Geo-Information Modeling of Soil Erosion for Sustainable Agriculture Land Management in Sambhunath Municipality

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KEYWORDS

Geo-information, Soil Erosion, Land Unit, RUSLE.

ABSTRACT

Geo-information science has attempted to estimate the actual soil loss and its correlative interpretation with land use and cover types in an agricultural land, Sambhunath Municipality. Among several empirical and physically based soil erosion models, Revised Universal Soil Loss Equation (RUSLE) are widely used and employed to estimate soil loss based on rainfall, topographic contour, and soil map. The soil erosion ranges values are found from 0 to 2635 t ha-1 yr-1 in terms of soil loss per year in the municipality. Soil erosion rates are found highly correlated with the increasing exposure of land surface in Chure range mostly on forest area. Agriculture lands spatially concentrated in 51.70% of the Municipality extent, is contributing significantly as of 16293 t ha-1 yr-1 of the total potential soil loss from fertile cropland. Based on severity of soil loss, cultivation agriculture areas are priority for reducing soil loss for optimum agriculture management practices in land use planning.

1. INTRODUCTION

Soil is defined as a loose inorganic particulate material formed from the mechanical and chemical disintegration and decomposition of rocks and minerals on the earth`s crust through the actions of natural or mechanical or chemical agent; with or without organic matter content that supports plant life (Kumar, 2014). Soil formed from the weathering of rocks by various agencies like wind, water, ice, gravity at the place of origin and transported towards along lower land form and termed as sedimentary soils. So, the top soil lost from the mountain area is major cause of raising the riverbeds through siltation in the Tarai and estimated annual rate of 15–30 cm in Nepal (Mandal, 2017).

Erosion is a natural geological phenomenon occurring continually over the earth`s surface resulting from the removal of soil particles by rainwater or wind, transporting them to another place. Soil erosion is a process that transforms soil into the sediment. Sediment consists of transported and deposited particles or aggregates derived from rock, soil, or biological material. It is removed the fertile topsoil and transports it into the water bodies, reducing the fertility of arable cultivable land and causing the loss of food production. The transported sediments in water bodies have also degraded water quality and cause eutrophication of freshwater bodies (Pimentel, 2006). It is a major issue in land use planning for minimizing the cause of destruction and sustainability of agriculture upland and ecological restoration through preparing erosion control plans. In humid regions, soil erosion is concerned with high risk in forests and paddy fields, however bare lands such as logging forests, construction areas, and upland crop fields on slopes (Koirala et. al.2019). Several models has used to predict the soil erosion from empirical as USLE (Wischmeier & Smith, 1978), MUSLE (Williams & Berndt, 1977), SLEMSA (Stocking, 1981; Morgan et al. 1984), RUSLE (Renard et al. 1997), EUROSEM (Morgan et al. 1998), WEPP (Flanagan et al. 2001) to physical or process-based as MMF (Morgan et al. 1984). In this research, Revised Universal Soil Loss Equation (RUSLE) has used for modeling the soil erosion. The RUSLE represents how climate, soil, topography, and land use affect rill and inter rill soil erosion caused by raindrop impacts. It has been extensively used to estimate soil erosion loss, to assess soil erosion risk, and to guide development and conservation plans in order to control erosion under different land-cover conditions, such as croplands, rangelands, and disturbed forest lands (Milward &Mersy, 1999; Koirala et. al, 2019). A combination of remote sensing, GIS and RUSLE has more compatible for the potential to estimate soil erosion loss and its spatial distribution on a cell-by-cell basis and feasible for better accuracy.

2. STUDY AREA

Sambhunath Municipality is formulated on 18th May, 2014 by integration of previous Village Development Committees of Khoksar Parbaha, Shambhunath, Mohanpur, Bhangha, Basbalpur and Rampur Jamuwa of Sapatari district in Pronince 2. The municipality got its shape after formulation of Nepalese Constitution 2072; the local level has been reconstructed by reducing the number of local level to 753 local units. However, Sambhunath Municipality has been expanded further in the year 2017 by merging previous Arnaha VDC. The municipality is located at the latitude from 26^{0} 23’ 35” to 26^{0} 42’ 36” and longitude from 86^{0} 37’ 39” to 86^{0} 44’ 54”. The Study area is shown in Figure 1.

