

Article

Spatial Sediment Erosion and Yield Using RUSLE Coupled with Distributed SDR Model

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Abstract: Estimating sediment yield in a river is a challenging task in the water resources field. Different methods are available for estimating sediment erosion and yield, but generally they are not spatially distributed in nature. This paper presents the application of the Revised Universal Soil Loss Equation (RUSLE) for estimating soil erosion and integrates it with spatially distributed Sediment Delivery Ratio (SDR) to calculate sediment yield in a Himalayan river. The study area is Kabeli sub-catchment, located upstream of the Koshi River Basin in the eastern part of Nepal. The Kabeli River is where numerous hydropower projects are envisaged, and sediment-related issues are of major concern. With the use of the RUSLE, the mean annual soil erosion is estimated at 35.96 tons/ha/yr. The estimated specific sediment yield (SSY) from the distributed SDR method is 6.74 tons/ha/yr, which is close to the observed SSY of 7.26 tons/ha/yr using the data records of ~8 years. Based on correlation analysis, the topographic factor (*LS*) is the most sensitive RUSLE parameter with respect to sediment erosion. The sloping areas near the river hillslope are particularly vulnerable to soil erosion. The results indicate that the approach employed in this study may be potentially applied in other catchments with similar physiographic characteristics for the estimation of sediment yield.



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Keywords: soil erosion; sediment yield; RUSLE; sediment delivery ratio

1. Introduction

Soil is a delicate layer of earth that has a dynamic and complex character. The top layer of soil is readily susceptible to erosion, which is a worldwide challenge that affects natural resources, water resources infrastructures and agricultural production. Soil erosion causes both on-site and off-site complications. On-site effects mainly refer to loss of arable land [1], desertification and induced economic losses [2]. Off-site erosion, which generally occurs far away from the erosion site, are clogged and polluted waterways [3], increased flooding [4,5], declines in aquatic species [6], lake volume depletion, water quality deterioration [7,8], landslides and sediment-related issues in water resources infrastructures [9]. Out of these challenges, loss of water storage capacity due to excessive sediment yield in reservoirs is the major off-site effect of soil erosion [10]. The reservoirs trap sediment over time, leading to a gradual depletion of the storage capacity, which can impact future functionality and shorten the reservoir's useful life [11–14].

The first step toward addressing these challenges is to quantify the sediment yield. It is necessary to know the sediment yield in order to manage sediment-related problems in water resource projects like hydropower plants [15]. Soil erosion models serve as effective tools for predicting sediment concentration and loads in reservoir sediment management [11,16]. Several models are available for estimating soil erosion from empirical

methods such as USLE [17], ANSWERS [18], EUROSEM [19], USPED, G2 [20], SEDD [21], ANGPS [22], EPIC [23], WEPP [24,25], etc. The Universal Soil Loss Equation (USLE) is the result of extensive research carried out over many years by several distinguished researchers [26]. Most erosion prediction models are based on the empirical USLE model, and the results of these models vary considerably depending upon input data. The USLE has been applied for various purposes, including assessing the rate of plutonium fallout into outlets from the landscape, food security, watershed planning etc. [27]. The USLE and Revised USLE (RUSLE) are widely described in the literature [28] and are by far the most used soil erosion predictive models globally [29]. A comprehensive review of different soil erosion models can be found in the literature [30–32].

Estimating soil erosion and yield within a catchment is particularly important in larger and ungagged catchments. The concept of the sediment delivery ratio (SDR) was developed to explain the variation in sediment load from a catchment by comparing it with the catchment's area. The SDR is the ratio of sediment yield in the river to the total erosion in the catchment. Several studies have estimated potential soil erosion in different regions of the Himalayas using the RUSLE model. While many of these studies focus solely on erosion estimation without assessing sediment yield [33–36], those that have predicted sediment yield often rely on lumped SDR values for the entire catchment [37,38]. However, to achieve a more accurate spatial representation of the sediment yield, the use of distributed SDR is essential. Additionally, predicting sediment transport and deposition, along with comparing results with observed values, is necessary to fully evaluate the applicability of the RUSLE model in the Himalayan catchments.

In a physical context, sediment erosion is related to the detachment of the sediment while sediment delivery is associated with the storage, mobilization and transportation of sediment towards the outlet. The RUSLE only estimates the average annual soil erosion by sheet and rill erosion in areas where erosion occurs. However, it does not account for deposition and cannot estimate sediment yield at downstream locations [27], highlighting the need for the SDR. Various studies have quantified spatially lumped SDRs for catchments, relating the results to factors such as catchment area or average slope of the stream [39–41]. The application of lumped SDR in the Himalayan context has been explored in some studies [37,38]. However, the SDR for any specific catchment depends upon a wide range of hydrogeological, geomorphological and environmental factors like relief, slope characteristics, ground water, drainage pattern, climatological variations, vegetation cover, soil texture, etc. The changes in land use and climatological patterns also regulate SDR, and it varies temporally with storm and flood events [42]. It is equivalent to unity in the perspective of the geological time scale [43] and varies between 0 and 1 on the present day time scale. In some studied catchments, it was found that the sediment yield always decreases with increasing catchment area, and a single relationship cannot represent the SDR over the range of catchment sizes. Theoretically, based on empirical relationships relating SDR and catchment area, the decreasing trend of SDR with the increase in catchment area suggests that the sediment yield would approach zero for very large catchments. However, this is not realistic and is not consistent with real observations. Moreover, an issue of autocorrelation arises because the SDR is typically calculated as a lumped value derived from sediment yield, defined as the ratio of sediment load to the catchment area. SDR is often compared against the catchment area itself, which can lead to potential false correlation effects. Aggregation of SDR spatially and temporally creates several misjudgments in estimation. Therefore, it is recommended to discontinue the use of lumped SDR calculated from the catchment area to predict sediment yield [44].

The original version of the USLE was developed for conservation of soil in farm planning in croplands and was complimented by research on small experimental plots [27]. These plots, typically 6 feet wide and 72.6 feet long, were located in relatively milder sloped areas [26]. While these conditions were suitable for farm fields, they differ significantly from the rugged and steep terrain of the Himalayas, suggesting that careful adaptation may be necessary for its application in such mountainous regions. The USLE has been

used to estimate soil erosion in several landscapes around the world, including Himalayan catchments. The USLE in combination with the SDR has been employed and compared against the observed values by Gashaw et al., 2002 [45]. However, the reliability of the erosion model coupled with the SDR has not been tested in the Himalayan rivers, which have distinct landscapes compared to the one upon which the model was originally built. This research uses the RUSLE to estimate sediment erosion in the catchment due to the availability of appropriate datasets, ease of use, accuracy and validity, GIS integration and spatial resolution of the model output. The main objective is modeling the soil erosion and sediment yield in spatially distributed form and comparing the model results with observations. To achieve this objective, firstly the RUSLE model was framed in the GIS environment to predict raster-cell-based spatially distributed soil erosion. It was then coupled with a distributed SDR model to obtain sediment yield, and finally, the modeled sediment yield is compared with the observed value.

2. Study Area

The Kabeli River Basin, which includes the Kabeli River—a tributary of the Tamor River—is located in the eastern part of Nepal. The Tamor River is one of the seven major tributaries of the Sapta Koshi Basin. The Kabeli basin lies between latitudes $27^{\circ}13'$ and $27^{\circ}32'$ N and longitudes $87^{\circ}43'$ and $88^{\circ}04'$ E. The primary reason for choosing this basin as the study area is the availability of relatively long-term data of sediment and river flow. The catchment area of the Kabeli River exhibits the features of a mountainous watershed. It covers an area of 862 km^2 at the intake location of the Kabeli hydropower project, where a streamflow and sediment sampling station has been set up. The area above the permanent snow line ($\sim 5000 \text{ masl}$) in the basin is approximately 1 km^2 . The elevation within the catchment ranges from 560 to 5487 m above sea level (masl). The location map of the study area is shown in Figure 1.

