



The significance of morphometric analysis to understand the hydrological and morphological characteristics in two different morpho-climatic settings

Avijit Mahala¹

Received: 26 June 2018 / Accepted: 10 December 2019 / Published online: 19 December 2019
© The Author(s) 2019

Abstract

Drainage morphometric parameters are important indicator to understand the hydrological and morphological characteristics of any region. Present study aims to understand the hydrological and morphological characteristics in two different morpho-climatic settings from drainage basin morphometric parameters. Remote sensing and GIS have been used as efficient tools in delineating and understanding of any drainage basin morphometry. The Kosi River basin of northern India for the mountain–plain tropical environment and Kangsabati River basin of eastern India for the plateau–plain sub-humid environment has been selected for the present study. The geological, geomorphological, hydrological, fluvial characteristics have been stressed out under linear, areal and relief aspects of morphometric parameters. The drainage morphometric parameters have been determined and measured after using the Advanced Space borne Thermal Emission and Reflection Radiometer global DEM (90 m) in ARC GIS 10.1. All the linear morphometric measures of mountain–plain humid Kosi River basin indicate its high flood potentiality, whereas, linear morphometric measures of Kangsabati River basin indicate less flood potentiality and plateau landform characteristics of sub-humid environment. The mean bifurcation ratio also indicates Kosi River has greater flood potentiality than Kangsabati River. Kosi River has drained large amount of water due to its near-circular basin shape than Kangsabati River which has an elongated shape. All the relief characteristics indicate that tropical mountain–plain environment dominated Kosi River basin is in rejuvenated or young stage of geomorphic development, whereas sub-humid plateau–plain dominated Kangsabati River basin is in mature stage of geomorphic development. Most of the morphometric characteristics indicate there are high geologic and geomorphological controls on river basin characteristics. The remote sensing and GIS tool have been successfully implemented throughout the study to understand the morphometric characteristics in two different morpho-climatic settings. Also, the results can be used for plan formation and sustainable management of the study area.

Keywords Morphometric parameters · Morpho-climatic settings · Remote sensing and GIS · Tropical environment · Sub-humid environment · Geomorphic development

Introduction

Drainage morphometry is defined as a measurement of linear, areal and relief characteristics of any drainage basin (Clarke 1966). Drainage morphometry was first initiated by Horton (1932). The drainage morphometric characteristics are important to understanding the underlain structure,

geomorphological formations and hydrological characteristics of any basin (Morisawa 1985). The relationship between drainage morphometric parameters to its underlain geology, geomorphology and hydrological characteristics is established through the work of different geologist and geomorphologist (Strahler 1952; Chorley et al. 1985). It also plays an important role to characterise the soil erosion, flood condition and geomorphological processes (Chavare and Potdar 2014). The evolutionary history of any basin can be best understood through the implication of different relief morphometric measures of drainage basin (Sharma and Sarma 2013). The different morphometric characteristics like linear parameters (stream order, stream number, bifurcation

✉ Avijit Mahala
mahala.avijit@gmail.com

¹ Center for the Study of Regional Development, Jawaharlal Nehru University, New Delhi 110067, India

ratio, strength length, mean stream length), areal or basin parameters (circularity ratio, elongation ratio, drainage density, drainage frequency) and relief parameters (dissection index, ruggedness index, hypsometric characteristics) are important for any river basin management. The hydrological and morphological behaviour of any basin can be best understood through the areal and relief morphometric parameters, respectively. Different fluvial processes with its morphometric characteristics are well established (Chorley et al. 1985; Vittala et al. 2004). The geomorphological stages of evolution with its erosional characteristics can also be best understood through the different drainage morphometric parameters (Strahler 1952). It provides enormous idea to identify the morphological, hydrological problems and helps with related management procedures. This study reveals to understand the hydrological and morphological characteristics from drainage morphometric parameters in two different morpho-climatic settings.

The remote sensing and GIS tool have been used for drainage morphometric characteristics from long past. The study of Vittala et al. (2004) has used remote sensing and GIS for morphometric analysis of sub-watershed in a south Indian plateau region. They found mature stage of geomorphic development in plateau environment and also give credits to remote sensing and GIS as an efficient tool for drainage morphometric analysis. Sreedevi et al. (2005) have used spatial technology to measure drainage morphometry in response to structural control and groundwater delineation. They proved remote sensing and GIS could find out the best groundwater resource as well as structural controls on drainage morphometry. Thomas et al. (2010) have successfully applied remote sensing and GIS to understand the soil loss and hydrological makeup in a mountain environment through the drainage morphometric characteristics. Ansari et al. (2012) found remote sensing and GIS as an efficient tool to understand the morphometric behaviour of any plain topographical area. The anomalies in drainage morphometric parameters are an important indicator of active tectonics, frequently seen in mountain glacial-fluvial environment. Remote sensing and GIS have proved as efficient tools to understand this phenomenon (Bali et al. 2011; Pareta and Pareta 2012). Parveen et al. (2012) have found remote sensing and GIS as a very helpful tool to understand the topographical and drainage morphometric characteristics in plateau regions of the world. The results of morphometric analysis from remote sensing and GIS techniques are useful for hydrological implication of river basin and artificial recharging structure (Golekar et al. 2013). The remote sensing and GIS-induced morphometric parameters are proved to be immense utility in natural resource management, water conservation and river basin evaluation (Singh et al. 2013). The drainage morphometric characteristics can be evaluated through the GIS model also (Magesh and Chandrasekhar

2014). The delineation of groundwater potential areas through different morphometric parameters of drainage by the use of remote sensing and GIS is an established phenomenon. The study of Waikar and Nilawar (2014) found there is strong relationship among different morphometric parameters with its groundwater potentiality. The GIS is proved to be a viable tool to understand the hydrological response behaviour of any drainage basin (Rai et al. 2017).

The morphometric study of mountain–plain front rivers of the world has found higher stream order, high bifurcation ratio, near-circular basin shape and relatively young geomorphic stages of development (Eckbld et al. 1997; Pareta and Pareta 2011; Nongkynrih and Husain 2011). These studies also give credits to remote sensing and GIS to explore the morphometric characteristics in mountain–plain tropical environment. Most of the study found mature stage geomorphic development in plateau regions of the world through the different drainage morphometric characteristics (Vittala et al. 2004; Rudraiah et al. 2008). These studies also found remote sensing and GIS as an efficient tool to understand the drainage morphometric characteristics in plateau–plain semi-humid environment. The plateau land river basin also has elongated characteristics (Singh and Singh 2011). This study selects Kosi river basin as a representative of mountain–plain tropical environment and Kangsabati river basin as a representative of plateau–plain sub-humid environment of India.

The Kosi river basin which is representative of the mountain–plain tropical environment of the present study is major attention from long past, especially due to its frequent channel shifting and flood characteristics. Studies indicate the relation between channel shifting characteristics of Kosi River to its morphometric characteristics (Singh et al. 2003). The changes of Kosi river morphometry is also related to the area of wetland changes in this region (Ghosh 2009). Most studies indicate the linear and areal morphometric characteristics of Kosi river basin to its irregular hydrological behaviour (Jain and Sinha 2008). Studies also indicate the relief morphometric characteristics behind the irregular hydrological characteristics of the Kosi river basin (Jain and Sinha 2008). Study of Sinha et al. (2008) identified the mega avulsion formation of Kosi River due to its morphometric characteristics. Most studies relate flood characteristics of Kosi river basin to its basin shape and size characteristics (Shrestha et al. 2010; Chen et al. 2013). Studies also indicate the multicyclic or rejuvenated stages of geomorphic development from its relief morphometric characteristics (Chorley et al. 1985). So, the morphometric characteristics support Kosi basin as a true representative of mountain–plain tropical river basin. The Kangsabati River basin which is representative of plateau–plain sub-humid river basin for the present study has plateau land morphometric characteristics (Mahala 2017, 2018). Low bifurcation ratio, elongated

basin shape and mature stages of geomorphic development are the general morphometric characteristics of any plateau river basin area (Vittala et al. 2004; Rudraiah et al. 2008). Studies of Nag and Lahiri (2012) identified regular hydrological behaviour from the linear and areal morphometric characteristics of Kangsabati river basin region. Changes of river courses are also limited due to its low hydrological pressure (Pan 2013). Studies of Dutta and Roy (2012) found the mature stages of geomorphological evolution after analysing the different areal and relief morphometric characteristic of the basin. The morphometric changes with the changes of geology and geomorphology of Kangsabati river basin is a well-established fact (Gayen et al. 2013). Kangsabati basin is a true representative plateau–plain sub-humid river basin, reflected through its morphometric characteristics (Gayen et al. 2013).

In general, most of morphometric studies of river basin are conducted to measure the morphometric values. There are very few studies aims to unearth the hydrological and morphological characteristics from its morphometric parameters in different morpho-climatic settings (Raux et al. 2011; Sharma and Sarma 2013). In addition to this, most of studies in the world are involved to understand the morphometric characteristics in either plateau, plain or mountain area (Vittala et al. 2004; Pareta and Pareta 2011). There is a serious lack of studies in adjoining parts of plateau–plain or mountain–plain areas which have a distinct hydrological and morphological behaviour. Also, there are few studies to compare the morphometric parameters in the above stated two distinct morpho-climatic areas. The remote sensing techniques along with the sufficient integration of GIS technology play an important role in unearthing the hydro-morphological characteristics from its morphometric parameters. So, in the present study, an attempt has been made to access the morphometric characteristics in two different morpho-climatic settings. Two main objectives of the present study are: (1) to understand the hydrological and morphological characteristics from morphometric parameters (2) compare the morphometric characteristics in two different morpho-climatic settings.

