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Morphometry Governs the Dynamics of Runoff and Sediment Production Rate: A case Study of Upper-Kosi Micro-watershed, Almora Uttarakhand

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ABSTRACT

Understanding the morphometric parameters of the watershed are critically important for shaping the management policies. In river watersheds, these parameters are sentinels that guide policymakers in framing sustainable land-use policies. This pilot study seeks to use watershed geo-morphometric parameters to estimate the runoff and Sediment Production Rate (SPR) of the upper Kosi watershed. It is tremendously important to have a good understanding of the dynamics of runoff, soil erosion, and drainage in the mid-Himalaya regions. The watershed is dominated by a partially rectangular drainage pattern with a drainage density of 0.868 km/sq km. The aerial parameters indicated that the watershed is elongated in shape with a lower peak flow period. The estimated values of runoff and Sediment Production Rate (SPR) for the watershed are 31.36 sq.km-cm/sq.km and 0.016 ha-m/100sq-km/year respectively, which indicates the watershed is under the zone of low runoff and sediment production. The runoff and SPR are dependent on the shape parameters of the watershed and the results indicate that the upper Kosi watershed is elongated in shape with the fine texture of surface/sub-surface materials and lower peak flow duration. The estimated and measured surface runoff was 31.36 and 34.46 sq.km-cm/sq-km respectively and it is nearly equal to the measured value which indicates this type of study can be used for the other remote locations having similar watershed characteristics. We believe that our study generates baseline data for the land-use planners to frame sustainable land use policies for the region.

Keywords: *Geo-morphometry, Kumaon Himalayas, remote sensing, Sediment Production Rate*

INTRODUCTION

River morphometry is a convenient method to explain fluvially originated landforms (Barman *et al.,* 2021). Morphometry is the measurement and mathematical exploration of the earth's configuration, its surface, shape, and the dimension of its landforms (Clarke, 1996, Girma *et al.,* 2020; Varma *et al.,* 2020). Morphometry is important in hydrological investigations concerning pedology, groundwater management, and environmental valuation (Hajam *et al.,* 2013). The morphometric parameters determine the form and structure of the drainage basins and their connected drainage networks (Biswas *et al.,* 2014). The morphometric parameters of a drainage basin typically reveals the underlying relief, geology, climate, and tectonics (Barman *et al.,* 2021). The geological, geomorphological, hydrological and hydrogeological features of any basin can be determined using morphometric and morphotectonic techniques (Mahala, 2020). The quantitative estimation of the morphometric parameters is of critical importance in watershed prioritization for soil and water conservation at micro watershed level (Kanth and Hassan, 2012). Furthermore, watershed morphometry analysis is essential for the development of water and land resources and provides reliable information for flood risk control and data on how the physical topographies of the region help in the progression of a watershed (Vandana, 2013). Thus, morphometric assessment is important in studying hydrology of the watershed for sustainable utilization of resources such as land and water and for efficient management of water related disasters (Mensah-Brako *et al.,* 2018; Sofi *et al.,* 2021; Dar *et al*., 2021 a, b).

The natural factors such as catchment shape and slope, relief, stream network and density, surface, and subsurface characteristics, soil characteristics, meteorological and climatic influences, etc. affect the water and the sediment entry in the channels (Roth *et al.,* 1996; Roy and Lamarre, 2011). Apart from the natural factors, anthropogenic factors such as deforestation, rapid urbanization, and improper land use and management practices also affect the water and sediment entry in the channels (Khatri and Tyagi, 2015; Sofi *et al*., 2020). Quantifying spatially distributed sediment yield and accurate source identification and erosion in vulnerable regions are important for prioritizing the conservation of watershed and in decreasing the socio-economic and environmental cost due to sedimentation on different irrigation and hydropower projects (Tenaw and Awulachew, 2009). Although management of land resources on a watershed is given top-most priority in India, most of the states of northern to eastern regions of India are not managed to conserve soil and nutrient state as per watershed management plan (Mythili and Goedecke, 2016; Dhawan, 2017). In the regions of the mid-Himalayas, most of the watersheds are un-gauged due to the inaccessibility of catchments, sparse topographical, and worst climatic conditions (Karmokar and De, 2020). This region is the source of most of the non-glacier-fed rivers which provide an adequate amount of water throughout the year to the downstream regions. It is thus important to have data on the spatio-temporal distribution pattern and erosion dynamics within the watersheds to formulate strategies to control the soil erosion (Ahmed and Srinivasa, 2015).