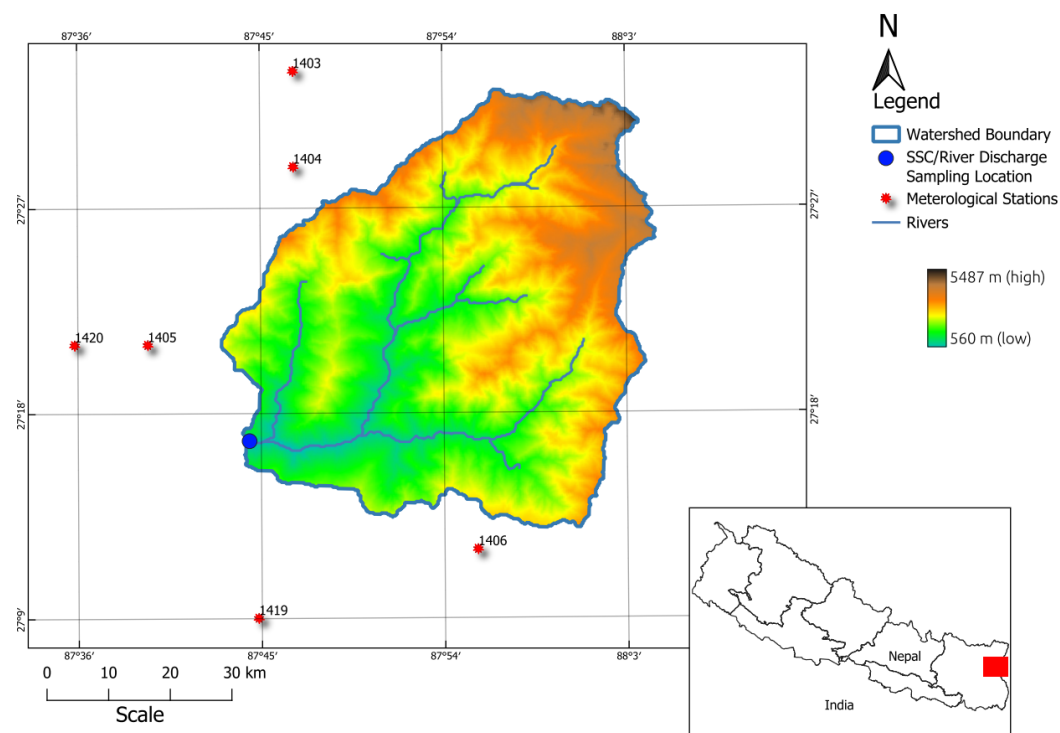


Figure 1. Location map of the study area [15].

Previous studies on the Kabeli catchment indicated that the hillslope/catchment contains a sufficient amount of erodible material (Figure 2b), with sediment supply exceeding transport capacity. However, during periods of extremely high precipitation, the river consistently receives sediment from the catchment, as illustrated in Figure 2a. This condition,

however, was not observed during the study period. The inflow of sediment into the river suggests that the sediment sources in the catchment are not exhausted [15]. The analysis of sediment concentration also showed a consistent increase with river discharge [46], indicating that the catchment contains significant amounts of weathered and fragmented material on the hillslopes (Figure 2b). Furthermore, the sediment yield is influenced by the intensity of rainfall, as represented by the blue line in Figure 2a. Notably, around 90% of the sediment yield occurs during the monsoon season, which spans from June to September.

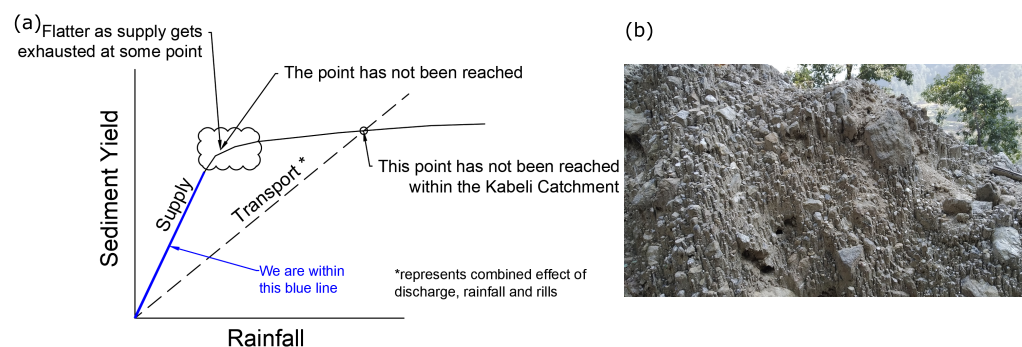


Figure 2. (a) Suspended sediment yield status and sediment transport process for the Kabeli catchment (modified from Ghimire et al., 2024 [15]). (b) Remnant of sheet erosion in fine-grained soils from a catchment located upstream of the Tamor River.

The Kabeli Basin is significantly influenced by the monsoon season, which is responsible for approximately 76% of the mean annual rainfall of 2022 mm/year. In contrast, only 54% of the total river flow occurs during this season. This variability in precipitation and river flow shapes the entire environment of the catchment, influencing factors such as vegetation, land cover, water availability and sediment erosion and yield. High precipitation levels are observed on the northwestern slopes of the watershed, with annual rainfall ranging from 2200 to 2700 mm/year. The rivers and streams draining the intake location typically flow in a north–south direction.

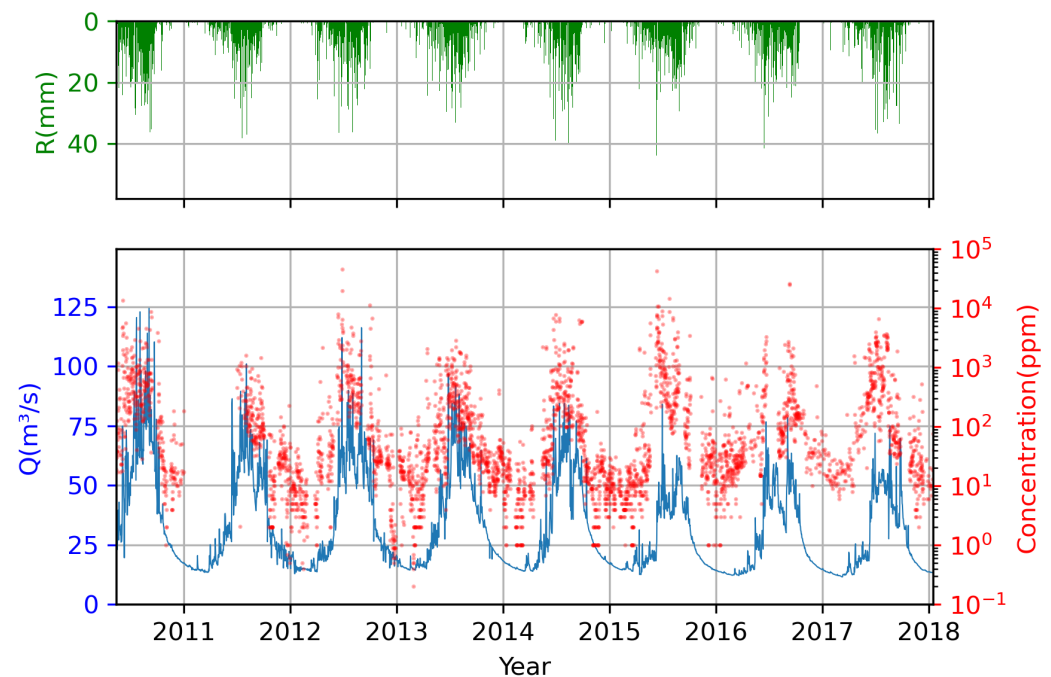
According to land use/land cover data published by ICIMOD in 2010, the catchment exhibits diverse land use patterns, with forest covering approximately 56% of the total area. Agriculture, primarily found on the lower slopes between 560 to 2000 masl, occupies around 20% of the catchment. The main soil types include Humic Leptosols and Eutric Cambisols, which cover 39% and 38.9% of the area, respectively. Other soil types in the catchment are Chromic Cambisols, Gelic Leptosols and Eutric Regosols, as indicated by the Soil and Terrain Database (SOTER). These soils are characterized by moderate infiltration rates and generally possess well-draining properties [46]. The predominant geological formations in the Kabeli catchment include the Seti Formation, the Himal Group and Taplejung Granites [47], which are rich in minerals such as quartz, feldspar and garnet.

3. Research Data

Daily recorded streamflow data were obtained from Kabeli Energy Limited and are available from the years 2010 to 2018. The streamflow station was set up at the headworks location of Kabeli 'A' Hydro Electric Project. Streamflow and sediment concentration data of the river were recorded by Hydro Lab Pvt. Ltd. from 15 May 2010 to 14 January 2018. Initially, a flow rating curve was developed. Following this, river discharge was calculated using the rating equation and recorded gauge heights, which were measured twice daily at 8 a.m. and 5 p.m. A summary of the observed sediment and river discharge data is presented in Table 1, while Figure 3 illustrates the time series plot of rainfall, observed discharge and suspended sediment concentration for the entire sampling period.