Study area

The Kosi river basin in Himalayan foothills of India has been selected as a mountain–plain humid river basin (Fig. 1). Major neo-tectonic Himalayan orogeny dominates the area. The irregular hydrological behaviour with rapid avulsion changes is the well-known identity of the basin (Sinha et al. 2008). The tertiary Himalayan geological formation in upper reaches with sedimentary deposition in middle and lower reaches are the major geological characteristics of the basin. High elevation, high slop and mountain landform dominated

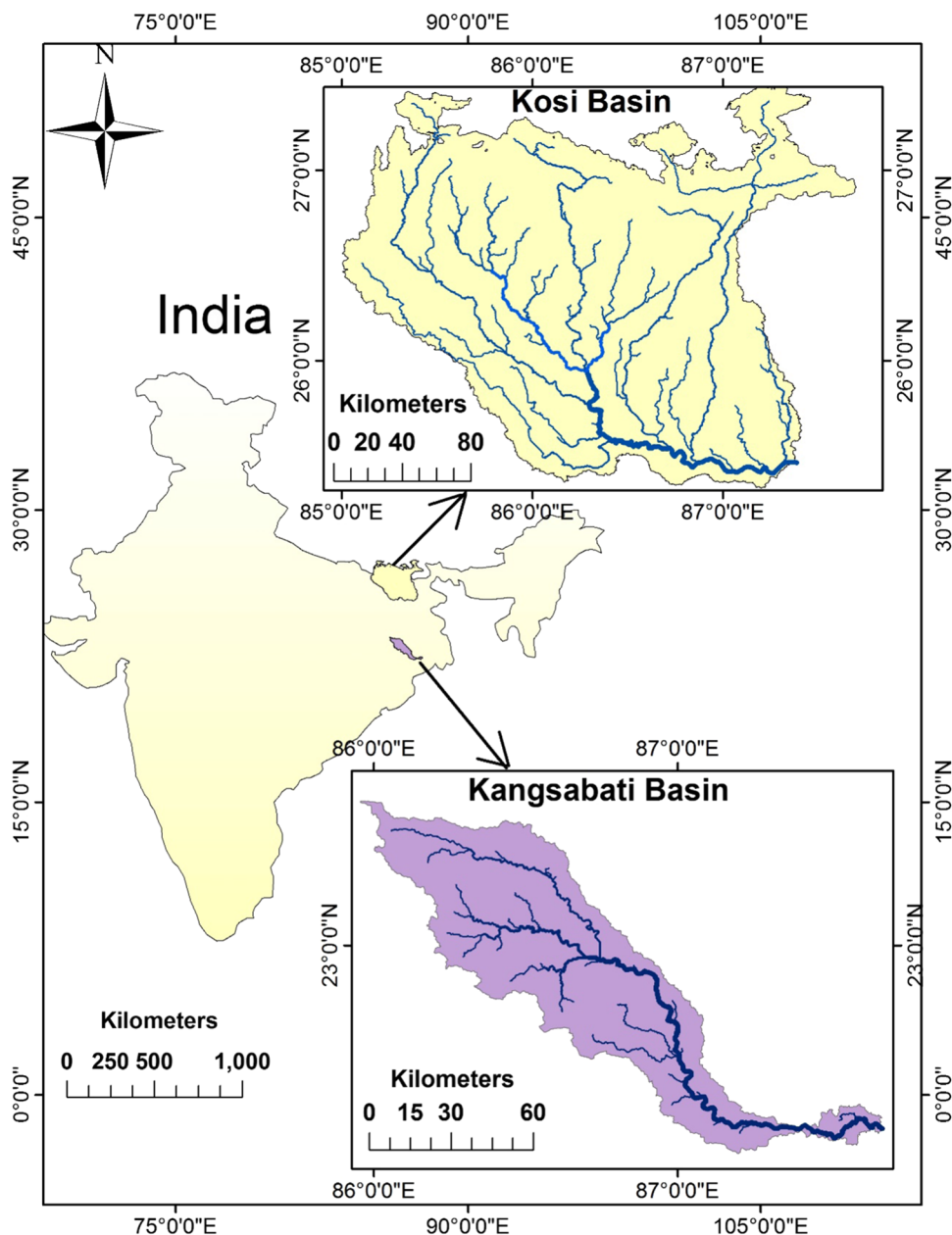
upper basin create potential source of river energy. It forms large amount of sediment deposition in Himalayan foothills and plain areas in middle and lower reaches of basin. This phenomenon causes major avulsion, frequent course changes and delta formation in lower basin reaches (Castillo et al. 1988). Sudden changes of slope in Himalayan foothill areas create large alluvial fan along the river courses. Out of total 720 km length of Kosi River, it flows as much as 320 km in plain lands of northern Bihar after crossing Siwalik Himalaya. Construction of embankments and dense settlement in floodplain areas increase flood potentiality of the basin. Kosi has changed its main course as much as 100 km eastward in August 2008 due to its embankments failure (Sinha et al. 2008).

The Kangsabati River basin in eastern Chotanagpur plateau of India has been selected for plateau–plain sub-humid river basin (Fig. 1). The upper reaches of basin comes under Pre-Cambrian granite–gneiss geological formation dominated undulating dissected plateau region. Primary and secondary laterite formation dominates the middle reaches. Alluvial deposition dominated plain landforms dominate lower reaches of basin. Lower regimes of water and seasonal characteristics dominate the streamflow characteristics. After originating from ‘Ajodhya hill’ of eastern Chotanagpur plateau, it flows through the plateau fringe regions of West Bengal in an eastward direction (Nag and Lahiri 2012). Out of its total length of 465 km, the dissected Chotanagpur plateau covers around 200 km in upper and middle reaches of basin. Studies indicate that the basin is in mature stages of geomorphic development (Dutta and Roy 2012; Pan 2013).

Geohydrological framework

The origin and development of drainage system depend upon the underlain geology, endogenetic and exogenetic forces operating in the area (Reddy et al. 2004). The Kosi and Kangsabati basin have varied geohydrological characteristics upon which the morphometric characteristics differ these two rivers. Geologically, the quaternary and recent alluvial deposits dominate in lower course of Kosi river geohydrological framework (Fig. 2). The Tertiary (Siwalik system) and Mesozoic (Jurassic, Cretaceous, Triassic) rock systems spread in upper course of Kosi river system. Structures which are linear geomorphic features have given the important impression in developing the drainage network of the region. The upper basin area of Kosi basin has experienced linear structural features in the form lower, middle and upper Himalaya have role on morphometric and hydrological characteristics. The Kosi basin has experienced structural disturbances which leads to development of well-marked set of joints and fractures. The Kosi basin has two types

Fig. 1 The location map of Kosi and Kangsabati River basin



of aquifer-weathered aquifer in lower course and fractured aquifer in upper course of basin.

The oldest rock system comprising of granite, granite gneiss and mica schist from the basement rock system of Kangsabati river basin (Fig. 2). The upper course of Kangsabati basin covers by unclassified crystalline mainly gneiss, granite gneiss and mica schist. The laterite and meta-volcanic rock encountered in middle basin and lower basin covers by alluvium and recent alluvial deposits. The Kangsabati basin has experienced structural disturbances in the forms of lineaments and joints. The main fractures/joints are in the direction of NE to SW. Like Kosi basin, Kangsabati basin has also experienced weathered aquifer in lower course of

alluvial plain and fractured aquifer in upper basin granite gneiss geological formation.

Materials and methods

The different indicators of drainage network (drainage morphometry) give inference about the hydrological and rock formation characteristics of the basin (Singh et al. 2013). The hydrological observations along with morphometric characteristics give useful clues about geological formations of the basin. Since the basic objective of the paper is to access the hydrological and morphological characteristics