Figure 1: Study Area

The total area of the municipality is 108.46 sq.km having 12 wards as its sub-units. The municipality headquarter office is located at Kathauna Bazar. This municipality is bordered with Dakneshwori Municipality, Belhichapena Rural Municipality and Bishnupur Rural Municipality in south, Khadak Municipality in west, Rupani Rural Municipality in east and Triyuga Municipality of Udaypur district in the north. The naming of the municipality as Shambhunath is because of the one of the famous temples which is situated within the municipality area.

3. DATA USED

The secondary data/information is collected from different sources and used in this research is presented in Table 1.

Table 1: Data Used

S.N.	Description	Source
1	WorldView-2 Satellite images, 2016	National Land Use Project, Nepal
2	Topographical map & digital databases	Survey Department, Nepal
3	VDC level soil chemical data	Survey Department, Nepal
4	Rainfall data	Department of Hydrology & Metrology

4. EXPLANATION OF FRAMEWORK

The framework of RUSLE Model with associated the parameters of the soil loss estimation is explained in Figure 2.

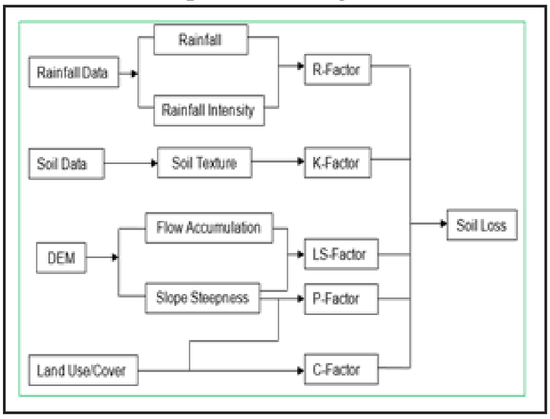

Figure 2: Soil Erosion Framework

Rainfall erosivity factor (R) is computed from the rainfall intensity data that located surrounding to the municipality area having six metrological stations (Rajbiraj, Lahan, Gaighat, Fatepur, Chatara and Barmajhiya). For annual rain, rainfall data of these metrological stations are collected from Department of Hydrology and Metrology at the period of 1970 to 2019 about 50 years. In this study, the average rainfall map was prepared by the spatial interpolation from the average annual rainfall using kriging geostatistical technique in GIS. The generated rainfall has been used for estimation of R factor with the following equation (Morgan, 1985; Mandal, 2017)

$$R = 38.5+0.35\,E \qquad (1)$$

where, E is the annual mean rainfall in mm.

Soil Erodibility Factor (K) describes the susceptibility quantity of soil in the flow of runoff water that transported through erosion process in a given specific rainfall. In this study, the absence of soil structure and soil permeability value, the K factor has estimated with the following equation (Sharpley & Williams, 1990).

$$K = Fcsand * Fsi - cl * Forgc * Fhisand * 0.1317 \qquad (2)$$

where,

$$\text{Fcsand} = [0.2 + 0.3 \exp(-0.0256\, \text{SAN}(1 - \text{SIL}/100))] \qquad (3)$$

$$\text{Fsi} - \text{cl} = \left[\frac{\text{SIL}}{(\text{Cl}+\text{SIL})}\right]^{0.3} \qquad (4)$$

$$\text{Forgc} = \left[1.0 - \frac{0.25\,c}{c+\exp(3.72-2.95c)}\right] \qquad (5)$$

$$\text{Fhisand} = \left[1.0 - \frac{0.70\text{SN1}}{\text{SN1}+\exp(-5.51+22.9\text{SN1})}\right] \qquad (6)$$

$$\text{SN1} = \frac{1-\text{SAN}}{100} \qquad (7)$$

where, SAN, SiL and Cl are % sand, silt and clay respectively and c is the organic carbon content (organic matter). Fcsand gives a low soil erodibility factor for soil with coarse sand and a high value for soil with little sand content. Fsi-cl gives a low soil erodibility factor with high clay to silt ration. Forgc is the factor that reduces soil erodibility for soil with high organic content. Fhisand is the factor that reduces soil erodibility for soil with extremely high sand content (Koirala et. al. 2019). The sand, silt, clay and organic matter map is generated using kriging technique based on the soil sample data.

