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ORIGINAL PAPER

Quantitative morphometric analysis in the hard rock Hirehalla sub-basin, Bellary and Davanagere Districts, Karnataka, India using RS and GIS

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Abstract Quantitative morphometric analysis of Hirehalla sub-basin has been carried out using GIS and remote sensing techniques which are found to be very useful and powerful tools to compute and decipher different characteristics of the basin and its drainage network. Linear, areal and relief aspects have been computed and evaluated using topographical maps and remote sensing data. Results arrived at through computation of different parameters using GIS capabilities have enabled to understand the characteristics of the drainage network and topographical aspects which have a bearing on the hydrogeology of the sub-basin. The average bifurcation ratio (R_b) is 3.75, which means the drainage sub-basin is not dominated by structural control but geomorphologically controlled. The form factor (F_f) is 0.42 indicating that the sub-basin is more of elongated in shape with dendritic to sub-dendritic drainage pattern. The relief ratio (R_r) is 0.013 depicting the low to moderate relief and slope. All the quantitative morphometric parameters have been computed using standard formulae. Overall GIS-based analysis of all quantitative morphometric parameters suggests that, lithologically, the sub-basin is composed of compact and resistant basement rocks and has low degree of slope thus less prone to erosion. Three of the catchments of the study area are found to have a moderate possibility for the occurrence of flash floods which has a bearing on their groundwater-recharge and thus, their groundwater occurrence and potentiality. These studies are very important and useful for proper planning and management of groundwater resources.

Introduction

In today's fast growing world, rapid increase in population, urbanization and industrialization are inevitable. The consumption of natural resources such as land and water is at considerably high rates. To meet the demands for these resources, optimum utilization is necessary for sustainable development. Thus, here, water resources have been emphasized.

The main source of water is precipitation, which when comes in contact with earth's surface joins streams and rivers and infiltrates down as groundwater which further depends on many factors such as soil type, topography and geologic control of the area such as rock types and its properties, structural units-faults, folds, joints and beds.

Morphometry is the measurement and mathematical analysis of the configuration of the earth surface, shape and dimension of its landforms (Clarke 1966). Due to irregular rainfall pattern and uncontrolled and overuse of surface and subsurface water, the groundwater levels have declined to very deeper levels. Thus, it becomes necessary to study, evaluate, plan and prepare for proper management of water resources at sub-basin scale. To do so, it is important to study and know its properties like subsurface lithology, infiltration, runoff, drainage pattern, topography and relief of the region. A detailed morphometric analysis of an area is of great help in

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understanding the drainage network and evaluating its effect and influence on landforms and other features (Leopold and Miller 1956).

The morphometric analysis of river basin helps to explore the interrelationship between hydraulic parameters and geomorphologic characteristics. Morphometric characterization and prioritization is important to recognize hydrological behaviour of the basin for carrying out management strategies. These studies have been carried out by many researchers like Yadav et al. 2014; Aher et al. 2014 and Rahaman et al. 2015.

The morphometric analysis can be carried out through measurement of linear, areal and relief aspects and slope contributions (Nag and Chakraborty 2003). Drainage basins are the fundamental units to understand geometric characteristics of fluvial landscape, such as topology of stream networks, and quantitative description of drainage texture, pattern, shape and relief characteristics (Obi Reddy et al. 2004, Subba Rao 2009).

In recent times, remote sensing- and GIS-based studies have been carried out for different purposes in the field of earth sciences such as in the assessment of groundwater potentiality in Tirnavos area of Greece (Oikonomidis et al. 2015); in the studies related to degradation risk of soil and soil erosion (Aiello et al. 2015, and El Baroudy and Moghanm 2014); in groundwater mapping studies (Elbeih 2014); landslide hazard zonation studies (Pandey et al. 2008); water storage studies (Douglas 2003); impact of storm along the coast of New Orleans (Klemas 2009); geo-environmental hazard studies (Arnous 2011); sea-level rise and coastal vulnerability studies along the coast of Andhra Pradesh, India and identification of such risk zones (Nageshwar Rao et al. 2008), etc. In the field of drainage basin morphometry, these techniques have been applied and studied by many hydrologists, hydrogeologists, geomorphologists and geoscientists on varied geographical areas (Krishnamurthy et al. 1996; Vittala et al. 2004; Sreedevi et al. 2005; Sameena et al. 2009; Singh et al. 2013; Singh et al. 2014; Banerjee et al. 2015).

The morphometric parameters of the study area have been studied by analysing topographical map and remote sensing data using GIS techniques. In the present study, an attempt has been made to evaluate the quantitative morphometric parameters and also analyse other parameters such as infiltration, runoff and erosional conditions for the proper assessment of groundwater potentials.

Study area

The Hirehalla sub-basin is one of the tributaries of the perennially flowing River Tungabhadra. The sub-basin is spread over an area of 485 km^2, covering parts of Hoovinahadagli and Harapanahalli taluks of Bellary and Davanagere districts, respectively, in Karnataka state. The basin is covered in the Survey of India toposheets numbered 48 M/16, 48 N/13 and 57B/01 and geographically falls between 75°45′ and 76°15′ east longitudes and 14°45′ and 15°15′ north latitudes (Fig. 1).

Physiographically, major part of study area is occupied by denudational plateau with some hills and valleys in southwestern part. The highest and lowest elevations of the area are 964 and 497 m, respectively. Red sandy soil covers most of the study area; black soil and mixed type soil are observed at some places in the southern part. In general, the climate of the region is semi-arid. The temperature reaches its high in the month of April and May and low in the month of December and January.

The study area exposes rocks of Peninsular Gneissic Complex, Chitradurga Group of Shimoga schist belt and Chitradurga Group of Chitradurga schist belt of Archaean age (Radhakrishna and Vaidyanadhan 1994). Dolerites and quartz veins of Paleoproterozoic age intrude these rocks. Vast continuous stretch of Peninsular Gneissic Complex with scanty outcrops forms the basement rock. The rock is medium to coarse grained, mesocratic, greyish coloured consists of quartz, plagioclase and biotite. The northeastern part is represented by Chitradurga Group of Chitradurga schist belt which is represented by Hiriyur Formation which comprises of amphibolites, greywacke/argillite, conglomerate, metabasalt and banded iron formation. While the southern part is represented by Chitradurga Group of Shimoga schist belt which is represented by Ranibennur Formation and this comprises of greywacke/argillite with bands of banded iron formation. Basic intrusive in the form of dolerite dykes are seen in southern part while quartz veins criss-crossing the PGC can be seen in the eastern part of the study area (Fig. 2). Therefore, granites and gneisses are the predominant lithounits followed by schistose rocks. BIFs, intrusive and quartz veins are minor lithounits. Thus, the study area forms a hard-rock terrain, typical of most parts of the Peninsular India.

