Proceedings of 12th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: October Volume: 12

Assessing Impact of Climate Change and Land Use Cover on Soil Erosion using RUSLE and SWAT model in Kaligandaki Watershed

Srijana Shrestha [a], Sadikshya Rana Dangi [b], Khem Narayan Poudyal [c]

[a, c] *Department of Applied Science and Chemical Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[b] *United States Department of Agriculture – Agriculture Research Service (USDA-ARS)*
[a] srishrestha2053@gmail.com, [b] sadikshya.dangi@usda.gov, [c] khem@ioe.edu.np,

Abstract

Soil erosion is becoming a greater global issue because of the impact of climate change and human action. In Kaligandaki watershed, soil erosion is a problem because it reduces the fertility of agricultural land in hilly terrain. Due to its vulnerability to climate change and reliance on agriculture, it is essential to estimate soil erosion in hilly regions of Nepal. The spatial variation of soil erosion exposed due to Land Use Land Cover (LULC) and climate change was identified using Revised Universal Soil Loss Equation (RUSLE) and Soil and Water Assessment Tool (SWAT) in the ArcGIS interface. The findings of this study demonstrate that the average soil erosion losses anticipated by the two models. The annual average soil rate was found 14.4 t/ha/yr and 8.89 t/ha/yr in 2019 by using the SWAT model and RUSLE model respectively. The most eroded area was identified in barren lands and agricultural areas having steep slopes. It was found that both models are suitable for soil erosion estimation. The strong correlation between rainfall, soil loss and surface runoff was found. The watershed was classified into seven priority categories for conservation intervention based on threats of soil loss. The result of the study strongly points to the necessity of sufficient quality and quantity of observed data. The finding is useful for policy-making and watershed management planning processes by land use planners and decision-makers for prioritization of different regions.

Keywords

Soil Erosion, RUSLE, SWAT, Remote Sensing, Kaligandaki

1. Introduction

The significant impact of climate change on soil erosion is one of the most severe environmental impacts of the twenty-first century. The abrupt change in the precipitation pattern and increasing rate of surface temperature causes serious ecological degradation in many developing countries like Nepal[1]. Soil erosion is the process that includes the detachment, transport of soil, and deposition. Soil erosion results due to erosive forces such as rainfall, wind, gravity, and human actions. In steep areas, soil erosion causes serious threats such as loss of fertile soil in agricultural land, forest covers, and human settlements [2]. Climate change and land use cover directly influences soil loss altering the weather patterns, surface runoff, infiltration rate, and biomass production [3, 4]. The assessment of the impact of climate change on soil erosion shows whether the severity of soil erosion is low, medium, or high. The LULC changes in the steep slopes are one of the major reasons for resource degradation and it causes landslides and mudslides in the hilly regions. Nearly, 24 million tonnes of soil are eroded from the country each year [5] which affects 34 percent of the agricultural land primarily through sheet and rill erosion [6].

There is a number of empirical and physical-based soil erosion estimation model with different level of complexity and data input. The application of remote sensing technologies and data from the existing soil erosion model significantly resolves the time-consuming and tedious conventional method of evaluating soil erosion. This study analyzes the spatial distribution of the annual soil erosion rate and the severity of the impact of climate change on soil erosion using the RUSLE and SWAT models. The Universal Soil Loss Equation (USLE) was first developed by Wischmeier and Smith in 1965 [7] and it was further revised by Renard in 1997 [8]. Whereas, the SWAT model is a semi-distributed, time-continuous hydrological model and estimates soil erosion on the basis of the Modified Universal Soil Loss Equation (MUSLE) [9] was developed by the United States Department of Agriculture-Agriculture Research Service (USDA-ARS) & Texas A & M University in the early 1990s. Globally, there is a growing problem with soil erosion, but the Himalayan region is particularly affected. With more than 70 % of its land covered in mountains [10], Due to the combination of extremely steep slopes, geological units of varied resistance, and the increase in rainfall pattern in the Himalayas, this region is highly vulnerable to geographic instability. In order to prevent damage and fatalities like those seen due to erosion in hilly areas of Nepal, [11] suggested regular analysis of soil erosion using different tools and models in the Kaligandaki watershed. This study aims to (a) identify the annual soil erosion rate and develop the spatial distribution soil losses map of the Kaligandaki watershed (b) analyze the impact of LULC and climate change on soil erosion, and (c) provide the information for decision makers for land management practices.

2. Materials and Methods

2.1 Study Area

The Kaligandaki watershed is significant in the upper Himalayas of Nepal as a major tributary of the Ganges River Basin. The Annapurna and Dhaulagiri Himalayas with altitudes of more than 8000m also lie in the Kaligandaki Watershed. It is situated between 27°43'N and 29°19'N, and 82°53'E and 84°26'E, with a catchment area of roughly 7400 sq. km. It covers Mustang district, most part of the Myagdi and some part of Kaski, Baglung, Parbat, Gulmi, Arghakhachi, Syangja, Palpa,Tanahu and Nawalparasi districts. The Kaligandaki watershed's elevation ranges from 457 to 8143 meters, resulting in significant topographic changes. The Kaligandaki watershed's upper reaches are covered by snow, and glaciers, the central part of the watershed is mountainous, with high-altitude terrain, and the southern plains have a mild climate. The intensity of the precipitation decreases from east to west and south to north part of the study area.

