



Quantitative Morphometric Analysis of Watershed of Upper Pahuj Basin, Bundelkhand Region, Central India

S. C. Bhatt, Rubal Singh, M. Taiyab, and S. Bhatt

Abstract

In the present study, a detail morphometric evaluation of upper Pahuj basin is attempted to delineate drainage pattern, linear, areal, relief, geological control and other aspects. The Arc GIS (10.4 version) and ASTER data were used to extract drainage, density, aspect, slope, contour and other thematic maps. The five orders of streams were identified in the study area. The relationship between geological structures and different orders of the stream was established. About fifty parameters were analysed. The higher values of the bifurcation ratio in higher orders and its mean value (4.47) indicate that the drainage pattern is inherently controlled by geological structures. The moderate drainage density (2.20) and low frequency (2.86) are suggestive of low infiltration rate and have a thin vegetal cover on less permeable rocky terrain. The low values of elongation ratio (0.62) and form factor ratio (0.30) infer that the basin catchment is elongated and is showing low peak flows of greater interval. The circulatory ratio (0.34) computed for upper Pahuj catchment implies that the youth stage was dominant in the evolution of the watershed. The ruggedness number (0.30) indicates that the terrain has a moderate slope and is showing slight morphology.

Keywords

Morphometric analysis • Upper Pahuj basin • Bundelkhand • Central India

S. C. Bhatt (✉) · R. Singh · M. Taiyab
Department of Geology, Institute of Earth Sciences, Bundelkhand
University Jhansi, Jhansi, UP, India
e-mail: scbhatt@bujhansi.ac.in

S. Bhatt
Institute of Environment and Development Studies, Bundelkhand
University Jhansi, Jhansi, UP, India

1 Introduction

The morphometry of a basin reveals the geological and geomorphological processes undergone in geological period and influence the drainage basin is significant in understanding the landform processes, a physical and erosional property of soil (Horton 1945; Strahler 1952, 1964). The development of quantitative physiographic methods for evolution and behaviour of surface drainage networks have been widely used in geomorphology for the last several years (Horton 1945). Morphometry is a measurement and mathematical evaluation of the earth's surface, shape, size and dimension of landforms (Agarwal 1998; Obi Reddy et al. 2002). The implications of linear, areal, relief and tectonic aspects of a drainage basin can be understood by carrying detail morphometric analysis (Singh and Singh 1997; Nag and Chakraborty 2003; Sreedevi et al. 2004; Pareta and Pareta 2011; Bhatt et al. 2017, 2020; Bhatt 2020). It will play an important role in the understanding of geo-hydrological behaviour of basin and expresses the prevailing climate, geology, geomorphology, structural antecedents of the catchment. Morphometry is also important in the assessment of groundwater potential, groundwater management, pedology and environmental assessment. The progressive development of fluvial landforms along with drainage pattern showing inherent control of lithology and tectonics is discussed under drainage basin analysis (Horton 1945; Faniran 1968; Pati et al. 2008). The proper management of watershed needs utilisation of various aspects like land, water, soil and forest resources of a particular watershed for better production and lesser hazard to natural resources (Biswas et al. 1999). The hydrological response of a river basin can be interrelated with the physiographic characteristics of the drainage basin, such as size, shape, slope, drainage density and size and length of the streams, etc. (Gregory and Walling 1973). The development of landforms and drainage network depends on the bedrock lithology and associated geological structures, hence,

information on geomorphology, hydrology, geology and land cover can be obtained by reliable information from the study of drainage pattern and texture.

The morphometric analysis of the drainage basin and channel network plays a significant role in the comprehension of the geo-hydrological nature of drainage basin and expresses the prevailing climate, geological setting, geomorphology and structural antecedents of the catchment area. A quantitative evaluation of the drainage system is a significant aspect of the drainage basin. Recently the morphometric and morphotectonic parameters of a watershed basin, geometrical characteristics of fluvial landscapes, structural anisotropy, planning of watershed and rainwater harvesting can be interpreted by carrying morphometric analysis and using Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topographic Mission (SRTM) data (Prareta 2011; Bhatt et al. 2017, 2020; Bhatt 2020).

In this work, the linear, areal and relief parameters of the watershed of Pahuj upper basin were analysed to understand the hydrological, geological, tectonic and geomorphological characters of the watershed. It gives information about the basin characteristics in terms of slope, topography, soil conditions, runoff characteristics and surface water potential, etc.

2 Study Area

The study area belongs to the upper part of the catchment of the Pahuj basin of Bundelkhand region of Central India. The toposheet G44M07 and G44M11 (1:50,000) of Survey of India were used as a base map to extract stream network and drainage map of the area and it is located in the northwestern sector of this craton. It is lying between latitude 25,018'30" to 25,027'27"N and longitude 78,017'33" to 78,031'22"E.

3 Geomorphology of the Study Area

The Study area located in the north-western part of Bundelkhand craton is represented by rugged and undulating topography with moderately elevated hills. The erosional and depositional landforms moderately elevated granitic and quartz reefs (200–300 m) and low lying alluvial plains are observed as common geomorphic features in the study area (Bhatt et al. 2015). The NE-SW trending quartz reefs are generally covered with thick vegetation. The granitic and gneissic terrains are characterised by hard and massive lithology and at few places are covered by scrub. The isolated granitic and gneissic boulders are frequently scattered at several places. The Pahuj Tal (lake) is an important water

body seen in the study area. The rest of the low lying area is covered by alluvium. The fractured, weathered and sheared hard rock terrain and low lying alluvial plains are considered good potential zones for groundwater.

