Global Journal of Engineering and Technology Advances
eISSN: 2582-5003
Cross Ref DOI: 10.30574/gjeta
Journal homepage: https://gjeta.com/

(Research Article)

Assessment of soil erosion by SLEMSA model using remote sensing and GIS: A case study of Taung Watershed of Ramotswa Agricultural District in Botswana

Motshereganyi Sylvester Moesi, Benedict Kayombo *, Rejoice Tsheko and Emmanuel Setlhabi

Department of Agricultural and Biosystems Engineering, Botswana University of Agriculture and Natural Resources, Private Bag 0027, Gaborone, Botswana.

Global Journal of Engineering and Technology Advances, 2023, 15(01), 008–018

Publication history: Received on 10 February 2023; revised on 26 March 2023; accepted on 29 March 2023

Article DOI: https://doi.org/10.30574/gjeta.2023.15.1.0056

Abstract

The Soil Loss Estimation Model for Southern Africa (SLEMSA) model integrated with Remote Sensing (RS) and Geographical Information Systems (GIS) was positively validated to spatially assess soil erosion risk in the Taung Watershed of Ramotswa Agricultural District during the period 2000 – 2020. The estimated annual soil erosion averaged 11.77 and 12.57 t/ha/year in 2000 and 2020, respectively. The Land Use/Land Cover (LULC) and topography were found to be key determinants of high soil erosion risk when using SLEMSA. The soil erosion assessment tools enabled prioritization of high erosion prone areas in the study area for soil conservation planning and watershed management.

Keywords: Taung watershed; Soil erosion; SLEMSA; RS; GIS

1. Introduction

Soil erosion has become a major component in the overall environmental degradation in the world that threatens food production [1]. Soil erosion can be accelerated by anthropogenic activities such as excessive cutting of trees, overgrazing [2] and tillage operations [3]. According to Pimentel and Burgess [4], about 10 million ha of arable land is dissipated due to soil erosion hence reducing the arable land that is available for world food production. About 16% of the land in Africa is degraded and soil erosion is of great concern in Sub- Saharan African countries [5]. Botswana, located in semi-arid environments, is most vulnerable to soil erosion threats due to less biomass to sustain soil structural integrity [6].

Population explosion, deforestation, unsustainable agricultural cultivation, and overgrazing are among the main factors causing soil erosion hazards in the highly degraded Kweneng, Kgatleng and Southern Districts of Botswana [7].

To select suitable conservation actions, the identification and quantification of soil loss sources are necessary [8]. Generally, soil erosion can be assessed using different soil erosion models which vary in degrees of complexity [9]. Soil erosion empirical models have proved to be the cheaper way of assessing the distribution and magnitude of erosion in watershed areas in Southern Africa [10]. The most widely applied empirical soil loss models are the Revised Universal Soil Loss Equation (RUSLE) and Soil Loss Estimation Model for Southern Africa (SLEMSA).

The introduction of Geographical Information Systems (GIS) and Remote Sensing (RS) technology has made it possible to implement the equation in a spatially distributed manner and prediction of soil erosion on a cell-by-cell basis [11]. It has several advantages in terms of identifying areas that are highly capable of being physically degraded, quantifying rates of soil loss, and mapping erosion prone areas [12].

* Corresponding author: Benedict Kayombo

Very little is currently known about the assessment and mapping of high erosion areas in the Southern District including South East of Botswana. The livelihood of the people in the Ramotswa Agricultural District of South East Botswana relies on crop and animal production. Soil erosion and soil fertility decline are accelerated by anthropogenic activities including use of crop residues as animal feed. It is vital to have information on the distribution patterns of soil loss hazard areas and their severity as it can be used for soil conservation planning. It is imperative to reduce soil erosion to raise agricultural productivity in the study area. The objective of the present study was, therefore, to assess the soil erosion risk in the Taung Watershed of Ramotswa Agricultural District.

2. Material and methods

2.1. Description of study area

The Taung Watershed is in Ramotswa Agricultural District and covers about 43 958 ha. It extends from 24° 50’ 0’’- 25⁰ 50’ 0’S latitude and 25° 35’ 0’’- 25⁰ 50’ 0’’ E longitude. The climate is semiarid. The rainfall is seasonal, with the wet season normally occurring between October and March while dry and cold winter months range from May to July. The mean total annual rainfall ranges from 400 to 550 mm. High temperatures are experienced during the wet season, recording between 30 to 32 °C on average during the day and between 16 to 20 °C on average at night. The watershed has a highly uneven elevation ranging from 1012 to 1489 m above sea level. The soils range from fine sands - loamy fine sand to sandy loams - sandy clay. The vegetation cover within the watershed is predominantly mixed shrub savannah and tree savannah [13]. An overview of the boundary of the study area is given in Figure 1.

2.2. Mapping of soil erosion risk

Mapping of soil erosion risk in the study area was carried out according to SLEMSA model. The model input data included rainfall energy, soil erodibility, slopes length and steepness, topographic factor, crop ratio and principal factor.

2.2.1. Rainfall Energy (E)

Long-time annual rainfall point data for a period of 26 years from 7 stations in and around Taung Watershed was obtained from the Department of Meteorological Services. Rainfall energy was then determined according to Equation (1) for erosive rainfall [14]. The mean annual rainfall was first interpolated to generate continuous rainfall data for each grid cell by using Analyst Tools Raster Inverse Distance Weighting (IDW) Interpolation in ArcGIS to create a raster map for the area. Details of the rainfall stations are presented in Table 1.

$$E = 18.846*P \quad \text{.......................................} \quad (1)$$

Where, E is the rainfall energy and P is the mean annual precipitation (mm).