Topographic factor (LS) is computed with the reference of two factors (slope length and slope steepness). In the study, both slope length and slope steepness are derived from the DEM and computed from these factors in grid format using the following relation.

$$LS = L * S \qquad (8)$$

where, L is the slope length factor and S is the slope steepness factor. The slope length (L) is computed using the following relation (Gao et.al, 2012; Koirala et. al, 2019).

$$\text{L} = \left(\frac{\lambda}{22.13}\right)^{m} \qquad (9)$$

where, λ is the contributing slope length and m is the variable slope length exponent that varies based on slope steepness. The contributing slope length λ is derived from flow accumulation map with the size of grid raster factor as the base for preparing L-Factor map. The flow accumulation map is generated from DEM using hydrological modeling. The slope length exponent 'm' is related to the ratio of rill erosion to inter rill erosion (caused by raindrop impact). The contributing slope length is measured from the flow accumulation of runoff in water enters a well-defined channel and grid raster size (Koirala et. al. 2019).

$$m=\frac{F}{1+F} \quad (9)$$

$$F=\frac{Sin\theta/_{0.0896}}{3(sin\theta)^{0.8}+_{0.56}} \quad (10)$$

where F is the ratio of rill erosion to inter rill erosion; θ is the slope angle in degree.

The slope steepness factor (S) was computed from the following relation (McCool et al., 1987).

$$s = 10.8 * sin\theta + 0.03, \; S < 9\% \; (tan\theta < 0.09)$$

$$S = \left(\frac{sin\theta}{sin5.143}\right)^{0.6}, \qquad S \geq 9\% \; (tan\theta \geq 0.09) \quad (12)$$

where θ is the slope angle in degree.

Erosion control practice factor (P-factor) is generated from the existing agriculture practice of land in different slope. Initially, existing land use is categorized into agricultural and other land in major types. Then, agricultural land is sub-divided into six slope classes and assigned p-value for each respective slope class as many management activities reference with highly dependent on slope of the area. In this study, the p-value is assigned with considering local management practices of agriculture land using the following relation in Table.2 (Wischmeier & Smith, 1978).

Table.2: Conservation Practices Factor Value

Land Use	Slope Gradient (%)	P-Factor
Agricultural Land	0-5	0.10
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Non-agricultural Land		1.00

(Source: Wischmeier & Smith, 1978)

Cover-management factor (C) is normally assigned based on the existing situation of land use and simply assessment of vegetation cover rather than close analysis of agricultural cropping patterns. In this study, the C factor is assigned with considering management practices of vegetation cover using the following relation in Table.3 (Koirala et. al, 2019).

Table.3: Cover Management Factor Value

S.N.	Land Use	C-Factor
1	Forest	0.03
2	Shrub land	0.02
3	Grass land	0.01
4	Agriculture	0.21
5	Barren land	0.45
6	Orchard/Plantation	0.02
7	Bamboo	0.02
8	Water body	0.00
9	Built-up	0.00

(Source: Koirala et. al, 2019)

The potential soil erosion map is produced from the R, K, LS, P and C factor map in ArcGIS 10.4 by the raster multiplication as the function used in RUSLE model.

5. RESULT AND DISCUSSION

In humid regions likes Sambhunath Municipality, soil erosion is concerned with high risk in forests and paddy fields, however bare lands such as logging forests, construction areas, and upland crop fields on slopes (Koirala et al., 2019). Soil erosion with RUSLE model is used rainfall erosivity, soil erodibility, topography, crop management, and conservation practice factors as parameters for estimation of soil loss through rainfall and surface water flow. The rainfall erosivity factor (R) is described the erosivity of rainfall at a particular location based on the rainfall amount and intensity that reflects the effect of rainfall intensity on soil erosion. The rainfall erosivity is used to quantify the effect of raindrop impact and explain the amount of rainfall and rate of runoff associate with rainfall i.e. rainfall intensity (Wischmeier & Smith, 1978; Koirala et. al, 2019). Soil loss is related to kinetic energy of rainfall through the detachment power of raindrops striking the soil surface and the entrainment of the detached soil particles by runoff water down slope (Mandal, 2017). The rainfall measurement data is essential for preparing R-factor. The rainfall map is prepared from spatial interpolation technique using Kriging from the average rainfall data and R-factor map is generated using Equation (1). The prepared R-prepared factor map is shown in Figure 3.

