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Potential Sedimentation Rate and its Prioritization in Kulekhani Watershed Using Invest Model

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Abstract: The present study was conducted in Kulekhani watershed of Makwanpur district under Bagmati Province of Nepal to understand the effects of land use land cover (LULC) change on potential sedimentation level of the Kulekhani reservoir. The results showed that the annual sedimentation rate of the Kulekhani watershed was found to continue to decrease at the rate of 13.3 (t / ha / year), 6.6 (t / ha / year) and 4.8 (t/ha/yr) in the year 2002, 2010 and 2018 respectively. Similarly, the potential soil loss predicted by RUSLE was also found to decrease at the rate of 157.0 (t / ha / year), 100.0 (t / ha / year) and 83.7 (t/ha/yr) in the three temporal analyzed years. In contrast, the sediment retention capacity of the watershed was found to increase at a rate of 3058.5 (t / ha / year), 3065.2 (t / ha / year) and 3067.0 (t/ha/yr) in those three years 2002, 2010 and 2018 respectively. Subwatersheds, namely, Palung andheri, Simbhanjyang and Shankhmool determined as the most sensitive were not only due to a single factor of having greater value of agriculture and built land cover but also due to the combined effects of rainfall erosivity index (R factor), the soil erodibility (K) factor including steep slope of the sites within the watershed. Probably, Simbhanjyang was found to occur within moderate R factor values. Similarly, the Palung has been almost occurred within the higher soil erodibility (K) factor and the remaining sub-watersheds belong to have lower to high values of K factor. Furthermore, the correlation coefficient (r = 0.31579) between sediment yield measured in the Kulekhani reservoir and predicted by the model shows that the result of the InVEST SDRmax model has been found in the right direction within its limitations.

Key words: Sediment yield · Sediment retention · InVEST SDR model · Soil loss · Watershed Prioritization · Land Use/Cover · Remote Sensing · GIS

INTRODUCTION

As the sub-watershed is considered the appropriate unit of watershed management, the government of Nepal since the ninth five-year plan (from 1997/98 to 2001/02) in which the sub-watershed must be ranked by erosion severity [1]. The siltation of reservoirs is one of the most important off-site impacts of soil erosion [2] that are closely linked to desertification problems such as reservoir sedimentation, flooding problems, loss of fertile foot slopes and floodplains, loss of nutrients, eutrophication and destruction of ecological habitats [3]. The level of sedimentation, as seen after the sediment measurement in the reservoir, indicates a serious threat to the life span of Kulekhani reservoir and demands urgent environmental solutions. The problem seems to be in the reservoir, but its causes and sources are around in its watershed or catchment area. For sustainable use of these natural resources, an urgent need for environmental conservation and management of subwatersheds is necessary. Due to limited available resources, it is not possible to manage a programme throughout the whole

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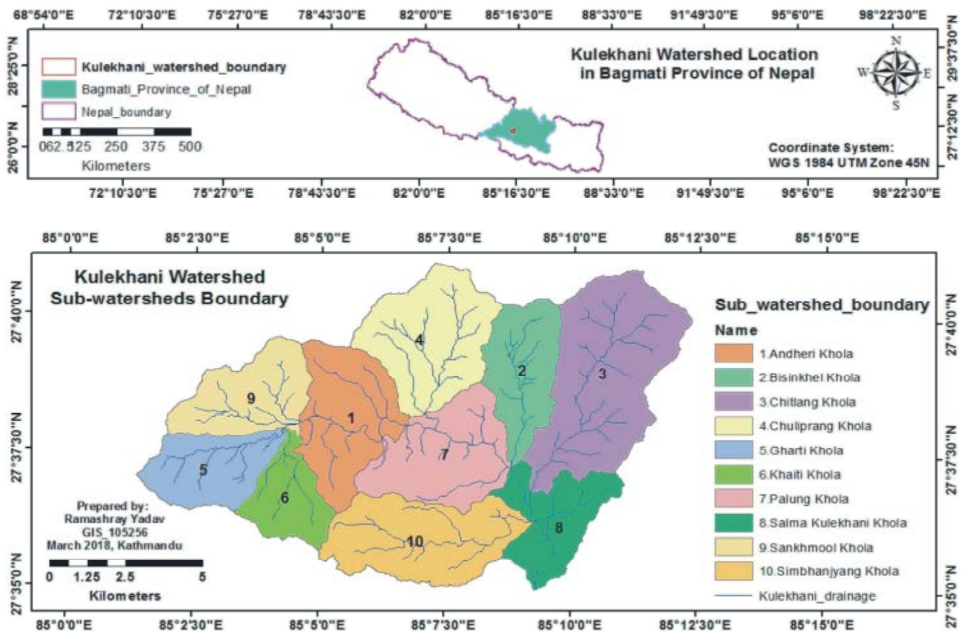

Fig. 1: Location map of study area

watershed area at a time [4]. To overcome this problem, Robinson [5] suggested estimating sediment yields by multiplying the estimated total erosion on hillslopes with a sediment delivery ratio (SDR) of the InVEST model where it is generally estimated as a function of the catchment area, topography and drainage network.

Out of so many researches, none of them have been found studied about prioritizing the sub-watersheds with respect to severity of sediment retention, sediment exporting to the stream and potential soil loss among the whole watershed area.

Hence, this study intended to use the SDR of InVEST model as an efficient tools to provide geospatial data on sediment retention ecosystem services [6] to estimate the sedimentation rate and determine the most sensitive sub-watershed area of the reservoir in 2002, 2010 and 2018.

Study Area: The Kulekhani watershed area of the Kulekhani reservoir is situated in Makwanpur district under Bagmati Province of Nepal. The reservoir is synonymously known as Kulekhani hydropower (the only a reservoir type hydropower in Nepal) at present context. Of the total three stations, this study was limited to Kulekhani I. The total area of the watershed is 124.67 km^2 (12467 ha). Geographically, it is extended from 27°34'52" N to 27°40'59"N and 85°01'21"E to 85°12'20"E (Fig. 1). Geomorphologically, precambrian to Cambrian metamorphic rocks of Markhu Formation, Kulekhani formation, Chisapani Formation, Kalitar formation and granites compose the geology of the Kulekhani watershed having its elevation range from 1534m at the dam site and 2533m at peak of Simbhanjyang area [7].

Tamang, Magar, Gurung, Chhetri and Brahmin are the major ethnic groups to make a heterogeneous composition. The watershed covers 17779 HHs having 102058 population those livelihood and daily life mainly depend on agriculture to meet their basic needs for food, feed, wood, firewood, fiber and shelter [8].

MATERIALS AND METHODS

Datasets: There were used both spatial as well as numerical data having different levels of processing in this study.