4 Geological Setup

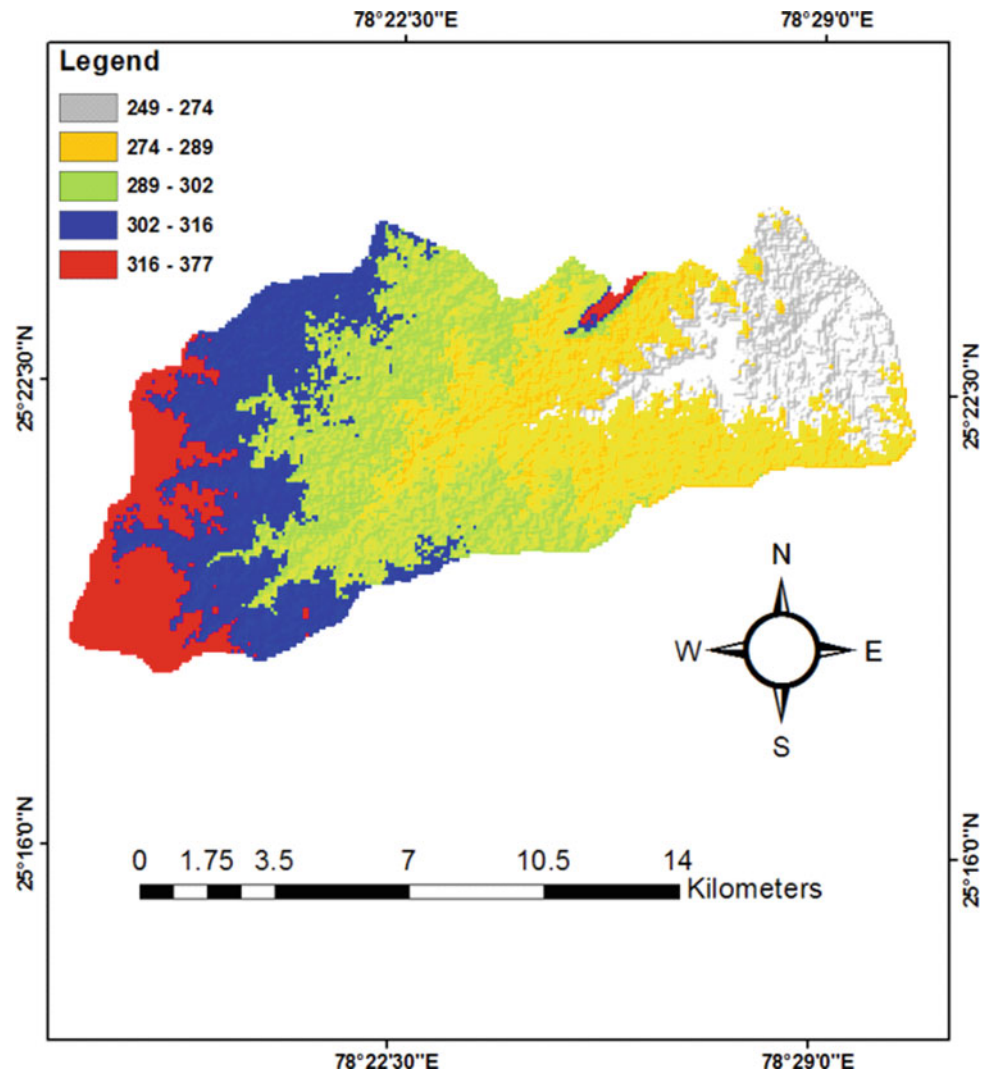
Bundelkhand TTG Gneissic Complex (3.1–3.5 Ga), Greenstone Belt and Bundelkhand Granitic Complex (2.5 Ga) are identified as important major Groups in the investigated area (Bhatt and Hussain 2008; Bhatt and Gupta 2009; Bhatt and Hussain 2012; Bhatt and Mahmood 2012; Bhatt and Gupta 2014; Bhatt 2014; Singh and Slabunov 2015; Bhatt et al. 2011, 2017; Singh et al. 2021). The Archean TTG gneisses (3.4 Ga), gneisses, granite gneisses and mylonitised granite gneisses and other rocks were observed as important rock units of Bundelkhand TTG gneissic complex. Bundelkhand Greenstone belt constitutes metasedimentaries and metavolcanic of Neoproterozoic age. The various types of granites (grey, pink and porphyritic granites) of Precambrian age (2.5 Ga), quartz reefs, doleritic dykes and pegmatic veins belong to Bundelkhand granitic complex.

5 Data Base and Methodology

The Arc GIS (10.4) and ASTER-DEM data (Fig. 1) were used to delineate drainage map, Digital Elevation Model (DEM), watershed delineation map, density, contour, aspect and other thematic maps. The toposheets (Survey of India) were scanned, georeferenced and mosaicked in Arc GIS 10.4 platform. Stream ordering schemes first proposed by Horton (1945) then revised by Strahler (1952), were applied to order Stream (by applying a numerical value to a stream's position and size) in the basin. In the present study, morphometric analysis of basin is based on the integrated use of remote sensing and GIS technique. The remotely sensed data is geometrically rectified with respect to Survey of India (SOI) topographical maps (the year 2010) at 1:50,000. The digitisation of the drainage pattern is carried out in Arc GIS 10.4 software. (Fig. 1). For stream ordering, Horton's law is followed by designating an un-branched stream as the first-order stream, when two first-order streams join it is designated as second order. Two-second order streams join together to form third order and so on. The number of streams of each order is counted and recorded. Direct measurements of geometric characteristics (e.g., area and perimeter of the basin, length and number of streams) were automatically obtained from GIS software.

The various morphometric parameters such as area, perimeter, stream order, stream length, stream number,

Fig. 1 Digital Elevation model (DEM) of the study area



bifurcation ratio, drainage density, stream frequency, drainage texture, length of basin, form factor, circulatory ratio, elongation ratio, length of overland flow, compactness coefficient, shape factor and texture ratio were computed (Tables 1, 2, and 3) based on the formula suggested by Horton 1945, Miller 1953, Schumn 1956 and Strahler 1964.

6 Morphometric Analysis

The linear aspects were computed by using the methods proposed by Horton (1945) and Chorley (1957). The areal aspects were quantified by using methods of Schumm (1956), Strahler (1956), Miller (1953), and Horton (1932),

Table 1 Stream order, streams number and bifurcation ratio

Su	Nu	Rb	Nu-r	Rb*Nu-r	Rbwm
I	328				4.47
II	76	4.32	404	1754.28	
III	19	4.00	95	380.00	
IV	2	9.50	21	199.5	
V	1	2.00	3	6	
Total	426	19.82	523	2339.78	
Mean		5.00			

Su: Stream order, Nu: Number of streams, Rb: Bifurcation ratio, Nu-r: Number of stream used in the ratio, Rbwm: Weighted mean bifurcation ratio

Table 2 Stream length, and stream length ratio in upper Pahuj basin

Su	Lu	Lu/Su	Lur	Lur-r	Lur*Lur-r	Luw _m
I	182.67	0.56				2.07
II	70.85	0.93	1.66	253.52	420.84	
III	47.86	2.52	2.71	118.71	321.70	
IV	12.02	6.01	2.38	59.88	142.51	
V	14.93	14.93	2.48	26.95	66.84	
Total	328.33	24.95	9.23	459.06	951.89	
Mean			2.31			

Su: Stream order, Lu: Stream length, Lur: Stream length ratio, Lurm: Mean stream length ratio, Lur-r: Stream length used in the ratio, Luw_m: Weighted mean stream length ratio

and the relief parameters were determined by applying the techniques of Horton (1945), Melton (1957), Schumm (1954), Strahler (1952). The average slope analysis of the watershed area was done using the Wentworth (1930) method. The Drainage density and frequency distribution analysis of the watershed area was done by using the spatial analyst tool in ArcGIS-10 software.