Table 1. A summary of observed sediment and flow data at Kabeli intake site (i.e., 4572 data points).

	Conc, ppm	Gage Height, m	Discharge (m ³ /s)
Mean	404.12	0.85	34.75
Standard Deviation	1468.69	0.46	20.75
Minimum	0.00	0.21	11.63
25%	15.00	0.43	16.98
50%	45.00	0.77	27.96
75%	262.00	1.23	48.85
Maximum	46,137.00	2.60	162.69

**Figure 3.** Temporal variability in precipitation, discharge and sediment concentration over an 8-year period (2010–2018). The daily precipitation hyetograph is represented in green, the daily river discharge hydrograph in blue and the suspended sediment concentration is depicted as a red scatter plot. Missing ground-based precipitation data were filled using the APHRODITE dataset (APHRO_MA_V1101EX_R1) [15].

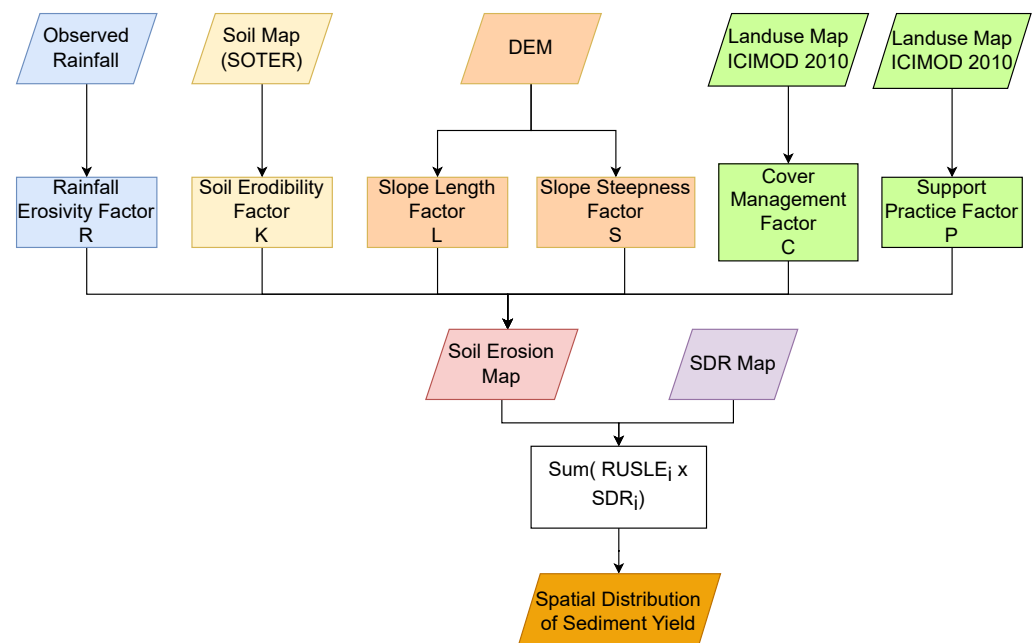
The availability of proximal meteorological stations is limited, as there is no rainfall station within the Kabeli River catchment (Figure 1). However, in the vicinity of the Kabeli catchment, there are six rainfall stations. For this study, daily observed meteorological data were collected from DHM for the years 2008 to 2020. Missing precipitation data from ground-based stations were filled using the APHRODITE dataset (Asian Precipitation Highly Resolved Observational Data Integration towards Evaluation of Water Resources), which is considered among the best datasets available with ground-based calibration [48]. A summary of the data and their sources is given in Table 2.

Table 2. Data types and their sources and resolutions.

Type of Data	Source	Spatial Resolution	Temporal Resolution	Stations
Daily Precipitation	Department of Hydrology and Meteorology (DHM)	Stations around the vicinity of the catchment	Daily	1403, 1404, 1405, 1406, 1419, 1420
Daily Precipitation	APHRODITE Dataset	30 km × 30 km	Daily	-
Sediment Concentration	Kabeli Energy Limited	Point Dataset	Twice a day	Kabeli Head-works Location
Daily Discharge	Kabeli Energy Limited	Point Dataset	Twice a day	Kabeli Head-works Location
Topography	ASTER GDEM 30 m × 30 m digital elevation data	30 m × 30 m	-	-
Land Cover	ICIMOD Land Cover Map 2010	30 m × 30 m	-	-
Soil Map	Soil and Terrain (SOTER) Database Programme, ISRIC	1:1,000,000	-	-

4. Methodology

The research methodology adopted comprises calculation of sediment load, estimating RUSLE parameters and creating a spatially distributed SDR map and then sediment yield map. To accomplish this, all the inputs are integrated in the Geographic Information System (GIS). The methodological framework used to obtain the distributed sediment yield map is shown in Figure 4.

**Figure 4.** Workflow for creating spatially distributed sediment yield map.

4.1. Sediment Load Calculation

The time series data of observed sediment concentration is required to be converted to the annual loads for comparison with sediment yield. To achieve this, various software like (LOADEST, FLUX32) are available [49] to recreate simulated sediment load. However,

in this study, daily measured sediment loads were available. Thus, the observed sediment load in the river was calculated using Equation (1).

$$SSL_{1-2} = \left[Q_1 \cdot C_1 \cdot \frac{(t_2 - t_1)}{2} + Q_2 \cdot C_2 \cdot \frac{(t_2 - t_1)}{2} \right] \cdot \frac{60 \cdot 60}{10^6} \quad (1)$$

where, SSL_{1-2} represents the suspended sediment load between two consecutive measurements (in tons); Q_1 and Q_2 are the river discharges at time t_1 and t_2 , respectively (in m^3/s); C_1 and C_2 are the sediment concentration at times t_1 and t_2 , respectively (in ppm); and t_1 and t_2 are the times of two consecutive measurements (in hours).

4.2. RUSLE

The soil erosion or loss in a catchment can be calculated using the RUSLE in a GIS environment [50]. It consists of six factors relating to rainfall, topography, geophysiography and land cover to evaluate the yearly soil erosion in an area. It is a widely used model for estimating soil erosion due to its compatibility with GIS.

The revised universal soil loss equation is given in Equation (2).

$$A = R K L S C P \quad (2)$$

where, A represents soil loss in tons/ha/year, R is the rainfall erosivity factor (MJ mm/ha/h), K is the soil erodibility factor (ton ha h/MJ/ha/mm), L is the slope length factor, S is the slope steepness factor, C is the cover management factor and P is the support practice factor. The factors L , S , C and P are dimensionless.

4.3. Rainfall Erosivity Factor (R)

The rainfall erosivity factor is a measure of the erosive impact and strength of rain splash. It is calculated as the product of the total energy from a storm and the maximum rainfall intensity recorded over a 30-min period (I_{30}). The R factor largely depends upon the intensity, amount, duration and pattern of rainfall and terminal velocity and rain drop size. R values are also determined by slope steepness as flat water ponding areas are less likely to be eroded by rainfall [51]. Due to complexity in acquiring all the variables influencing the R factor, it is obtained using Equation (3) [52].

$$R = 38.5 + 0.35P_{ann} \quad (3)$$

where P_{ann} is the mean annual precipitation in mm, and P_{ann} for each climatological station is calculated from year 2010 to 2018. Spatially distributed P_{ann} was computed by using IDW interpolation of mean annual precipitation for six stations in the vicinity of study area for each raster cell in GIS environment.

4.4. Soil Erodibility Factor (K)

The soil erodibility factor is the susceptibility of soil to being detached and transported by rainfall, which is measured under a standard plot. It depends on the inherent properties and constituents of soil such as silt percentage, sand percentage, organic matter percentage, permeability and soil structure. The theoretical K factor ranges from 0 to 1, where 0 indicates least susceptibility of soil to be eroded and 1 indicates the soil which is highly susceptible to erosion. These parameters were obtained from SOTER map in the ISRIC data hub. The K factor is calculated using Equation (4) [17].

$$K = \frac{0.00021 \cdot M^{1.14} \cdot (12 - OM) + 3.25 \cdot (c_{soilstr} - 2) + 2.5 \cdot (c_{perm} - 3)}{100} \quad (4)$$

where M represents the particle size parameter, OM represents organic matter percentage, $c_{soilstr}$ represents soil structure code used in classification and c_{perm} represents profile permeability class.