Satellite Imagery: Satellite imagery of Landsat 7ET M+, Landsat 5 and Landsat 8 having path 141 and row 41 was downloaded from USGS home page (https://earthexplorer.usgs.gov/) for 2002, 2010 and 2018 respectively. The acquired dates of these satellite images were selected almost the same to match each other to obtain more accuracy in land use land cover change detection as far as possible. The acquired date for all images was last week of the month from 25^{th} to 31^{st} October of the year. The RGB bands for Landsat 7 ETM+ image and Landsat 5 were set as 3,4 and 5 and for land sat 8 image was set as 2,4 and 6 respectively as common

Table 1: Sediment deposition data from 1982 to 2002, 2010 and 2018

	Sediment Deposition			Reservoir Capacity		
Year	Total (Mm^3)	Average (m^3/ha)	Cumulative Average (m^3/ha)	Total (Mm^3)	Live Storage Volume (Mm^3)	Dead Storage Volume (Mm^3)
1982	0.000	0.000	0.00	85.30	73.30	12.00
Till, Mar 1993	2.200	16.000	16.00	83.10	72.30	10.80
Dec. 1993	4.800	384.000	46.00	78.30	70.70	7.60
Sept.1994	10.500	840.000	107.00	67.80	61.30	6.50
Nov. 1995	4.000	320.000	122.00	63.80	68.00	3.00
Dec.1996	0.400	32.000	116.00	63.40	66.00	2.80
Nov. 1997	0.200	16.000	110.00	62.19	55.55	7.60
Nov. 1998	0.560	44.800	106.00	62.63	55.20	7.42
Nov. 1999	0.660	52.800	99.91	62.64	55.66	6.98
Nov. 2000	0.260	20.800	95.73	62.38	55.58	6.80
Nov. 2001	0.020	1.600	91.03	62.36	55.57	6.79
Nov. 2002	0.060	4.800	86.92	62.30	55.56	6.74
Sept. 2010	0.001	0.069	74.38	59.99	56.21	3.78
April.2018	0.060	-	-	61.66	-	-

Source: NEA[11-13]; Upadhyaya[14, p. 8]

Landsat bands RGB composite guideline provided by USGS [9] experienced appropriate to assign the training sample for LULC classification of the study area. The all image with resolution 30m were used for the study.

Digital Elevation Model: The DEM with 30m resolution ID: The SRTM1N27E085v3 published on September 23, 2014, was downloaded from the website (https://earthexplorer.usgs.gov/) for the study area. It was used for generating contour lines, slope and drainage basin extraction of the particular area.

Sedimentation Data for Kulekhani Watershed Reservoir: Data on sedimentation rate in Kulekhani reservoir were collected from the NEA office through the NEA sedimentation survey report (2003, 2011 and 2018). The measured data on sedimentation of Kulekhani reservoir for 2002, 2010 and 2018 was found as 0.06 million m^3, 0.001 million m^3 and 0.06 million m^3 respectively. The dry density of the sediment record for the Kulekhani reservoir has been found adopted as 2.60 ton/m^3 [10]. The sedimentation rate shows an increasing trend up to year 1994 and a decreasing trend afterwards (Table 1).

Methods: The preprocessing of the downloaded images, parametric data collection for the model and watershed/subwatershed boundary delineation based on the drainage basin were carried out. Parameter preparation required to run the InVEST $SDRmax_{max}$ model, interpretation of the output obtained from the running model was performed.

Description of Parameters Required for the InVEST Model: 11 total eleven types of parameters are required as input to run the InVEST SDR_{max} model (Fig. 2).

Of them, the nine types of data must be prepared locally to obtain the reliable output as far as practicable. The similar coordinate system (WGS_UTM_Zone_45N) was used for all data set required to run the model. Similarly, 30m resolution was adopted for all the raster datasets to match the modeling. The required input data are as follows:

Digital Elevation Model (DEM): It needs the DEM to be filled to remove the sink to obtain good results, which was performed by using the ArcGIS10.6 fill tool. The size of the DEM was made enough to be a bit larger than that of the watershed boundary for appropriate functions having unit in meter.

Rainfall Erosivity Index (R): The model needs the rainfall erosivity index (R factor) in raster format of the study area. To achieve this purpose, the mean annual precipitation data from the rain gauge stations within and around the study area (Table 2) were acquired from secondary literature sources already applied for the site from [15]. Afterwards, the approach recommended by Parveen & Kumar [16] for the sub-tropical region was applied to evaluate the R factor that has been presented as in equation (1) below:

$$R = 79 + 0.363P \quad (1)$$

where

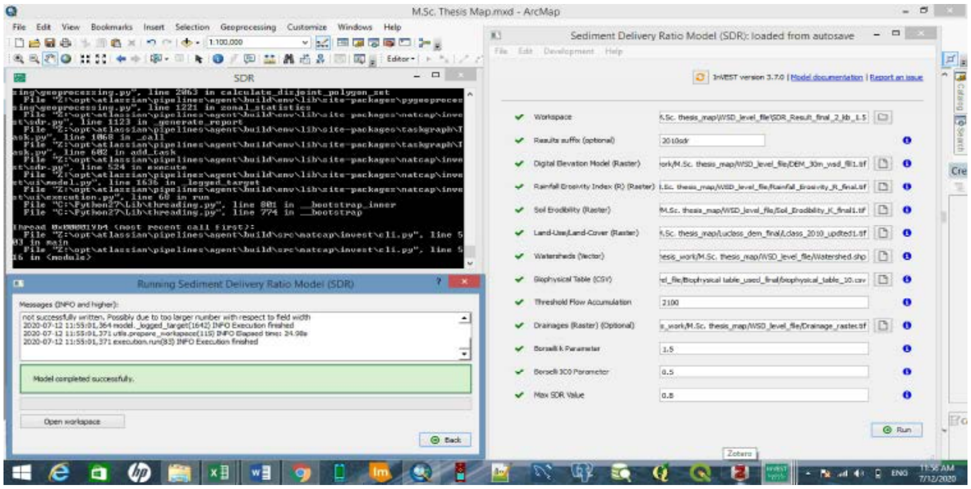

Fig. 2: Sediment Delivery Ratio Model Example

Table 2: Mean Annual Precipitation Data for the Study Area, 2016

S.N.	Station Index	Station Name	Longitude	Latitude	Elevation (m)	Precipitation (mm)	Annual R Factor
1	915	Markhugaun	85.15	27.62	1514	1461	609.34
2	905	Daman	85.08	27.6	2328	1786	727.32
3	904	Bhimphedi	85.13	27.55	1219	2178	869.61
4	1015	Thankot	85.2	27.68	1893	1912	773.06
5	1038	Dhunibesi	85.18	27.72	976	1576	751.09
6	1075	Lele	85.28	27.58	1313	1847	749.46
7	1005	Dhading	84.93	27.87	1520	2121	848.92
8	920	Beluwa	84.84	27.55	365	2026	814.44

Source: Ban [15]

Table 3: Eight sub-watershed width distribution of the rainfall erosivity index

Sub-watersheds (ID)	Sub-watersheds (Name)	Area (KM^2)	Elevation (m)	Rainfall Erosivity Index (R) MJ.mm $(ha.h.yr)^{-1}$
1	Andheri Khola	13.1	1880	750
2	Bisinkhel Khola	9.8	1770	742
3	Chitlang Khola	23.0	1897	755
4	Chuliprang Khola	15.3	1824	771
5	Gharti Khola	9.0	2037	726
6	Khaiti Khola	6.6	2073	727
7	Palung Khola	13.5	1783	740
8	Salmakulekhani Khola	8.9	1644	750
9	Sankhmool Khola	10.2	1964	739
10	Simbhanjyang Khola	15.2	2079	727

R = Rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} $year^{-1}$)
P = Mean annual precipitation in mm.

Furthermore, the factor R was generalized for the site using the interpolation tool named Spline with Barrier available in ArcGIS10.6 software to locally suit enough to produce a reliable result (Fig. 4).

The acquired rainfall erosivity from the interpolation methods was obtained for the all ten sub-watersheds and found to have unique value having an appropriate correlation coefficient (r = -0.63673) between rainfall erosivity index (R factor) and elevation (Table 3).

Figure 4 showed the clear visualization of relatively distinct values of rainfall erosivity index (R factor) within the ten subwatersheds. Out of the total sub-watersheds, Chuliprang seems to have been situated comparatively within the higher rainfall erosivity (R factor) values, whereas Gharti, Khaiti and Simbhanjyang seem to occur within relatively moderate R factor values. Similarly, Sankhmool andheri and Palung seem to occur within moderate to high values. The remaining Salmakulekhani, Bisinkhel and Chitlang occur within relatively mixed with lower values to high values (Table 3, Fig. 3 and Fig. 4).