Materials and methods

The boundary of the Hirehalla sub-basin has been delineated using Survey of India topographical maps—48 M/16, 48 N/13 and 57B/01 which are of 1:50,000 scale. Catchments (HSB-I, II, III and IV) and drainage network have been extracted by digitizing the Survey of India toposheets using ArcGIS v10. While dividing the catchments (HSB-I, II, III and IV), procedure as suggested by All India Soil and Land Use Survey (AIS and LUS 1990) was adopted. The basin morphometric parameters (both, linear and areal) such as basin area, perimeter and length, stream number and length of each stream for different order were extracted and calculated using 'Calculate Geometry' and 'Statistics' capabilities ArcGIS and other parameters such as drainage density, stream frequency, stream length ratio, mean stream length, form factor, circulatory ratio, elongation ratio, lemniscate ratio, length of overland flow, etc.
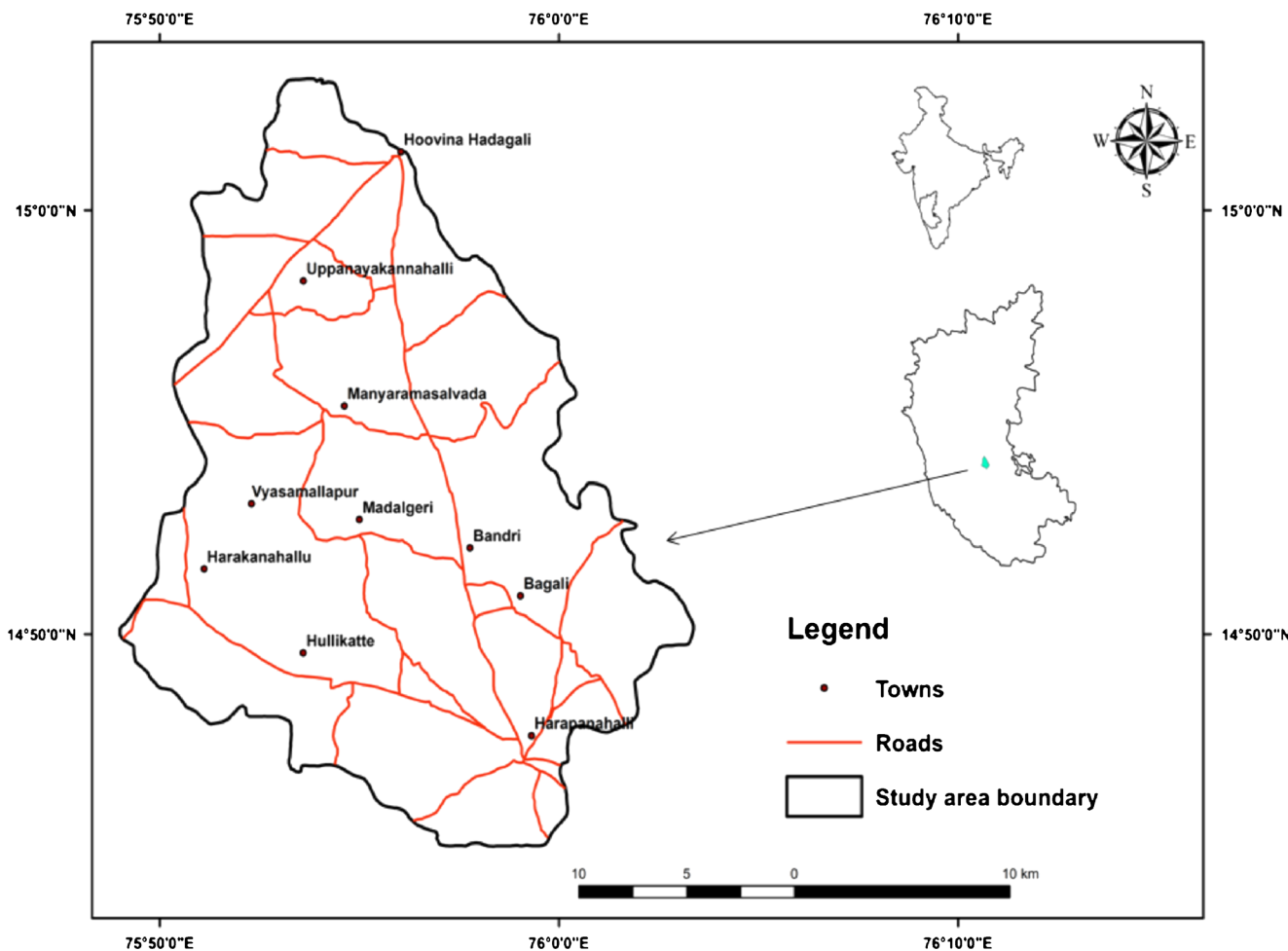
Fig. 1 Location of Hirehalla sub-basin

were derived from these parameters. Digital elevation model (DEM) of the study area was extracted by analysing Shuttle Radar Topographic Mission (SRTM) data of 90 m resolution by using spatial analyst tool in ArcGIS. The SRTM data was obtained from the website of www.earthexplorer.usgs.gov where it is freely downloadable. All the topographical maps and satellite images were first georeferenced using ground control points (GCPs) and mosaiced using ArcGIS tools. After georeferencing of images, they were rectified and projected with geographical coordinate system (GCS) and later reprojected into Universal Transverse Mercator (UTM) WGS 1984, Zone 43 North. The elevation and other characteristics were verified using the global positioning system (GPS) during field visit. Geology map of the study area was prepared using the District Resource Map of Bellary district published by the Geological Survey of India in 2005 as a base map.

Results and discussion

Morphometric analysis of a basin is an important technique to evaluate and understand the behaviour of hydrological system. It provides quantitative specification of basin geometry to understand slope or inconsistencies in rock hardness, structural controls, recent diastrophism, geological and geomorphic history of drainage basin (Strahler 1964; Esper Angillieri 2008). In the present study, quantitative analysis of the basin characteristics has been computed from linear (unidimensional), areal (two dimensional) and relief (three dimensional) aspects (Table 1), details of which have been discussed below.

Linear aspects

Linear aspects include stream order, stream number, bifurcation ratio, stream length, stream length ratio, rho coefficient and length of overland flow.

The first step in morphometric analysis of basin is delineation of boundary and designating stream orders. Here, due to its simplicity, Strahler's (1957) system of ordering of streams has been applied over Horton's (1932) system of stream ordering. Wherein the channel network map includes all intermittent and permanent flow lines located in clearly defined valleys, the smallest finger-tip tributaries are designated order
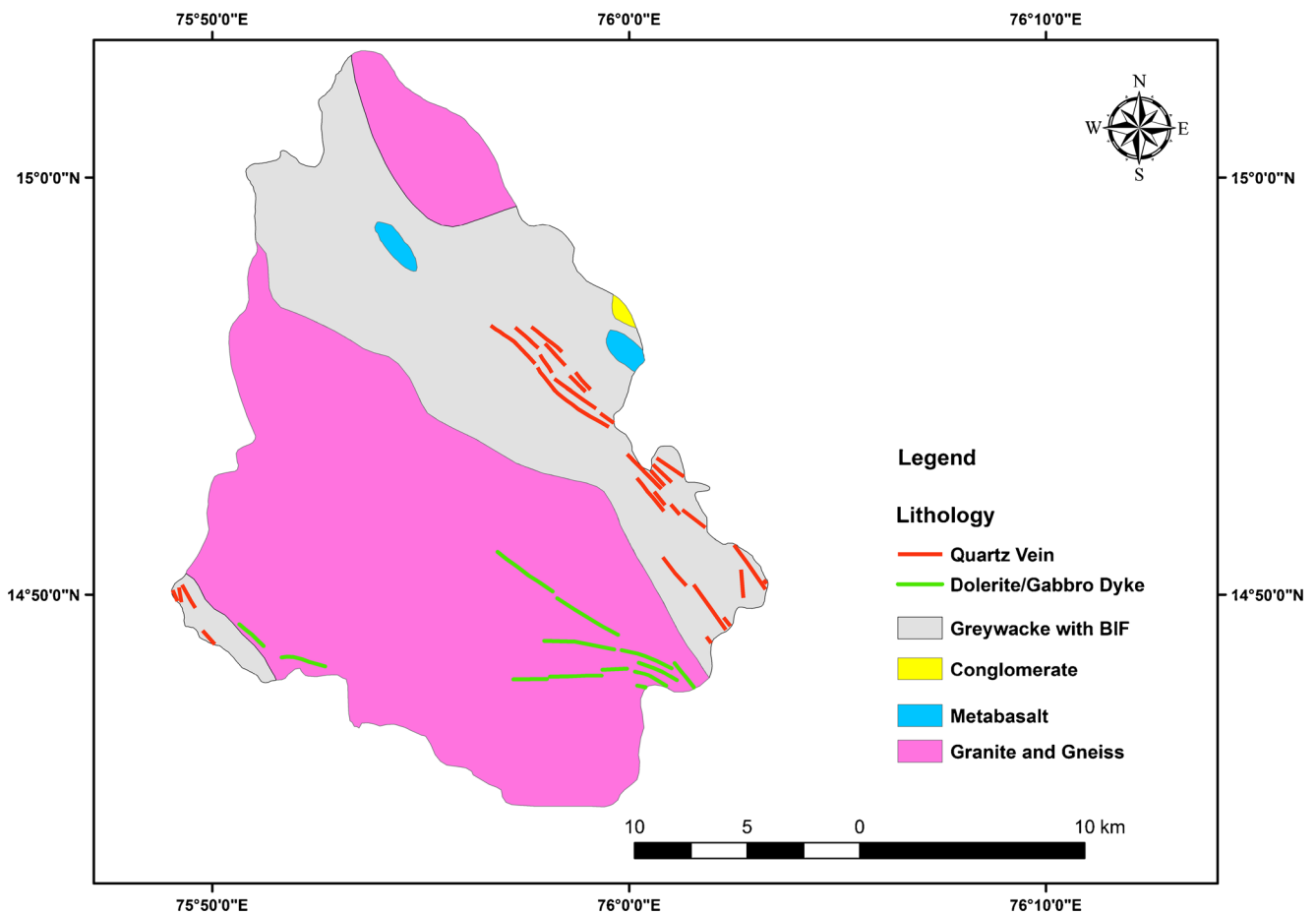
Fig. 2 Geology of Hirehalla sub-basin