Table 1 Mean annual rainfall of meteorological stations in the study area

Weather Stations No	Rainfall Weather Stations	Years of Observation	Mean Annual Rainfall (MAR) in mm	Northings	Eastings
1	Seapapitso-Kanye	1990-2015	453	-24.93333	25.36667
2	Moshupa Police Station	1990-2015	510	-24.76667	25.43333
3	Mogobane	1991,1992,1993,1997,2001 and 2005	480	-24.95000	25.70000
4	Ramotswa Station	1971-2014	483	-24.88333	25.86667
5	Gaborone MET H.Q	1989-2015	498	-24.66667	25.91667
6	Moeding College	1995-2019	505	-25.01667	25.73333
7	Lobatse Police Station	1999-2015	488	-25.25000	25.65000

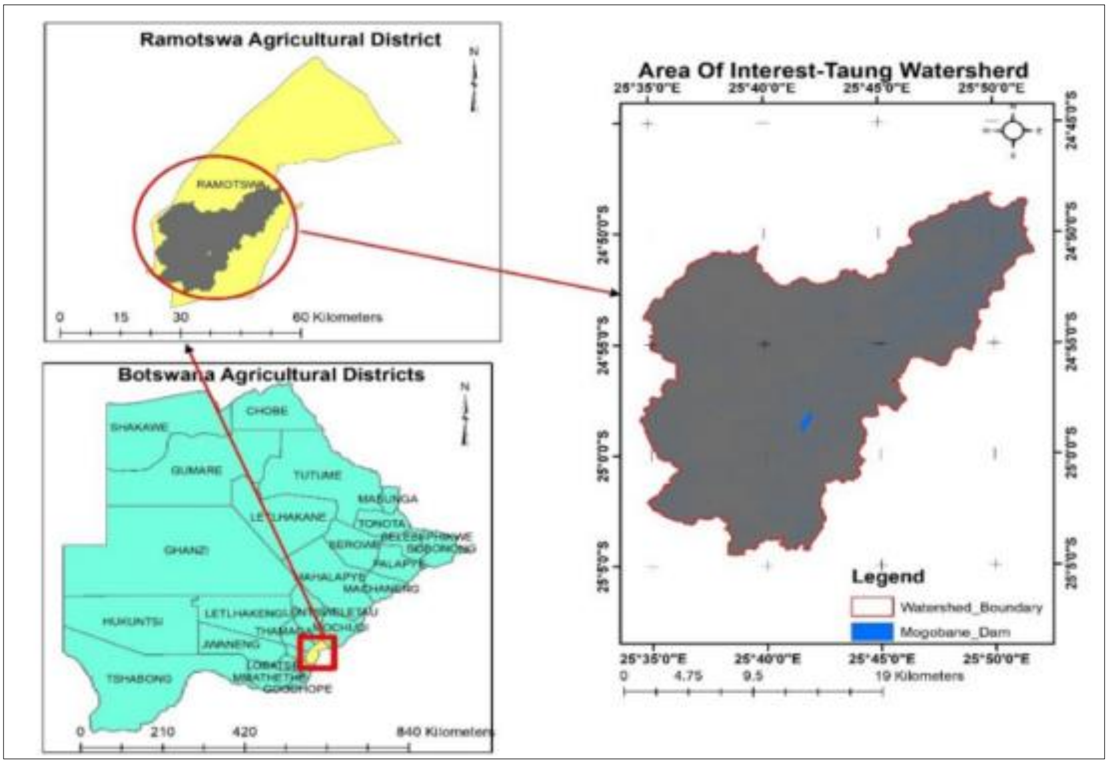


Figure 1 Location of Taung Watershed in Ramotswa Agricultural District of Southern District, Botswana

2.2.2. Soil Erodibility Factor (F)

Table 2 proposed by Morgan [15] was used to obtain the F-value.

Table 2 Calculation of the F value for soil erodibility in SLEMSA

The first calculation of the F value			**Adjustments to the 1st calculation of the F value Add**	
Soil texture	Class	F value	Add	Soil and manage characteristics
Sands	Light	4	-1	Light textured soil consisting mainly of sand and silts
Sandy loams			-1	Restricted vertical permeability within 1m from the surface or severe crusting
Loamy sand			-1	Ridging up and down the slope
			-1	Deterioration in soil structure due to more than 20ton/ha/yr. in the previous year
Sandy clay loam	Medium	5	-1	Poor management
Clay loam			-0.5	Slight to moderate surface crusting
Sandy clay			-0.5	Soil loss 10-20 t/ha/yr. in the previous year
			2	Deep well-drained light-textured soil
Clay	Heavy	6	1	Tillage operations encouraging high water retention (contour ridging)
Heavy clay			1	First season on no-tillage
				Subsequent season on no-tillage

2.2.3. Slope length and slope steepness

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of spatial resolution of 30 m was used to generate slope using Spatial Analyst Tools within ArcMap 10.7 environment. Flow accumulation and slope steepness were then calculated using filled DEM with a Raster Calculator in ArcGIS, using Equations (2) and (3):

$$l = \text{Flow accumulation} * \text{cell size} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

$$S = (0.43 + 0.30\ s + 0.043\ s^2)/6.613 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3)$$

Where:
l is the slope length,
S is the slope gradient factor and s is the gradient (%).