Remote sensing and Geographic information system (GIS) tools permit more effective and accurate application for the quantification of runoff and the sediment production rate of the micro watersheds (Shinde *et al.,* 2011). Estimation of these two parameters is used to conserve land and water resources so that sustainable development activities could be carried out simultaneously. Most of the studies were done in the catchment of the mid-Himalayan river but no such type of study presents the information about runoff and sediment production rate at the upstream section of the river (Bisht *et al.,* 2017). There is a research gap in the quantitative assessment of morphometric parameters and associated geomorphological features such as Sediment production rate and run-off dynamics. In this context this study was conducted to relate these two parameters together in the upstream section of the Kosi river in the Kumaon region of Uttarakhand, India. The manuscript provides valuable information to planners and decision-makers to frame soil and water conservation policies.

Study Area

Kumaon is a mountainous region of eastern Uttarakhand in India. This region consists of the great Himalayan tract. Many rivers and their tributaries emerge from here. The river Kosi, a perennial river originates in the middle Himalaya of Kumaon hills, arising out of Rudradhari waterfall, Budha Peenath of Koshimool near Kausani in Almora district. Kosi is a major tributary of the holy river Ganga with a total length of about 240 kms (Seth *et al.,* 2016). The stream travels a total distance of 13 km from the source to the outlet of the watershed with very high velocity. The watershed of the upper Kosi River is restricted between the latitudes 29°48′50″-29°52′60″ N and longitudes 79°9′01″-79°8′80″ E and it covers an area of 44.2 km^2. River Kosi plays an important role in supplying water to farmlands of native population as well as acts as the source of drinking water for the wildlife in the Corbett Tiger Reserve (Johnson *et al.,* 2020).

