		5.6-6.5	Moderately acidic	1481.5	26	1.6
		6.6-7.4	Neutral	2000.0	36	1.2
		>7.5	Alkaline	1241.6	22	1

Table 6: Ranges of the three classes of SQI

Class	Description	Index	Area (km^2)	Area (%)
1	High quality	<1.13	2410.9	43
2	Moderate quality	1.13 – 1.45	1177.4	21t
3	Low quality	>1.46	2018.4	36

specifically in terms of water availability for vegetation. The calculation process is as follows:

$$Climate\ Quality\ Index(CQI) = \sqrt[2]{Rainfall * Rainfall\ erosivity}$$

The rainfall erosivity (R) factor quantifies the potential of rainfall to cause soil erosion and is derived from long-term precipitation data. In this study, rainfall data were obtained from the CHIRPS dataset and processed in the ArcGIS. The rainfall erosivity index was estimated using the empirical equation proposed by Hurni (1985), developed specifically for Ethiopian conditions:

$$R = -8.12 + 0.562 * P$$

where R is the rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$) and P is the mean annual precipitation (mm). Spatial interpolation of the CHIRPS rainfall data was performed using the Inverse Distance Weighted (IDW) method to ensure continuous and accurate representation of erosivity values across the watershed.

3. **Vegetation Quality Index (VQI)** is closely linked to the state of vegetation cover, which plays a significant role in both preventing and mitigating land degradation processes. In this paper, vegetation cover is used as a key indicator to find the extent of desertification, focusing on vegetation cover and erosion protection (Table 4). In order to assess vegetation cover, the percent vegetation cover (Pv) is calculated using the NDVI, a widely used remote sensing tool particularly effective for regional vegetation quality assessments. NDVI data was obtained from Sentinel-2A remote sensing imagery for February 2024 and the following formula was used to compute the percent vegetation cover:

$$Pv = \left(\frac{NDVI - NDVIS}{NDVI - NDVIS}\right)^2$$

Where NDVI represents the normalized difference vegetation index, and NDVIS refers to a baseline or reference value for the NDVI in the study area. Once the percent vegetation cover (Pv) is determined, the VQI is calculated. The VQI integrates the percentage of vegetation cover and erosion protection into a composite index, reflecting both the amount of vegetation present and its effectiveness in preventing soil erosion. The formula for the VQI is:

$$Vegetatin\ Quality\ Index(VQI) = \sqrt[2]{percent\ vegetation\ cover * Erosion\ protection}$$

Results and discussion

As discussed in methodology section, the MEDALUS model has been applied in the Bilate watershed to calculate the ESAI- a composite index made up of three sub-indices: soil quality, climate quality, and vegetation quality. This section presents the analysis results for each individual index, followed by the composite analysis of 3 indexes suggesting the potential for land degradation in the watershed.

Soil Quality Index (SQI)

The SQI in the watershed is determined by overlaying five key soil characteristics: slope, soil depth, soil organic carbon (SOC), soil texture, and soil acidity (pH). The soil depth in the watershed is classified into two categories- deep (74.4%) and moderate (25.6%) (Table 5 and Fig. 2a). It is seen that the soil depth in the watershed is not shallow, ranging from 15 to 30cm. Approximately 68.3 percent of the watershed has good-quality texture (Table 5 and Fig. 2b). Much of the watershed has very gentle flat slope or gentle

Table 7: Quality indicators, parameters, description, assigned weight indices of climate

Quality indicators	Parameters	Class	Description	Area (km^2)	Area (%)	Weight
Climate Quality Index (CQI)	Rf (mm/yr)	>1200	High	3764.7	67	1
		900-1200	Medium	1842.0	33	1.2
	Rain fall ero-sivity (MJ mm ha^{-1} yr^{-1})	>700	High	2616.87	46.7	2
		351-700	Medium	2989.83	53.3	1.6

Table 8: Ranges of the three classes of Climate quality (CQI)

Class	Description	Index	Area (km^2)	Area (%)
1	High quality	<1.15	1155.0	20.6
2	Medium quality	1.15-1.81	1836.0	32.8
3	Low quality	>1.81	2615.7	46.6