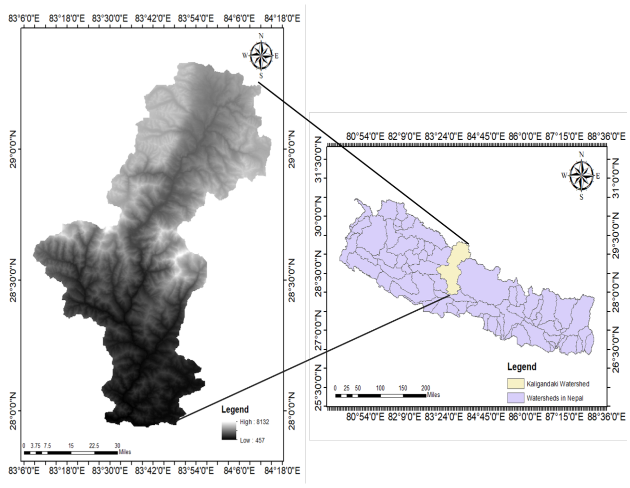

Figure 1: Study Area Map

2.2 Data Used

The data used to carry out this study is listed in the table(1). The data processing was done in ArcGIS, ArcSWAT, and Python interface. Digital Elevation Model (DEM) with 30 m resolution was downloaded from the United States Geographical Survey (USGS). The Food and Agriculture Organization(FAO) Digital Soil Map of the World (DSMW) was acquired and clipped to prepare the soil type map required for the study area in the ArcGIS interface. The land cover map of Nepal for the years 1990 and 2019 was retrieved from the International Center for Integrated Mountain Development(ICIMOD) at the resolution of 30m and extracted for the study area. The precipitation and temperature data were retrieved from the Department of Hydrology and Meteorology (DHM) of Nepal. The daily observed precipitation for the stations Lumle, Jomsom, Tatopani, and Baghara was collected between 1992 and 2021. Likewise, due to the unavailability of continuous observed data in other stations, temperature data of stations Lumle and Jomsom was taken between 1992 and 2020.

2.3 Methods

2.3.1 RUSLE Model

The annual average soil loss estimation in the RUSLE model requires five factors: Rainfall Erosivity (R), Soil Erodibility (K), Slope Length Steepness (LS), Cover Management(C), and Conservation Practice (P) factors as shown in equation 1:

$$SE = R * K * LS * C * P \tag{1}$$

where SE is the average annual erosion rate in ($t ha^{-1}$ $year^{-1}$); R = Rainfall Erosivity Factor in MJmm ha^{-1}

Table 1: Data Used

Dataset	Spatial Resolution	Data sources/Links
DEM	30m	USGS
		https://earthexplorer.usgs.gov/ digitalelevation/SRTM
Soil Map	1:5000000	Digital Soil Map of the World developed by FAO
		https://www.fao.org/land-water/land/ land-governance/land-resources/-planning-toolbox/category/details/en/c/1026564/
Landcover Map	30m	ICIMOD
		http://rds.icimod.org
Rainfall Data	30 year (1992-2021)	Daily mean precipitation and temperature of Nepal recorded by DHM
		http://www.dhm.gov.np/

h^{-1} yr^{-1}; K = Soil Erodibility Factor in t ha MJ^{-1} mm^{-1}; LS = Slope Length Steepness Factor and is dimensionless; C = Cover Management factor and is dimensionless; and P = Conservation (Support) Practice Factor and also is dimensionless.

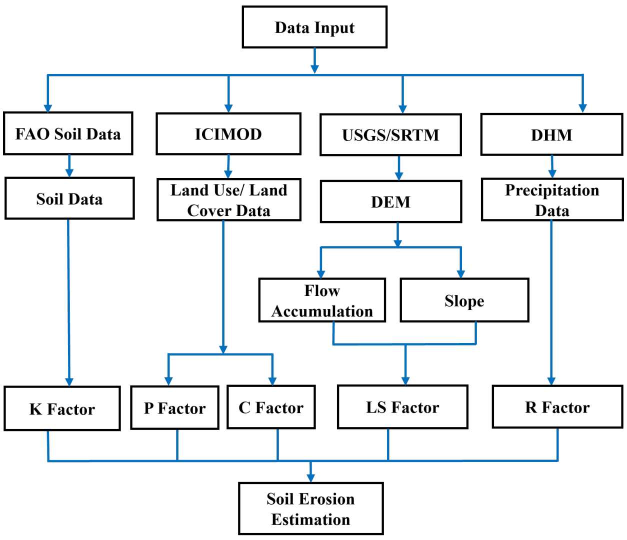

Figure 2: RUSLE Model Methodology

Rainfall Erosivity Factor (R) : Rainfall erosivity factors in the study area depend on the rainfall intensity and it describes the effect of rainfall on soil erosion. It is expressed as:

$$R = 38.5 + 0.35P \tag{2}$$

where R and P are the rainfall erosivity factor and Mean Annual Precipitation in mm respectively.

Soil Erodibility Factor (K) : The K-factor value shows the soil's vulnerability to erosion, soil detachment, and the volume and rate of runoff in response to an appropriate input of rainfall. The soil maps for the study area were then used to evaluate the soil classes, and K-factor values for each type of soil were obtained from the literature and entered into ArcGIS for analysis to create a K-factor map [12].

Slope and Steepness Factor (LS): The DEM dataset was used to derive the Slope gradient factor (S) and slope-length factor (L). The LS factor expresses the effect of topography, slope length, and steepness on soil erosion. The DEM data was used for flow accumulation and slope angle analysis in the ArcGIS interface using a spatial analyst tool with the following expression [13]:

$$L = \left(\frac{\text{Flow accumulation} * \text{Cell Size}}{22.13}\right)^{m} \tag{3}$$

$$S = \sin\left(\frac{\text{Slope}\% * 0.01745}{0.09}\right)^{1.3} \tag{4}$$

where m varies between 0.2 to 0.5 and slope% is a slope in percentage.