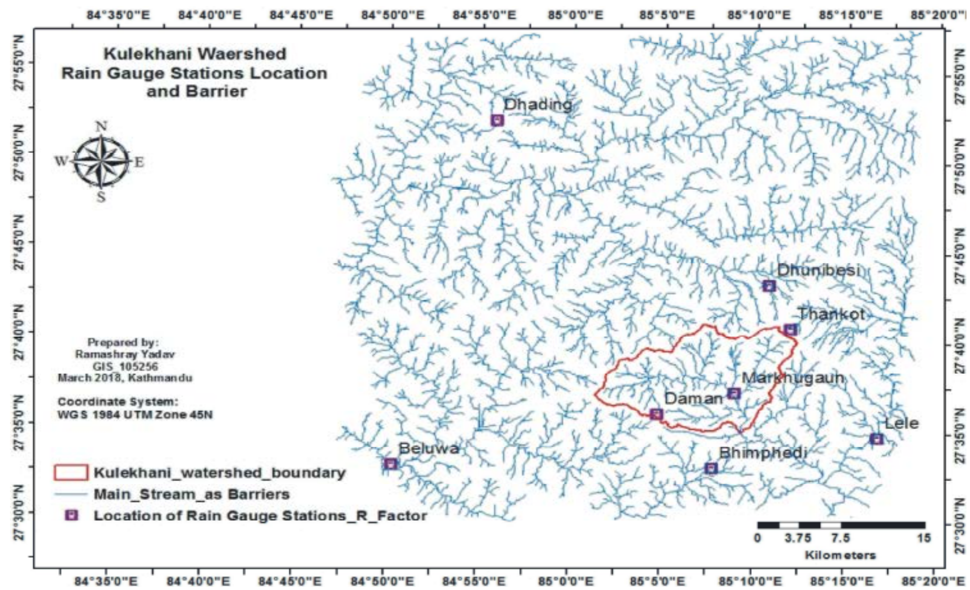

Fig. 3: Distribution of Rain Gauge Stations in Main Stream

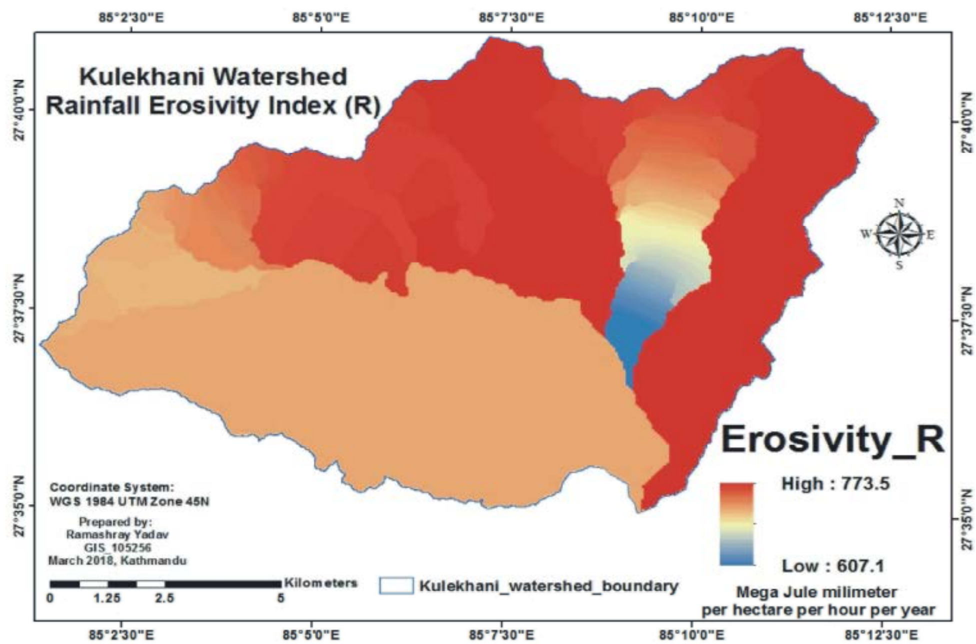

Fig. 4: Rainfall Erosivity Index (R) of the Study Area

Soil Erodibility (K): The K-factor values typically range from 0.10 to 0.45 [17]. The ArcGIS 10.6 environment was used to calculate the K factor to obtain soil unit's map of the Kulekhani watershed soil unit map derived from the soil and terrain (SOTER) database for Nepal [18] map at 1:50000 scale. Afterward, overlaying the watershed boundary layer of the watershed on the soil layer obtained from SOTER, it was found that the watershed is dominated by two types of soils, namely Cme (eutric cambisols) and Cmx (Chromic cambisols). The soil erodibility factor (K) values proposed by Vopravil *et el*. [19, p. 5] is 0.32 tons h MJ^{-1} for Eutric cambisols and average value of 0.33 ton h MJ^{-1} for Chromic cambisols was adopted for this study Ban [06]. As the model needs the K-factor in raster format, the soil map (vector file) was converted into raster image assigning those K values by using the 'polygon to raster' tool (available in ArcGIS 10.6) for the site with 30m resolution to be suited for the model (Fig. 5).

