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ORIGINAL ARTICLE

A GIS-based approach in drainage morphometric analysis of Rihand River Basin, Central India

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Abstract The study on morphometric attributes of the Rihand River Basin (RRB) in Central India was carried out for characterizing the hydrological response behavior using geographic information system (GIS). The RRB supports production of more than 20,000 MW electricity from coal-based thermal power plants. In light of this the management of RRB becomes paramount to sustain the industrial needs and livelihood of more than two million people in the study area. The Rihand River Basin comprises a dendritic drainage pattern where the maximum number of streams was found in the first order and the stream order increased with decrease in stream number. The mean bifurcation ratio was 1.57 which indicates that the drainage pattern is not affected by structural disturbances. The mean value of stream frequency, drainage density and drainage texture was 0.60 km/km^2, 0.06 and 0.03, respectively. These characteristics showed dominance of coarse drainage texture, low runoff, low erosional potential, permeable subsurface material, high vegetation cover and low relief. The elongation ratio and form factor were 0.25 and 0.30, respectively, which suggest elongated shape of the basin having a flatter peak of flow for longer duration. Flood flows of such elongated basin are easier to manage and would be helpful in determining the effect of the catchment characteristics on hydrological assessment of the study area. The dominant slopes were east facing indicating high moisture content and low evaporation in the study area. The slope map revealed gentle and moderate nature which are excellent for groundwater recharge in the RRB.

Keywords Drainage · GIS · Rihand River Basin · SRTM DEM · Morphometry

Introduction

Urban expansion and population explosion due to industrial development and infrastructure growth in countries like India lead to stress on water resources (Singh and Thakur 2011; Thakur et al. 2011). Over-exploitation of river water by constructing reservoir increases siltation and decreases live storage capacity of river basins in Indian subcontinent. In the winter and summer, the river basins are widely used for cultivation of vegetables resulting in enrichment of organic matter and nutrients causing eutrophication. These direct and indirect usage of river basin have affected both surface and groundwater quality and quantity resulting in an acute water crisis (Thakur et al. 2011). In addition, low intensity and erratic monsoon creates further shortage of surface water supply (Singh et al. 2013). It is, therefore, essential to increase the recharge of the basin for the sustainability of livelihood and regional economics throughout the world (Eyquem 2007; Rao 2008; Ellis and Revitt 2010; Sreedevi et al. 2013; Singh et al. 2014).

Geology, relief, tectonic framework, and climate are the primary determinants of running water ecosystem functioning at the basin scale (Mesa 2006; Thomas et al. 2012). Remote Sensing and GIS-based drainage basin evaluation has been carried out by number of researchers for different terrains and it is proved to be very scientific tool for

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generation of precise and updated information for characterization of drainage parameters (Godchild and Haining 2004; Grohmann et al. 2007; Korkalainen et al. 2007; Hlaing et al. 2008; Yu and Wei 2008; Javed et al. 2009). Digital elevation models (DEMs) such as from Shuttle Radar Topography Mission (SRTM) or the ASTER GDEM product (USGS, Denver, Colorado, USA) are widely used by researchers to analyze meaningful interpretation of the morphometric parameters including linear parameters [stream number, stream order and stream length], areal parameters [basin area, perimeter, length, drainage density, stream frequency and drainage texture] and relief characteristics [aspect, elevation and slope] (Farr and Jobrick 2000; Maathuis 2006; El Bastawesy et al. 2013; Panhalkar 2014). The linear, relief and areal aspects of a drainage basin provide the quantitative information on the geometry of a fluvial system, and can be correlated with the hydrologic information (El Bastawesy et al. 2015). Various hydrological phenomena can be correlated with the physiographic characteristics of an drainage basin such as size, shape, slope of the drainage area, drainage density, size and length of the contributories, etc. (Magesh et al. 2012).

The Rihand River originates from semi-arid region of the Vindhyan Supergroup and important tributary of the Son River. The study area receives maximum recharge through rainfall (Anshumali et al. 2012). The Rihand River supplies water to industries (Northern Coalfield, NTPC units, Reliance and ESSAR Ultra Thermal Power Plants, HINDALCO, etc.), municipality of Singrauli and Sonbhadra districts and irrigation usages. These activities are associated with direct discharge of mine water, waste water, increased sediment and dust deposition, and surface runoff, which lead to increased delivery of ions to surface water (Anshumali et al. 2014). In view of this, the main aim of present study was to investigate and identify various drainage parameters to understand the geometry of the Rihand River Basin for the conservation and management of water resources in a sustainable manner. The study combined with geology and geomorphology studies, helps to construct a primary hydrological diagnosis (Hungr 2000). The morphometric parameter extractions of Rihand River Basin (RRB) were carried out through the use of SRTM DEM.