2.2.4. Topographic factor (X)

The topographic ratio is a product of two factors: a slope gradient factor and a slope length factor. The slope length and slope gradient factors were calculated using the filled DEM and entered the Equation (4) to produce the topographic factor grid map [16]. To calculate the slope length, derivation of flow accumulation was based on the DEM after conducting the Fill and Flow direction process respectively in ArcGIS [17].

$$X=\sqrt{\ } (l/22.1)\ (0.065+0.045S+0.0065S^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (4)$$

Where:
X is the topographic ratio,
l is the slope length (m), S is slope (%).

2.2.5. Crop ratio (C)

The crop factor was obtained from two classified Landsat images for the years 2000 and 2020. The prepared LULC maps of the watershed were used to find the C values corresponding to each land cover class. The C-factor values were assigned to every class in a GIS using a raster calculator, based on literature data in Table 3.

Table 3 The C factor values for the study area

No	LULC	C-value	Source
1	Built-up	0.09	[9]
2	Cultivated land	0.63	[9]
3	Shrubland	0.1	[18]
4	Woodland (Tree Savanna)	0.06	[9]
5	Waterbody	0	[8, 9]

2.2.6. Principal factor (K)

It combines the influences of the rainfall energy and soil erodibility to give the estimated mean annual soil loss from conventionally tilled bare soil on 4.5% slopes and 30 m by 10 m [19]. In this study, the K factor was derived from soil erodibility (F) and soil erosivity (E) using Equation (5) [20]:

$$K=\exp\ [(0.468 + 0.766F)\ \text{In}E + 2.88 - 8.121F] \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

2.2.7. Soil loss analysis

The overall procedure involved the use of the SLEMSA model in a GIS environment. The input parameters obtained from meteorological stations, soil map, topographic map, satellite images and DEM were processed as shown in Figure 2. A cell-by-cell analysis of the soil loss was done to determine annual soil loss rate by overlaying and multiplying the respective SLEMSA sub-model values (K, C, and X) interactively by using Spatial Analyst Tool Map Algebra Raster Calculator in ArcGIS 10.7 environment as shown in Equation (6) [14].

$$Z = KCX \qquad (6)$$

Where:
Z is the predicted mean annual soil loss in $tha^{-1}yr^{-1}$;
K is the mean annual soil loss in $tha^{-1}yr^{-1}$ from a standard field plot 30 x 10 m with a slope of 4.5% and for a soil of a known erodibility rating F under a weed-free bare fallow;
C is the ratio of soil lost from a cropped plot to that lost from bare fallow;
X is the ratio to account for different slope steepness and length.
The K and X were assumed to be the same for both 2000 and 2020 while the C factor varied.

The soil loss potential was then categorized into different severity classes to determine erosion risk priority areas for conservation planning [21].