4.5. Topographic Factor (*LS*)

The topographic factor is determined by processing the DEM, as it entirely depends on the physical features of an area. The topographic factor measures the influence of both slope length and steepness of a given area. Slope length is defined as the distance from the ridge to the point where deposition begins, typically near the toe of the slope or where runoff enters well-defined streams [40]. It is to be noted that soil erosion is more sensitive to slope steepness than slope length [27]. Determination of the *LS* factor involves conditioning of different situations, which are processed using raster calculator in QGIS. The topographic factor (*LS*) is calculated using Equation (5) [53].

$$LS = \left(\frac{\lambda}{22.13} \right)^m (10.0 \sin\theta + 0.027) \text{ for } s \leq 8\% \quad (5)$$

$$LS = \left(\frac{\lambda}{22.13} \right)^m (17.2 \sin\theta - 0.55) \text{ for } s \geq 8\% \quad (6)$$

where *LS* is the slope length and steepness factor, λ is the horizontal projection of slope (*m*), *m* is the slope length exponent and θ is the slope angle. The slope length exponent “*m*” is associated with the ratio “ β ” of rill erosion to interill erosion, as in Equation (7).

$$m = \frac{\beta}{1 + \beta} \quad (7)$$

The value of β is obtained from Equation (8) [54].

$$\beta = \frac{E(\sin\theta/0.0896)}{(2.96 \sin^{0.79}\theta + 0.56)} \quad (8)$$

where *E* is the rill to interill erosion.

4.6. Cover Management Factor (*C*)

The cover management factor indicates the combined influence of vegetation and land management practices. It is defined as the ratio of soil loss under a specific support practice to the soil loss associated with conventional straight-row tillage both upslope and downslope. The cover management factor is affected by several sub-factors, such as previous land use, canopy cover, surface cover, surface roughness and soil moisture. However, the input data for these factors were not available. Hence, general simplified values were adopted based on land cover data produced by ICIMOD. The *C* factor is adopted using literature in Panagos et al. 2015, and Kim, 2006 [28,55], and is listed in Table 3 for different land cover types.

Table 3. Cover management factor, *C*.

Land Cover	C Factor
Forest	0.03
Shrubs	0.03
Grass	0.01
Agriculture	0.21
Bare	0.45
Built-up	0
Water body	0
Snow	0

4.7. Support Practice Factor (*P*)

The support practice factor is adopted based on literature following Kim 2006 [55] and is only used for the agricultural land (for other land types, *P* = 1 is used) based on

slope classification. The support for protection against erosion can only be attributed to the land where conservation practice can be provided. In Nepal, the agricultural practice in sloped land is carried out by construction of terraces that is closely related to contouring. The P value ranges from 0 to 1, where a value of 0 represents the good erosion-resistance facility of farming practices. The P factor is listed in Table 4.

Table 4. Support practice factor, P , only for agricultural land.

Slope (Degrees)	Contouring
0–4	0.55
4–6.45	0.6
6.45–9.98	0.8
9.98–15	0.95
>15	1

4.8. Sediment Delivery Ratio (SDR)

The sediment delivery ratio (SDR) is the ratio of sediment yield to the gross erosion. Lumped SDR is calculated using empirical equations provided in literature and is given in Table 5.

Table 5. Equations used to estimate lumped SDR.

Equation	Reference
$SDR = 0.4724A^{-0.125}$	[40]
$SDR = 0.5656A^{-0.11}$	[39]
$SDR = 0.627SLP^{-0.11}$	[41]

In Table 5, A is the catchment area and SLP is the % slope of the mainstream channel. Most of the expressions relating SDR and catchment area suggest that, as the catchment area increases, the SDR tends to decrease. This implies that larger catchments tend to have lower SDRs, indicating that larger catchments are more effective at retaining sediment and preventing it from reaching the downstream channels.

To determine the SDR in a distributed approach, the SDR for any raster cell i is calculated with the use of the conductivity index IC , as expressed in Equation (9), which is hydrologic or sediment connectivity of a cell in the catchment [56]. Two approaches are utilized in this method: the upslope approach and the downslope approach. The upslope approach characterizes the drainage area, where the SDR decreases with increasing basin size, as larger basins typically have lower average slopes and more sediment storage sites. The downslope approach considers the length of flow path that a particle must travel to reach the nearest outlet or sink. The longer the path, the lower the likelihood that sediment will reach the outlet, the IC is obtained from Equation (9).

$$IC = \log_{10} \left(\frac{D_{up}}{D_{dn}} \right) = \log_{10} \left(\frac{\bar{C}\bar{S}\sqrt{A}}{\sum_i \frac{d_i}{C_i S_i}} \right) \quad (9)$$

where $\bar{C}$ is the mean USLE cover management factor for the upslope contributing area, $\bar{S}$ is the average gradient of the upslope contributing area (m/s) and A is the upslope contributing area (m²). The variable d_i is the length of the path along the i th cell following the steepest downslope direction toward the stream, while C_i and S_i are the cover management factor and the gradient of the i th cell, respectively. Finally, the SDR is obtained as in Equation (10). The schematic representation of these components is illustrated in Figure 5b.

$$SDR_i = \frac{SDR_{max}}{1 + e^{\left(\frac{IC_0 - IC_i}{k} \right)}} \quad (10)$$

where SDR_{max} is the maximum theoretical SDR, which is taken as 1, and IC_0 and k are the calibration parameters, which are set to 0.5 and 2, respectively. The minimum value of IC has been set to 0.005 m/m to avoid it having infinite values and a maximum of 1 m/m to limit the bias due to very high values of IC , especially on steep slopes. The threshold for flow accumulation cells has been set to 10,000 cells for generation of streams.

The `r.sdr` module was implemented, and the initial grass code written in python script was obtained from De Rosa 2020 [57] with some modifications and translation of the script to V3 script of python. It uses other modules of GRASS GIS, viz., `r.watershed` and `r.water.outlet`, and finally derives the SDR map from Equation (10). The depressions are filled by smoothing of them DEM, and drainage direction is calculated. The flowchart of the `r.sdr` module is illustrated in Figure 5a. The workflow for the estimation of sediment yield in the Kabeli catchment is illustrated in Figure 4.

Finally, the sediment yield in the catchment is derived using Equation (11).

$$SedimentYield = \sum RUSLE_i \times SDR_i \quad (11)$$

where $RUSLE_i$ and SDR_i are the specific erosion rate and sediment delivery ratio of the i th cell, respectively.

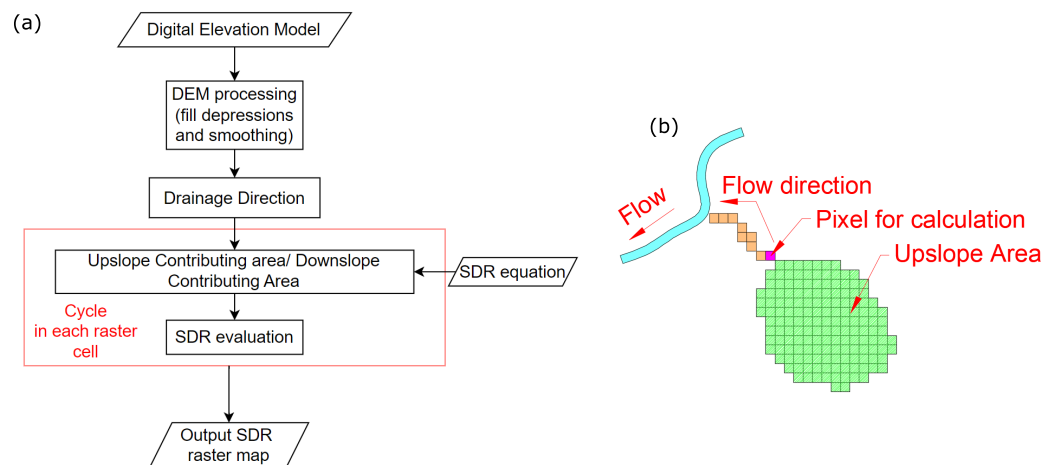


Figure 5. (a) Workflow for GRASS GIS module (`r.sdr`) (modified from DeRosa et al. 2016 [58]). (b) Schematic representation of components of SDR calculation.