Study area

The Rihand River is a tributary of the Son River flows through the Indian states of Chhattisgarh, Uttar Pradesh and Madhya Pradesh. The Rihand River lies between geographic latitudes 22°30′N to 24°30′N and longitudes 82°00′E to 83°45′E (Fig. 1). Rihand River Basin has three sub-basins namely Moran, Mahan and Ghunghutta. The Rihand River rises from Matiranga hills, in the region south west of the Mainpat plateau, which is about 2100 m above mean sea level. The river flows north roughly through the central part of Surguja district for 160 km. Thereafter, it flows north into Sonbhadra district of Uttar Pradesh via Singrauli district of Madhya Pradesh, where it is called Rhed and finally joins the Son. It is principal tributaries in

Fig. 1 Location map of the Rihand River Basin
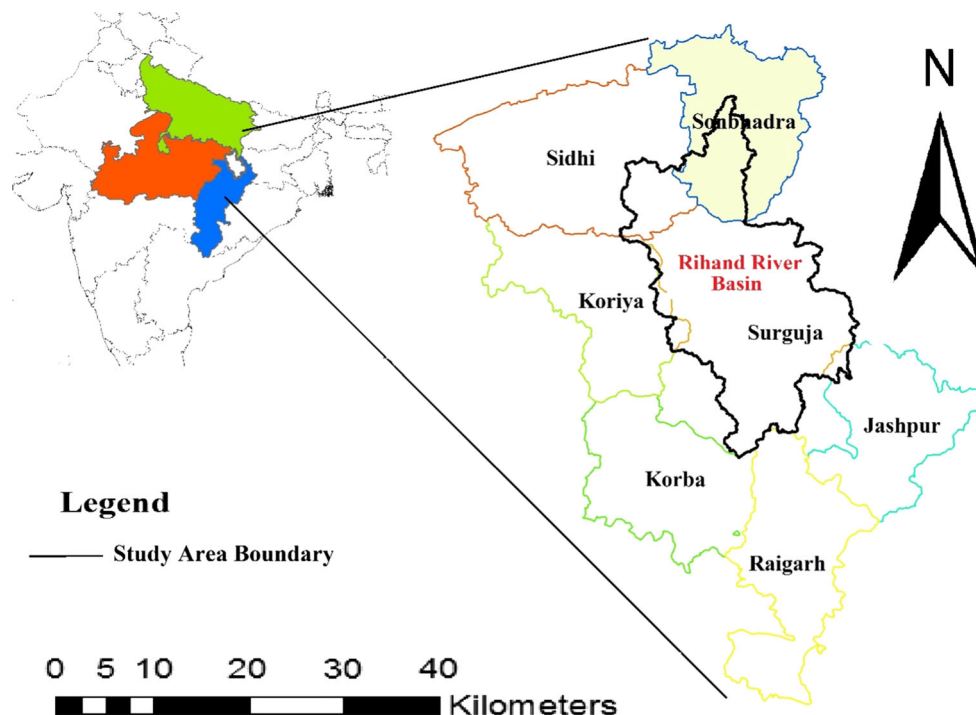
Table 1 Data used in the present work

Sl. no.	Type of data/software	Detail of data	Sources
1	Topo sheet	Topo sheet no. 64I/9, 63 L/16, 64 M1, 63P/4, 64 I/13 and 63 L/12.	Survey of India (SOI), Dehradun, India
2	SRTM DEM	3 ARC (90 m)	http:/srtm.csl.cgiar.org

Surguja district are the Mahan, Morana (Morni), Geur, Gagar, Gobri, Piparkachar, Ramdia and Galphulla. Many perennial rivers such as Kanchan, Mayar and Azir join the Rihand River in Singrauli district of Madhya Pradesh. The dense rich forest area provides an abode to thousands of species of flora and fauna. The climate of the study area is characterized by hot summer and well-distributed rainfall during the monsoon season. The Rihand Dam was constructed across the Rihand River near Pipri in Sonbhadra district of Mirzapur division in 1962 for hydropower generation; the reservoir impounded behind the dam is called Govind Ballabh Pant Sagar.

