

Morphometric analysis of the upper catchment of Kosi River using GIS techniques

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Abstract Geographical Information System (GIS) have proved to be an efficient tool in the delineation of drainage pattern for water resources management and its planning. In this study, GIS and image processing techniques have been adopted for the identification of morphological features and analyzing the properties of the upper catchment of Kosi River. The basin area includes the high-altitude Himalayan Mountains, including Mount Everest and Kanchenjunga peaks. This basin is the main contributing area for devastating floods in 2008 in the Bihar state of India. The catchment can be divided into three sub-catchments, namely, Arun, Sunkosi, and Tamur. A morphometric analysis shows the nature of drainage in the upper catchment of Kosi River and some causes behind the high-intensity floods by comparing the properties of these three sub-catchments. It shows that the highest-order drains are present in both Arun and Sunkosi and the length of the first-order drains is very high (6,088 km) due to the absence of vegetation and also due to the barren/rocky surface which has

tremendous potential to generate runoff. Due to highest mean channel gradient in Tamur sub-basin compared to others, it has the highest flow kinetic velocity. Also, the results show that the Arun sub-catchment has the highest potential to contribute runoff and sediment. One of the major causes behind the high intensity of floods is that the sub-catchments Arun and Sunkosi have a nearly equal time of concentration, so they contribute their peak floods at the same time and hence double the intensity of floods.

Keywords Morphometric analysis · Kosi · Remote sensing techniques · Surface water study

Introduction

Morphometric analysis using GIS methods has emerged as a powerful tool in recent years. Remote sensing has the ability of obtaining a synoptic view of the large inaccessible area at one time and is very useful in analyzing the drainage morphometry. In water resources management, catchments form basic functional areas. Catchment hydrology, influenced by the interactions of meteorological phenomena, vegetation, topography, and soil, controls the quantity and quality of runoff. Topography, in particular, has been found to control catchment-scale water transport rather than the catchment area itself. The topography also controls the spatial distribution of surface water content and of water flow path geometry. Therefore, catchment should be the study area for a better understanding of the hydrologic system. The optimal and sustainable development of the natural resources is a prerequisite so that it is assessed rationally to avoid any future problems regarding its qualitative and quantitative availability.

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Accurate predictions of inflow into reservoirs are needed for a reliable management of water resources for power generation, irrigation, and drinking, especially during the lean season. To make these predictions, information about drainage parameters such as time of concentration and time of lag is important.

Description of the study area

The Kosi River is a trans-boundary river between Nepal and India and is one of the largest tributaries of the Ganga River. Local people call the Kosi River as “Sorrow of Bihar” for its regular floods and its ability to quickly change course. The catchment of Kosi falls in the eastern part of Nepal and Tibet Himalayan region. Based on the digital elevation model, the entire catchment was sub-divided into three sub-catchments viz. Arun, Sunkosi, and Tamur.

The area under the sub-catchment of Arun is the largest (32,396 km²) followed by Sunkosi (17,623 km²), and Tamur (5,849 km²). The outlet point located at the confluence of Sunkosi, Arun, and Tamur (10 km upstream of Barakhshetra) is bounded by 26°48'34" N to 29°07'48" N latitude and 85°22'19" E to 88°55'44" E longitude, covering a total area of 55,868 km². These tributaries encircle Mt. Everest from all sides and are fed by some of the world's highest glaciers. The river travels a distance of 729 km from its source to the confluence with the Ganga River. The Kosi catchment with sub-catchments is shown in Fig. 1.

The northern half of the catchment falls in a rain shadow area and is dominated by barren areas and grasslands especially in the large portion of Arun. The lower half is dominated by dense forests. The average elevation of the catchment is 3,858 m and the maximum is at 8,825 m. As it

emerges out of the Shivalik hills into the Ganga plains, there is a sudden drop in the gradient. This makes the river dump the extra sediment load, which fans out. Due to extensive soil erosion and landslides in its upper catchment by both natural and human factors, the silt yield of Kosi, which is one of the highest in the world, is about 19 m³/ha/year (Varghese 2008). On account of the steep slopes and narrow gorges in the upper reaches of the river in Nepal, silt in the river is carried to the plains where the slopes are flatter beyond the city of “Chhatra,” resulting in deposition of sediment bed load and high aggradation of the river bed that cause a number of interlacing channels, which shift laterally from time to time. The excessive rains, large flood discharge during the monsoon season, and erosion-prone low banks in the plains compound the problem of floods in the highly braided river in the plains of Nepal and north Bihar, inducing pendulum action starting at the bends and triggering extensive damages to life and property in the thickly populated lower plains of the river basin in Nepal and Bihar (Sinha 2008). The river has an average water flow (i.e., discharge) of 1,564 m³/s. During peak floods, it increases to about 18 times that amount.

Data used and methodology

Satellite data

Landsat MSS (1975–1976: October, November, and December), Landsat TM (1988–1989: October, November, December), and Landsat ETM+ (2000–2001: October, November, December) were used to study the decadal change analysis of land use/land cover. Land use classes

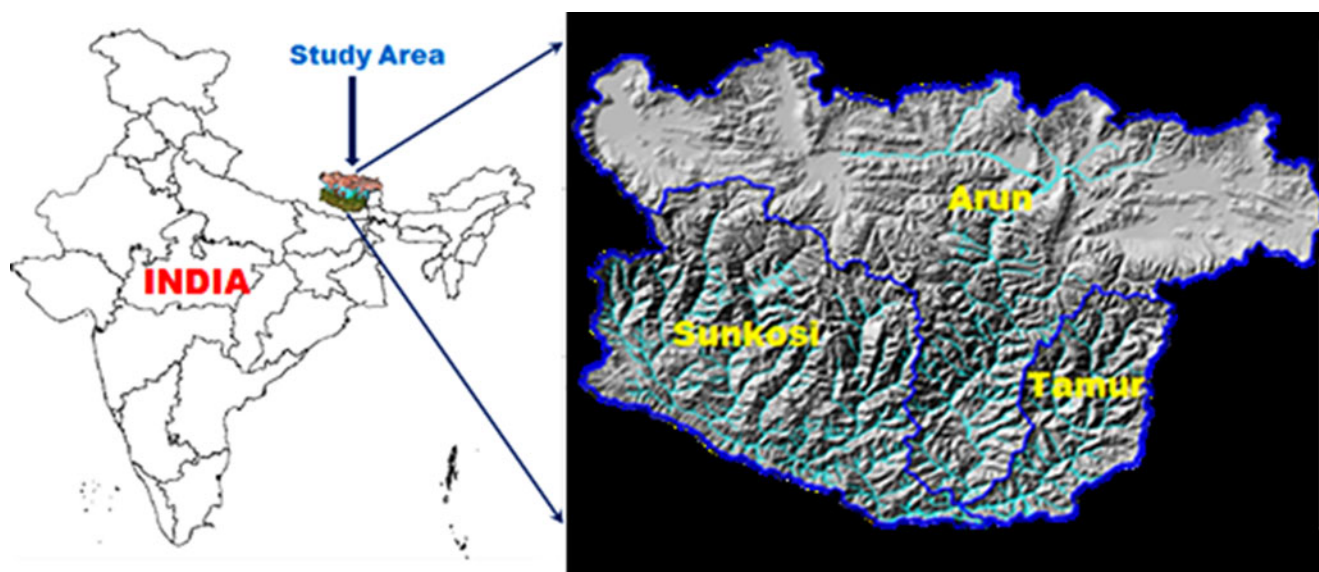


Fig. 1 Location and hill shade view of the Kosi River, upper catchment

for each of the scenes were generated with proper codes. A look-up table (LUT) was generated, qualifying positive change, negative change, and no change areas. The Modeller function of ERDAS was used with pre-decided LUT to generate the output, which shows color depiction of change types. Also, Landsat ETM+(2005) images are used for detailed digitization of drainage network of the catchment.