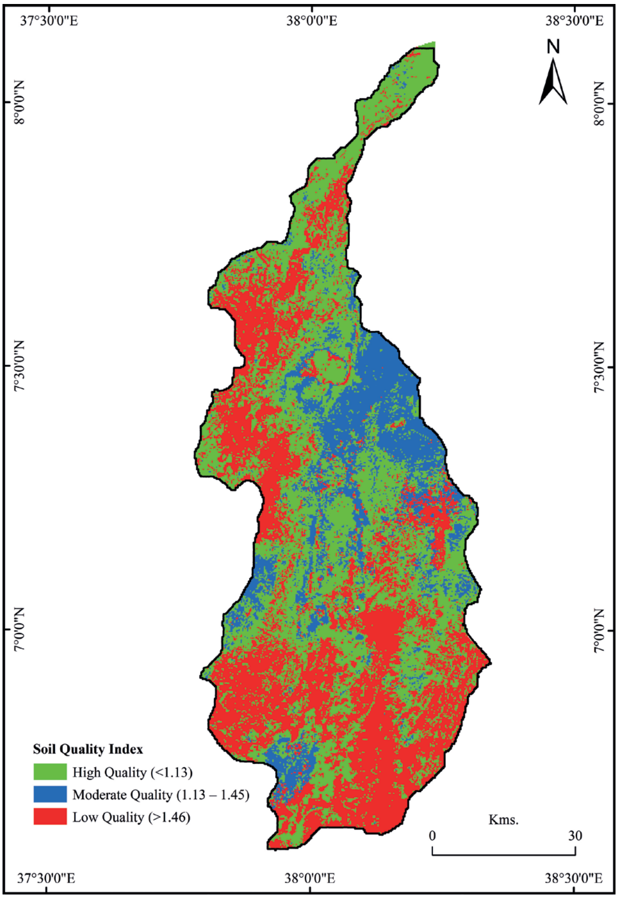

Fig. 3: Soil quality Index map of the Bilate watershed

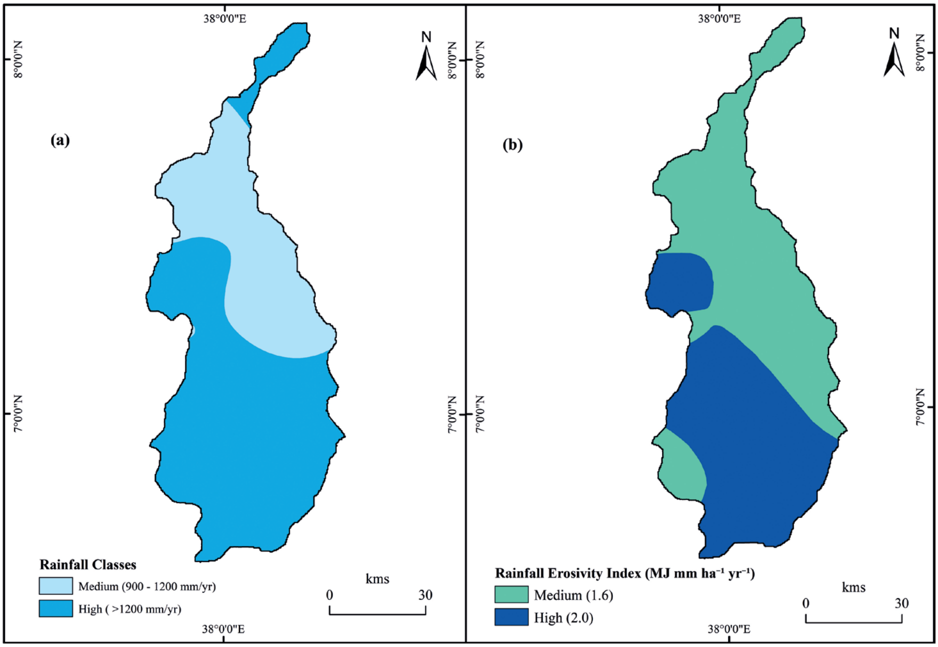

Fig. 4: Spatial distribution of CQI sub-indices in the Bilate watershed: (a) rainfall (b) rainfall erosivity