Cover Management Factor (C) : The land use cover map produced by the ICIMOD was first reclassified into seven major land classes of the watershed and a C value was assigned for each land class. The C factor value ranges between 0-1 where the least value means no erosion as compared to the soil from the barren land and the higher value shows the high probability of soil erosion[14].

Table 2: Cover Management Factor

Land Class	C Value
Forest	0.01
Grassland/Shrubland	0.35
Barren land	0.20
Agriculture Area	0.50
Waterbody	0.001
Snow/Glacier	0.00
Built-up area	0.10

Conservation (Support) Practice Factor (P) : The P-factor represents the difference in soil loss in an area using a specific conservation technique and not using any type of conservation technique. The P values vary from 0 to 1, with 0 denoting a facility with very good land management practices and 1 denoting a without conservation practices [15].

Table 3: Conservation Practice Factor

Slope%	P factor
0-7	0.55
7-11.3	0.6
11.3-17.6	0.8
17.6-26.8	0.95
>26.8	1

2.3.2 SWAT Model

The SWAT model requires meteorological data, soil properties data, land use and land cover map, and DEM for the analysis [16]. SWAT divides a basin into a number of sub-basins that are connected by a stream network, and then simulates surface runoff and soil erosion and other parameters for each sub-basin using all required data input. It is commonly used to assess hydrological components of a basin and also used for analyzing land use and climate change impact on water resources, sediment, and crop chemical yields [17]. The SWAT model is based on the following water balance equation and simulates the land phase of the hydrological analysis, land and water management practices, nutrients, and pesticides in the large watershed area:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{Surf} - ET_i - W_{seep} - Q_{gw}) \tag{5}$$

where SW_t = Final soil water content, SW_0=initial soil water content on day i, the time(days), R_{days}=precipitation on day i, Q_{surf}=surface runoff on day i, ET=evapotranspiration on day i, W_{seep}=water entering the vadose zone from the soil profile on day i, and Q_{gw}=return flow on day i. The unit of all parameters except the time is mm.

The SWAT model applies the MUSLE model to calculate the sedimentation yield and surface for each sub-basin.

$$Sed = 11.8 * (Q_{surf} * Q_{peak} * area_{hru})^{0.86} * K_{USLE} * P_{USLE} * C_{USLE} * LS_{USLE} * CFRG \tag{6}$$

where *Sed* is Soil erosion in tons/ha, Q_{surf} = Surface runoff volume in mm of water/hectares, q_{peak} = Peak runoff rate in m^3/s, $area_{hru}$ = HRU area in Hectares, K_{USLE} = soil erodibility factor, P_{USLE} = Support practice factor, C_{USLE} = Cover management factor, LS_{USLE} = Topographic factor, and $CFRG$ = coarse fragment factor.

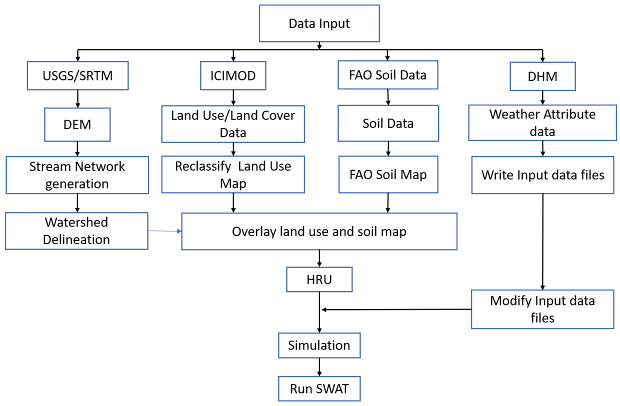

Figure 3: SWAT Model Methodology

A dataset of sub-basins and stream reaches is created as a result of the watershed delineation procedure and was used in the simulation. The watershed was delineated into a number of sub-basins to measure by overlaying the land use map, soil data, and DEM. Each sub-basin is connected to the reaches of streams. The sub-basins were further divided into the smallest unit Hydrological Response Unit(HRUs). The surface runoff flow and sedimentation were simulated for each HRU and the overall value of each sub-basin was measured. SWAT model was set up from 2006 to 2010 with the year 2006 to 2010 serving as the warming period. The simulated results could not be validated due to the lack of measured data.

3. Results and discussions

3.1 Results

3.1.1 Land Use Land Cover change

The Kaligandaki watershed was classified into seven land cover type classes based on the major land use types. The results show the significant changing trend of the land use cover in the study period. Table (4) shows the percentage change in LULC over time and the proportional percentages of various LULC classes during the study periods. The analysis of land use data reveals the degree of changes in the composition of the LULC dynamics over 29 years. The agriculture area of the study area decreased from 13.64 % to 9.34% of the total area and in the same way, the barren land reached 14.91 % of the total area in 2019 from 26.99% of total barren land in 1990. Fig 4 shows a large portion of the barren land is converted into the grassland/shrubland categories. The major causes of this change might be an increase in average surface temperature and shifting of treeline as one of the major impacts of climate change on the physical environment [18].