7 Results and Discussion

The main objective of the present study is to delineate the morphometric parameters of the upper catchment of Pahuj watershed and to explore the structural control on drainage pattern and to establish the relationship between drainage morphometry and various landforms. The quantitative morphometric analysis based on GIS ASTER DEM data reveals that the drainage pattern and evolution of each stream order was influenced by lithological characters and morphotectonic setup of the basin. The hydrological behaviour of each watershed is also documented by all computed values of linear, areal and relief data. About fifty-five parameters pertaining to linear, areal and relief aspects were quantified by using Arc GIS software and ASTER DEM data. The drainage pattern is represented by dendritic to subdendritic pattern (Fig. 2).

7.1 Linear Parameters

The linear property is a one-dimensional character used to define the linear parameters in the morphometric analysis. The stream order may be defined as a measure of the position of the stream in the hierarchy of tributaries (Strahler 1964; 1952; Horton 1945). Five order of stream were classified for the Pahuj upper catchment basin (Fig. 2). I to III orders were categorised as lower order and IV to V orders were classified as a higher order. The values of a stream number and stream length are shown in Tables 1 and 2. The total of order wise stream segments is known as stream

number. Horton (1945) states that the numbers of stream segments of each order form an inverse geometric sequence with the order number. The first order has 328 and second order contributes 76 streams, respectively (Table 1). The number of the stream decreases in the higher third (19), fourth (02) and fifth (01) order of streams (Table 1). An inverse relationship between the stream order and stream number with a percentage of variables is established (Figs. 3 and 4). It indicates that the total number of streams gradually decreases in higher stream order (Fig. 4). This will follow Horton's law.

In the present study, the maximum length of the stream was measured in the first order and it decreases as stream order increases (Table 2). Horton (1945) states that the stream length is the total length of stream segment of each order. The lower order has a shorter length with a larger number of streams than the higher order. The highest order has a single stream with longer stream length. The change of stream length ratio from one order to another order is indicating their late youth stage of geomorphic development. The total length of the Pahuj catchment basin is 328 kms. The bifurcation ratio (R_b) varies from 2.00 to 9.5. The highest value (9.5) of R_b was estimated in higher order streams while the lower values were observed in lower order streams. The variable value of bifurcation ratio (ranging from 2.0 to 9.5) indicates that the drainage evolved in a homogenous geological terrain and influenced by geological structures. The value of Rho Coefficient ($\rho = 0.46$) is suggestive of high hydrologic storage during a flood.

7.2 Areal Parameters/Basin Geometry

Length of the Basin (L_b) is a maximum length of watershed measured from head to mouth (Strahler 1964) and it was measured by using Arc GIS software (Table 3). Basin Area (A) is a maximum area drained by a basin and is measured by using Arc GIS software (Table 3). The upper catchment of Pahuj basin occupies 149 km² area and it has a total of 22.33 km basin length. Its perimeter is 73.89 km. Form

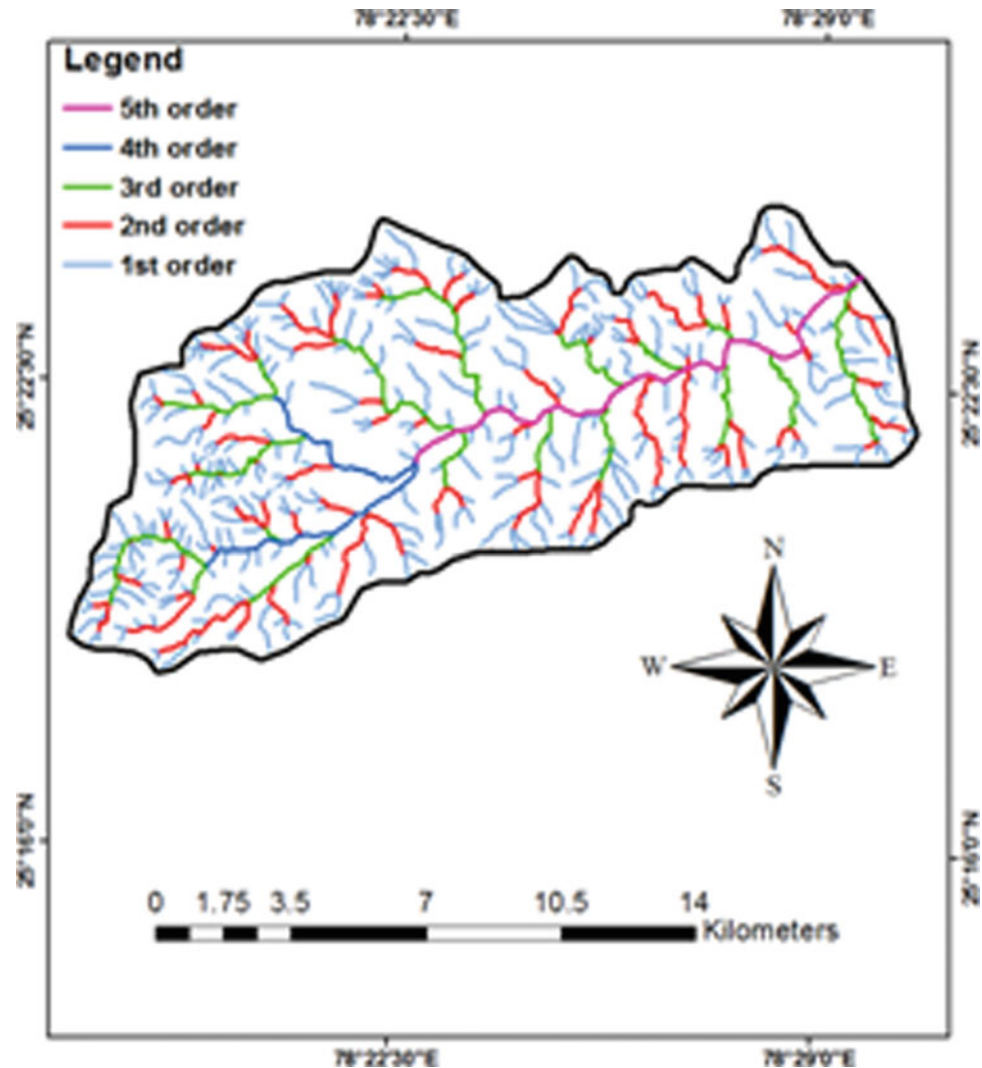
Table 3 Morphometric analysis of upper Pahuj basin