1. Where two such first order channels join a channel segment of order 2 is formed and so on. The trunk stream through which all discharge of water and sediment passes is therefore the stream segment of highest order.

Stream order (*u*) and stream number (N_u)

Stream ordering (*u*) refers to the determination of hierarchical ranking of the stream within a drainage basin. Stream number (N_u) refers to the total number of stream segments of the order '*u*'. The highest stream order in the Hirehalla sub-basin is 6; the sub-basin comprises of 712 streams of First Order, 204 of Second Order, 49 of Third Order, 12 of Fourth Order and 3 streams of Fifth Order. The total number of streams for the entire basin is 981 (Fig. 3 and Table 2).

The drainage pattern of Hirehalla sub-basin shows dendritic to sub-dendritic. Within the Hirehalla sub-basin, the catchment of HSB-I has the highest stream order of 4 while each of the remaining catchments HSB-II, III and IV have highest stream order of 5. These catchments have been studied in detail along with the entire Hirehalla sub-basin so as to understand different aspects of morphometry and their implications.

Horton's (1932) law of stream number states that the number of stream segments of each order forms an inverse geometric sequence with order number. A logarithmic regression of number of streams of each order against stream order usually gives a straight line plot with very little scatter. The regression plot of stream number against stream order showed validation of law of stream number for Hirehalla sub-basin (Fig. 4).

The high number of first order streams depicts terrain complexity and compact bedrock. The variation in order and size of the basin is largely due to physiographic and structural conditions of the region (Sreedevi et al. 2009).

Bifurcation ratio (R_b)

Bifurcation ratio (R_b) can be defined as a ratio of the number of stream segment of given order (N_u) to the number of stream segment of the next higher order (N_{u+1}). The bifurcation ratio reflects the complexity and degree of dissection of a drainage basin. After studying a diverse range of drainage basins, Horton (1945) stated that bifurcation ratio ranges up to about

Table 1 Definitions and formulae used for computation of morphometric parameters

Sl. no.	Morphometric parameters	Formula/definition	Reference
Linear aspects			
1	Stream order (u)	Hierarchical rank	Strahler 1964
2	Stream number (N_u)	Total number of stream segments of the order 'u'	Strahler 1957
3	Bifurcation ratio (R_b)	$R_b = N_u/N_{(u+1)}$ where N_u = total number of stream segments of the order 'u' and $N_{(u+1)}$ = number of stream segments of the next higher order	Schumm 1956
4	Stream length (L_u)	Total length of the stream segments of that particular order	Horton 1945
5	Mean stream length (L_{sm})	$L_{sm} = \sum L_u/N_u$ where L_u = total length of the stream segments of that particular order N_u = total number of stream segments of the order 'u'	Strahler 1964
6	Stream length ratio (R_l)	$R_l = L_u/L_{(u-1)}$ where L_u = the mean length of all stream segments of a given order (u) and $L_{(u-1)}$ = the mean length of all stream segments of one order less to given order (u)	Horton 1945
7	RHO coefficient (ρ)	$\rho = R_l/R_b$ where R_l = stream length ratio and R_b = bifurcation ratio	Horton 1945
8	Length of overland flow (L_g)	$L_g = 1/2D_d$ where D_d = drainage density of basin	Horton 1945
Areal aspects			
9	Form factor (F_f)	$F_f = A/L_b^2$ where A = area of the basin (km^2) and L_b = basin length (km)	Horton 1932 & Horton 1945
10	Circulatory ratio (R_c)	$R_c = 4\pi A/P^2$ where A = area of the basin (km^2) and P = perimeter of basin (km)	Miller 1953 & Strahler 1964
11	Elongation ratio (R_e)	$R_e = D/L_b = 1.128\sqrt{A}/L_b$ where D = diameter of a circle of the same area (A) as the basin, A = area of basin (km^2) and L_b = basin length	Schumm 1956
12	Lemniscate ratio (K)	$K = \pi L_b^2/4A$ where L_b = basin length and A = area of the basin	Chorley 1957
13	Drainage density (D_d)	$D_d = \sum L_u/A$ where L_u = total length of the stream segments of that particular order and A = area of the basin (km^2)	Horton 1945
14	Stream frequency (F_s)	$F_s = \sum N_u/A$ where N_u = total number of stream segments of the order 'u' and A = area of the basin (km^2)	Horton 1932
15	Drainage texture (T)	$T = D_d * F_s$ where D_d = drainage density and F_s = stream frequency	Horton 1945
16	Constant of channel maintenance (C)	$C = 1/D_d$ where D_d = drainage density of basin	Schumm 1956
17	Compact coefficient (C_c)	$C_c = P/2\sqrt{\pi A}$ where P = perimeter of basin (km) and A = area of the basin (km^2)	Gravelius 1914
Relief aspects			
18	Basin relief (R)	R = (maximum−minimum) elevation	Hadley and Schumm 1961
19	Relief ratio (R_r)	$R_r = R/L$ where R = basin relief and L = basin length	Schumm 1956
20	Ruggedness number (R_n)	$R_n = R * D_d$ where R = basin relief and D_d = drainage density of basin	Strahler 1956
21	Melton ruggedness number (M_{rn})	$M_{rn} = (H_{maxi} - H_{mini})/A^{0.5}$	Melton 1965

2 for flat areas, up to 3 for rolling drainage basins and 4 for highly dissected or mountainous basins.

According to Strahler (1964), where the R_b is ranging between 3 and 5, geological structures do not hold a dominant control over the drainage pattern. While R_b greater than 5 indicates structural control over the drainage network (Strahler 1957).

The mean R_b values calculated for sub-basins HSB-I, II, III and IV are 4.68, 3.77, 4.02 and 3.56, respectively, while mean R_b for the entire as a whole Hirehalla sub-basin is 3.75 (Table 3). This indicates that in the present study area, the structural control over the development of drainage network is not as pronounced as the geomorphic control, i.e. the lower values of R_b indicate that the sub-basin is less affected by structural disturbances. These values of R_b also indicate that the sub-basin belongs to the 'normal basin' category (Strahler 1957).

