Soil loss estimation of Karnali river basin, Nepal

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RESEARCH

Soil loss estimation of Karnali river basin, Nepal

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Abstract
Soil loss estimation is the prerequisite for deciding priorities for watershed management which in turn is important to maintain human needs and ecosystem services. Karnali River Basin in Nepal is highly susceptible to soil erosion but limited studies have elucidated its basin-specific erosion status utilizing advanced computations. This study was designed with the objectives of delineating the river basin and estimating its soil loss using the Revised Universal Soil Loss Equation (RUSLE) and Geographical Information System (GIS). The study individually calculated the required factors through Google Earth Engine and raster analysis in Arc GIS to create the potential soil loss map. The map depicted that the largest proportion (27%) of the area of the river basin was expected within the erosion category of 3 to 10 t ha^{-1} $year^{-1}$, followed by 10 to 25 t ha^{-1} $year^{-1}$ (22%) and less than 1 t ha^{-1} $year^{-1}$ (22%). Only 2% of the land within the basin was at risk of erosion of more than 50 t ha^{-1} $year^{-1}$. The Average soil loss from Karnali was estimated at 9.85 t ha^{-1} $year^{-1}$. The total soil being lost per year from the Karnali River is 48,279,696 tonnes. The highest amount of soil loss was estimated in Dolpa followed by Mugu, Humla, Rukum East, and then Rukum West districts of the Karnali river basin. The results can be of pivotal inference in further planning, and prioritizing management and protection areas for the local and provincial governments.

Keywords Google Earth Engine · Geographic Information System · Potential soil erosion · RUSLE model

1 Introduction

Soil is a panacea for all sorts of living things found on the earth. Humans, in particular, directly utilize more than 70% of the global, ice-free land surface (Rivera et al., 2017; Shukla et al., 2019) and the anthropogenic pressures on the land and water systems are exacerbating and being stretched to their limits of productivity (FAO, 2021). Globally, about 40% of the land is degraded, directly impacting half of humanity and threatening an estimated economic output worth more than 50% of the annual Gross Domestic Product (GDP) (UNCCD, 2022). The prominent drivers of global land degradation are acidification, contamination, desertification, salinization, landslides, and soil erosion (Brady & Weil, 2017). Global Soil Partnership (GSP) reports 75 billion tonnes (Pg) of global annual erosion from arable lands, amounting to an estimated financial loss of US$400 billion per year (GSP, 2017).

Water-induced erosion is the major form of land degradation (Bai et al., 2008; Borrelli et al., 2020) and its ecological detriments include the loss of fertile topsoil, soil quality deterioration, and the increasing soil sediments in stream channels (Xiong et al., 2013). Soil erosion is high in the fragile hills and steep slopes of Nepal where livelihood highly depends on land-based ecosystem services. Nepal's productive soil is flashed out perpetually thereby reducing crop productivity and on-farm income, and polluting lowland land and water resources (Chalise et al., 2019; Gardner & Gerrard, 2003). A study estimated the nationwide mean annual soil loss of Nepal at 25 t ha^{-1} $year^{-1}$ with a total of

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369 million tons of potential soil loss (Koirala et al., 2019). The annual soil erosion rate is around 64 t ha^{-1} $year^{-1}$ in Siwalik Hills (Gardner & Gerrard, 2003), 22 t ha^{-1} $year^{-1}$ in the barren lands of the Koshi basin (Uddin et al., 2016), and 11.17 t ha^{-1} $year^{-1}$ in the Aringale Khola watershed of Nepal (Chalise et al., 2018).

Soil loss estimation is regarded as the imperative factor for the proper management of watersheds to maintain human needs and the ecosystem. Both policymakers responsible for land use decisions and earth-system modelers seeking to minimize uncertainty on global projections must have a better comprehension of the likely rates of soil erosion (Borrelli et al., 2020). Information regarding soil erosion quantity, spatial pattern, and dynamics is pivotal in the characterization and prioritization of watersheds (Pan & Wen, 2014; Pham et al., 2018) and thus assists in strategically planning conservation policies. More specifically, the inferences from the soil erosion estimation are crucial to addressing the problems of siltation along the major rivers and downstream in the floodplain areas. The existing soil erosion estimation models can be segregated into three major categories: conceptual, physical-based, and empirical (Merritt et al., 2003).

The process-based physical models are complex with rigorous data requirements (Jetten et al., 2003; Nearing, 2013) and also impractical beyond the scale of field level or small catchments (De Vente & Poesen, 2005). The Revised Universal Soil Loss Equation (RUSLE) model is a simple and empirical method modified from the Universal Soil Loss Equation (USLE) model. RUSLE calculates the expected annual soil loss from a unit of land using a mix of geophysical and land cover data. RUSLE maintains the empirical equation of USLE to calculate erosion but it better handles the terrain convergence and divergence and also integrates the regions with net sedimentation. RUSLE also better captures the role of prolonged rain, surface residues, and runoff to rills and gullies in soil erosional process. RUSLE has more flexibility and efficiency in modeling as compared to USLE and its empirical plus process-based design means it optimizes the data use (Biswas & Pani, 2015).

RUSLE is regarded as an extremely reliable model and is adopted for estimating soil loss on wider spatial scales on regional scales like landscapes or watersheds. One of the obvious advantages of the RUSLE is its seamless combination with Remote Sensing (RS) and Geographical Information system (GIS) tools to estimate soil loss. RS and GIS approach is currently one of the most popular technologies for conducting spatiotemporal analyses which otherwise may not be achievable through the traditional mapping techniques (Mishra et al., 2020a, 2020b). The combination of RUSLE with RS and GIS can also be instrumental in gathering inferences in a wide variety of topographic terrain including the ones most hostile and vast for physical or field-based studies. Therefore, the model has been widely used in Ethiopia (Atoma et al., 2020; Getu et al., 2022), Turkey (Tanyaş et al., 2015), Malaysia (Roslee & Sharir, 2019), China (Pan & Wen, 2014; Yin et al., 2015), Bhutan (Gyeltshen et al., 2022), India (Ganasri & Ramesh, 2016; Markose & Jayappa, 2016) to the mountainous regions of Nepal (Koirala et al., 2019; Thapa, 2020; Uddin et al., 2016).

Karnali Province, the largest province in the country, is characteristically occupied by sloppy mountains and hills. The Karnali River System, flowing across Nepal for 507 km, is the longest river in the country making up more than 90% of the basin's area. Karnali River Basin has 742 glacial lakes and 1459 glaciers. Soil erosion is reported as a major driver in changing the basin hydrology and inundation in such Himalayan river basins (Gardner & Gerrard, 2003). However, the provincial governments are only nascent and do not yet have the required institutional capacity to undertake all the assigned functions (Shrestha, 2019). There is a dearth of reliable provincial-level soil loss data computed based on more advanced computerizations and refined variables. Very few existing studies specifically cover solely and exclusively the Karnali River Basin in terms of spatial scale. The most recent study (Pandey et al., 2015) does focus on the Karnali River Basin and incorporates RS and GIS but instead utilizes the USLE model.

Therefore, this study was designed to estimate the soil loss of the Karnali River Basin in Nepal using RUSLE modeling in combination with RS and GIS. The objective of the study is to conduct a basin-wide quantification of soil loss together with a calculation of soil loss and potentially vulnerable areas. The study intended to provide inferential data to conserve soil and thereby preserve the numerous ecosystem services. The study is also expected to generate the region-specific potential erosion and pinpoint risk zones to assist in supporting decisions for planners to develop priority protection areas. Similar studies may also be extended to other unexplored areas for proper soil and watershed management practices in hilly terrains of the country.