S. No	Morphometric parameter	Formula	Result
<i>A</i>			
<i>Drainage network</i>			
01	Stream order (Su)	Hierarchical ran	1–5
02	1st order stream (Suf)	$Suf = N1$	328
03	Stream number (Nu)	$Nu = N1 + N2 + \dots Nn$	426
04	Stream length (Lu) Kms	$Lu = L1 + L2 \dots Ln$	328.33
05	Stream length ratio (Lur)	see Table 2	1.66–2.71
06	Mean stream length ratio (Lurm)	see Table 2	2.31
07	Weighted mean stream length ratio (Luw m)	see Table 2	2.07
08	Bifurcation ratio (Rb)	see Table 1	2.0–9.5
09	Mean bifurcation ratio (Rbm)	see Table 1	5.00
10	Weighted mean bifurcation ratio (Rbwm)	see Table 1	4.47
11	Main channel length (Cl) Kms	GIS Software	22.46
12	Rho coefficient (ρ)	$\rho = Lur/Rb$	0.46
<i>B</i>			
<i>Basin geometry</i>			
01	Basin length (Lb) Kms	GIS Software Analysis	22.33
02	Mean basin width (Wb)	$Wb = A/Lb$	6.67
03	Basin area (A) SqKms	GIS Software Analysis	149.00
04	Basin perimeter (P) Kms	GIS Software Analysis	73.89
05	Relative Perimeter (Pr)	$Pr = A/P$	2.02
06	Length area relation (Lar)	$Lar = 1.4 * A^{0.6}$	28.19
07	Lemniscate's (k)	$k = Lb^2 / A$	3.35
08	Form factor ratio (Ff)	$Ff = A/Lb^2$	0.30
09	Shape factor ratio (Sf)	$Sf = Lb^2/A$	3.35
10	Elongation ratio (Re)	$Re = 2/Lb * (A/\pi)^{0.5}$	0.62
11	Texture ratio (Rt)	$Rt = N1/P$	5.77
12	Circularity ratio (Rc)	$Rc = 12.57 * (A/P^2)$	0.34
13	Circularity ration (Rcn)	$Rcn = A/P$	2.02
14	Drainage texture (Dt)	$Dt = Nu/P$	5.77
15	Compactness coefficient (Cc)	$Cc = 0.2841 * P/A^{0.5}$	1.37
16	Fitness ratio (Rf)	$Rf = Cl/P$	0.30
17	Wandering ratio (Rw)	$Rw = Cl/Lb$	1.01
<i>C</i>			
<i>Drainage texture analysis</i>			
01	Stream frequency (Fs)	$Fs = Nu/A$	2.86
02	Drainage density (Dd) Km / Kms ²	$Dd = Lu/A$	2.20
03	Constant of channel maintenance (Kms/Km)	$C = 1/Dd$	0.45
04	Drainage intensity (Di)	$Di = Fs/Dd$	1.30
05	Infiltration number (If)	$If = Fs * Dd$	6.29
06	Drainage pattern (Dp)		Dn-SubDn
07	Length of overland flow (Lg) Kms	$Lg = A/2 * Lu$	0.23
<i>D</i>			
<i>Relief characterizes</i>			
01	Height of basin mouth (z) m	GIS analysis/DEM	249.00
02	Maximum height of the basin (Z) m	GIS analysis/DEM	377.00
03	Total basin relief (H) m	$H = Z - z$	128.00
04	Relief ratio (Rhl)	$Rhl = H/Lb$	0.006

(continued)

Table 3 (continued)

S. No	Morphometric parameter	Formula	Result
05	Relative relief ratio (Rhp)	$Rhp = H * 100/P$	0.20
06	Gradient ratio (Rg)	$Rg = (Z - z)/Lb$	0.006
07	Watershed slope (Sw)	$Sw = H/Lb$	0.006
08	Ruggedness number (Rn)	$Rn = Dd * (H/1000)$	0.30
09	Melton ruggedness number (MRn)	$MRn = H/A^{0.5}$	9.67

Fig. 2 Drainage map of Upper Pahuj basin

factor (R_f) is defined as the representation of the shape of the watershed (Horton 1945). The lower values of form factor are indicative of more elongated basin. The watershed with high form factors has high peak flows of shorter duration, whereas elongated watershed with low form factor has low flow peak of longer duration (Horton 1945). The value of the form factor for upper Pahuj catchment is calculated at 0.33

(Table 3). It infers that the basin is more elongated and shows lower peak flows over a longer interval of time. Elongation ratio (R_e) explained as the ratio of the diameter of a circle of the same area as the watershed to the maximum basin length (Schumm 1956). The value of the elongation ratio grouped into five categories as circular (0.9–0.10), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and