RHO coefficient (ρ)

It was defined by Horton (1945), as the ratio between the stream length ratio and the bifurcation ratio. It is an important factor, relating drainage density to physiographic development of a watershed which facilitates evaluation of storage capacity of drainage network and hence is a determinant of ultimate degree of drainage development in a given watershed. It also depends upon the climatic, geologic, biologic, geomorphologic and anthropogenic factors.

In the present study area, mean rho value for the study area as a whole is 0.15 and varies from 0.15 to 0.51 for the four catchments HSB-I, II, III and IV (Table 3). The slight higher value of $\rho = 0.51$ for sub-basin HSB-IV indicates higher hydrologic storage
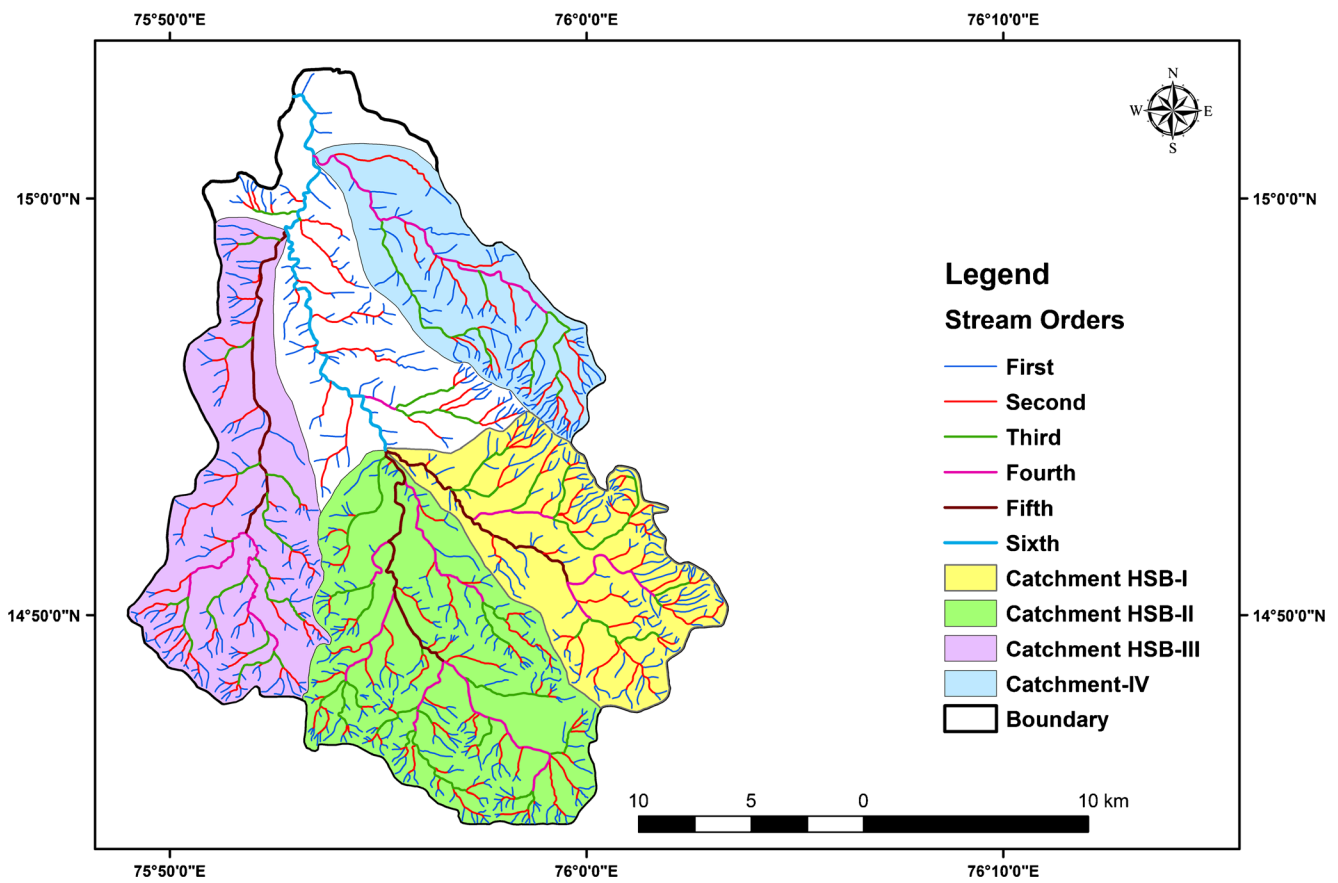
Fig. 3 Drainage network of Hirehalla sub-basin with catchments

during floods and attenuation of effects of erosion during elevated discharge.

Length of overland flow (L_g)

Horton (1945) used this term to refer the length of flow path of the rainwater on the ground surface before it gets localized into definite channels. It is the length of water over the ground before it gets concentrated into definite stream channels and affects both hydrologic and physiographic development of drainage basin. It can be considered as the most dominant hydrologic and morphometric

factor in the development of drainage network and is a measure of stream spacing and degree of dissection and is approximately one half the reciprocal of drainage density (Chorley 1969).

For a comparison of the sub-basins in respect of the nature of flowpath, the L_g is classified as (1) low (<0.20 km^2/km), (2) medium (0.20–0.30 km^2/km) and (3) high (0.30–0.40 km^2/ km).

The L_g value for the study area as a whole is 0.27, while it varies from 0.23 to 0.32 for the four catchments HSB-I, II, III and IV (Table 3). L_g = 0.32 for HSB-III sub-basin has slightly high flow path but overall indicating ground slopes, flow-

Table 2   Linear aspects of Hirehalla sub-basin

Sub-basin/catchment	A	P	No. of streams (N_u) of order 1 to 6							Order-wise total length of streams (L_u) in km						
			N1	N2	N3	N4	N5	N6	Total	L1	L2	L3	L4	L5	L6	Total
HSB-I	68	40	89	27	04	01			121	59	31	19	14			124
HSB-II	101	56	141	44	13	02	01		201	85	37	26	12	15		174
HSB-III	132	50	250	70	18	05	01		344	131	66	36	27	12		271
HSB-IV	89	47	155	42	10	03	01		211	101	46	24	11	11		193
Hirehalla	485	110	712	204	49	12	03	01	981	426	215	114	66	38	22	880

A area of basin in km^2, P perimeter of basin in km
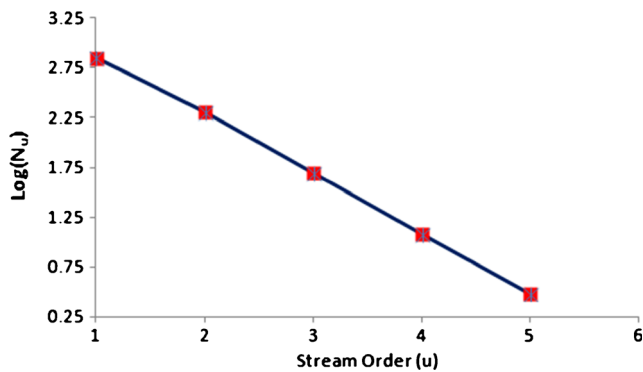
Fig. 4 Logarithm regression of stream number (N_u) and stream order (u) for the study area

Mean stream length (L_{sm})

Mean stream length (L_{sm}) is a characteristic property related to the size of drainage network components and its contributing basin surfaces (Strahler 1964). This has been calculated by dividing the total stream length of order 'u' and number of stream of segments of the same order 'u'.

In the present study area, the values of mean stream length for the study area as a whole varies whole of basin vary from 0.59 for the first order streams to 21.8 for the sixth order stream (Table 4) and mean stream length of any given order is greater than that of the lower order and less than that of its next higher order.