Data obtained from images captured by Advanced Wide Field Sensor (AWiFS) on board Indian Remote Sensing (IRS) satellite pertaining to the Kosi catchment were used. It was geo-referenced with respect to Landsat ETM ortho-product which is in UTM projection system and WGS datum. The AWiFS data have 56-m spatial resolution and acquire images in four bands, viz., 0.52–0.59, 0.62–0.68, 0.77–0.86, and 1.55–1.7 μm , with a ground swath of 740 km.

Digital elevation models

The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) for over 80% of the globe. The SRTM data are available as 3 arc sec (approximately 90-m resolution) DEMs. The generation of DEM is based on radar interferometry (INSAR). The data of tile N30E80 having projection geographic and datum WGS84 were re-projected into UTM system for further use.

Soil maps from FAO-UNESCO

For the calculation of runoff coefficient for different areas, the maps of hydrologic soil group are necessary. It was prepared by reclassifying the soil map of 1:5,000,000 scale obtained from the FAO-UNESCO website—<http://www.lib.berkeley.edu/EART/fao.html>—for the Southeast Asia. To enable spatial mapping of different soil types and their attribute values, the soil map of Kosi upper catchment was clipped from the digitized soil map of Southeast Asia using the ArcView and re-projected to UTM system. The map obtained thus contained the major soil mapping units based on FAO-UNESCO (1998) classification.

Basin morphometric analysis

Delineation of Kosi catchment and sub-catchment boundaries

The sinks of DEM were filled using FILL command in GRID module of Arc/Info. Filling was done interactively and in several steps based upon the result of sink under a given threshold. After filling the sinks, flow direction was generated using FLOWDIRECTION function of grid. Besides flow direction, flow accumulation grid was also

generated using FLOWACCUMULATION function of grid. The pore points of Arun, Sun Kosi, and Tamur were digitized separately to make a point cover which was thereafter rasterized with cell size compliant with the SRTM DEM. Sub-catchments were delineated using WATERSHED function of GRID module where “flow direction” grid and the “pore point” grid were used. The boundaries were delineated based on water divide. The sub-catchment boundaries were vectorized and polygon topology was generated for labeling of attributes. The area of the sub-catchments along with their perimeter and maximum drain length (from outlet point to the water divide line) was recorded for morphometric analysis.

Digitization of stream network

The detailed drainage network was digitized from Landsat ETM+(2005) data as arc layer. After digitization, the layer was edited for dangle, overshoot, undershoot, etc. Arc topology was built and ordering of the drains was done following Strahler's (1957) method of stream ordering. Orderwise length and frequency of the drains were recorded for morphometric analysis.

Areal aspects of basin morphometry

All the morphometric variables are to some extent expressions of basin size, being significantly correlated with catchment area. Thus, it is apparent that runoff is greatly increased by catchment dimensions.

Drainage area: The drainage area (A) is the single most important watershed characteristic for hydrologic design (Nighat 2010). The larger the catchment area and the greater its range of relief, the higher is its discharge.

Basin shape: Watersheds have an infinite variety of shapes, and the shape supposedly reflects the way that runoff will “bunch up” at the outlet. An elliptical watershed having the outlet at one end of the major axis produces a smaller flood peak than that of the circular watershed. A number of watershed parameters have been developed to reflect basin shape. The following are a few typical parameters (Nag 1998):

- Circularity ratio (R_c): It is expressed as the ratio of the area of the basin (km^2) to the area of the circle having the same perimeter as that of the basin (km^2).
- Elongation ratio (R_e): It is expressed as the ratio of the diameter of the circle having the same area as that of the basin (km) to the maximum length of the basin (km).
- Form factor (R_f): It is the ratio of the area of the basin (km^2) to the square of the length of the basin (km^2).

Linear aspects of basin morphometry

Watershed length: The length (L) of a watershed is the second watershed characteristic of interest. Watershed length is usually defined as the distance measured along the main channel from the watershed outlet to the basin divide. Various linear aspects of drainage morphometry include (Nag 1998):

- Stream frequency: i.e., ratio of total number of streams to the area of the drainage basin (km^{-2}).
- Bifurcation ratio (R_b): i.e., the slope of the regression line relating stream order and corresponding number.
- Drainage density: i.e., the ratio of total length of the streams of all order to the area of the basin (km/km^2).
- Constant of channel maintenance: It is measured as the reciprocal of drainage density (km^2/km).

Watershed slope

Both the watershed and channel slopes are important factors in the momentum of the runoff (Nag 1998). Also, it is one of the important factors which affect the time of

concentration of runoff, which ultimately affects the runoff yield. Typically, the principal flow path is delineated, and the watershed slope (S) is computed as the difference in elevation (ΔH) between the endpoints of the principal flow path divided by the hydrologic length of the flow path (L).

In the present study, a continuous surface slope (% slope) was generated using SLOPE function of grid. Thereafter, the output was reclassified into three discrete classes, as required for calculating runoff coefficient, using RECLASS function of grid. The classes include 0–2%, 2–6%, and >6%.

Typical water flow paths, stream surface profile, and stream gradient

The catchments were characterized by using the concept of the typical water flow path from the water divide to the confluence of three tributaries, viz., Sunkosi, Arun, and Tamur. The properties of the typical water flow path included length, slope, relative width, and soil type. The approach used here simplifies the three-dimensional catchment domain into 2-D (Merz and Bardossy 1999). Determination of the surface geometry of a typical water