Fig. 3 Shows the relation between stream order and logarithm of stream length

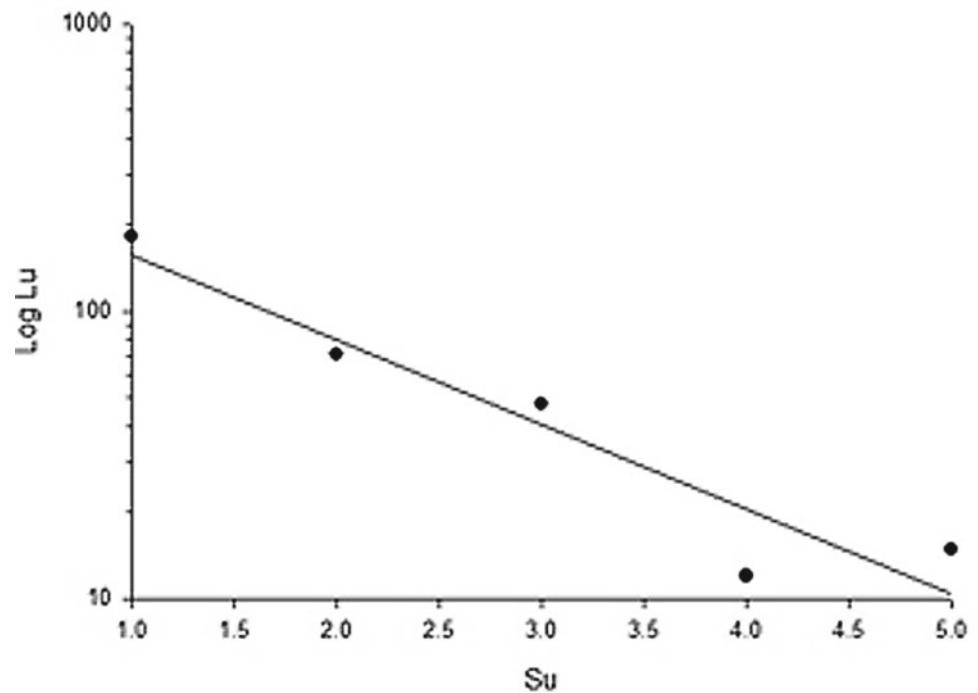
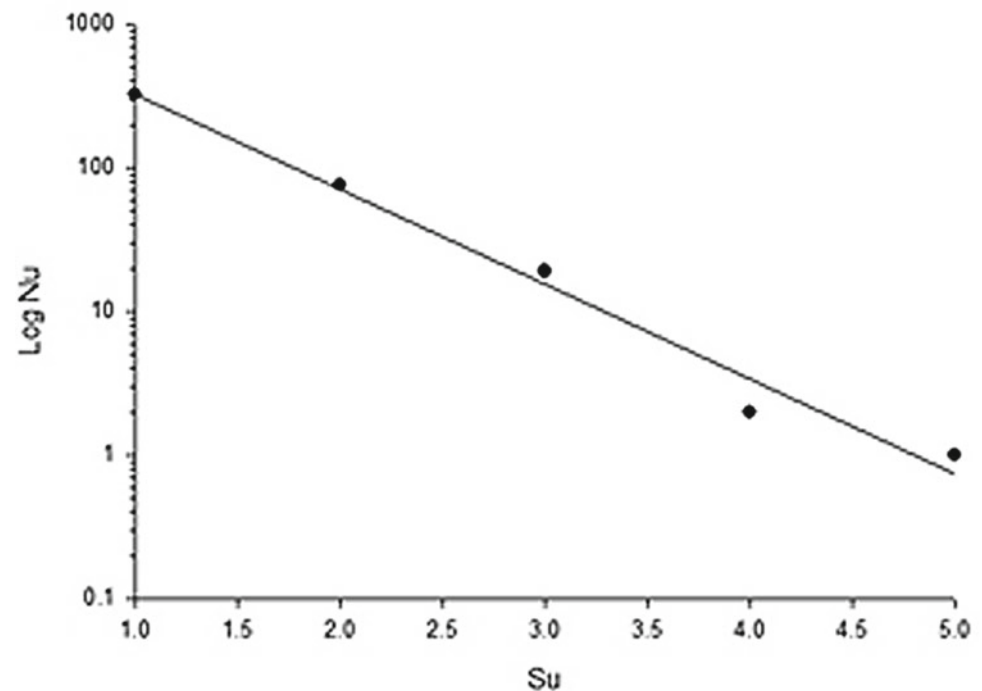


Fig. 4 The relation between stream order and logarithm of stream number



more elongated (<0.5). The elongation ratio (0.64) calculated for upper Pahuj basin implies that the basin is elongated and shows steeper slope.

Texture Ratio (Rt) is a total number of stream segments of all orders per perimeter of that area (Horton, 1945). It can be classified into five categories; very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8) and very fine (>8). The

upper Pahuj catchment basin has a moderate texture ratio of 5.77 (Table 3). It reveals that the basin consists of softer and more resistant harder rocks. Drainage density (Dd) is defined as the sum of stream lengths per unit area and is an expression of closeness or spacing of channels (Horton 1932). The density can be classified as extremely low (0–1), low (1–2), moderate (2–4), moderately high (4–6), and high

(>6). The moderate drainage density (2.20) determined for the area (Fig. 5) is indicative of the presence of moderate permeability with relatively good vegetative cover. Drainage texture is 5.77, infiltration number (If) is 6.29. The higher infiltration number 6.29 of upper Pahuj basin is showing low percolation of water on the ground and may have good erosion exposure. Stream Frequency (Fs) is defined as the number of streams per unit area or is the ratio between the total number of stream segments of all orders in a basin and the basin area (Horton 1945; Table 3). The low to moderate frequency (2.86) computed for upper Pahuj catchment basin indicates that the basin has slightly permeable soil with less vegetative cover.