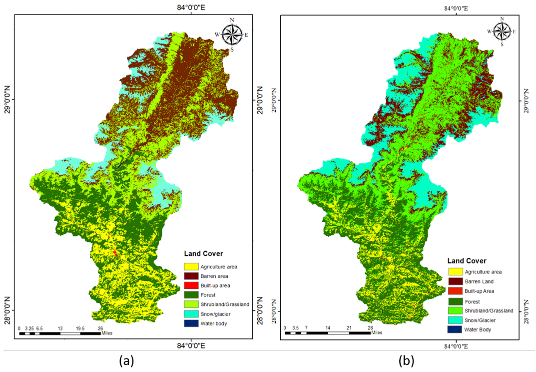

Figure 4: Land Use Map (a) 1990 (b) 2019

Table 4: Land Cover Status 1990 & 2019

	1990		2019	
Land Class	Area(Sq.km)	Area (%)	Area(Sq.km)	Area(%)
Snow /Glacier	725.00	9.77	1,205.08	16.23
Water bodies	21.00	0.28	20.99	0.28
Forest Cover	1,850.00	24.92	1,919.98	25.87
Barren land	2,004.00	26.99	1,106.44	14.91
Built-area	4.00	0.05	39.90	0.54
Agriculture Area	1,013.00	13.64	693.46	9.34
Grassland/Shrubland	1,807.00	24.34	2,437.16	32.83

3.1.2 Soil Loss Map

The Rainfall erosivity factor(R) value ranges between 45.1 to 199.13 MJmm $ha^{-1}h^{-1}yr^{-1}$ with higher intensity in the southwestern part and the lowest value in the northern part of the study area. The K factor value ranges from 0.04 to 0.28. The LS factor value ranges between 0-1937.33. The C factor value was found between 0 and 0.5 with a lower value signifying no loss and a higher value signifying uncover and a high probability of soil loss The P Factor ranged from 0.55 to 1. Fig. (7) shows the RUSLE factor maps for the annual average soil loss estimation of the Kaligandaki watershed. The factors of the RUSLE

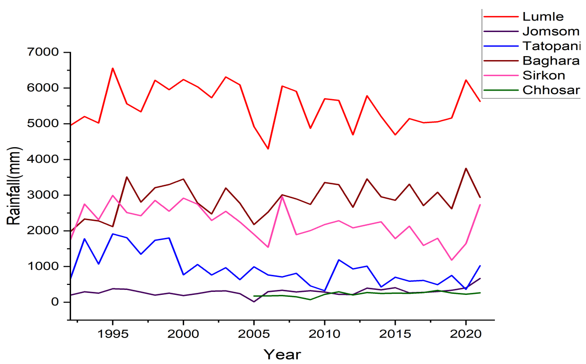

Figure 5: Annual mean precipitation pattern of stations (1992-2021)

Figure 6: Annual Mean Temperature Patterns of Lumle and Jomsom Stations(1992-2020)

model were analyzed in the ArcGIS environment for soil erosion estimation within the study area. The total annual soil loss rate ranges between 0 to 7638 t/ha/yr. The watershed was categorized into seven erosion classes based on the severity as in [19, 10].In 2019, 69.01% area have 0-1 t/ha/yr soil erosion, 18.81% have 0-5 t/ha/yr, 3.55% have 5-10 t/ha/yr,5.23% have 10-20 t/ha/yr, 0.7% have 20-40 t/ha/yr, 1.8% area have severe soil erosion condition with soil erosion rate 40-80 t/ha/yr and 0.8% area of the watershed is in the very severe condition (>80t/ha/yr) and need immediate action Table (6).

The main factors that tended to affect the quantity of soil loss in the watershed were soil type, land use/cover, and slope gradient. In general, the estimated rates of soil loss were generally higher in barren land and agricultural areas, and slope steepness higher than 26.8%. The mean soil erosion in the agricultural areas and barren land was found to be 8.89 t/ha/yr and 11.09 t/ha/yr as shown in Fig. 9a. The soil erosion rate was identified as lower in the human settlement. Compared to land use categories with mid or natural vegetation including grassland, shrubland, and forest, land use types with crop cultivation area and barren land are far more vulnerable to soil loss.

In 2019, the average soil erosion rate for forest cover, cropland, shrubland, and barren land is 3.23 t/ha/yr, 8.89t/ha/yr, 3.16t/ha/yr, 11.09 t/ha/yr respectively. The soil erosion rate was 6.73 t/ha/year for steep slopes(26.8 %) and about 3.44 t/ha/yr soil loss was estimated in slopes below 7%. Particularly on fragile and steep terrain that had been turned from forests to agricultural fields, there was a significant rate of erosion. The low infiltration rate and high potential runoff capacity of soil texture make this area more vulnerable to soil erosion. Estimated soil loss rates were low in regions

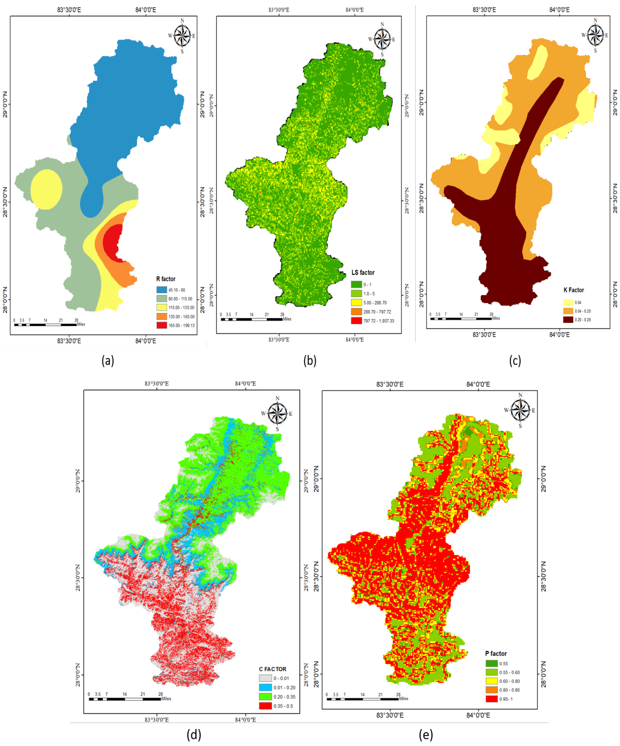

Figure 7: (a) Rainfall Erosivity Factor (R) (b) Slope Steepness Factor(LS) (c) Soil Erodibility Factor(K) (d) Cover Management Factor(C) (e) Conservation Practice Factor(P)