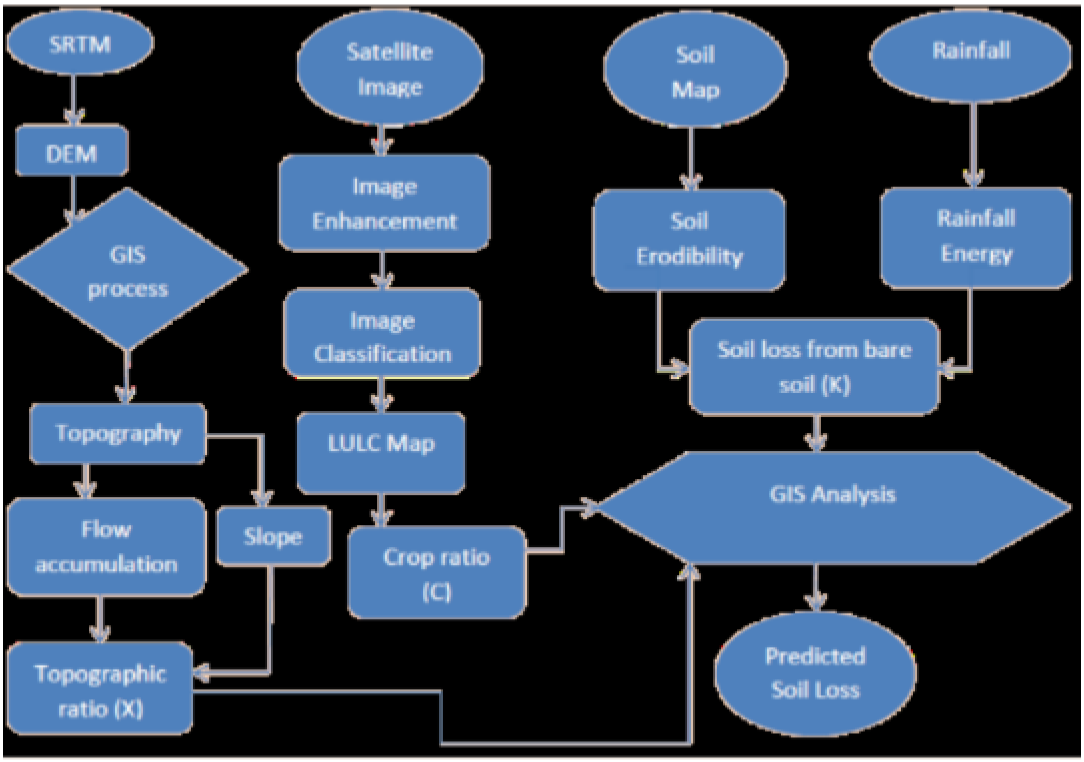


Figure 2 Flowchart for implementation of SLEMSA model

2.3. Software Packages and Data Processing

Geomatica 2018 Catalyst Professional software was used for image processing and digital image classification or spectral class recognition was accomplished by supervised classification. The classification results (i.e. land cover raster image) were exported into ArcMap 10.7 for accuracy assessment with the aid of high-resolution imagery software, Google Earth and Google Earth Pro. Layers were spatially organized with the same resolution and coordinate system within ArcGIS environment [22]. Microsoft Office was used for presentation, documentation and pre-processing calculations in excel environment. The GeoConverter-Geoplaner software package was used for converting geographical coordinates.

2.4. Validation of SLEMSA erosion model

A method of soil erosion accuracy assessment by Phinzi [23] was adopted to ascertain the quality and reliability of the model's results. Kappa coefficient was used to