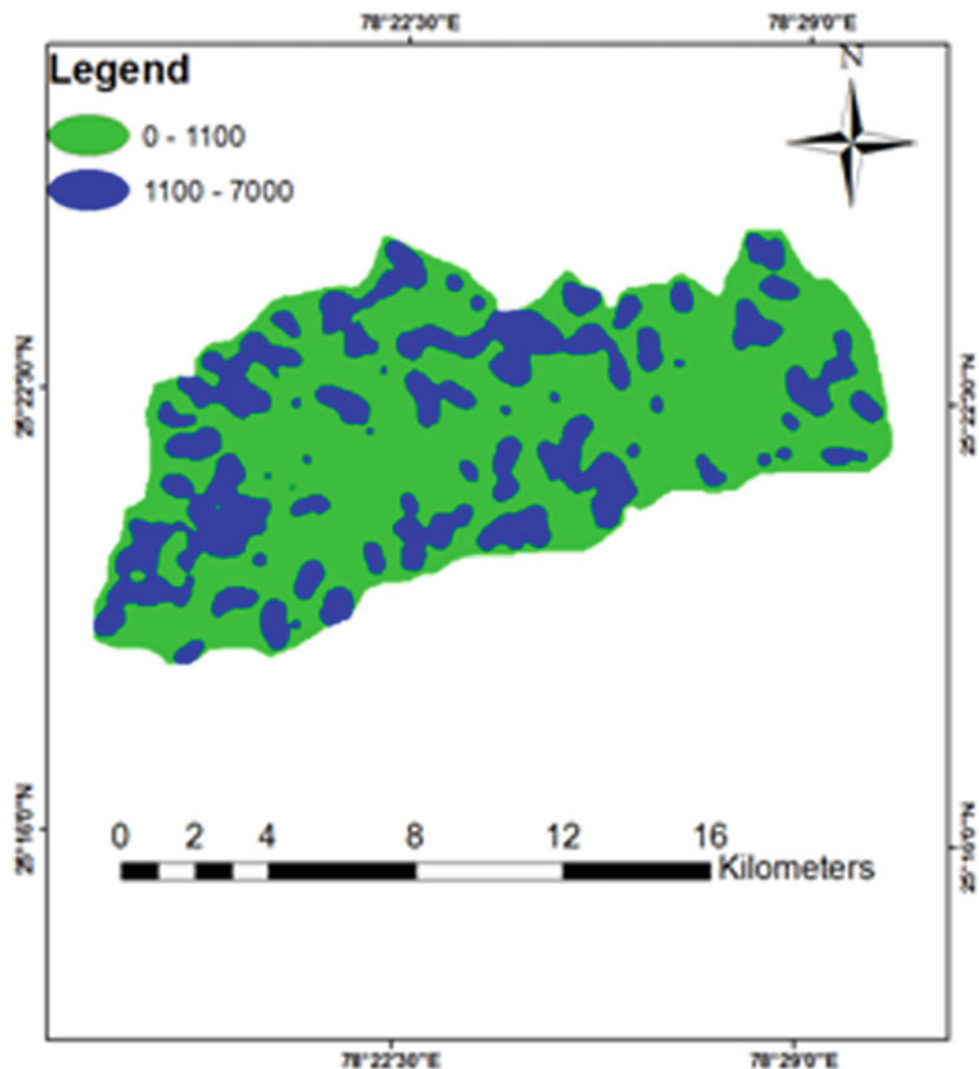
7.3 Relief Parameters

The relief is a three-dimensional property of a basin and is expressed in terms of area. The highest point of a catchment basin is 377 feet (Fig. 6). The elevation is an important

factor to understand the denudational processes of a basin. Relief is expressed as the maximum vertical distance between the lowest and highest points of a basin (Schumm, 1956). The relief ratio (0.006) indicates that the steepness of basin catchment is moderate and less susceptible to erosion. Ruggedness Number (Rn) is the product of maximum basin relief (H) and drainage density (Dd), where both parameters are in the same unit (Strahler 1956; Schumm, 1956). It refers to the level of smoothness and roughness of a basin terrain and vulnerability to soil erosion (Gutema et al. 2017). The low ruggedness value (0.30) of upper Pahuj catchment basin (Table 3) infers that the terrain is moderately steeper and is less prone to soil erosion.

E-W, NE-SW, N-S and NW-SE major lineaments are identified in the Bundelkhand craton. In the study area, the watershed is more or less in an elongated shape and is following the NE-SW lineament (Fig. 7). It reveals that the higher order streams are controlled by the major tectonic unit (NE-SW). The channel pattern and low values of sinuosity manifest less tectonic control.