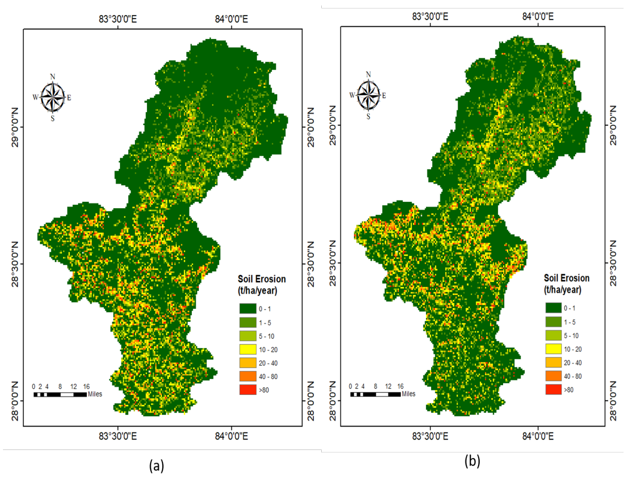

Figure 8: Soil Erosion Map by RUSLE Model (a)2000 (b)2019

covered with forest cover regardless of slope gradients, indicating that land cover is crucial in the process of soil erosion.

3.1.3 Soil Loss Map by SWAT model

The Kaligandaki Watershed was separated into 25 sub-basins based on drainage systems, and each of them was further divided into 1152 small units of

Table 5: Soil erosion Class by Severity (RUSLE Model)

Soil Loss (t/ha/year)	Severity	2000		2019	
		Area (Sq.km)	Area (%)	Area (Sq.km)	Area (%)
0-1	Very Low	4891.06	67.00	4609.63	63.15
1-5	Low	948.49	12.99	1145.94	15.70
5-10	Moderate	471.09	6.45	289.09	3.96
10-20	High	301.58	4.13	542.15	7.43
20-40	Very High	144.47	1.98	93.92	1.29
40-80	Severe	444.87	6.09	471.20	6.45
>80	Highly Severe	99.12	1.36	146.86	2.01

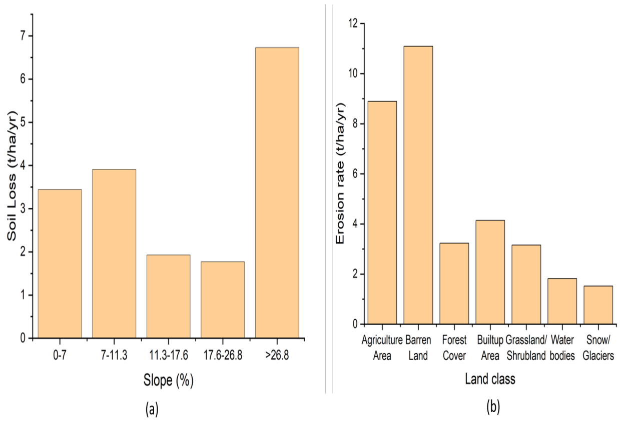

Figure 9: Soil loss by (a) Slope (b) Land use (RUSLE Model)

HRU based on the dominant land use, the characteristics of the soil and slope, and the erosion danger map. The simulation of the SWAT model shows the soil erosion rate of different sub-watershed of Kaligandaki and was reclassified for the severity level. The result of the simulation shows that the annual average soil erosion rate ranges from 0.0545 t/ha/yr to 93.09 t/ha/yr measured in subbasin 5 and subbasin 23 respectively.

The spatial distribution of the soil erosion of the Kaligandaki watershed is shown in Fig. (11(a) & (b)). Based on the soil erosion map result, 21.77% of the total area falls under the 1-5 t/ha/year, 1 % in the 5-10t/ha/year, 2.67 % of the total area in 10-20 t/ha/year, 1.06 % of the total area in 20-40t/ha/year, and 0.52 % of the total area in 40-80t/ha/year soil erosion category. Similarly, 5.6 % of the total area has soil erosion of more than 80t/ha/year. Based on the soil erosion estimation results 4 out of 25 sub-basin fell under severe to very severe soil erosion categories. These two categories of soil erosion combinedly cover 17.54 % of the total sub-watershed area and need land management techniques immediately.

The R-square coefficient between simulated surface runoff and soil erosion in the SWAT model was significant as shown in Fig (13). It shows that soil