2 Materials and methods

2.1 Study area

Karnali Province is situated in the northwestern part of Nepal. It covers the whole part of the Dolpa, Humla, Mugu, Bajhang, Bajura, Jumla, Kalikot, Rukum West, Jajarkot, Dailekh, Achham, Doti, and Surkhet; most of the Rukum East and some part of the Baglung, Myagdi, Rolpa and Salyan, Bardia, Kailai, Dadeldhura and Baitadi Districts (Fig. 3). The total area of this province is 27,984 km^2. According to the population census of 2011, the total population of this province is 15,70,418. Raji and Raute communities are indigenous to the Karnali Province. Raji's are found in Surkhet in a small number ($n = 1271$) (CBS, 2012). The province is expected to harbor a large proportion of Nepal's birds (46%), mammals (42%), butterflies (22%), fishes (32%), reptiles (11%), amphibians (43%) and flowering plants (42%) (Acharya & Paudel, 2020). Of a total of 89 mammalian species that are known and expected to be present in Karnali Province, 10% are globally threatened. Dolpa alone shares 57% ($n = 400$) of Nepal's medicinal and aromatic plants (MAPs), therefore, Karnali Province is the habitat of at least 400 medicinal and aromatic plants. Almost 90 percent of the Dolpa lies above 3500 m and its inhabitants use complex livelihood strategies by synergizing agriculture, animal husbandry, and trade to survive in such inhospitable landscapes (Lama et al., 2001).

2.1.1 Karnali River Basin

Karnali River Basin in Nepal is the area of the study. Karnali River Basin covers a vast 43,147 km^2 area of Nepal and some parts of China. This study considered only the regions inside Nepal for estimating soil erosion. The major rivers of the Karnali River Basin are Humla Karnali, Mugu Karnali, Tila, and Budhi Ganga. Forests, bare land, snow/glacier, agriculture, grassland, and shrubland are major land use types of this river basin (Figs. 1 and 2).

Along with other snow-fed rivers, the Karnali River System, which flows across Nepal for 507 km, is the longest river in the country. It makes up more than 90% of the basin's area. Tibet is the source of Humla Karnali, which joins Mugu Karnali in Galwa to form the Karnali River. Other tributaries of the Karnali River System include the West Seti, Bheri, Kawari, and Tila Rivers. Karnali basin has 742 glacial lakes and 1459 glaciers. The summer monsoon brings roughly 80% of the region's precipitation, with winter droughts being the most common. About 1479 mm of precipitation falls on average each year in the basin. At Chisapani, the average annual flow of the Karnali basin is 1392 m^3/s. However, the river basin which extends to numerous administrative districts, remains one of the least studied in the country due to its sheer area, and topographical and technical difficulties (Fig. 3).

2.2 River basin delineation

River basins were delineated with shape files of larger areas than expected basin areas were created with the help of ArcGIS (Esri, 2011). Subsequently, the Digital Elevation Model (DEM) having a 30 m spatial resolution was downloaded from the website of the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/) and masked by