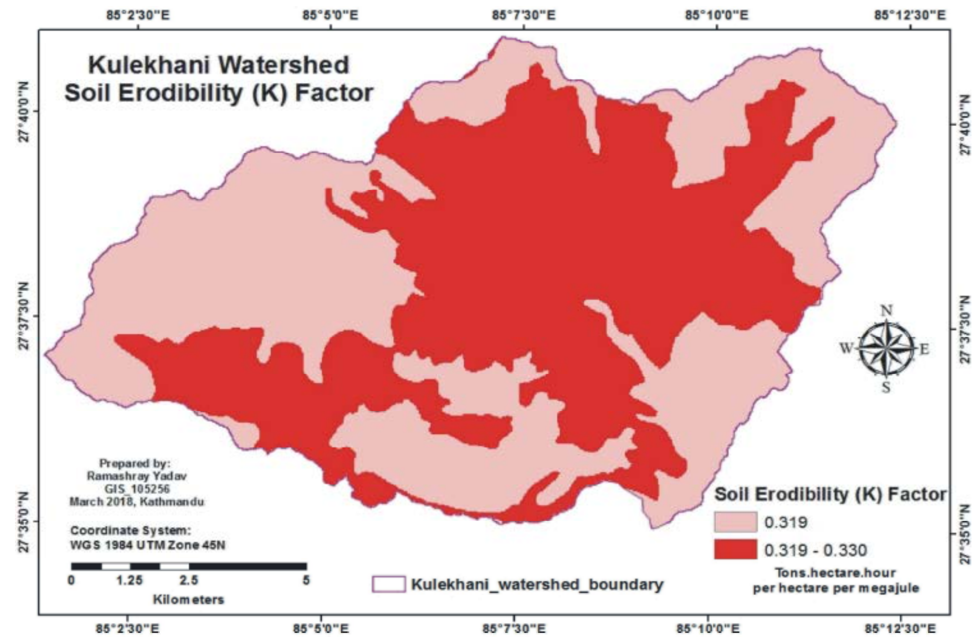

Fig. 5: Soil Erodibility Factor (K) of the Kulekhani Watershed Area

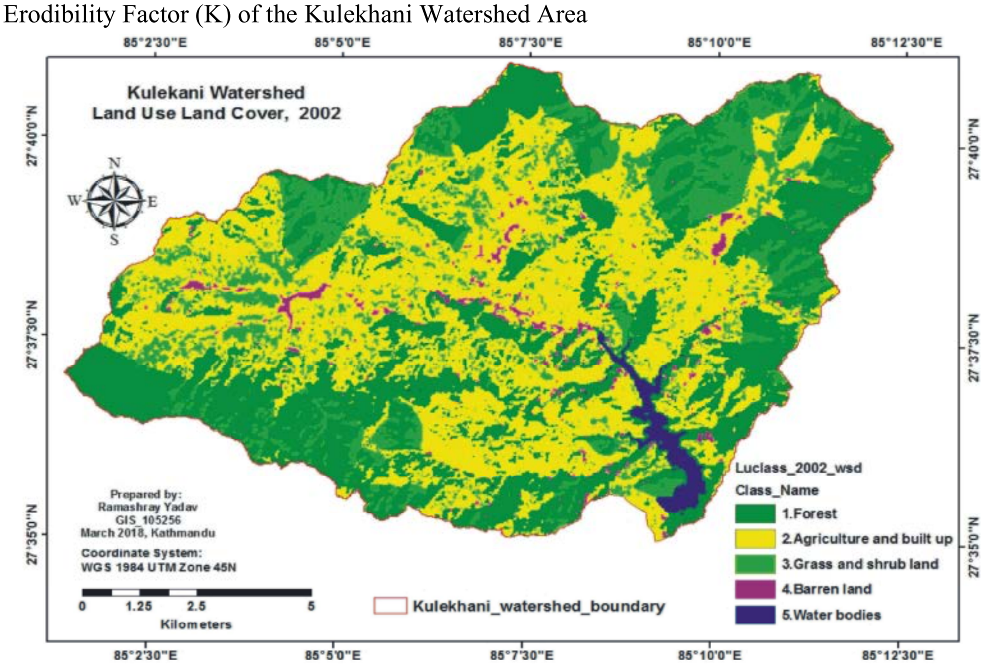

Fig. 6: Land Use Land Cover Map of 2002

Out of total sub-watersheds, the Khaiti, Palung, Bisinkhel and Chuliprang have been almost occurred within the higher soil erodibility (K) factor values. Similarly, the remaining sub-watersheds belong to have lower to higher values of K factor (Fig. 5).

Land Use Land Cover: Land use classification and accuracy assessment was done for the imagery of 2002, 2010 and 2018 and all classified LULC maps were to have 30m spatial resolution in the raster format to be used for the model with clear integer LULC code to each. The Fig. 6, Fig. 7 and Fig. 8 shows the hierarchical status of land use land cover classes within the study area in year 2002, 2010 and 2018 respectively.

Watershed (Shape File): The delineated sub-watershed boundary map was coded with integer field named ws_id values for each sub-watersheds having shape file format.

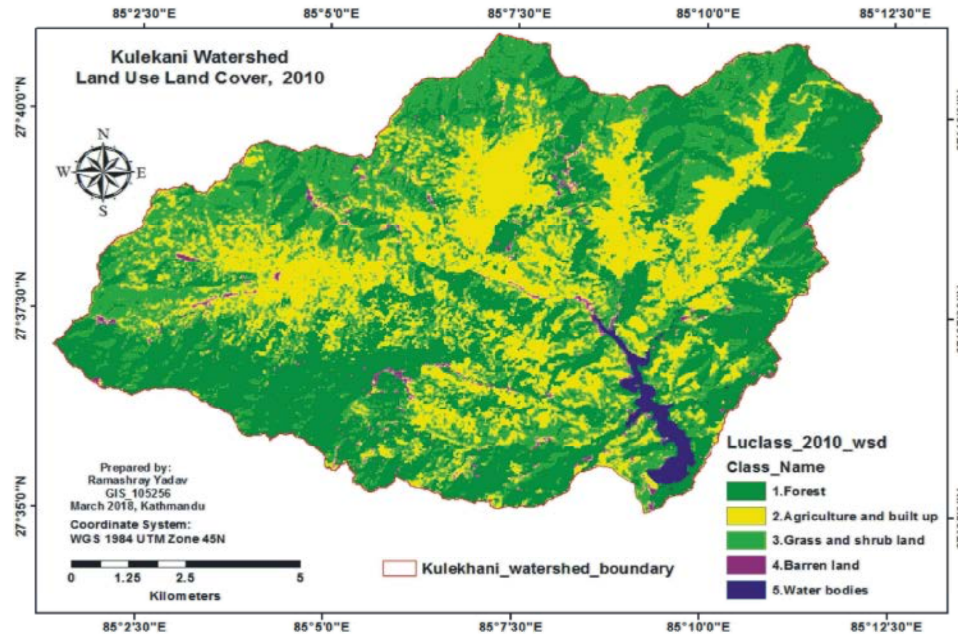

Fig. 7: Land Use Land Cover Map of 2010

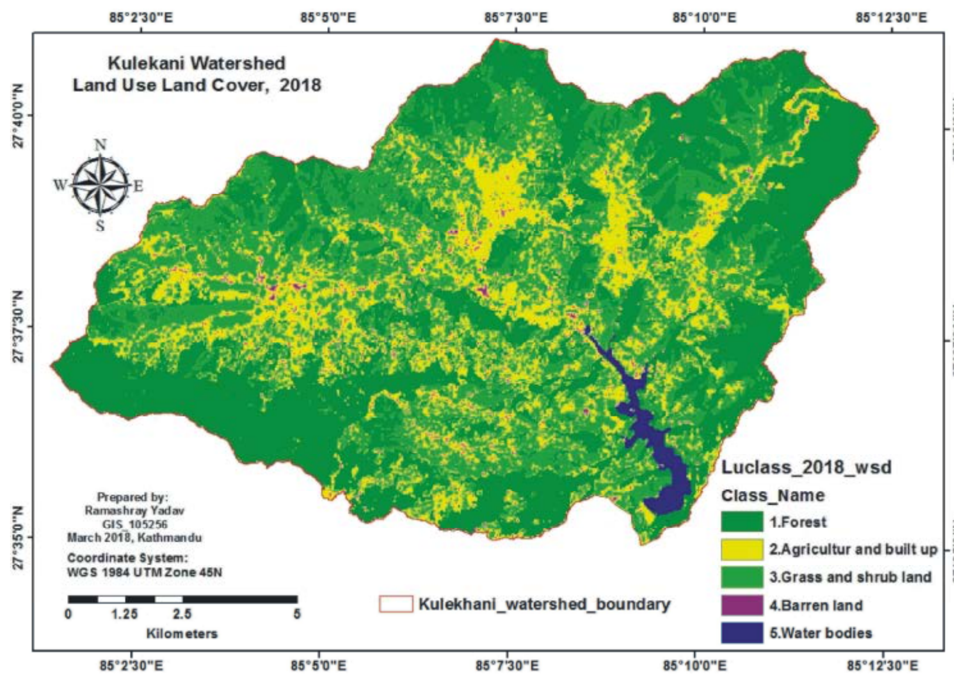

Fig. 8: Land Use Land Cover Map of 2018

Biophysical Table: This table needs to be in. csv (Comma separated values) format having at least three field values i.e. Lucode, usle_c-factor and usle_p-factor.

Lucode: The obtained land use land cover maps were prepared with unique integer lucode enough to be used for the model.

Usle C-factor: It is the cover management factor (c- factor) that must have a floating-point value between o and 1. Its higher value means no cover effect, whereas lower values means very strong cover effect resulting in no erosion at that management status of the crop.