5. Results

5.1. *RUSLE* Factors

The results of *RUSLE* factors show that the rainfall erosivity factor (R) ranges from 631 to 1002 MJ mm/ha/h. Higher R values are predominantly found in the northwestern part of the catchment, where the mean annual rainfall is higher. Conversely, the northeastern region of the catchment lacks a rainfall station, resulting in lower rainfall by interpolation effect and, consequently, reduced R factor values. Since there are only two soil types in the area, the soil erodibility factor (K) is represented by two distinct values, ranging from 0.249 to 0.252. The topographic factor (LS) ranges from 0 to 29.2. The variation in the topographic factor is highest among the other factors. The cover management and support practice factor for the entire catchment ranges between 0 to 0.45 and 0.55 to 1, respectively. The spatial distribution of different *RUSLE* factors in the Kabeli catchment is shown in Figure 6.

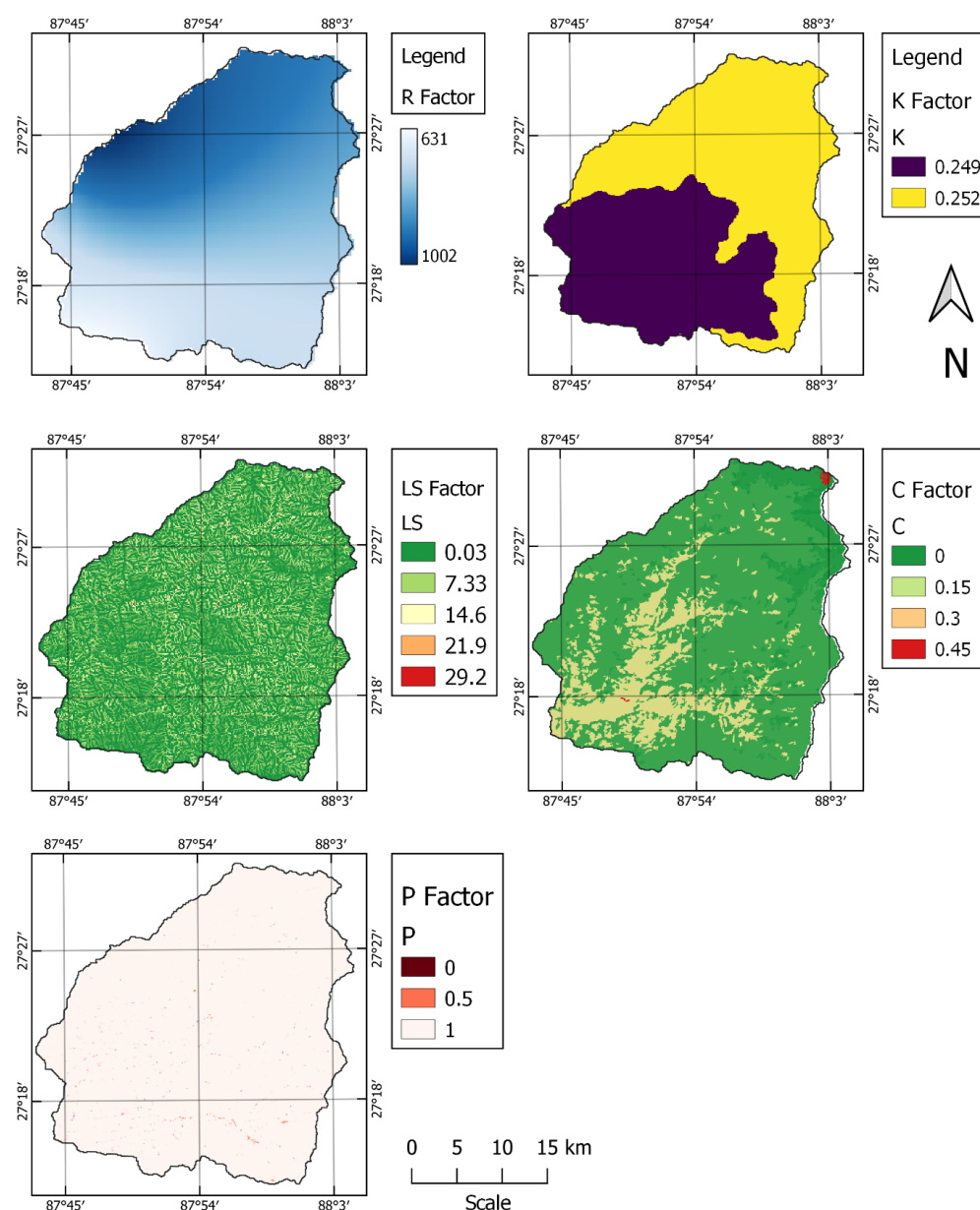


Figure 6. Spatial distribution of different RUSLE factors. *R*, *K*, *LS*, *C* and *P* serially from left to right.

5.2. Potential Soil Erosion Rate

The potential soil erosion rate in Kabeli catchment is obtained by overlaying RUSLE factor maps in QGIS. The average estimated erosion rate thus obtained is 35.93 tons/ha/yr. Figure 7 shows the potential soil erosion rate in the Kabeli catchment along with categorization of soil erosion risk done in reference to Singh et al. 1992 [59]. The erosion rate for different risk categories along with their coverage areas is shown in Figure 8. It shows that around 60% of the land has a slight erosion rate which is not concerning. Around 22% of the total land has a higher erosion rate. It is seen that the erosion rate is higher in barren land followed by agricultural, shrub land, forest and grassland, respectively.

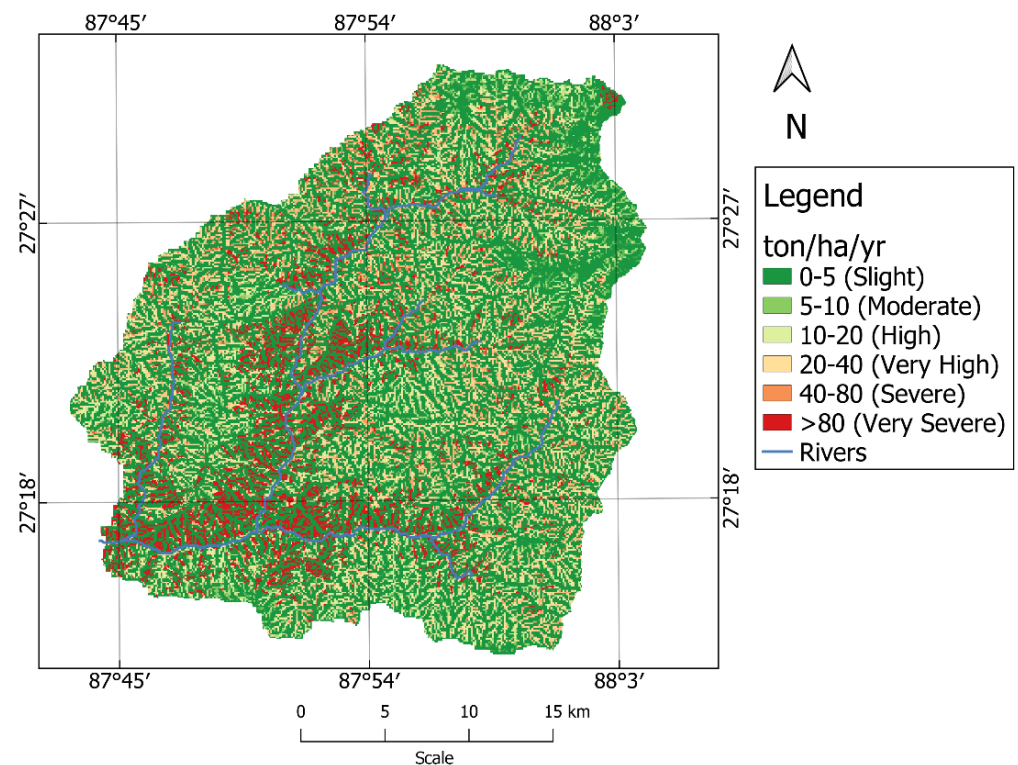


Figure 7. Soil erosion rate of the Kabeli catchment. The categorization of erosion risk is based on Singh et al., 1992 [59].