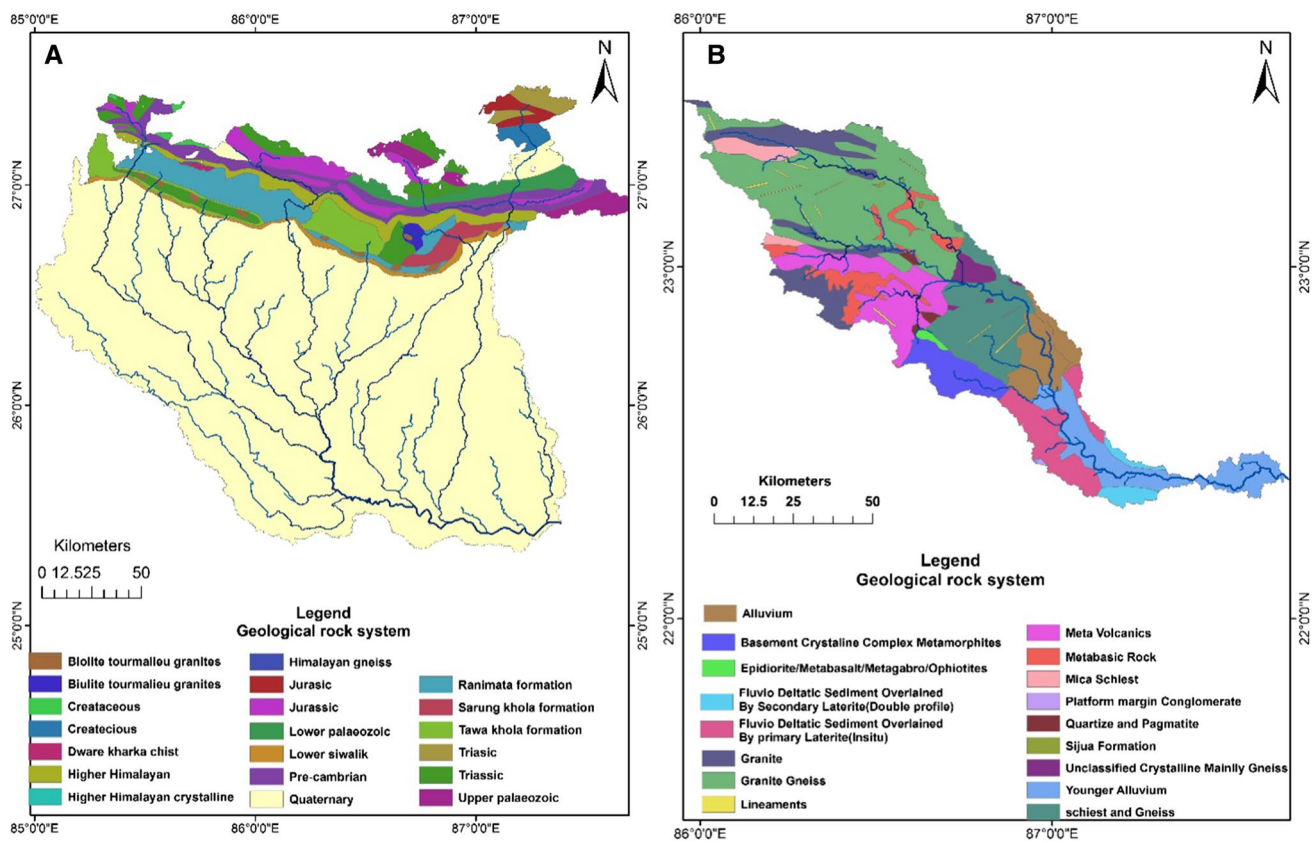


Fig. 2 Geological map of River basin a Kosi and b Kangsabati

of river basin from different morphometric parameters in two different morpho-climatic settings, several morphometric parameters (linear, areal, relief) need to calculate and interpret (Table 1) (Fig. 2). Like, linear aspect (stream order, bifurcation ratio, mean bifurcation ratio, stream length, mean stream length, stream length ratio), areal aspect (stream frequency, drainage density, texture ratio, form factor, circularity ratio, elongation ratio) and relief aspect (relative relief, relief ratio, dissection index, ruggedness index). The different morphometric parameters have been successfully evaluated by remote sensing and GIS (Singh et al. 2013). Georeferenced with precisely orthorectified Global Digital Elevation Model (GDEM) data of ‘Advanced Spaceborne Thermal Emission and Reflection Radiometer’ (ASTER 30 m) has been used for present study. The data have been downloaded from United State Geological Survey (USGS) website. GDEM of ASTER has following parameters:

- Datum name: WGS 84.
- Spheroid name: WGS 84.
- Projection type: Universal Transverse Mercator (UTM).

Both the study area falls under UTM zone of 44. The whole area of two basins covers more than two scenes. The

mosaic tools of ERDAS-IMAGINE 14 have been used for mosaicking and clipping of required area for two different basins. The consecutive topographical sheet of ‘Survey of India’ (SOI) has been georeferenced and used to cross verify the drainage system extracted from ASTER GDEM 30 m data. The different morphometric parameters of linear, relief and areal aspects have been calculated through the use of ASTER GDEM 30 m data with ArcGIS 10.1.

Extraction of Kosi and Kangsabati River watershed

The river basin of Kosi and Kangsabati has been automatically extracted from the ASTER DEM (30 m) through the pour point identification with the various geoprocessing tool of Arc GIS 10.1. The pour point is the user-defined cell of highest flow accumulation within DEM. The extracted drainage basin has been verified through SOI Topo sheet (1: 50,000).

Calculation of drainage morphometry

The different drainage morphometric parameters (linear, areal, relief) have been extracted and calculated through a combination of geoprocessing tools available in Arc GIS

Table 1 Morphometric parameters of a river basin

Morphometric aspects	Parameters	Formulae	Description	References
Linear aspect	Stream order (u)	Hierarchical rank	u has been calculated through the use of Strahler formula in Arc GIS 10.1	Strahler (1964)
	Stream no. (N_u)	N_u = number of streams of a particular order ' u '	N has been calculated for each order (u) through the use of Strahler formula in ArcGIS 10.1	Strahler (1964)
	Bifurcation ratio (R_b)	$R_b = (N_u/N_{u+1})$; where, N_u = number of streams of a particular order ' u ', N_{u+1} = Number of streams of next higher order ' $u+1$ '	R_b has been calculated as the ratio of total number of streams in a given order to its next higher order	Schumm (1956)
	Mean bifurcation ratio (R_{bmn})	R_{bmn} = mean of bifurcation ratios of all orders	R_{bmn} has been calculated as the mean of R_b of all order	Schumm (1956)
	Stream length (L_u)	L_u = total length of streams (km) of a particular order ' u '	L_u has been calculated through the use of Horton formula in ArcGIS 10.1	Horton (1945)
	Mean stream length (L_{um})	$L_{um} = L_u/N_u$; where, L_u = total length of streams (km) of a particular order ' u ', N_u = Total number of streams of a particular order ' u '	L_{um} has been calculated as the ratio of total length of streams of each order (L_u) to its total number of streams (N_u)	Horton (1945)
	Stream length ratio (R_l)	$R_l = L_{um}/L_{um+1}$; where, L_u = mean stream length of a particular order ' u ', L_{u+1} = mean stream length of next higher order ' $u+1$ '	R_l has been calculated as the ratio of L_{um} in a given order to its next higher order	Horton (1945)
	Form factor (F_f)	$F_f = A/L^2$; where, A = area of the basin (km^2), L = basin length (km)	F_f has been calculated as the ratio between the basin area to the square of basin length	Horton (1945)
	Circularity ratio (R_c)	$R_c = 4\pi A/P^2$; where, A = area of the basin (km^2), P = outer boundary of a drainage basin (km)	R_c has been calculated as the area of the basin to the area of circle having the same circumference as the perimeter of the basin	Strahler (1964)
	Areal aspect	Elongation ratio (R_e)	$R_e = P/\pi L$; P = outer boundary of a drainage basin (km), L = basin length (km)	R_e has been calculated as the ratio of diameter of a circle which have same area as that of basin to the total length of basin
Constant of channel maintenance (CCM)		$CCM = 1/D_d$; where, D_d = drainage density	CCM has been calculated with the reciprocal of drainage density	Strahler (1964)
Stream frequency (F_s)		$F_s = N/A$; where, N = total number of streams of a given basin, A = total area of basin (km^2)	F_s has been calculated as the ratio of number of streams per unit area of basin	Horton (1945)
Drainage Density (D_d)		$D_d = L/A$; where, L = length of streams (km), A = Basin area (km^2).	D_d has been calculated as the length of stream channel per unit area of basin	Horton (1945)
Texture ratio (R_t)		$R_t = D_d * F_s$, where, D_d = drainage density (km/km^2), F_s = stream frequency (numbers/ km^2)	R_t has been calculated as the product of drainage density and stream frequency	Smith (1950)
Relative relief (H)		$H = R - r$, where, R = highest relief, r = lowest relief	H has been calculated after maximum vertical range between highest and lowest point of any basin	Schumm (1956)
Relief ratio (R_r)		$R_r = (H/L \text{ max})$; where, H = relative relief (m), L = length of basin (m)	R_r has been calculated after dividing the relative relief to the total length of basin	Schumm (1956)
Dissection index (D_i)		$D_i = H/R$; where, H = absolute relief (m), R = relative relief (m)	D_i has been calculated as the ratio between relative relief to the absolute relief in per unit area of basin	Schumm (1956)
Ruggedness index (R_i)		$R_i = D_d * H/1000$; where, D_d = drainage density, H = relative relief	R_i has been calculated as the product of drainage density and relative relief	Schumm (1956)

10.1. First of all, the drainage network has been extracted through the Strahler's formula where segments with no tributaries identified as a first-order stream. When the two 1st-order stream joins form a 2nd-order stream and so on. The different aspects of drainage morphometry like bifurcation ratio (R_b), mean bifurcation ratio (R_{bm}), mean stream length (L_{um}), stream length ratio (R_l), form factor (F_f), circularity ratio (R_c), stream frequency (F_s), drainage density (D_d), dissection index (D_i), ruggedness index (R_i) have been calculated through the standard formula given in Table 1. The slope characteristics also derived through the spatial analysis tool available in Arc GIS 10.1.

Results and discussion

Drainage morphometric parameters are essential to understand the hydrological and morphological characteristics of any basin (Thomas et al. 2010; Castillo et al. 1988). It is also useful to understand the structural controls of any basin (Sharma and Sarma 2013). The hydro-sedimentary flow regimes are also determined by basin characteristics (Raux et al. 2011). The present study was conducted with the aim of hydrological and morphological understanding from different morphometric parameters in two different morpho-climatic settings. The Kosi basin which is representative of the mountain–plain humid environment has tertiary Himalayan geology in upper reaches, and recent sediment deposited Gangetic plain areas in lower reaches of basin. Kosi is highly notorious due to its high sediment load and migratory trends with antecedent river characteristics. Failure of Kosi embankment and changes in avulsion characteristics are major concerns of recent past. This phenomenon can be interpreted through the local geological adjustment, plate motions, geotectonic, etc., (Arogyaswamy 1971; Agarwal and Bho 1992) whereas Kangsabati river basin which is representative of plateau–plain sub-humid environment falls under Archaean Gneiss and Schist geological formations in upper reaches. The middle and lower reaches are dominated by laterite and alluvial deposition, respectively. As Kangsabati flows through the eastern Chotanagpur plateau which is sub-humid characteristics, it remains dry in most of the times (Raux et al. 2011). The different hydrological and morphological characteristics about the different morphometric parameters have discussed below-