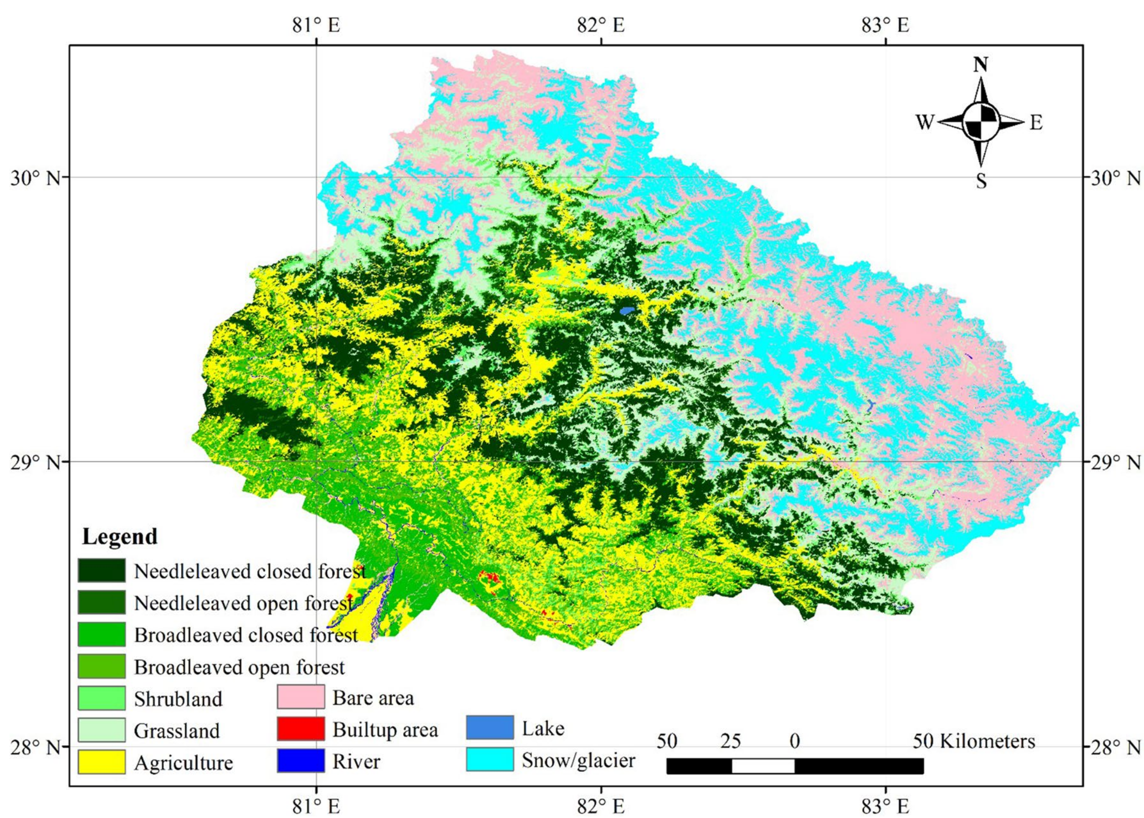

Fig. 1 Karnali River Basin

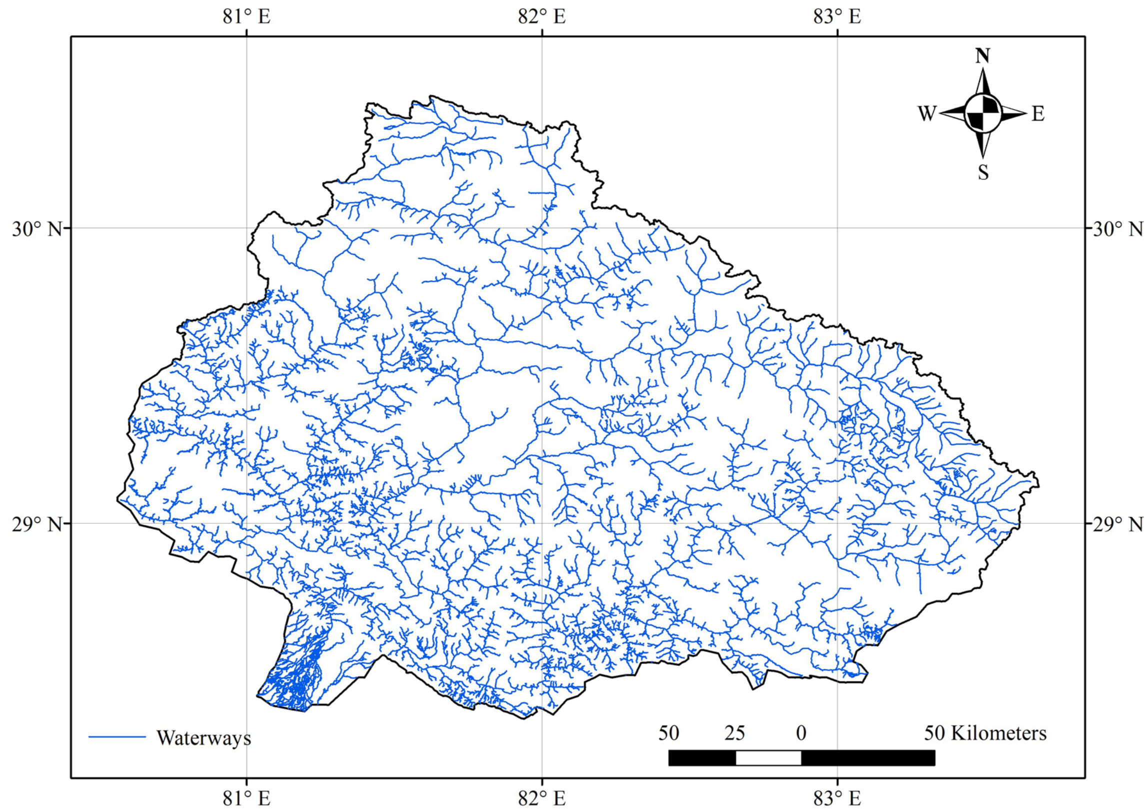

Fig. 2 Drainage map of Karnali River Basin

the created shape file of the previous step. DEM files were refined by the fill tool; then, the flow direction tool was used to prepare the flow direction raster. The flow accumulation tool was then used to prepare the flow accumulation raster; a raster calculator was used ("flow_accumulation_raster > 5000") and given the name "flow_accumulation_raster5000.tif to extract the streams where water comes from more than 5000 pixels. The point shape files of pour points were then created at the outlet of the rivers; the basin tool of ArcGIS was used (use flow direction raster as input raster) to prepare the raster file of River basins. The raster files of River basins were then converted to polygons using the 'raster-to-polygon' tool. Finally, River basins were delineated and the area was calculated.

2.3 Estimating the soil loss

Universal Soil Loss Equation (USLE) is widely used for soil loss estimation (Devatha et al., 2015; Girmay et al., 2020; Sekyi-Annan et al., 2021). The Revised Universal Soil Loss Equation (RUSLE) is being more widely used for soil loss estimation. (Chadli, 2016; Hu et al., 2019; Koirala et al., 2019; Prasannakumar et al., 2012; Thapa, 2020). The RUSLE stands for the effects of raindrops on climate, soil, topography, and land use on rill and inter-rill soil erosion. The annual soil loss is estimated as the product of the layer values of the following factors in RUSLE i.e. erosivity (R), erodibility of the soil (K), topographic (LS), crop management (C), and conservation practice (P). For preprocessing and post-processing, Geographical Information System (GIS) is a widely used software to estimate soil loss (Jain & Kothyari, 2000). This study was re-processed and post-processed in ArcGIS. Analysis was performed in Google Earth Engine. To calculate soil erosion loss on a cell-by-cell level, remote sensing, GIS, and RUSLE are applied (Millward & Mersey, 1999) and this combination aids in optimizing the potential for diverse applications, including spatial computation (Luvai et al., 2022). This study estimated soil erosion using RUSLE (Eq. 1).

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

where A = soil loss (t ha^{-1} $year^{-1}$), R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1}, $year^{-1}$), K = soil erodibility factor (t h MJ^{-1} $mm^{-1.}$ LS stands for slope length and slope steepness factor, C for land management component, and P for conservation practice factor (dimensionless)

The rainfall erosivity factor (R) is the erosive potential possessed by rain to trigger erosion. It is quantified as the product of kinetic energy and maximum intensity of the rainfall over 30 min (Yin et al., 2015). Meanwhile, the inherent

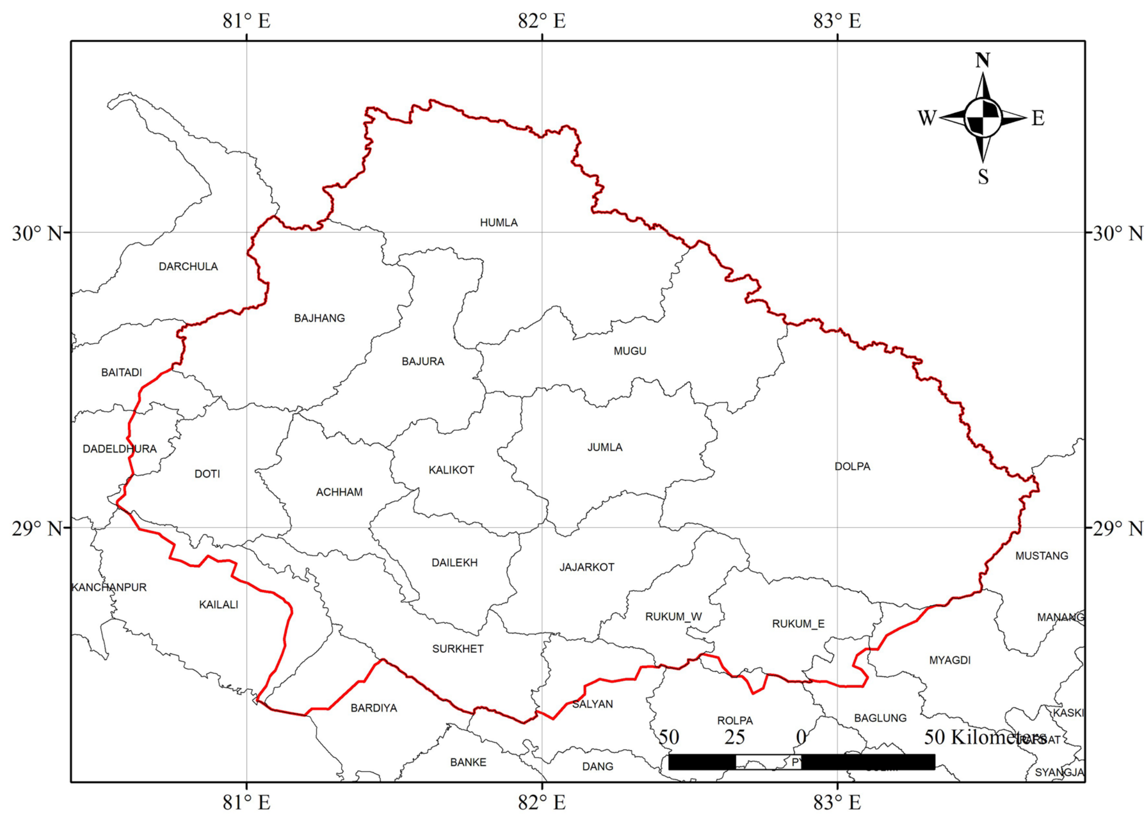

Fig. 3 Karnali River basin in the political map

erodibility of soil particles to be detached by rainfall and then transported by the subsequent runoff is the Soil erodibility factor (K) (Millward & Mersey, 1999). It characterizes the long-term reaction of the soil to heavy erosive precipitation events (Fu et al., 2006). The slope length (L) and slope steepness (S) are the two significant parameters to characterize the influence of topography on erosion in the RUSLE model. The cumulative distance from the point where surface runoff occurs up until where it reaches a clearly defined channel is the slope length (Gelagay & Minale, 2016; Kidane et al., 2019). Similarly, the slope gradient factor elucidates how the steepness of the slope influences soil erosion (Koirala et al., 2019). The C-factor measures the combined effect of vegetation cover and the varied land management practices on the soil erosion process. Similarly, the Conservation Practice (P) factor is expressed as the ratio between the rate and soil loss amount while using a particular conservation practice and when farming is implemented in an up-and-downslope manner.