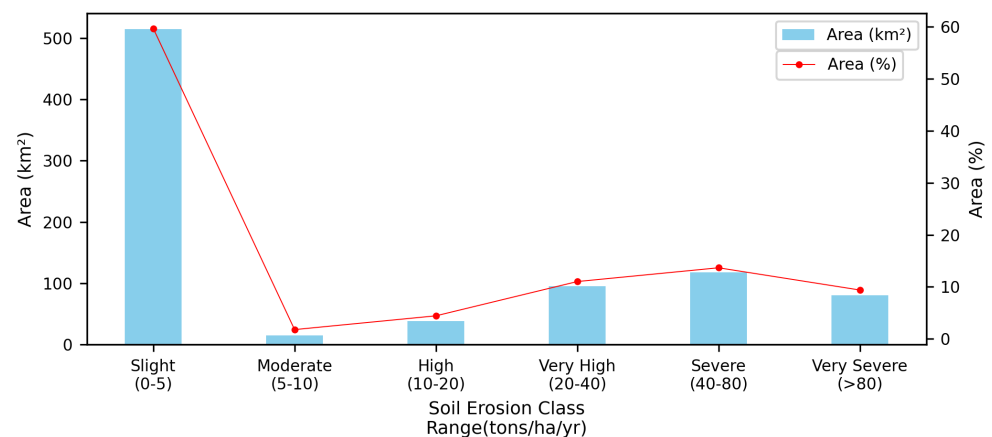


Figure 8. Erosion rate for different soil erosion categories.

5.3. Sediment Delivery Ratio

A lumped values of SDR calculated from empirical relations provided in Table 5 yield 0.202, 0.268 and 0.205 from Vanoni 2006 [40], USDA 1972 [39] and Williams and Berndt 1977 [41], respectively, with an average of 0.225. From the RUSLE erosion rate and lumped SDR, the SSY of the Kabeli catchment is 8.07 tons/ha/yr. The observed SSY over the study period is 7.26 tons/ha/yr. However, sediment yield obtained by using lumped SDR does not provide spatial distribution of the delivery ratio and sediment yield. Moreover, deducing SDR from catchment area alone would result in spurious correlations. Therefore, the spatially distributed SDR is derived by applying $r.sdr$ [57,58] using DEM and raster of the RUSLE cover factor (C). Figure 9 shows the SDR raster map of the Kabeli catchment, and Figure 10 shows the distribution of SDR values in the catchment that ranges from 0 to 0.55 with a median value of 0.124.

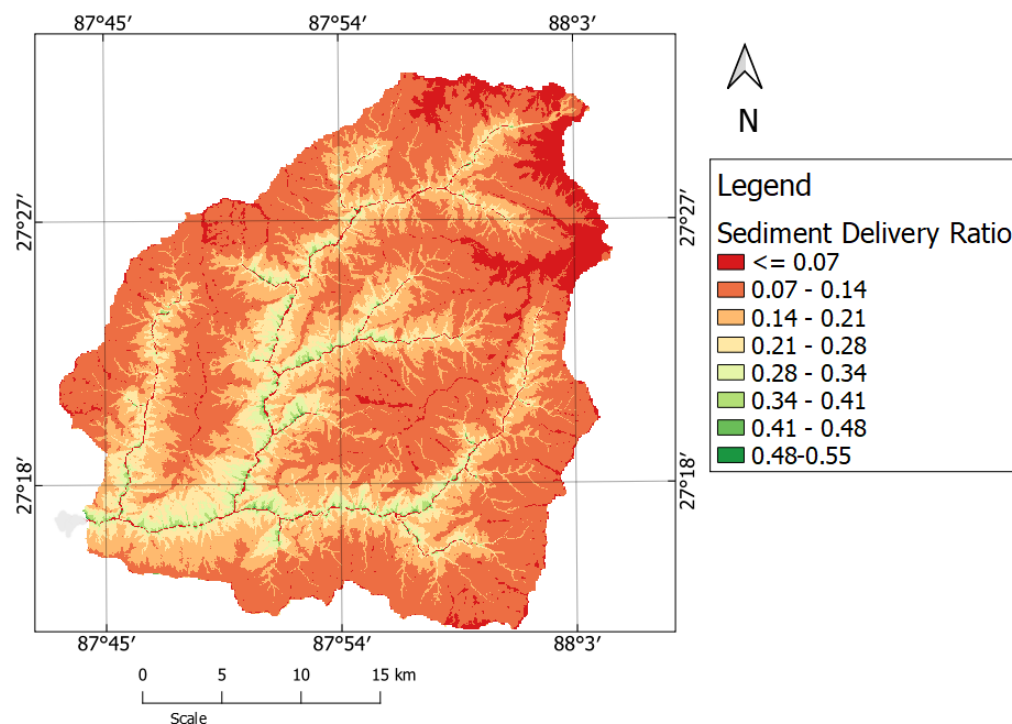


Figure 9. SDR raster map of the Kabeli catchment.

The sediment yield in the Kabeli catchment was obtained by overlaying erosion maps from the RUSLE with the SDR map in the GIS environment. This approach provides information about the export and retention of sediment in the catchment. The estimated SSY from RUSLE and SDR model is 6.74 tons/ha/year. Figure 11 shows the spatial distribution of SSY in the Kabeli catchment.

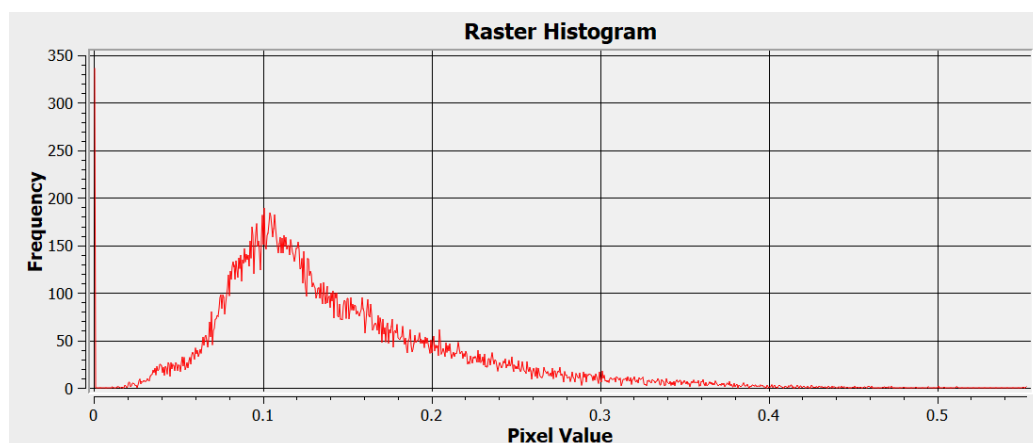


Figure 10. Histogram distribution for the SDR values in the Kabeli catchment.

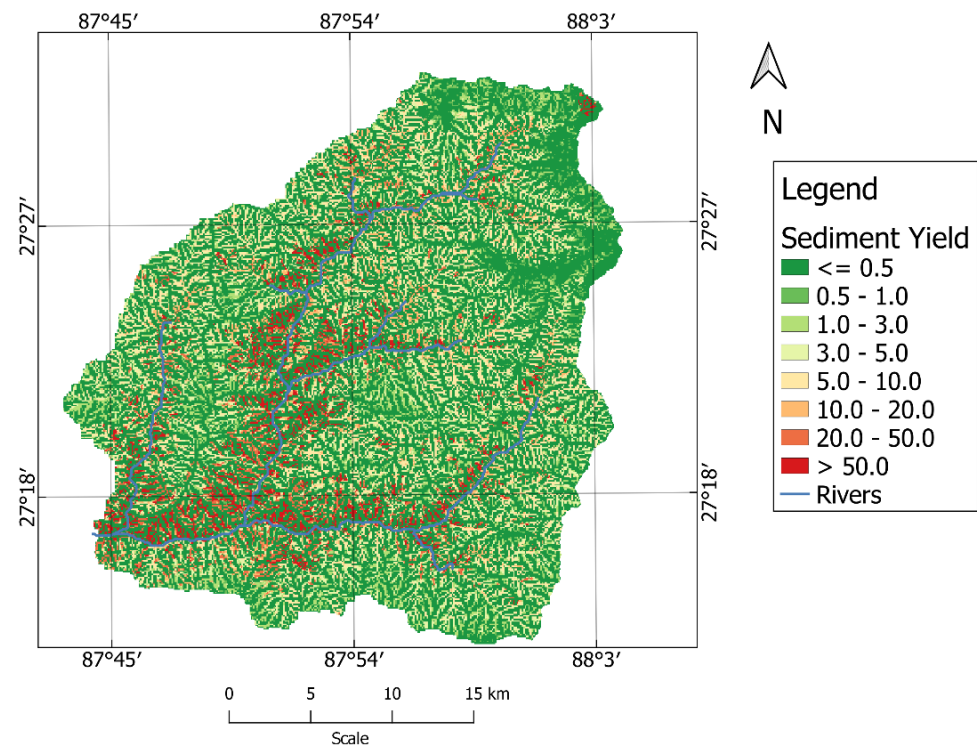


Figure 11. Sediment yield from Kabeli catchment from the RUSLE and SDR model.