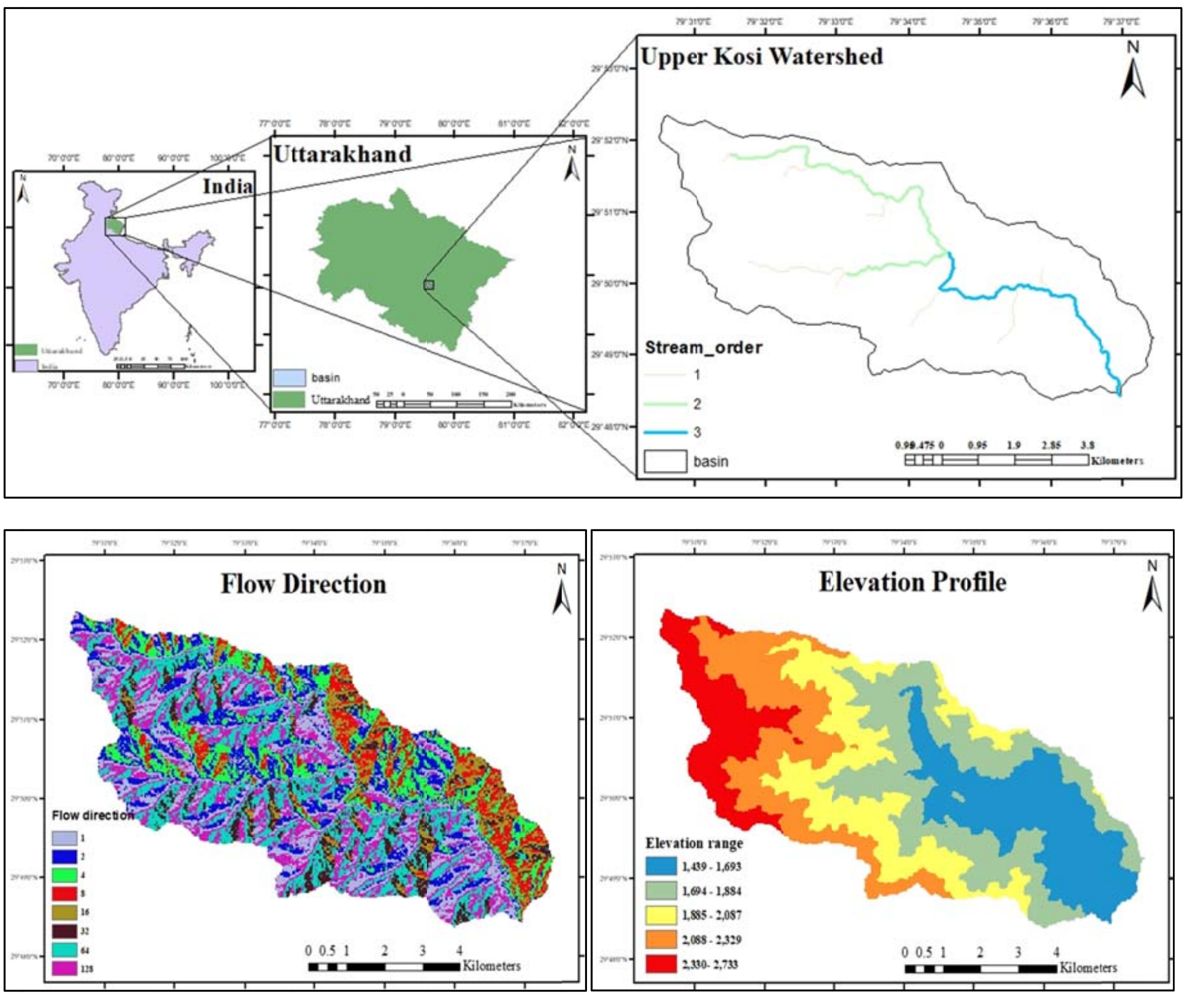

Fig. 1 (a) Watershed boundary & Stream network, **(b)** Flow direction, and **(c)** Elevation range of upper Kosi watershed.

Methods

The morphometric parameters of the upper Kosi watershed are quantified using the RS and GIS tools. The parameters of the watershed are analyzed by the digital images by using the ArcGIS 10.6 tool. The watershed boundary and the stream networks are delineated and digitized from STRM-DEM of 30m resolution and validated through Google earth imaginary. Various steps involved in calculating drainage networks, and different aspects are shown in Fig. 2. The stream length and stream order was calculated as per the law of Horton (1945) and the system of classification used by Strahler (1964). Other parameters were computed with the help of different mathematical approaches given in Table 1. Sediment production rate and run-off were estimated based on a mathematical model proposed by Jose and Das (1982).

Sediment Production Rate (SPR): According to Jose and Das (1982), the Sediment Production Rate of the basin is estimated by using geomorphic, drainage, and topographic parameters.

$$\text{Log SPR} = 4919.80 + 48.64\ \text{Log}\,(100 + \text{R}_\text{f}) - 1337.77\ \text{Log}\,(100 + \text{R}_\text{c}) - 1166.64\ \text{Log}\,(100 + \text{C}_\text{c})$$

Where SPR is the Sediment production rate in ha-m/100 Sq.km/year, R_f is the Form factor, R_c is Circulatory ratio and C_c is the Compactness coefficient.

Runoff (Q): According to Jose and Das (1982), the Runoff of the basin is estimated by using geomorphic, drainage, and topographic parameters.

$$\text{Log Q} = 2238.43 + 22.12\,\{\text{Log}\,(100 + \text{R}_\text{f})\} - 608.28\,\{\text{Log}\,(100 + \text{R}_\text{c})\} - 530.02\{\text{Log}\,(100 + \text{C}_\text{c})\}$$

Where: Q is Run-off in Sq.km-cm/Sq.km, R_f is the Form factor, R_c is the Circulatory ratio and C_c is the Compactness coefficient.

The estimated value of the runoff (Q) was further validated with the measured runoff at the outlet of the watershed by separating base flow from the total runoff. The WHAT (Web based Hydrograph Analysis Tool) has been used to separate the base flow from the total runoff. Further the contribution from rainfall is correlated through the estimated values.