validate the model's result in terms of eroded and non-eroded areas. The soil loss was reclassified into high and low soil loss classes from the different soil loss severity classes. After the reclassification of the soil loss maps, 10 random points were generated and loaded into a handheld GPS. The GPS was then used to locate and verify these points on the ground.

3. Results and discussion

3.1. Mapping of soil erosion risk

Mapping of soil erosion in the study area was carried out according to SLEMSA model. The SLEMSA model includes topographic indices derived from the DEM, climatic factors, vegetation and soil characteristics.

3.1.1. Rainfall energy (E)

The mean annual precipitation data interpolated over the entire study area using IDW interpolation technique was converted to rainfall energy by applying Equation (1). The annual rainfall of Taung Watershed ranges from 480 to 505 mm resulting in rainfall and erosivity variation shown in Figure 3.

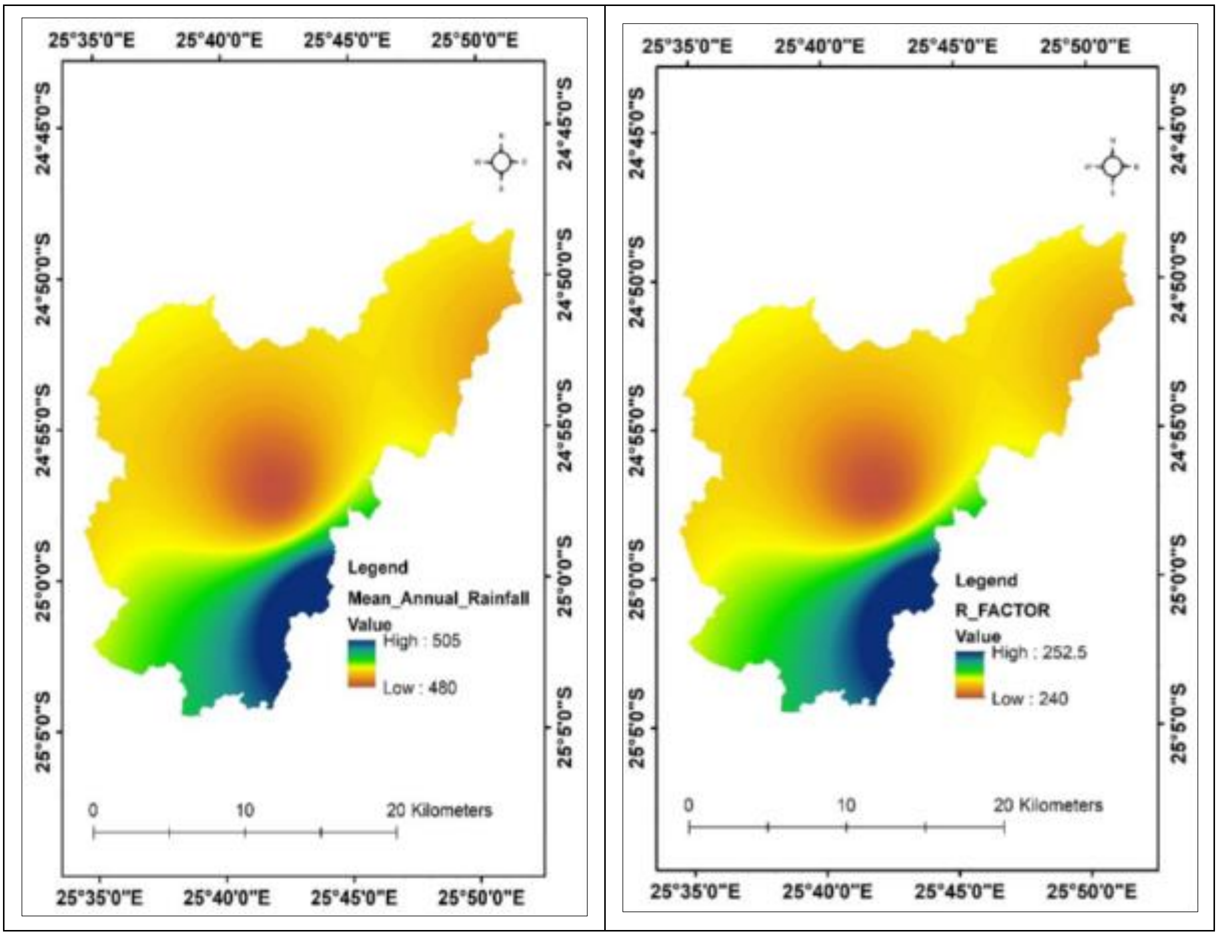
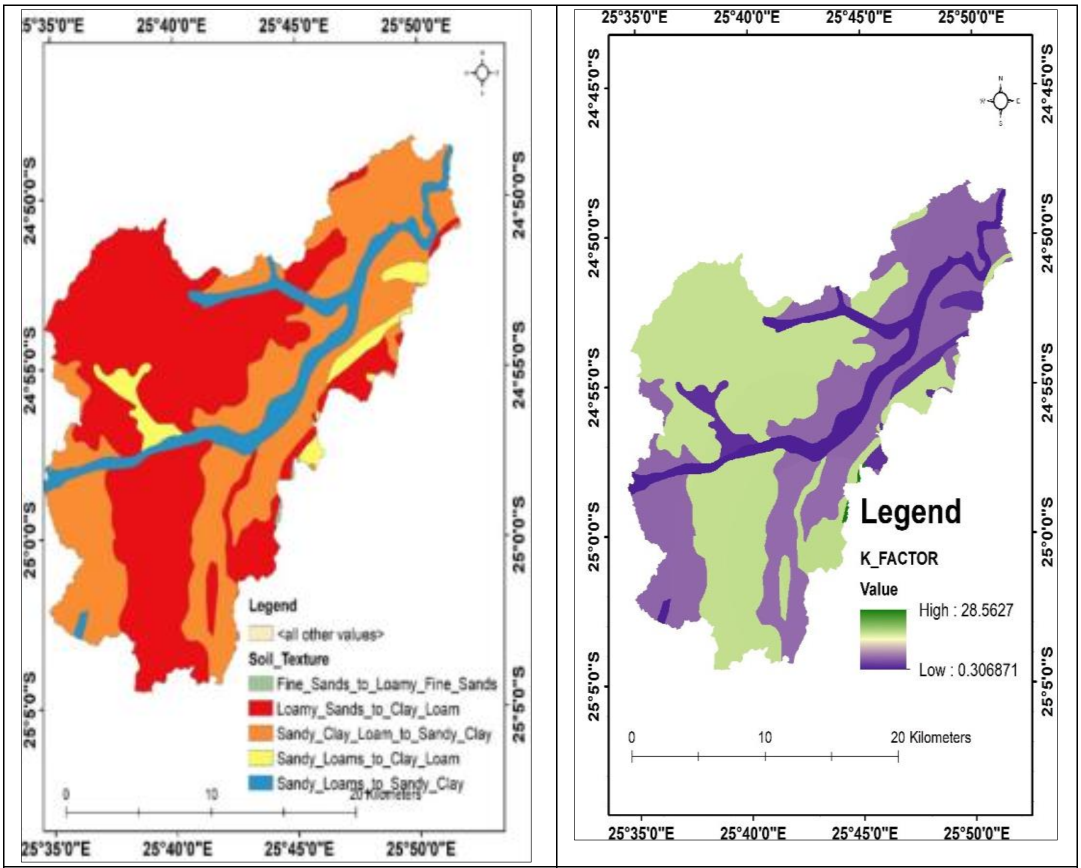