2.3.1 Calculation of rainfall erosivity factor

The daily precipitation data for 2021 was obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) which is a 30 + year quasi-global rainfall dataset having 0.05° resolution satellite imagery (Funk et al., 2015). It was prepared from in situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. Based on it, mean annual precipitation was computed in GEE. R factor was calculated using the following equation (Morgan, 1985).

$$\mathbf{R} = 38.5 + 0.3\boldsymbol{P},$$

where R refers to the Rainfall Erosivity Factor, and P refers to the Mean Annual Rainfall in mm

2.3.2 Calculation of soil erodibility factor

Typically, the soil map functions as a basis for deriving the erodibility factor layer for a watershed. Therefore, the essential raster files of sand, silt, clay, and organic matter of the study area were downloaded from Nepal's digital soil map accessible on the web portal of the National Soil Science Research Center of Nepal Agricultural Research Council (https://soil.narc.gov.np/soil/soilmap/). The organic carbon of soil was estimated assuming 58% organic matter (Bianchi et al., 2008). Finally, soil erodibility factors of both Karnali

River basins were calculated using the equation given by Sharpley and Williams (1990).

$$\mathbf{k = Fcsand * Fsi - cl * Forgc * Fhisand} * 0.1317$$

where,

$$Fcsand = \left[0.2 + 0.3\exp\left(-0.0256SAN\left(1 - \frac{SIL}{100}\right)\right)\right]$$

$$Fsi - cl = \left[\frac{SIL}{CLA + SIL}\right]^{0.3}$$

$$Forgc = [1.0 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}$$

$$Fhisand = \left[1.0 - \frac{0.70SNI}{SNI + \exp(-5.51 + 22.9SNI)}\right],$$

where C represents the total amount of organic carbon; SAN, SIL, and CLA represent the percentages (%) of sand, silt, and clay; and SN1 represents the amount of sand divided by 100 after taking away one.

Fcsand provides a high value for soil with little sand content while offering a low value for soil with coarse sand.

It has a high clay-to-silt ratio and a low soil erodibility factor, or Fsi-cl.

Forgc is the element that reduces soil erosion in areas with a lot of organic matter.

Fhisand = The factor that reduces soil erodibility in situations where the sand content is exceptionally high in soil.

2.3.3 Calculation of slope length and slope factor

Various equations have been developed for the derivation of the LS factor majorly based on the digital elevation model (DEM). The DEM is a key input parameter where the variation of topographic features on a particular area is represented numerically. (Phinzi & Ngetar, 2019). Elevation data were obtained from the Digital Elevation Model (DEM) as provided by the Shuttle Radar Topography Mission (SRTM) in this study (Farr et al., 2007). This SRTM V3 product (SRTM Plus) was provided by NASA JPL at a resolution of 1 arc-second (approximately 30 m). Then, slope was extracted from elevation data using an algorithm in GEE. Finally, the L factor was estimated using the following relations (Gao et al., 2012).

$$l = \left(\frac{\lambda}{22.13}\right)^m,$$

where L = slope length factor, λ = slope length (m), m = slope-length exponent

$$\boldsymbol{m} = \frac{\boldsymbol{F}}{1 + \boldsymbol{F}'}$$

where, $\boldsymbol{F} = \frac{\frac{\sin\beta}{0.0896}}{3(\sin\beta)^{0.8} + 0.56}'$ where F = Ratio of rill erosion to inter-rill erosion, β = slope angle (degree).

Slope in degree was converted to slope in percentage and the slope gradient factor was calculated using the following equation as cited in (Uddin et al., 2016).

$$S = (0.43 + 0.30s + 0.043s^2)/6.613,$$

where 'S' is the Slope Gradient Factor, and 's' is the slope in percent.

2.3.4 Calculation of land management factor

This study accomplished an estimation of the C-factor by applying the vegetation indices derived from satellite imageries. Sentinel data with 10 m spatial resolution having snow cover less than twenty-five percent for 2021 was used for this study. This was used to calculate the normalized difference vegetation index (NDVI) using two bands namely band 8 and band 4 using the following formula prescribed by (Koirala et al., 2019), Knijff et al. (2000). The normalized difference vegetation index (NDVI), which is used in this study, has been among the increasingly popular indices used during the last decades. Harper (1987) presented that the NDVI index was found to better detect the land cover in his study area as compared to the other indexes.

$$C = \exp\left[-\alpha\left(\frac{NDVI}{\beta - NDVI}\right)\right],$$

where a and b are unitless parameters and equal to 2 and 1, respectively, and specify the relationship between C and $NDVI$.

2.3.5 Calculation of conservation practice factor

The common conservation practices generally include the use of contours, terraces, crop strips, grassed waterways, and cross-slope cultivation (Renard & Forster, 1983; Renard et al., 1996; Tanyas et al., 2015). Lower P values indicate the effectiveness of conservation practices. Farming in Karnali Province is usually prevalent along with the integration of terraces. Farming practices in Nepal occur by constructing

Table 1 P factor values for slope as per agricultural practice

Slope percent	Contouring
0–7	0.55
7–11.3	0.60
17.6–26.8	0.80
17.6–26.8	0.95
> 26.8	1.00

terraces in the sloppy lands which can be considered a conservation practice that shares a resemblance to contour farming. The Slope in percentage was reclassified into five classes as practiced before (Shin, 1999; Koirala et al., 2019) (Table 1).

2.4 Preparation of soil loss map

Soil loss maps of Karnali River Basins were prepared in the ArcGIS platform. The soil erosion maps of both River basins were prepared using ArcGIS after the estimation of soil loss with the Google Earth Engine (Esri, 2011). The code utilized for the calculation of RUSLE factors for estimating soil loss in the river basin via Google Earth Engine

Table 2 Spatial and Non Spatial data used in the study

S. No	Spatial & non-spatial data	Sources	Resolution
1	Daily precipitation data for 2021	Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) https://www.chc.ucsb.edu/data/chirps	0.05° resolution satellite imagery
2	Digital Elevation Model (DEM)	United States Geological Survey (USGS) SRTM V3 product (SRTM Plus), National Aeronautics and Space Administration (NASA) https://earthexplorer.usgs.gov/	30 m spatial resolution
3	Digital Soil map (raster file)	National Soil Science Research Center, Nepal Agricultural Research Council https://soil.narc.gov.np/soil/soilmap/	250 m
4	Digital Land Use Land Cover Map (2021)	Sentinel data	10 m spatial resolution having snow cover less than 25 percent