5.4. Factors Responsible for Sediment Yield

Correlation analysis is carried out between sediment erosion, SDR and SSY and each factor of RUSLE, i.e., R , K , LS , C and P , to evaluate the dependency of erosion on each RUSLE factor in the Kabeli catchment. From Figure 12, it is evident that the sediment erosion is dependent on the topographic factor, LS ($r = 0.58$), followed by the cover management factor (C) ($r = 0.44$). The wide variability in the LS factor (Figure 6) also indicates that the sediment yield in the Kabeli Basin would be highly governed by the topographic characteristics and slope of the terrain. Other factors did not yield significant correlation with sediment erosion, indicating that LS and C have higher effect on sediment erosion than factors R , K and P . Figure 12 shows correlation between factors of RUSLE with sediment erosion, yield and SDR.

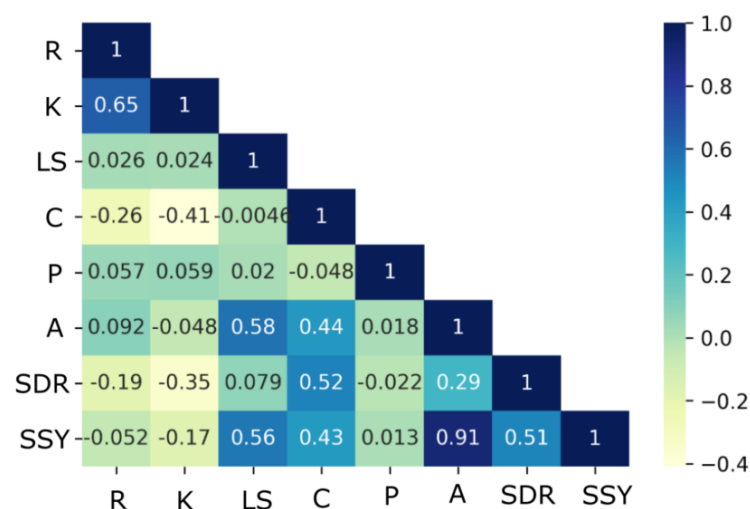


Figure 12. Correlation between factors of RUSLE, sediment erosion, sediment delivery ratio and sediment yield.

6. Discussion

6.1. Sediment Erosion and Yield

In the Kabeli catchment, sediment erosion shows a stronger dependency on topographic factors, followed by the cover management factor. This is consistent with findings of Yigez et al., 2021 [38], which shows a high correlation between SSY and *LS* factor, which is also observed in Figure 12. The weaker correlation between other factors (*R*, *K* and *P*) and sediment erosion in the Kabeli catchment may be attributed to nearly uniform input raster values (Figure 6) from these parameters. Even though the *R* factor showed a weak correlation with sediment erosion and yield from the RUSLE approach, rainfall generating direct runoff has been identified as the primary driver of sediment transport in such catchments [15]. By integrating insights from this study with prior research, it can be inferred that steep slopes exposed to higher rainfall are particularly vulnerable to soil erosion.

Sediment erosion and yield in the Kabeli catchment show large spatial and scale variability. The results of erosion from the RUSLE show that the rate of erosion of 35.93 tons/ha/yr seems to be on the higher side in a catchment in a mountainous area, where a soil loss up to 25 tons/ha/yr is considered bearable and the natural rate of soil erosion is high [52]. High tectonic activity, rapid weathering, young fractured rock mass and steep topography enhances the erosion rates in the Himalayan region [15], which are higher than in other parts of the world. Around 60% of the land in the study area is above the tolerable limits of erosion. The erosion is comparatively lower (less than 15 tons/ha/yr) under land use types such as forest and grassland, which is in line with the results obtained by Shrestha 2009 [60] in Likhu Khola valley. The grassland has the lowest erosion rate due to the cover management factor ascribed to the interruption of rill formation, limiting erosion induced by rainfall in the catchment. Similar magnitudes of erosion rates are seen in Kabeli catchments as compared to the study of Thapa 2020 [34], which was carried out in similar physiographic range. However, the erosion rates reported by Koirala et al., 2019 [33] for all of Nepal are relatively lower compared to the findings of the present study. This difference may be attributed to the larger spatial extent considered in their research, which likely resulted in an averaging effect over the broader area.

The SDR map (Figure 9) shows that the areas nearer to the streams have higher value of SDR. It is due to greater upslope area that contribute large amount of sediment and smaller flow path to the steepest downslope direction that increases the likelihood of observing sediment in the stream. Conversely, the highlands have a lower SDR due to the lesser contribution of sediment from upslope areas and the longer flow path towards the stream. The SDR map is also consistent with the fact that areas with high gradient are supposed to have higher SDRs than areas with flat terrain. The LULC map of the Kabeli catchment reveals that the area near streams is cultivable land where the cover management factor is on higher side. The sediment yield map (Figure 11) shows that the area lying in the vicinity of streams contributes greater sediment yield as compared to the other areas. This is due to collective effect of the SDR and the erosion in those areas where agriculture is prevailing.

The SDR calculated in a studied catchment using time of travel of overland flow within the topographic cell by Bhattarai 2013 [61] resulted significantly higher values of SDR than the present study. Similarly, a study shows that the SDR is lower in basins with gentle slope and higher in short and steep drainage basins [37]. This supposition does not match with our SDR model in this study because it has the capability of scale independence, which accounts for landscape variables with sedimentological connectivity concepts [56]. A similar approach was implied by Gashaw et al., 2021 [45], called the InVEST SDR method, where close alignment between observed and estimated sediment yield values was found in two catchments in the Ethiopian highlands.

The long-term observed SSY over the study period is 7.26 tons/ha/yr. The estimated SSY calculated with the lumped SDR method is 8.07 tons/ha/yr, while the yield calculated by overlaying the erosion map with the SDR map is 6.47 tons/ha/yr. These results show good consistency between the observed and estimated values from both methods. It is

important to note that the SDR calculated using the lumped method is dependent on the area of catchment, and the relationship between the SDR and catchment area may not follow a particular relationship across varying catchment sizes and characteristics. Moreover, the relationship between SDR and catchment area presents issues of self-correlation, hence requiring cautious application [44]. In contrast, the sediment yield calculated from the distributed SDR method accounts for not only the catchment area but also other factors such as land cover type, steepness of the area, and the length of the steepest downslope direction towards the stream. This approach also provides spatially detailed information about sediment yield values, making it a more effective method for yield estimation. The results from this study demonstrate that the approach used is capable of estimating sediment yield in the Kabeli catchment. Additionally, advantages such as scale independence and ease of implementation using landscape variables make it a valuable tool for assessing future impacts of changes in landscape drivers.

6.2. Data and Limitations of Model

The available geospatial data, such as land use and land cover, do not always match temporally with the data of suspended sediment sampling. The processes investigated in this research are at the catchment scale (hydrological scale). The phenomena occurring at the channel cross-section scale (hydraulic scale), which is not considered in this study, may also influence the sediment measurements and yield. At our research scale, it is difficult to predict the occurrence and effects of temporal activity like agriculture, road construction, hydropower development, and others, which could impact the results of the study.

The spatial variability associated with climatic stations is also a concern in this study. There is no rain gauge station within the catchment area. This can lead to errors in rainfall estimations and further proliferate in faulty sediment yield estimation. No gauge station is used to represent an entire watershed, as distributed hydrological models require spatially distributed input data. The daily sediment yield record is not available for some time periods, and missing data are thus interpolated, which may have caused errors while calculating observed sediment yield. There are no available data on the quantity of bed load sediments in the river. Moreover, the soil erosion model, the RUSLE, which is based on the USLE, only incorporates rill and inter-rill erosion processes. Other sediment erosion processes like gully erosion, stream bank erosion, mass wasting and landslide are not included in the model. Mass erosion is one of the major sources of erosion in areas like Nepal [62]. There is also uncertainty in the estimation of RUSLE's C and P factors, as they are taken from the published literature and had not been calibrated in similar catchments.