The rainfall erosivity range is varied between 561 and 580 mm ha-1 h-1 yr-1 in R-factor map having highest in North-western part and the lower values in the South of the municipality.

The Soil Erodibility Factor (K) is characterized the susceptibility of soil or surface material to erosion, transportability of the sediment, and the quantity and rate of runoff given a specific rainfall input as measured under a standard circumstance. K-factor is used for representing the quantitative description of the inherent erodibility component of a particular soil type; based on the susceptibility of soil particles to detachment and transport by rainfall and runoff.

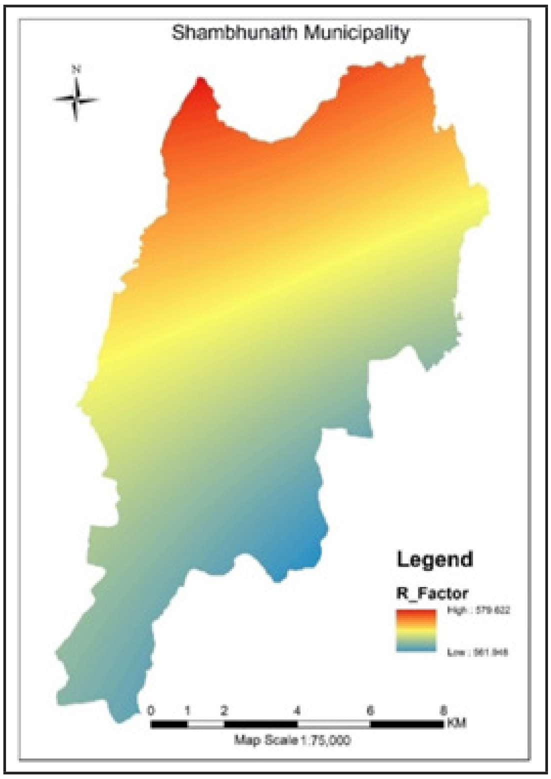

Figure.3: R-Factor Map

The main soil properties influencing the K factor is soil texture, organic matter, soil structure and permeability of the soil profile and reflected the rate of soil loss per rainfall erosivity (R) index. For a particular soil, the soil erodibility factor is based on the rate of erosion per unit erosion index from a standard unit plot of 22.13m long slope length with 9% of slope gradient (Ganasri & Ramesh, 2016) maintained in continuous fallow, tilled up and downcast the hill slope (Kim, 2006). Based on the collected soil sample data; sand, silt, clay and organic matter maps are generated using Kriging spatial interpolation technique in geo-statistical analysis. The R-factor map is prepared using Equation (2) and presented in Figure.4.

The soil erodibility range is varied from 0.024 to 0.058 in the K-factor map. The distribution of K factor is found in the scattered nature on the soil texture properties within the municipality.