Figure 3 Rainfall and erosivity variation in Taung Watershed

3.1.2. Soil erodibility factor (F)

Soils which are highly susceptible to erosion have erodibility values close to 1, whereas corresponding values close to 10 indicate the resistive nature of the soil. Table 2 was applied to derive site F values according to soil texture map of Taung Watershed in Figure 4a. The F values varied with the soil texture.



a	b

Figure 4 Soil texture (**a**) and associated K factor (**b**) maps of Taung Watershed

3.1.3. Principal factor (K)

After determining the values of E and F, the value of K was calculated using Equation (5) in a GIS environment to produce a map. Principal K factor values varied from 0.31 tons/ha/yr to 28.56 tons/ha/yr as shown in Figure 4b.

3.1.4. Crop ratio factor (C)

The crop ratio factor was obtained from two classified Landsat images for the years 2000 and 2020. The prepared LULC maps of the watershed (Figure 5) were used to find the C values corresponding to each land cover class. The corresponding C values for each land cover class were sourced from other studies as given in Table 3. The C values varied from 0.0 to 0.63 as shown in Figure 6.

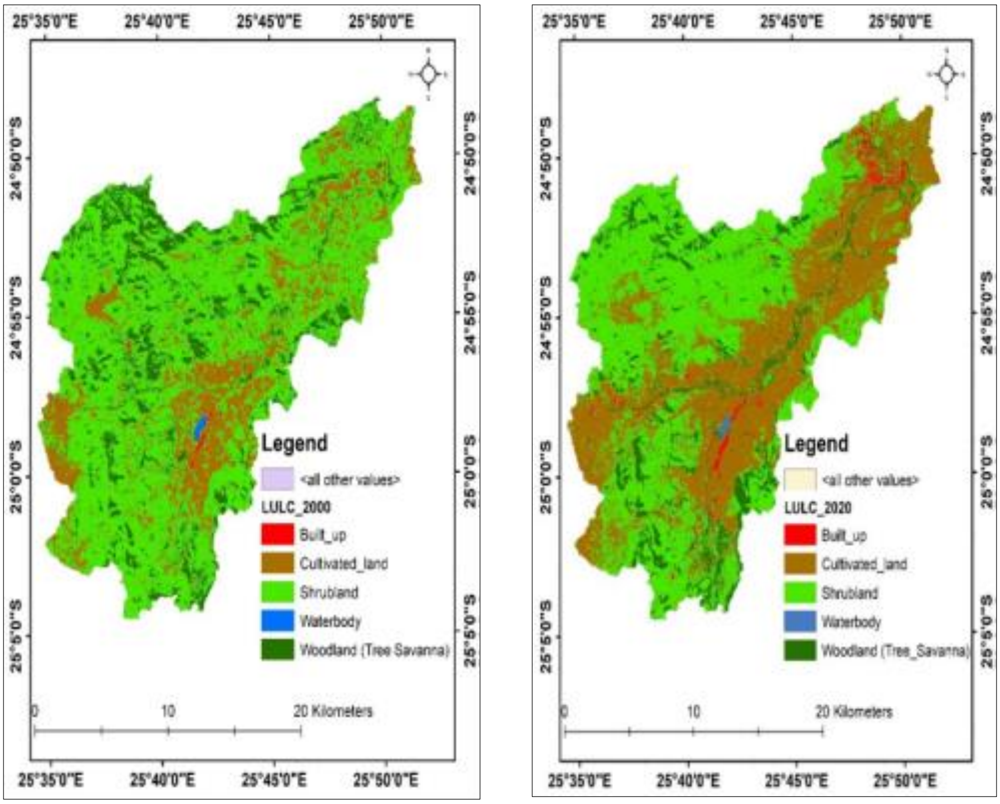


Figure 5 The LULC maps of 2000 and 2020 for Taung Watershed

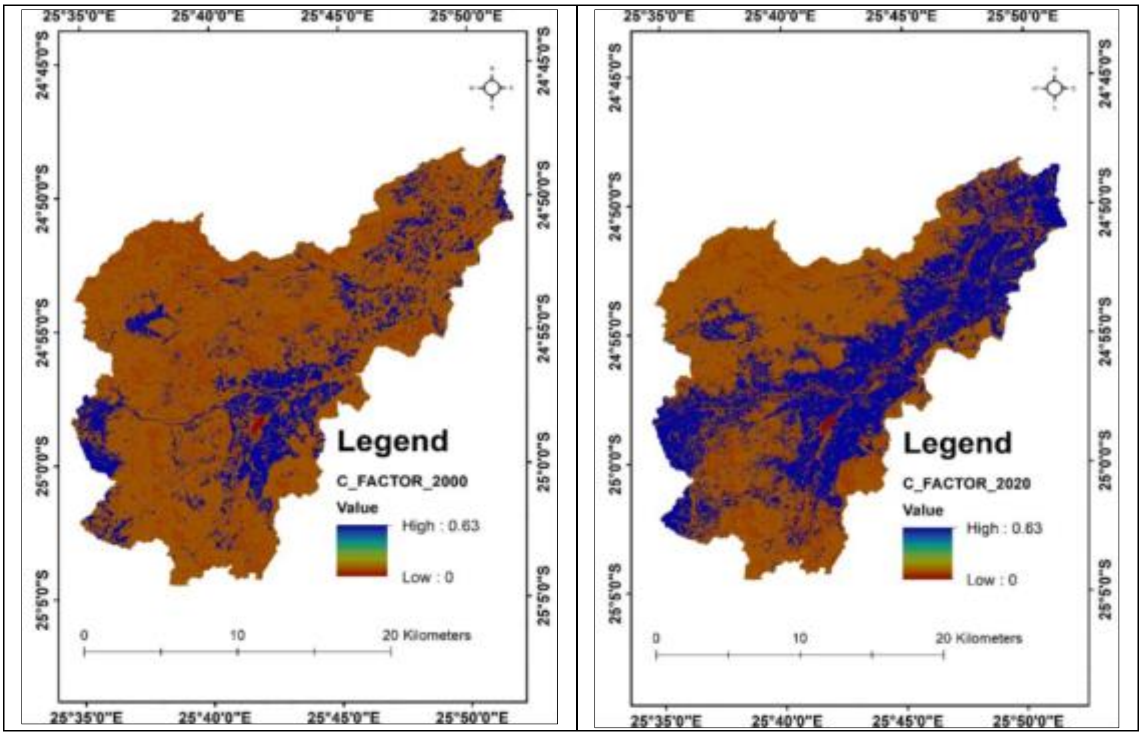


Figure 6 The C factor maps of 2000 and 2020 for Taung Watershed

3.1.5. Topographic factor (X)

The topographic factor map (Figure 7) was determined using Equation (4). The X factor values ranged from 0 to 417.7.