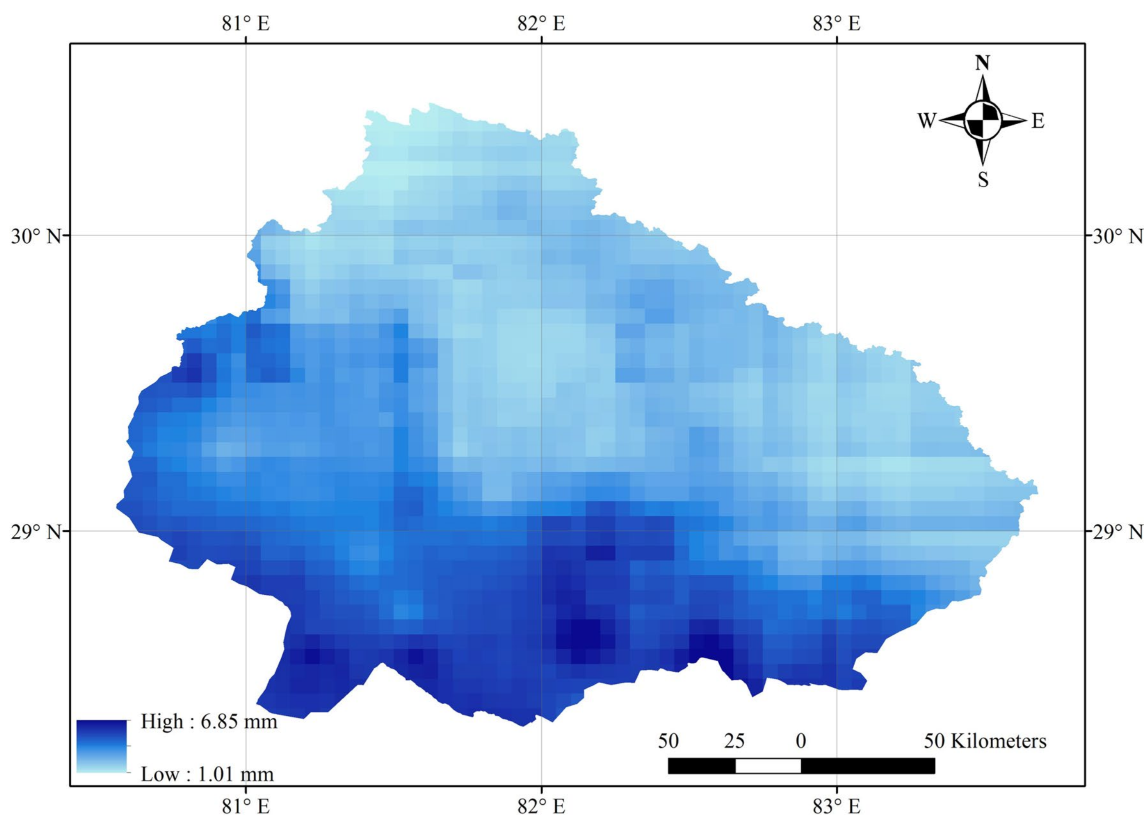

Fig. 4 Precipitation of Karnali River Basin

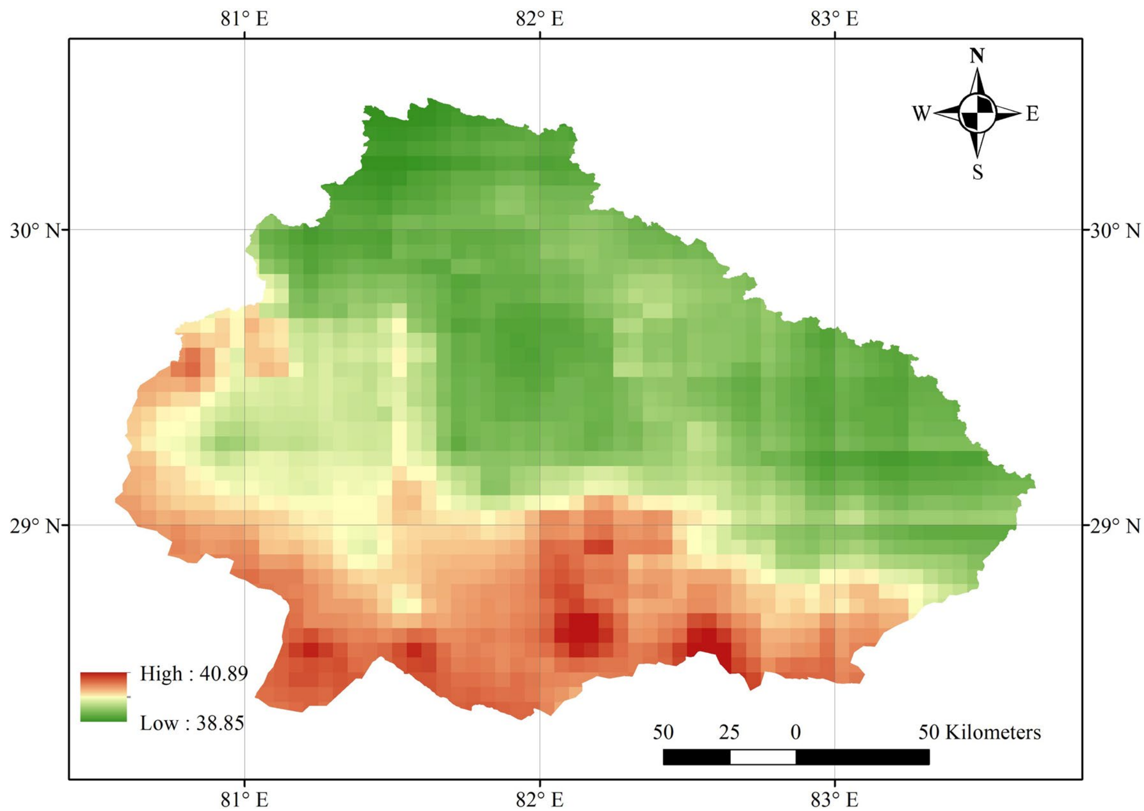

Fig. 5 R factor for Karnali River Basin

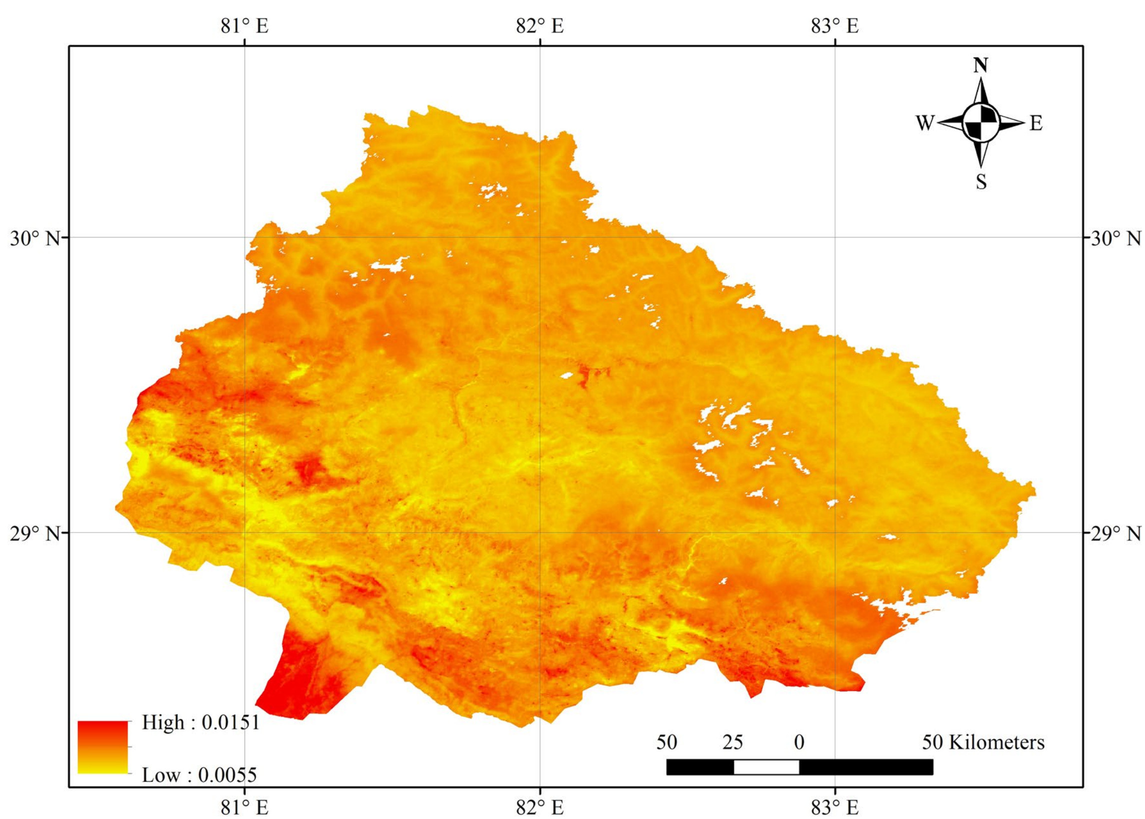

Fig. 6 K factor for Karnali River Basin

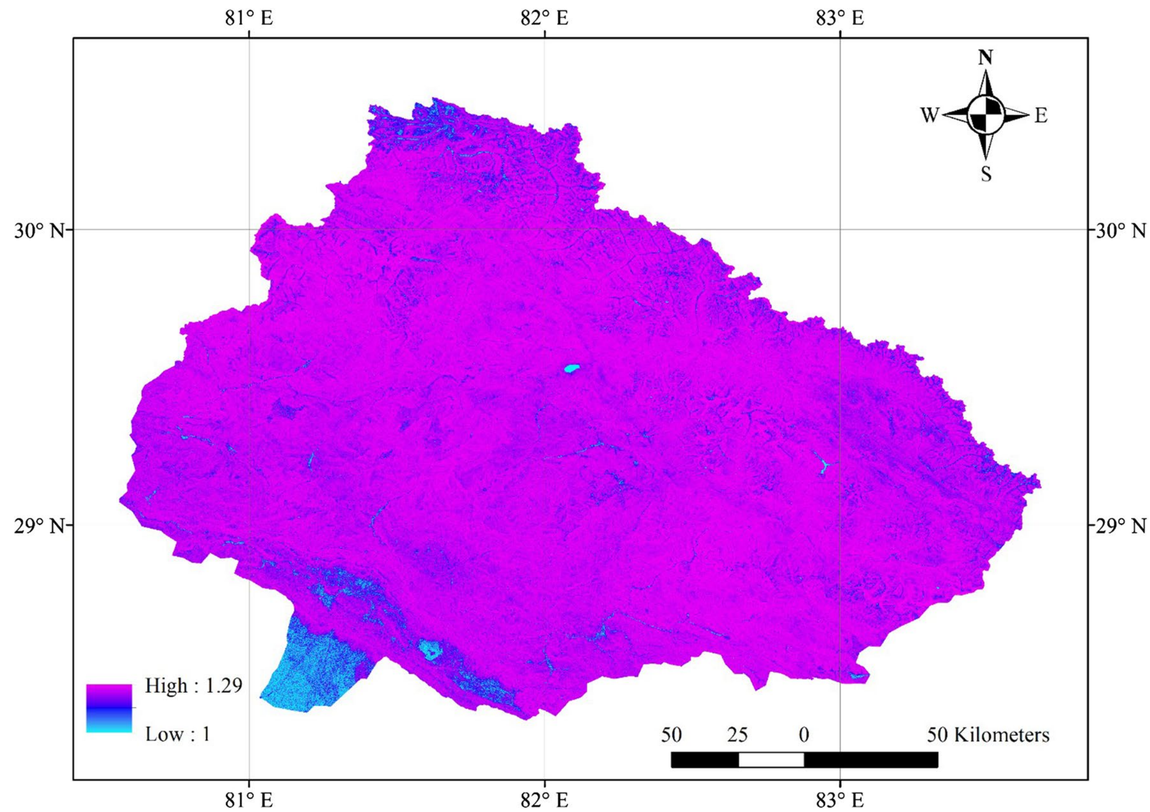

Fig. 7 L factor for Karnali River Basin

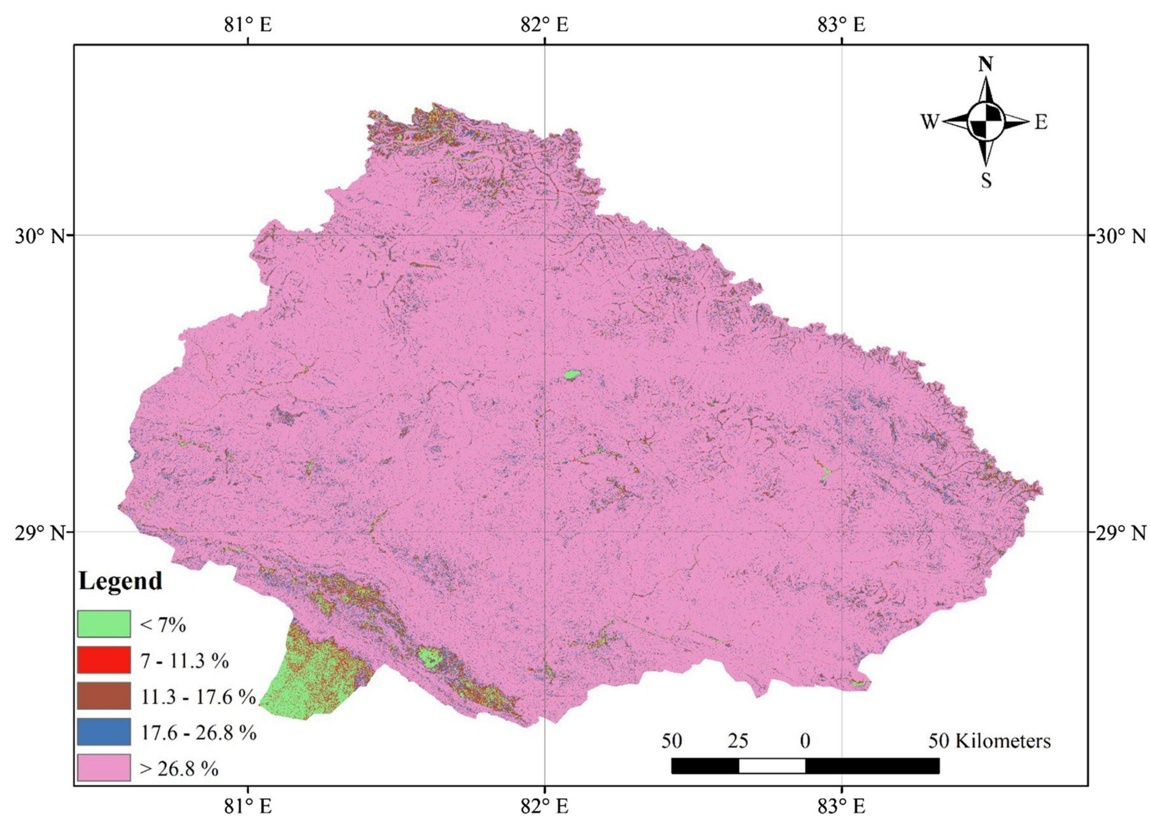

Fig. 8 S factor for Karnali River Basin

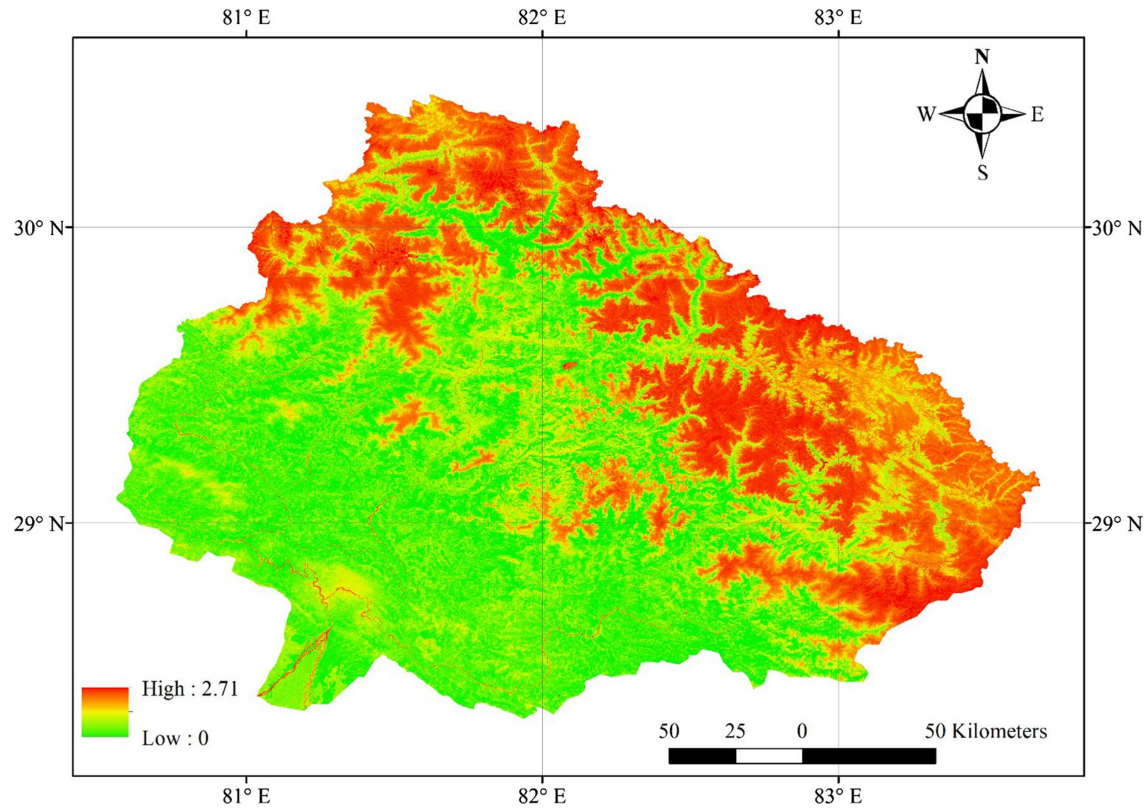

Fig. 9 C factor for Karnali River Basin

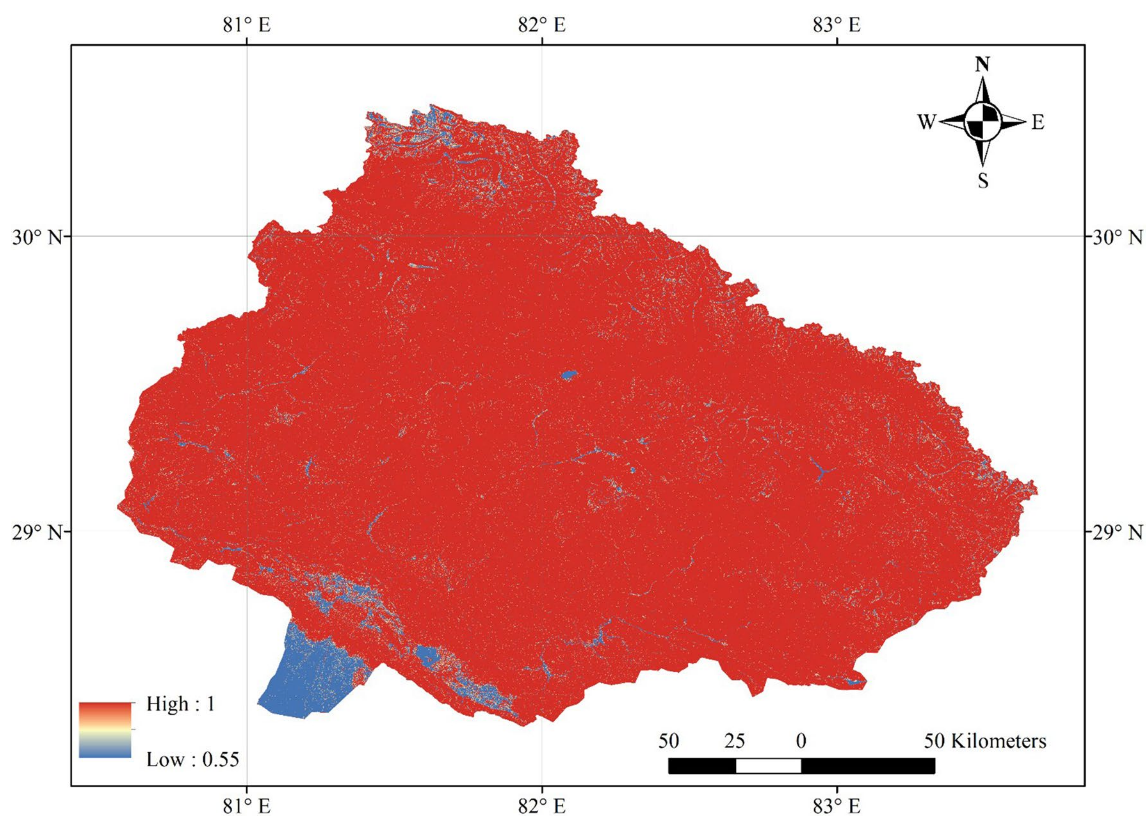

Fig. 10 P factor for Karnali River Basin

is attached hereby. (https://code.earthengine.google.com/8ab91967ca1548399b8d5720b6309321). The spatial and Non Spatial databases used to prepare the soil loss maps are enlisted in Table 2.

3 Results

Precipitation of the Karnali River Basin ranged from 6.85 mm to 1.01 mm (Fig. 4). Furthermore, the R factor of the Karnali River Basin ranged from 38.85 to 40.89 (Fig. 5). The soil erodibility factor (t h MJ^{-1} mm^{-1}) of the Karnali River basin ranged from 0.0151 to 0.0055, (Fig. 6). The slope-length and slope steepness (L) factor of the Karnali River Basin ranged from 1.29 to 1 (Fig. 7). Furthermore, the largest proportion of the area was encompassed within the slope range