Geologically, the RRB is part of Vindhyan Supergroup, composed of low dipping formations of sandstone, shale and carbonate, with a few conglomerate and volcanic beds, separated by a major regional and several local unconformities (Bhattacharyya 1996). The rocks of Mahakoshal and Dudhi Groups of Palaeo-Proterozoic age and Damuda group (Gondwana Supergroup) of Permian to Carboniferous age are exposed in the study area (Geological Survey of India Northern Region 2009). The rocks of Mahakoshal Group are made of phyllite with quartzite, andalusite mica schist, limestone, acid intrusive, metabasic rocks, cherty quartzite, slate, marble and tuff. The rocks of Dudhi group overlie the Mahakoshal Group and consist of medium- to fine-grained diorite, gray granodiorite, epidotized pink tourmaline gneiss, leucocratic granite, and enclaves of metamorphites, amphibolites, granite gneiss, migmatite and metasedimentaries. The rocks of Damuda Group consist of coarse ferruginous sandstone intercalated with coal seams and green shale.

Morphometric parameter extractions and methodology

In the present study, an integrated use of digital elevation model (DEM) and survey of India topographical sheets were utilized for generation of database and extraction of various drainage parameters. Details of data used are shown in Table 1. The following procedure was followed for morphometric parameter extraction and analysis:

(a) The SOI topo sheets were geometrically rectified and georeferenced by taking ground control points (GCPs) by using UTM projection and WGS 84 datum. Further, all geocoded topo sheets were mosaic using Arc GIS 10.2 software.

(b) Catchment area of the Rihand River Basin delineated from SRTM DEM and Survey of India topographical sheets of the study area by using data preparation option of Arc GIS by making AOI (Area of Interest) of the basin.

(c) Digital Elevation Model (DEM) of the catchment was extracted from Shuttle Radar Topographic Mission (SRTM) data obtained with resolution of 90 m (downloaded from the srtm.csi.cgiar.org).

(d) The SRTM DEM was utilized to prepare topographic, slope and delineation of drainage map of the basin using Spatial Analyst tool of ARC GIS 10.2

(e) All the extracted parameters as the number and lengths of streams of each different order; drainage area, basin perimeter and total basin length, and width were calculated using ARC GIS software; drainage density, drainage frequency, shape, form factor, circulatory ratio, and elongation ratio, etc., were calculated from these parameters. The methodologies adopted for the computation of morphometric parameters are given in Table 2.

Results and discussion

In present study, morphometric analysis has been carried out as linear morphometric parameters [stream order, stream number, stream length, bifurcation ratio, length ratio], areal parameters [basin area, perimeter, length, drainage density, stream frequency and drainage texture] and relief characteristics [aspect, elevation and slope] using mathematical formulae as given in Table 2.

Drainage pattern, stream orders (U) and stream number (N_u)

The total drainage area of the Rihand River Basin is 13,411 km^2. The Rihand River Basin comprises a dendritic drainage pattern which shows there are many contributing streams, which are joined together in the tributaries of the Rihand River, which develop into the branches and trunk of

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Table 2 Methodology adopted for computations of morphometric parameters

S. no.	Parameters	Formulae	References
1	Stream order (N_u)	Hierarchical rank	Strahler (1964)
2	Stream length (L_u)	Length of the stream	Horton (1945)
3	Mean stream length	(L_{sm}) $L_{sm} = L_u/N_u$	Strahler (1964)
4	Stream length ratio (R_L)	$R_L = L_u/(L_u-1)$	Horton (1945)
5	Bifurcation ration (R_b)	(R_b) $= N_u/N_u + 1$	Schumm (1956)
6	Mean bifurcation ratio (R_{bm})	R_{bm} = average of bifurcation ratios of all order	Strahler (1957)
7	Drainage density (D_d)	$D_d = L_u/A$	Horton (1945)
8	Drainage texture (T)	$T = D_d \times F_s$	Smith (1950)
9	Stream frequency (F_s)	$F_s = N_u/A$	Horton (1945)
10	Elongation ratio (R_e)	$R_e = D/L$	Schumm (1956)
11	Circularity ratio (R_c)	$R_c = 4\pi A/P^2$	Strahler (1964)
12	Form factor (F_f)	$F_f = A/L^2$	Horton (1945)
13	Relief	$R = H-h$	Hadley and Schumm (1961)

the trees and indicates the homogeneity and uniformity in hydrogeological properties (Fig. 2).