Stream length ratio (R_l)

Stream length ratio (R_l) can be defined as the ratio of the mean length of a stream (L_u), of any given order (u) to the mean length of a stream of the next lowest order (L_{u-1}). According to Horton's law of stream length (1945), the ratio of stream length is constant throughout the series. The stream length ratio shows an important relationship with discharge of the surface flow and erosional stage of the basin (Sreedevi et al. 2005).

In the present study area, mean R_l for the study area as a whole is 0.55 and varies from 0.63 to 1.86 for the four catchments HSB-I, II, III and IV (Table 4). Thus, it is noticed that the R_l between successive stream order does not vary much which may be due to homogeneity of topographic conditions.

Areal aspects

Areal aspects of the drainage basin include the basin shape, drainage density, stream frequency, drainage texture, drainage intensity and constant of channel maintenance.

Basin shape

Following factors describe the shape of the basin- form factor, circulatory ratio, elongation ratio and lemniscate ratio.
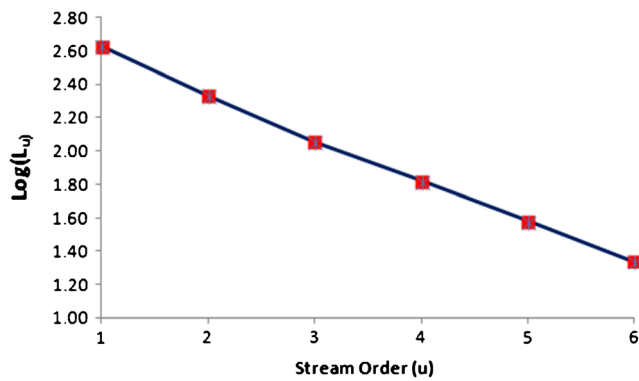
paths, runoff and infiltration being moderate for the entire Hirehalla sub-basin.

Stream length (L_u)

The stream length (L_u) is a dimensional property used to understand the characteristic size of the components of a drainage network. It reflects the hydrological characteristics of the underlying rock surface over the areas of consecutive stream orders. A smaller number of relatively longer stream lengths are formed, where the rock formations are permeable, while a larger number of smaller stream lengths are developed where the rock formations are less permeable (Pakhmode et al. 2003). Stream length is measured from origin of a river to drainage divide using GIS tools. It has been computed based on the laws proposed by Horton (1945).

The geometrical relationship is shown graphically in the form of a straight line, using when the plot of logarithm of stream length (L_u) against stream orders (u) (Fig. 5). The plot depicts a set of points lying essentially along the straight line which fulfils Horton's (1945) law of stream length. The straight line indicates that the ratio between L_u and u is constant throughout the successive order of a basin and suggests that geometrical similarity is maintained in basins of increasing order. Also, the total length of stream segments is higher in first order streams and decreases as the stream order increases.

Table 3 Linear aspects of Hirehalla sub-basin

Sub-basin/catchment	Bifurcation ratio (R_b)						RHO coefficient (ρ) for each order							Length of overland flow (L_g)
	1/2	2/3	3/4	4/5	5/6	Mean R_b	1	2	3	4	5	6	Avg	
HSB-I	3.30	6.75	4.00			4.68	0.16	0.09	0.19				0.15	0.27
HSB-II	3.20	3.38	6.50	2.00		3.77	0.71	0.42	0.35	0.39			0.47	0.29
HSB-III	3.57	3.89	3.60	5.00		4.02	0.56	0.47	0.37	0.46			0.46	0.32
HSB-IV	3.69	4.20	3.33	3.00		3.56	0.60	0.46	0.65	0.33			0.51	0.23
Hirehalla	3.49	4.16	4.08	4.00	3.00	3.75	0.14	0.13	0.14	0.14	0.19		0.15	0.27

Fig. 5 Logarithm regression of stream length (L_u) and stream order (u) for the study area

Form factor (F_f)

Horton (1932) defined form factor as the ratio of the area of the basin to the square of the length of the basin. According to him, the value of F_f varies from zero (0) for highly elongated shape to one (1) for perfect circular shape. Also, F_f is used to predict the intensity of flow of a defined basin and has direct relation to peak discharge (Horton 1945; Gregory and Walling 1973).

The calculated value of F_f for the study area as a whole is 0.42 while it varies from 0.27 to 0.40 for the four catchments HSB-I, II, III and IV (Table 5), thus indicating that the Hirehalla basin being elongated in shape and has peak flows of longer duration of time.

Circulatory ratio (R_c)

Circulatory ratio (R_c) is the ratio of the area of the basin to the area of a circle having the same circumference as the perimeter of the basin (Miller 1953). It depends and varies on many factors such as length of and frequency of streams, geological units, landuse/landcover, climate, topography and slope of the basin.

R_c value nearing one implies that the shape of basin is circular and there exists scope for uniform infiltration and longer duration for excess water to be drained out of the basin.

The value of R_c is a reflection of the stage of evolution of the basin. The low and high values indicate youth and mature stage of the basin, respectively.

The computed R_c value for the entire Hirehalla sub-basin is 0.50 and varies from 0.41 to 0.66 for the four catchments HSB-I, II, III and IV (Table 5), indicating that the Hirehalla basin is elongated in shape.

Elongation ratio (R_e)

Schumm (1956) defined R_e as the ratio between the diameter of the circle of the same area as the drainage basin and the maximum length of the basin. A circular basin is more efficient in the discharge of runoff than an elongated basin (Singh and Singh 1997). The value of R_e generally varies from 0.6 to 1.0 over a wide variety of climatic and geologic types. Values close to 1.0 are typical of regions of very low relief, whereas values in the range of 0.6–0.8 are usually associated with high relief and steep ground slope (Strahler 1964).

These values can be grouped into following categories: (>0.9) = circular; (0.9–0.8) = oval and (<0.7) = less elongated.

The calculated R_e value for the entire Hirehalla sub-basin is 0.73 while it varies from 0.59 to 0.72 for the four catchments HSB-I, II, III and IV (Table 5), indicating that Hirehalla sub-basin is less elongated in shape.

Lemniscate ratio (K)

Chorley (1957) have devised a method for estimation of drainage shape. They defined the basin shape as the degree approach of actual basin form to the pure lemniscates form measured by a lemniscates ratio (K), the ratio of perimeter of basin.

Lemniscate ratio (K) value in the present study area is 1.87 while it varies from 1.92 to 2.80 for the four catchments (Table 5).

Compact coefficient (C_c)

Compact coefficient (C_c) is defined as the ratio of actual basin perimeter to the perimeter (circumference) of a circle of equal

Table 4 Linear aspects of Hirehalla sub-basin

Sub-basin/catchment	Mean stream length (L_{sm}) for each order							Stream length ratio (R_l)				
	1	2	3	4	5	6	Total	2/1	3/2	4/3	5/4	6/5
HSB-I	0.66	1.16	4.82	14.38			21.02	0.53	0.62	0.75		
HSB-II	0.60	0.84	2.00	5.81	14.95		24.20	2.29	1.42	2.24	0.78	
HSB-III	0.52	0.94	1.98	5.40	11.85		20.69	2.00	1.84	1.32	2.28	
HSB-IV	0.65	1.09	2.39	3.67	11.15		18.96	2.21	1.92	2.17	0.99	
Hirehalla	0.60	1.05	2.32	5.49	12.66	21.83	43.95	0.50	0.53	0.58	0.58	0.58

Table 5 Areal aspects of Hirehalla sub-basin

Sub-basin/catchment	F_f	R_c	R_e	K	C_c km^2/km	D_d km/km^2	F_s km^{-2}	T km^{-3}	C
HSB-I	0.27	0.41	0.59	2.80	1.54	1.83	1.79	3.29	0.54
HSB-II	0.36	0.44	0.68	2.12	1.50	1.72	1.98	3.41	0.58
HSB-III	0.40	0.66	0.72	1.92	1.22	1.55	2.60	4.04	0.64
HSB-IV	0.39	0.51	0.70	1.98	1.40	2.18	2.38	5.20	0.46
Hirehalla	0.42	0.50	0.73	1.87	1.40	1.81	2.03	3.68	0.55

F_f form factor, R_c circularity ratio, R_e elongation ratio, K lemniscate ratio, C_c compact coefficient, D_d drainage density, F_s stream frequency, T drainage texture, C constant of channel maintenance

area (Gravelius 1914). This coefficient is equal to unity when the basin shape is a perfect circle, increasing to 1.128 in case of square and may exceed 3 for a very elongated basin (Zavoianu 1985).

