Chapter 3
Evaluation of the Hydrological Process Prevalent in Ghaggar River Basin Using Interferometrically Derived Sentinel-1 DEM

Nitin Chauhan, Vipin Kumar, and Rakesh Paliwal

Abstract The deleterious effects of anthropogenic activities on the environment can be traced back to the era when man came into existence on this earth. The environment is being severely degraded due to over exploitation of the existing natural resources in order to meet the never-ending demand of human beings for food, fuel, and fiber. Globally, an estimated 1,965 million hectares of land is subjected to one or other kind of degradation out of which soil erosion by water and wind accounts for 1,904 million hectares. According to the report's areas such as Shivalik Hills, North-Western Himalayan regions, Western Ghats, and parts of Peninsular India are most severely affected by soil erosion, i.e., about 20 Mg/ha/year (Singh et al. 1992). The present research focuses on the flimsiest ecosystem in India, i.e., lower Shivaliks because of highly erodible soils which are lost at an alarming rate of 25–225 tones/hectare/year. Various techniques have evolved over a period of time to evaluate soil erosion and to develop a watershed management protocol out of which morphometric analysis has given promising results in synergy with advanced techniques such as Geographical Information System and Remote Sensing. This study emphasizes the geospatial evaluation of hydrological processes using interferometrically derived DEM from Sentinel—1 Satellite for the Ghaggar river basin. The watershed delineation and stream extraction from the DEM is done using ARCSWAT which works as an extension with ArcGIS software as well as through hydrology extension of ArcGIS. The morphometric analysis is being carried out for 33 fourth-order drainage basins of Ghaggar river up to its confluence with Medkhali River.

Keywords Morphometry · Ghaggar basin · Sentinel-1 · Interferometry

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3.1 Introduction

Morphometry is defined as the mathematical analysis of the Earth's surface, and the shape and dimension of its landform (Clarke 1996). R.E. Horton, America's most renowned hydrologist made an attempt to pronounce the erosional morphology in a quantitative way based on morphometric techniques even when the landform development by erosional and gradational process persisted principally qualitative (Horton 1945). The erosional drainage basin is considered a basic unit of study in the science of geomorphometry (Chorley et al. 1957). It acts as an ideal unit for sustainable management of natural resources such as water and land which supports in averting natural disasters arising otherwise. Morphometric analysis is a vital characteristic for watershed characterization which involves the computation of quantitative traits of the landscape such as linear, relief, and aerial aspects from the stream networks and elevation information within the watershed. Morphometric analysis is an imperative tool that provides a holistic insight into the watershed's hydrological behavior by describing its soil physiological properties, landform formation processes, and its erosional characteristics (Strahler 1964). The drainage morphometric studies have acted as a prerequisite criterion for runoff modeling, site suitability of recharge sites, groundwater prospect zonation, and many other geotechnical investigations. But the conventional methods of morphometric characterization were very expensive, time and labor-intensive for large watersheds. Recently, with the advent of remote sensing technologies data with synoptic coverage and improvised spatial accuracies now available making it easier to perform drainage morphometric analysis of inaccessible areas. Similarly, advancements in computational power of the systems and Geographic Information System (GIS) have enabled the morphometric parameters extraction and evaluation in a more precise and easy manner. In order to explore holistic stream properties through analysis of varied drainage attributes, in-depth morphometric analysis is being carried out for 33 fourth-order drainage basins of Ghaggar river up to its confluence with Medkhali River and also an attempt has been made in order to identify the geomorphic development stages with the help of linear, areal and relief aspect evaluation.

3.2 Study Area

The present study focuses on the flimsiest ecosystem in India, i.e., lower Shivaliks because of highly erodible soils which are lost at an alarming rate of 25–225 tones/hectare/year (Singh and Khera 2009). The Shivaliks are composed of sandstones and conglomerates having characteristic fluvial deposits, making them geologically weak structures and simultaneously prone to erosion. Large-scale deforestation, road construction, mining, and faulty agriculture practices have resulted in the desertification of land in the Shivalik hills. The studies of (Patnaik 1981) revealed that degraded land has increased in the Shivaliks from 194 km^2 in 1852, 2000 km^2 in

1939 to 20,000 km^2 in 1981. The Ghaggar river is one of the major ephemeral streams which drains the Shivaliks and Himalayas. The Ghaggar river basin extends over an area of about 42,200 km^2 extending over parts of states such as Haryana, Himachal Pradesh, Rajasthan, Punjab, and Union Territory of Chandigarh. The Ghaggar basin is a part of Indo-Gangetic basin. The river originates from Dagshai village near Shimla in Himachal Pradesh from the foothills of Shivaliks. Its main tributaries are Markanda, Saraswati, Tangri, and Chotang River. The overall length of Ghaggar river is about 291 ^{km} and it terminates in Hanumangarh of Bikaner district. The Ghaggar is a non-perennial river, which carries its optimum flow throughout the year in the upstream part only. Therefore, for the current research upper part of the Ghaggar river basin up to confluence of Medkhali River is taken. The study area extends from 76°51′45.06″ and 30°36′46.50″ to 77°12′45.30″ and 30°54′27.18″ and covers an area of 559.14 km^2 (Fig. 3.1).

3.3 Methodology and Data Used

The European Commission in association with European Space Agency (ESA) is evolving a new series of Satellite constellations named Sentinel. One of the satellites designed by ESA with all-weather and day and night capability is Sentinel 1A & B. It is a C band spaceborne SAR that collects the images with 250 km of swath in Interferometric Wide Swath (IW) mode. The spatial resolution of the images is 5 m in range direction and 20 m in Azimuth direction. The Sentinel 1 Satellite provides dual polarization data, i.e., VV and VH. One scene each from Sentinel 1 A and Sentinel 1 B of date 19 September 2016 were used for generating the DEM. The preprocessing of the pair of single look complex products acquired in IW mode was performed in SNAP software version 6.0. The data acquired is in form of sub-swath and is formed on bursts that are demarcated by zones of no data value. The first step of the preprocessing Sentinel data is co-registering the two images to create a stack utilizing the Precise Orbit Ephemerides (POE) orbit files. In this one image is master and slave and pixel values of the slave images are moved to align with the master dataset to attain a sub-pixel accuracy so as to ensure the same range and azimuth is contributed by each ground object. The next step is the generation of the interferogram by multiplying the complex conjugate of master image with slave. The images are then seamlessly merged into one file by the process of TOPS Deburst and Tops Merge. The SAR images are associated with speckle noise which is nothing but the collective response of many small reflectors within a particular pixel. The SNAP software comes with many inbuilt speckle filtering algorithms and Goldstein Phase Filtering (Goldstein et al. 1988) was used to reduce the speckle while maintaining the radiometric information. The resultant phase generated as a result of filtering was unwrapped using SNAPHU (Chen and Zebker 2000). The unwrapped phase was imported using the NEST software and DEM was prepared from it. The DEM generated from Sentinel -1 is having a spatial resolution of 13.96 m against the most popularly used SRTM data with 30 m resolution which generates optimum

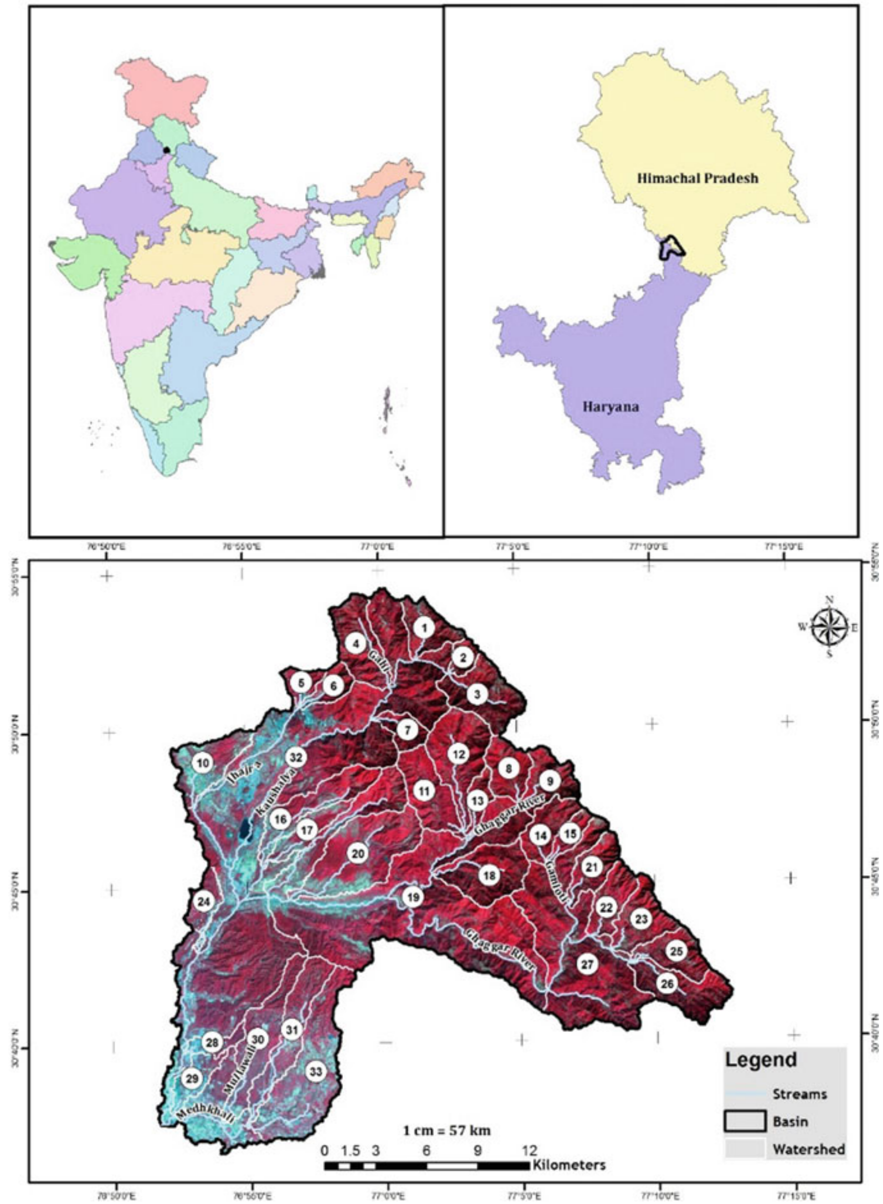

Fig. 3.1 Location map of the study area

results for morphometric analysis. The watershed delineation and stream extraction from the DEM is done using ARCSWAT which works as an extension with ArcGIS software (version 10.2.2) as well as through hydrology extension of ArcGIS. The list of morphometric parameters calculated for this study are given in Table 3.1.

3.4 Results and Discussion

3.4.1 Linear Aspects

Linear aspects of the basin deal with the detailed aspects of the stream network morphometry which act as a means of water and sediment transport through a single outlet point. The first stage of basin analysis is stream ordering.

3.4.1.1 Stream Order (SO_u)

The technique of designating a numeric order to links in a stream network is known as stream ordering. This order facilitates the identification and categorization of stream types based on their tributaries number. Strahler, Quantitative Analysis of Watershed Geomorphology (1957) designated the smallest fingertip tributaries as Order 1; When two first-order streams join an Order 2 stream is created; When two of Order 2 join a channel segment of Order 3 is formed and so on. Similar work on stream ordering has been done by (Horton 1945) and (Shreve 1967). In the current study, Sentinel 1 data is used for automatic delineation of the streams from the interferometrically generated DEM. The data is of 2016 so changes in river morphology as per the recent topographical changes are easily identified. The delineated streams are categorized according to (Strahler 1957) as given in Fig. 3.2 and Table 3.2.

3.4.1.2 Stream Number (SN_u)

The total stream segments number in a particular order is known as stream number. It is being observed that as the stream order increases there is a gradual decrease in stream number (N_u). This is in accordance with the Horton's Law of drainage composition (Horton 1945) which states that the "stream number falling in each order follows an inverse geometric progression with order number". The total stream numbers in the Ghaggar basin up to its confluence with Madhekali is 6943 (Table 3.2).