greater than 26.8% for Karnali River Basin (Fig. 8). The land management (C) factor of the Karnali River Basin ranged from 0 to 2.71 (Fig. 9). The conservation practice factor for the Karnali River Basin ranged from 0.55 to 1 (Fig. 10).

The final soil loss map (Fig. 11) generated for the Karnali River Basin depicted that the largest proportion (27%) of the area of the river basin was included within the erosion category of 3–10 t ha^{-1} $year^{-1}$, followed by 10 to 25 t ha^{-1} $year^{-1}$ (22%) and less than 1t ha^{-1} $year^{-1}$ (22%). Only 2% of the land within the basin was at risk of erosion of more than 50 t ha^{-1} $year^{-1}$(Table 3, Fig. 11). The average soil loss from Karnali River Basins is 9.85 t ha^{-1} $year^{-1}$. In total, 48,279,696 tonnes of soil is being lost per year in the Karnali River Basin. The highest soil loss was observed in the Dolpa, Mugu, Humla, Rukum East, and Rukum West districts of the Karnali River Basin. The soil erosion-prone areas and their proportion out of the total area of the river basin are illustrated in ascending order of severity in Table 3.

4 Discussion

The study achieved geographical evaluation of the erosion risk in the Karnali River Basin with the aid of remotely sensed data, automated land cover, and slope gradient analysis. Although studies utilizing the same method and specifically covering the whole extent of this exact river basin do not exist, the method has been applied in similar geographical regions. This study estimates the annual average soil erosion loss in the basin to be 9.85 t ha^{-1} $year^{-1}$ which is lower than the country's average of 25 t ha^{-1} $year^{-1}$ as estimated by a recent study (Koirala et al., 2019). The rate is also lower than the 22 t ha^{-1} $year^{-1}$ estimated in the major eastern Koshi River (Uddin et al., 2016). The soil erosion value in the eastern hills is known to be considerably higher due to a major chunk of the annual precipitation being influenced by monsoon rain annually. Karnali river basin, being toward the western region, is dealing with surging temperatures and dwindling precipitation trends in the latest decades (Dahal, 2020). Soil erosion was classified into six severity classes based on (Table 3) and (Fig. 11). The classes ranged based on the annual loss value less than 1, 1 to 3, 3 to 10, 10 to 25, 25 to 50, and more than 50 t ha^{-1} $year^{-1}$. Only 2% of the land within the basin was at risk of erosion of more than 50 t ha^{-1} $year^{-1}$ and the overall soil loss was 48,279,696 tonnes.