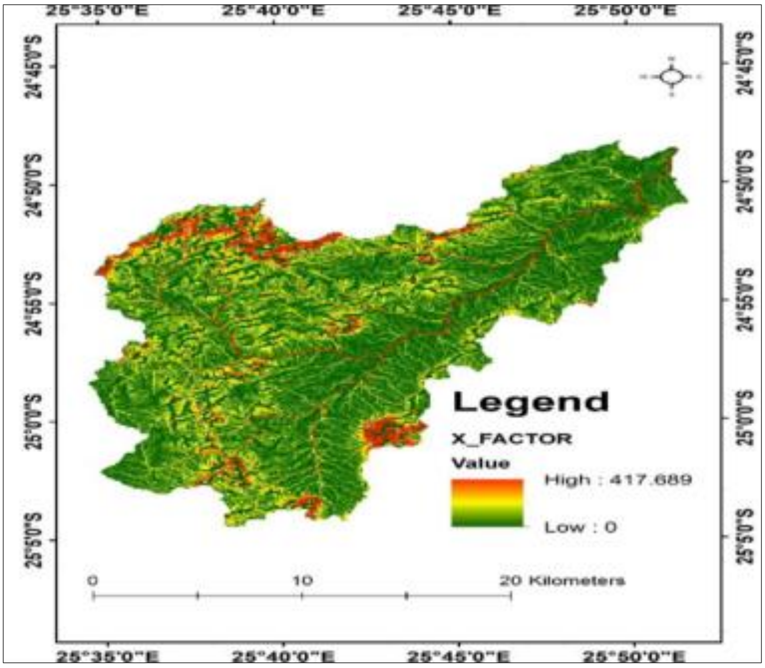


Figure 7 Topographic factor map of Taung Watershed

3.2. Determination of SLEMSA model (Z)

The calculation of erosion in this model was carried out through equation Z = KCX [14] to obtain the soil loss maps of 2000 and 2020 shown in Figure 8. The results were then used to determine different categories of erosion-risk areas shown in Table 4 and Figure 8.

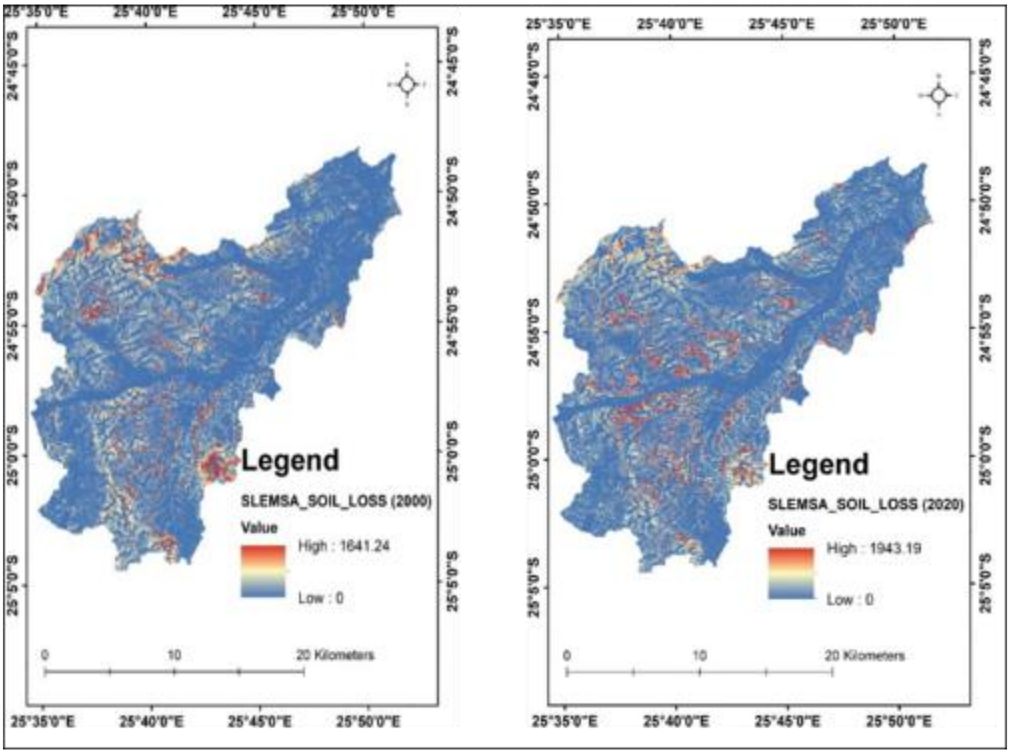


Figure 8 SLEMSA soil loss severity maps of 2000 and 2020 for Taung Watershed

Table 4 SLEMSA soil loss severity in 2000-2020 for Taung Watershed

Severity Class	**Priority Class**		**2000**			**2020**
(Tonne/ha/year)			**(ha)**	**Area (%)**	**(ha)**	**Area (%)**
0-5	Very low	5	22730.85	51.71	20236.61	46.04
5-12	Low	4	5197.71	11.82	4592.98	10.45
12-25	Moderate	1	6970.24	15.86	7575.21	17.23
25-60	High	1	5772.11	13.13	6980.97	15.88
60-150	Very high	2	2639.06	6.00	3318.92	7.55
>150	Extremely high	3	648.10	1.47	1253.38	2.85

Whereas the area under very low (0 – 5 t/ha/year) and low (5 – 12 t/ha/year) soil erosion decreased moderately in 2020 compared to 2000, areas susceptible to moderate (12 – 25 t/ha/year) and high (25 – 60 t/ha/year) erosion risk increased markedly in 2020 (Table 4). The area under very high (60 – 150 t/ha/year) and extremely high (>150 t/ha/year) erosion risk also increased in 2020 compared to 2000 although the area covered was small. The model validation recorded a fair agreement (Kappa = 0.40).

These pronounced changes in erosion-risk severity were driven by a major increase in cultivated land and built-up area coverage while other LULC categories such as shrubland and woodland decreased during the period. This is confirmed by Matlhodi et al. [24] in the Gaborone Catchment, which covered the Taung watershed.