Table 1. Linear, relief, and aerial morphometric parameters used for Kosi watershed

S.No.	Parameter	References
1.	Stream order(U)	Strahler (1964)
2.	Stream length (Lu)	Horton (1945)
3.	Mean stream length (Lsm)	Strahler (1964)
4.	Stream length ratio (RL)	Horton (1945)
5.	Bifurcation ratio (Rb)	Schumm (1956)
6.	Mean bifurcation ratio (Rbm)	Strahler (1957)
7.	Drainage density (Dd)	Horton (1945)
8.	Texture Ratio(Rt)	Smith (1950)
9.	Stream frequency (Fs)	Horton (1945)
10.	Elongation ratio (Re)	Schumm (1956)

11.	Circulatory ratio	Strahler (1964)
12.	Form factor (Ff)	Horton (1945)
13.	Rotundity factor (Rf)	Chorley *et al.* (1957)
14.	Shape index (Si)	Horton (1932)

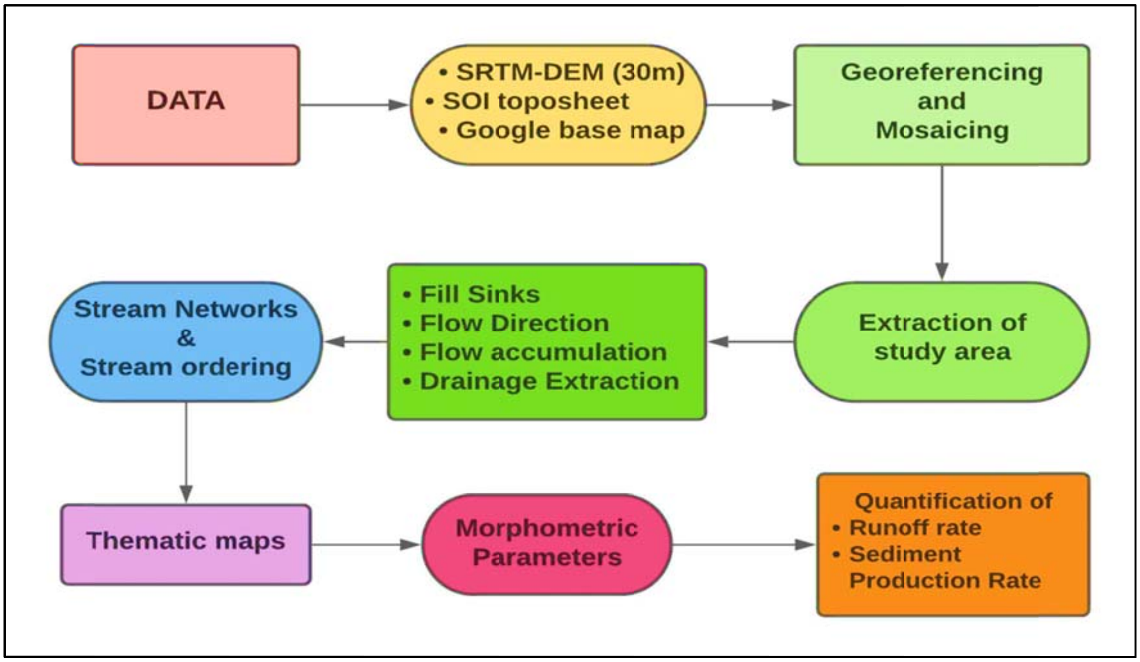

Fig. 2 Flow diagram showing the methodology followed for Kosi basin drainage extraction

Results and Discussion

The systematic description of drainage basin characteristics of the upper Kosi watershed such as drainage parameters, drainage texture, shape parameters, relief, runoff and Sediment Production Rate (SPR) etc. are discussed in the following sections.

Drainage Parameters

Drainage parameters such as slope, roughness parameters of the channel, soil type, bedrock type, permeability of soil/rock, etc. of the upper Kosi watershed controls the runoff in the watershed. These parameters are based on the texture and density of drainage and directly affect the runoff in the watershed. Runoff in the watershed is directly affected by the drainage parameters (Ahmed and Srinivasa, 2015). The upper Kosi watershed shows a semi-dendritic drainage pattern which is developed on the rocks that are approximately uniform to erosion (Feldman *et al.,* 1968).