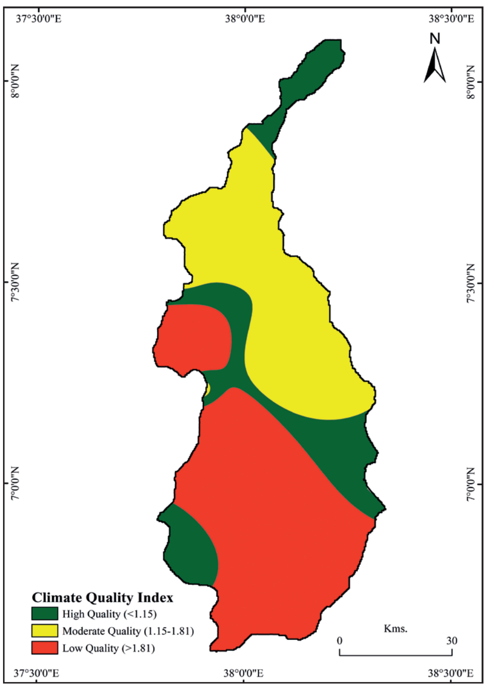

Fig. 5: Bilate watershed-climate quality index

accounting for 97.2 percent area leaving the rest of the watershed with steep or very steep terrain (Table 5 and Fig. 2c). Nearly half of the area has low (1.1–2%) to very low (<1%) soil organic carbon, the former being more prevalent (41%). High (>6%) SOC covers 9.3 percent and medium (2.1–6%) 31.9 percent. The result shows 58.8 percent of the area to be vulnerable to degradation due to low to very low soil organic carbon levels (Table 5 and Fig. 2d). Soil acidity (pH) is quite varied over the area (Table 5 and Fig. 2e).

The findings presented in table 6 and fig. 3 provide important insights into the spatial distribution of soil quality within the watershed, emphasizing the variability in soil characteristics and their implications for land use and agricultural practices. The watershed is predominantly composed of high-quality soils, covering approximately 43 percent of the total area. A substantial portion (about 36%) is characterized by low-quality soils, which may pose challenges for sustainable agricultural productivity. The remaining 21 percent consists of moderate-quality soils. This distribution underscores the need for targeted land management strategies that account for spatial differences in soil quality to enhance agricultural efficiency and ensure long-term soil health.

Climatic Quality Index (CQI)

The measurement of CQI based on two sub-indices- rainfall and rainfall erosivity, following the methodo-logical farmwork developed by Kosmas *et al.* (1999). The CQI provides a comprehensive understanding of the spatial variability in climatic conditions across the watershed, based primarily on rainfall amount (Rf) and rainfall erosivity. As shown in Table 7 and Figure 4a, approximately 67 percent of the watershed expe-riences high rainfall with an index of 1.0, while one third experience medium rainfall (index value of 1.2). A little less than half of the watershed is subject to high erosivity (>700 MJ mm ha^{-1} yr^{-1}) with an index value of 2.0, while the remaining experiences medium erosivity (351–700 MJ mm ha^{-1} yr^{-1}) with an index value of 1.6 (Table 7and Fig. 4b).

These two layers of climate parameters were used to prepare the climatic quality distribution within the watershed (Table 8 and Fig. 5). About a fifth of the watershed has high climate quality (index <1.15), of favourable climatic conditions for crop growth and sustainable land use. In about a third (32.8%) of the watershed, climate quality is moderate suggesting some climatic limitations that might require adaptive management strategies such as planting drought-resistant crops and irrigation. Much of the watershed- 46.6 percent- suffers from low climate quality (index >1.81), with conditions such as erratic rainfall, high temperatures etc. This distribution emphasizes the need to integrate climate considerations into land management and planning, promoting practices that increase resilience to climatic variability and mitigate potential risks.