In the present study, the ranking of stream has been carried out based on a method proposed (Strahler 1964) from the digitized streams from topo sheets and DEM. The order-wise stream numbers and their linear characteristics

are shown in Table 3. The stream order of the basin varies from 1st to 3rd order stream. The maximum stream-order frequency is observed in case of first-order streams and then for second order. It is noticed that there is a decrease in the stream frequency as stream order increases and vice versa. The maximum number of streams was found in the

Fig. 2 Drainage map of the Rihand River Basin

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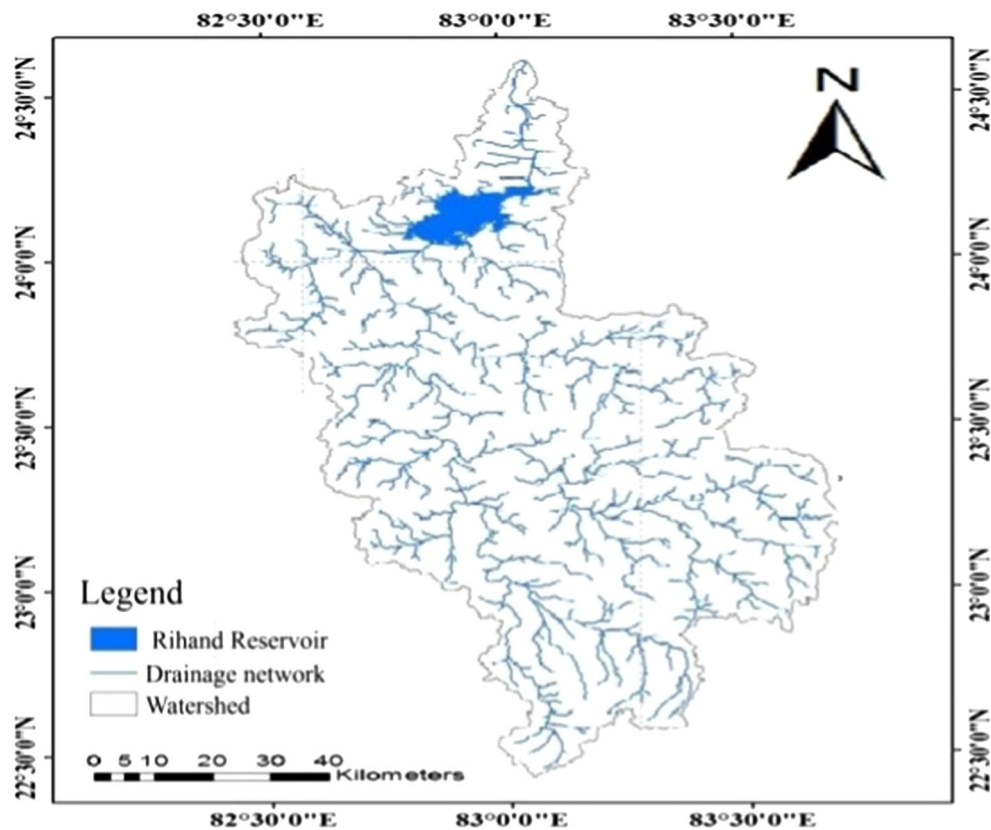
Table 3 Linear aspect of the Rihand River Basin

Stream order (w)	No. of streams (N_u)	Bifurcation ratio (R_bF)	Mean bifurcation ratio (R_bm)	Total length of streams (km)	Mean length of streams (km)	Length ratio (R_L)
1	4113		1.57	414.18	0.10	
2	2240	1.83		224.88		1.85
3	1699	1.31		176.28		1.27
Total	8052			815.34		

first order and as the stream order increases there is a decrease in stream number (Fig. 3).

According to Strahler (1964), when two streams of different orders join, neither increases in order. For example, a second-order stream joins a third-order stream, the second-order stream simply ends by flowing its contents into the third-order stream, which then maintains its place in the hierarchy. It signifies that the Rihand River Basin has the maximum third-order stream as a second-order stream joins to form a third-order stream.

Stream count of stream channel in each stream order of the Rihand River Basin was computed using ARC GIS software by applying standard method (Horton 1945). The number of streams gradually decreases as the stream order
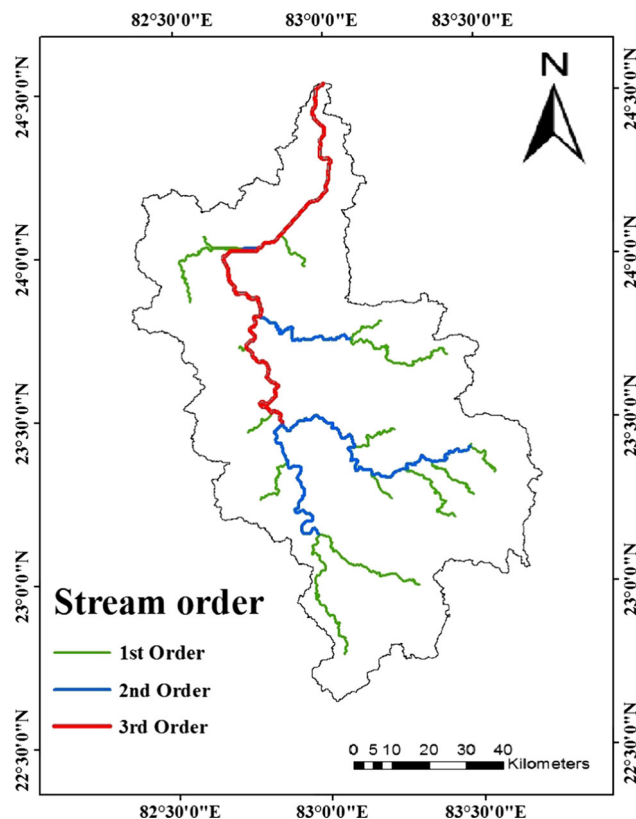