Fig. 5 Drainage density map of the watershed



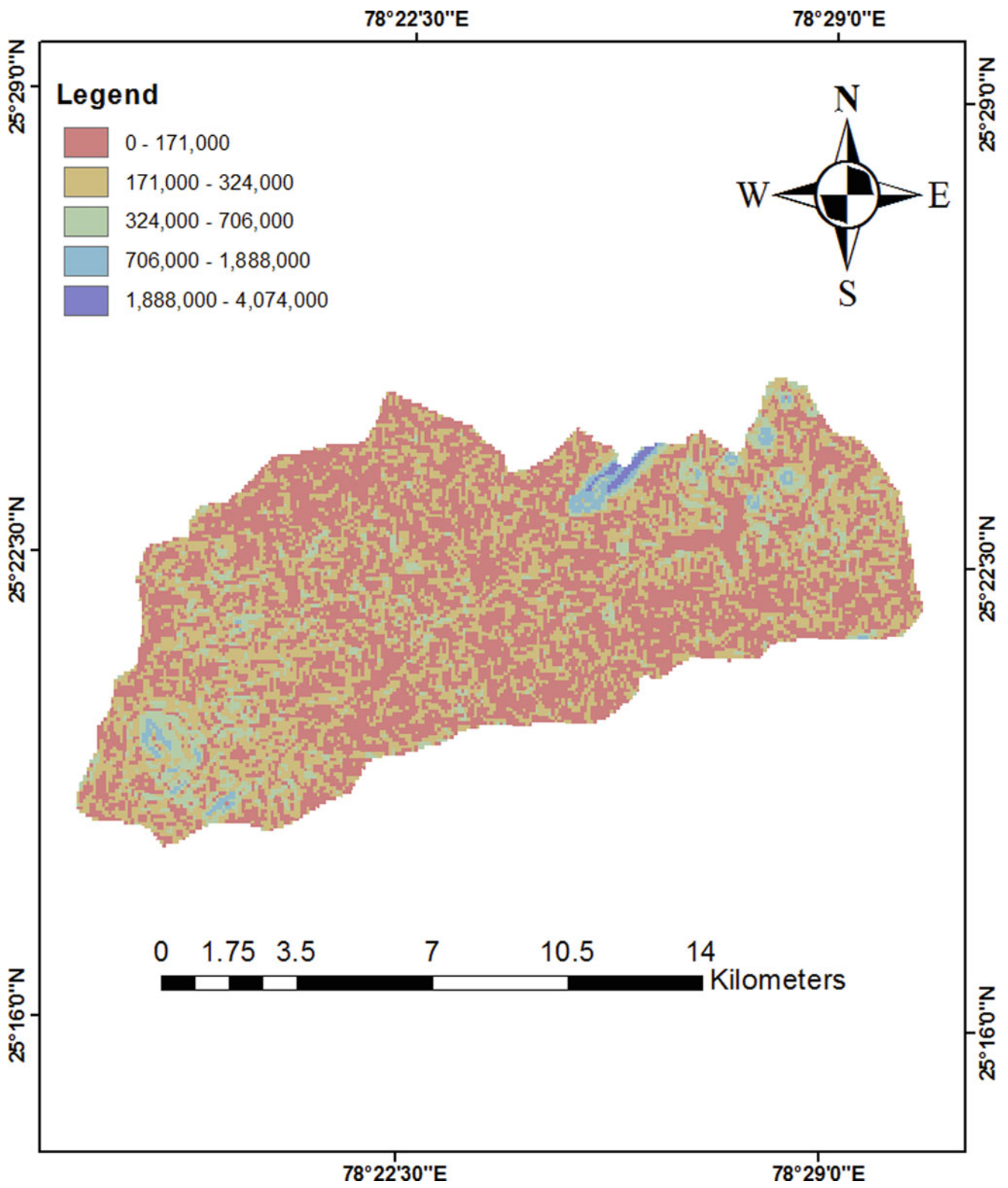


Fig. 6 Hill shade map of study area

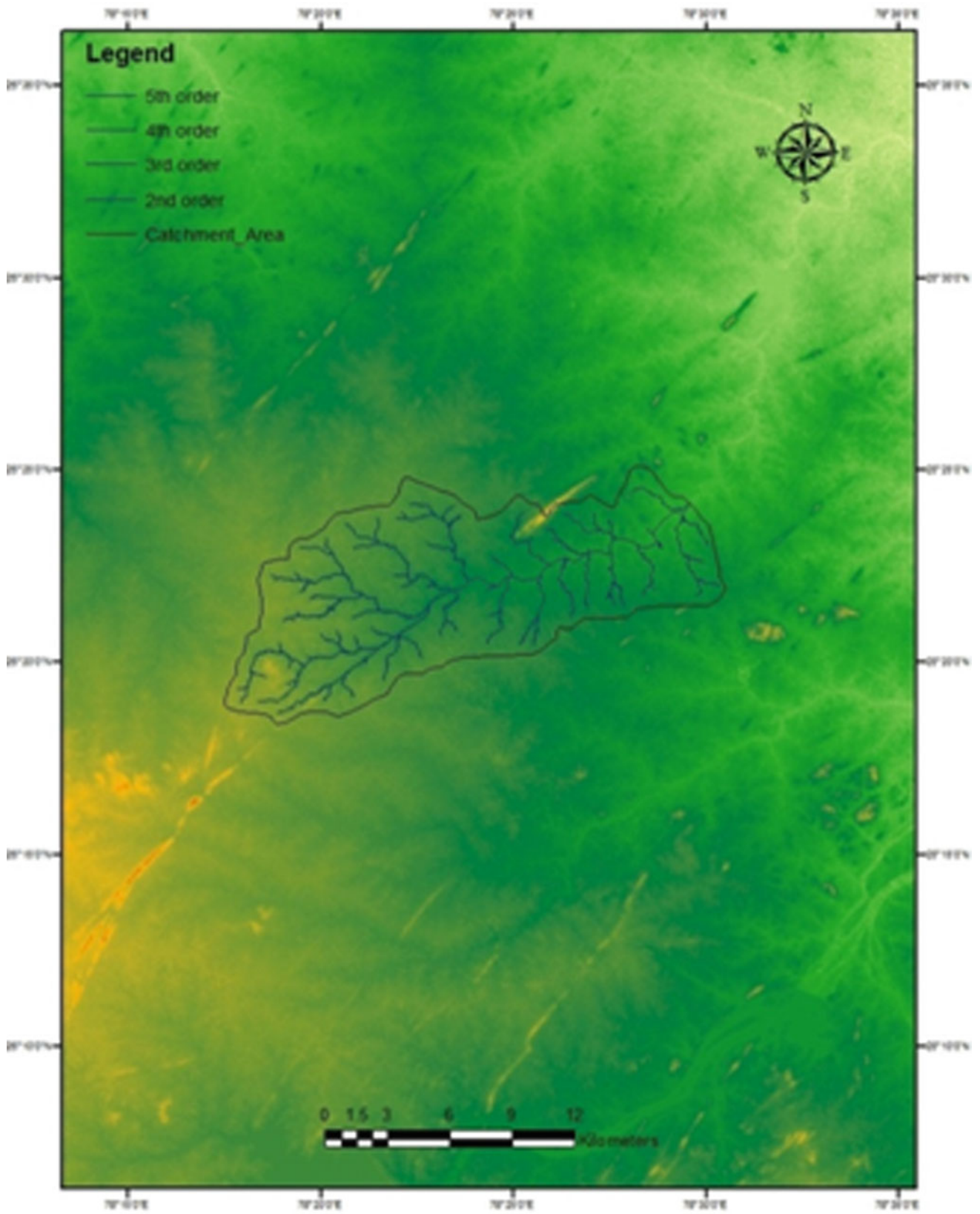


Fig. 7 The relationship between drainage network and major lineaments of the study area

8 Conclusions

Based on the above analysis the following conclusive remarks were drawn.

The morphometric analysis of Upper Pahuj basin will be helpful in depicting nature of subsurface lithology, infiltration capacity and surface runoff. The drainage evolved in a homogenous geological terrain and influenced by geological structures. The elongated basin shows moderately steeper slope and semipermeable soil with less vegetal cover. The upper Pahuj catchment basin is moderately steeper and is less prone to soil erosion. These studies would be useful in making planning for watershed management and water harvesting.

Acknowledgements The authors are extending their thanks to Department of Geology, Bundelkhand University, India for providing necessary facilities. We are extremely thankful to Professor S.N. Mohapatra, School of Studies in Earth Science Jiwaji University Gwalior, India and Dr Vignesh, SRM School of Public Health, SRM Institute of Science and Technology Kattankulathur, Chennai, Tamilnadu, India for reviewing the manuscript and giving valuable suggestions.