Stream order, Stream length (L_b), and Stream Length Ratio: In the upper Kosi watershed 17 number of small streams were identified out of which 14 streams are categorized as of 1st order, 2 streams are categorized as of 2nd order and only one single stream is categorized as of 3rd order. The total length of the streams that lies in the upper Kosi watershed is 30.33 km out of which

10.94 km of stream length lies under the 1st order stream, 12.16 km of stream length lies under the 2nd order streams and the rest of 7.23 km of stream length lies in the 3rd order streams. As the order of streams increases the length of streams decreases (Singh and Singh, 1997). The 3rd order has less length as compared to lower order streams but carries higher runoff. The sudden decrease observed in the later order streams indicates towards the morphological variation (Mahala, 2020). The stream length ratio, which is defined according to Horton (1945), as the ratio of the mean length of streams of a given order (L_u) to the mean length of the streams of the next lower order (L_{u-1}), has an important relationship to deal with the surface flows and erosional stages of the watershed. The stream length ratio between consecutive streams order is subjected to the slope and topographic features of the watershed. The stream length ratio of the upper Kosi watershed is in the range of 0.89 to 1.68 which indicates the young stage of geomorphic development of streams (Ahmed and Srinivasa, 2015) (Table 2) and the difference in stream length ratio may be attributed to alteration in slope and topography (Vittala *et al.,* 2004)

Table 2. Watershed parameters of Kosi basin

Area of watershed (A) sq.km	**Length of watershed (Lb) (km)**	**Length of main stream (Ls) (km)**	**Perimeter of watershed(Lp) (km)**	**Number of streams**
44.20	12.40	13.00	35.50	17

Bifurcation Ratio (R_b): The bifurcation ratio is affected by the variation in the watershed geometry and lithology. Normally natural drainage systems have Bifurcation Ratio values ranging between 3.0 and 5.0. High Bifurcation ratio indicates early peaks in the hydrograph (runoff/time graph) shows the quick drainage and flash flooding during the specific storm events. The higher 'Rb' value for river basins is the result of a difference in frequencies between consecutive orders and designates the mature topography (Magesh and Chandra-sekar, 2014). The mean bifurcation ratio of the upper Kosi watershed is 4.5 which indicates geology is reasonably homogeneous and there is strong structural control over the drainage development (Ahmed and Srinivasa, 2015) and it also leads to the development of delayed hydrograph peak (Schumn, 1956).

Drainage Texture

The aspects considered of drainage texture for the present study contains stream frequency, drainage density, and texture ratio are described below:

Stream frequency (S_f): Stream frequency is sometimes called the drainage frequency which depends on the permeability and infiltration rate of surface/sub-surface materials, infiltration capacity, and relief of a catchment (Altaf *et al.,* 2013). A high value of stream frequency indicates larger surface runoff that is early peak discharge and Low stream frequency indicates high permeability and low relief (Soni, 2017). The stream frequency of upper Kosi watershed is 0.38, which indicates the high vegetal cover over the catchment (Fig. 3) and shows delayed runoff with a higher lag time in the peak discharge.

Drainage Density (D_d): Closeness of streams in any watershed is given by the drainage density (Carlston, 1963). Its value change with geomorphic features such as relief, soil, vegetation and rock features, and the watershed with higher drainage density and stream frequency has high runoff (Tucker and Bras, 1998; Kumari *et al.,* 2021). The drainage density of the upper Kosi watershed is 0.868 km/sq.km as shown in Table 2 and lies under the category of low drainage density. This is probably due to the large vegetal cover over the watershed surface and permeable surface materials. As per the LULC of the study area (Fig. 3), it shows more than 90 percent of the area having the vegetal cover and also there is a presence only one type of rock i.e. undivided Precambrian rocks (pC) which shows very high permeability (Fig. 4)