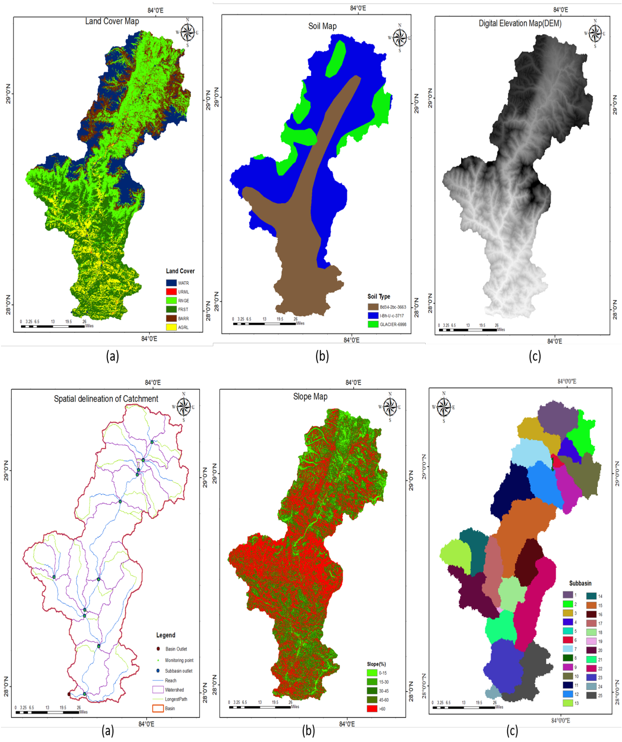

Figure 10: (a)Land Use Map (b)Soil Map (c) DEM (d) spatial delineation (e)Slope map (f)Sub-basins

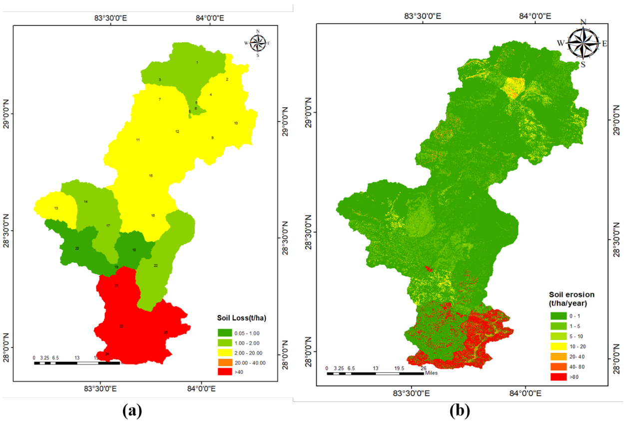

Figure 11: Soil Erosion map by SWAT model

Table 6: Soil erosion Class by Severity (SWAT Model)

Soil Loss (t/ha/year)	Area (Sq.km)	Area (%)	Min	Max	Mean (t/ha/year)	Total loss (t/year)	Severity
0-1	4,960.12	67.39	0	0.997	0.19	161.79	Very Low
1-5	1,602.07	21.77	1	4.91	2.30	378.68	Low
5-10	73.51	1.00	5.03	9.82	7.00	342.77	Moderate
10-20	196.24	2.67	10.08	18.54	13.60	476.10	High
20-40	78.02	1.06	21.5	38.3	29.44	500.51	Very High
40-80	38.14	0.52	42.09	73.81	58.61	351.64	Severe
>80	412.43	5.60	84.6	1231.42	380.99	14,096.71	Highly Severe

erosion is directly dependent on the peak rate of surface runoff and rainfall patterns. The result shows detachment, deposition, and transportation are due to rainfall and runoff.

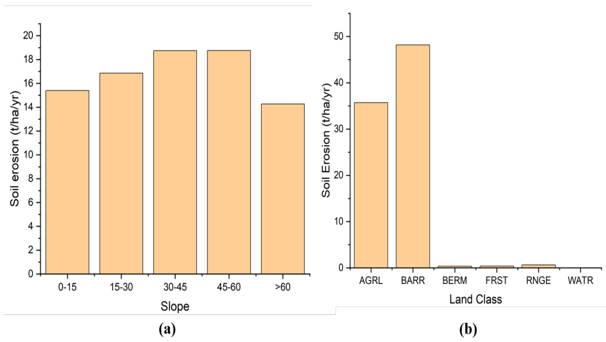

Figure 12: Soil Erosion map by (a) Slope % (b) Land Use (SWAT model)