References

- Agarwal CS (1998) Study of drainage pattern through aerial data in Naugarh area of Varanasi district, U.P. *J Indian Soc Remote Sensing* 26:169–175
- Bhatt SC (2014) Geological and tectonic aspects of Bundelkhand Craton, Central India. Angel Publication, Bhagwati Publishers and Distributors C-8/77-B, Keshav Puram, New Delhi, 190
- Bhatt SC (2020) Natural resources, water harvesting and drought in Central India. Shree Publishers and Distributors 22/4735, Prakash Deep Building Ansari Road, Daryaganj, New Delhi 110002:130
- Bhatt SC, Husain A (2008) Structural history and fold analysis of basement rocks around Kuraicha and adjoining areas, Bundelkhand Massif Central India. *J Soc India* 2:331–347
- Bhatt SC, Gupta MK (2009) Tectonic significance of shear indicator in the evolution of Dinara-Garhmanu shear zone, Bundelkhand Massif, Central India. In: Santosh K (ed) MTM. Macmillan Publishers India Ltd., New Delhi, pp 122–132
- Bhatt SC, Gupta MK (2014) Microstructural analysis and strain pattern in mylonites and implications of shear sense indicators in evolution of Dinara- Garhmanu shear zone, Bundelkhand Massif, Central India. *The Indian Mineralogist. J Mineral Soc India* 48(2):186–206
- Bhatt SC, Hussain A (2012) Shear indicators and strain pattern in quartz mylonites of Chitwad – Deori shear zone, Bundelkhand Massif, Central India. *Earth Sci India* 5(II):60–78
- Bhatt SC, Mahmood K (2012) Deformational pattern and microstructural analysis of sheared gneissic complex and mylonitic metavolcanics of Babina-Prthipur sector, Bundelkhand Massif, Central India. *Indian J Geosci* 66(1):79–90
- Bhatt SC, Singh VK, Hussain A (2011) Implications of shear indicators for tectonic evolution of Mauranipur shear zone, Bundelkhand Craton, Central India. In: Singh VK, Chandra R (eds) 2nd Proceeding of precambrian continental growth and tectonism. Angel Publication, New Delhi, pp 36–49
- Bhatt SC, Suresh M, Gupta MK (2015) Structural control on drainage pattern of upper- middle Pahuj river and implication of remote sensing in watershed management, BundelkhandCraton, Central India. *J Multidiscip Sci Res* 2(4):9–14
- Bhatt SC, Hussain A, Suresh M, Balasooriya NWB (2017) Geological structure control on Sukhnai basin and land use/ land cover pattern in Mauranipur and adjoining areas, Bundelkhand Craton, Central India. *J Geol Soc Sri Lanka* 18(2):53–61
- Bhatt SC, Singh R, Ansari MA, Bhatt S (2020) Quantitative morphometric and morphotectonic analysis of Pahuj catchment basin Central India. *J Geol Soc India* 96(5):513–520
- Biswas S, Sudhakar S, Desai VR (1999) Prioritisation of sub-watersheds based on morphometric analysis of drainage basin: a remote sensing and GIS approach. *J Indian Soc Remote Sens* 27 (3):155–166
- Chorley RJ, Maim DEG, Pogorzelski HA (1957) A new standard for estimation drainage basin shape. *Am J Sci* 255:138–141
- Faniran A (1968) The index of drainage intensity- a provisional new drainage factor. *Australian J Sci* 31:328–330
- Gregory KJ, Walling DE (1973) Drainage basin form and process a geomorphological approach. Edward Arnold, London
- Gutema D, Kassa T, Sifan A, Koriche (2017) Morphometric analysis to identify erosion prone areas on the upper blue Nile using GIS: case study of Didessa and Jema sub basin, Ethiopia. *Int Res J Eng Technol* 04(08)
- Horton RE (1932) Drainage basin characteristics. *Trans Am Geophys Union* 13:350–361
- Horton RE (1945) Erosional development of streams and their drainage basins: a hydrophysical approach to quantitative morphology. *Geol Soc Am Bull* 56(3):275–370
- Melton MA (1957) An analysis of the relations among elements of climate, surface properties and geomorphology. Technical Report, 11: Proj NR389- 042.off of Nav Res Newyork, Department of Geology, Columbia University
- Melton MA (1965) The geomorphic and palaeoclimatic significance of alluvial deposits in Southern Arizona. *J Geol* 73(1):1–38
- Miller VC (1953) A quantitative geomorphic study of drainage basin characteristics on the Clinch Mountain Area, Virginia and Tennessee. Proj., NR 389–402, Technical Report 3, Columbia University, Department of Geology, ONR, New York
- Nag SK, Chakraborty S (2003) Influences of rock types and structures in the development of drainage network in hard rock area. *J Indian Soc Remote Sens* 31(1):25–35
- Obi Reddy GE, Maji AK, Gajbhiye KS (2002) GIS for morphometric analysis of drainage basins. *GIS India* 4:9–14
- Pareta K, Pareta U (2011) Quantitative morphometric analysis of a watershed of Yamuna basin, India using ASTER(DEM) data and GIS. *Int J Geo Geosci* 2(1):248–269
- Pati JK, Lal J, Prakash K, Bhusan R (2008) Spatio- temporal shift of western bank of Ganga river, Allahabad city and its implications. *J Indian Soc Remote Sens* 36:289–297
- Schumm SA (1954) The relation of drainage basin relief to sediment loss. *Int Assoc Sci Hydrol* 36:216–219
- Schumm SA (1956) Evolution of drainage systems and slopes in Badlands at Perth Anboy New Jersey. *Bull Geol Soc Am* 67:597–646
- Singh S, Singh MC (1997) Morphometric analysis of Kanhar River basin. *Natl Geogr J India* 43(1):31–43
- Singh VK, Slabunov A (2015) The Central Bundelkhand Archaean greenstone complex, Bundelkhand Craton, Central India: geology, composition, and geochronology of supracrustal rocks. *Int Geol Rev* 57(11–12):1349–1364
- Singh VK, Slabunov AI, Nesterova NS et al (2021) Tectonostratigraphic terranes of the Bundelkhand Craton (Indian shield). In: Shandilya AK,

- Singh VK, Bhatt SC, Dubey CS (eds) Geological and Geo-environmental Processes on Earth, pp 155–164 (this volume)
- Sreedevi PD, Subrahmanyam K, Ahmad S (2004) The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. *Environ Geol* 47:412–420
- Strahler AN (1952) Hypsometric analysis of erosional topography. *Bull Geol Soc Am* 63:1117–1142
- Strahler AN (1956) Quantitative slope analysis. *Bull Geol Soc Am* 67:571–596
- Strahler AN (1964) Quantitative geomorphology of drainage basin and channel network. In: *Handbook of applied hydrology*, pp 39–76
- Wentworth CK (1930) A simplified method of determining the average slope of land surfaces. *Am J Sci* 21:184–194