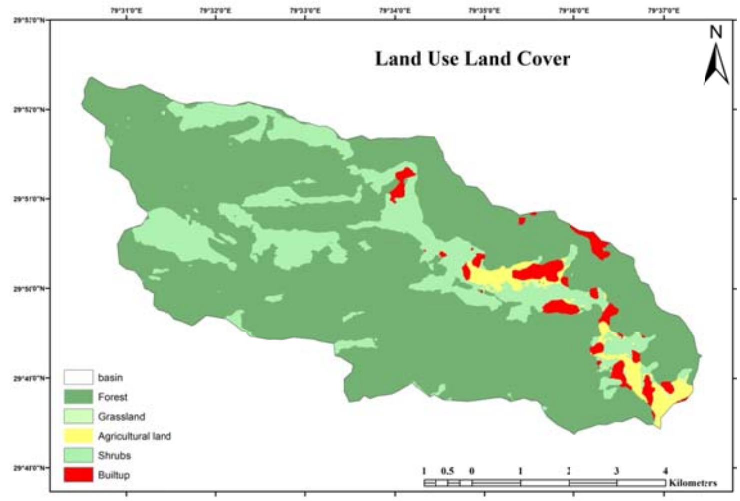

Fig. 3 Land use Land cover map of the upper Kosi watershed

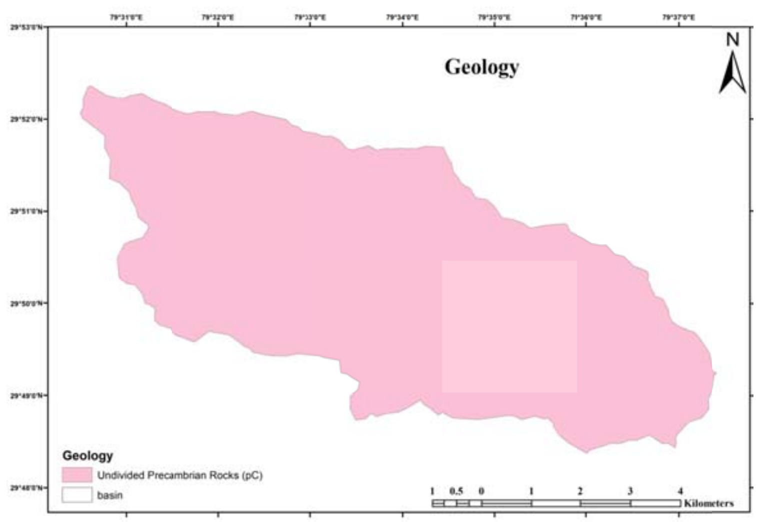

Fig. 4 Geological map of the upper Kosi watershed

***Texture Ratio**:* According to Horton (1945), a texture ratio is defined as the total number of the stream segments of all orders to the perimeter of the watershed. It depends on the geology of terrains at different stages of development (Smith, 1950). The texture ratio of the upper Kosi watershed is 0.48, which identifies that watershed is composed of coarse texture, low drainage density, and low relief with a gentle slope. Texture ratio helps to understand the relative spacing of the drainage lines and underlying lithology, infiltration capacity and relief aspect of the watershed (Rama, 2014).

Shape Parameters

Shape parameters are very important geo-morphometric features for identifying and regulating the hydrologic features and erosion rate of any watershed. The shape of the watershed controls the peaks of the hydrograph in other terms the shape of the watershed controls the runoff at the outlet of the basin. The shape parameters of the upper Kosi watershed is described in the following sub-sections:

Shape Index (S_i): Shape index is defined as the ratio of the square of the length watershed along the mainstream to the area of the watershed. It depends on the relief and length of the watershed. When the shape index is nearer to the unity the watershed shows the maximum erosion rate. The shape index of the upper Kosi watershed is 3.48, which shows the low erosion rate of the watershed (Rymbai and Jha, 2012).

Form Factor (F_f): Form factor is defined as the ratio of the area of the watershed to the square of the length of the basin. If the value of form factor for any watershed approaches 0.785, the watershed is considered as circular watershed and if the value of form factor approaches unity than the watershed is considered as more elongated in shape as a result watershed has a higher peak flow for a shorter time period. If the form factor approaches zero, lower peak flow will take place for the longer time period. The form factor of the upper Kosi basin is 0.29 which shows that the basin is elongated in shape with a lower peak flow for a longer time period (Chopra *et al.,* 2005).

Compactness Coefficient (C_c): If the compactness coefficient approaches unity the watershed is considered as the circular basin and the runoff takes the shortest time (Ratnam *et al.,* 2005). A larger value of the compactness coefficient shows the watershed deviates from its shape and loses its circular shape and becomes elongated (Rymbai and Jha, 2012). The estimated value of the Compactness coefficient of the upper Kosi watershed is 1.5 which shows the watershed is elongated and the runoff takes a larger time to reach the outlet (Zakaria *et al.,* 2016).

Circulatory Ratio (R_c): Generally the low values of Circulatory ratio indicates impermeable surface materials and mountainous relief which leads to less lag time as a result runoff will be more and high values of Circulatory ratio indicates the permeable surface materials which leads to higher lag time so runoff will be less (Altaf *et al.,* 2013). The estimated Circulatory ratio of the upper Kosi watershed is 0.44 which indicates a high value for the watershed may be due to permeable surface materials which lead to the higher lag time.