Usle P-factor: It is a support practice factor that needs to be a floating point value between 0 and 1. It is considered

Table 4: Biophysical table (having C-values and P-values)

		Usle_C- factor		Usle_P- factor	
LULC_description	Lucode	Values	Source referenced	Values	Source referenced
Forest	17	0.001	[20-22]	0.50	[23-25]
Agriculture and built up	11	0.15	[21-23]	0.20	[23-25, 27]
Grass and shrub land	14	0.01	[21,23]	0.60	[22, 23, 27, 28]
Barren land	13	0.1326	[20, 22, 24, 25]	0.95	[23-25, 27]
Water bodies	12	0	[20, 22-26]	0.00	[25, 31]

as control practices to decrease the erosion potential caused by the influence of runoff on the drainage pattern, its concentration, velocity and hydraulic forces exerted by runoff on the soil surface [17, pp: 31-32].

The c-factor and p-factor values were prepared by referencing different relevant sources of literature review adopted by previous researchers in their studies with incorporating local condition to have biophysical table to run the model with reliable output (Table 4).

Threshold Flow Accumulation: Initially, the model was run with flow accumulation value '1000' and its appropriate value was found to be used as '2100' after overlaying & comparing the flow accumulation raster and stream raster maps created by the model with real-world stream map in ArcGIS10.6 environment to get reliable output of the model.

K_b and IC_0: The default values for K_b and IC_0 have been given as 2 and 0.5 respectively for the model [32]. According to Hamel *et el*. [33, pp. 166-177] and Vigiak *et el*. [34], K_b was only the parameter used for calibration. Vigiak *et el*. [34] suggested that IC_o is landscape independent. Therefore, the calibration should be based on K_b only. Hence, the value of K_b parameter was selected as 1.5 to get minimized relative difference between predicted and observed value for 2002, 2010 and 2018.

SDR_{max}: The default value for this parameter has been given as 0.8 [32].

Drainage Layer: This layer is optional to use in raster format for the model that corresponds to the pixels to be artificially connected to stream. Using this layer has to stop flow routing before reaching the stream network and having the assumption with exported sediment to reach the catchment outlets [32].

Interpretation of the Output Obtained from the Model: The output from applying this model is obtained in the form of shape file map as well as in the raster images having attribute values with respect to sediment retention, sediment exported and potential soil loss of the watershed.

Watershed results (.shp): The biophysical values for each subwatershed are provided in the attribute table having three fields as:

Sed_export (units: tons/watershed): In this field, the amount of sediment exported to the stream per subwatershed per year was obtained in this field that should be compared to any observed data on sediment loads at the outlet of the watershed. The result was finally presented as sediment exported per unit (t/ha/yr).

Usle_tot (Units: tons/watershed): This output is the total potential soil loss in each sub-watershed per year as calculated by the revised universal soil loss equation (RUSLE) as presented in equation (2) as follows:

$$A = R * K * LS * C * P \tag{2}$$

where

A = Soil loss (t/ha/yr); R = Rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1});
K = Soil erodibility factor (t h MJ^{-1} mm^{-1});
LS = Slope-length and slope steepness factor (dimensionless);
C = Cover management factor (dimensionless);
P = Support practice factor (dimensionless)

The result was finally presented as the total potential loss of soil per unit (t/ha/yr).

Sed_retent (Units: Tons/watershed): This output is obtained from the difference between sediment amount delivered by the current sub-watershed and a hypothetical sub-watershed where the all land use land cover would have been converted to bare land. The result was finally presented as sediment retention per unit (t / ha / year).

The Basin Result in the Form of Raster Images: The results regarding the raster images above are provided as tons/pixel. The pixel size of the maps in this study is 30 m (that is, 1 pixel = 900m2) [32].

Table 5: Annual Sedimentation Rate (Yield), Retention and Potential Soil Loss of Kulekhani Watershed

Total area of the watershed (ha)	Sedimentation Types	Year 2002	2010	2018	Mean
12467	Sediment exported (t/ha/yr)	13.3	6.6	4.8	8.2
	Sediment retention (t/ha/yr)	3058.5	3065.2	3067.0	3063.6
	Soil loss (t/ha/yr)	157.0	100.0	83.7	113.6

Table 6: Overall Status of Sub-watersheds with Respect to Potential Sedimentation Rate

Sub-watershed		Sediment exported (t/ha/yr)			Sediment retention (t/ha/yr)			Soil loss (t/ha/yr)		
ID	Name	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	Andheri Khola	6.9	22.5	13.6	3076.4	3092.1	3085.3	98.7	197.5	140.3
2	Bisinkhel Khola	4.2	8.4	6.1	2190.2	2194.3	2192.5	74.8	121.7	96.2
3	Chitlang Khola	3.4	7.0	5.2	3544.8	3548.4	3546.6	66.2	102.4	83.6
4	Chuliprang Khola	3.4	8.1	5.5	2020.4	2025.1	2023.0	73.9	127.2	99.8
5	Gharti Khola	3.6	10.2	5.9	3051.6	3058.2	3055.8	65.3	117.2	87.3
6	Khaiti Khola	1.8	5.9	3.6	3133.4	2819.3	3135.7	37.6	81.7	57.3
7	Palung Khola	9.0	22.2	14.0	3668.6	3681.7	3676.8	132.8	246.8	175.6
8	Salmakulekhani Khola	3.8	9.4	6.5	3213.8	3219.4	3216.7	80.4	148.7	110.6
9	Sankhmool Khola	5.4	17.5	9.5	3004.5	3016.6	3012.5	107.3	250.5	159.4
10	Simbhanjyang Khola	5.4	21.5	12.1	3681.3	3697.4	3690.7	85.3	175.8	125.5

RESULTS

Potential Sedimentation Rate of the Kulekhani Watershed in 2002, 2010 and 2018: The result obtained from running the model showed that the annual sedimentation rate of the Kulekhani watershed was found continuously decreasing at the rate of 13.3 (t/ha/yr), 6.6 (t/ha/yr) and 4.8 (t/ha/yr) for the year 2002, 2010 and 2018 respectively. Similarly, the potential soil loss predicted by RUSLE was also found to decrease at the rate of 157.0 (t / ha / year), 100.0 (t / ha / year) and 83.7 (t/ha/yr) for the three-term analyzing year. On the contrary, the sediment retention capacity of the watershed was found to increase at a rate of 3058.5 (t / ha / year), 3065.2 (t / ha / year) and 3067.0 (t/ha/yr) for those three years 2002, 2010 and 2018 respectively (Table 5).

Analysis of Sub-watersheds based on Sedimentation Rate: Overall, Palung was found as the highest contributing subwatershed for annual sediment yield (13.98 t / ha / year) followed by Andheri (13.62 t / ha / year), Simbhanjyang (12.14 t / ha / year), Shankhmool (9.5 t/ha/yr) and others (between 3.59 and 6.48 t / ha / year). Regarding the sediment retention, the Simbhanjyang was found the highest contributor for sediment retention (3691 t/ha/yr) followed by Palung (3677 t/ha/yr), Chitlang (3547 t/ha/yr), Salmakulekhani (3217 t/ha/yr), Khaiti (3136 t/ha/yr) andheri (3185 t/ha/yr) and others (between 2023 to 3057 t/ha/yr). Similarly, Palung was found the highest contributing subwatershed for potential soil erosion (175 t / ha / year) followed by Sankhmool (159 t / ha / year) andheri (140 t / ha / year), Simbhanjyang (126 t / ha / year), Salma Kulekhani (111 t / ha / year) and others (between 57 and 96 t / ha / year) for the study period 2002 to 2018 (Table 6).

Ultimately, the scenario of sediment export and potential soil loss were found in decreasing trend whereas the sediment retention was found in increasing with low rate but continuously (Fig. 9, Fig. 10 and Fig. 11).