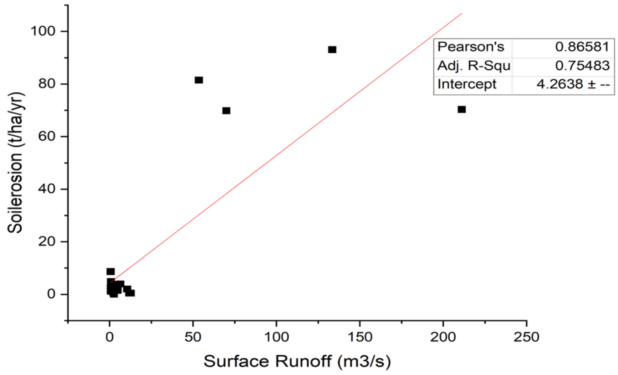

Figure 13: Correlation between soil erosion rate and surface runoff rate

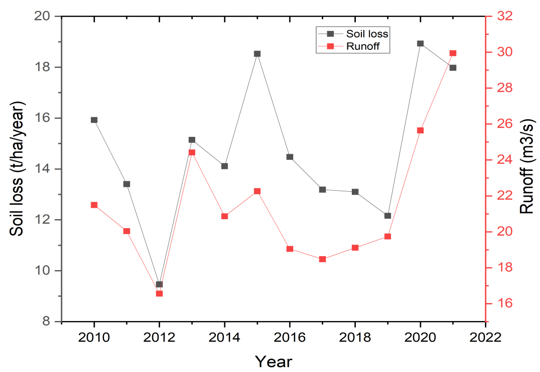

Figure 14: Relation between Yearly Surface runoff and Soil loss

3.2 Discussions

In this study, soil erosion rate was analyzed based on the land use cover, slope, and change in the pattern of the climate using two commonly used RUSLE and SWAT models. Due to the unavailability of observed data, it was not possible to validate with simulated data but the result was compared with the published field data and previous studies results and found similar. The studies used for validation was similar research having identical geographic characteristics and other model based results. The results analyzed in one study show that 11 % of the area was found to be under high to severe erosion risk whereas this study found 9.85 % and 8.53 % by SWAT and RUSLE model [10]. This study found the average rate of soil erosion in the Kaligandaki watershed is greater than the average rate of soil loss in flat areas and chure region, which is also greater than that of most other regions of the world [20]. In another soil erosion study conducted in Siwalik hills using the RUSLE method, the soil erosion ranges between 8.77 to 9.84 t/ha/yr [21] and this study found soil erosion at 8.89 t/ha/year using the same model. Similar to our findings, the Phewa and jimruk watersheds average annual rate of soil erosion was found 14.7 t/ha/year and 13.4 t/ha/year [6, 22]. A study found that agricultural land experiences more erosion than natural grasslands or forests [23]. The results also show that the presence of forest cover can considerably decrease the rate of soil erosion. The expansion of agricultural lands at the loss of barren land and forest areas of hilly areas accelerated soil erosion over time, with a rate of 6.03 t/ha/year [21] whereas, this study found 8.89 t/ha/year soil erosion in agriculture area of Kaligandaki watershed. The forest cover of the study area contributes 17.8 % of total soil erosion whereas, barren land and cropland contribute 34.81 % and 18.38 % of total soil erosion per year. Global annual mean soil erosion data 2012 shows 10.54 t/ha/year soil loss in the Kaligandaki area [20] and this study found 9.76 t/ha/year in 2012.

Conservation-based agriculture strategies including minimal soil disturbance, use of cover crops to preserve the soil, contour farming on steep slopes, strip cropping, bunding, terracing of agriculture fields, and other landscaping techniques are some strategies to manage and reduce soil erosion in agriculture areas [24]. Comparing the result of this study with different similar kinds of research shows that the results are identical. The result of both models shows that the soil erosion in the Northern part is less than the soil erosion rate in the Southern region. It might be due to the low precipitation in the upper regions. Fig(5) shows the precipitation pattern of the different meteorological stations in the study area. The enormous heterogeneity of the topography, soil, cultural practices, and rainfall distributions of the middle hills of Nepal causes a wide range of erosion levels on different spatial and temporal scales. The low mean annual precipitation in the northern part of the study region attributed the lower rainfall erosivity value in the High Himalayan area, which is lower than the other part of the region. Rainfall erosivity is directly related to the quantity of rainfall. Even though RUSLE and SWAT model was used separately in some studies at watershed and regional scales, this study first time used both model combinedly to assess soil erosion risk in the Kaligandaki watershed [10, 25, 26, 21]. This study offers a useful way of identifying higher soil erosion area and their severity status to take into consideration for interventions to reduce soil erosion.

Concentrating on these findings, this study reveals the most vulnerable and critical regions. In young alpine ecosystems, soil losses up to 25 t/ha/yr may be common [27] but this study founds soil erosion up to 7678 t/ha/yr. This shows soil loss may be greater than what the topography can tolerate, necessitating action to stop it in vulnerable areas. Along with having an adverse effect on the land, erosion also causes sedimentation downstream to have a number of detrimental effects. Designing and putting into practice erosion control and watershed management techniques are crucial [28]. Targeting the most vulnerable regions where the impact is most likely to occur will optimize the effectiveness of the control measures [29].

4. Conclusions and Recommendations

The quantitative evaluation of the average annual soil erosion rate of the Kaligandaki watershed with rainfall, soil, land use, and topographic datasets was done using the RUSLE model and SWAT model. The Kaligandaki watershed appears to suffer significant losses from the different factors of soil erosion, according to these two methods used to measure soil degradation. The annual average soil rate was found 14.4 t/ha/yr and 8.89 t/ha/yr by the SWAT model and RUSLE model respectively. The study's findings indicate that soil erosion has a substantial negative impact on productivity rates as well as its severity. The most significant reasons of the increase in soil erosion are topography, conventional practices in agricultural areas, and changing patterns of rainfall and temperature.

Finally, the result illustrates that both models are useful tools to predict soil erosion rates. The evaluation and identification of higher soil erosion areas, the prioritization of necessary action for conservation management, and the efficient use of natural resources can all be accomplished following the methodology of this study in various watersheds. Maintaining sediment data gauges may be challenging due to the topographic and climatic circumstances, yet sufficient quality and quantity of sedimentation data are required to support the comprehensive soil erosion estimation. A feasible way to achieve sustainable environmental management is to introduce appropriate site-specific measures, such as minimum soil disturbance, agroforestry, water management, and conservation measures based on the model erosion finding of this study showed for the study catchment. Bio-engineering techniques are crucial for stabilizing stream banks and lowering landslides. The spatial distribution of soil erosion in watersheds from this study is useful for policy-level conservation and management planning processes by land use planners and decision-makers for prioritization of different regions.

Acknowledgments

The authors are thankful to the Department of Hydrology and Meteorology, ICIMOD, USGS, and FAO for providing the data, special thanks to Prof. Dr. Tirtha Raj Adhikari for technical support and guidance and Prof. Dr. Mohan B Dangi, California State University Fresno USA for the financial support and encouragement.

References

[1] K. Awasthi, Bishal Sitaula, Bal Singh, and Roshan Bajracharya. Land-use change in two nepalese watersheds: Gis and geomorphometric analysis. *Land Degradation & Development*, 13:495 – 513, 11 2002.