Vegetation Quality Index (VQI)

The VQI consists of two parameters of vegetation i.e., NDVI of the watershed and erosion protection (LULC). These two layers highlight the vegetation health and ecosystem stability, soil preservation and land degradation. With 50-70 percent cover, vegetation is robust in a third of the watershed (Fig. 6a and Table 9). It is moderate (30-50% cover) in half (48.9%) of the watershed. However, over 18 per cent of the watershed has only 10-30 percent vegetation cover (Table 9 and Fig. 6a).

Table 9: Influence of sub-indexes and evaluation of the vegetation quality index (VQI)

Quality indicators	Parameters	Class	Description	Area (km^2)	Area (%)	Weight
Vegetation Quality Index (VQI)	NDVI (percent vegetation cover (pv)	50-70%	High	1851.72	33.0	1
		30-50%	Moderate	2741.88	48.9	1.4
		10-30%	Low	1012.91	18.1	1.6
	LULC (Erosion protection)	Forest, shrub land, wood land, grass land	High	1274.68	23.0	1.2
		Marshland, water body and Settlement area	Moderate	896.49	16.0	1.4
		Agricultural lands, bare land	Low	3435.53	61.0	1.6

Table 10: Ranges of the three classes of vegetation quality (VQI)

Class	Description	Index	Area (km^2)	Area (%)
1	High quality	1 - 1.6	1042.8	18.6
2	Moderate quality	1.7 – 3.7	2646.4	47.2
3	Low quality	>3.8	1917.5	34.2

The LULC is taken as a proxy of erosion protection. Around 23 percent of the watershed is covered with forests, shrub lands, woodlands, and grasslands providing high protection from erosion (Table 9 and Fig. 6b). However, 16 percent of the land offers only moderate erosion protection, particularly settlement areas and marshlands which require additional management to maintain their protective capacity (Table 9 and Fig. 6b). The most concerning portion of watershed, accounting for 61 percent of the total area, exhib-its low protection. These areas dominated by agricultural land and bare lands are particularly vulnerable to severe soil erosion and habitat degradation (Table 9 and Fig. 6b).

Vegetation quality distribution within the watershed (Fig. 7 and Table 10) reveals significant variation in ecological health of the watershed. Only 18.6 percent of the watershed have high quality, healthy vegetation suggesting minimal degradation, good soil fertility and strong erosion protection maintaining biodiversity, regulating water flow, and preventing soil erosion. On the other hand, nearly half (47.2%) of the watershed reflect a transitional state with adequate but not optimal vegetation cover and soil health. These areas are more vulnerable to degradation and require targeted management to prevent further loss. With poor vegetation cover, high erosion rates, and a high risk of soil fertility loss and habitat destruction, a little over one third (34.2%) of the watershed suffers from significant degradation.

Environmentally sensitive area to land degradation (ESALD)

Table 11 and fig. 8 show the spatial pattern of land degradation sensitivity across the Bilate watershed, designated as critical, fragile, potential, and unaffected. Table 11 lists the