Most Sensitive Sub-watershed within the Watershed Based on Sediment Yield: The subwatersheds were primarily ranked on the basis of annual sediment yield rate exported by them. The values of annual sediment yield rate obtained from the analysis of result were sorted in descending order to assign the sensitivity rank for the sub-watersheds as suggested by Welde [35]. According to Borrelli [36], the subwatersheds having sedimentation rate from 1 to 5 (t / ha / year) belong to the moderate soil erosion risk and greater than 5 (t/ha/yr) considered to be in high soil erosion risk in terms of sedimentation occurrence. Hence, the 90% of the sub-watersheds (rank 1 to 9 in table 13 & 14) belong to the high erosion risk remaining one sub-watershed (Khaiti). However, the Palung sub-watershed was found to be the most sensitive in terms of sediment producers to the reservoir (13.98 t / ha / year) followed by other three major sensitive sub-watersheds Andheri (13.62 t / ha / year), Simbhanjyang (12.14 t / ha / year) and Shankhmool Khola (9.5 t / ha / year) where their erosion risks are very close to each other (Table 7).

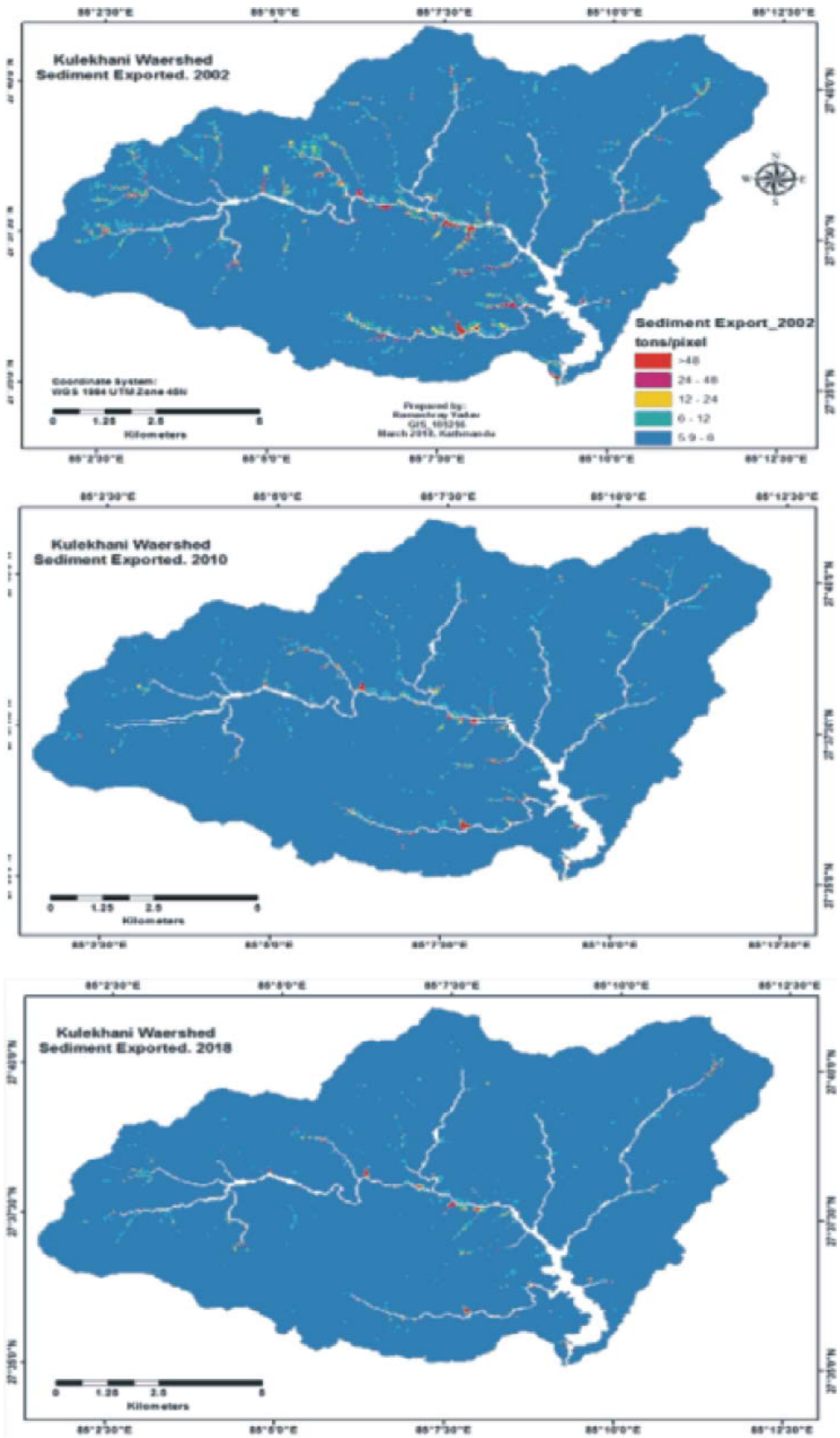

Fig. 9: Sediment Export of Study Area in 2002 (Top), 2010 (Middle) and 2018 (Bottom).

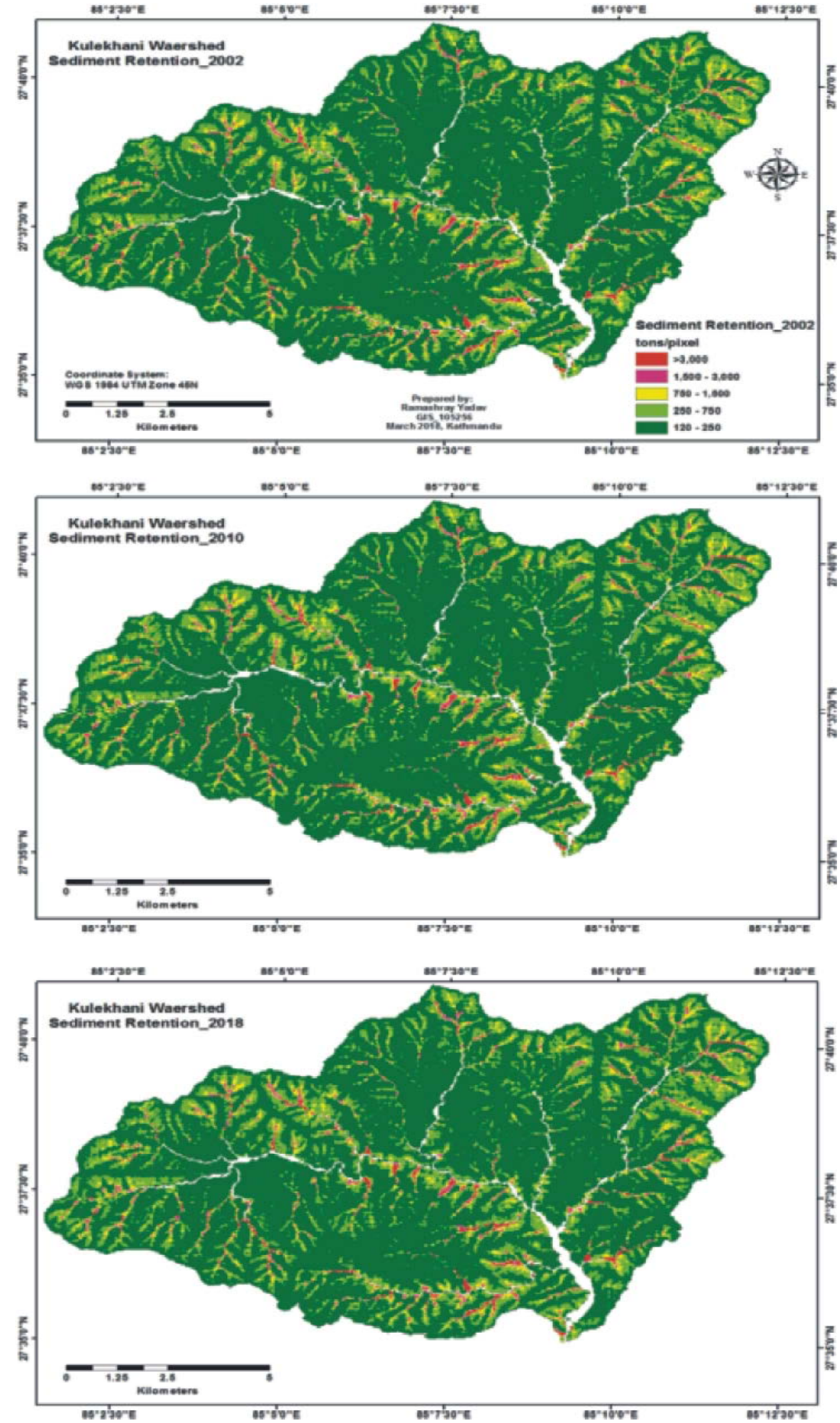

Fig. 10: Sediment Retention of the Study Area in 2002 (Top), 2010 (Middle) and 2018 (Bottom)