The study divulges that the development of 1st order streams is maximum in the Structural Hills Highly Dissected region of lower Shivalik and minimum in the alluvial plains. Similarly, second, third, and fourth order are also more prominent

Table 3.1 Methods used to calculate the Morphometric Parameter along with their formulae

Sr. No.	Parameter	Formula	References
1	Stream order	$SO_u = \text{Hierarchical rank}$	Strahler (1957)
2	Stream number	$SN_u = SN_1 + SN_2 + \ldots SN_n$	Horton (1945)
3	Stream length	$SL_u = SL_1 + SL_2 \ldots\ldots SL_n$	Strahler (1964)
4	Mean stream length	$MSL_u = \frac{\sum_{i=1}^{N} SO_u}{SN_u}$	Strahler (1964)
5	Mean stream length ratio	$MSLR_u = \frac{MSL_u}{MSL_u - 1}$	Horton (1945)
6	Bifurcation ratio	$R_b = \frac{SN_u}{SN_u + 1}$	Strahler (1964)
7	Valley length	VL	Mueller (1968)
8	Channel length	CL	Mueller (1968)
9	Air distance	AD	Mueller (1968)
10	Coefficient of topographical sinuosity (Ts) or Valley index (VI)	$Ts or VI = \frac{VL}{AD}$	Mueller (1968)
11	River sinuosity coefficient (Ks) or Channel index (CI)	$Ks or CI = \frac{CL}{AD}$	Mueller (1968)
12	Hydraulic sinuosity index (HSI)	$HSI = \frac{CI - VI}{CI - 1}$	Mueller (1968)
13	Topographic sinuosity index (TSI)	$TSI = \frac{VI - 1}{CI - 1}$	Mueller (1968)
14	Coefficient of hydraulic sinuosity (Hs)	$Hs = \frac{CL}{VL}$	Mueller (1968)
15	Rho coefficient	$\rho = \frac{MSLR_u}{Rb}$	Horton (1945)
16	Basin area (A)	ArcGIS/DEM	Schumm (1956)
17	Perimeter (P)	ArcGIS/DEM	
18	Basin length (Lb)	$L_b = 1.312A^{0.568}$	Schumm (1956), Gardiner (1975), Nookaratnam et al. (2005)
19	Lemniscate's value	$L_k = \frac{L_b^2 \pi}{4A}$	Chorley et al. (1957)
20	Form factor	$F_f = \frac{A}{L_b^2}$	Horton (1932)
21	Elongation ratio	$R_e = \frac{1}{L_b} \times \sqrt{\frac{4A}{\pi}}$	Schumm (1956)
22	Ellipticity index	$I_e = \frac{\pi VL^2}{4A}$	Stoddart (1965)

(continued)

Table 3.1 (continued)

Sr. No.	Parameter	Formula	References
23	Circularity ratio	$R_c = \frac{4\pi A}{P^2}$	Miller (1953)
24	Drainage density	$D_d = \frac{\sum SL_u}{A}$	Horton (1932)
25	Drainage texture	$D_t = \frac{1}{(t+P)/2}$ $t = \frac{(t_1+t_2)/2}{\sqrt{2}}$ $P = \frac{P_1+P_2+P_3+P_4}{4}$ Where t1 & t2 = number of intersections between the drainage network and grid diagonal P1 to P4 = number of intersections between the drainage network and grid edges	Horton (1932), Singh (1976)
26	Stream frequency	$S_f = \frac{\sum_{i=1}^{K} SN_u}{A}$	Horton (1945)
27	Drainage intensity	$D_i = \frac{S_f}{D_d}$	Faniran (1968)
28	Infiltration number	$I_f = D_d \times S_f$	Faniran (1968)
29	Relative relief	$R_r = Max.Elevation - Min.Elevation$	Smith (1935)
30	Relative relief ratio	$R_{hp} = 100 \times \frac{R_r}{Perimeter of the basin}$	Melton (1958)
31	Dissection index	$D_i = \frac{R_r}{R_a}$	Nir (1957)
32	Ruggedness number	$R_n = R_r \times D_d$	Strahler (1964)
33	Slope	ArcGIS/DEM	
34	Aspect	ArcGIS/DEM	
35	Hypsometric analysis		Strahler (1952), Pike and Wilson (1971)

in the Structural Hills Highly Dissected region whereas fifth-, sixth-, and seventh-order streams availability is more in Piedmont Alluvium and Valley fills. Figure 3.3 displays the relation of stream order to stream number in different sub-basins.

3.4.1.3 Stream Length (SL_u)

The stream length is the total length of individual stream segments of a particular order. The stream length acts as an important parameter for the calculation of drainage density. The stream segment lengths have been measured in kilometers and represented in Table 3.3 for different orders of all the basins. The total length

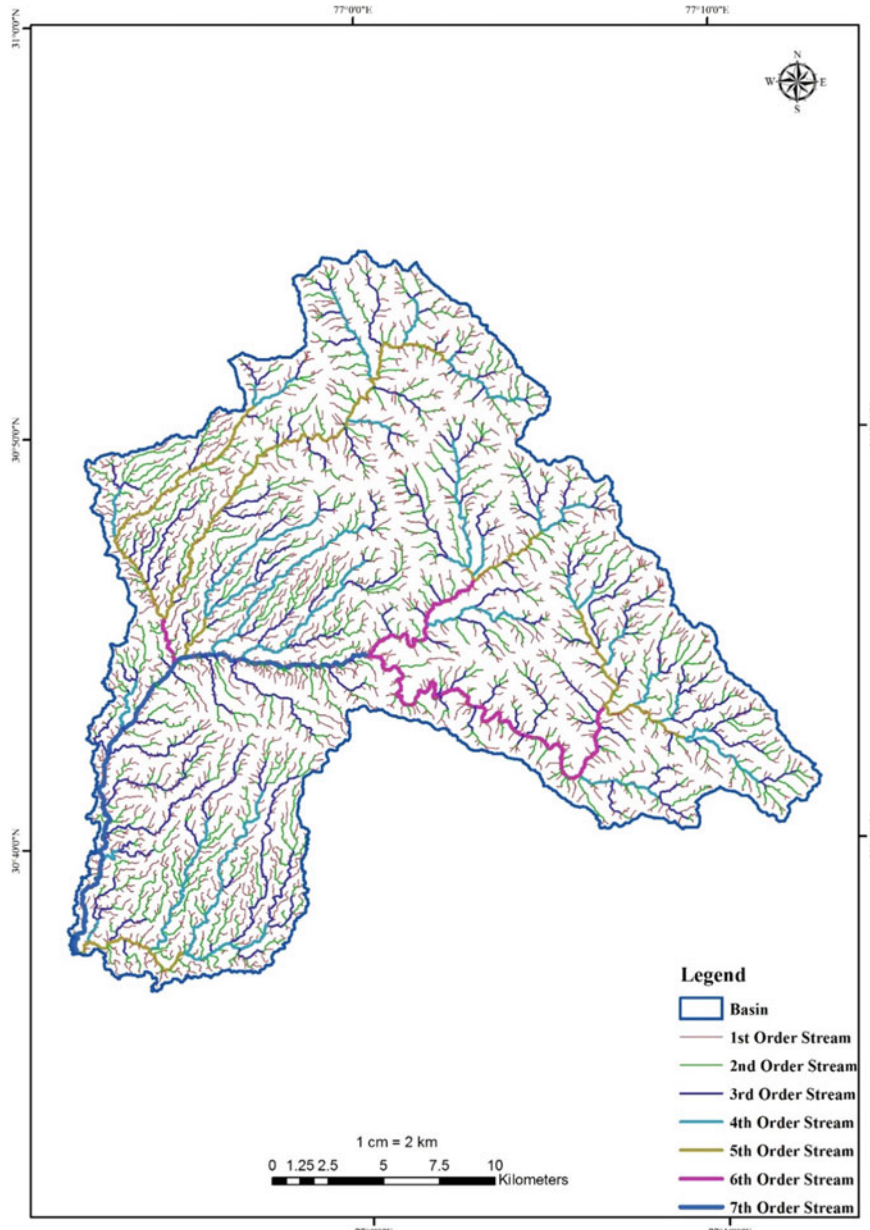

Fig. 3.2 Stream order in Ghaggar river basin as extracted from Sentinel 1 DEM

Table 3.2 Stream order in Ghaggar river basin

Sub-basin	Stream order							
	1	2	3	4	5	6	7	Total number of streams within a sub-basin
1	50	10	3	1				64
2	19	4	2	1				26
3	83	19	5	1				108
4	74	20	4	1				99
5	21	6	2	1				30
6	25	5	2	2	1			35
7	32	7	2	1				42
8	49	13	3	1				66
9	58	17	4	2	1			82
10	59	12	2	1				74
11	63	16	2	1				82
12	101	21	6	1				129
13	21	5	2	3	1			32
14	45	9	3	2	1			60
15	18	5	2	1				26
16	66	11	4	1				82
17	32	8	3	1				44
18	72	17	4	1				94
19	569	130	22	3	2	2	1	729
20	139	24	6	1				170
21	52	11	3	1				67
22	46	11	2	1				60
23	63	12	3	1	1			80
24	27	7	3	1				38
25	45	11	2	1				59
26	71	16	3	1	1			92
27	270	59	14	4	2	1		350
28	21	5	2	1				29
29	34	6	2	1				43
30	86	18	4	1				109
31	78	15	3	1				97
32	934	186	33	13	4	1	1	1172
33	153	33	5	1				192
Total number of streams within the watershed								4462

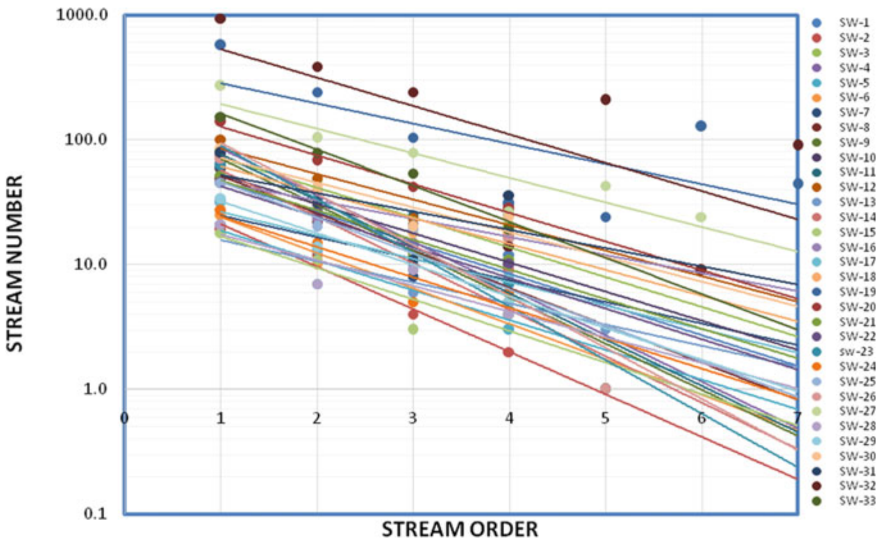

Fig. 3.3 Relation of stream order to stream number in different sub-basins of Ghaggar river basin

of various orders has no significant deductions since they may not be compared. Strahler (1964) has explained the **Mean Stream Length (MSL$_\mathbf{u}$)** as a dimensional property that unveils the distinguishing size of drainage network components and its contributing sub-basin surfaces. The order-wise mean stream lengths of all the sub-basin are given in Table 3.4.

3.4.1.4 Mean Stream Length Ratio (MSLR$_\mathbf{u}$)

The stream length ratio is the ratio of the mean stream length of a particular order (MSLu) to the mean stream length of the next lower order (MSL$_{u\text{-}1}$). It is similarly calculated for each subsequent pair of the orders. The mean stream length ranges from 0.033 to 22.493. According to Horton's Law of stream length (Horton 1945), the mean stream length of the successive orders of a basin closely approximates a direct geometric series with an increase in streams length with an increase in order. The MSLR$_u$ in the study area divulges that there is a variation in MSLR$_u$ in each sub-basin given in Table 3.5. The variation in stream length ratio is accredited to dissimilarity in topographic slope indicating the youth stage of geomorphic development in the streams of the study area (Vittala et al. 2004). The stream length ratio displaying an increasing trend from smaller order to higher order indicates their matured geomorphological development stage as against the sub-basins displaying abrupt changes between the orders indicating the late youth stage of geomorphological development.

Table 3.3 Stream length in Ghaggar river basin

Sub-basin	Stream order							
	1	2	3	4	5	6	7	Total length
1	10.89	5.43	1.37	2.50				20.19
2	4.48	2.84	0.87	0.59				8.78
3	16.67	11.75	2.70	4.67				35.79
4	15.25	9.94	4.00	4.94	0.02			34.16
5	4.68	1.85	2.21	1.02				9.76
6	6.71	2.16	1.12	2.43	0.01			12.43
7	6.89	1.87	1.65	2.33				12.74
8	9.88	5.19	4.51	1.28				20.85
9	12.27	4.54	2.86	3.18	0.01			22.85
10	18.20	15.52	2.71	2.53				38.96
11	14.16	11.99	5.36	1.12				32.62
12	19.10	11.99	5.83	6.70				43.62
13	4.72	1.21	2.62	2.06	0.47			11.09
14	12.01	7.12	2.63	1.82	0.01			23.59
15	3.01	4.43	1.48	1.34				10.27
16	17.48	9.49	4.24	8.54				39.74
17	10.35	6.48	4.77	3.33				24.93
18	15.52	8.85	7.19	5.63				37.19
19	147.30	65.06	29.25	11.08	4.45	26.21	8.48	291.82
20	42.82	23.39	11.29	8.86				86.35
21	13.01	4.83	3.51	2.24				23.59
22	10.39	7.60	2.65	2.33				22.96
23	13.49	8.62	6.53	1.99	0.01			30.64
24	6.95	6.90	2.32	3.12				19.29
25	11.88	7.07	5.19	1.53				25.66
26	13.41	12.14	2.78	4.56	0.01			32.91
27	65.09	26.67	21.41	4.27	10.34	3.83		131.60
28	5.93	2.65	3.18	1.45				13.21
29	10.66	4.45	4.02	1.18				20.31
30	23.66	18.99	6.45	8.25				57.35
31	24.16	13.53	2.82	10.27				50.78
32	244.70	121.96	69.49	0.15	48.90	2.36	19.17	506.71
33	44.28	29.63	20.24	5.24				99.40

Table 3.4 Mean stream length in Ghaggar river basin

Sub-basin	Stream order						
	1	2	3	4	5	6	7
1	0.21	0.18	0.17	0.21			
2	0.24	0.24	0.22	0.30			
3	0.20	0.25	0.23	0.22			
4	0.21	0.33	0.33	0.17	0.02		
5	0.22	0.27	0.22	0.34			
6	0.27	0.22	0.22	0.27	0.01		
7	0.22	0.14	0.21	0.23			
8	0.20	0.24	0.22	0.26			
9	0.21	0.18	0.20	0.19	0.01		
10	0.31	0.49	0.25	0.18			
11	0.23	0.36	0.22	0.28			
12	0.19	0.25	0.25	0.25			
13	0.23	0.17	0.44	0.30	0.16		
14	0.27	0.31	0.22	0.20	0.01		
15	0.17	0.40	0.50	0.34			
16	0.27	0.41	0.28	0.34			
17	0.32	0.50	0.43	0.42			
18	0.22	0.27	0.40	0.31			
19	0.26	0.27	0.28	0.36	0.19	0.21	0.19
20	0.31	0.34	0.27	0.32			
21	0.25	0.18	0.29	0.20			
22	0.23	0.29	0.29	0.23			
23	0.21	0.25	0.33	0.28	0.01		
24	0.26	0.46	0.46	0.52			
25	0.26	0.35	0.27	0.31			
26	0.19	0.30	0.21	0.29	0.01		
27	0.24	0.26	0.27	0.16	0.24	0.16	
28	0.28	0.38	0.35	0.36			
29	0.31	0.32	0.31	0.24			
30	0.28	0.46	0.32	0.34			
31	0.31	0.44	0.26	0.29			
32	0.26	0.32	0.29	0.01	0.24	0.26	0.21
33	0.29	0.38	0.38	0.28			