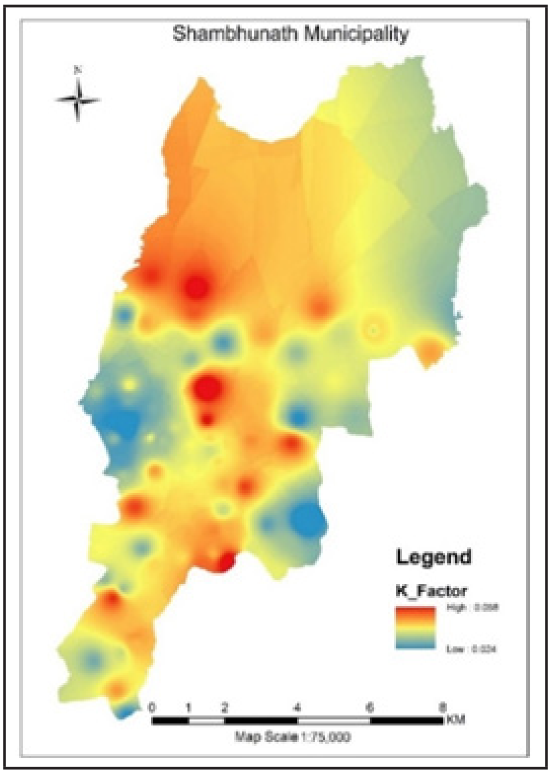

Figure..4: K-Factor Map

Topographical factors are based on the slope length and steepness for calculating the transport capacity of overland flow (surface runoff). The higher the velocity and greater the concentration of water, there is occurred greater occurrence rate of the soil erosion. Therefore, the topographical factors are the key component for estimating soil erosion risk based on slope length (L) and slope steepness (S). The L is represented the distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins or the runoff water enters a well-defined channel that may be part of a drainage network or a constructed channel (Mandal, 2017). The S is represented the effect of slope steepness on soil loss to terrain gradient and influenced by the vegetation coverage and the soil particle size (Koirala et. al, 2019). These both L-factor and S-factor are based on flow accumulation map (presented in Figure5).

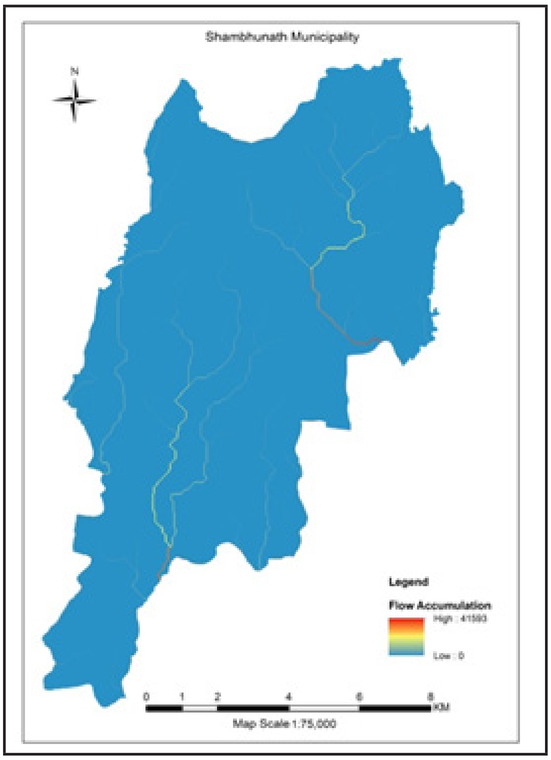

Figure. 5: Flow Accumulation Map

The slope length (L-factor) map is generated from Equation (9) and shown in Figure. 6.

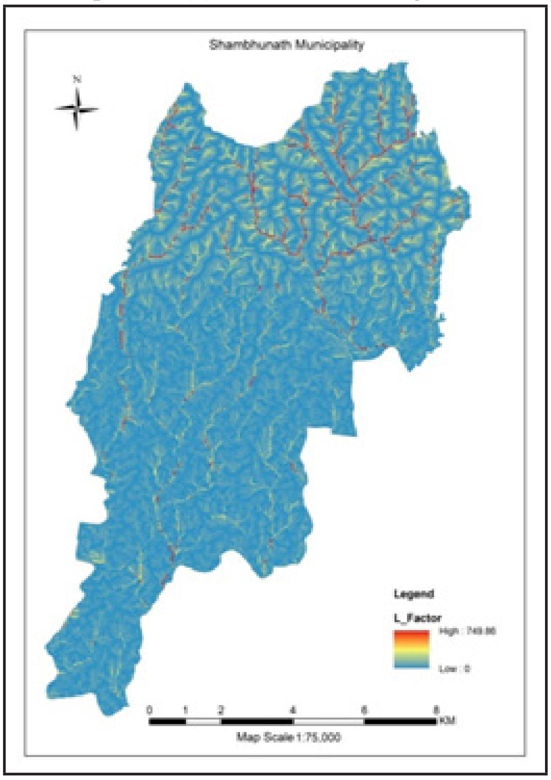

Figure. 6: L-Factor Map

Likewise, slope steepness (S-factor) map is generated from Equation (12) and shown in Figure 7.