It is imperative, therefore, that soil conservation efforts be directed to moderate, high, very high, extremely high, low and very low erosion-risk areas, in that order of priority (Table 4).

4. Conclusion

The objective of the present study was to spatially assess soil erosion risk in the Taung watershed during the period 2000 – 2020 using SLEMSA model integrated with RS-GIS. The model estimated the mean annual soil loss of 11.77 t/ha/year in 2000 and 12.57 t/ha/year in 2020. The topography and LULC markedly contributed to a high soil erosion risk. Most of the area in the watershed was converted into croplands from 2000 to 2020, and that accelerated the susceptibility of soil to erosion.

The model validation recorded a fair agreement (Kappa = 0.40).

The study provides valuable information that may help land-use planners, policy makers, and decision-makers on soil conservation practices for the area.

Compliance with ethical standards

Acknowledgments

The authors are grateful to the Ministry of Agricultural Development and Food Security for providing digital soil data, the Department of Meteorological Services (DMS) for availing climatic data, and the United States Geological Survey (USGS) Earth Resources Observation Systems (EROS) for downloading satellite images of the study area.

Disclosure of conflict of interest

We the authors hereby declare that there are no competing interests in this publication.

References

[1] Rahman MR, Shi ZH, Chongfa C. Soil erosion hazard evaluation-An integrated use of remote sensing, GIS and statistical approaches with biophysical parameters towards management strategies. Ecological Modelling. 2009; 220(13–14):1724–34.

[2] Snyman HA. Soil erosion and conservation. In: Tainton NM, ed. Veld Management in South Africa. Scottsville: University of Natal Press; 1999. p. 355-380.

[3] Department of Primary Industries [Internet]. Sydney: Department of Primary Industries; © 2014. Available from http://www.dpi.nsw.gov.au/agriculture /resources/s.

[4] Pimentel D, Burgess M. Soil erosion threatens food production. Agriculture (Switzerland). 2013; 3(3):443–463.

[5] Bai ZG, Dent DL, Olsson L, Schaepman ME. Proxy global assessment of land degradation. Soil Use & Management. 2008; 24:223–234.

[6] Manyiwa T, Dikinya O. Using universal soil loss equation and soil erodibility factor to assess soil erosion in Tshesebe village, North East Botswana. African Journal of Agricultural Research. 2013; 8(30):4170–78.

[7] Foster RH. Methods for assessing land degradation in Botswana. Earth & Environment. 2006; 1:238–276.

[8] Zerihun M, Mohammedyasin MS, Sewnet D, Adem AA, Lakew M. Assessment of soil erosion using RUSLE, GIS and remote sensing in NW Ethiopia. Geoderma Regional. 2018; 12:83-90.

[9] Ganasri BP, Ramesh H. Assessment of soil erosion by RUSLE model using remote sensing and GIS - A case study of Nethravathi Basin. Geoscience Frontiers. 2016; 7(6):953–961.

[10] Smith HJ. Application of Empirical Soil Loss Models in southern Africa: a review. South African Journal of Plant and Soil. 1999; 16(3):158-163.

[11] Vargas R, Omuto C. Soil loss assessment in Malawi. Food and Agriculture Organization of the United Nations, UNDP-UNEP Poverty-Environment Initiative and Ministry of Agriculture, Irrigation and Water Development, Malawi; 2016.

[12] Chen Y, Yu J, Khan S. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. Environmental Modelling & Software. 2010; 25(12):1582-91.

[13] Huete AR, Jackson RD, Post DF. Spectral response of plant canopy with different soil backgrounds. Remote Sensing of Environment. 1985; 17:37-53.

[14] Elwell HA. Modelling Soil Losses in Southern Africa. Journal of Agricultural Engineering Research. 1978; 23:117-127.

[15] Morgan RPC. Soil erosion and conservation. London: Blackwell; 1986.

[16] Morgan RPC, Davidson DA. Soil Erosion and Conservation. London: Longman Group; 1991.

[17] Bvindi A. Assessment of soil erosion hazard around the abandoned Nyala mine in formerly Mutale Municipality, Limpopo Province, South Africa [M.Sc. thesis]. KwaZulu Natal: University of KwaZulu Natal; 2019.

[18] Wischmeier WH, Smith DD. Predicting rainfall erosion losses: a guide to conservation planning. USDA Handbook No.537: USDA; 1978.

[19] Stocking MA. Soil loss estimation for rural development: a position for geomorphology. Geomorphology. 1980; 36:264-273.

[20] Morgan RPC. Soil erosion and conservation. 2nd ed. London: Longman Group Limited; 1995.

[21] Marondedze AK, Schütt B. Assessment of soil erosion using the RUSLE model for the Epworth District of the Harare Metropolitan Province, Zimbabwe. Sustainability- MDPI. 2020; 12(20):1-24.

[22] Parece T, Campbell JB, McGee J. Remote sensing analysis in an ArcMap environment. 2nd ed. Independently published; 2017.

[23] Phinzi K. Spatio-temporal appraisal of water-borne erosion using optical remote sensing and GIS in the Umzintlava Catchment (T32E), Eastern Cape, South Africa [M.Sc. thesis]. KwaZulu Natal: University of KwaZulu Natal; 2018.

[24] Matlhodi B, Kenabatho PK, Parida BP, Maphanyane JG. Evaluating land use and land cover change in the Gaborone dam catchment, Botswana, from 1984-2015 using GIS and remote sensing. Sustainability-MDPI. 2019; 11(19),5174.