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Research Article

GI-Science Based Morphometric Analysis for Geo-Hydrological Studies of Ghaggar River Basin, North-West India

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ABSTRACT

Morphometric analyses play a vital role in hydrological investigations. The application of GI-Science and processing techniques have greatly facilitated this through delineation of morphological features or drainage pattern, development and management of drainage basin, groundwater potential mapping, etc. to meet sustainable development goals. The Ghaggar river basin is located between Latitudes 27°39' N – 32° 32'N and Longitudes 73° 55'E – 77°36' E and covering an area of 20,454.08 sq.km elevation ranges from 169 metres to 1884 metres above MSL. The river originates from District Sirmaur in Himachal Pradesh and flows through Punjab, Haryana and Rajasthan. In the present study, the morphometric analysis of Ghaggar river basin has been performed to study the various drainage parameters using geospatial technique. The morphometric analysis shows that the watershed has five mini watersheds, sixth order stream segment, drainage network is dendritic in nature, drainage density is 0.434 km per sq. km, stream frequency is 0.096 streams per sq. km, bifurcation ratio of all mini watersheds is 2 to 12, Various morphometric parameters such as linear, aerial and relief aspects have been correlated with each other to apprehend their fundamental association and their influence over basin hydro-geomorphology, soil and topography. The geomorphic parameters are of immense utility in developing proper disposition and decision making of watershed for natural resource appraisal, catchment area advancement, watershed characteristics, planning and drainage development.

Keywords: morphometric analysis, geomorphic parameters, GI-Science, hydro-geomorphology, Ghaggar basin

INTRODUCTION

The evolution of a drainage system and the course of a river over space and time are greatly dependent on a number of variables such as structural components, geology, geomorphology, vegetation cover, soil and slope of the region through which it flows. Morphometry deals with measurement and mathematical study of the configuration of the earth's size, shape, surface, linear

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features, gradient of the channel network in context with the slope and dimensions of the landforms. Morphometric analysis of a basin provides important drainage characteristics such as its geometry, topography, structural control, rock hardness, recent diastrophism, geological and geomorphic history. The morphometric features are classified into three categories viz. Linear (one-dimensional parameters such as stream order, stream number, bifurcation ratio), Areal (two-dimensional parameters such as stream length, stream-length ratio, drainage density, drainage texture, stream frequency, form factor, circulatory ratio) and Relief (three-dimensional parameters such as relief, relief ratio, slope, gradient ratio). It is a qualitative study of various components such as stream segments, basin length, basin area, basin parameters, slope, volume, profiles of the land, which indicates the nature of the development of the basin. Watershed is defined as a natural system that receives, accumulates or distributes water through an outlet point such as lake, streams, reservoirs, etc. Watersheds can be grouped into different categories such as micro-watershed, sub-watershed, watershed, sub-catchment, catchment and basin depending upon the area (increasing order). The concept of the formation of the basins and streams quantitatively was first proposed by Horton (Horton, 1945). He also gave the concept of stream ordering which was later modified by Strahler (Horton, 1945; Strahler, 1952). The morphometric analysis of basins have been carried out by many scholars using various techniques such as remote sensing and GIS (Horton, 1945; Strahler, 1957, 1964; Lattman and Parizek, 1964; Bedi and Bhan, 1978; Anderson, 1989; Palanivel et al, 1996; Srinivasa Rao et al, 1997; Grohmann, 2004; Kaplay et al., 2004; Hodgkinson et. al, 2006; Sreedevi et al., 2009; Dinesh et. al, 2012; Magesh & Chandrashekhar, 2012; Rai et. al, 2017; Das & Pardeshi, 2018; Mahala, 2020). The main objective of the present study is morphometric analysis of the Ghaggar river basin, North-Western, India with the aim to have proper understanding of the hydrologic characteristics of the watershed so that demarcation of groundwater potential zones, run off measurement, water resource management, sustainable watershed management, groundwater supervision, pedological assessment, identification of sites for water harvesting structures, environmental and ecological evaluation can be carried out.

STUDY AREA

The study area comprises the Ghaggar River basin lying between Latitudes 27°39' N – 32° 32'N and Longitudes 73° 55'E – 77°36' E and covering an area of 20,454.08 sq.km flows through the North-Western states of India viz. Himachal Pradesh Panjab, Haryana, and Rajasthan (Figure 1). Geomorphologically, the region is divided into six major physiographic units namely Siwalik Hills, piedmont plain, alluvial plain, sand dunes, flood plains and paleochannels. The Ghaggar appears to be structure controlled and flows along well-defined tectonic lines. The paleochannels occupy a low-lying topographic position on the landscape and are the remnants of old active channels. These are the resultant of the continual changes in the courses of the major rivers and their tributaries, which are rendered defunct and silted over a period of time.