Table 3.5 Stream length ratio in Ghaggar river basin

Sub-basin	Stream length ratio					
	2/1	3/2	4/3	5/4	6/5	7/6
1	0.85	0.94	1.22			
2	1	0.92	1.36			
3	1.25	0.9	0.99			
4	1.61	1.01	0.49	0.1		
5	1.19	0.84	1.54			
6	0.81	1.04	1.21	0.03		
7	0.67	1.43	1.13			
8	1.17	0.91	1.19			
9	0.86	1.12	0.92	0.04		
10	1.57	0.51	0.73			
11	1.62	0.59	1.3			
12	1.29	1.04	0.98			
13	0.77	2.52	0.68	0.54		
14	1.16	0.71	0.92	0.05		
15	2.41	1.23	0.68			
16	1.56	0.68	1.21			
17	1.54	0.87	0.96			
18	1.24	1.49	0.78			
19	1.04	1.04	1.27	0.52	1.11	0.93
20	1.12	0.78	1.18			
21	0.72	1.64	0.7			
22	1.29	1.01	0.79			
23	1.18	1.29	0.87	0.04		
24	1.79	1.01	1.12			
25	1.34	0.77	1.12			
26	1.61	0.71	1.33	0.04		
27	1.07	1.05	0.61	1.47	0.66	
28	1.34	0.94	1.03			
29	1.01	0.97	0.76			
30	1.68	0.7	1.07			
31	1.41	0.59	1.11			
32	1.2	0.92	0.04	22.49	1.11	0.81
33	1.3	1	0.74			

3.4.1.5 Bifurcation Ratio (Rb)

Horton (1945) defined bifurcation ratio as the ratio of number streams of a particular order to that of the next higher order. The bifurcation ratio is usually constant for all orders of stream in a given basin or sub-basin but there is the chance of the presence of lithological and geological developmental irregularities causing its deviation (Strahler 1964). Horton (1945) explained the results of the bifurcation values and stated that the value ranges from 2 for flat or rolling basins and may go up to 3–4 for highly dissected or mountainous river basins. Strahler (1964) concluded from his study that the bifurcation ratios values between 3 to 5 for the watersheds indicates that the geological development of the basin is ineffective in altering the drainage patterns. He further indicated that basins with higher R_b values produce a low but extended peak flow whereas basins with lower R_b will produce a sharp peak flow. The Mean Bifurcation ratio for the 33 sub-basins is given in Table 3.6.

3.4.1.6 Sinuosity Indices

Rivers are of enormous significance in the landscape evolution and many studies have revealed a number of quantitative Sinuosity Indices characterizing the river channel configuration. Mueller (1968) identified two of such indices hydraulic sinuosity index and topographic index. The calculation of these sinuosity coefficients requires Channel Length (CL), Valley Length (VL), and Air Distance (AD) of the stream channel are required. Channel Length (CL) is measured along the river course. Valley Length (VL) is the length of a line between the base of the valley walls. Valley length and channel length wherever the valley and water course are near to each other whereas it will be less than channel length in case of floodplains. Air distance is the shortest aerial distance between the source and mouth of the river stream or two extreme points of individual sub-basin. Coefficient of Topographical Sinuosity (Ts) or Valley Index (VI) is the ratio of Valley Length (VL) to the Air Distance (AD) (Mueller 1968). Topographical sinuosity is indicative of present relief formation due to interaction of geological and geomorphological factors. Mueller (1968) gave Hydraulic Sinuosity Index (HSI) which is a percentage equivalent of how much a stream departs from a straight-line course within the valley owing to hydraulic sinuosity. Mueller (1968) gave Topographic Sinuosity Index (TSI) which is a percentage equivalent of how much a stream departs from a straight-line course within the valley owing to topographic interferences. Coefficient of hydraulic sinuosity (Hs) is given by ratio of Channel Length (CL) to the Valley length (VL). The values of Hs are generally higher than unity except where Valley length is equal to the channel length. Topographical sinuosity is explicitly associated with regions that are in an early stage of geomorphological evolution, whereas hydraulic sinuosity arises typically in flatlands or in regions matured relief evolution. The Sinuosity Indices for the 33 sub-basins are given in Table 3.6.

Table 3.6 Bifurcation ratio, sinuosity indices and Rho coefficient in Ghaggar river basin

Sub-basin	Mean bifurcation ratio	Valley length	Channel length	Air distance	Topographical sinuosity coefficient (Ts)- Valley index	Hydraulic sinuosity coefficient (Hs)	River sinuosity coefficient (Ks) - Channel index	Hydraulic sinuosity index	Topographic sinuosity index	Rho
1	2.04	4.02	4.28	3.47	1.16	1.07	1.23	32.00	68.00	0.49
2	2.19	2.23	2.37	1.98	1.13	1.06	1.20	36.56	63.44	0.50
3	2.09	5.34	5.75	4.82	1.11	1.08	1.19	43.59	56.41	0.50
4	8.84	6.16	6.65	5.44	1.13	1.08	1.22	40.79	59.21	0.09
5	2.34	2.53	2.72	2.30	1.10	1.08	1.18	45.45	54.55	0.51
6	3.51	3.72	4.00	3.53	1.06	1.08	1.13	58.99	41.01	0.22
7	1.63	3.60	3.86	2.96	1.22	1.07	1.31	28.96	71.04	0.66
8	2.49	4.13	4.29	3.94	1.05	1.04	1.09	46.89	53.11	0.44
9	5.48	4.38	4.79	3.41	1.29	1.09	1.41	29.55	70.45	0.13
10	1.85	6.67	7.22	5.46	1.22	1.08	1.32	31.19	68.81	0.51
11	3.16	6.13	6.49	5.57	1.10	1.06	1.17	39.09	60.91	0.37
12	1.68	7.61	8.30	6.60	1.15	1.09	1.26	40.62	59.38	0.66
13	1.84	4.34	4.87	4.07	1.07	1.12	1.20	66.64	33.36	0.61
14	3.55	4.79	5.14	3.89	1.23	1.07	1.32	28.15	71.86	0.20
15	2.02	3.97	4.34	3.66	1.08	1.09	1.19	54.48	45.52	0.71
16	1.67	9.83	10.64	8.73	1.13	1.08	1.22	42.31	57.69	0.69
17	1.67	7.38	8.08	6.55	1.13	1.09	1.23	45.55	54.46	0.67
18	1.67	6.61	7.35	5.41	1.22	1.11	1.36	38.08	61.92	0.70

(continued)

Table 3.6 (continued)

Sub-basin	Mean bifurcation ratio	Valley length	Channel length	Air distance	Topographical sinuosity coefficient (Ts)- Valley index	Hydraulic sinuosity coefficient (Hs)	River sinuosity coefficient (Ks) - Channel index	Hydraulic sinuosity index	Topographic sinuosity index	Rho
19	2.07	24.51	27.15	17.35	1.41	1.11	1.57	26.97	73.04	0.48
20	1.72	10.77	11.81	8.86	1.22	1.10	1.33	35.34	64.66	0.60
21	1.76	5.15	5.57	4.62	1.12	1.08	1.21	43.86	56.14	0.58
22	1.85	5.01	5.37	4.55	1.10	1.07	1.18	43.25	56.76	0.56
23	3.35	5.10	5.44	4.43	1.15	1.07	1.23	33.72	66.28	0.25
24	1.88	5.43	6.59	4.94	1.10	1.21	1.33	70.54	29.46	0.70
25	2.37	5.36	5.84	4.48	1.20	1.09	1.30	35.14	64.86	0.45
26	5.42	6.92	7.36	6.04	1.14	1.06	1.22	33.69	66.32	0.17
27	1.87	12.48	13.48	10.14	1.23	1.08	1.33	29.91	70.09	0.52
28	2.01	4.80	5.78	3.86	1.24	1.20	1.50	51.06	48.95	0.55
29	2.04	5.54	6.34	4.83	1.15	1.14	1.31	52.45	47.55	0.45
30	1.66	12.05	13.86	10.75	1.12	1.15	1.29	58.29	41.71	0.69
31	1.88	12.09	13.39	10.62	1.14	1.11	1.26	46.97	53.03	0.55
32	7.42	40.62	44.94	33.95	1.20	1.11	1.32	39.32	60.68	0.60
33	2.08	13.07	15.07	10.92	1.20	1.15	1.38	48.08	51.92	0.49

3.4.1.7 Rho Coefficient (*ρ*)

This Rho Coefficient (ρ) was defined by (Horton 1945) as the ratio of stream length ratio (MSLRu) and the bifurcation ratio (Rb). The Rho Coefficient is dependent on hydrologic, geologic, and physiographic factors which ultimately determine the relation of drainage composition and physiographic development of a sub-basin. Rho values of the Ghaggar sub-basin are given in Table 3.6. Rho Coefficient values of sub-basin number 1,2,3,4,5,6,8,9,10,11,14,19,23,25,26,29,33 are low ranging from 0.0908 to 0.5077 indicative of low water storage during flood periods and has high erosion effect while sub-basin number 7,12,13,15,16,17,18,20,21,22,24,27,28,30,31,32 have higher value ranging from 0.5188 to 0.7128 indicative of higher hydrologic storage during floods and thus reduces erosion effects at peak discharges.

3.4.2 Areal Aspects

The two-dimensional properties of the basin are defined by the areal aspects. The basin area contributing water at an outlet point can be delineated for individual streams. The outline of a watershed can be delineated from the stream having its union with higher-order stream network along the ridgeline to move upslope of the source and finally returning to the junction. This watershed boundary separates the area feeding the water toward its stream from the areas which drain in streams falling in another watershed boundary. The configuration of a basin plays a vital role in understanding the hydrological nature of the basin. The basin area and perimeter control the spatial distribution of a number of morphometric parameters such as drainage frequency, drainage density, Lemniscate's value, Form Factor, Elongation Ratio, Circularity Ratio, etc. which will be discussed in the following section.

3.4.2.1 Basin Area (*A*)

The basin area is the total area that is being drained by a stream or its system so the water falling at its farthest point on ridge is collected and discharged at a single outlet also known as pour point. The total area of Ghaggar river basin up to its confluence of Madhekali river is 559.14 km^2 and the individual area of all the 33 fourth-order streams is given in Table 3.7. It has been evident from several studies that alluvial region basins are large when compared to other geomorphological zones. Generally, the basin area and the basin length both follow a positive relation and are proportional to each other.

Table 3.7 Sub-basin-wise areal aspects in Ghaggar river basin

Sub-basin	Area (Km^2)	Perimeter (Km)	Valley length	Basin length	Lemniscate's value	Form factor	Elongation ratio	Ellipticity index	Circularity ratio
1	7.24	17.23	4.02	4.04	1.77	0.44	0.75	1.75	0.31
2	2.75	9.44	2.23	2.33	1.55	0.51	0.80	1.42	0.39
3	12.37	22.16	5.34	5.48	1.90	0.41	0.73	1.81	0.32
4	11.60	20.60	6.16	5.28	1.89	0.42	0.73	2.57	0.34
5	3.30	11.05	2.53	2.58	1.59	0.49	0.79	1.52	0.34
6	4.13	13.00	3.72	2.94	1.64	0.48	0.78	2.63	0.31
7	4.41	13.14	3.60	3.05	1.65	0.48	0.78	2.30	0.32
8	7.43	15.37	4.13	4.10	1.78	0.44	0.75	1.80	0.40
9	8.27	19.49	4.38	4.36	1.80	0.44	0.75	1.83	0.27
10	10.51	23.39	6.67	4.99	1.86	0.42	0.73	3.33	0.24
11	11.08	19.99	6.13	5.14	1.88	0.42	0.73	2.66	0.35
12	15.02	24.72	7.61	6.11	1.95	0.40	0.72	3.03	0.31
13	3.87	15.65	4.34	2.83	1.63	0.48	0.78	3.82	0.20
14	7.40	16.87	4.79	4.09	1.78	0.44	0.75	2.43	0.33
15	3.46	12.70	3.97	2.65	1.60	0.49	0.79	3.59	0.27
16	11.88	30.93	9.83	5.35	1.89	0.42	0.73	6.39	0.16
17	6.04	21.80	7.38	3.64	1.73	0.46	0.76	7.09	0.16
18	13.40	21.33	6.61	5.73	1.92	0.41	0.72	2.56	0.37
19	91.26	121.47	24.51	17.04	2.50	0.31	0.63	5.17	0.08
20	22.77	32.85	10.77	7.74	2.07	0.38	0.70	4.00	0.27
21	6.88	17.37	5.15	3.93	1.76	0.45	0.75	3.03	0.29

(continued)

Table 3.7 (continued)

Sub-basin	Area (Km^2)	Perimeter (Km)	Valley length	Basin length	Lemniscate's value	Form factor	Elongation ratio	Ellipticity index	Circularity ratio
22	7.32	17.37	5.01	4.06	1.77	0.44	0.75	2.70	0.31
23	9.61	20.77	5.10	4.74	1.84	0.43	0.74	2.13	0.28
24	5.18	19.04	5.43	3.34	1.69	0.46	0.77	4.47	0.18
25	7.95	18.32	5.36	4.26	1.79	0.44	0.75	2.84	0.30
26	11.64	24.30	6.92	5.29	1.89	0.42	0.73	3.23	0.25
27	44.89	61.64	12.48	11.39	2.27	0.35	0.66	2.72	0.15
28	3.22	15.98	4.80	2.55	1.59	0.50	0.79	5.61	0.16
29	5.28	19.88	5.54	3.38	1.70	0.46	0.77	4.57	0.17
30	14.56	36.75	12.05	6.01	1.95	0.40	0.72	7.83	0.14
31	13.27	35.75	12.09	5.70	1.92	0.41	0.72	8.65	0.13
32	145.29	197.92	40.62	22.19	2.66	0.30	0.61	8.92	0.05
33	25.86	41.68	13.07	8.32	2.10	0.37	0.69	5.19	0.19

3.4.2.2 Basin Perimeter (P)

The outer boundary of the basin enclosing its area is known as its perimeter. It is measured along the watershed divide line separating it from other sub-basins and is a vital indicator reflecting the size and shape of the basin. The basin perimeter is positively correlated to basin area and channel length. The individual perimeter of all the 33 fourth-order streams is given in Table 3.7.