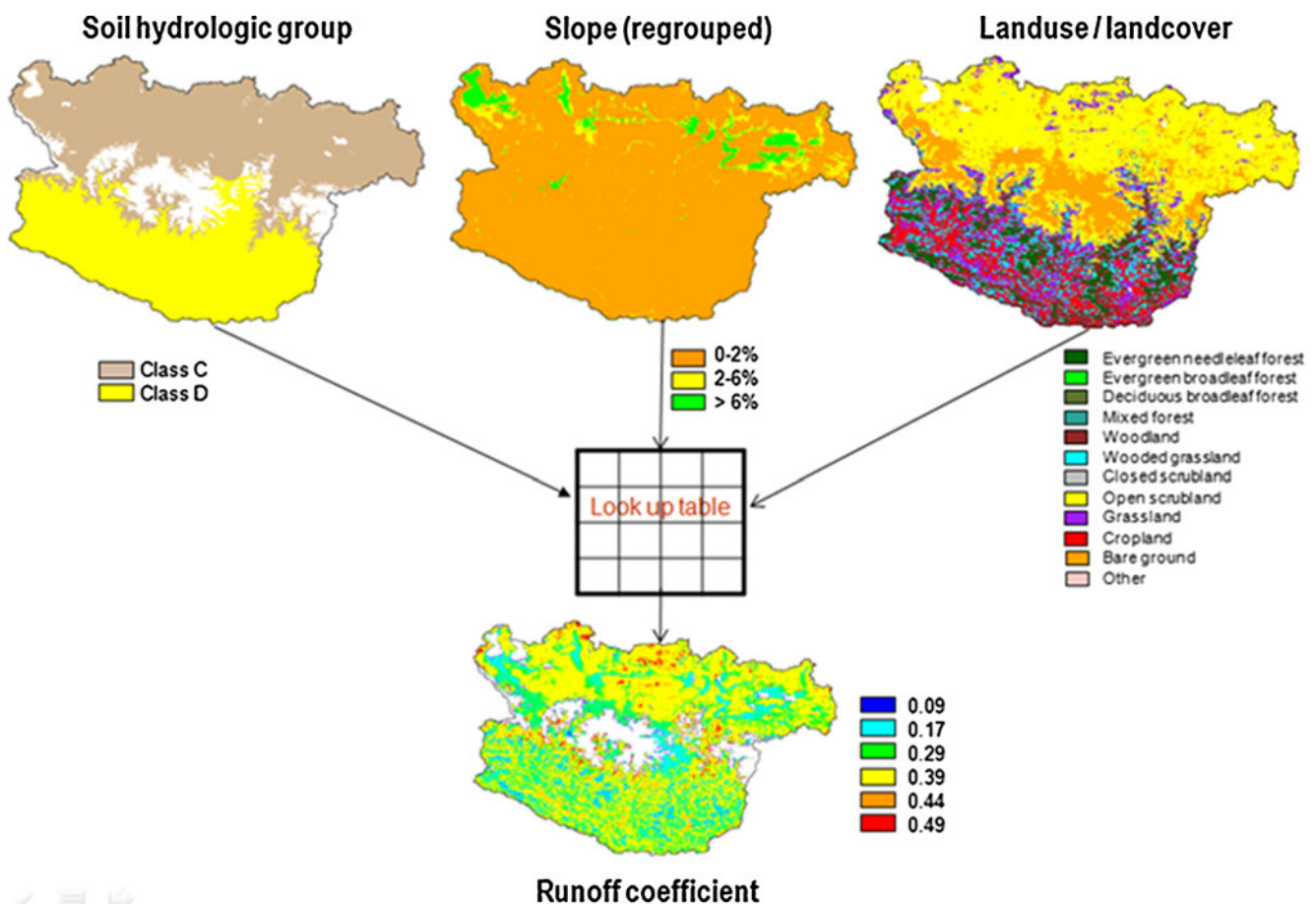


Fig. 2 Generation of runoff coefficient map

Table 1 Spatial and morphometric characteristics of the sub-catchments

Parameter	Arun	Sunkosi	Tamur
Area (km ²)	32,396.61	17,623.36	5,849.65
Perimeter (km)	1,478.42	826.21	442.42
Circularity ratio (R_c)	0.186	0.324	0.375
Elongation ratio (R_e)	2.093	1.188	1.035
Form factor (R_f)	0.640	0.359	0.315

flow path, i.e., length and slope, is based on analyzing the DEM of a catchment. By means of DEM, the direction of the flow was calculated for each pixel according to the direction of the steepest descent. Information on the flow direction allowed the computation of flow accumulation grid that shows how large an area is which drains through each pixel. Based on the location of the water bodies on the map and the information on flow accumulation, a stream network that was consistent with the DEM was delineated. Having the flow direction and the water body masks at hand, the flow paths from each grid cell within a catchment were followed until the flow paths intersected a water body. The difference in elevation between each pixel and its receiving water body pixel were recorded. These differences were then categorized according to their distance from the confluence along the water flow path.

The principal flow paths of all the three rivers, viz., Arun, Sunkosi, and Tamur (up to their confluence), were digitized from satellite data and a channel cross-section was generated using the SURFACEPROFILE function of grid where DEM and the stream line vector is used for generating ASCII file containing x , y coordinates and elevation values. The sampling distance was provided at 500-m interval. The profile data were stored in Excel file format for graphical presentation and further calculation. Stream channel gradient was gener-

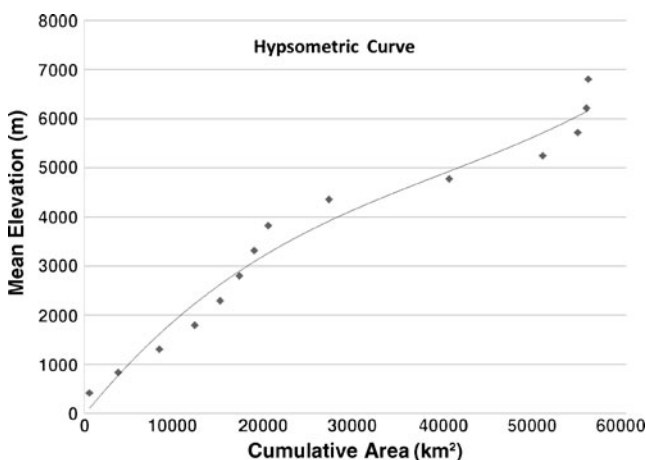


Fig. 3 Area–elevation (hypsometric) curve for the upper catchment of Kosi River

Table 2 Area and zonal mean hypsometric elevation of different zones

Zone	Elevation	Area (km ²)	Zonal mean hypsometric elevation (m)
1	≤500	648.8045	407.02
2	501–1,000	3,171.39	822.39
3	1,001–1,500	4,530.46	1,292.03
4	1,501–2,000	3,946.436	1,786.72
5	2,001–2,500	2,827.327	2,286.41
6	2,501–3,000	2,114.076	2,787.85
7	3,001–3,500	1,650.137	3,307.86
8	3,501–4,000	1,543.897	3,814.78
9	4,001–4,500	6,742.527	4,349.38
10	4,501–5,000	13,301.97	4,766.26
11	5,001–5,500	10,336.48	5,238.74
12	5,501–6,000	3,868.778	5,705.57
13	6,001–6,500	997.8421	6,204.97
14	6,501≤	209.6301	6,794.77

ated for every 10-km segment along downstream and is expressed as:

$$\text{Channel gradient } (\Delta) = (H_2 - H_1) / 10$$

where H_2 and H_1 are the elevation of the upper and lower ends of the 10-km segment, respectively.

Land use/land cover

Vegetation has an important control over minimum discharge. Catchments with a large proportion of their area under forest have higher minimum flows than those without forest. This is probably because the dense vegetation retards the runoff and tends to smooth out the hydrograph. During periods of low rainfall, there is still runoff available because of this storage effect.

The land cover map was generated from high-resolution scenes from MSS, ETM, and IRS LISS II by providing training data sets for the classification. For most scenes, only one cover type was identified within the scene. However, in some of the scenes, more than one class were identified if croplands are visually identifiable based on the spatial patterns of fields or if vegetation maps showed the

Table 3 Drainage properties of the sub-catchments

Parameter	Arun	Sunkosi	Tamur
Watershed length (km)	224.85	221.43	136.12
Length of principal flow path (km)	380.50	336.47	179.71
Mean main channel gradient (m/km)	13.76	12.00	23.23
Drainage density	0.32	0.41	0.35

presence of clearly identifiable cover types. These training data provide the basis for carrying out a complete land cover classification.

There were altogether 14 classes identified as given below:

- 0 Water (and Goode's interrupted space)
- 1 Evergreen needle leaf forest
- 2 Evergreen broadleaf forest
- 3 Deciduous needle leaf forest
- 4 Deciduous broadleaf forest
- 5 Mixed forest
- 6 Woodland
- 7 Wooded grassland
- 8 Closed shrub land
- 9 Open shrub land
- 10 Grassland
- 11 Cropland
- 12 Bare ground
- 13 Urban and build-up

Hydrologic soil groups

Soil hydrological characteristics, viz., infiltration rate, hydraulic conductivity, and water holding capacity, which is a function of soil texture, pore space, and organic matter,

are the key variables influencing the rates of runoff. Soil hydrologic groups (HSG) along with land use, management practices, and hydrologic conditions determine soil cover complexes and their associated runoff curve numbers. Soil hydrologic groups are assigned to soil series and phase of series using the criteria adopted by the National Resource Conservation Service (NRCS). Based on NRCS, soils are classified into four hydrologic soil groups based on the soil's runoff potential. Based on the soil depth and infiltration rate and vegetation surface, soils are grouped into four types of hydrological classes, viz., A, B, C, and D, where As generally have the smallest runoff potential and Ds the greatest.