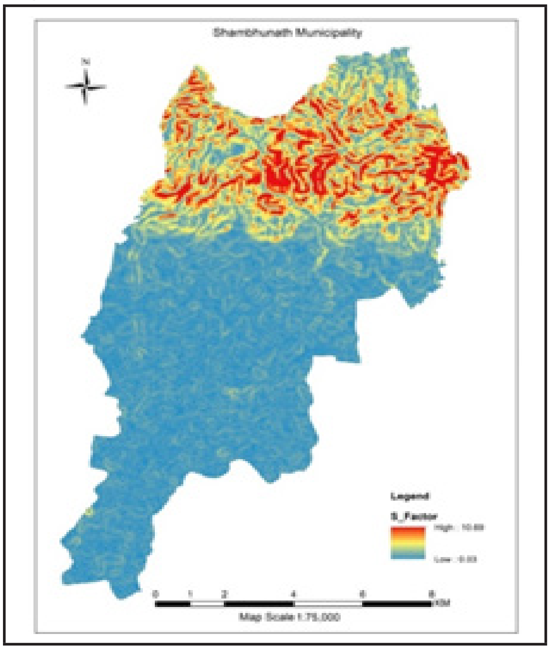

Figure 7: S-Factor Map

The topographical (LS factor) is represented the combined effect of slope length and steepness relative to a standard unit plot and increased LS factor through increase in hill slope length and steepness. The topographical factor map is generated using Equation (8) and shown in Figure.8.

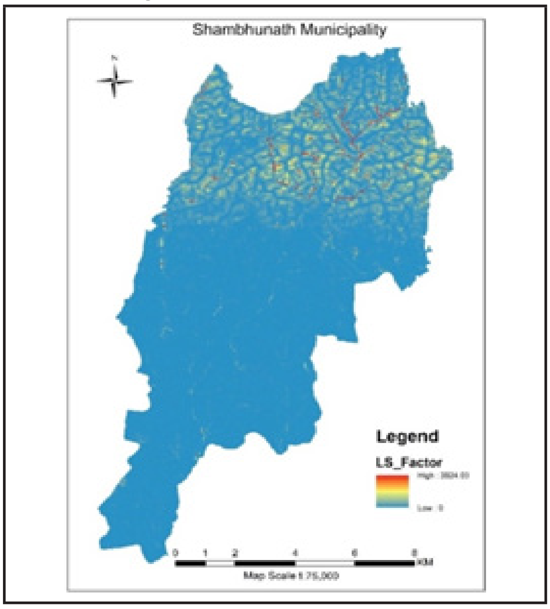

Figure.8: LS-Factor Map

From the slope length factor (L) showed that the L-factor value ranges from 0 to 750 having scattered pattern depending upon the terrain condition and water runoff in drainage channel course in the South of the municipality. From the Slope Steepness Factor (S) map showed that the S-factor value ranges from 0.03 to 10.69 having highly depending upon northern part in the Siwalik hill with steepness of terrain and lesser in southern part of the municipality. The topographical factor (LS) ranges from 0 to 3824 is found from LS-factor map and depicting the highly intensity of LS-factor in northern part of the municipality depending with steepness of terrain and lesser intensity in southern part of the municipality having flat terrain.

Erosion control practice factor (P-factor) is the ratio of soil loss with a specific support practice to the corresponding loss with up slope and down slope cultivation (Wischmeier & Smith, 1978). The P-factor is considered for the control practices to reduce the eroding power of rainfall and runoff by their impact on drainage patterns, runoff concentration, and runoff velocity. The supporting mechanical practices included the effects of contouring, strip cropping, or terracing (Hyeon & Pierre, 2006). The P-factor is generated based on agriculture practices in different slope regimes and assigned for each respective slope class on the many control management activities. The conservation practice value is applied in the integrating land use and slope gradient. The prepared P-factor map is shown in Figure 9.

The cover-management factor (C) is used to reflect the effect of cropping and other management practices on erosion rates. Vegetation cover is the second most important factor next to topography that controls soil erosion risk.