Linear aspects of River basin morphometry

Stream order (N_u) treated as the first step of drainage analysis based on the hierarchical ranking of streams. Strahler (1964) invented ordering method has been selected for the present study. According to Strahler (1964), the smallest fingerprint tributaries numbered as 1st order. The 2nd order of stream

forms where two 1st-order streams join. A 3rd-order stream forms when two 2nd-order streams join and so on. The main channel through which most of water discharged marked as highest order stream of any particular drainage basin. This stream order depends on basin shape, size and relief characteristics of such basin (Haghipour and Burg 2014). Most studies indicate the increasing order of streams in the mountain–plain humid environment than plateau–plain sub-humid environment (Wakode et al. 2013). The total number of streams of Kosi basin are 10,591 of which 5315 (50.2%), 2449 (23.1%), 1338 (12.6%), 768 (7.8%), 551 (5.2%), 71 (0.7%) and 99 (0.9%) streams belongs to 1st, 2nd, 3rd, 4th, 5th, 6th, and 7th order, respectively (Table 2) (Fig. 3). Lower order streams are in higher number due to its upper mountain course. Also, higher number of streams in upper reaches indicates the occurrence of young topography adjacent to the stream concerned. The sudden decrease in 3rd and 4th order of streams indicates its major morphological change. Higher number of streams throughout the different orders indicates its high erosion characteristics. It is proved from high sediment load of Kosi river basin. The high number of lower order streams (1st, 2nd and 3rd order) increase the amount of water received which ultimately creates huge water flux in lower reaches of basin, whereas Kangsabati basin has total 1216 number of streams of which 609 (50.1%), 279 (22.9%), 152 (12.5%), 68 (5.6%), 25 (2.1%) and 83 (6.8%) number of streams belongs to 1st, 2nd, 3rd, 4th, 5th and 6th order, respectively (Table 2) (Fig. 3). The consistent decrease in number of streams in relation to stream order (N_u) (except 5th order) throughout the basin indicates the dominance of erosional landform throughout the basin. The lower number of streams in 1st, 2nd and 3rd order indicates its mature topography adjacent to the stream concerned. Higher order streams (4th, 5th, 6th order) are less in number due to its alluvial deposited plain course. The lower number of streams in upper reaches and consistent number of streams (except 5th order) throughout the basin indicates its lower water regimes and water stress condition.

Bifurcation ratio (R_b) expresses the ratio of number of streams of a given order (u) to its next higher order ($u + 1$) (Horton 1945). Strahler (1952) indicates that without strong controls of geological formation, the R_b shows only small variation in different regions. It is considered an important parameter, denoting the water carrying capacity and related flood potentiality of any basin. The value normally ranges from 2 to 5 (Joji et al. 2013). Studies identified high R_b values in mountain–plain areas than plateau–plain fringe areas of tropical environment due to its young morphological adjustment and high water pressure (Kim and Jung 2015). The bifurcation ratio for different order of streams in Kosi basin is 2.17 for 1st to 2nd, 1.83 for 2nd to 3rd, 1.74 for 3rd to 4th, 1.39 for 4th to 6th, 7.76 for 5th to 6th, 0.71 for 6th to 7th, respectively (Table 2). The values of R_b in Kosi basin

Table 2 Linear morphometric aspects of river basins

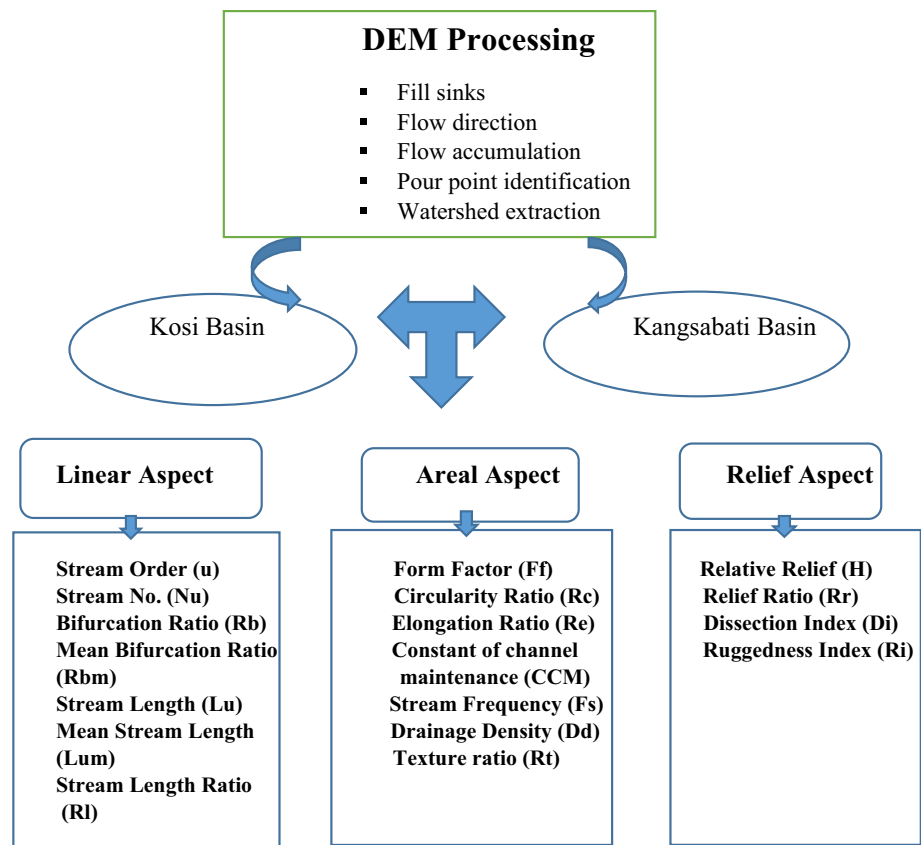
Morphometric parameters	Kangsabati Basin						Kosi Basin						
	I	II	III	IV	V	VI	I	II	III	IV	V	VI	VII
Stream no (N_u) (%)	609 (50.1)	279 (22.9)	152 (12.5)	68 (5.6)	25 (2.1)	83 (6.8)	5315 (50.2)	2449 (23.1)	1338 (12.6)	768 (7.3)	551 (5.2)	71 (0.7)	99 (0.9)
Bifurcation ratio (R_b)	–	2.18	1.83	2.23	1.30	0.30	–	2.17	1.83	1.74	1.39	7.76	0.71
Mean bifurcation ratio (R_{bm})	1.56	2.6											
Stream length (L_u) in km	1559	790	350	154	62	194	12,396	6595	3463	1756	1327	162	216
Mean stream length (L_{um})	2.55	2.83	2.30	2.26	2.48	2.33	2.33	2.69	2.59	2.29	2.41	2.28	2.18
Stream length ratio (R_l)	–	0.90	1.23	1.01	0.91	1.06	–	0.86	1.04	1.13	0.95	1.06	1.04

are indicative of inconsistency in morphological adjustment (as the R_b values are not consistent throughout the different order). The irregularities are due to strong geological and lithological controls of the basin. Also, high bifurcation ratio in higher order streams indicates large amount of water received in upper basin area. But low R_b and related lower number streams in lower reaches increase water pressure. The frequent flood characteristics of Kosi river support this phenomenon, whereas the R_b values of Kangsabati river basin are 2.18 for 1st to 2nd, 1.83 for 2nd to 3rd, 2.23 for 3rd to 4th, 1.30 for 4th to 5th and 0.30 for 5th to 6th order streams (Table 2). The consistency of R_b values throughout the basin and low average bifurcation ratio is indicative of mature geomorphological adjustment. Low mean R_b is also indicative of water stress condition for river basin. A constant decrease of R_b throughout the different stream order as well as low mean R_b (1.56) indicates low flood potentiality for the basin.

Stream length (L_u) is calculated according to law proposed by Horton (1945). It indicates the successive stage of stream segment development (Castillo et al. 1988). A direct geomorphic and hydrological sequence can approximate from different order stream lengths. Generally, the total length of streams is maximum in 1st order, and L_u decreases as stream order increases. The irregularities in this trend are indicative of discrepancies in lithology. Studies suggest high stream length in mountain–plain front than plateau–plain front river basin (Vittala et al. 2004; Sreedevi et al. 2005). The stream length for different orders of the Kosi basin in 1st (12,396 km), 2nd (6595 km), 3rd (3463 km), 4th (1756 km), 5th (1327 km), 6th (162 km), and 7th order (216 km) (Table 2). The irregularities of stream length between 6th and 7th order indicates geological and morphological control on river basin. Irregularities are also indicative of lithological inconsistency of drainage basin whereas the L_u values of plateau–plain front Kangsabati basin in 1st (1559 km), 2nd (790 km), 3rd (350 km), 4th (154 km), 5th (62 km) and 6th (194 km) (Table 2). The low length of streams in upper reaches and consistency of stream length throughout the basin is indicative of mature to old geological formation and sufficient morphological adjustment throughout the basin.

Mean stream length (L_{sm}) is the characteristics property of drainage network and associated surface according to Strahler (Strahler 1964). It is an important dimensionless morphometric characteristic calculated by dividing the total length of streams of a given order (u) to the total number of streams (N_u) of such order. In general, the ratio of L_{sm} increases with increasing order of streams (Shrestha et al. 2010). Most of the studies indicate low L_{sm} value in mountain environment than plateau or plain morphology (Rai et al. 2017). The mean L_{sm} ratio of Kosi basin in 1st (2.33 km), 2nd (2.69 km), 3rd (2.59 km), 4th (2.29 km), 5th (2.41 km), 6th (2.28 km) and for 7th order (2.18 km)

Fig. 3 Flow diagram of methodology for River basin morphometric analysis



(Table 2). Low L_{sm} values in the upper reaches of the Kosi basin indicate young morphological development and high erosion potentiality. The mean stream length for higher order, e.g. 2nd order and above (except 4th and 6th order), is greater for Kosi basin is due to the fact that higher order streams completed their channel lengthening, whereas 1st order streams need times for extending its length. The fact indicates young stage of geomorphic development of Kosi basin. The anomalies in L_{sm} throughout the different orders suggesting slope changes and changes in the geological set up which in turn denotes abrupt changes in flow characteristics. This has also brought discrepancies of surface flow discharge and sedimentation. The mean stream length for Kangsabati basin in 1st (2.55 km), 2nd (2.88 km), 3rd (2.26 km), 4th (2.48 km), 5th (2.33 km), respectively (Table 2). The low value of L_{sm} for higher order streams, i.e. 2.26 km for 3rd order or 2.33 km for 5th order, is due to the fact that the streams fall within these order has stopped their channel lengthening much before than the lower order streams. Relatively higher L_{sm} values (1st and 2nd order) in upper reaches of Kangsabati are indicative of low erosion potentiality which in turn denotes old erosional landform development. The consistency of L_{sm} values throughout the basin and higher average L_{sm} values is indicative of mature geomorphological adjustment and low flood regimes.