Group A is sand, loamy sand, or sandy loam types of soils. It has low runoff potential and high infiltration rates even when thoroughly wetted. It consists chiefly of deep, well to excessively drained sands or gravels and has a high rate of water transmission.

Group B is silt loam or loam. It has a moderate infiltration rate when thoroughly wetted and consists chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.

Group C soils are sandy clay loam. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes the downward

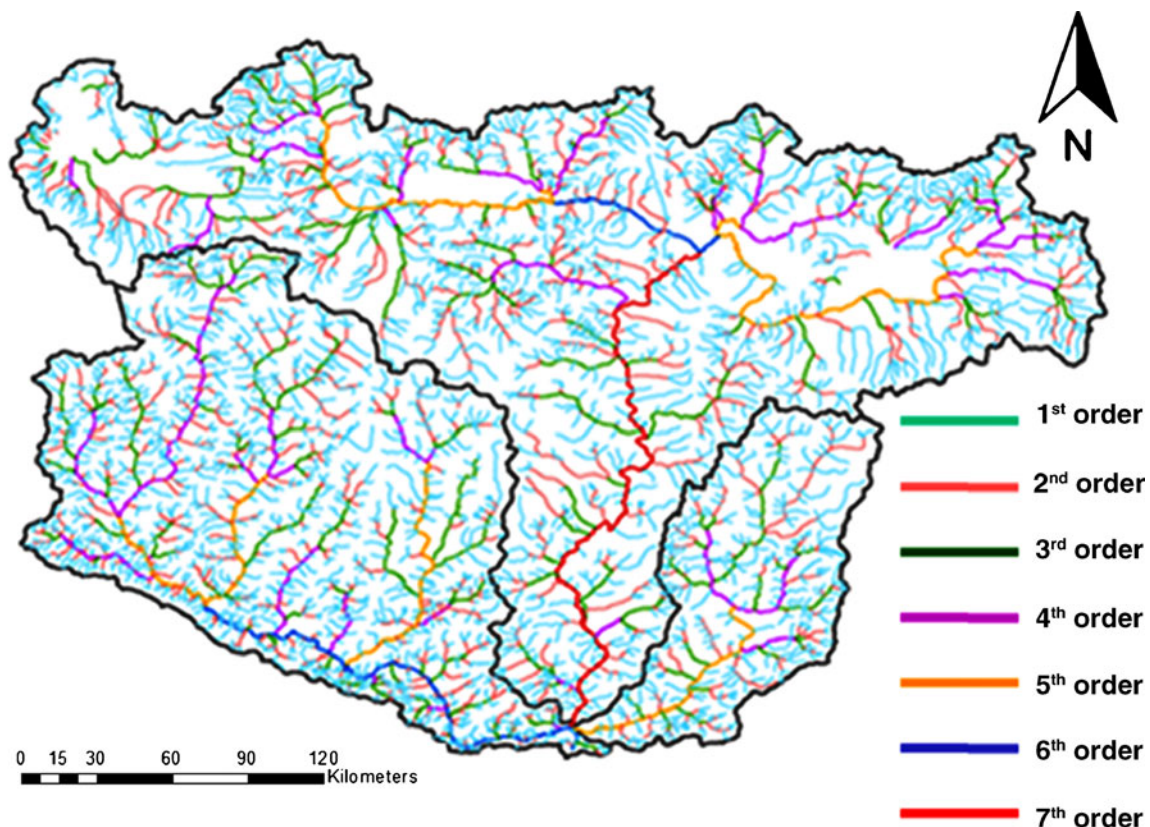


Fig. 4 Stream ordering by Strahler's method

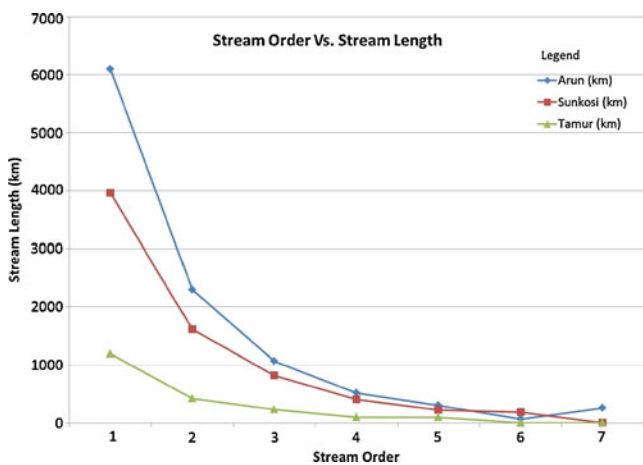


Fig. 5 Relation between stream order and length

movement of water and soils with a moderately fine to fine structure.

Group D soils are clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanently high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material.

The FAO-UNESCO soil map of the world (1:5,000,000 scale) published during 1974 to 1978 was used for the present study.

Runoff coefficient, C_r

This coefficient is the fraction of rainfall and snowfall that goes as runoff and can be estimated using the ratio of measured discharge to the measured precipitation (Church et al. 1999). The runoff coefficient of the Kosi catchment was calculated using the soil/hydrologic information, slope, and land use.

In order to find a representative runoff coefficient, an overall catchment runoff coefficient has to be determined using the areas of the different land cover/hydrologic soil group complexes as weighting factor. To achieve this, firstly, the soils map is reclassified into a map showing the HSG. Also, the land use map is reclassified. The reclassification of this map is based on a newly created attribute

table that correlates information about land cover with a certain type of crop. To determine the area occupied by the different land cover/hydrologic soil group complexes, both reclassified maps are overlaid. A look-up table is generated using all the possible combinations of land use and HSG and used in Modeller function of ERDAS Imagine software to generate curve number map.

The soil map of FAO was reclassified based on soil properties into four hydrological groups, viz., A, B, C, and D. In the Kosi catchment, only groups C and D are present. Percent slope map was generated from SRTM DEM using GRID function of Arc/INFO GIS. The continuous slope map was further reclassified into three classes, viz., 0–2%, 2–6%, and >6%. The land use/land cover map downloaded from FAO site was also reclassified according to the C_r table. A look-up table was generated using MODEL function of ERDAS where, for each combination of soil hydrologic group, slope, and land use/land cover, a coefficient value is assigned. The model output is written as a runoff coefficient (C_r) map. Zone-wise mean runoff coefficient value was extracted using the zonal function of ERDAS. The overall methodology is given in Fig. 2.

Time of lag (t_{lag}) and time of concentration (t_c)

These variables indicate the response time at the outlet of a watershed for a rainfall event and are primarily functions of the geometry of the watershed. Time of concentration (t_c) is the longest time required for a particle to travel from the watershed divide to the watershed outlet. It is a fundamental watershed parameter and used to compute the peak discharge for a watershed.