It is also seen that the soil erosion is less sensitive to slope length than the slope steepness [54], and most of the measured lengths while developing the USLE are less than 120 m and usually do not exceed 300 m [63]. However, the slopes of the Himalayas are more irregular, and the lengths may exceed the typical limits necessary for concentrating runoff in a well-defined channel, as assumed in the conditions under which the RUSLE model was originally developed. Due to the limitations of current technology, this is the only available database primarily derived from runoff plot experiments, which may introduce increased uncertainty in the model. The simplicity of the complex process of sediment erosion, mobilization and yield represented by the RUSLE has also made the input parameters quite sensitive and challenging to estimate. Although the RUSLE model's output shows consistency with the observed sediment yield, it is necessary to optimize the parameters used in the model. The model should be tested in similar catchments before general recommendations of the use of this model in similar physiographic conditions can be made.

Sediment supply within the catchment may be limited due to exhaustion of sediments (Figure 2a). However, the RUSLE model assumes an unlimited sediment supply, as an increase in the R factor directly translates to higher erosion rates, irrespective of sediment availability in the catchment. To enhance model's applicability, future studies could inte-

grate RUSLE with concepts of sediment supply dynamics and transport mechanisms [15] for a more realistic representation of sediment erosion and yield processes.

Geomorphological patterns and land forms have not been incorporated in the model, and the sediment is sampled considering the catchment as a single unit. Geological distribution and mineralogical characteristics are also not included in the model. A categorized dataset based on geological distribution [64], sediment provenance studies [65] and comprehensive hydrology–sediment modeling [66] would provide valuable insights into sediment erosion and yield mechanisms. For this, multi-site sampling of suspended sediment would be necessary.

6.3. Sediment Yield in Relation with Other River Basins

A general understanding of magnitude of sediment yield of the Kabeli river by comparing with other rivers helps to perceive and quantify the severity class of sediment yield. Several studies suggest that the erosion and sediment yield rates are higher in mountainous catchments, and Himalayan rivers exceed 100 tons/ha/yr in some areas [67]. However, the results in the Kabeli River from the observed sediment concentration resulted in an SSY of 7.26 tons/ha/yr over the study period, which is comparatively on the lower side than most of the rivers in Nepal. A brief site visit to the Kabeli River during the monsoon seasons indicated that the water is relatively clearer than most of the rivers in Nepal. This may be due to the fact that the rock formation in the catchment consists mainly of hard rock and there is no sediment feed from the glacier. A comparative study of the SSY of the Kabeli River along with other notable rivers is illustrated in Figure 13.

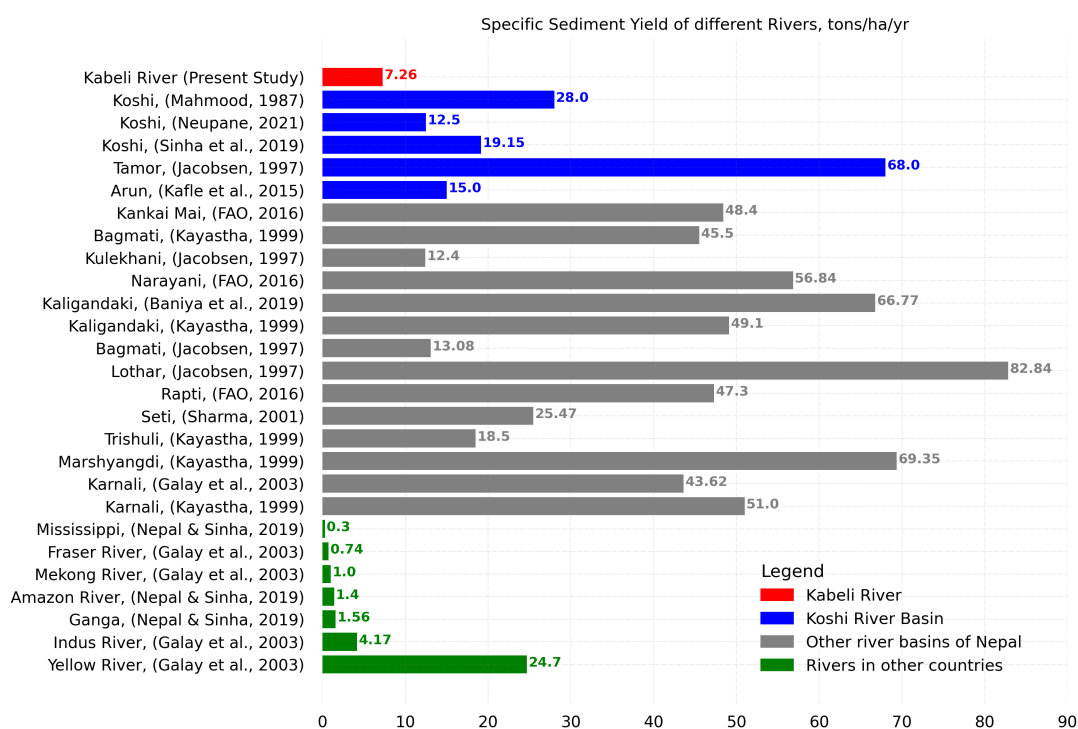


Figure 13. Specific sediment yield of different rivers. Red color bar is for Kabeli River, blue is for Koshi River Basin, gray is for other river basins of Nepal and green is for rivers in other countries [68–78].

7. Conclusions

The RUSLE coupled with SDR model is presented as a useful tool to estimate and quantify the sediment erosion and yield in the Kabeli catchment. The estimations were possible using rainfall, soil, land use and topography data. Different factors have contributed to the sediment erosion in the catchment. The estimated erosion rates are consistent with past studies in physiographically homogeneous areas. Area with a higher slope near the riverbank with a high erosion rate are indicated as areas are vulnerable to erosion and

potential hotspots for sediment yield in the river. The estimated specific erosion rate from the RUSLE in the Kabeli catchment is 35.96 tons/ha/yr. The compatibility of observed (7.26 tons/ha/yr) and estimated (6.47 tons/ha/yr) SSY from the SDR approach is encouraging and hence demonstrated that this model may be potentially used in estimating the sediment yield in the Kabeli catchment.

To gain more insights into sediment erosion and its estimation, some topics for further investigations are as follows:

- The use of this model in mountainous terrain/ Himalayan catchments with steep slopes is still questionable, and this model might not have incorporated actual underlying physical sediment transport processes occurring in the catchment. Validations of this approach in other catchments are still needed to verify the reliability of the model.
- The sediment erosion from other sources like streambank, gully and landslides erosion cannot be incorporated by the model. So, an appropriate model needs to be selected to address these processes in the catchment.
- Changes in climatological patterns and land use and their effects on sediment yield need to be evaluated. The factors and parameters used in this study have been adopted from existing literature. Fewer attempts have been made to date to calibrate or find physical parameters either by experiments or extensive study related to RUSLE factors in the Himalayas. So, future research should focus on obtaining the parameters supplemented by more soil monitoring and mapping in these environments.
- The approach used in this study can give the impression of the rate of erosion in a specified area, which is supported by the consistency between observed and estimated specific sediment yield. However, the approach should be used with caution, especially in an ungauged basin, as the parameters are spatially sensitive.

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Abbreviations

The following abbreviations are used in this manuscript:

AGNPS	Agricultural Non-Point Source model
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation
APHRODITE	Asian Precipitation Highly Resolved Observational Data Integration towards Evaluation of Water Resources
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
EPIC	Environmental Policy Integrated Climate
EUROSEM	European Soil Erosion Model
GIS	Geographic Information System
GRASS	Geographic Resources Analysis Support System
IC	Connectivity Index
ICIMOD	International Centre for Integrated Mountain Development
IDW	Inverse Distance Weighting
ISRIC	International Soil Reference and Information Center

LS	Slope Length and Steepness factor
LULC	Land Use Land Cover
masl	Meters Above Sea Level
QGIS	Quantum Geographic Information System
RUSLE	Revised Universal Soil Loss Equation
SDR	Sediment Delivery Ratio
SEDD	Sediment Delivery Distributed Model
SOTER	Soil and Terrain Digital Databases
SSL	Suspended Sediment Load
SSY	Specific Sediment Yield
USLE	Universal Soil Loss Equation
USPED	Unit Stream Power-Based Erosion Deposition Mode
WEPP	Watershed Erosion Prediction Project

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