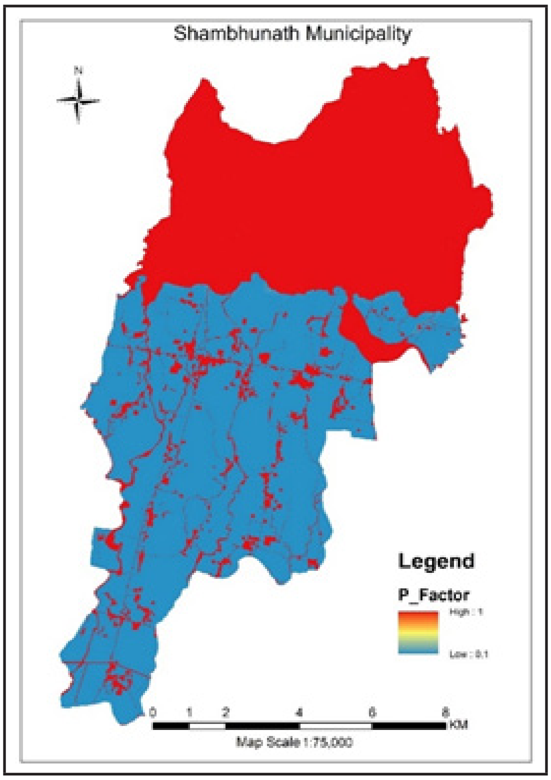

Figure 9: P-Factor Map

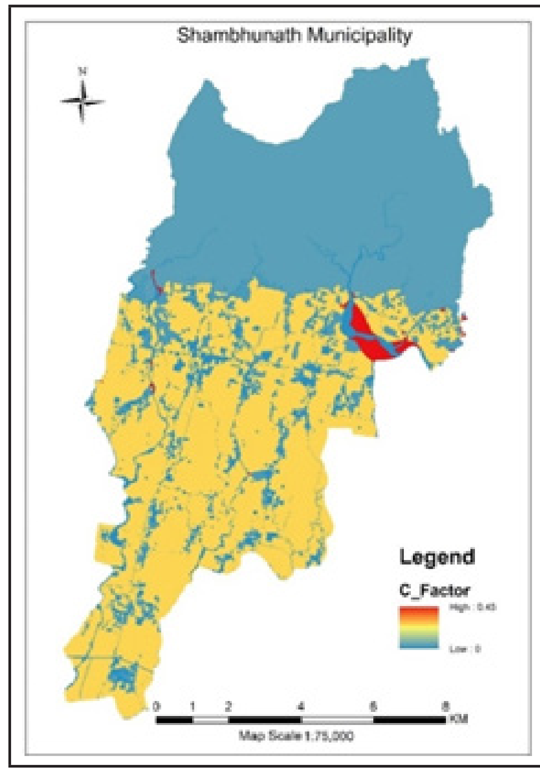

Figure.10: C-Factor Map

The land cover intercepts rainfall, increases infiltration, and reduces rainfall energy. In areas where land uses other than cropping dominate C-factor value is comparatively lower than the cropping area. The C factor ranges is varied from 0 to approximately 1, where higher values indicate no cover effect and soil loss comparable to that from a tilled bare fallow, while lower C means a very strong cover effect resulting in no erosion (Koirala et. al, 2019). The C-factor is generated in term of vegetation covers from land use class based on land cover management activities. The prepared C-factor map is shown in Figure.10.

The potential soil erosion map is produced from the R, K, LS, P and C factor map in ArcGIS by the raster multiplication through map algebra as the function used in RUSLE model.

The soil erosion ranges values are occurred from 0 to 2635 t ha-1 yr-1 in terms of soil loss per year with total 362810 t ha-1 yr-1 in the municipality.