Fig. 3 Stream order of the Rihand River Basin

increases; the variation in stream order and the size of tributary basin largely depend on physiographical, geomorphological and geological condition of the region. A total of 8052 stream lines including the Rihand River were recognized in the whole basin, of out which 51.08% (4113) was part of the first-order stream, 27.81% (2240) was second-order stream and the third-order stream comprised 21.10% (1699). This change in stream orders indicates streams flowing from high altitude to low altitude regions with decrease in diversity of lithological characteristics.

Bifurcation ratio (R_b)

According to Schumn (Schumm 1956), the term bifurcation ratio (R_b) may be defined as the ratio of the number of the stream segments of given order to the number of segments of the next higher orders. It is a dimensionless property and shows the degree of integration prevailing between streams of various orders in a drainage basin. Based on standard method of bifurcation ratio analysis (Strahler 1964), the values of bifurcation ratio for the Rihand River Basin varied from 1.31 to 1.83 indicating the observed bifurcation ratio is not the same from one order to its next order (Verstappen 1983). The mean bifurcation ratio (1.57) shows that the drainage pattern of the basin has not been affected by structural disturbances. The mean bifurcation ratio of Rihand River Basin is less than Morar River Basin (Singh et al. 2013) and Kanhar River Basin (Rai et al. 2017) originating from different parts of Vindhyan Supergroup in Central India. This shows higher chance of flooding in the Rihand River Basin, as the water will be concentrated in one channel rather than spread out, as a higher would indicate.

Stream length (L_u) and stream length ratio (R_L)

The values of total length, mean length and length ratio of different stream orders of the Rihand River Basin are shown in Table 3. The stream length and stream length ratio for the Rihand River Basin were computed using GIS on the basis of the law proposed by Horton (1945). The total length of streams in the Rihand River Basin is

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815.34 km, out of which first-order stream, second-order stream and third-order stream contribute 50.77% (414.18 km), 27.58% (224.88 km) and 21.62% (176.28 km) of total length, respectively. It is clearly identified that the cumulative stream length is higher in first-order streams and decreases as the stream order increases. The value of mean length of the stream is 0.10 km in the study area. The stream length ratio varied from 1.27 to 1.85, shows a change in each stream order. This change might be attributed to variation in slope and topography conditions, indicating the late youth stage of geomorphic development (Vittala et al. 2004) in the streams of the Rihand River Basin.
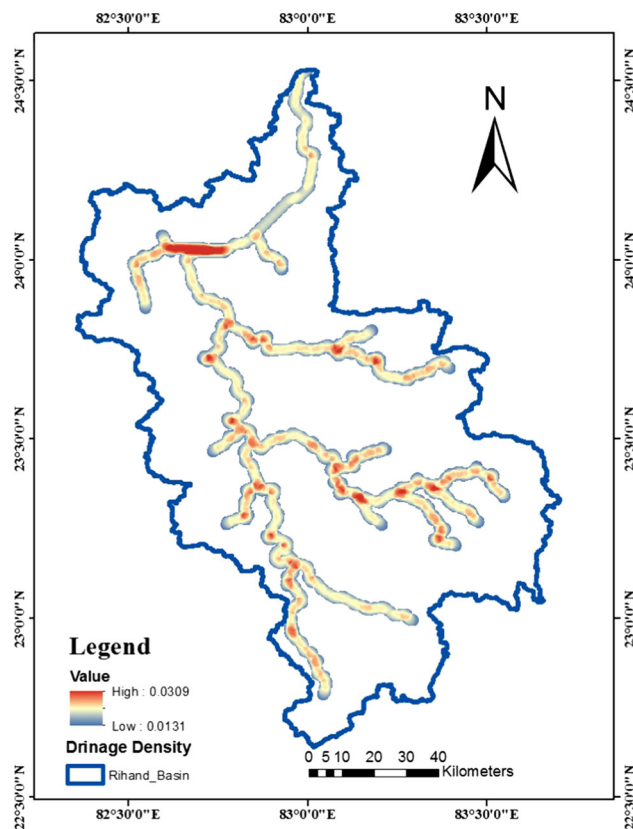
Stream frequency (F_s), drainage density (D_d) and drainage texture (T)