3.4.2.3 Basin Length (Lb)

Schumm (1956) while explaining the relief ratio described basin length as the longest dimensional part of basin which is parallel to primary stream channel line. According to (Gardiner 1975) basin length is measured from the basin's mouth up to a point to its perimeter which is equidistant from the basin's mouth in any direction around the perimeter. Although to explain it in a more quantitative manner (Nookaratnam et al. 2005) gave the equation as given in

Sr. No	Parameter	Formula	References
36	Stream order	SOu = Hierarchical rank	Strahler (1957)
37	Stream number	$SN_u = SN_1 + SN_2 + \ldots SN_n$	Horton (1945)
38	Stream length	$SL_u = SL_1 + SL_2 \ldots\ldots SL_n$	Strahler (1964)
39	Mean stream length	$MSL_u = \frac{\sum_{i=1}^{N} SO_u}{SN_u}$	Strahler (1964)
40	Mean stream length ratio	$MSLR_u = \frac{MSL_u}{MSL_u - 1}$	Horton (1945)
41	Bifurcation ratio	$R_b = \frac{SN_u}{SN_u + 1}$	Strahler (1964)
42	Valley length	VL	Mueller (1968)
43	Channel length	CL	Mueller (1968)
44	Air distance	AD	Mueller (1968)
45	Coefficient of topographical sinuosity (Ts) or valley index (VI)	$TsorVI = \frac{VL}{AD}$	Mueller (1968)

to calculate the basin length. The basin lengths for all the 33 sub-basins are given in Table 3.7.

3.4.2.4 Lemniscate's Value (L_k)

Chorley et al. (1957) derived the Lemniscate's value since the conventional circularity ratio used in sedimentary petrology provides very little insight into the actual shape of the drainage basin. The Lemniscate's values are given in Table 3.7 for Ghaggar basin. The L_k values drastically control the shape of the drainage basin. The L_k values are one for circular basins and as its value increases, the shape of the drainage basins becomes more and more elongated.

3.4.2.5 Form Factor (Ff)

Horton (1932) defined the Form Factor as the ratio of the area to the length of the drainage basin. The basin length is to be measured from a point on the watershed perimeter opposite the mouth of the mainstream. The length of the drainage basins having a side outlet may have less length as compared to the width. Form Factor is an indicative morphometric parameter of the flood-regime of the stream in case of long and elongated drainage basins but the same is not the case with drainage basins of irregular shapes. The value of F_f varies from 0 for highly elongated basins to unity, i.e., 1 for perfectly circular shaped basins. The sub-basins of Ghaggar river basins evidently show that they have slightly elongated basin shape having low Form Factor with a flatter peak of flow for a longer duration which results in groundwater percolation. The Form Factor (F_f) values of sub-basins of Ghaggar river basin are shown in Table 3.7.

3.4.2.6 Elongation Ratio (Re)

Schumm (1956) defined Elongation Ratio as the ratio of diameter of a circle having the same area as that of the basin to the maximum basin length. It acts as an imperative index for basin shape analysis. The areas having higher Elongation Ratio values possess high infiltration capacity and low surface runoff. An elongated basin is less effectual in runoff discharge as compared to a circular basin (Singh and Singh, Morphometric analysis of Kanhar river 1997). According to (Strahler 1964) following inferences about the shape of a basin were deduced from the Elongation Ratios: circular (>0.9), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7) and more elongated (<0.5). The Re values of sub-basins of Ghaggar basins range from 0.613 to 0.803 and are tabulated in Table 3.7. The Re values of Ghaggar sub-basins reveal that majority of the them are elongated in shape and are associated with strong relief and steep slope.

3.4.2.7 Ellipticity Index (Le)

The ellipticity index similarly to Form Factor and Elongation Ratio provides a comparable relationship between morphometry and hydrology (Stoddart 1965). Lower ellipticity values indicate a quick runoff draining basin because of which the stream channels might swell or overflow resulting in downstream flooding in case of heavy rainfall. The values of the ellipticity index are given in Table 3.7.

3.4.2.8 Circularity Ratio (R_c)

Circulatory ratio was defined by (Miller 1953) as the ratio of basin area of the area of a circle having an equal perimeter as that of the basin. Circularity ratio defines the circularity of the basin and is a dimensionless entity. R_c values of the Ghaggar river sub-basin ranges from 0.046 to 0.3953. The lowest value of R_c (0.3953) lies in Sub-Basin 8 attributes to the high to moderate relief and structurally controlled drainage system. The values of the circularity ratio are given in Table 3.7.

3.4.3 Drainage Characteristics

Drainage density, drainage texture, stream frequency, Infiltration number, and drainage intensity are the vital elements reflecting the areal and relief characteristics of a basin as a whole. These elements supplemented the prediction of overland flow, runoff estimation, sediment yield of a river, etc. the analysis of these elements supports the spatio-temporal distribution of drainage basin processes.

3.4.3.1 Drainage Density (D_d)

Horton (1932) defined drainage density as the ratio of stream length to that of drainage area. Drainage density act as a permeability indicator of the drainage basin surface. High drainage densities are pertinent to the regions having impervious subsurface with weak structure whereas low densities are associated with highly resistant subsurface covered by vegetation and having low relief. But there are limitations associated with Horton's methods that first it indicates a single value for drainage density and secondly it doesn't take into consideration the study of frequency analysis and spatial variations of drainage density within a physiographic region. Gardiner (1971) suggested the use of grid square method of equal sizes to minimize the scale distortion. This methodology is the most widely accepted providing a faster and easier method for the drainage density analysis by dividing the complete basin into a number of grids of 1 Km^2 and then measuring the stream links, junctions intersecting with the boundary of grid square and grid square diagonal. The drainage density spatial distribution within the Ghaggar basin is depicted in Fig. 3.4. The sub-basins-wise values of the drainage density of Ghaggar basin are given in Table 3.8.

3.4.3.2 Drainage Texture (D_t)

Horton (1945) defined drainage texture on the basis of stream frequency, i.e., number of streams per unit of basin area. Drainage texture is defined as the cumulative length of permanent and temporary streams per unit of area. Singh (1976) defined the drainage texture on the basis of relative spacing of the streams per unit length in a square grid. In

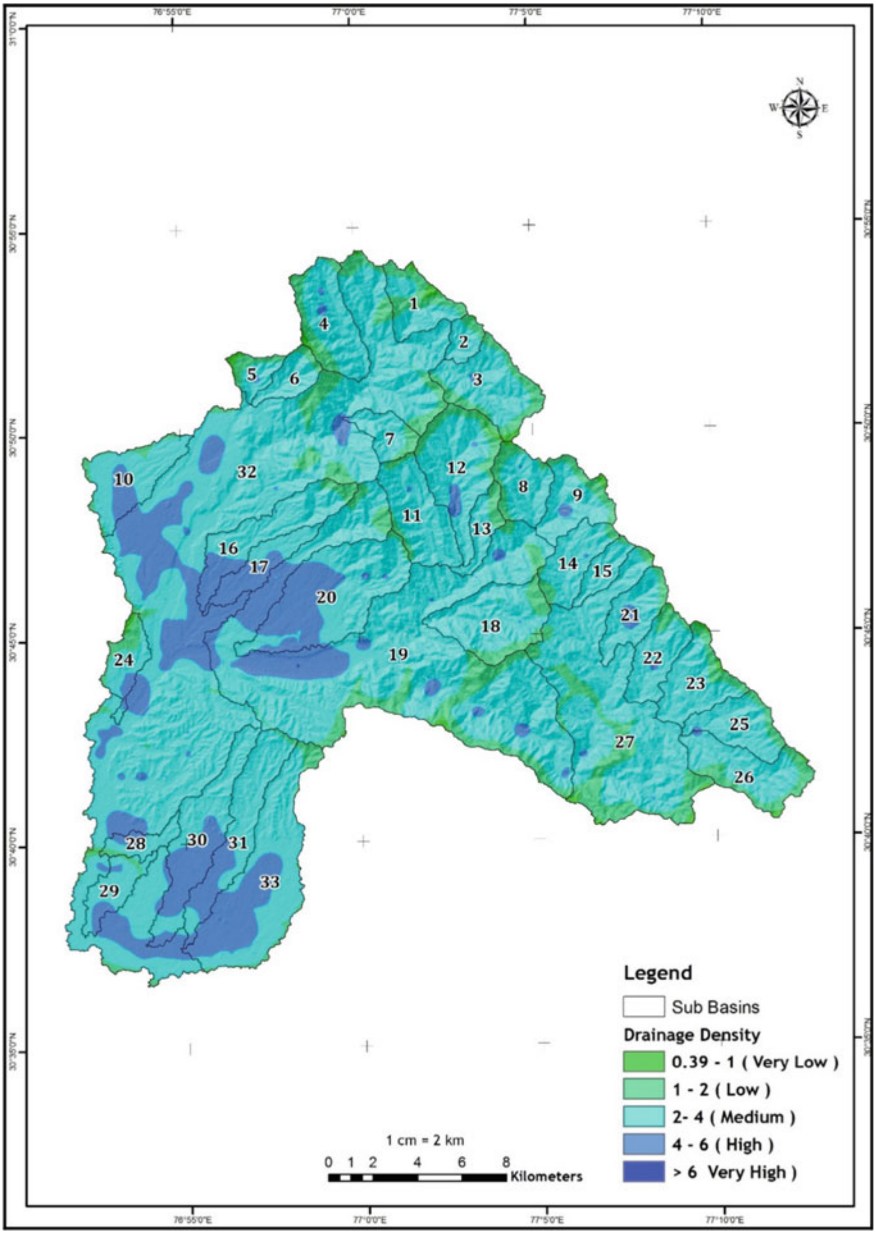

Fig. 3.4 Spatial distribution of drainage density in Ghaggar basin

Table 3.8 Sub-basins wise drainage characteristics values of the Ghaggar basin

Sub-basin	Drainage characteristics (Mean values)				
	Drainage density	Drainage texture	Stream frequency	Drainage intensity	Infiltration number
1	2.10	1.16	15.24	6.16	37.48
2	2.58	0.72	12.60	5.17	38.97
3	2.48	0.73	15.19	5.79	39.71
4	2.61	0.78	14.60	5.80	47.47
5	2.33	1.20	11.67	5.88	50.72
6	2.71	0.74	12.86	5.45	42.47
7	2.66	0.68	16.64	5.89	52.31
8	2.41	0.67	15.04	6.19	39.42
9	2.64	0.82	15.90	5.91	52.41
10	3.13	0.68	13.70	4.11	61.73
11	2.75	0.61	15.14	5.50	45.98
12	2.80	0.63	16.54	5.63	51.12
13	2.56	0.56	14.34	5.87	36.66
14	2.84	0.63	15.46	5.14	51.03
15	2.86	0.70	14.33	4.97	46.25
16	3.24	0.54	14.39	4.66	52.24
17	4.02	0.41	13.99	3.93	63.88
18	2.52	0.61	13.63	5.57	38.74
19	2.96	0.63	15.27	5.27	55.95
20	3.74	0.43	16.82	4.73	66.15
21	3.08	0.60	17.18	5.55	63.29
22	2.77	0.61	15.58	5.68	51.14
23	2.85	0.68	16.09	5.68	53.97
24	2.60	1.08	12.38	4.30	54.85
25	2.98	0.65	13.44	4.73	48.05
26	2.49	0.71	13.19	5.35	46.82
27	2.57	0.65	14.19	5.45	50.24
28	3.44	0.48	15.14	4.13	64.53
29	3.44	0.57	15.78	4.26	56.57
30	3.78	0.45	15.91	4.26	62.88
31	3.57	0.44	16.02	4.51	59.87
32	3.25	0.58	15.62	4.97	60.44
33	3.46	0.65	14.29	4.24	61.42

the current work, his method of counting the streams crossing the perimeter (4 edges) of the square grid and two of its diagonals is used. The drainage texture spatial distribution within the Ghaggar basin is depicted in Fig. 3.5. The sub-basins-wise values of the drainage density of Ghaggar basin are given in Table 3.8.

3.4.3.3 Stream Frequency (S_f)

Horton (1945) defined the computation of stream frequency as the total number of streams per unit area. Stream frequency shows a positive correlation with the drainage density. He also used it as an index of drainage texture but the concept lasted not long. But it signifies a single value of stream frequency and hence is practically not useful. Therefore, a most widely accepted methodology of providing a faster and easier method for the stream frequency analysis is adopted by dividing the complete basin into a number of grids of 1 km^2 and then counting the stream orders within the grid square. The sub-basins wise values of the drainage density of Ghaggar basin are given in Table 3.8.