In order to determine the time of concentration using the Kirpich/Ramser method (Kirpich, 1940), one needs to calculate the longest water course length in the watershed (L) and the distance of the weighted channel slope (S) or the average slope of that watercourse and a coefficient representing the type of ground cover. The river length is calculated by performing a weighted distance operation on the rasterized river map using the most downstream point of the river map as the starting point. To evaluate the weighted channel slope, a DEM of the catchment is created.

$$\text{Therefore, } t_c = 0.0195 \times L^{0.77} \times S^{-0.385}$$

Table 4 Stream-order-wise total length (km) of the streams

Sub-catchment	Stream order						
	1	2	3	4	5	6	7
Arun (km)	6,088.44	2,296.14	1,065.65	515.70	301.32	65.13	255.02
Sunkosi (km)	3,955.06	1,613.90	814.94	408.68	224.34	184.99	2.42
Tamur (km)	1,189.46	424.72	232.73	93.83	95.63	–	–
Total (km)	11,232.96	4,334.76	2,113.32	1,018.21	621.29	250.12	257.44

Table 5 Distribution of different slope categories

Slope (%)	Description	Arun	Sunkosi	Tamur
0–1	Nearly level	1,731.20 (5.34)	159.63 (0.91)	4.56 (0.08)
1–3	Very gently sloping	1,963.38 (6.06)	29.41 (0.17)	1.69 (0.03)
3–5	Gently sloping	1,024.64 (3.16)	29.75 (0.17)	2.61 (0.04)
5–10	Moderately sloping	2,803.72 (8.65)	246.54 (1.40)	46.22(0.79)
10–15	Strongly sloping	2,117.03 (6.53)	232.53 (1.32)	47.15(0.81)
15–35	Moderately steep to steeply sloping	10,249.78 (31.64)	4,092.86 (23.22)	1,145.08 (19.58)
> 35	Very steeply sloping	12,506.88 (38.61)	12,832.64 (72.82)	4,602.33 (78.68)

Figures in parentheses indicate the percent of total area of the sub-catchment

where t_c =time of concentration (min), L =length of main river (m), and S =distance weighted channel slope (m/m). For the calculation of the lag time, in the absence of CN, t_{lag} (h) is estimated as 60% of time of concentration (t_c).

Results

Areal aspects of basin morphometry

The largest watershed area is under the Arun sub-watershed (32,396.61 km²) followed by Sunkosi (17,623.36 km²), and Tamur (5,849.65 km²). Most of the glaciers are nested with the catchment of Arun River. The details of the sub-catchments are given in Table 1.

From Table 1, it is apparent that neither of the sub-catchment is circular but all are mostly elongated in shape as the value of R_c varies from 0.186 to 0.375. However, the sub-catchment of Arun is extremely elongated ($R_c=0.186$).

Area–elevation curve

The area below the hypsometric curve is known as hypsometric integral which is used to calculate the hypsometric mean elevation. To derive an area–elevation curve for the Kosi catchment, the area and elevation data were plotted as shown in Fig. 3.

The zonal mean hypsometric elevation and the area of each zone are listed in Table 2.

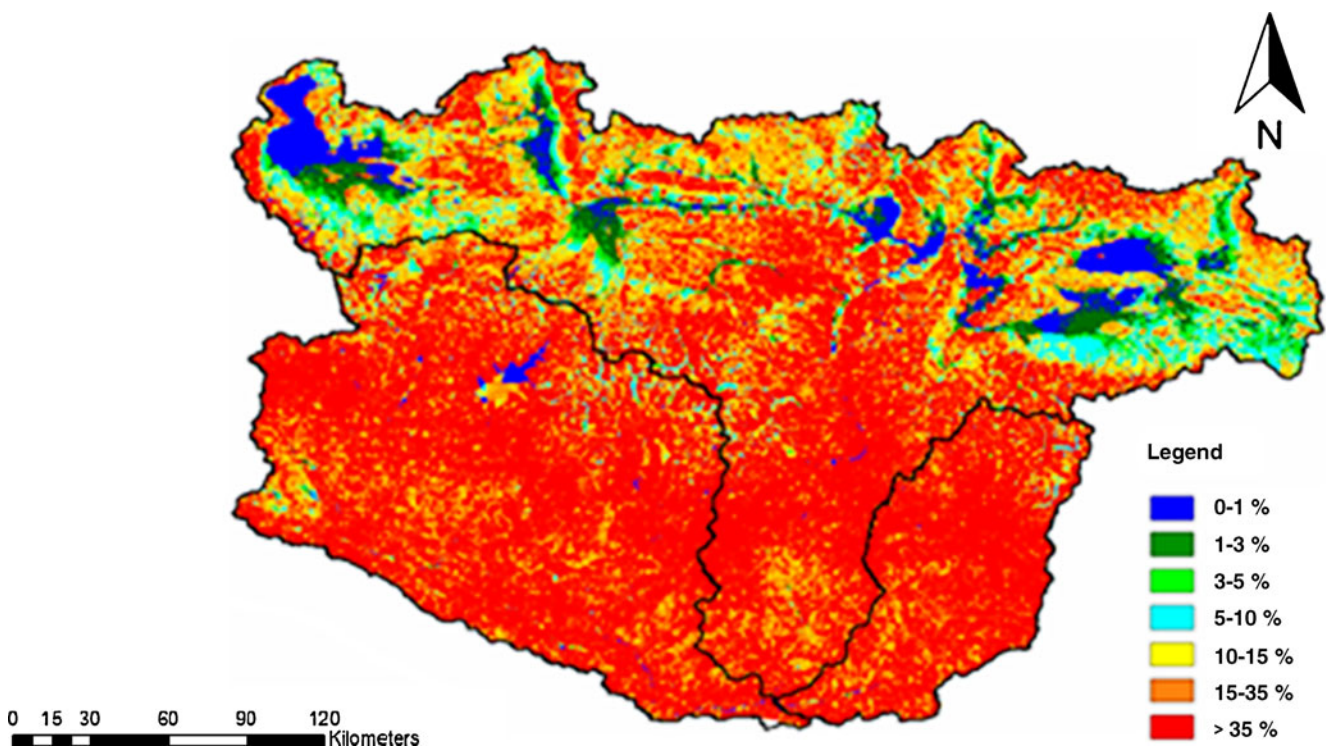


Fig. 6 Spatial distribution of slope

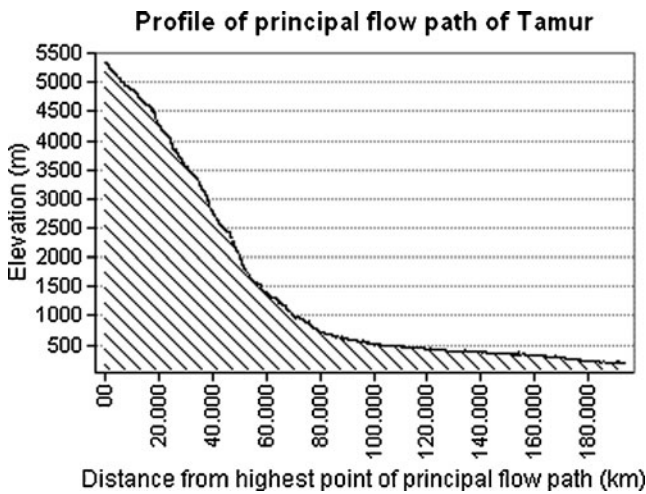


Fig. 7 Surface profile of the principal flow path of Tamur

Linear aspects of basin morphometry

Some of the important linear parameters of watershed morphometry are given in Table 3. The minimum mean length of the sub-catchment is observed in Tamur (136.12 km). Principal flow length is the highest in Arun (380.50 km), i.e., a long travel time is expected for flood water to reach the outlet. All the sub-catchments have low drainage density (less than 0.5 km/km²), which indicates better infiltration opportunity.

Stream ordering was done following the method given by Horton (1945) and modified by Strahler (Fig. 4). In general, the total length of the streams decreases with increasing stream order. Stream order, when plotted against

total length, gives an exponential fit (Fig. 5). The graph shows an exponential relation between them, which indicates that with an increase in the number of streams in an order the total length of the stream decreases. The maximum stream order found in both Arun and Sunkosi is 7, whereas in Tamur it is only 5 due to the smaller aerial expanse. Orderwise total stream length is given in Table 4.

Even though the size of the catchment of Arun is almost double that of Sunkosi, there is not much difference in the average watershed length of both due to their shape. In comparison to Arun and Sunkosi, the watershed length of Tamur is almost half (Table 3). Maximum length of the drain is also the highest in Arun (380.50 km) and lowest in Tamur (179.71 km).