Stream length ratio (R_l) is the ratio between mean stream lengths of one order to the next higher order. Generally, it tends to be similar throughout the different orders. Mean stream length segment of each successive order of basin tends to direct geometric series with stream length increasing towards higher order according to Horton (Horton 1945). Studies suggest mountain–plain front river basin have irregular tendency of stream-length ratio than regular plateau fringe river basin (Magesh and Chandrasekhar 2014). The stream length ratio of Kosi basin starts with 0.86 for 1st to 2nd order, 1.04 for 2nd to 3rd order, 1.13 for 3rd to 4th order, 0.95 for 4th to 5th order, 1.06 for 5th to 6th order and 1.04 for 6th to 7th order (Table 2). The changes in stream length ratio denote that the area is in early stage of geomorphic development, and the area has the high potentiality of frequent changes in near future. This is also indicative of irregular hydrological behaviour, whereas the R_l values Kangsabati basin is 0.90 for 1st to 2nd, 1.23 for 2nd to 3rd, 1.01 for 3rd to 4th, 0.91 for 4th to 5th and 1.06 for 5th to 6th order of streams, respectively. The R_l value for each order of Kangsabati basin is higher than Kosi basin. This is indicative of younger stage of geomorphic development for Kosi basin than Kangsabati basin. The R_l of Kangsabati basin is indicative of late young stage of geomorphic development as well as low water regimes. The low difference

of R_1 values in 1st to 2nd order for Kosi and Kangsabati basin is due to their geomorphic controls. In other words, like Kosi basin, Kangsabati basin faces more or less same geomorphic constraints in channel lengthening in its upper order (1st and 2nd order).

Areal aspects of River basin morphometry

Stream frequency (S_f) is the total number of stream segments irrespective of the order in per unit area (Horton 1945). It may also define as the ratio between the total number of stream segment cumulative of all orders and the basin area. It may be possible to have different stream frequency, through the basin has same drainage density. Stream frequency is related to permeability, infiltration capacity and relief of the basin. It provides drainage basin response to runoff processes. Stream frequency depends on the rainfall, relief, initial resistivity of rocks as well as drainage density of the basin. The lower value of S_f indicates poor drainage network (Thomas et al. 2010). High slope and greater rainfall increase stream frequency (S_f) in mountain areas, whereas low permeability and less available surface flow decrease the S_f value in plateau environment (Bali et al. 2011). Stream frequency of mountain–plain front Kosi river basin is 0.27 (number/km²), which can categorise as a moderate stream frequency (Table 3). The higher S_f values in upper reaches indicate high slope and lower permeability. But the plain course of lower basin area shows low S_f due to less available relief, the plateau–plain front Kangsabati basin shows very low S_f as it is 0.17 (number/km²). The low S_f value of Kangsabati river basin is indicative of lower permeability of rock, less relief and low slope in plateau environment. Also semi-humid environment, low relative relief helps for lower S_f in Kangsabati basin.

Drainage density (D_d) is the expression of the closeness of spacing of channel within a basin as per Horton (1945). As it provides a numerical measurement of runoff potentiality and landscape dissection, D_d is the important indicator of landform element. D_d measures as the ratio of the total length of streams irrespective of stream order to the per unit area of the basin. It ranges from 0.55 to 2.09 km/km² in humid region (Joji et al. 2013). D_d considers as an important parameter determining the travel time of water.

The capability of any basin to drain is depended upon the drainage density of such area. Drainage density itself depends upon underlain geology, relief, geomorphology, climate, vegetation, etc. of that basin. The amount and types of precipitation determined D_d value directly. Studies suggest high drainage density in mountain environment due to impermeable surface materials, sparse vegetation and high relief, whereas plateau environment bears low D_d due to high infiltration and low relief (Magesh and Chandrasekhar 2014; Parveen et al. 2012). The overall drainage density of Kosi river basin is 0.67 (km/km²) (Table 3). It shows a direct relationship between drainage frequency and drainage density. High drainage density in upper reaches of Kosi basin indicates less permeable rock in bed surface, high slope and high water flow regimes (Fig. 4). Very low D_d is observed in lower reaches plain areas of the basin due to low relief and high permeability. Thus, higher runoff with greater flow velocity results in potentiality of downstream flooding in the basin, whereas for Kangsabati basin, the overall D_d is 0.43, which is very low (Fig. 4) (Table 3). Low D_d is indicative of low relief, low slope, high infiltration capacity and low water regimes throughout the basin.

Texture ratio (R_t) is the product of stream frequency and drainage density (Horton 1945). R_t can also be defined as the ratio between total numbers of stream segments to the perimeter of the basin. Infiltration capacity is the single important factor influencing texture ratio recognised by Horton. It is also an important fluvial parameter which denotes the relative spacing of drainage network of any basin. R_t depends upon numbers of natural factors like the amount of rainfall, density of vegetation, soil types, infiltration capacity, stages of geomorphic development and relief (Smith 1950). Collectively drainage density and drainage frequency can be called drainage texture. The R_t values of <2 indicate very coarse, 2–4 coarse, 4–6 moderate, 6–8 fine, > 8 very fine drainage texture (Smith 1950). The texture ratio of mountain–plain environment Kosi basin is 7.60, which indicates coarse drainage texture (Table 3). The values indicate low infiltration capacity, less permeability of rock and high relief and sparse vegetation. The R_t values of Kosi basin are also indicative of high water regimes, whereas the R_t of Kangsabati basin is very low as 1.65 (Table 3). The value indicates low rainfall, high infiltration, low relief in Kangsabati basin.

Form factor (F_f) is the ratio of the area of the basin to the square of basin length (Horton 1932). The value of F_f is always less than 0.7854 (for a perfectly circular basin) (Bali et al. 2011). Smaller the value of F_f , more elongated is the basin. The value ‘0’ indicates elongated characteristics of basin and ‘1’ indicates near-circular characteristics of basin with high peak flow. It indicates the flow characteristics of a basin (Castillo et al. 1988). Higher the value of F_f , more circular is the basin which indicates high peak flow in shorter duration, whereas lower the value of F_f , more elongated is

Table 3 Areal morphometric aspects of river basins

Relief aspect	Kosi Basin	Kangsabati Basin
Absolute relief (R)	3597	659
Relative relief (H)	3588	657
Relief ratio (R_r)	0.012	0.0028
Dissection index (D_i)	0.990	0.996
Ruggedness index (R_i)	2.40	0.282

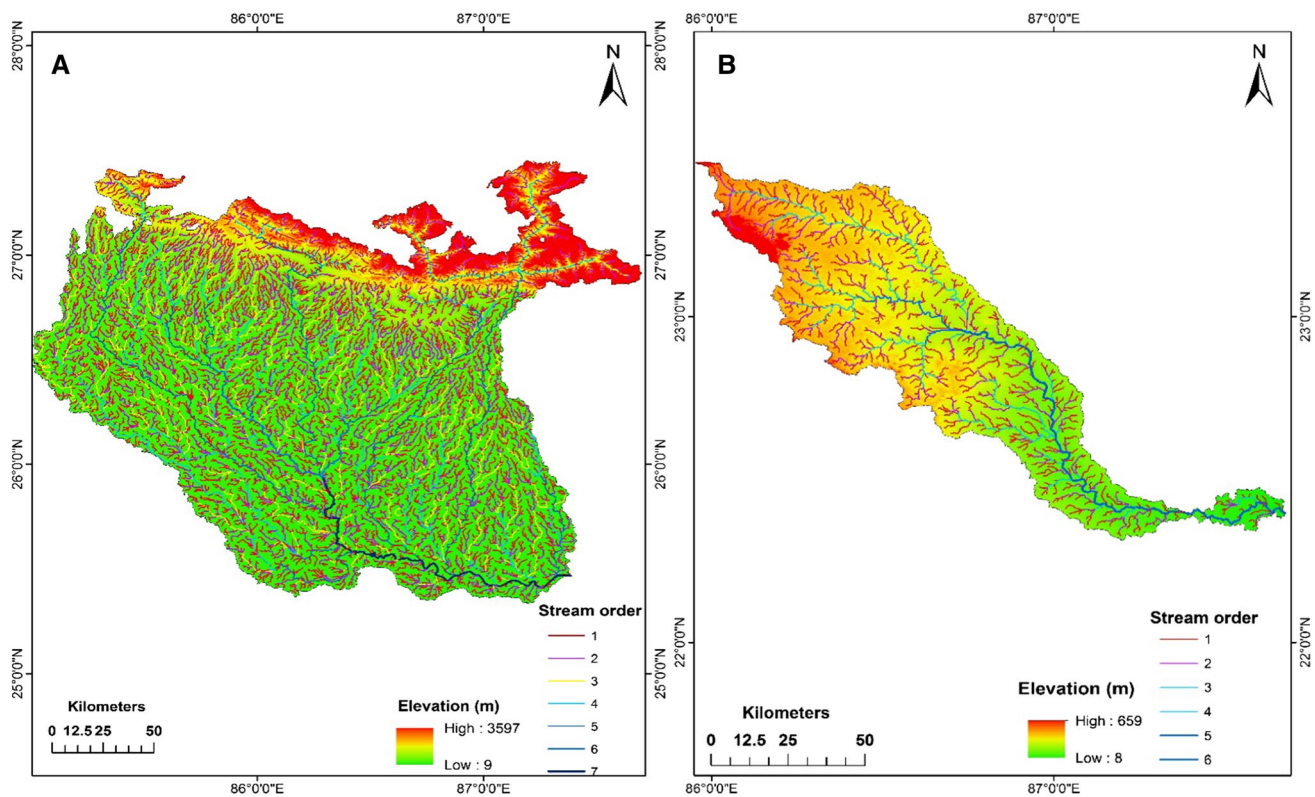


Fig. 4 Linear aspects of River basin morphometry **a** Kosi and **b** Kangsabati

the basin which indicates low peak flow with longer duration (Bali et al. 2011). Flood flows of elongated basin can be easily managed than that of circular basin. Mountain–plain front river basin tends to form circular basin than plateau–plain front river basin. The F_f value of Kosi basin is 0.45, which indicates the basin is near-circular (Table 3). It also indicates higher peak flow in limited times. This phenomenon has been proved by its recent embankment failure and frequent flood characteristics (Sinha et al. 2008). Large basin area with near-circular shape helps Kosi to become an important flood-prone basin in India (Sinha 2009), whereas the F_f value of plateau–plain front Kangsabati basin is 0.12. It indicates its elongated shape with less peak flow. Comparatively small basin area and elongated shape of Kangsabati basin indicate lower water regimes of Kangsabati river basin. This phenomenon has been supported as the basin comes under semi-humid areas of tropical India.