3.4.3.4 Drainage Intensity (D_i)

Drainage intensity was defined by (Faniran 1968) as the ratio of the stream frequency (S_f) to the drainage density (D_d). But it signifies a single value of drainage intensity and hence is practically not useful. Therefore, a most widely accepted methodology of providing a faster and easier method for the drainage intensity analysis is adopted by dividing the complete basin into a number of grids of 1 Km^2 and then using it to calculate the drainage density and stream frequency to further calculate the drainage intensity. The entire region was divided into 646 grids of one square km. Figure 3.6 portrays the drainage intensity spatial distribution within the Ghaggar basin. The study area has low to moderate drainage intensity implying that drainage density and stream frequency have marginally low effects (if any) on the extent to which the surface has been depressed by denudational agent. The sub-basins-wise values of drainage intensity of the Ghaggar basin are given in Table 3.8.

3.4.3.5 Infiltration Number (I_n)

Faniran (1968) defined the Infiltration number of a drainage basin as the product of drainage density (D_d) and stream frequency (S_f) of a basin. But it signifies a single value of Infiltration Number and hence is practically not useful. Therefore, a most widely accepted methodology of providing a faster and easier method for the Infiltration Number analysis is adopted by dividing the complete basin into a number of grids of 1 Km^2 and then using it to calculate the drainage density and stream frequency based upon which Infiltration Number is calculated. The Infiltration Number spatial distribution within the Ghaggar basin is depicted in Fig. 3.7. The sub-

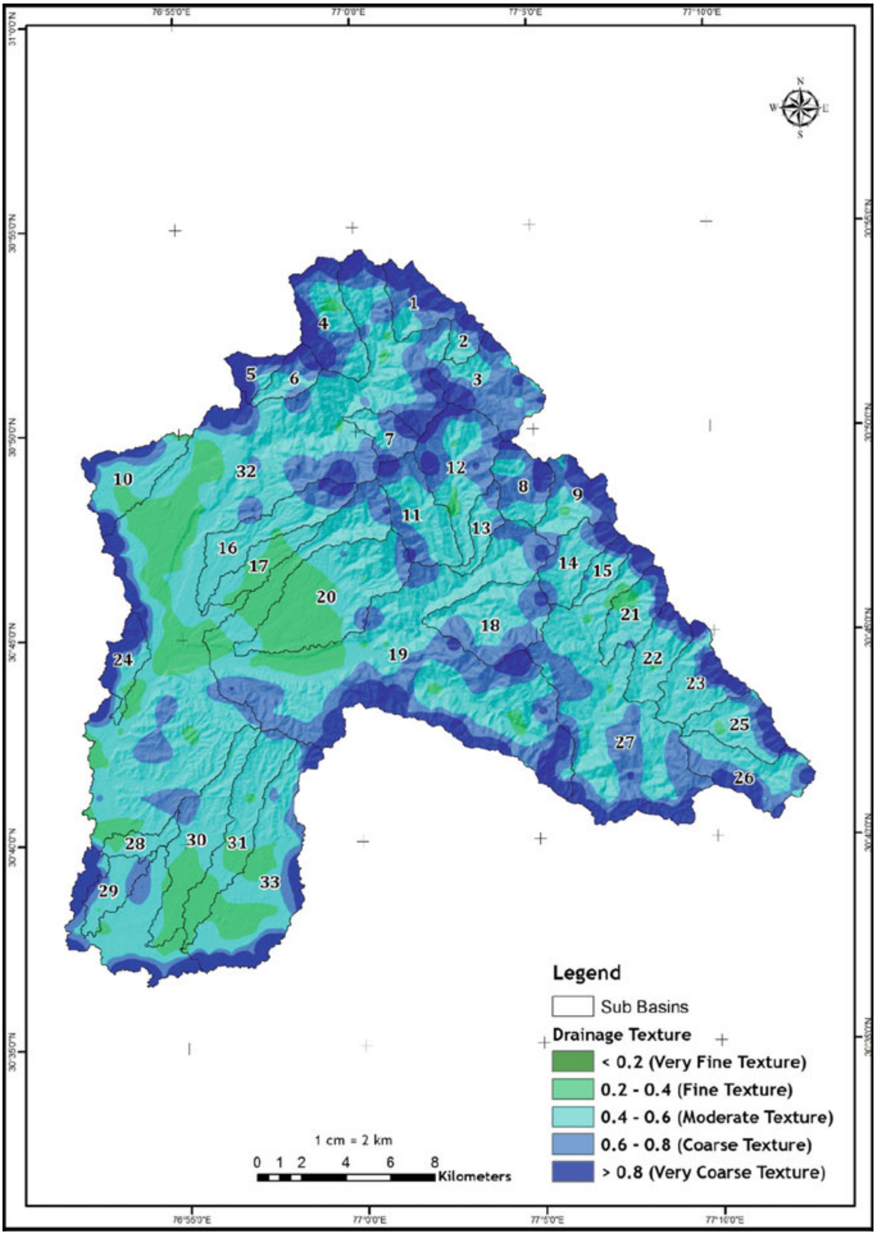

Fig. 3.5 Spatial distribution of drainage texture in Ghaggar basin

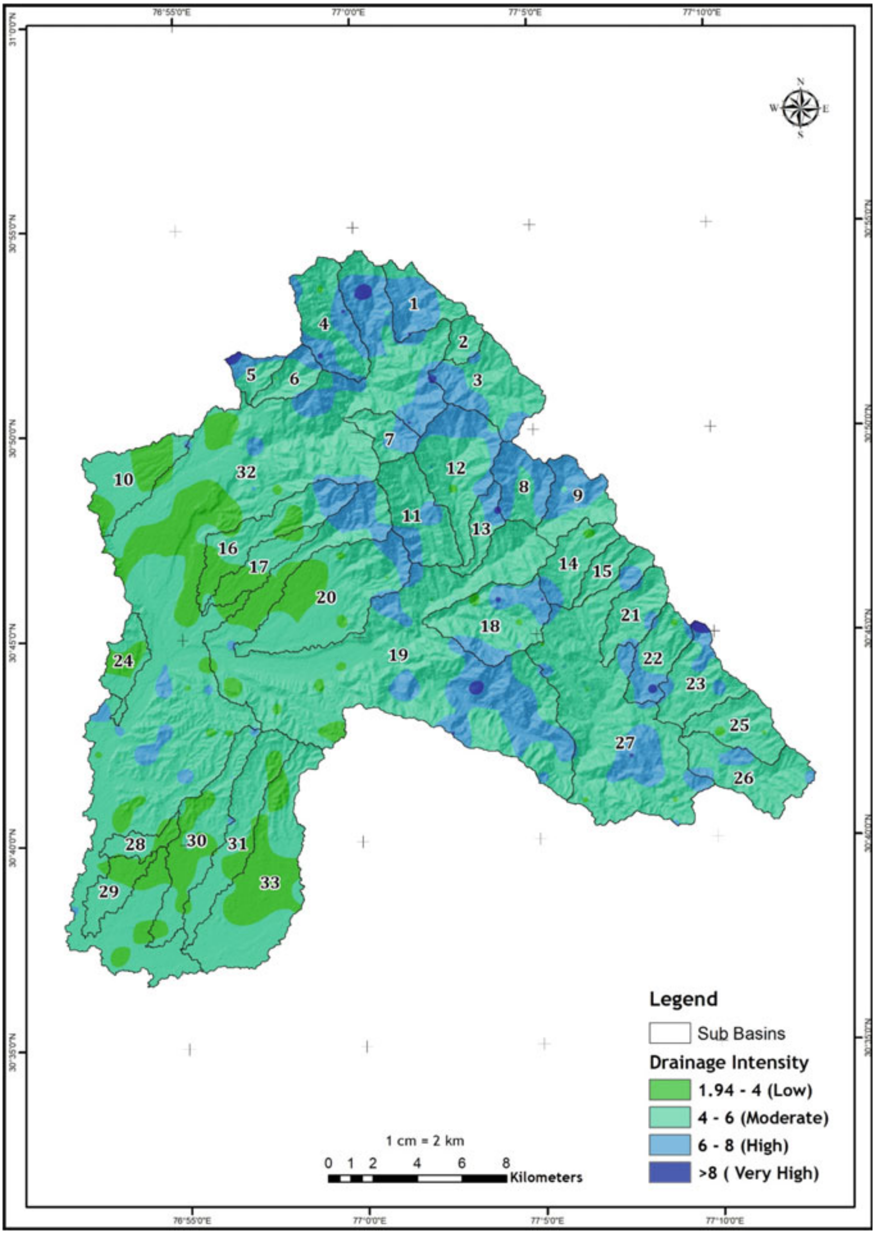

Fig. 3.6 Spatial distribution of drainage intensity in Ghaggar basin

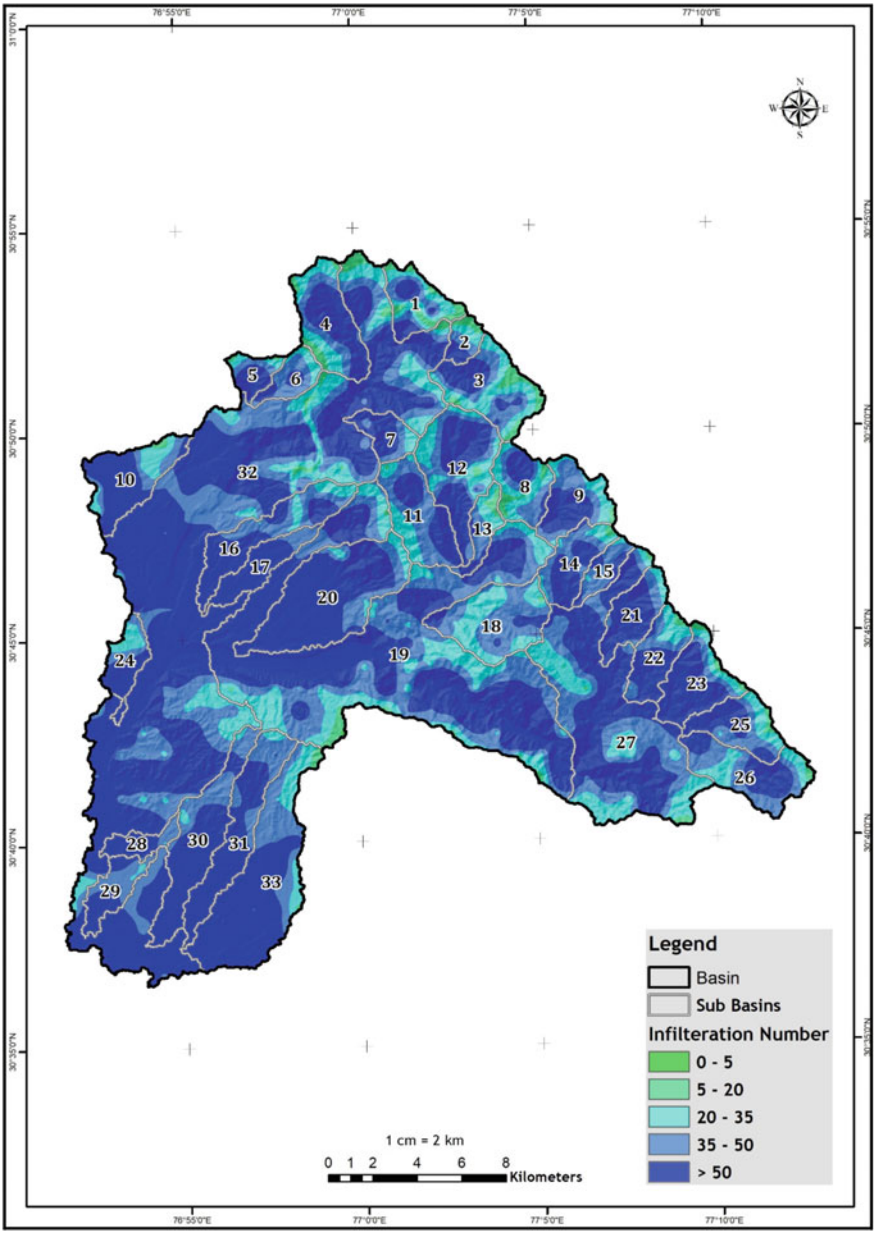

Fig. 3.7 Spatial distribution of infiltration number in Ghaggar basin

basins-wise values of the drainage density of Ghaggar basin are given in Table 3.8. The Infiltration Number within the Ghaggar basin ranges from 0.707 to 205 and about 46 percentage of this is above 50 and this value indicates low infiltration and medium to high runoff, the lithology of basin is hard and impermeable. The higher values of Infiltration Number contribute to lower infiltration rates and result in the higher runoff.

3.4.4 Relief Characteristics

The relief characteristics of a basin are a representation of the areal, volume, and altitudinal aspects of the basin landscape. The relief characteristics of morphometric analysis include absolute relief, aspect, dissection index, relative relief ratio, relative relief, Ruggedness Number, and slope.

3.4.4.1 Absolute Relief (Ra)

Absolute relief defines the maximum elevation of a basin area. This parameter helps in determining the rate of erosion with respect to the current summit or hilltops of a basin since these hilltops or summits act as the last remnant of the endangered relief. The absolute relief of Ghaggar basin ranges from 260 to 1858 m and the mean height of the basin stands at 910.2 m. The sub-basins wise values of absolute relief of the Ghaggar basin are given in Table 3.9. The absolute relief of the Ghaggar basin has been grouped into five classes, i.e., low (<300 m) occupying 5.81%, moderately low (300–600 m) occupying 28.74%, moderate (600–900 m) occupying 12.97%, moderately high (900–1200 m) occupying 23.00% and high (>1200 m) occupying 29.48% of area respectively. The absolute relief spatial distribution within the Ghaggar basin is shown in Fig. 3.8.