Watershed slope

Most of the area is under a very steep slope (>35%) in all the sub-catchments. In the valley areas, the slope varies from 15% to 35% and in small patches it varies from 10% to 15%. A large area in the north of the catchment is perfectly plain with a slope of 0–1% only and with a gradual increase of up to 5%. A vast plain area in the north of the catchment is barren and or consists of grasslands and glaciers. The spatial distribution of the different slope types is given in Table 5 and Fig. 6.

Typical water flow paths, stream surface profile, and stream

Surface profile along the principal flow path for Arun, Sunkosi, and Tamur were generated. Differing significantly from Tamur (Fig. 7) and Sunkosi (Fig. 8) is the

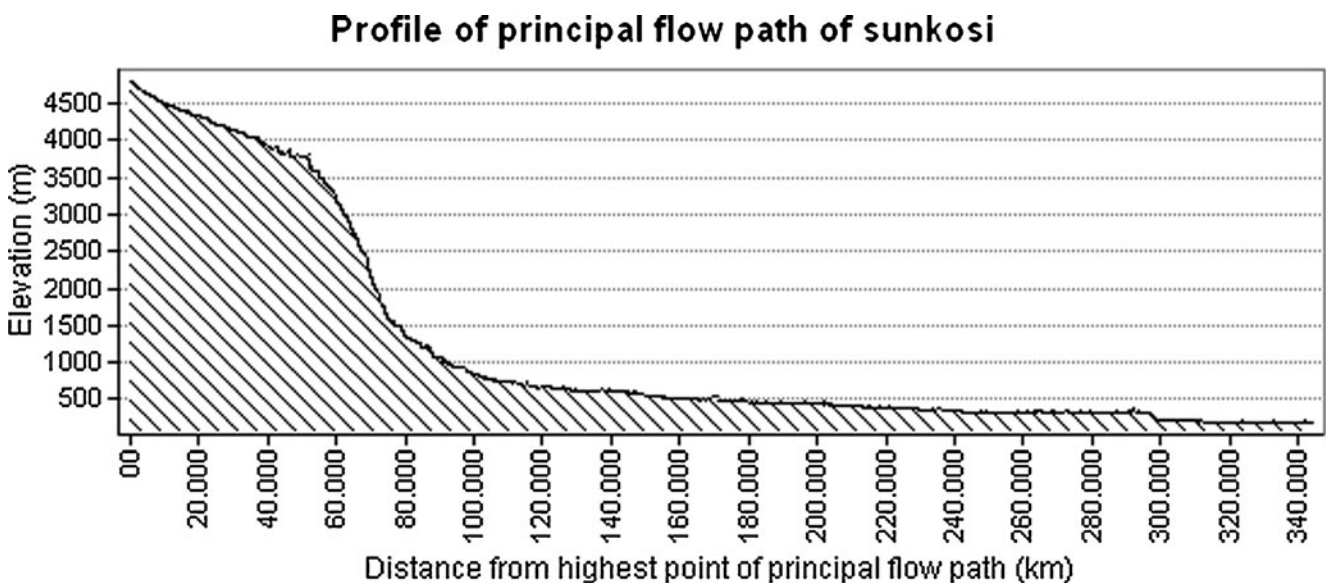


Fig. 8 Surface profile of the principal flow path of Sunkosi

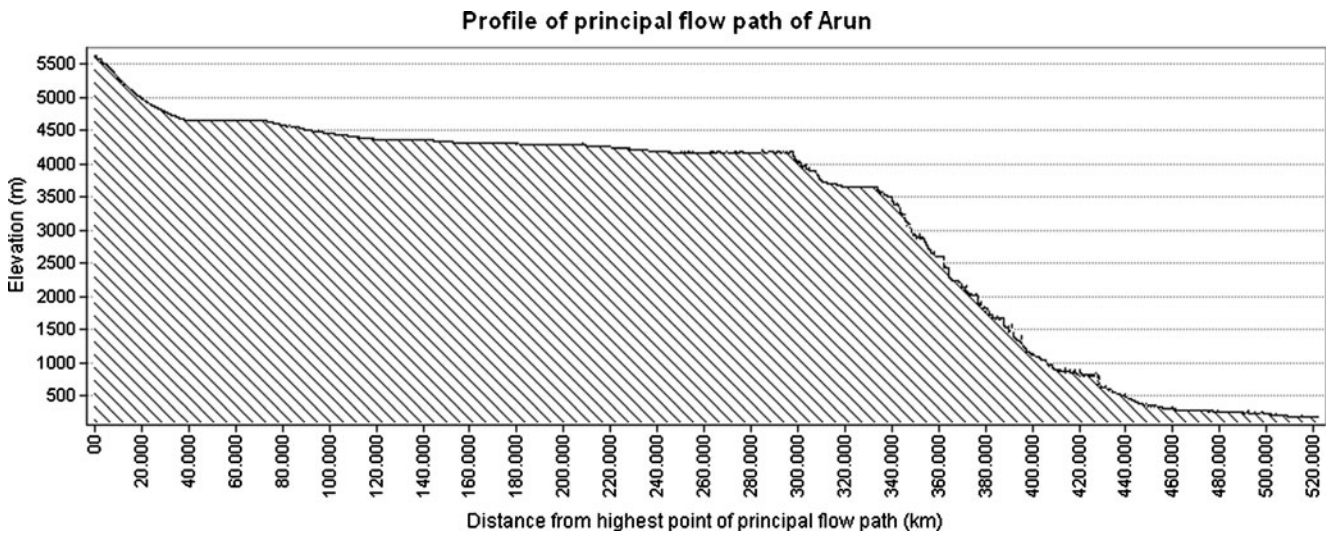


Fig. 9 Surface profile of the principal flow path of Arun

profile of Arun River (Fig. 9). Its entire course can be sub-divided into four segments, viz., moderately steep up to 45 km, nearly leveling up to 160 km, very steeply sloping up to 300 km, and thereafter nearly level again. On the other hand, Sunkosi (Fig. 8) shows a moderately steep slope of up to 45 km, very steep up to 70 km, and thereafter gentle to nearly level. The course of Tamur is comparatively smooth (Fig. 7) with a gradual decrease in gradient; however, it is mostly gently sloping after 60 km.

Land use/land cover classification

Most of the area in the catchment is under open scrubland (65.38%) and bare ground (17.18%), mostly falling in the northern and central part of the study area which is a rain shadow zone as shown in Fig. 10. Less than 4% of the area is under woodland and an almost equal area under wooded grassland. The grasslands are scattered in the central portion of the sub-catchment Arun. The sub-catchment Sunkosi, on the other hand, has a substantial area under