Elongation ratio (R_e) is the ratio of the diameter of a circle having the same area as of basin to the maximum basin length (Schumm 1956). It is also a significant index of basin shape (Gayen et al. 2013). The value of R_e varies from ‘0’ (maximum elongated) to near ‘1’ (maximum circularity). The R_e values of near ‘1’ indicate that there are less geomorphological controls on river basin (Strahler 1964). The mountain–plateau front humid environment river basin tends to form less elongated river basin than

plateau–plain front river basin of sub-humid environment (Chen et al. 2013). It also helps to give the idea about hydrological character of a drainage basin. The elongated basin has a low peak discharge. The R_e value of the Kosi basin is 1.52, which denotes perfect circular characteristics of the basin (Table 3) (Fig. 1). The R_e values of Kosi indicate its high flood characteristics and high peak flow. The R_e value of Kangsabati basin is 1.00, which indicates its elongated characteristics (Table 3, Fig. 1). This value is indicative of lower flood regimes and mature geomorphological adjustment for Kangsabati basin.

Circularity ratio (R_c) is defined as the ratio between the area of the basin to the area of a circle having the same perimeter (Strahler 1964). Value of R_c varies from ‘0’ (minimum circularity) to ‘1’ (Maximum circularity). Cr values depend upon stream frequency, drainage density, climate, geological structure, slope, relief, etc. of any basin. The higher circular basin will affect by peak discharge in high rainfall season. It is an indicative value determined the geomorphological stages of development of any basin. The high, medium and low value of R_c is indicative of old, mature and young stages of geomorphological adjustment of any basin. Generally, the mountain–plain front river basin of world tends to form circular basin due to its young morphological adjustment, whereas plateau–plain front river basin forms elongated basin in response to mature morphological

adjustment (Vittala et al. 2004; Thomas et al. 2010). The R_c value of the Kosi basin is 0.25, which indicates its near-circular characteristics (Table 3). It also indicates neo-tectonic upliftment and high peak flood runoff in monsoon season. The R_c value for plateau–plain front Kangsabati basin is 0.16, which indicates elongated characteristics. It also refers to mature geomorphological adjustment and less peak flow characteristics.

Constant of channel maintenance (CCM) is defined as the reciprocal of drainage density as property to define overland flow (Schumm 1956). Indirectly, it can be expressed as a required minimum area for the maintenance and development of a channel (Dutta and Roy 2012). CCM is expressed in km^2/km . The lower value of CCM indicates higher flood potentiality and young geomorphological adjustment. Mountain environment generally has low CCM values due to lower infiltration of bare soil and high overland flow. On the other hand, plateau–plain environment tends to high CCM value due to low drainage density and high infiltration in comparison to plateau–plain environment. The CCM value of the Kosi basin is 1.49 (Table 3). It indicates less channel availability to drain out the excess amount of water and low infiltration capacity of soil. All these ultimately indicates high flood potentiality. The CCM value for Kangsabati basin is 2.27, which indicates high infiltration capacity, low drainage density and mature geomorphological adjustment.

Relief aspects of River basin morphometry

Basin relief (R , H) includes absolute relief (R) and relative relief (H). The maximum relief of any basin and the maximum altitudinal difference is termed as absolute and relative relief, respectively. These are general morphometric parameters used to understand the morphological characteristics of basin (Raux et al. 2011). Basin relief depends upon the underlain geology, geomorphology and drainage characteristics of the region. It is the best indicator of erosional stages of any river basin. Normally, the mountain–plain front river basin has higher basin relief than plateau–plain front river basin (Thomas et al. 2010). The highest relief of Kosi basin is 3597 m., which found near upper reaches of Himalayan peak (Table 4). The relative relief is 3588 m., which seems very high for erosional activity. Basin relief characteristics of Kosi basin are indicative of young stages of geomorphic development and huge potentiality for further erosion. The abrupt changes of basin relief in mountain–plain conjunction of Kosi river basin are indicative of prone to geomorphological hazards. On the other hand, the R and H value for Kangsabati is as low as 659 and 657, respectively. The basin relief characteristics of Kangsabati basin are indicative of dissected erosional landform and mature stages of geomorphological evolution (Parveen et al. 2012; Rai et al. 2017).

Table 4 Relief morphometric aspects of River basins

Areal aspect	Kosi Basin	Kangsabati Basin
Basin perimeter (P) (km)	1392	736
Basin area (A) (km^2)	38,689	7073
Form factor (F_f)	0.45	0.12
Circularity ratio (R_c)	0.26	0.16
Elongation ratio (R_e)	1.52	1.00
Compactness constant (C_c)	2.00	2.46
Constant of channel maintenance (CCM)	1.49	2.27
Stream frequency (S_f)	0.27	0.17
Drainage density (D_d)	0.67	0.43
Texture ratio (R_t)	7.60	1.65

Relief ratio (R_r) denotes the ratio between total reliefs to the length of the principal drainage line (Lindsay and Seibert 2013). The R_r value depends upon different factors of areal and relief characteristics of basin. The high basin relief, circular basin shape, small basin area increase the R_r value of any basin. It indicates the overall steepness of the drainage basin and related degradation processes (Schumm 1956). The R_r values generally higher in mountain environment than plateau river basin (Thomas et al. 2010). The R_r value of Kosi basin is 0.012, which falls under moderate category (Table 4). Though Kosi River has originated from Himalayan Mountain, most of basin area falls under lower relief plain area causes low R_r value. This value also indicative of high overland flow. The R_r value for Kangsabati basin is as low as 0.0028. This very low R_r value of Kangsabati basin is indicative of elongated basin shape, low basin relief as well as maximum denudation stages of geomorphic evolution.

Dissection index (D_i) is defined as the ratio between relative reliefs to its absolute relief. It indicates the vertical erosion and dissected characteristics of a basin (Haghipour and Burg 2014). The value of D_i ranges between ‘0’ (absence of vertical dissection) to ‘1’ (Vertical areas). D_i values near to ‘0’ indicate maximum denudation stages of evolution and near ‘1’ indicates minimum denudation stages of geomorphic evolution. Mountain basins have relatively higher D_i values in comparison to plateau–plain river basin (Waikar and Nilawar 2014). The D_i value of Kosi basin is 0.99, which indicate its young or rejuvenated stage of geomorphic development and minimum denudation stage (Table 4). It is also indicative of its further potentiality of erosion. Though the D_i value of Kangsabati basin shows near ‘0.9’, Kangsabati has mature denudation stages of evolution.

Ruggedness index (R_i) is defined as the product of drainage density and relative relief. The high value of R_i occurs when both drainage density and relative relief are high (Ansari et al. 2012). The ruggedness index depends upon

underlain geology, geomorphology, slope, steepness, vegetation cover, climate, etc. of that region. The higher R_i value of any area indicates that the area is in primary stage of geomorphic development or denudation activity. Studies suggest mountain environment basin have higher R_i than plateau river basin (Parveen et al. 2012). The high value of R_i (2.40) for Kosi basin indicates its youthful or rejuvenated stage of geomorphic development (Table 4). The R_i value of Kangsabati is as low as 0.282. Very low R_i value of Kangsabati river basin is indicative of mature and maximum denudation stages of erosion. This phenomenon is supported by its granite–gneiss and schist geology, rolling plateau fringe landform characteristics.

Channel gradient ratio can be defined as changes in vertical inclination in per unit area changes of horizontal distance. It is an indication of the stages of geomorphic evolution as well as its potentiality for further erosion. The high channel gradient is seen in the mountainous course of river and least in plain course of river (Sreedevi et al. 2005). The Kosi River is almost vertical from source region up to Himalayan foothill areas in its upper reaches (Fig. 1), whereas, it is near horizontal from Himalayan foothills up to river mouth in its plain course. Such types of gradient characteristics have the potentiality of frequent flooding and

consequent embankments failure, whereas Kangsabati River which flows through the eroded eastern Chotanagpur plateau indicates constant channel gradient decline throughout its main course.

Slope (Θ) is an important morphometric parameter controlled by morpho-climatic processes of any area underlain by varying resistance of rock surface. As slope determines the infiltration vs runoff relation, it is important to understand the nature of slope in any region. Infiltration capacity is inversely related to the slope. The very high slope ($> 40^\circ$) dominated upper reaches of Kosi basin is the indication of low infiltration related high drainage density and frequency (Figs. 5, 6) (Table 4). It also indicates primary stages of geomorphic evolution. But slope dramatically decreases as Kosi enters in foothill plain areas. This typical slope characteristic developed intense flood characteristics as well as specific geomorphic landforms like alluvial fan, etc., whereas slope of Kangsabati river basin is low ($< 10^\circ$) throughout the basin, indicates high infiltration and low drainage density characteristics (Figs. 5, 6) (Table 4). This is also indicative of its mature topographical development.