[2] R.P.C. Morgan. Soil erosion and conservation, 3rd edition. blackwell publishing, oxford, 2005. x + 304 pp. £29.95, paperback. isbn 1-4051-1781-8. 2005.

[3] Zhiying Li and Haiyan Fang. Impacts of climate change on water erosion: A review. *Earth-Science Reviews*, 163:94–117, 2016.

[4] D. Serpa, J.P. Nunes, J. Santos, E. Sampaio, R. Jacinto, S. Veiga, J.C. Lima, M. Moreira, J. Corte-Real, J.J. Keizer, and N. Abrantes. Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting mediterranean catchments. *Science of The Total Environment*, 538:64–77, 2015.

[5] Manoj Jha and Ram Paudel. Erosion predictions by empirical models in a mountainous watershed in nepal. *Journal of Spatial Hydrology*, 10, 08 2010.

[6] Krishna Bhandari, Jagannath Aryal, and Rotchanatch Darnsawasdi. A geospatial approach to assessing soil erosion in a watershed by integrating socio-economic determinants and the rusle model. *Natural Hazards*, xx:1–22, 07 2014.

[7] Walter H Wischmeier, Dwight David Smith, et al. Predicting rainfall-erosion losses from cropland east of the rocky mountains. 1965.

[8] Kenneth G Renard. *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. United States Government Printing, 1997.

[9] J. R. Williams. Sediment routing for agricultural watersheds1. *JAWRA Journal of the American Water Resources Association*, 11(5):965–974, 1975.

[10] Pooja Koirala, Sudeep Thakuri, Subesh Joshi, and Raju Chauhan. Estimation of soil erosion in nepal using a rusle modeling and geospatial tool. *Geosciences*, 9(4), 2019.

[11] M. Fort, E. Cossart, and G. Arnaud-Fassetta. Hillslope-channel coupling in the nepal himalayas and threat to man-made structures: The middle kali gandaki valley. *Geomorphology*, 124(3):178–199, 2010.

[12] E. Roose. Land husbandry-components and strategy. 1996.

[13] Steven M. De Jong. Derivation of vegetative variables from a landsat tm image for modelling soil erosion. *Earth Surface Processes and Landforms*, 19(2):165–178, 1994.

[14] Zihni Erencin. C-factor mapping using remote sensing and gis : a case study of lom sak / lom kao, thailand. 01 2000.

[15] GJ Shin. The analysis of soil erosion analysis in watershed using gis. 1999.

[16] Richarde da Silva, Celso Santos, Valeriano Silva, and Leonardo Pereira e Silva. Erosivity, surface runoff, and soil erosion estimation using gis-coupled runoff–erosion model in the mamuaba catchment, brazil. *Environmental monitoring and assessment*, 185, 05 2013.

[17] Taia, Soufiane, Erraioui, Lamia, Mbrenga, Noella Claire, Chao, Jamal, El Mansouri, Bouabid, Haida, Souad, and Taj-Eddine, Kamal. Assessment of soil erosion using two spatial approaches: Rusle and swat model. *E3S Web Conf.*, 234:00082, 2021.

[18] N. P. Gaire, M. Koirala, D. R. Bhuju, and H. P. Borgaonkar. Treeline dynamics with climate change at the central nepal himalaya. *Climate of the Past*, 10(4):1277–1290, 2014.

[19] Gurmel Singh, Ram Babu, Pratap Narain, L. S. Bhushan, and I. P. Abrol. Soil erosion rates in india. *Journal of Soil and Water Conservation*, 47(1):97–99, 1992.

[20] Pasquale Borrelli, David A. Robinson, Larissa R. Fleischer, Emanuele Lugato, Cristiano Ballabio, Christine Alewell, Katrin Meusburger, Sirio Modugno, Brigitta Schütt, Vito Ferro, Vincenzo Bagarello, Kristof Van Oost, Luca Montanarella, and Panos Panagos. An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, 8, 2017.

[21] Devraj Chalise and Lalit Kumar. Land use change affects water erosion in the nepal himalayas. *Public Library of ScienceE*, 15:1–19, 04 2020.

[22] Parbati Pandey and Anup Gurung. Soil loss and erosion potential estimation of jhimruk watershed, nepal, 2021.

[23] Altaf S Romshoo SA, Yousuf A and Amin M. Evaluation of various dems for quantifying soil erosion under changing land use and land cover in the himalaya. *Frontiers Earth Science*, 9, 2021.

[24] Rody Nigel and Soonil Rughooputh. Application of a rusle-based soil erosion modelling on mauritius island. *Soil Research*, 50:645–651, 01 2013.

[25] Devraj Chalise, Lalit Kumar, Chandeshwar Prasad Shriwastav, and Sushil Lamichhane. Spatial assessment of soil erosion in a hilly watershed of western nepal. *Environmental Earth Sciences*, 77(19):1–11, 2018.

[26] Pawan Thapa. Spatial estimation of soil erosion using rusle modeling: a case study of dolakha district, nepal. *Environmental Systems Research*, 18, 07 2020.

[27] R. Lal. Effects of slope length on runoff from alfisols in western nigeria. *Geoderma*, 31(3):185–193, 1983.

[28] David R. Lee, Svetlana Edmeades, Erwin De Nys, Andrew McDonald, and Willem Janssen. Developing local adaptation strategies for climate change in agriculture: A priority-setting approach with application to latin america. *Global Environmental Change*, 29:78–91, 2014.

[29] Legese Abebaw Getu, Attila Nagy, and Hailu Kendie Addis. Soil loss estimation and severity mapping using the rusle model and gis in megech watershed, ethiopia. *Environmental Challenges*, 8:100560, 2022.