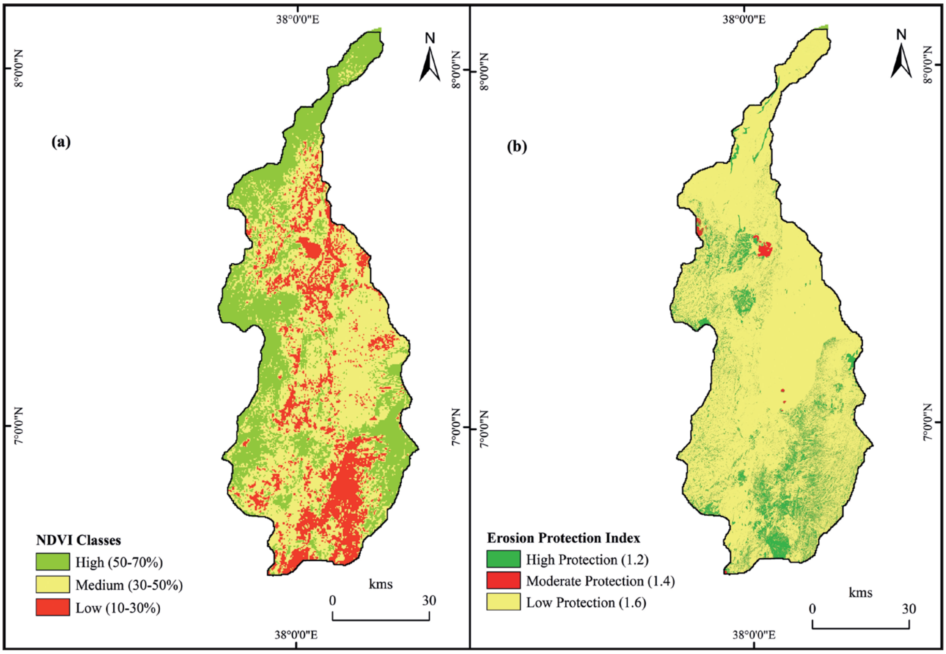

Fig. 6: Spatial distribution of vegetation quality sub-indices in the Bilate watershed: (a) NDVI (b) Erosion pro-tection Index

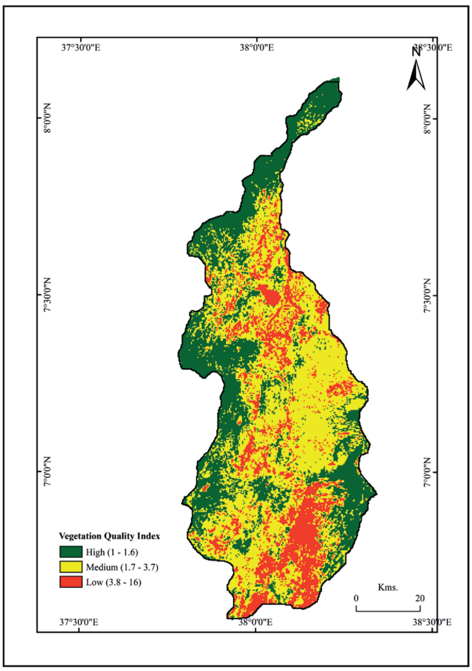

Fig. 7: Vegetation quality index of Bilate watershed

Table 11: Bilate watershed- Environmentally sensitive areas to land degradation

Category	Class	Index range	Area (km^2)	Area (%)
Critical class total areas 37.2%(2085.7km2)	Critical 3	>1.53	628.0	11.2
	Critical 2	1.42-1.53	1194.2	21.3
	Critical 1	1.38-1.41	263.5	4.7
Fragile class total areas 45.9% (2573.4 km2)	Fragile 3	1.33-1.37	695.2	12.4
	Fragile 2	1.27-1.32	1844.6	32.9
	Fragile 1	1.23-1.26	33.6	0.6
Potential class total areas 2.5% (140.2 km2)	Potential	1.17-1.22	140.2	2.5
Not Affected class total areas 14.4% (807.4 km2)	Not affected	<1.17	807.4	14.4