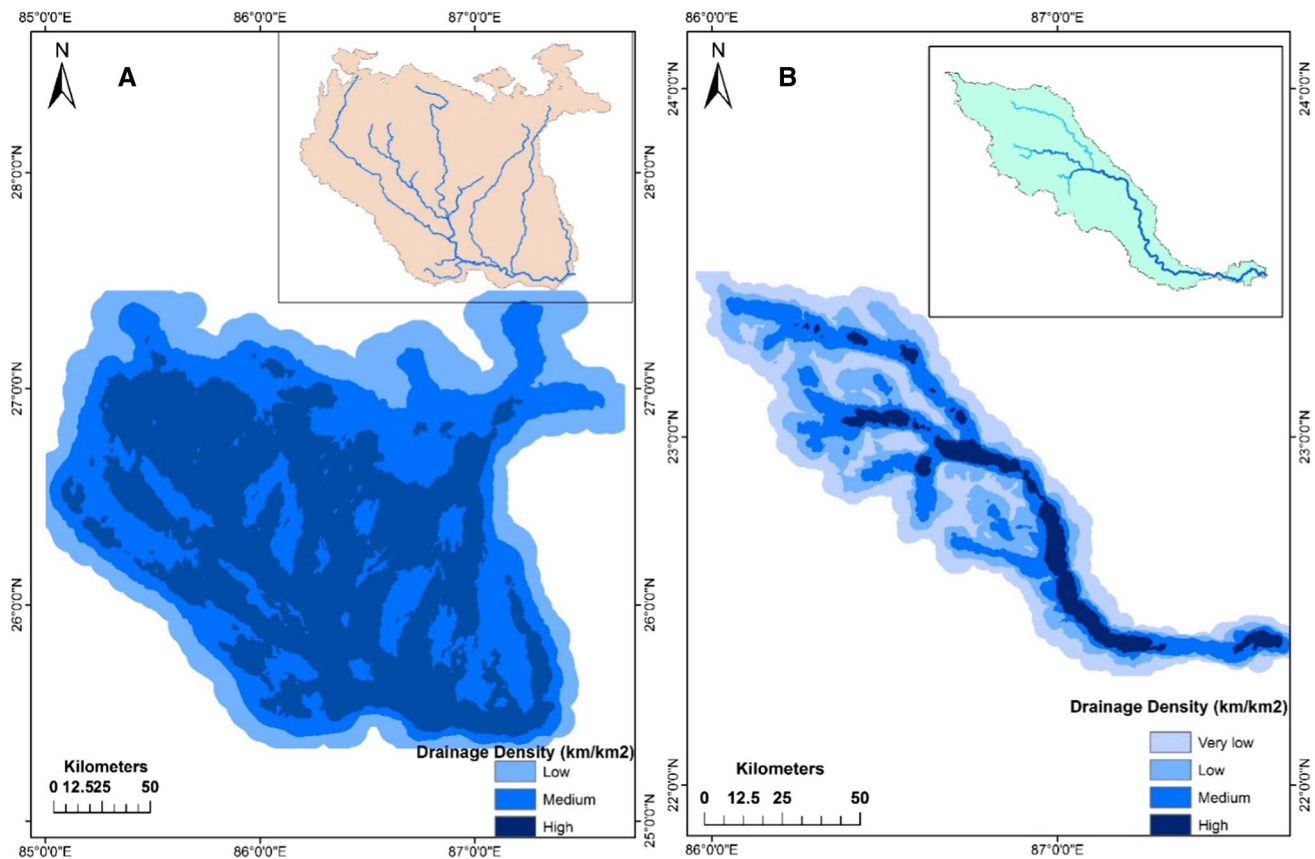


Fig. 5 Drainage density characteristics of River basins **a** Kosi and **b** Kangsabati

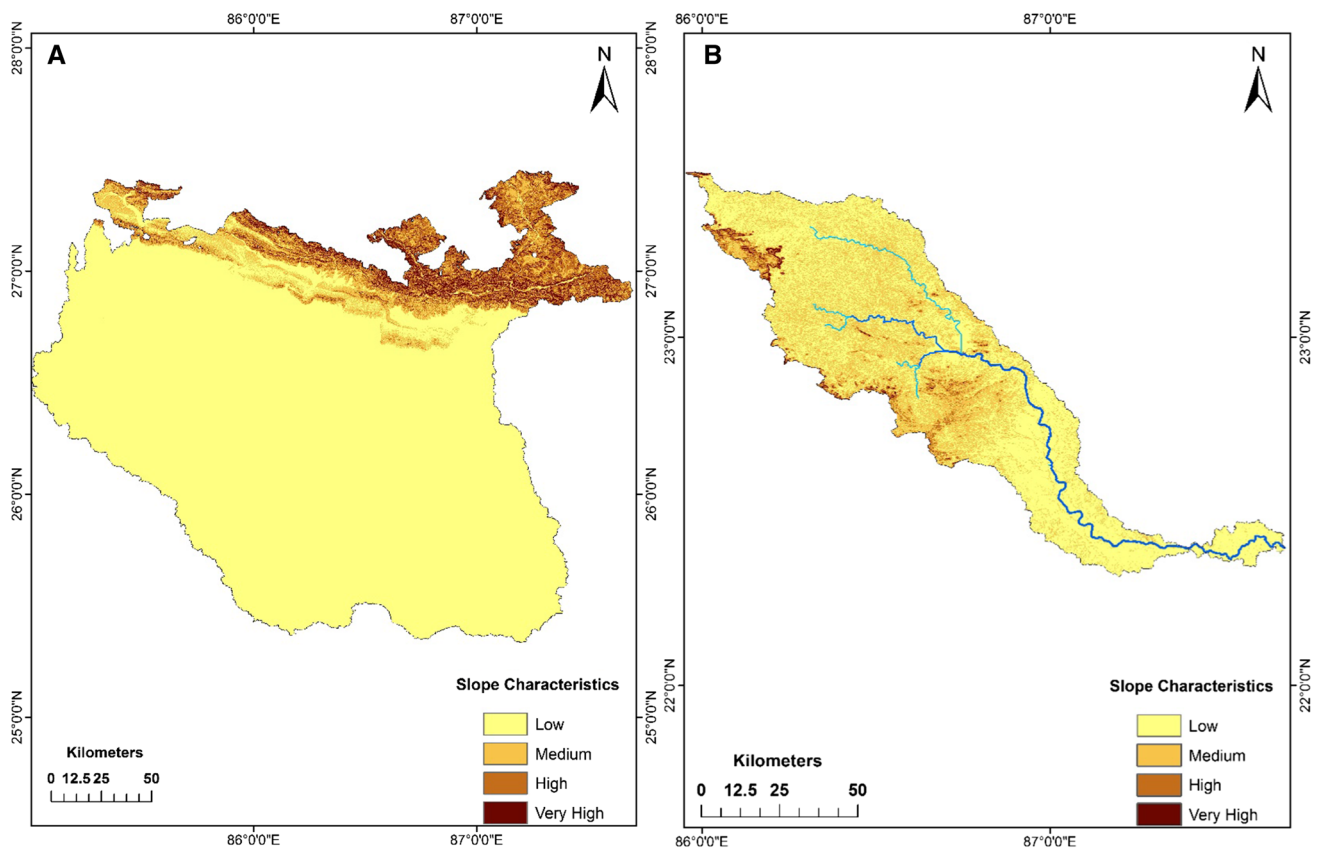


Fig. 6 Slope characteristics of River basins **a** Kosi and **b** Kangsabati

Conclusion

The different morphometric parameters of a basin are the best representative of underlain geology, geomorphology, relief, slope, climate as well as hydrological dynamics. The parameter also indicates stages of geomorphic evolution of any area. Morphometry plays an important role in basin-level construction and flood control planning. The present study tries to unearth the morphological and hydrological characteristics from different morphometric parameters as well as changes of morphometric parameters in different morpho-climatic settings. The Kosi basin which is representative of the mountain–plain humid tropical environment has highest number stream order (up to VIIth order) related with large amount of water discharge and low-velocity flow. It indicates the basin is highly susceptible to flooding. Rapid decline of bifurcation ratio with increasing order as well as irregular nature of R_b values bear the indication of geological unconformity and high susceptibility to flooding. The irregular changes of stream length of Kosi River basin throughout the different order indicate the younger or rejuvenated stage of river basin development, whereas Kangsabati basin which is representative of the plateau–plain sub-humid tropical environment has lower number of stream order indicates low

susceptible to flooding. The constant decline of R_b values with increasing stream order is characteristics of sub-humid region of tropical environment. The low mean value of R_b is also indicative of low flood susceptible water stress region. Medium mean stream length and regular changes of stream length ratio are also indicative of mature stages of geomorphic development in Kosi river basin. The areal morphometric characteristics of Kosi basin indicate large amount of water discharge and peak flow in less available time. These are also indicative of younger stages of geomorphic development in the mountain–plain environment, whereas the areal morphometric characteristics of plateau fringe Kangsabati basin indicates low overland flow and low flood regimes. This is also evidence of its mature geomorphic development. Old geomorphic development, highly dissected topography and pre-Cambrian geological formation is also get justified by its areal morphometric characteristics. The relief characteristics of Kosi basin supports young stages of geomorphic development and rejuvenated morphological characteristics in mountain–plain front. The geomorphic and hydrological instability is more common in high relief areas, whereas relief morphometric characteristics of Kangsabati river basin indicate late mature stages of geomorphic development and maximum denuded landform cover.