3.4.4.2 Relative Relief (R_r)

Relative relief plays a vital role in the calculation average slope, dissection determination, and in assessing the terrain development stages. Smith (1935) coined the term relative relief in order to highest and lowest altitude points of a particular area. The sub-basins-wise values of relative relief of the Ghaggar basin are given in Table 3.9. The relative relief of the Ghaggar basin has been grouped into six classes, i.e., low (<70 m) occupying 22.31%, moderately low (70–140 m) occupying 14.57%, moderate (140–220 m) occupying 12.20%, moderately high (220–320 m) occupying 19.59%, high (320–420 m) occupying 20.78%, and very high (> 420 m) occupying 10.55%, of area respectively. The absolute relief spatial distribution within the Ghaggar basin is shown in Fig. 3.9.

Table 3.9 Sub-basins wise relief characteristics values of the Ghaggar basin

Sub-basin	Relief characteristics (Mean values)					
	Absolute relief	Relative relief	Relative relief ratio	Dissection index	Ruggedness number	Slope
1	1803.12	838.01	4.86	0.47	1.76	44.05
2	1803.71	728.70	7.72	0.40	1.88	46.34
3	1743.79	668.79	3.02	0.38	1.66	39.40
4	1869.24	1007.27	4.89	0.54	2.63	47.79
5	1467.04	757.43	6.85	0.52	1.77	40.32
6	1691.08	982.09	7.55	0.58	2.66	54.91
7	1572.49	825.86	6.29	0.53	2.20	47.45
8	1499.51	696.31	4.53	0.46	1.68	43.77
9	1724.91	921.71	4.73	0.53	2.44	44.58
10	595.74	159.12	0.68	0.27	0.50	7.91
11	1612.31	962.44	4.82	0.60	2.65	45.12
12	1568.10	918.23	3.71	0.59	2.57	43.94
13	1382.21	745.25	4.76	0.54	1.91	41.48
14	1757.03	865.36	5.13	0.49	2.46	36.28
15	1749.25	857.58	6.76	0.49	2.45	37.91
16	1522.85	1127.72	3.65	0.74	3.65	28.49
17	1026.53	631.41	2.90	0.62	2.54	9.93
18	1447.10	882.60	4.14	0.61	2.22	45.73
19	1610.25	1250.60	1.03	0.78	3.70	35.79
20	1318.35	937.23	2.85	0.71	3.50	21.50
21	1850.07	1030.22	5.93	0.56	3.17	41.32
22	1840.28	1048.79	6.04	0.57	2.90	38.03
23	1804.79	983.59	4.74	0.55	2.80	40.92
24	501.00	189.50	1.00	0.38	0.49	11.65
25	1624.53	776.53	4.24	0.48	2.32	38.51
26	1560.62	712.62	2.93	0.46	1.77	38.05
27	1782.66	1073.64	1.74	0.60	2.76	37.65
28	393.22	127.64	0.80	0.33	0.44	7.33
29	315.72	65.86	0.33	0.21	0.23	5.11
30	692.80	433.93	1.18	0.63	1.64	11.70
31	727.48	460.46	1.29	0.63	1.64	13.59
32	1721.41	1471.75	0.74	0.86	4.78	22.54
33	740.73	473.72	1.14	0.64	1.64	8.83

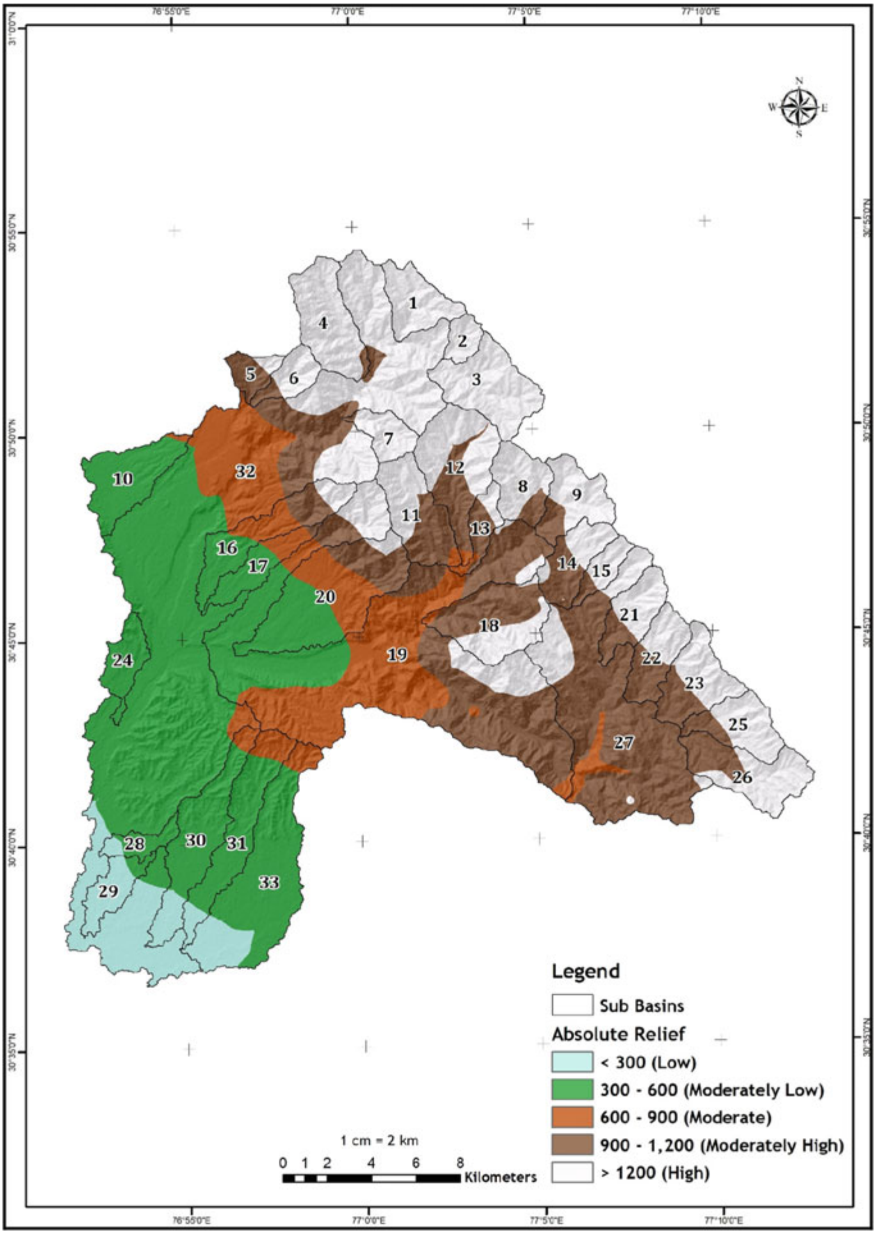

Fig. 3.8 Spatial distribution of absolute relief in Ghaggar basin

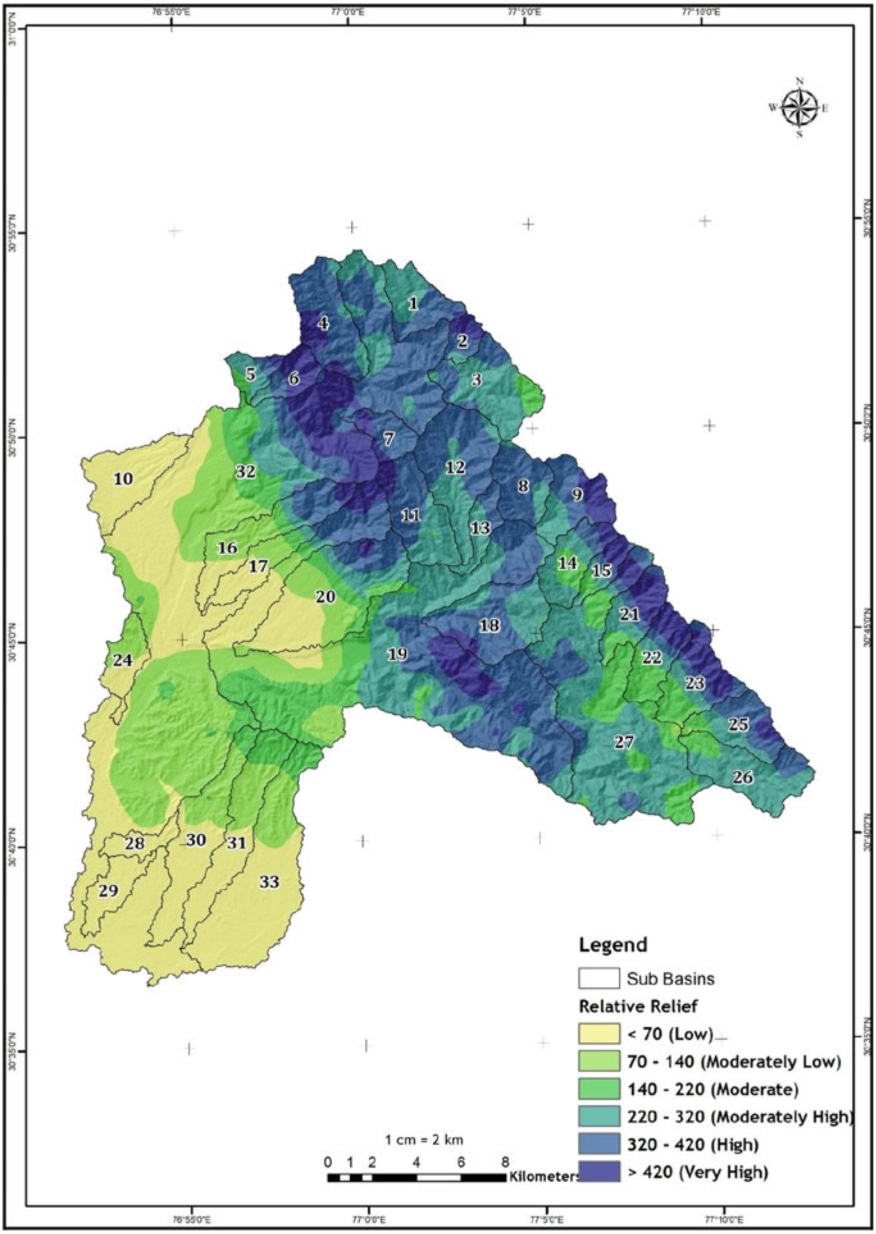

Fig. 3.9 Spatial distribution of relative relief in Ghaggar basin

3.4.4.3 Relative Relief Ratio (R_{hp})

Relative relief ratio (Melton 1958) is the ratio of the difference between maximum altitude and minimum altitude for a given area denoted by R_r, and the perimeter (P) of the area. Relative relief ratio acts as an indicator of relative velocity of the perpendicular tectonic movements. The sub-basins-wise relative relief ratio values of the Ghaggar basin are given in Table 3.9. The lower values of the relative relief ratio pertain to the less resistive rocks.

3.4.4.4 Dissection Index (Di)

Dissection index is expressed as the ratio of relative relief to absolute relief of an area (Nir 1957). It acts as a vital parameter for developing an understanding of the degree of dissection (high, moderate, or low) and evolution of the stages of landform (young, mature, and old) development in any given physiographic region. Dissection index also offers valuable insight into the slope nature (steep, moderate, or gentle). The values of dissection range from 0 (implying a theoretical value as there is no region in nature which is passive to erosion) to 1. However, the ratio can be more than 1 only in case of incomparable cases of cliff. The sub-basins-wise dissection index values of the Ghaggar basin are given in Table 3.9. The dissection index spatial distribution within the Ghaggar basin is shown in Fig. 3.10.

3.4.4.5 Ruggedness Number (R_n)

The structural complexity of the terrain is measured by Ruggedness Number. It is a dimensionless property which is a product of R_r and drainage density of a given basin area having the same units. If the drainage density D_d is increased keeping the R_r constant there is an increase in slope steepness whereas if the R_r is increased keeping D_d constant it is also accompanied by slope steepness. In case the values of R_r and D_d are both high then slopes will be steep as well as long (Strahler 1964). The sub-basins-wise Ruggedness Number values of the Ghaggar basin are given in Table 3.9. The Ruggedness Number spatial distribution within the Ghaggar basin is shown in Fig. 3.11. Patton and Baker (1976) discussed that the areas having higher ruggedness numbers accompanied with fine drainage texture, and minimalistic length of overland flow on steep slopes have the expectancy of potential flash flooding. These morphometric parameters combination may lead to higher flood peaks for an are having low Ruggedness Number even for equivalent of rainfall events.