Elongation Ratio (R_e): The estimated value of the Elongation ratio for the upper Kosi watershed is 0.60 which shows the watershed is elongated which also indicates a higher time of concentration leading to the low runoff generated by the watershed. For any watershed, the values of the Elongation ratio can be grouped out into three categories as elongated (<0.7), oval (0.9-07), and circular (> 0.9) (Ahmed and Srinivasa, 2015).

Rotundity Factor (R_f): Generally for any watershed, if the value of the Rotundity factor approaches unity it indicates the perfectly circular watershed (Rymbai and Jha, 2012). The estimated value of the Rotundity factor is 0.87, which indicates the watershed is elongated in shape (Sofi et *al.,* 2021).

Runoff and Sediment Production Rate (SPR)

Hydrological features such as precipitation, evaporation, infiltration, transpiration, interception, etc. influence the runoff of a watershed. These hydraulic features of a watershed are influenced by lithological features, structure of surface materials, relief, slope, climatic and meteorological conditions. The estimated value of runoff for the upper Kosi watershed is 31.36 sq.km-cm/sq.km (Table 4) which indicates the watershed is categorized by low runoff zone (Rymbai and Jha, 2012). This may be due to the permeable surface and subsurface materials which allows quick infiltration and higher evaporation rate. The land use and the surrounding geology of the watershed indicates almost more than 90 percent of the watershed area has been covered by forest and whole watershed is covered by the undivided Precambrian rocks (pC) so as a result in the watershed quick access of the surface runoff is not possible and higher amount of the surface runoff was infiltrate into the ground and contributes to base flow. The estimated value of Sediment Production Rate (SPR) calculated for the upper Kosi watershed is 0.016 ha-m/100sq.km/year (Table 4) which indicates that the region is low sediment production zone (Rymbai and Jha, 2012). These estimated values of runoff and SPR are compared with the other micro watersheds, which also show the basin produces low runoff and sediment production rate (Table 5). For instance, the elongation ratio clearly indicates that the runoff generated from the basin is low, which is clearly indicated in the results (Ahmed and Srinivasa, 2015). Low circularity ratio also augments our results as it is indicative of the elongated basins with homogeneous ground and high permeability (Tamrakar and Karki, 2019). These features play a vital role in determining the sediment yield due to their influence on the erosion process of the river and its tributaries to carry sediment (Salim, 2014). The results obtained offer a clear indication that hydro-sedimentological flows are influenced by morphometric features of the terrain in the catchment.

Table 3. Total Runoff (Q) and Sediment production rate (SPR) of upper Kosi watershed

Total runoff (Q) and Sediment production rate SPR	**Values**
Form factor(Ff)	0.290
Circulatory ratio(Rc)	0.441
Compactness coefficient(Cc)	1.506
Total runoff, Q(sq.km-cm/sq.-km)	31.358
SPR (ha-m/100 sq.km/year)	0.016

Table 4. Total runoff and SPR compared with the other micro watersheds

Form Factor	Rotundity Factor	Circulatory Ratio	Compactness Coefficient	Runoff (sq.km-cm/sq.km)	SPR (ha-m/100sq-km/year)	References
0.01	2.639	0.372	1.639	22.988	0.008	Rymbai (2012)
0.14	1.778	0.414	1.553	20.893	0.006	
0.13	1.987	0.436	1.574	21.878	0.007	
0.26	3.040	0.460	1.480	77.630	0.160	Rymbai and Jha (2012)
0.29	0.870	0.441	1.506	31.358	0.016	Present Study

The monthly average measured streamflow and its components at the outlet of the basin were shown in the figure 3. Mostly in the dry seasons of year the streamflow was only due to the base flow whereas in the other time the flow was due to combination of the surface runoff and base flow. The measured annual runoff was 47.66 sq.km-cm/sq-km, whereas the surface runoff and base flow was 34.46 sq.km-cm/sq-km and 13.2 sq.km-cm/sq-km respectively. The measured surface runoff was 34.46 sq.km-cm/sq-km which is nearly equal to the estimated surface runoff of 31.36 sq.km-cm/sq-km using the geo-spatial modelling (Table 4). So runoff estimate by Jose and Das (1982) equation could help us to make preliminary data sets for the baseline information for the policy makers for a remote location which cannot be accessed.