The computed value of C_c in the present study area for the entire study area is 1.40 while it varies from 1.22 to 1.54 for the catchments HSB-I, II, III and IV (Table 5).

Drainage density (D_d)

Horton (1932) defined drainage density (D_d) as the length of streams per unit area divided by the area of the drainage basin. The D_d indicates the closeness of spacing of channels. It is an important indicator of the topography, lithology, vegetative cover, relief, etc. of the basin. Based on the observations made over a wide range of geologic and climatic types, it has been found that for an area of highly or permeable subsurface, with dense vegetative cover and low relief, the drainage density tends to be low.

On the contrary, in an area of weak or impermeable subsurface with sparse vegetation and high relief, the drainage density tends to be high (Nag 1998; Nag and Chakraborty 2003).

The calculated value of D_d for the study area as a whole is 1.81 km^2 while it varies from 1.55 to 2.18 for the four catchments HSB-I, II, III and IV (Table 5). Thus, the study area falls in the category of low drainage density and indicating highly permeable subsurface and coarse texture.

Stream frequency (F_s)

Horton (1945) defined stream frequency (F_s) as the ratio between the total number of segments cumulated for all orders within a basin and the basin area. Hypothetically, two basins may have same drainage density but different stream frequency. Similarly, they may have same stream frequency but different drainage density. The relationships between these two parameters are well studied by Melton (1957). According to him, low value of stream frequency (1 to 3.5) indicates the stream or channel

being controlled by fractures and high stream frequency (4 to 10) indicates a more slope from surface run-off.

The computed value of F_s for the Hirehalla basin is 2.03, and it varies from 1.79 to 2.60 for the four catchments HSB-I, II, III and IV (Table 5). Thus, low values of F_s indicate gentle slope and high permeable rocks, thus low run-off and high infiltration.

Drainage texture (T)

Drainage texture (T) is the product of drainage density and stream frequency. It is mainly dependant on climate, rainfall, vegetation, soil and rock type, infiltration capacity, relief and stage of development (Smith 1950).

Based on values of T, Smith (1950) has given the following classification: (>4)-Coarse; (4–10)-Intermediate; (>10)-Fine and (>15)-Ultra fine.

The soft or weak rocks without vegetation produce a fine texture, while massive and resistant rocks cause coarse texture. Sparse vegetation of arid climate causes finer textures than those developed on similar rocks in a humid climate. The drainage texture is commonly dependent upon the vegetation type and climate (Dornkamp and King 1971).

The calculated value of (T) for the Hirehalla sub-basin is 3.68 while it varies from 3.29 to 5.20 for the catchments HSB-I, II, III and IV (Table 5). This indicates that the study area is characterized by coarse drainage texture and has formations having high permeability and infiltration except for catchment HSB-IV (T = 5.20) which has intermediate texture.

Constant of channel maintenance (C)

Constant of channel maintenance is simply the reciprocal of drainage density. Schumm (1956) first coined the term constant of channel maintenance (C) for inverse of drainage density, which can be simply defined as the area of basin surface needed to sustain a unit length of stream channel and is expressed in km^2. The C depends on duration of erosion and climatic regime,
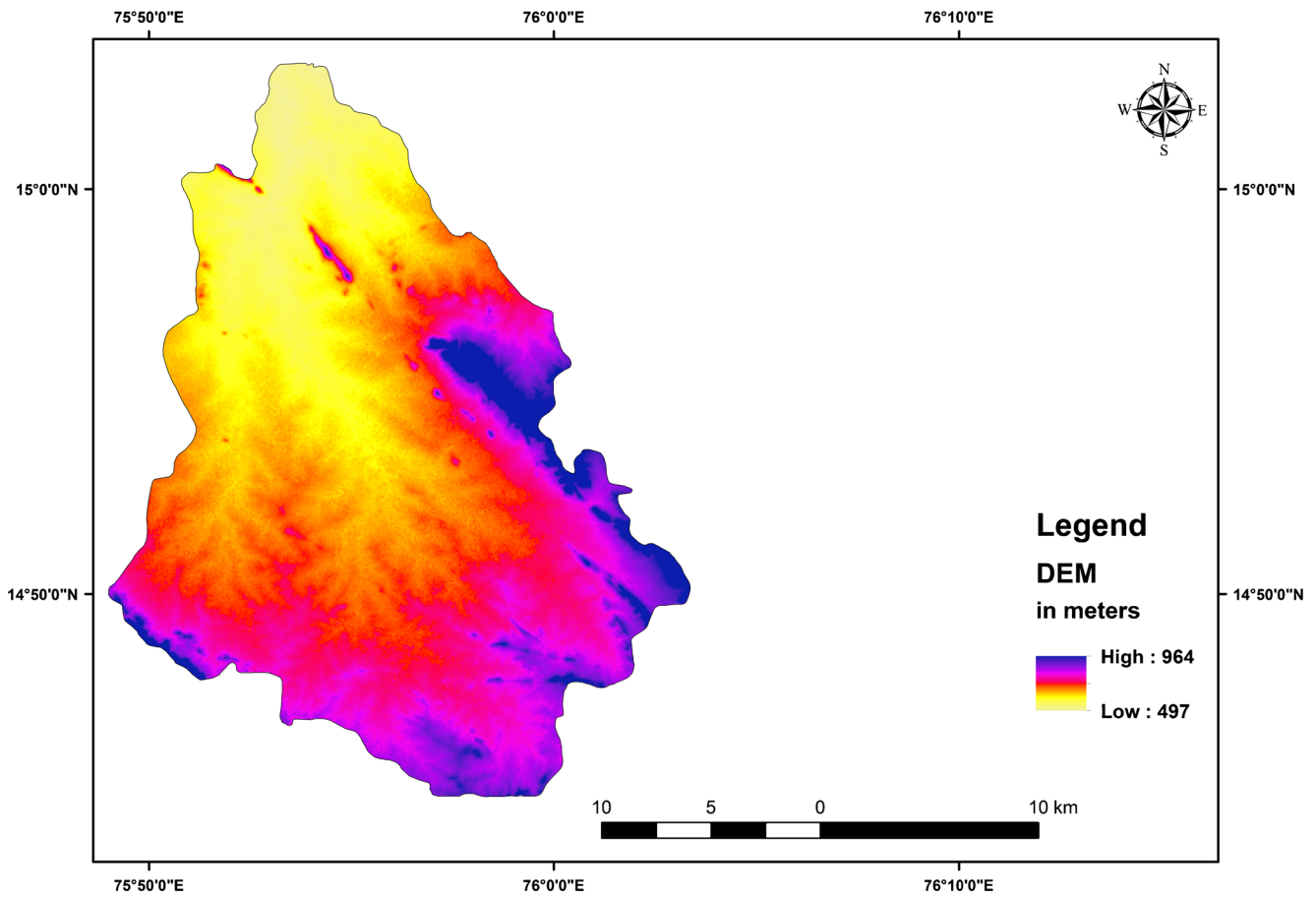
Fig. 6 Elevation (DEM) distribution in the Hirehalla sub-basin

vegetation cover and relief. The constant is extremely low in areas of close dissection.