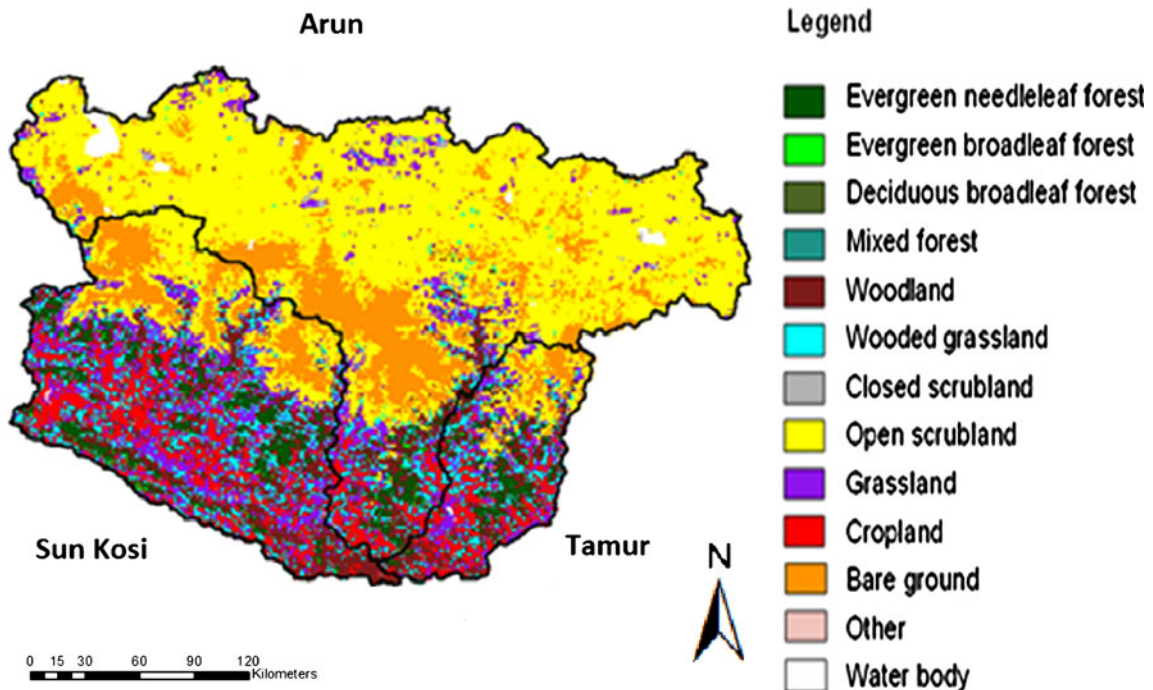


Fig. 10 Spatial distribution of land use/ land cover

Table 6 Land use/land cover distribution

Land use classes	Arun		Sunkosi		Tamur	
	Area (sq km)	% of total	Area (sq km)	% of total	Area (sq km)	% of total
Evergreen needle leaf forest	400.51	1.24	1,303.67	7.40	479.69	8.20
Evergreen broadleaf forest	30.94	0.10	61.35	0.35	16.83	0.29
Deciduous needle leaf forest	0.00	0.00	0.00	0.00	0.00	0.00
Deciduous broadleaf forest	25.78	0.08	52.83	0.30	10.94	0.19
Mixed forest	12.03	0.04	34.08	0.19	9.26	0.16
Woodland	1,227.31	3.79	3,368.23	19.11	1,233.72	21.09
Wooded grassland	990.96	3.06	2,494.01	14.15	879.43	15.03
Closed shrub land	372.15	1.15	176.38	1.00	67.32	1.15
Open shrub land	21,179.75	65.38	2,543.43	14.43	812.94	13.90
Grassland	1,897.69	5.86	2,882.55	16.36	869.33	14.86
Crop land	695.31	2.15	2,638.86	14.97	970.31	16.59
Bare ground	5,564.17	17.18	2,053.49	11.65	499.88	8.55
Others	0	0	14.49	0.08	0	0
Total	32,396.61		17,623.36		5,849.65	

woodland (19.11%), grassland (16.36%), wooded grassland (15.15%), and also cropland (14.97%) confined along the valleys. Open scrub and bare ground is confined to the northern part of the sub-catchment. The sub-catchment Tamur located in the eastern side of the study area is dominated by woodland (21.09%), wooded grassland (15.03%), grassland (14.86%), and significant cropland of 16.59%. The open scrub and bare ground is confined to a small extent in the eastern part only. The detailed land use distribution is given in Table 6 and their spatial distribution in Fig. 10.

Land use/land cover change analysis

Decadal change in overall land use was carried out using MSS, Landsat TM, and ETM+ data. For ease and lack of ground observation, the land use classes were divided into four, viz., forest vegetation, snow and glacier, barren and scrub, and water body. Change detection was performed using model function of ERDAS. Changes were performed between TM (1988–1989) and MSS (1975–1976), ETM+(2000–2001), and TM (1988–1989) and ETM+(2000–2001) and MSS (1975–1976). The result of change analysis is given in Table 7 (Fig. 11).

In this case, criteria to consider the change as positive or negative are based on considering change in an ecological or economical aspect. For example, if the barren land is converted into forest or in an industrial area, then it is considered as a positive change and vice versa.

More than 85% of the area remained unchanged during 1975 to 2001. There was more of a positive change (about

7.0%), whereas the negative change is very less—accounting for 4.37% only. The direction of change remained consistent with time, which indicates that anthropogenic disturbance in the catchment is minimum.

Runoff coefficient (C_r)

Zonewise runoff coefficient (C_r) values were extracted using zonal analysis function of ERDAS Imagine after integration of soil, slope, and land use map. The look-up table generated for model running in ERDAS uses the coefficient values for a 25-year return period. The zonewise

Table 7 Land cover change in the Kosi Catchment

Change type	Area (sq km)	% of total area
(2000–2001)~(1988–1989)		
Negative change	2,570.13	4.60
No change	49,352.82	88.34
Positive change	3,946.67	7.06
(2000–2001)~(1975–1976)		
Negative change	1,721.82	3.08
No change	50,221.56	89.89
Positive change	3,926.25	7.03
(1988–1989)~(1975–1976)		
Negative change	3,043.53	5.45
No change	49,049.28	87.79
Positive change	3,776.81	6.76