Stream frequency is the total number of stream segments of all orders per unit area (Horton 1932) and depends on the lithology of the basin and reflects the texture of the drainage network. Stream frequency of Rihand River Basin is 0.60 km/km^2 indicating presence of a permeable subsurface material and low relief. The stream frequency value of Rihand River Basin is less than other river basins present in Central India (Singh et al. 2013; Rai et al. 2014).
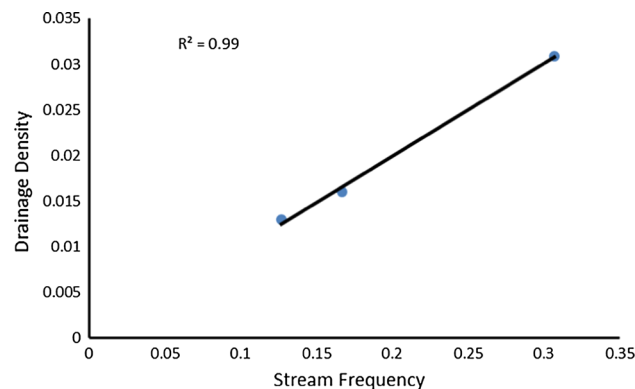
Drainage density (D_d) is a measure of the total stream length in a given basin to the total area of the basin (Strahler 1964). The drainage density of the study area is 0.06 km/km^2 (Table 4) which reveals that drainage density leads to coarse drainage texture, low runoff, low erosional potential of the basin area, and the closeness of spacing of channels (Fig. 4). The low value of drainage density shows highly resistant permeable material with vegetative cover and low relief in the Rihand River Basin. Stream frequency values indicate a positive correlation with the drainage density of the basin ($r^2 = 0.99$) suggesting that an increase in stream population occurs with respect to increase in drainage density (Fig. 5). The drainage texture of the basin is 0.03 which suggests that it is mainly depends upon a

Fig. 4 Drainage density map of the Rihand River Basin

Fig. 5 Graph between stream frequency and drainage density

number of natural factors such as climate, rainfall, vegetation, rock, soil type and their infiltration capacity and relief of the basin.

Elongation ratio (R_e) and circularity ratio (R_c)

Elongation ratio (R_e) is the ratio between the diameter of the circle of the same area as the drainage basin and the maximum length of the basin (Schumm 1956). It is a measure of the shape of the river basin and it depends on the climate and geologic types. The elongation ratio of the

Table 4 Areal aspect of the Rihand River Basin

Sl. no.	Areal aspect	Values
1	Basin area (km^2)	13,411
2	Perimeter (km)	1187
3	Length (km)	815.34
4	Form factor	0.30
5	Elongation ratio (R_e)	0.25
6	Circularity ratio (R_c)	0.11
7	Drainage density (km)	0.06
8	Stream frequency	0.60
9	Drainage texture	0.03

basin is 0.25 which suggests that the basin belongs to the elongated shape (Strahler 1964). Miller (1953) defined dimensionless circularity ratio (R_c) as ratio of basin area to the area of circle having the same perimeter as the basin. A circularity ratio of the basin is 0.11 which indicates strongly elongated and highly permeable homogenous geologic materials (Table 4). Low value of R_c indicates the young stages of the life cycle of the tributaries in Rihand River Basin (John et al. 2012). R_c is influenced by the length and frequency of streams, geological structures, land use/land cover, climate, relief and slope of the basin.

Form factor (F_f)

According to Horton (1932), form factor (F_f) may be defined as the ratio of the basin area to square of the basin length. The form factor indicates the flow intensity of a basin for a defined area. The form factor value should always be less than 0.78 for non-circular basin. The observed form factor value of the basin is 0.30 suggesting that the shape of the basin is elongated (Table 4). The elongated basin with low-form factor indicates that the basin will have a flatter peak of flow for longer duration. Flood flows of such elongated basin are easier to manage than those of the circular basin (Christopher 2010). The smaller the value of the form factor, the more elongated will be the basin. Basins with high-form factors experience larger peak flows of shorter duration, whereas elongated basin with low-form factors experience lower peak flows of longer duration.