The computed value of C for the Hirehalla sub-basin is 0.55 km^2 while it varies from 0.46 to 0.64 km^2 for the four catchments HSB-I, II, III and IV (Table 5). Thus indicating high permeability, low to moderate slope, less surface runoff and less structural disturbances.

Relief aspects

Relief aspects include basin relief, relief ratio and ruggedness number.

Basin relief (R)

Basin relief (R) can be defined as the elevation difference of the highest and lowest points in the basin. As the stream gradient depends on the basin relief and thus R favours the flood patterns and the amount of sediment to be transported (Hadley and Schumm 1961). R also plays an important role in denudational characteristics of basin such as drainage and landform development, surface and subsurface water flow and permeability.

The value of R for the study area as a whole is 467 m, where highest and lowest elevations are 964 and 497 m, respectively (Fig. 6). While R for the catchments HSB-I, II, III and IV have been mentioned in the Table 6.

Table 6 Relief aspects of Hirehalla sub-basin

Sub-basin/catchment	Basin relief (R) in metres	Relief ratio (R_r) in m/km	Ruggedness number (R_n)	Melton's ruggedness number (M_{rn})
HSB-I	440	0.0258	0.81	0.053
HSB-II	280	0.014	0.48	0.027
HSB-III	120	0.0066	0.19	0.01
HSB-IV	340	0.0226	0.74	0.036
Hirehalla	467	0.0137	0.8491	0.0212

Table 7 Morphometric parameters used for calculation of flood hazard

Catchment	Bifurcation ratio	Stream frequency (km^{-2})	Drainage density (km/km^2)
HSB-I	4.68	1.79	1.83
HSB-II	3.77	1.98	1.72
HSB-III	4.02	2.60	1.55
HSB-IV	3.56	2.38	2.18

Relief ratio (R_r)

Relief ratio (R_r) is the ratio of the basin relief to the basin length. And according to Schumm (1956), the relief ratio is the dimensionless height-length ratio equal to the tangent of the angle formed by two planes intersecting at the mouth of the basin, one representing the horizontal, the other passing through the highest point of the basin. It also depends on the nature of rocks and slope of the basin. While high values are characteristic of hilly region, low values are characteristic of pediplains and valley.

The R_r for the study area as whole is 0.013, while it varies from 0.006 to 0.0258 for catchments HSB-I, II, III and IV (Table 6). This indicates low to moderate relief and slope. This is mainly due to the resistant basement rocks of the basin and low degree of slope.

Ruggedness number (R_n)

Strahler's (1958) ruggedness number is the product of the basin relief and the drainage density. It lays emphasis on the structural complexity and denudational characteristics of the terrain. The high values of R_n suggest structural complexity and highly susceptible to erosion, while on the contrary, low values suggest lesser proneness to erosion.

The value of R_n for the Hirehalla sub-basin is 0.84 while it varies from 0.19 to 0.81 for the four catchments of the sub-basin HSB-I, II, III and IV (Table 6) and indicating terrain is less prone to erosion.

Melton ruggedness number (M_{rn})

The M_{rn} is a slope index that provides spatialised representation of relief ruggedness within the watershed (Melton 1965) and distinguishes among basins prone to flooding from those subject to debris flows and debris floods (Wilford et al. 2004).

According to the above classification of Wilford et al. (2004), the M_{rn} for the whole study area is 0.021 (Table 6) and it suggests that the basin is prone to debris flood wherein bedload component dominates sediment under transport.

Flood hazard zones

Identification of flood hazard possibility for the four catchments of the study area was calculated using El-Shamy's method (El-Shamy 1992a, 1992b). In this method, El-Shamy has derived two graphical diagrams based on his studies on Egyptian drainage basins. Accordingly, he plotted diagrams based on parameters such as bifurcation ratio versus stream frequency and bifurcation ratio versus drainage density. According to him, these parameters are very important when assessing the flood risk condition of a basin. He divided the diagrams into three zones viz. Zone A—having high possibility of flash flood, Zone B—having moderate possibility of flash flood and Zone C—having low possibility of flash flood.

The above-said parameters (Table 7) were plotted in El-Shamy's diagram (Fig. 7) for all the four catchments of Hirehalla sub-basin. Accordingly, plot of stream frequency versus bifurcation ratio revealed that catchments HSB-II, III and IV fall in Zone B, indicating moderate possibility of flash flood and moderate possibility for recharge of the aquifer.
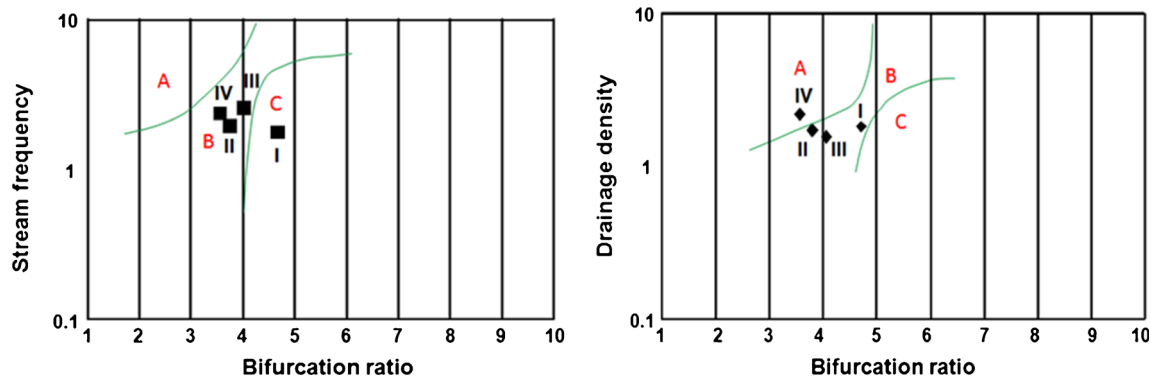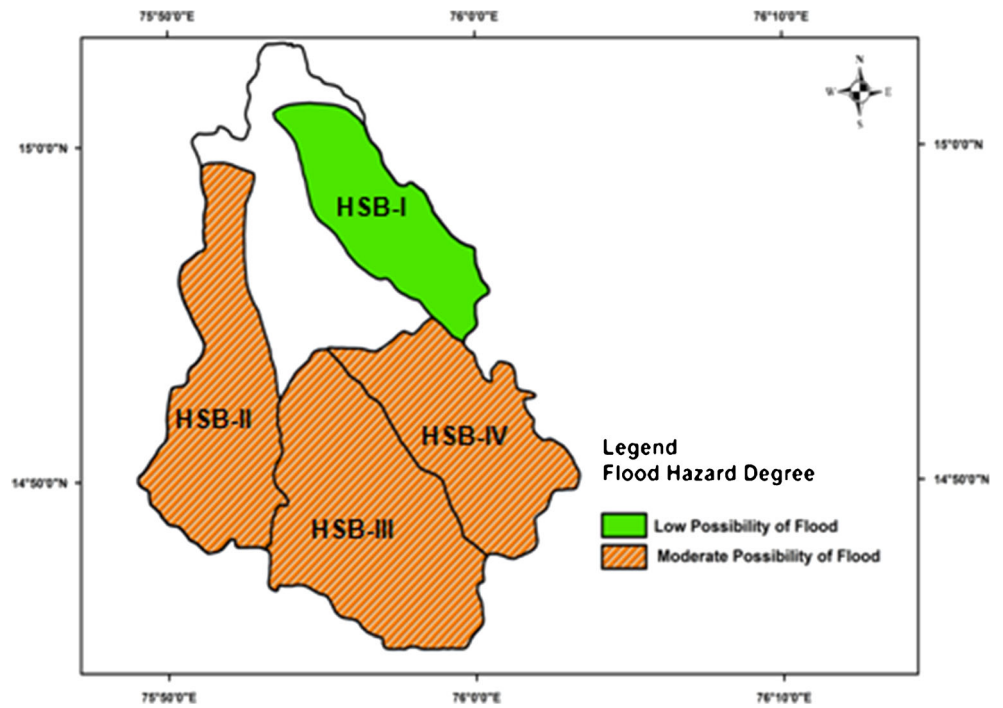