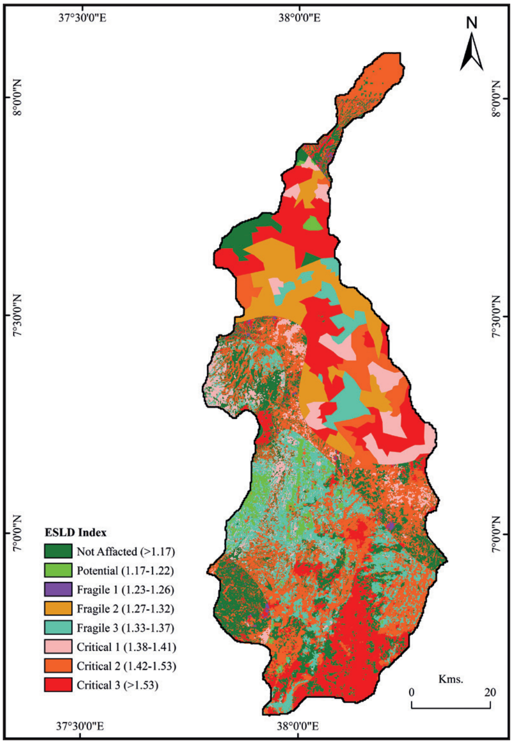

Fig. 8: Environmentally sensitive areas to land degradation in Bilate watershed

classification of ESAI ranges for each type along with three subclasses each. To further integrate the borders of the subsequent classes of the ESAIs, each type is defined on a three-point scale from 3 (high sensitivity) to 1 (low sensitivity) (Kosmas *et al*., 1999). The watershed is divided into eight groups based on the ESA index value: critical 3, critical 2, critical 1, fragile 3, fragile 2, fragile 1, potential, and unaffected (Table 11 and Fig. 8). Approximately 37.2 percent of the watershed is critically sensitive, much of it (21.3%) at critical 2 level. A little under half (45.9%) of the watershed is under the fragile category, particularly fragile 2 (32.9%). Only about 14.4 percent area is unaffected (Fig. 8). The critical areas (C1, C2, and C3) are located in the lower and middle eastern parts of the watershed, significantly impacted by land degradation primarily driven by severe soil erosion, low vegetation cover, low soil organic matter, and soil acidity, low vegetation quality, poor soil quality, and unfavable climate conditions, including low and erratic rainfall and high rainfall erosivity. The fragile areas (F1, F2, and F3) are not as severely impacted but still vulnerable to rapid deterioration- even a slight deterioration in any of the key factors can lead to severe degradation, highlighting sensitivity to land degradation if not managed carefully. This underscores the importance of targeted intervention into critical and fragile areas to prevent further degradation and promote sustainable land management practices throughout the watershed.

The potentially environmentally sensitive areas are mainly restricted to relatively deep soils of nearly flat to gently sloping areas under good vegetation cover. These areas are sensitive to degradation under sig-nificant changes in climate and of human activity. Non-affected areas by land degradation are confined to parts of the watershed with very deep soils and nearly flat topography. In general, the watershed is facing significant environmental challenges due to an amalgamation of natural fragility and anthropogenic activities.

Conclusion

This study provides a comprehensive assessment of land degradation sensitivity in the Bilate watershed, where land degradation remains a persistent problem. By integrating nine biophysical factors using the MEDALUS framework, the study mapped environmentally sensitive areas offering a spatially explicit un-derstanding of the degradation processes and their underlying drivers. The results found substantial proportion of the watershed either critical or fragile in terms of sensitivity to land degradation reflecting areas with pronounced biophysical limitations such as low vegetation cover, shallow and acidic soils, reduced soil organic matter, and unfavourable climatic conditions. In contrast, though small in areal extent, the potential and unaffected zones represent areas with comparatively higher resilience, but require continued monitoring to prevent future land degradation. The spatial classification of environmentally sensitive areas offers an important decision-support tool for land-use planning, watershed restoration, and resource allocation. The identification of critical and fragile hotspots underscores the need for targeted and context-specific land management interventions, including soil and water conservation measures, agroforestry systems, climate-resilient agriculture, and improved watershed management. Moreover, the findings highlight the importance of integrating community-based land management practices and local knowledge systems to ensure sustain-ability and long-term adoption of soil and water conservation practices. The establishment of routine monitoring mechanisms and early warning systems would further strengthen the capacity of local authorities and stakeholders to respond to emerging degradation risks in real time.

However, the study also identifies significant data gaps, particularly in terms of socioeconomic factors (rural households, poverty), and grazing land per hectare, climate conditions (acidity, wind speed), vegetation types, and groundwater availability. These gaps hinder the full application of the MEDALUS model in assessing land degradation in Ethiopia, highlighting the need for more comprehensive data collec-tion and research to improve the accuracy and effectiveness of land management strategies in the country. Overall, this study contributes valuable insights into the spatial dynamics of land degradation in the Bilate watershed and provides a scientific foundation for informed decision-making, policy formulation, and sustainable land management strategies. Addressing the identified data gaps through interdisciplinary research will be essential for refining degradation assessments and ensuring the long-term resilience of Ethiopian watersheds under growing environmental and socioeconomic pressures.

Competing interest

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

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