After crosschecking the results from field verification and related literature, the study concludes that drainage morphometric parameters have the huge potentiality to unveil the hydro-morphological characteristics of any river basin. The study concludes that morphometric characteristics of any region can successfully reveal the hydrological and morphological characteristics. There is sufficient difference among different morphometric parameters in different morpho-climatic regions. In other words, drainage morphometry has the sufficient ability to differentiate morpho-climatic areas of the world through its different values. Remote sensing and GIS can successfully use for accessing the drainage morphometric characteristics. The results can be used for sufficient hydrological and morphological planning for such areas.

Acknowledgements The author is currently working under the PhD programme of Jawaharlal Nehru University. The work has been conducted under NET-JRF program of University Grants Commission (UGC). The author is also thankful to his supervisor Dr. Padmini Pani (Associate Professor, CSRD, JNU) for continuous guidance and support.

Compliance with ethical standards

Conflict of interest The corresponding author states that there is no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Agarwal RP, Bho R (1992) Evolution of Kosi river fan, India: structural implications and geomorphic significance. *Int J Remote Sens* 13(10):1891–1901
- Ansari ZR, Rao LA, Yusuf A (2012) GIS based morphometric analysis of Yamuna drainage network in parts of Fatehabad area of Agra District, Uttar Pradesh. *J Geol Soc India* 79:505–514
- Arogyaswamy RNP (1971) Some geological factors influencing the behavior of the Kosi. *Rec Geol Surv India* 96:42–52
- Bali R, Agarwal KK, Ali SN, Rastogi SK, Krishna K (2011) Drainage morphometry of Himalayan Glacio-fluvial basin, India: hydrologic and neotectonic implications. *Environ Earth Sci* 66(4):1163–1174
- Castillo V, Diazsegovia A, Alonso SG (1988) Quantitative study of fluvial landscapes, case study in Madrid, Spain. *Landscape Urban Plan* 16:201–217
- Chavare S, Potdar M (2014) Drainage morphometry of Yerla River Basin using geoinformatics techniques. *Neo Geogr* 3(3):40–45
- Chen NS, Hu GS, Deng W, Khanal N, Zhu YH, Han D (2013) On the water hazards in the trans-boundary Kosi River basin. *Nat Hazards Earth Syst Sci* 13:795–808
- Chorley RJ, Schumm SA, Sugden DE (1985) *Geomorphology*. Methuen and Co., Ltd., London
- Clarke JJ (1966) *Morphometry from map. Essays in geomorphology*. Elsevier, New York, pp 235–274
- Dutta S, Roy S (2012) Determination of erosion surfaces and stages of evolution of Sangra drainage basin in Giridih district, Jharkhand, India. *Int J Geomat Geosci* 3(1):63–73
- Eckblod JW, Peterson NL, Ostile K (1997) The morphometry, benthos and sedimentation rates of a floodplain lake in pool of the Upper Mississippi River. *Am Midl Nat* 97(2):433–443
- Gayen S, Bhunia GS, Shit PK (2013) Morphometric analysis of Kangsabati–Dwarakeswar interfluvies area in West Bengal, India using ASTER DEM and GIS techniques. *Geol Geosci* 2(4):1–10
- Ghosh AK (2009) Changing geomorphology of the Kosi River system in the Indian subcontinent. Association of American Geographers, Washington
- Golekar RB, Baride MV, Patil SN (2013) Morphometric analysis and hydrogeological implication: Anjani and Jhiri river basin Maharashtra, India. *Arch Appl Sci Res* 5(2):33–41
- Haghipour N, Burg JP (2014) Geomorphological analysis of the drainage system on the growing Makran accretionary wedge. *Geomorphology* 209:111–132
- Horton RE (1932) *Drainage basin characteristics*, 2nd edn. transactions, American Geophysical Union, New York
- Horton RE (1945) Erosional development of streams and their drainage basins: hydro physical approach to quantitative morphology. *Bull Geol Soc Am* 56:275–370
- Jain V, Sinha R (2008) Geomorphological manifestations of the flood hazard: a remote sensing based approach. *Geocarto Int* 18(4):1752–1762
- Joji VS, Nair AS, Baiju KV (2013) Drainage basin delineation and quantitative analysis of Panamaram Watershed of Kabani River Basin, Kerala using remote sensing and GIS. *J Geol Soc Ind* 82:368–378
- Kim JC, Jung K (2015) Fractal tree analysis of drainage patterns. *Water Resour Manag* 29:1217–1230
- Lindsay JB, Seibert J (2013) Measuring the significance of a divide to local drainage patterns. *Int J Geogr Inf Sci* 27(7):1453–1468
- Mahala A (2017) Processes and status of land degradation in a plateau fringe region of tropical environment. *Environ Process* 4(3):663–682
- Mahala A (2018) Identifying the factors and status of land degradation in a tropical plateau region. *GeoJournal* 84(5):1199–1218
- Magesh NS, Chandrasekhar N (2014) GIS model-based morphometric evaluation of Tamiraparani sub basin, Tirunelveli district, Tamil Nadu, India. *Arab J Geosci* 7:131–141
- Morisawa M (1985) *Rivers-forms and process*. Longman Group, London
- Nag SK, Lahiri A (2012) Hydrochemical characteristics of groundwater for domestic and irrigation purposes in Dwarakeswar watershed area, India. *Am J Clim Change* 1:217–230
- Nongkynrih JM, Husain Z (2011) Morphometric analysis of the Manas river basin using earth observation data and geographical information system. *Int J Geomat Geosci* 2(2):647–654
- Pan S (2013) Application of remote sensing and GIS in studying changing river course in Bankura District, West Bengal. *Int J Geomat Geosci* 4(1):149–163
- Pareta K, Pareta U (2011) Quantitative morphometric analysis of a watershed of Yamuna Basin, India using ASTER (DEM) data and GIS. *Int J Geomat Geosci* 2(1):248–269
- Pareta K, Pareta U (2012) Quantitative geomorphological analysis of a watershed of Ravi River Basin, H.P. India. *Int J Remote Sens GIS* 1(1):41–56

- Parveen R, Kumar U, Singh VK (2012) Geomorphometric characterization of Upper South Koel Basin, Jharkhand: a remote sensing & GIS approach. *J Wat Resour Prot* 4:1042–1050
- Rai PK, Mohan K, Mishra S, Ahmad A, Mishra VN (2017) A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. *Appl Water Sci* 7:217–232
- Raux J, Copard Y, Laignel B, Fournier M, Massei N (2011) Classification of worldwide drainage basins through the multivariate analysis of variables controlling their hydro sedimentary response. *Glob Planet Change* 76:117–127
- Reddy GPO, Maji AK, Gajbbiye KS (2004) Drainage morphometry and its influence on landform characteristics in a basaltic terrain, Central India—a remote sensing and GIS approach. *Int J Appl Earth Observ Geoinf* 6(1):1–16
- Rudraiah M, Govindaiah S, Vittala SS (2008) Morphometry using remote sensing and GIS techniques in the sub-basins of Kagna River Basin, Gulburga District, Karnataka, India. *J Indian Soc Remote Sens* 36:351–360
- Schumm SA (1956) The evolution of drainage system and slopes in Badlands at Perth Amboy, New Jersey. *Bull Geol Soc Am* 67:214–236
- Sharma S, Sarma JN (2013) Drainage analysis in a part of the Brahmaputra Valley in Sivasagar District, Assam, India, to detect the role of nontectonic activity. *J Ind Soc Rem Sens* 41(4):895–904
- Shrestha RK, Ahlers R, Bakker M, Gupta J (2010) Institutional dysfunction and challenges in flood control: a case study of the Kosi flood 2008. *Econ Polit Wkly* 14(2):45–53
- Singh V, Singh UC (2011) Basin morphometry of Maingra River, district Gwalior, Madhya Pradesh, India. *Int J Geomat Geosci* 1(4):891–902
- Singh RK, Bhatt CM, Prasad VH (2003) Morphological study of a watershed using remote sensing and GIS techniques. *Hydrol J* 26(1–2):55–66
- Singh P, Thakur JK, Singh UC (2013) Morphometric analysis of Morar River Basin, Madhya Pradesh, India, using remote sensing and GIS techniques. *Environ Earth Sci* 68(7):1967–1977
- Sinha R (2009) Dynamics of a river system—the case of the Kosi River in North Bihar. *Earth Sci India* 2:33–45
- Sinha R, Bapalu GV, Singh LK, Rath B (2008) Flood risk analysis in the Kosi River Basin, North Bihar using multi-parametric approach of analytical hierarchy process (AHP). *J Ind Soc Rem Sens* 36:335–349
- Smith KG (1950) Standards for grading texture of erosional topography. *Am J Sci* 248:655–668
- Sreedevi PD, Subrahmanyam K, Ahmed S (2005) The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. *Environ Geol* 47(3):412–420
- Strahler AN (1952) Hypsometric analysis (area-altitude) of erosional topography. *Geol Soc Am Bull* 63:117–142
- Strahler AN (1964) Quantitative geomorphology of basins and channel networks. In: Chow VT (ed) *Handbook of applied hydrology*. McGraw Hill Book Company, New York
- Thomas J, Joseph S, Thirvikramaji KP (2010) Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. *Int J Digit Earth* 3(2):135–156
- Vittala SS, Govindaiah S, Gowda HH (2004) Morphometric analysis of sub-watersheds in the Pavagada area of Tumkur District, South India using remote sensing and GIS techniques. *J Ind Soc Remote Sens* 32(4):351–362
- Waikar ML, Nilawar AP (2014) Morphometric analysis of a drainage basin using geographical information system: a case study. *Int J Multidiscip Curr Res* 2:179–184
- Wakode HB, Dutta D, Desai VR, Baier K, Azzam R (2013) Morphometric analysis of the upper catchment of Kosi River using GIS techniques. *Arab J Geosci* 6(6):395–408

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.