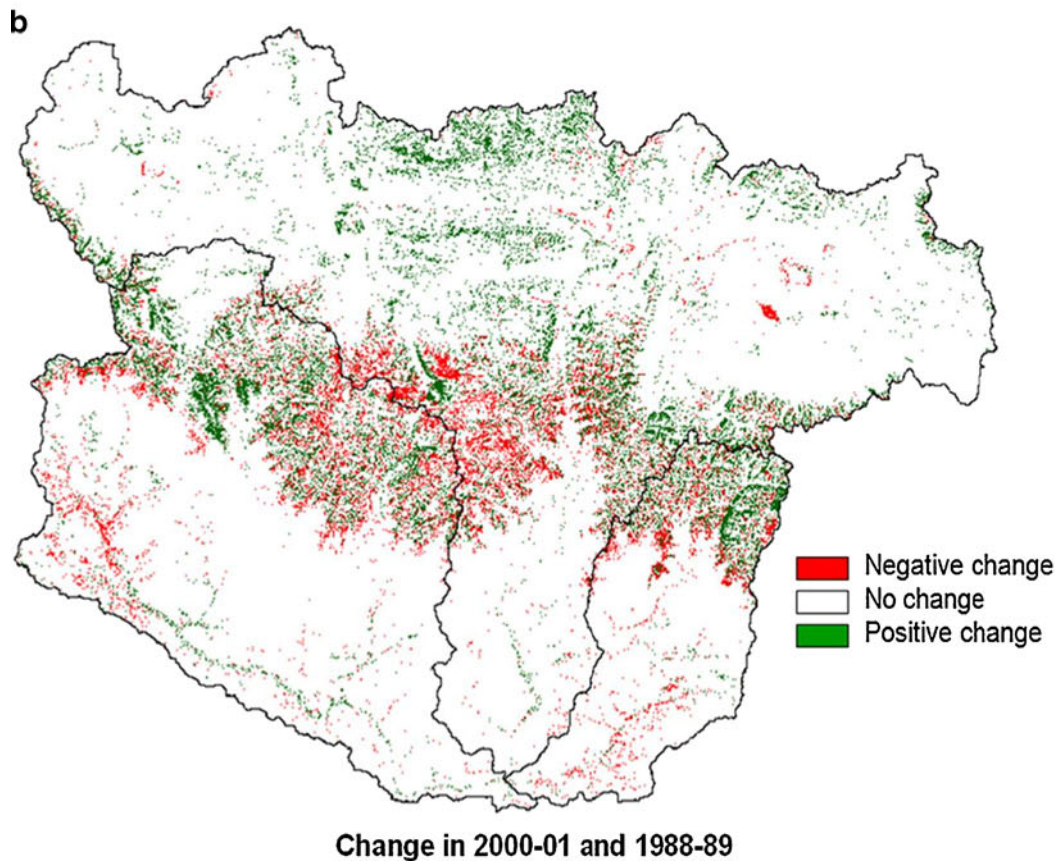
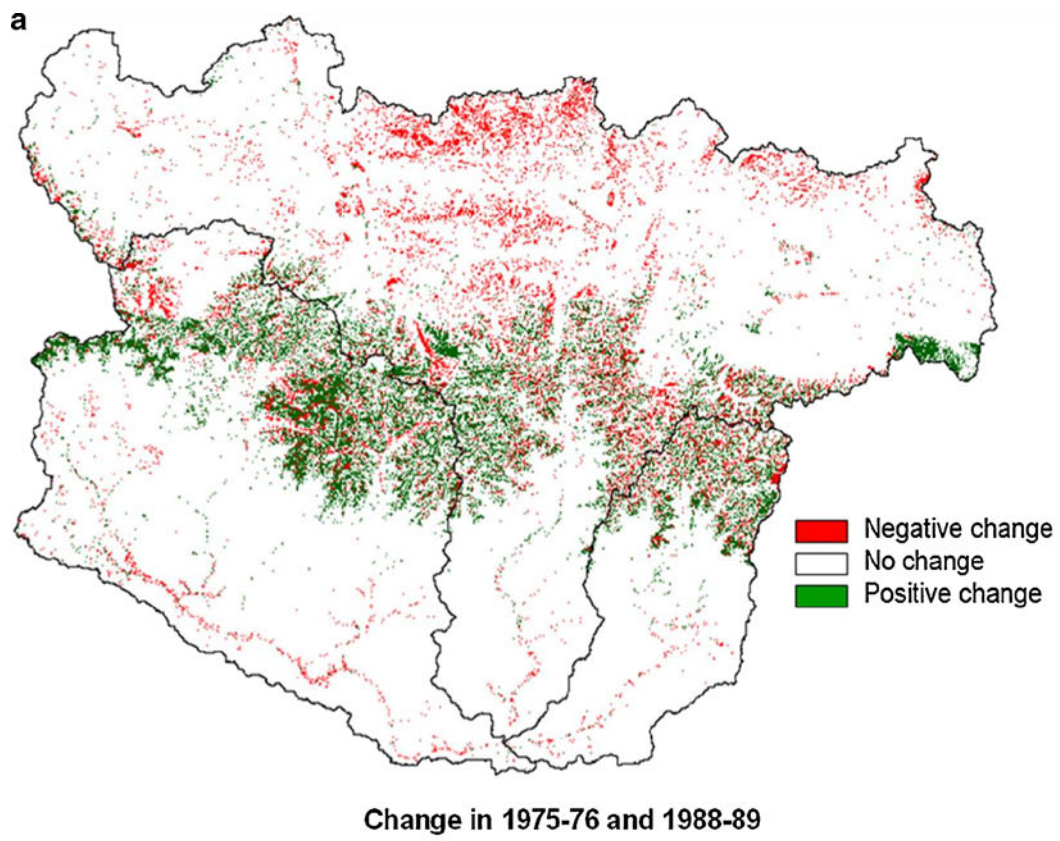


Fig. 11 Land use change analysis

C_r values are given in Table 8. The mean value of C_r is lowest in zone 5 (0.27) and highest in zone 12 (0.39).

Time of lag (t_{lag}) and time of concentration (t_c)

The estimation of time of concentration by Kirpich formula as given in Table 9 shows that the t_c values for the sub-catchments Arun and Sunkosi are nearly the same. If there will be precipitation in both catchments at the same time, then they both will contribute their peak floods at the same time, which will thus double the intensity of flood in the downstream area.

Likewise, time of lag is estimated as 60% of t_c (subcatchment/ t_{lag} (h): Arun—20.41, Sunkosi—19.71, and Tamur—9.41).

Conclusions

This study gives us the basic idea about the nature of drainage in the upper catchment of Kosi River and some causes behind the high-intensity floods and high sediment yield. It clearly shows that the Sunkosi and Tamur sub-catchments with form factors 0.359 and 0.315 indicate a semi-circular basin and will have a high peak flow for a shorter duration. Flood flows of an elongated basin are easier to manage than that of the circular basin (Nautiyal, 1994). The values of circulatory ratio of sub-catchments Arun, Sunkosi, and Tamur vary between 0.186, 0.324, and 0.375, respectively, and the elongation ratios vary between 2.093, 1.188, and 1.035, respectively, which indicates that sub-catchment Arun is elongated in nature and sub-catchments Sunkosi and Tamur are semi-circular in nature; thus, the area is characterized by high to moderate relief and the drainage system is structurally controlled. The sub-

Table 8 Elevation-zone-wise average values of runoff coefficient

Zone	Mean C_r value
1	0.35
2	0.30
3	0.35
4	0.32
5	0.27
6	0.35
7	0.37
8	0.36
9	0.31
10	0.36
11	0.36
12	0.39
13	0.34
14	0.28

Table 9 Calculation of time of concentration (t_c)

Catchment	L (m)	H_1 (m)	H_2 (m)	S (m/m)	Time of concentration, t_c (h)
Arun	385,475.79	5,432	195	0.013586	34.03
Sunkosi	342,395.9	4,216	195	0.011744	32.85
Tamur	182,933.58	4,370	195	0.022822	15.69

catchment of Arun is elongated as characterized by its elongation ratio of 2.093, which is almost double the corresponding value for both Sunkosi and Tamur. Hence, even though Arun has the largest basin area with a huge network of first-order drains, the nature of hydrograph is expected to be long and extended. Sub-catchment Arun has the highest drainage density at 0.32, which indicates that in some regions it is weak and consists of impermeable sub-surface material and sparse vegetation cover and mountainous relief. Sunkosi and Tamur have low drainage density which indicates that the area is covered by resistant permeable rocks with a dense vegetation cover.

The highest-order drains are present in both Arun and Sunkosi and the length of first-order drains is very high (6,088 km) due to the absence of vegetation and barren/rocky surface which has a tremendous potential to generate runoff. The mean channel gradient is the highest in Tamur, i.e., 23.23 m/km is almost double that of Sunkosi and Arun; hence, the flow velocity of flood will be the highest.

Also, a morphometric analysis of the sub-catchments reveals the general causes behind the high-intensity floods and high sediment yield, which can be summarized as follows:

1. The sub-catchment Arun having the largest area has the highest potential to contribute in the runoff at the outlet.
2. Also, land use/land cover analysis shows that sub-catchment Arun has most of the area covered by open shrub land and bare ground and less forest cover, so it is less resistant to runoff and thus causing erosion. However, the sub-catchments Sunkosi and Tamur have most of the area covered by vegetation like wooded land, crops, grass, and forest; so, due to the storage effect in this catchment, there is less erosion.
3. Land cover change analysis shows that, although there is less anthropogenic disturbance in the catchment, some of this disturbance is along the stream network—so this factor is one of the contributors for erosion and sediment yield.
4. The contribution of the peak floods by the sub-catchments Arun and Sunkosi, the two biggest sub-catchments, at the same time due to nearly equal time of concentration is the main reason behind the high flood intensity.

Since Kosi upper catchment consists of three out of the four tallest peaks of the world, viz., Mt. Everest, Kanchenjunga and Makalu, and Kosi lower catchment consists of one of the most unstable river banks, there is a need for an intensive flood modeling and an effective flood mitigation program to minimize flood damage and also to conserve the fragile ecology of the catchment. Thus, this study shows that GIS techniques have become efficient tools in the delineation of the drainage pattern to understand terrain parameters such as surface runoff, which helps in better understanding the status of land form and their processes. It will also help in future planning for watershed management practices.

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