3.4.4.6 Slope (S)

The angular inclination of topography formed between top of the hills and valley bottoms is known as slope. It may also be defined as the maximum rate of change in

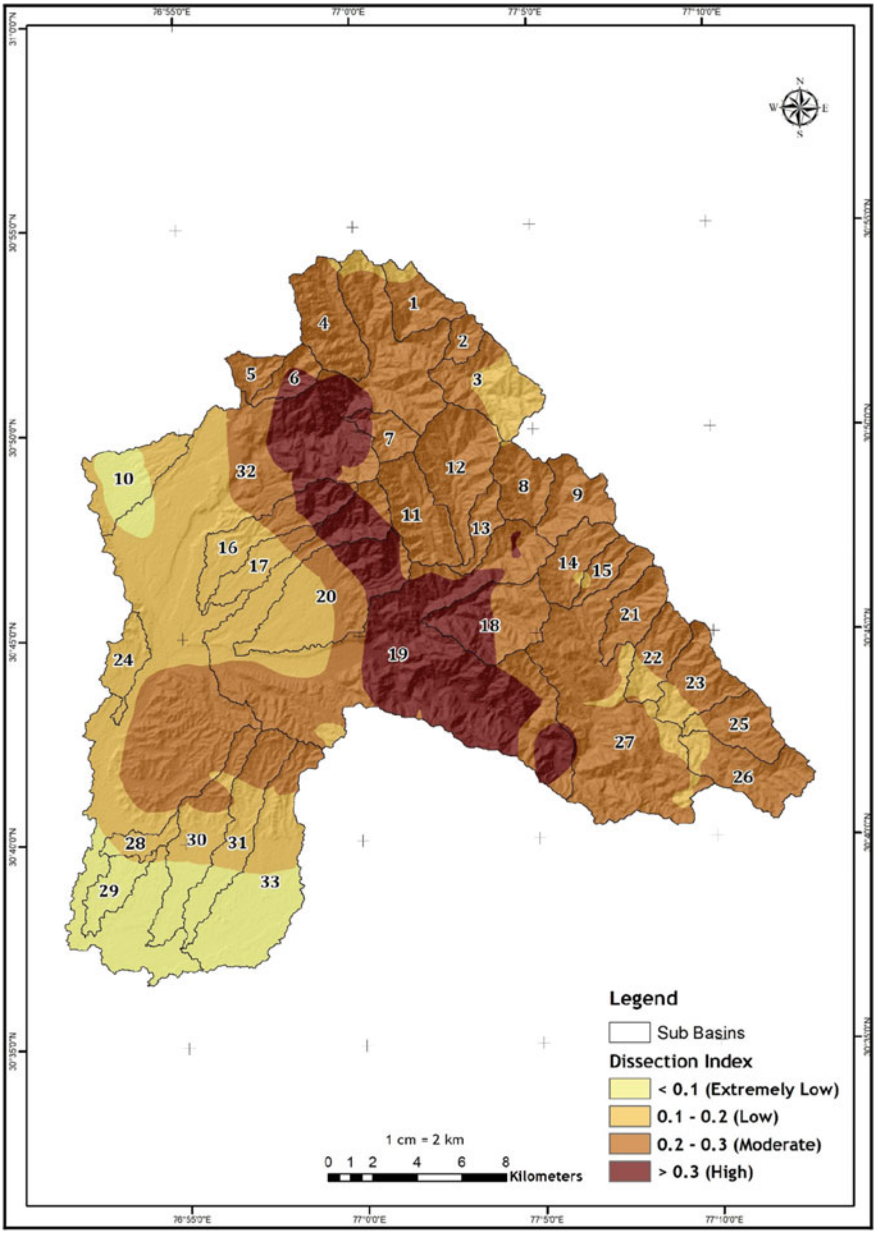

Fig. 3.10 Spatial distribution of dissection index in Ghaggar basin

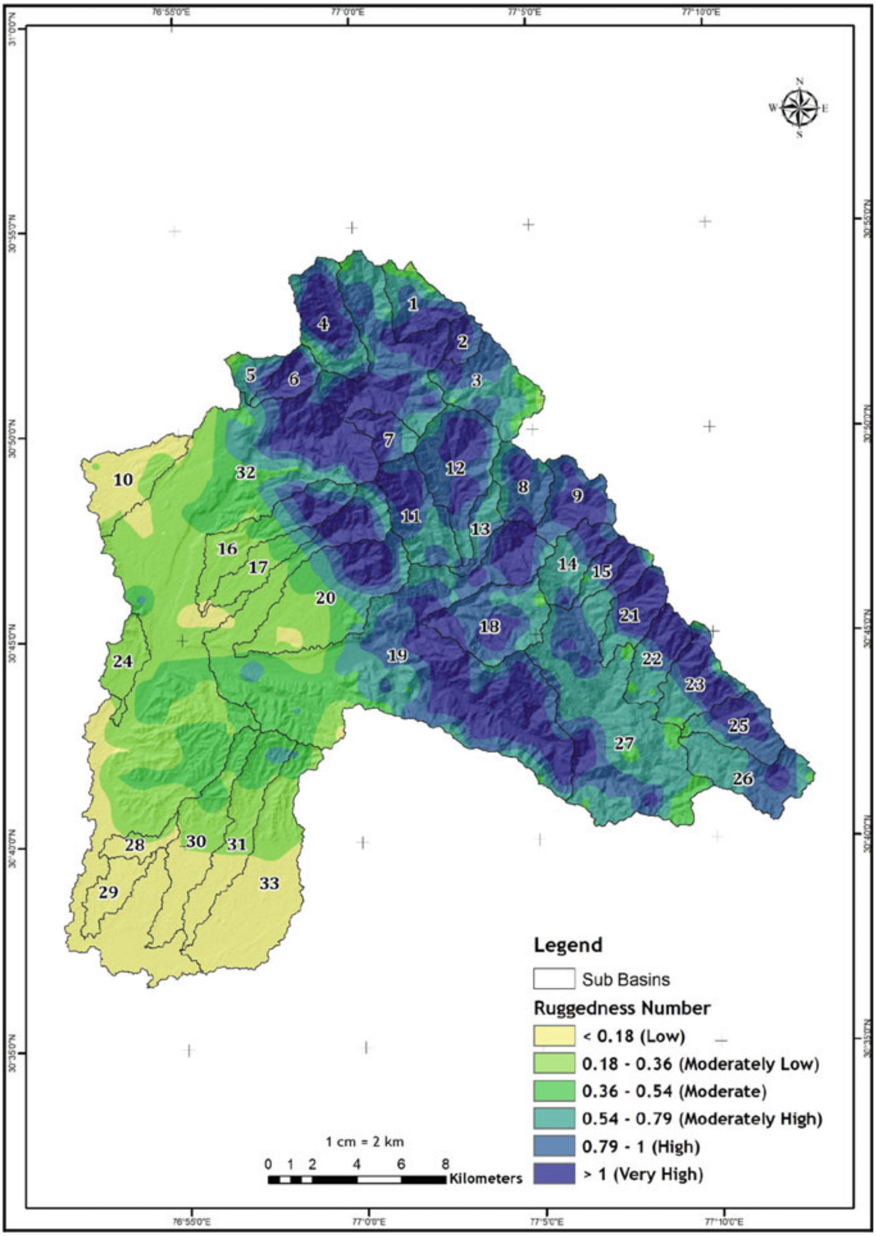

Fig. 3.11 Spatial distribution of ruggedness number in Ghaggar basin

elevation values for each cell to its neighboring cells. The slope plays a vital role in geomorphic studies as it acts act a controlling factor for natural and anthropogenic activities such as soil, agriculture, communication, transport, and settlements. The steepness of a drainage basin slope is an indicator of erosion intensity operable in the basin. The slope map of Ghaggar basin is prepared using Sentinel 1 DEM in ArcGIS. The slope angles of Ghaggar basin have been grouped into five categories (1) level (0–2°), gentle (2–5°), moderate (5–10°), high (10–15°) and very high (>15°). The sub-basins-wise slope values of the Ghaggar basin are given in Table 3.9. The slope spatial distribution within the Ghaggar basin is shown in Fig. 3.12.

3.4.4.7 Aspect (AS)

Aspect as calculated from the ArcGIS software shows the relative position of slopes with respect to sun angle direction. It can be also described as the downward slope direction of the extreme change in value from each cell to its neighbors. The values in the output raster indicate the compass direction which the surface faces at that particular cell value location. The aspect is clockwise in degrees from 0 (due north) to 360 (again due north). Flat areas are given a value of −1. The aspect spatial distribution within the Ghaggar basin is shown in Fig. 3.13.

3.4.5 Hypsometric Analysis

Strahler (1952) defined the hypsometric analysis as the relationship between horizontal cross-sectional drainage basin area to its elevation for small basin. It is being used extensively in identifying the stages of evolution of the erosional landforms. Hypsometric curves and integrals are important watershed conditions indicator. The interpretation of the hypsometric curves and integrals is based upon the degree of basin dissection and relative age of landform. The shape of the curve is convex-up with high integrals for youth stage; disequilibrium stage for undissected landscape; smooth S-shaped curve signifies mature landscapes in mature stage and finally concave up curves having lower integrals curve values represent old and deeply dissected landscapes (Strahler 1952). The difference in the shape of the curve implies the relationship between erosion and tectonic forces balance prevailing within the basin. The hypsometric curve for the current study is expressed as the ratio of relative height to the relative area in respect to the total height and total area of a drainage basin. The hypsometric curve of the entire Ghaggar basin represents a typical S-shaped curve indicating the mature development of the basin as given in Fig. 3.14. The sub-watershed of Ghaggar basin have varied shaped hypsometric curves from convex, concave to S-shaped characterizing their development from youth to mature stage. The difference in the shape of the curve owes to the lithological characteristics, bedrock incision, sediment removal, and downward movement of eroded materials prominent within the individual watersheds.