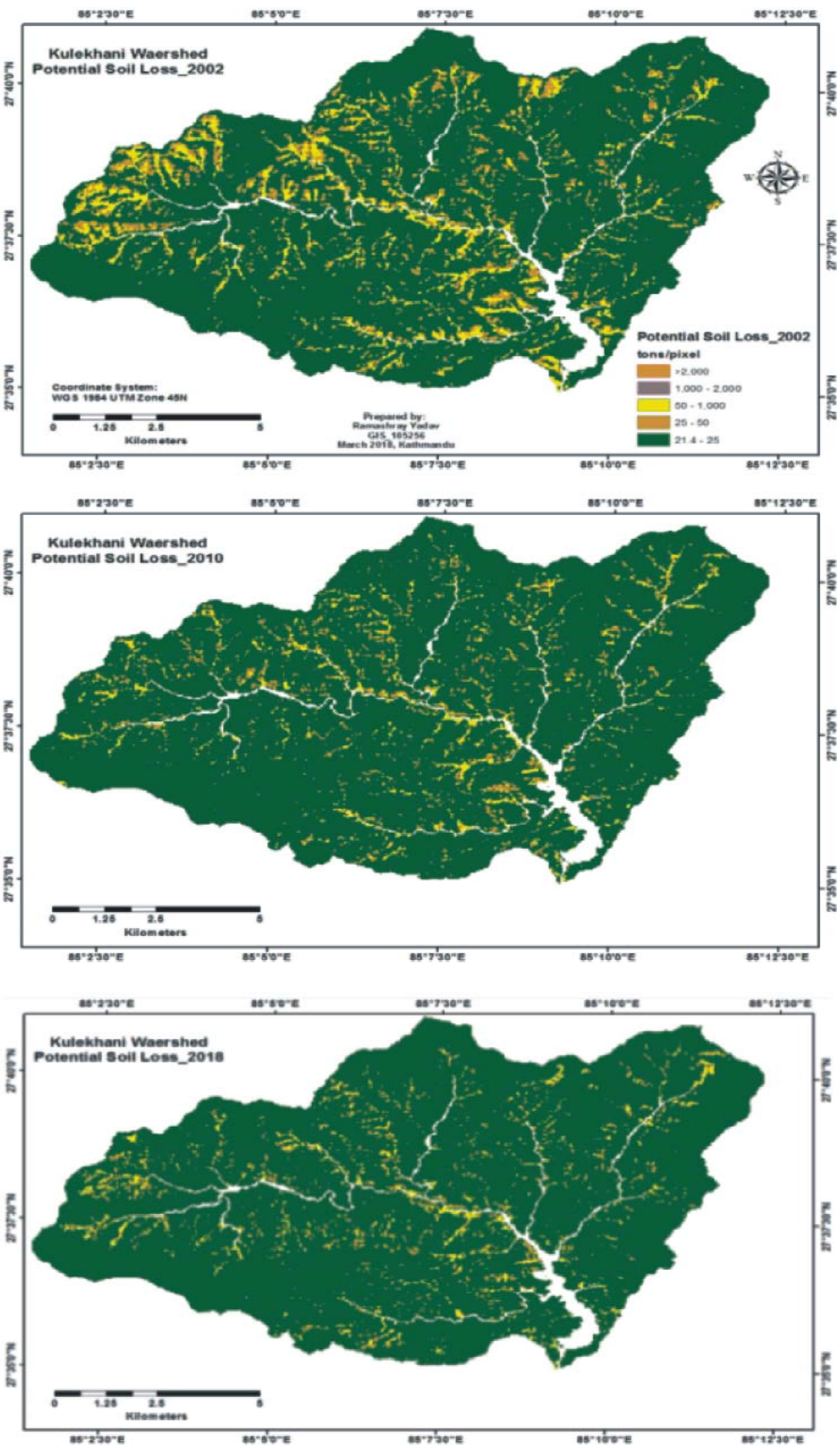

Fig. 11: Potential Soil Loss of Study Area in 2002 (Top), 2010 (Middle) and 2018 (Bottom)

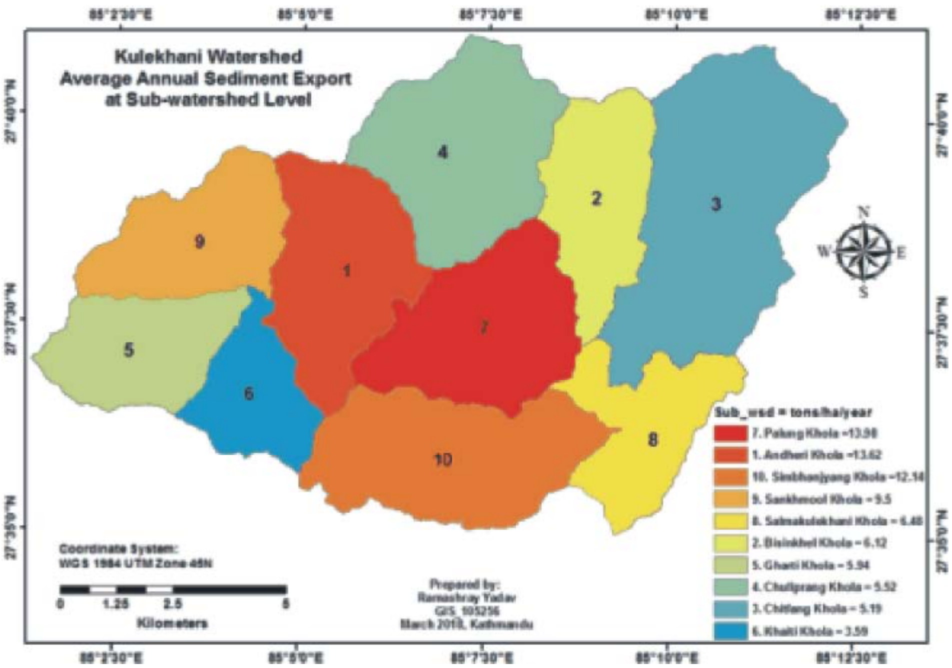

Fig. 12: Average annual sediment yield of Kulekhani Watershed at the sub-watershed level

Table 7: Prioritization of Sensitive Subwatersheds Based on Annual Sedimentation Yield