Relief (R)

The elevation difference between the highest and lowest points on the valley floor of a basin is known as the total relief of that basin. The relief ratio (R_h) of maximum relief to horizontal distance along the longest dimension of the basin parallel to the principal drainage line is termed as relief ratio (Schumm 1956). It measures the overall steepness of a drainage basin and is an indicator of the intensity of the erosion processes operation on the slope of the basin. The highest relative relief is calculated as 1234 m, while the lowest value recorded as 145 m (Fig. 6). The low relief indicates northern part of the Rihand Basin is flat to gentle slope type.

Aspect map

Aspect map generally refers to the direction to which a mountain slope faces. The aspect map is a very important parameter to understand impact of sun on local climate of the area. Generally west-facing slope shows the hottest time of day in the afternoon and in most cases a west-
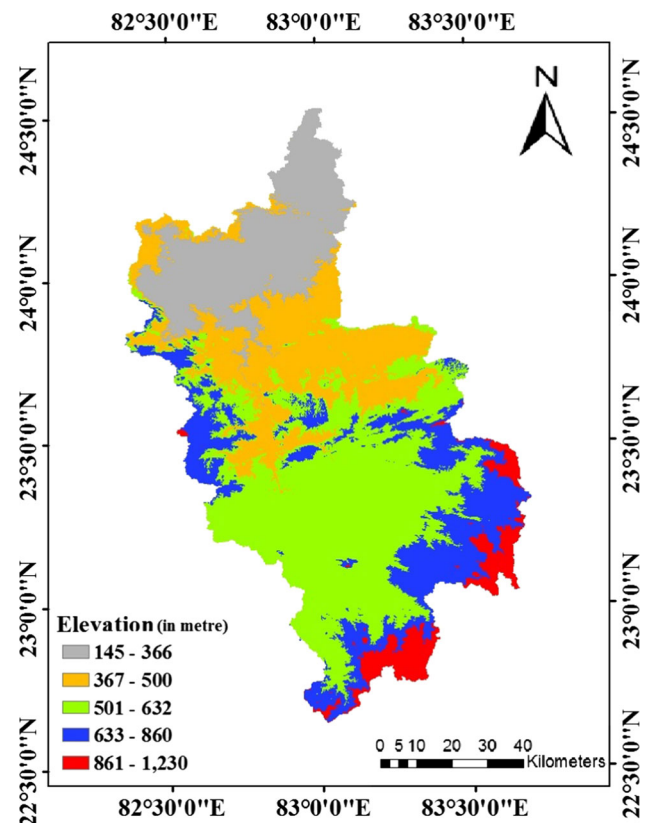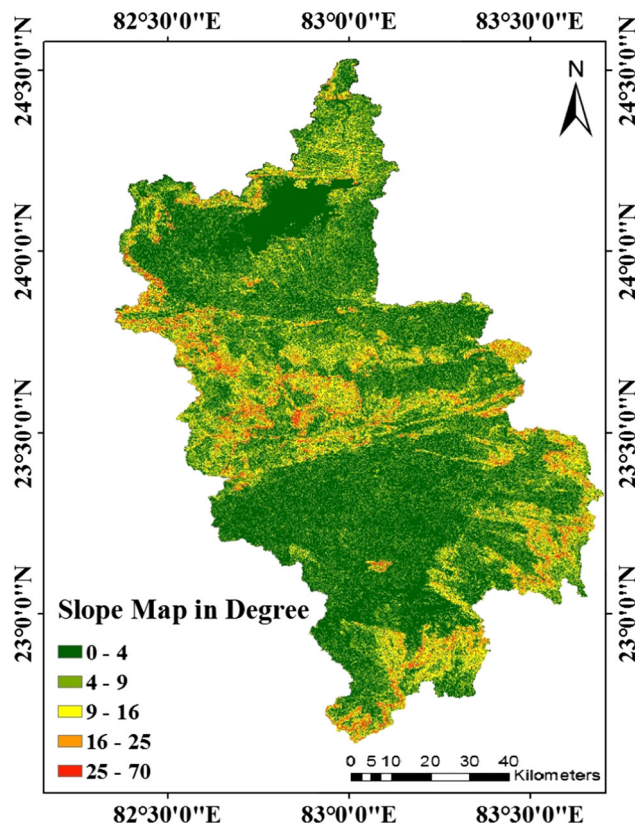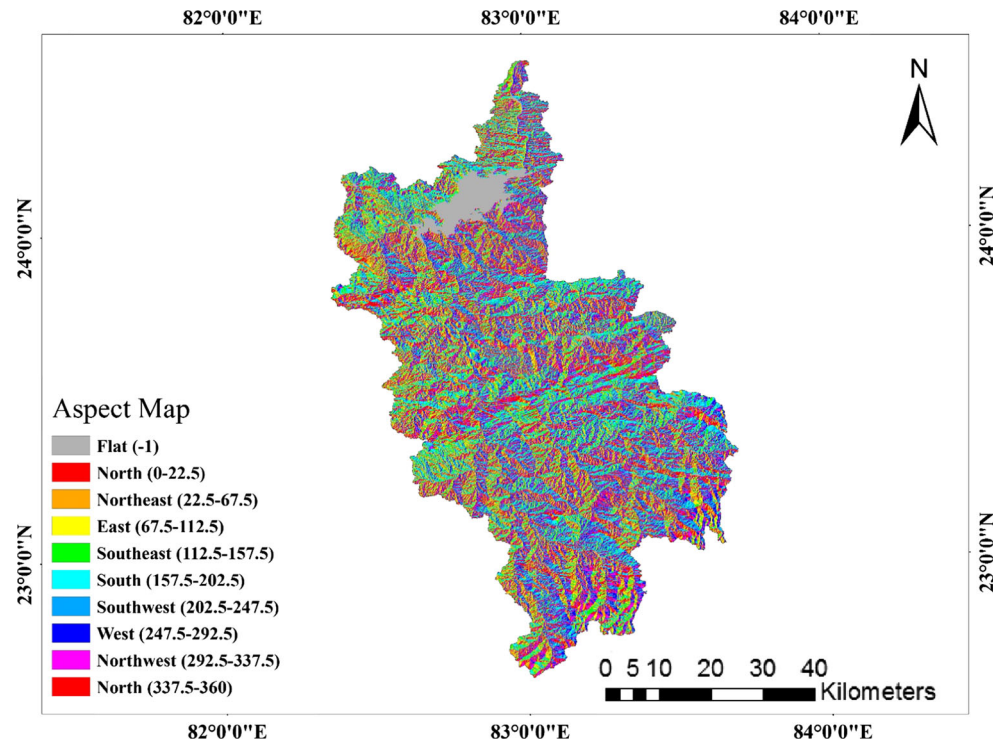