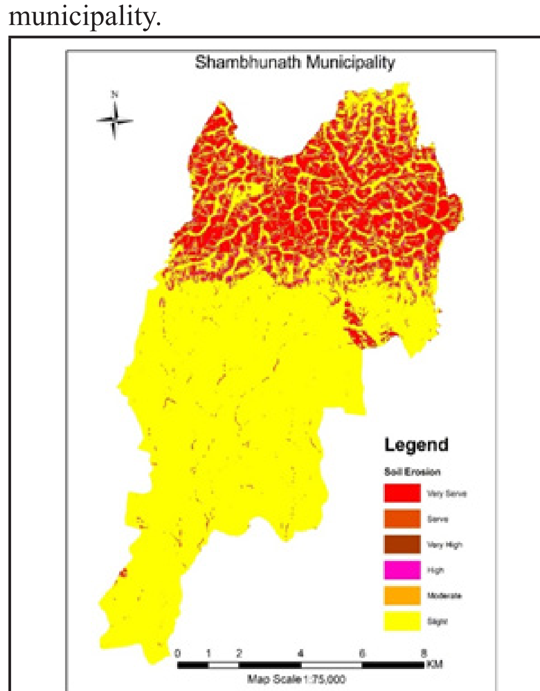

Figure 11: Soil Erosion Map

From the soil erosion results showed that the distribution of the low risk of soil risk has slightly erosion area with 72% having less than 5 t ha-1 yr-1, medium risk of soil risk has moderate erosion area with 5% having soil erosion rate between 5-10 t ha-1 yr-1 and the high risk of soil risk has high, very high, serve and very serve erosion area with 5% having soil erosion rate greater than 10 t ha-1 yr-1. The impact of potential soil risk assessment has carried out by the process of spatial overlay operation using zonal statistics of soil erosion potential layer to land use layer 2017. The potential soil erosion risk in the land use categories is shown in Table 4.

Table 4: Soil Erosion Impact on Land Use

S.N.	Land Use Description	Potential Soil Loss (tons/ha)			
		Max	Avg	Total	%
1	Agriculture	174.83	0.26	16293.11	4.49
2	Forest	2635.78	6.81	333104.27	91.81
3	Water body	202.33	0.44	1681.36	0.46
4	Residential	38.69	0.04	109.58	0.03
5	Other	574.72	10.17	11475.92	3.16
6	Public Use	10.45	0.14	139.44	0.04
7	Industrial	1.15	0.01	4.88	0.00
8	Commercial	0.38	0.01	0.93	0.00
9	Cultural & Archeological	0.00	0.00	0.00	0.00
	Total			362809.50	100.00

Potential soil losses in Sambhunath Municipality have estimated with references to the land use and cover types in order to understand its role in determining erosion rate. The potential soil loss by land use and land cover types and its summary statistics are given in Table 4. Soil erosion rates are found highly correlated with the increasing exposure of land surface. In potential soil loss estimation, degraded forest area is sharing about 92% of total soil loss within the municipality extent. Similarly, in case of agriculture, about 4.49% of total soil loss has causal to soil loss in the municipality which has in Terai agriculture watershed as comparatively less than Siwalik hill in the upper portion. Likewise, the other land mainly open space is causal rate of soil loss about 3.16% total soil loss within the municipality extent.

After soil loss analysis, the severity of agriculture land is essential to priorities the areas having high rate of soil erosion for sustainability of agriculture practices. In this context, the priorities in agriculture areas where high rate of soil erosion estimated are observed (Table 5).

Table 5: Priority of Soil Loss in Agriculture Use

Soil loss (t ha-1 yr-1)	Risk Level	Area (ha)	Priority
< 5	Slight	55.20	Low
5-10	Low	38.55	Low
10-20	Moderate	16.76	Moderate
20-40	High	10.45	High
40-80	Serve	6.38	High
>80	Very Serve	16.90	High
Total		144.24	

These areas are spatially concentrated in north east direction of municipality having agriculture practices in degraded situation and instable slope that are to be given high attention for upstream of Khando River watershed conservation and also for sustainability of agriculture development in downstream. Based on severity of soil loss, cultivation areas are also to be given priority with optimum agriculture management practices for reducing soil loss. Soil conservation measures are to be adopted on more degraded areas for sustainable agriculture management required for sustainable land use planning.

6 CONCLUSION

A total of 3.6 million tons soil is estimate the soil lost annually through soil erosion with the ranges of intensity from 0 to 2635 t ha-1 yr-1. Soil erosion rates are found highly correlated with increasing exposure of land surface mostly on forest area in Chure range. Agriculture practices land is concentrated spatially with 51.70% having significantly soil loss 0.16 million ton annually. So, there is required essential management in cultivation areas and prioritized based on severity of soil loss for optimum agriculture management practices in land use planning.

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