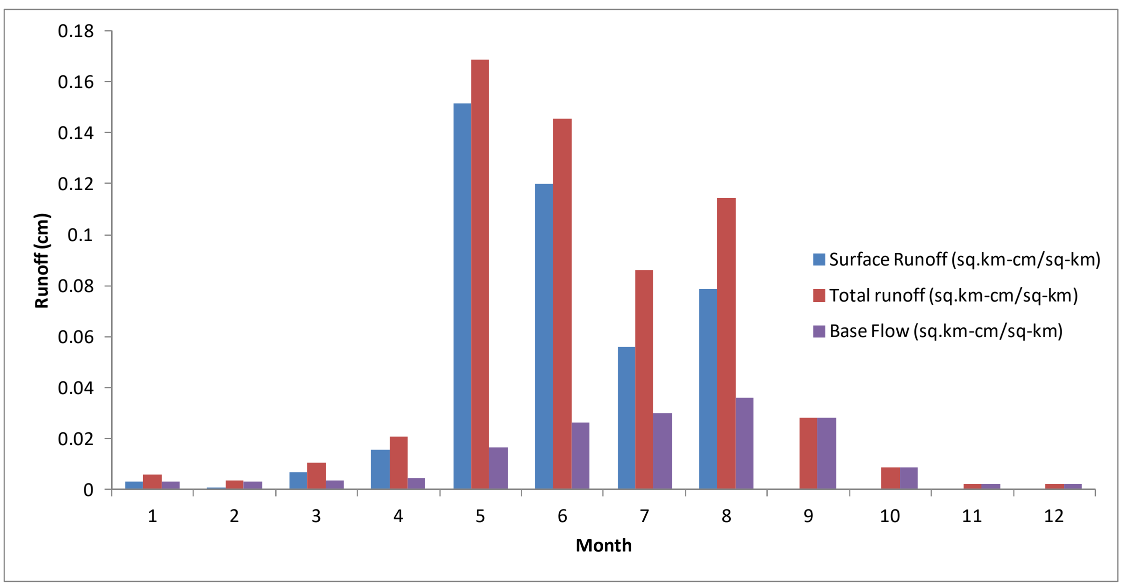

Fig. 3. Monthly average runoff and its components at the outlet of upper Kosi basin.

Linking land use policy with erosion and sediment yield in the Upper Kosi basin

Watersheds of rivers are not only the hydrological entities but are also biophysical and socio-political units that play an important part in shaping food, social, habitat, and economic services for the people (Worku and Tripathi, 2015; Taye and Moges, 2020). Thus, sustainable watershed management is essential for conserving and improving natural resources such as soil, water, and vegetation environmentally and ecologically (Worku and Tripathi, 2015). Results obtained from the numerical model (Jose and Das (1982), used in the study provide clear evidence of the influence of basins drainage characteristics on the erosion rates and the over sediment yield. The intricate issue of evaluating the scale of the effect of land use change and anthropogenic activities on river sediment loads is aggravated by the general deficiency of long-term records of sediment transport by the rivers of the world (Walling and Webb, 1981). Investigations regarding the sensitivity of river sediment loads to the change in land use, in many cases need to extricate the impacts of both land use change and climate change, which may however be closely associated (Walling, 1999). Understanding the role of sediment production within a drainage basin inevitably means to understand the linkages between land use, erosion and sediment yield within a river basin. Thus, for proper land use planning to alleviate the imminent consequences of sedimentation of rivers, the implementation of suitable conservation measures are vital.

CONCLUSION

The present study used remote sensing with GIS and a mathematical equation for estimating runoff and SPR. In this study, we found that the geomorphometric features of a river basin can be applied in inferring the sediment yield to help assess the erosion status. The estimated values of shape parameters of the watershed indicated that the watershed is elongated in shape with high concentration-time so that the hydrograph at the outlet of the watershed has a lower peak flow. This provided evidence that morphometry of the drainage basins may contribute in the variation of SPR. The values obtained from the numerical model clearly show that the catchment responds in an integrated fashion in terms of erosion and sediment yield. Thus, policymakers need to take a holistic view while framing policies concerning management, conservation, and development of land resources in the region.

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