The R factor in the river basin ranged from 38.85 to 40.89. In the case of rainfall with high intensity, the cumulative soil loss increases with the slope gradient and is more pronounced on steeper slopes. The support techniques are pivotal for minimizing soil erosion in sloping and highly erosive locations. The open earthen canals and the flooding system of irrigation are key causes of landslides and soil erosion in the sloppy terrace of hills and mountains in Karnali (KPPR, 2020). A study reports high overland flow, loss of soil and nutrients in barren land, and the least soil loss for agroforestry with particularly less overland flow (Mishra et al., 2022). It is also demonstrated that at least one order of magnitude less soil loss is prevalent on soils with permanent vegetation cover as compared to arable lands (Cerdan et al., 2010). In arable areas, the cover and crop management factor (C factor) can also lessen water-induced soil erosion, limiting the loss of nutrients and maintaining soil organic carbon. The value of the C factor in the Karnali River was 0.271 in this study. Similarly, the conservation Practice (P) ranged from 0.55 to 1. Studies suggest a plethora of resourceful approaches that can enrich the positive influence of Crop/land management and conservation practices. A study in Sikkim Himalaya showcased terraces in conjugation with other conservation practices that trapped eroded soils, decreased their movement, and increased agricultural production. (Mishra et al., 2020b). Increased gross margins, continued upkeep of stone walls, and the use of contour farming can all further lower soil loss rates in agricultural areas (Panagos et al., 2015). Forty percent plant cover has been deemed a necessity to combat accelerated erosion (Francis & Thornes, 1990).

Soil loss estimation is a very vague task. This study used a digital soil map accessible on the web portal of the National Soil Science Research Center of Nepal Agricultural Research Council (https://soil.narc.gov.np/soil/soilmap/) to calculate soil erodibility but the data from few of the areas were found to be missing. Due to the unavailability of access to more reliable and complete digital data, this study applied the aforementioned database. When evaluating the uncertainties of the model, the R-factor, LS factor, and all other variables should be properly taken into account. And due to

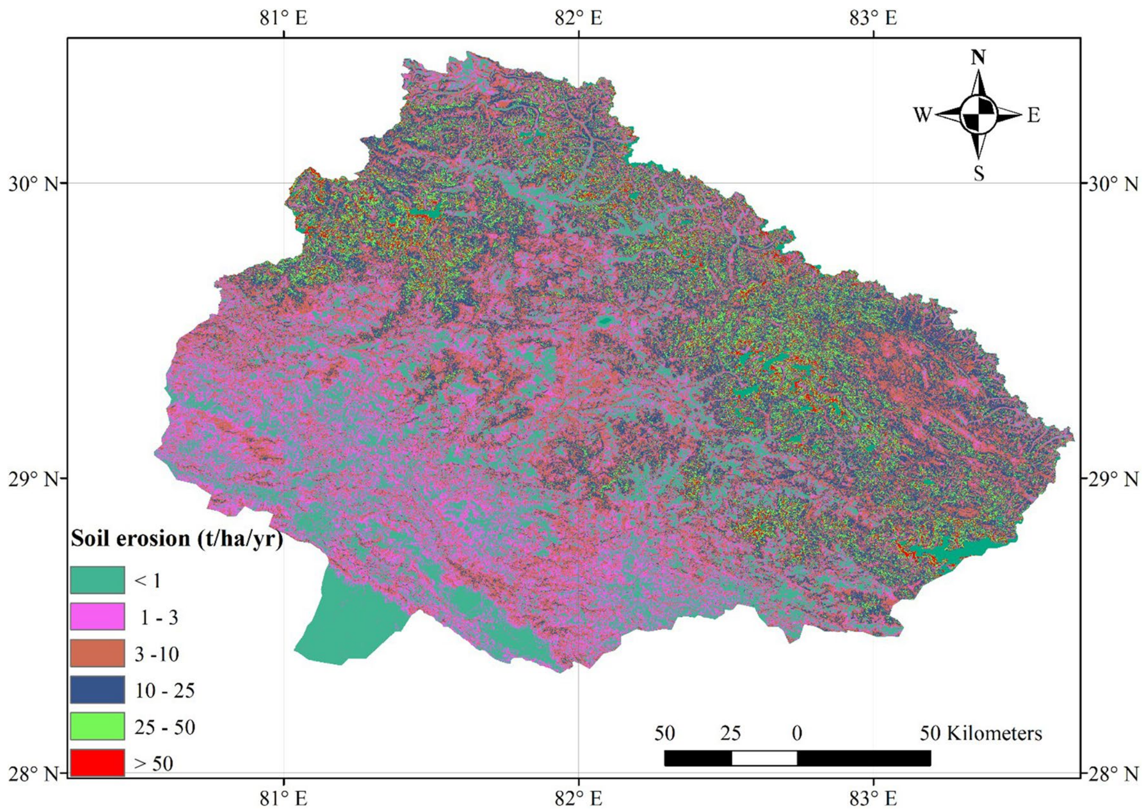

Fig. 11 Soil loss map for Karnali River basin

the unavailability of high temporal resolution data at such a vast spatial scale, this study used an annual precipitation map to calculate the R-factor using a regression equation. Because it only takes consideration of the soil loss from sheet and rill erosion, RUSLE overlooks the repercussions of erosion in gullies and dispersive soils. But the study does have its limitations in addition to the inherent limitations of a model. One-to-one comparison of the estimates over a set of sites was not possible due to challenges posed by topography, time, and budget. The field assessment and quantification in particular sites in the basin via other models essential for proper validation and refinement of the findings remains a limitation of the study. Due to the enormous geographic heterogeneity of the mid-hills and the varied soil features, agricultural practices, and rainfall patterns, a wide range of erosion levels might still be found in different spatial levels within the Karnali River Basin.

Table 3 Soil erosion area and proportion out of the total area of Karnali River Basin

Soil erosion (t ha^{-1} $year^{-1}$)	Karnali (area km^2)	Proportion out of the total area (%)
Less than 1	9566.86	22
1 to 3	8234.91	19
3 to 10	11544.79	27
10 to 25	9643.38	22
25 to 50	3307.14	8
More than 50	849.92	2
Total	43147	100

5 Conclusions and recommendations

This study used the broadly used Revised Universal Soil Loss Equation (RUSLE) for soil loss estimation in combination with the Geographical Information System (GIS). The average soil loss from the Karnali River Basin is 9.85 t ha^{-1} $year^{-1}$. In total 48,279,696 tonnes of soil is being lost per year in the Karnali River Basin. The final soil loss map generated for the Karnali River Basin depicted that the largest proportion (27%) of the area of the river basin was included within the erosion category of 3–10 t ha^{-1} $year^{-1}$, followed by 10 to 25 t ha^{-1} $year^{-1}$ (22%) and less than 1 t ha^{-1} $year^{-1}$ (22%). Only 2% of the land within the basin was at risk of erosion of more than 50 t ha^{-1} $year^{-1}$. Conservation practices should be improved to lessen soil erosion. The study, despite its limitations, represents a formidable alternative to estimating soil loss with the field-based measurement not being a viable option in such a vast river basin. The result of this study and the map showing the intensity of soil loss can be used in further planning and can be prioritized for conservation efforts. This study also recommends conducting a similar kind of study in the other river basins of the country. And for the model to be properly validated and improved, a one-to-one comparison of the estimates over a range of sites is deemed essential. Such studies should be expanded in the future as part of investigations into regions that have been specially identified for conservation efforts, and an iterative approach could be utilized to enhance suggestions and further improve the model.

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Declarations

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Ethical approval 'Not applicable' due to the observational/computational nature of the study.

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