Sub-watersheds ID	Dominant soil type Sediment exported	Sensitivity Rank (t/ha/yr)	FG LULC total area Order	AB LULC total area Ha	Water bodies area Ha	AB/FG Ha	A/F Ratio	Ratio
7	Eutric Cambisol and Chromic Cambislols	13.98	1	691.0	654.1	7.4	0.95	1.28
1	Chromic Cambislols only	13.62	2	721.9	590.5	0.0	0.82	1.41
10	Eutric Cambisol and Chromic Cambislols	12.14	3	984.3	527.6	6.4	0.54	0.70
9	Eutric Cambisol and Chromic Cambislols	9.50	4	610.3	409.5	0.0	0.67	1.59
8	Eutric Cambisol and Chromic Cambislols	6.48	5	499.9	247.9	145.6	0.50	0.67
2	Eutric Cambisol and Chromic Cambislols	6.12	6	587.2	393.4	1.9	0.67	1.06
5	Eutric Cambisol and Chromic Cambislols	5.94	7	682.9	215.0	0.0	0.31	0.42
4	Eutric Cambisol and Chromic Cambislols	5.52	8	901.6	624.0	0.0	0.69	1.12
3	Eutric Cambisol and Chromic Cambislols	5.19	9	1707.5	586.4	8.1	0.34	0.46
6	Eutric Cambisol and Chromic Cambislols	3.59	10	554.2	108.3	0.0	0.20	0.20

The ratio values (AB/FG) for the combined agricultural and built up (A) and barren land (B) to the combined area of forest cover (F) and grassland and shrub land (G) was calculated to know the factors more sensitive to influence sedimentation. Similarly, the ratio values (A/F) of absolute agriculture and built-up (A) to the forest cover (F) were also calculated to support the above similar results. The sub-watersheds having sensitive rank order 1 to 4 were found to have relatively higher ratios values for AB/FG as well as A/F compared to the sub-watersheds having the lowest sensitive rank order from 8 to 10 (Table 7 and Fig.12).

DISCUSSION

Scenario of Sensitive Sub-watershed with respect to Sedimentation Level: According to suggestions provided by Welde [35] and Bouguerra *et al*. [37], the sub-watersheds were primarily ranked on the basis of annual sediment yield rate exported by them having sorting in descending order to assign the sensitivity rank for the sub-watersheds. According to Borrelli *et al*. [36], the sub-watersheds having sedimentation rate from 1 to 5 (t/ha/yr) belong to the moderate soil erosion risk and the greater than 5 (t/ha/yr) considered to be in high soil erosion risk in terms of sedimentation occurrence. Hence, the 90% of the sub-watersheds (rank 1 to 9 in table 4.18) belong to the high erosion risk remaining one sub-watershed (Khaiti Khola). However, the Palung sub-watershed was found to be the most sensitive in terms of sediment producers to the reservoir (13.98 t/ha/yr) followed by the other three major sensitive sub-watersheds Andheri (13.62 t/ha/yr), Simbhanjyang (12.14 t/ha/yr) and Shankhmool (9.50 t/ha/yr) where their erosion risks are very close to each other.

As sediment yield is known as a function of runoff and other processes occurring in the watershed [35], the subwatersheds namely Palung andheri, Simbhanjyang and Shankhmool were determined as most sensitive due not only due to a single factor of having greater proportions of agriculture and built up land but also to a combined effects of the rain erosivity index (R factor), soil erodibility factor including steep slope of the sites within the watershed. Among the four sub-watersheds andheri, Shankhmool and Palung seem to occur within relatively moderate to high rainfall (R factor) values. It is likely that Simbhanjyang occurred within moderate rainfall (R factor) (Table 3, Fig. 3 and Fig. 4). Similarly, the Palung has been almost occurred within the higher soil erodibility (K) factor values and, the remaining sub-watersheds belong to have lower to high values of K factor (Fig. 5). This result is also evidenced by the previous studies as the Palung Khola is known as main stream of the Kulekhani watershed; Where the discharge increases from June to September during the rainy season [4] and extensive over use of agriculture land and forest has also been evidenced by the previous studies [8]. Comparatively, the two sub-watersheds of the groups second; namely Khaiti and Chitlang having lowest sediment exporting values; were found to have relatively reverse characteristics with respect to rainfall erosivity index (R factor), soil erodibility (K) factor, forest cover as well as agriculture and built up land cover within the watershed (Fig. 4 and Fig. 5).

Scenario of the Relationship between Sediment Yield Predicted and Observed in the Reservoir: The correlation between sediment yield measured in the Kulekhani reservoir and predicted by the model showed significant relationship with low positive value having correlation coefficient r = 0.31579. However, the predicted value for the drainage basin has been usually significantly found greater than the measured sediment yield [38, 39], the predicted value of sediment yield for 2018 was found comparatively less than the measured. This might be due to the other factors' influence like landslides, streambank erosion or gully erosion occurrences that is not covered by the result of this InVEST model as its limitations. As the previous researcher Pokharel & Thapa, [40] was found stated that the slope in range 30°-65° had undergone failure in the past years and further the chance of failure was very high in the slope lying in the range of 40°-60° in the Kulekhani watershed.

Calibration and Validation of the Model: According to the suggestions provided by Vigiak [34] and Welde [35, pp. 35-38], after selecting the sensitive input parameters, the InVEST SDR_{max} model was calibrated for threshold flow accumulation and parameter K_b. The model was calibrated by changing the parameter sequentially for obtaining optimum agreement between observed and simulated sediment yield values. The optimum value for threshold flow accumulation was obtained as 2100 from starting value 1000. Likely, the optimum value for K_b was selected as 1.5 instead of its provided default value as 2.

Comparison of sedimentation rate measured in the reservoir with the obtained predicted sedimentation rate by the model is a means of validation of the obtained result [32]. The result of the comparison showed the data on sedimentation yield measured in the reservoir for 2002, 2010 and 2018 relatively closed to each other in quantity with similar decreasing trend in their respective year. However, the data of 2010 was found relatively far from each other compared to that of 2002 and 2018. The correlation between sediment yield measured in the Kulekhani reservoir and predicted by the model showed significant relationship with low positive value having correlation coefficient r = 0.31579. This shows that the result of the InVEST SDR_{max} model has been found in right direction within its limitations.

CONCLUSION

The result showed that the annual sedimentation rate of the Kulekhani watershed was found continuously decreasing at the rate of 13.3 (t/ha/yr), 6.6 (t/ha/yr) and 4.8 (t/ha/yr) in the year 2002, 2010 and 2018 respectively. Similarly, the potential soil loss predicted by RUSLE was also found in decreasing at the rate of 157.0 (t/ha/yr), 100.0 (t/ha/yr) and 83.7 (t/ha/yr) in the three temporal analyzing year. On contrast, the sediment retention capacity of the watershed was found increasing at the rate of 3058.5 (t/ha/yr), 3065.2 (t/ha/yr) and 3067.0 (t/ha/yr) for those three year 2002, 2010 and 2018 respectively.

The sub-watersheds namely Palung andheri, Simbhanjyang and Shankhmool determined as most sensitive were not only due to a single factor of having greater value of agriculture and built up land area but also due to a combined effects of rainfall erosivity index (R), soil erodibility factor (K) including steep slope of the sites within the watershed. Comparatively, the three sub-watersheds of the groups second namely Khaiti, Chitlang and Chuliprang having relatively lowest sediment exporting values were found to have relatively reverse characteristics with respect to rainfall erosivity index (R factor), soil erodibility (K) factor, forest cover as well as agriculture and built up land cover within the watershed.

The InVEST SDR_{max} model was found appropriate to provide the sediment yield closed to the sedimentation rate and trend of the reservoir within the three timeline 2002, 2010 and 2018 having total life span of 16 years of the Kulekhani watershed for this study. Furthermore, the correlation coefficient (r = 0.31579) between sediment yield measured in the Kulekhani reservoir and predicted by the model shows that the result of the InVEST SDR_{max} model has been found in right direction within its limitations.

Data Availability: The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

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