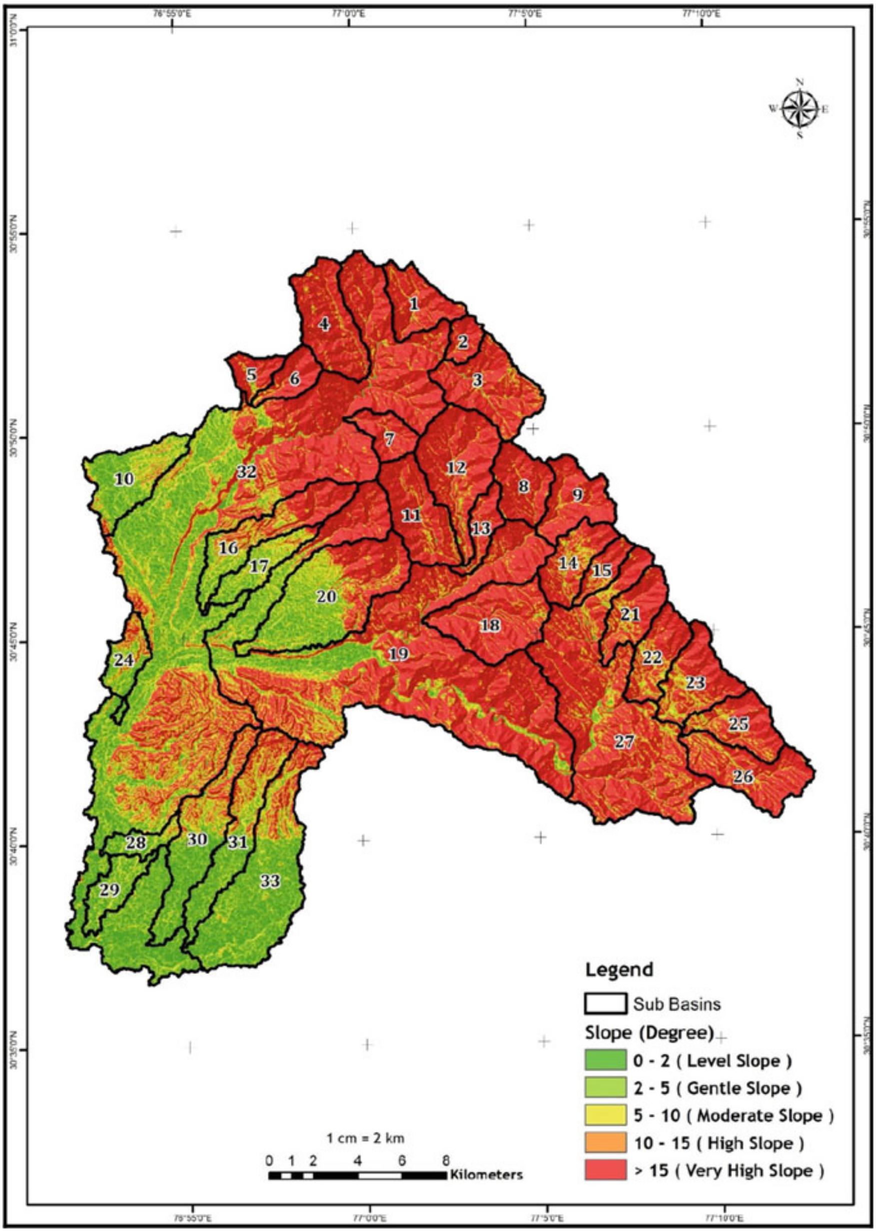

Fig. 3.12 Spatial distribution of slope in Ghaggar basin

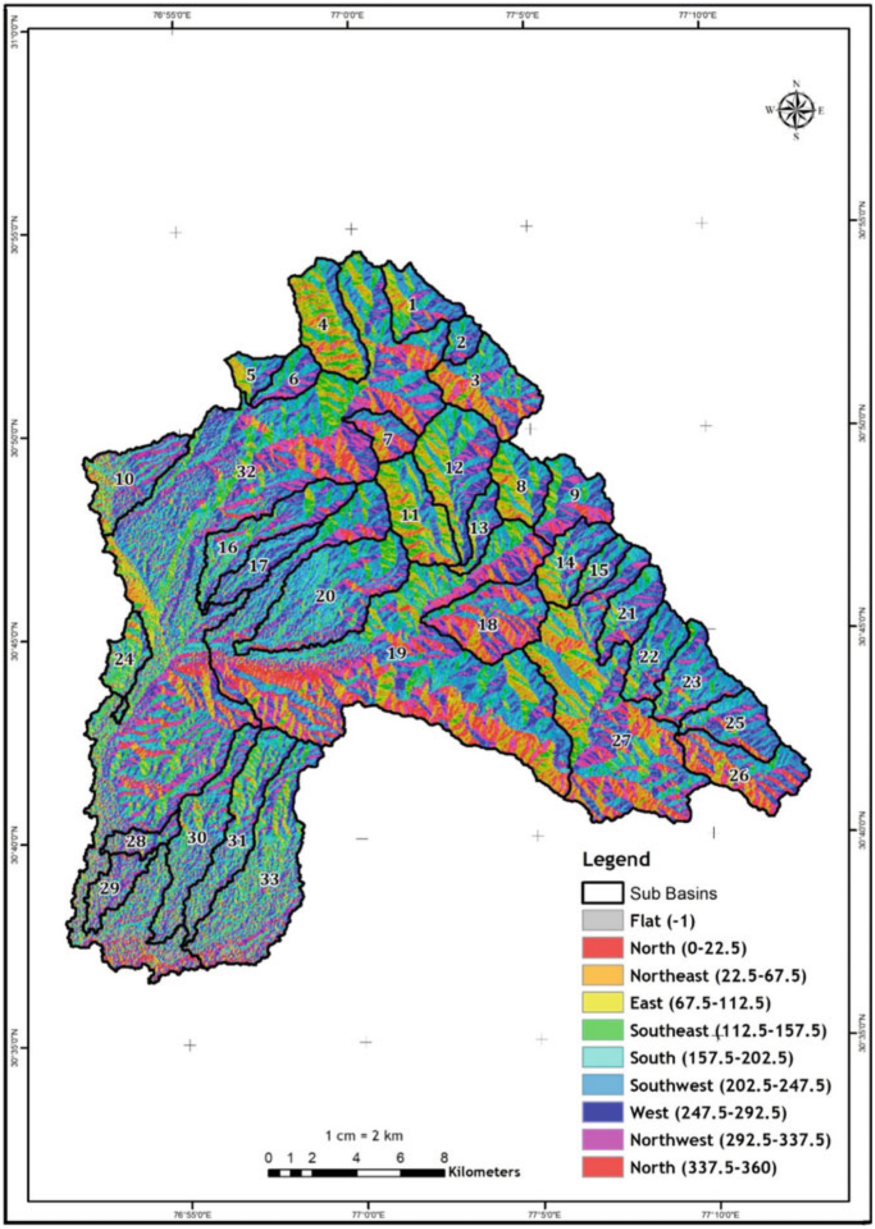

Fig. 3.13 Spatial distribution of aspect in Ghaggar basin

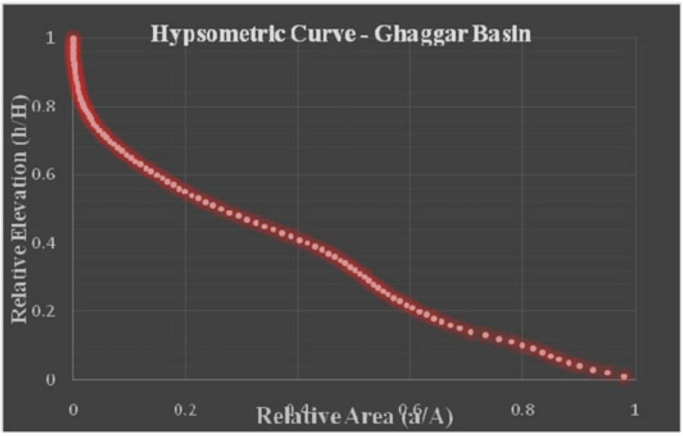

Fig. 3.14 Hypsometric curve of the Ghaggar basin

3.4.5.1 Hypsometric Integral

Pike and Wilson (1971) expressed the hypsometric integral based upon the mean, maximum and minimum elevation prevalent in the sub-watershed. Strahler (1952) classified the hypsometric integrals values base upon three threshold limits representing the characteristic phases of geomorphic cycle.

HI $\geq$ 0.60: in equilibrium or young stage.

0.35 $\leq$ HI $\leq$ 0.60: the equilibrium or mature stage and

HI $\leq$ 0.35: the monadnock or old stage.

In the equilibrium or young stage of early development, the transformation of the slopes is rapid owing to the expansion and branching of the drainage system. An equilibrium stage signifies the mature stage wherein the steady-state has been attained resulting due to diminishing of the relief. The monadnock phase signifies the old stage which is in the transitory phase since the removal of the monadnock results in refurbishment of the curve toward the equilibrium stage. The hypsometric integral value of the Ghaggar basin is calculated to be 0.33, which reveals that 33 percent of the rock masses still exist in basin. The calculated hypsometric integral values for all the sub-watersheds of the Ghaggar basin range from 0.15 to 0.58 as shown in Table 3.10. The spatial distribution of hypsometric integral (HI) values obtained for thirty-three sub-watersheds are shown in Fig. 3.15.

Table 3.10 Hypsometric integral values of sub-watershed within Ghaggar basin

Sub-watersheds	Elevation			Integral	Geological stage
	Minimum	Maximum	Mean		
1	965.11	1803.12	1343.35	0.45	Maturity stage
2	1075.01	1803.71	1413.10	0.46	Maturity stage
3	1075.01	1743.79	1366.69	0.44	Maturity stage
4	861.96	1869.24	1377.71	0.51	Maturity stage
5	709.61	1467.04	934.67	0.30	Old stage
6	708.99	1691.08	1182.91	0.48	Maturity stage
7	746.63	1572.49	1230.83	0.59	Maturity stage
8	803.20	1499.51	1120.64	0.46	Maturity stage
9	803.20	1724.91	1176.78	0.41	Maturity stage
10	436.62	595.74	492.70	0.35	Maturity stage
11	649.87	1612.31	1039.78	0.41	Maturity stage
12	649.87	1568.10	1092.19	0.48	Maturity stage
13	636.96	1382.21	943.48	0.41	Maturity stage
14	891.67	1757.03	1144.84	0.29	Old stage
15	891.67	1749.25	1218.53	0.38	Maturity stage
16	395.13	1522.84	701.32	0.27	Old stage
17	395.13	1026.53	530.77	0.21	Old stage
18	564.50	1447.10	1004.45	0.50	Maturity stage
19	359.65	1610.25	732.69	0.30	Old stage
20	381.13	1318.35	631.36	0.27	Old stage
21	819.85	1850.07	1209.62	0.38	Maturity stage
22	791.49	1840.28	1132.43	0.33	Old stage
23	821.21	1804.79	1166.50	0.35	Maturity stage
24	311.51	501.00	388.26	0.41	Maturity stage
25	848.00	1624.53	1169.82	0.41	Maturity stage
26	848.00	1560.62	1125.09	0.39	Maturity stage
27	709.01	1782.66	980.55	0.25	Old stage
28	265.58	393.22	303.30	0.30	Old stage
29	249.86	315.72	271.47	0.33	Old stage
30	258.87	692.80	362.54	0.24	Old stage
31	267.02	727.48	398.33	0.29	Old stage
32	249.66	1721.41	611.89	0.25	Old stage
33	267.02	740.73	340.39	0.15	Old stage
Ghaggar basin	249.66	1869.24	787.91	0.33	Old stage

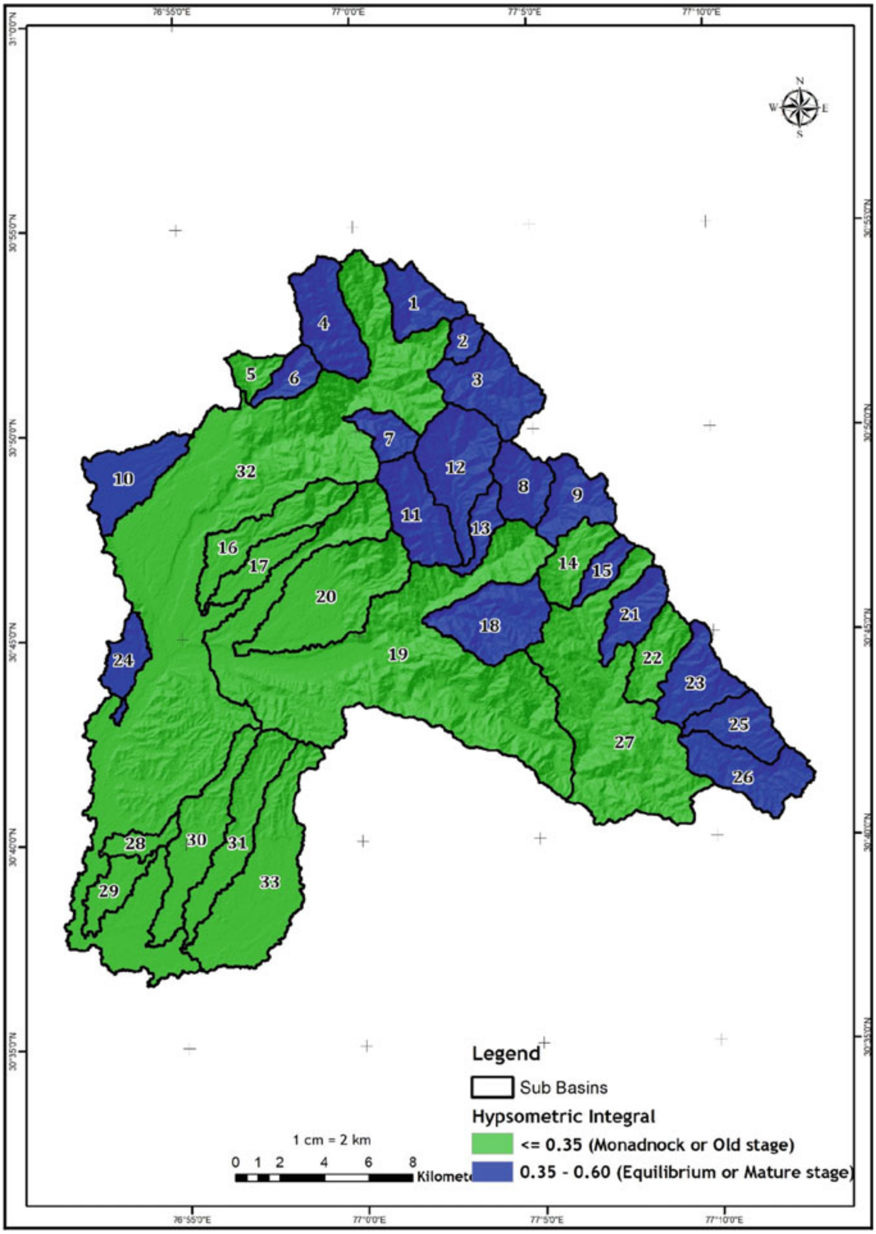

Fig. 3.15 Hypsometric integral map of the Ghaggar basin

3.5 Conclusion

This current study has helped in deciphering the geomorphological and hydrological processes prevalent in the 33 watersheds of the Ghaggar river basin up to its confluence with Madhekali river. This morphometric analysis coupled with landuse/Landcover, climate, soil data can provide vital results on prioritizing the watersheds based upon their erosion extent. This data can further supplement the site suitability analysis of water harvesting structures to recharge the groundwater level.

References

Chen CW, Zebker HA (2000) Network approaches to two-dimensional phase unwrapping: intractability and two new algorithms. J Opt Soc Am 17:401–414

Chorley RJ, Malm DE, Pogorzelski HA (1957) A new standard for estimating drainage basin shape. Am J Sci 255:138–141

Clarke JJ (1996) Morphometry from Maps. Essays in Geomorphology. Elsevier Publishing Company, New York, pp 235–274

Faniran A (1968) The index of drainage intensity—a provisional new drainage factor. Aust J Scienec 31:328–330

Gardiner V (1971) A drinage density map of Dartmoor. Trans Devon Assoc 103:167–180

Gardiner V (1975) Drainage basin morphometry. Br Geomorphol Res Group.

Goldstein RM, Zebker HA, Werner CL (1988) Satellite radar interferometry' Two-dimensional phase unwrapping. Radio Sci 23(4):713–720

Horton RE (1932) Drainage basin characteristics. Trans Am Geophys Union 13(1):350–361

Horton RE (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geol Soc Am Bull 56(3):275–370

Melton MA (1958) Correlation structure of morphometric properties of drainage systems and their controlling agents. J Geol 66(4):442–460

Miller VC (1953) Quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee. Columbia University, Department of Geology, Columbia

Mueller JE (1968) An introduction to the hydraulic and topographic sinuosity indexes. Ann Assoc Am Geogr 58(2):371–385

Nir D (1957) The ratio of relative and absolute altitudes of Mt. Carmel: a contribution to the problem of relief analysis and relief classification. Geogr Rev. 47(4):564–569.

Nookaratnam K, Srivastava YK, Rao VV, Amminedu E, Murthy KR (2005) Check dam positioning by prioritization of micro-watersheds using SYI model and morphometric analysis—remote sensing and GIS perspective. J Indian Soc Remote Sens 33(1):2–38

Patnaik N (1981) Role of soil conservation and deforestation for flood moderation. In: Proceedings of conference on flood disasters. New Delhi, India.

Patton PC, Baker VR (1976) Morphometry and floods in small drainage basin subject to diverse hydrogeomorphic controls. Water Resour Res 12(5):941–952

Pike RJ, Wilson S (1971) Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. GSA Bull 82(4):1079–1084

Schumm SA (1956) Evolution of drainage systems and slopes in Badlands at Perth Amboy, New Jersey. Bull Geol Soc Am 67:597–646

Shreve RL (1967) Infinite topologically random channel networks. J Geol 75(2):178–186

Singh G, Babu R, Narain P, Bhushan LS, Abrol IP (1992) Soil erosion rates in India. J Soil Water Conserv 47(1):97–99

Singh MJ, Khera KL (2009) Physical indicators of soil quality in relation to soil erodibility under different Landuses. Arid Land Res Manag 23(2):152–167

Singh S (1976) On the quantitative parameters for the computation of drainage density, texture and frequency: a case study of a part of the Ranchi Plateau. National Geographer 10(1):21–31

Singh S, Singh MC (1997) Morphometric analysis of Kanhar river. Natl Geogr J India 43(1):31–43

Smith GH (1935) The relative relief of Ohio. Geogr Rev 25:247–248

Stoddart DR (1965) The shape of atolls. Mar Geol 3(5):369–383

Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. Geol Soc Am Bull 63(11):1117–1142

Strahler AN (1957) Quantitative analysis of watershed geomorphology. Trans Am Geophys Union 38(6):913–920

Strahler AN (1964) Quantitative geomorphology of drainage basins. In: Chow VT (ed) Handbook of applied hyrology. McGraw Hill Book Company, New York, pp 4–11

Vittala SS, Govindaiah S, Gowda HH (2004) Morphometric analysis of sub- watershed in the Pavagada area of Tumkur District, South India using remote sensing and GIS techniques. J Indian Soc Remote Sens 32(4):351–362