Fig. 6 Elevation map of the Rihand River Basin

facing slope will be warmer than a sheltered east-facing slope. The aspect map derived from SRTM DEM clearly shows that east-facing slopes mainly occur in the Rihand River Basin (Fig. 7). Therefore, these slopes have high moisture content and higher vegetation although some part are falling towards west facing which have lower moisture content and have a high evaporation rate.

Slope map

Slope is the measure of change in surface value over distance and can be expressed in degrees or as a percentage. In present study, topographical elevation map for the study area was developed by SRTM DEM data. For this, the DEM was subjected to two directional gradient filters (one in x-direction and another in y-direction). The resultant maps were used to generate a slope map of the study area using Arc GIS Spatial Analyst tools. Slope grid is identified as "the maximum rate of change in value from each cell to its neighbors" (Burrough 1986). The slope map of the study area is grouped into five classes in degrees viz. 0–4 (gentle), 4–9 (moderate), 9–16 (steep), 16–25 (very steep) and 25–70 (extremely steep) (Fig. 8). It is observed that most of the area of Rihand River Basin comes under gentle and moderate slope which indicates almost flat topography

Fig. 7 Aspect map of the Rihand River Basin

Fig. 8 Slope map of the Rihand River Basin

of the area favorable for maximum infiltration. Slope is a critical parameter which directly controls runoff and infiltration of any terrain. Runoff in higher slope regions causes less infiltration. This factor significantly controls the development of aquifers.

Conclusion

Quantitative morphometric characterization of the Rihand River Basin reveals the relationship among different aspects of the drainage pattern including geology and geomorphology. Morphometric analysis confirms the occurrence of dendritic drainage patterns, coarse drainage texture, low runoff and low erosional potential in the basin area. The low relief, elongated shape and low circulatory ratio indicate low discharge of surface runoff and highly permeable subsoil conditions in the Rihand River Basin. The dominant slope is east facing, gentle and moderate indicating an almost flat topography, high moisture content and lower evaporation rate in the basin. The Rihand River Basin therefore needs immediate attention.

The results of morphometric parameters obtained through SRTM DEM analysis of can be used for (a) integrated watershed development program and management of water resources in the study area; (b) integration with

land use/cover, land forms, geology, water level and soil in the GIS domain to suggest suitable sites for soil and water conservation structures (nala bund, check dam, percolation tank, recharge shaft, etc.) and (c) delineating the carrying capacity of Rihand River Basin for long-term sustainability of the exiting Northern Coal Field (NCL) and various thermal power plants in Central India.

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