Fig. 7 Flood hazard degree for the four catchments of the study area (after El-Shamy 1992a, 1992b)

Fig. 8 Degree of flash flood hazard for the four catchments of the study area based on bifurcation ratio and stream frequency

Catchment HSB-I falls in Zone C, which indicates low possibility of flash flood and high possibility of recharge of the aquifer. On the other hand, plot of drainage density versus bifurcation ratio revealed that catchments HSB-I, II and III
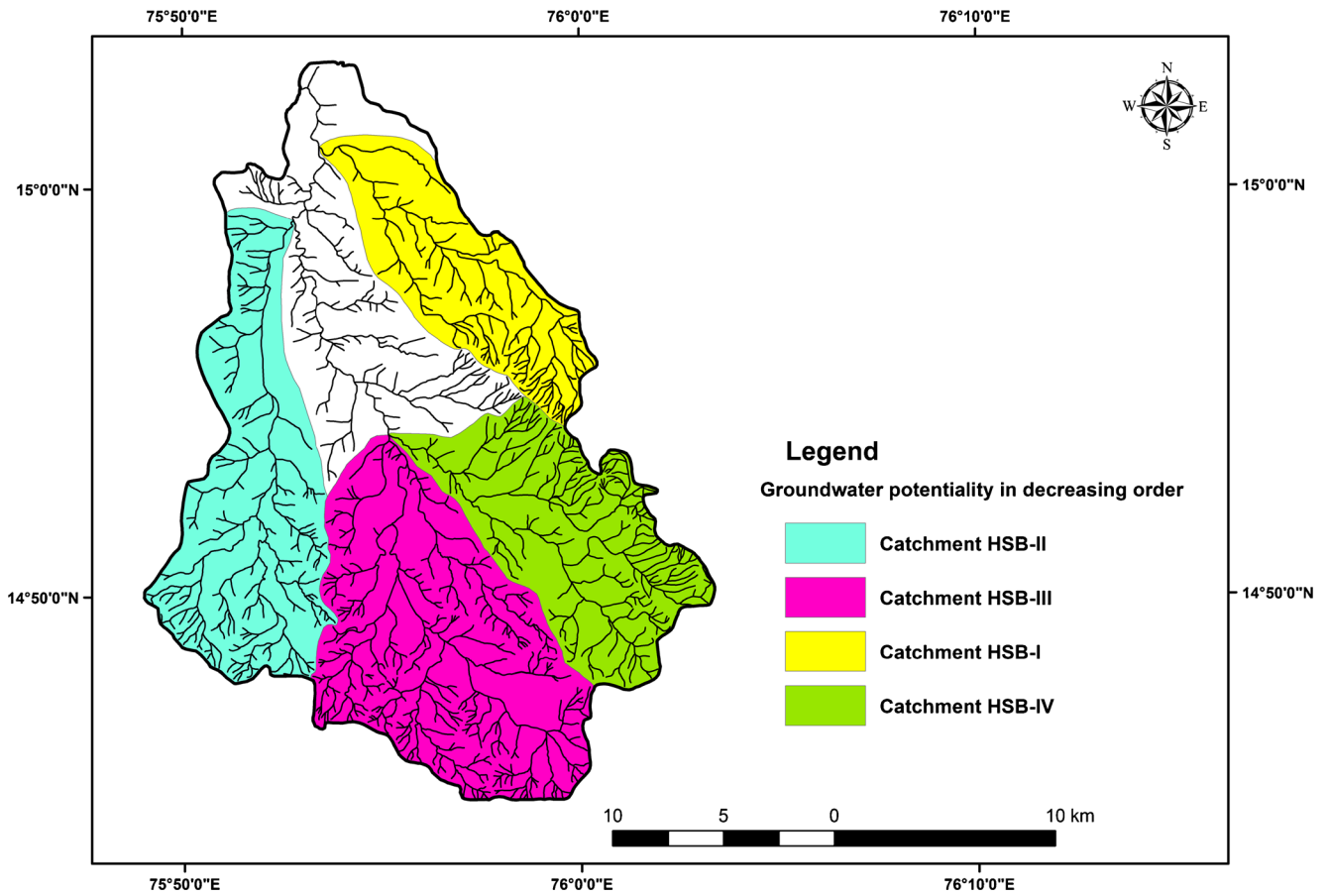

Fig. 9 Groundwater potentiality of the catchments of study area based on morphometric parameters

fall in Zone B, indicating moderate possibility of flash flood and moderate possibility for recharge of the aquifer; while catchment HSB-IV falls in Zone A, which indicates high possibility of flash flood and low possibility for recharge of the aquifer. If a catchment falling in zone C (low possibility for flash floods) in the first diagram falls in zone B (moderate possibility for flash floods) of the second diagram, then the overall hazard degree for this catchment will be moderate possibility for flash floods. The flood hazard degree for the four catchments based on the parameters bifurcation ratio and stream frequency is depicted in Fig. 8.

Groundwater potential

The quantitative morphometric analysis of Hirehalla sub-basin as a whole indicates that it is characterized by permeable sub-surface, gentle slope, less run-off and high infiltration and less structural distortion. The sub-basin has moderate length of overland flow and coarse drainage, low drainage density, low ruggedness number and is elongated in shape. This can be a good source of groundwater recharge (Jasmin and Mallikarjuna 2012).

In comparison among the four catchments, HSB-II and III have low drainage density and ruggedness number and high infiltration rates as compared to catchment HSB-I and IV (Tables 5 and 6). Hence, catchments HSB-II and III are having better potential for groundwater recharge. Thus, these catchments may be preferred over remaining parts of the sub-basin while selecting groundwater potential sites (Fig. 9).

Conclusions

Quantitative morphometric analysis of Hirehalla sub-basin has been carried out for linear, areal and relief aspects. Remote sensing- and GIS-based approach has been of great help for accurate and efficient computational results and also time saving than conventional methods. The analysis of different morphometric parameters leads to the following conclusions.

The drainage pattern in the hard rock Hirehalla sub-basin is found to be dendritic to sub-dendritic with coarse drainage texture. The value of relief ratio indicates low to moderate relief and slope. The low value of form factor indicates that the sub-basin is elongated in shape. While low values of drainage density and stream frequency indicate the sub-basin to be highly permeable with gentle slope, less run-off and high infiltration. Besides, the two catchments HSB-II and III having low values of drainage density and ruggedness number and high infiltration rates can turn out to be sites of groundwater recharge and ultimately yield good amount of water. So, these sub-basins can be deciphered as groundwater potential zones.

Use of some morphometric parameters has enabled to identify the flash flood possibility of catchments of the study area. The catchments HSB-II, III and IV have been identified as those with moderate possibility of flash floods and hence moderate possibility for recharge of the aquifer.

Thus, study of morphometric analysis of a basin with the application of remote sensing and GIS results in better understanding of its hydrological and hydrogeological characters such as slope and topography, nature of sub-surface lithology, landforms, erosional processes, etc. This suggests that the morphometric analysis of a basin is a good proxy to evaluate the deficit and surplus zone of groundwater potentials by which proper measures can be taken for assessment, conservation and optimum utilization of water resources.

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