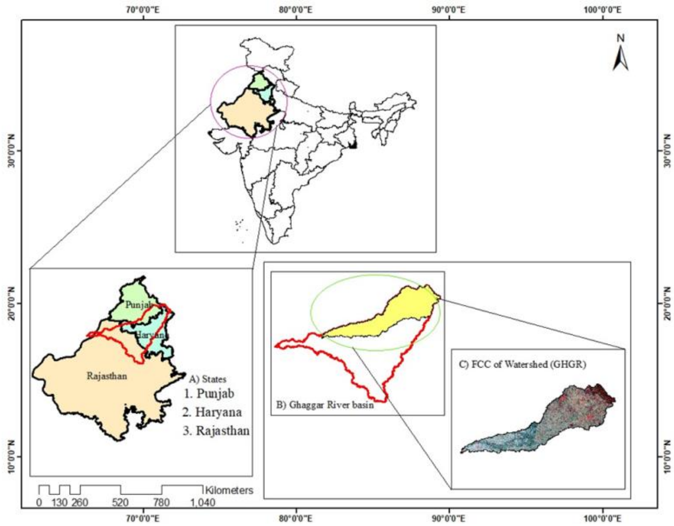

Fig. 1 Location map of the Ghaggar basin

METHODOLOGY

Morphometric analyses have evolved from traditional methods using topographical maps and field analysis to the present use of GI-science which has vastly facilitated the measurements for large drainage basins (Boulton, 1968; Delta et.al, 2004; Grohmann, 2004; Das and Pardeshi, 2018). In the present study, Shuttle Radar Topographic Mission (SRTM) datasets with 3 arc-sec (30 m) resolution have been used in ArcGIS software for delineation of drainage basins (Figure 2).

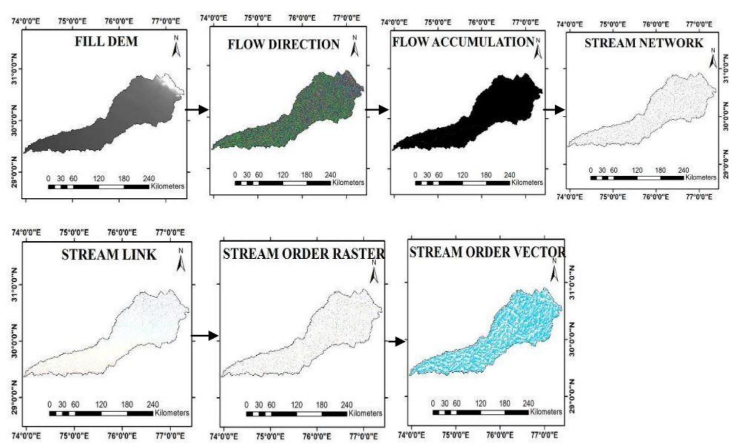

Fig. 2 Extraction of Drainage Networks from DEM

The systematic study of basin morphometry requires correlation of geometry of drainage basin, stream network and the transmission of water and sediment load through the basin. This is well understood through the measurement of linear, areal and relief aspects of the stream channel network. In the present study, the morphometric analysis of all the parameters viz. stream number, stream order, stream length, bifurcation ratio, stream frequency, drainage density, elongation ratio, circulatory ratio, form factor, basin relief, relief ratio, slope or channel gradient, asymmetry factor, etc. have been calculated using appropriate formulae to evaluate the basin characteristics and drainage development, morphometric (Table 1).

Table-1 Morphometric parameters used in the study

S No.	Parameters	Formula	Reference
Linear parameters			
1	Perimeter (p)	GIS software	Schumm (1956)
2	Stream order (Su)	Hierarchical Rank	Strahler (1952)
3	Stream Number (Nu)	GIS Software	Horton (1945)
4	Stream length (Lu)	GIS Software	Strahler (1964)
5	Mean Stream Length (Lsm)	Lu/Nu	Horton (1945)
6	Bifurcation Ratio (Rb)	Nu/Nu+1	Strahler (1964)
7	Basin Length (LB) (in km)	GIS software	Schumm (1956)
Aerial parameters			
8	Basin Area (A) (km^2)	GIS software	Schumm (1956)
9	Drainage Density (Dd) (Km/km^2)	LU/A	Horton (1932)
10	Drainage texture(T) (km)	Dd*Fs	Horton (1932)
11	Constant of channel maintenance (km2/km)	*C* = 1/Dd	Schumm (1956)
12	Length of overland flow (Lg)(km^2/km)	1/2*Dd	Horton (1945)
13	Form Factor(Ff)	A/Lb^2	Horton (1932)
14	Circulatory Ratio(Rc)	$4\pi A/P^2$	Miller (1953)
15	Stream frequency(Fs)(km^2)	NU/A	Horton (1932)
Relief Parameters			
16	Basin relief (R) (km)	H-h	Strahler (1952)
17	Relief ratio (Rr)	R/Lb	Schumm (1956)
18	Ruggedness number (Rn)	Dd*R	Patton (1976)
19	Gradient Ratio (Rg)	R/Lb	Sreedevi (2004)
20	Melton ruggedness ratio (MRn)	MRn=H-h/A0.5	Melton (1965)
21	Elongation ratio (Re)	$1.128[(A)^{1/2}/ Lb]$	Schumm (1956)
22	Asymmetry factor (AF)	Ar/At*100	Molin (1933)

RESULTS AND DISCUSSION

The Ghaggar drainage basin covers an area (A) of approx. 20,454 sq.km and has been divided into 5 sub-watersheds to get broader aspect inferences of smaller channels, their developments and variations in the basin morphology. On the basis of geology, geomprphology and elevation, the drainage is delineated into six order stream with dendritic to sub-dendritic patterns.

The morphometric parameters in terms of Linear, Areal and Relief aspects of Ghaggar River Basin (Table I). Figures 4 & 6 show the River Basin boundary and stream network generated using the technique recommended by Strahler (1957).

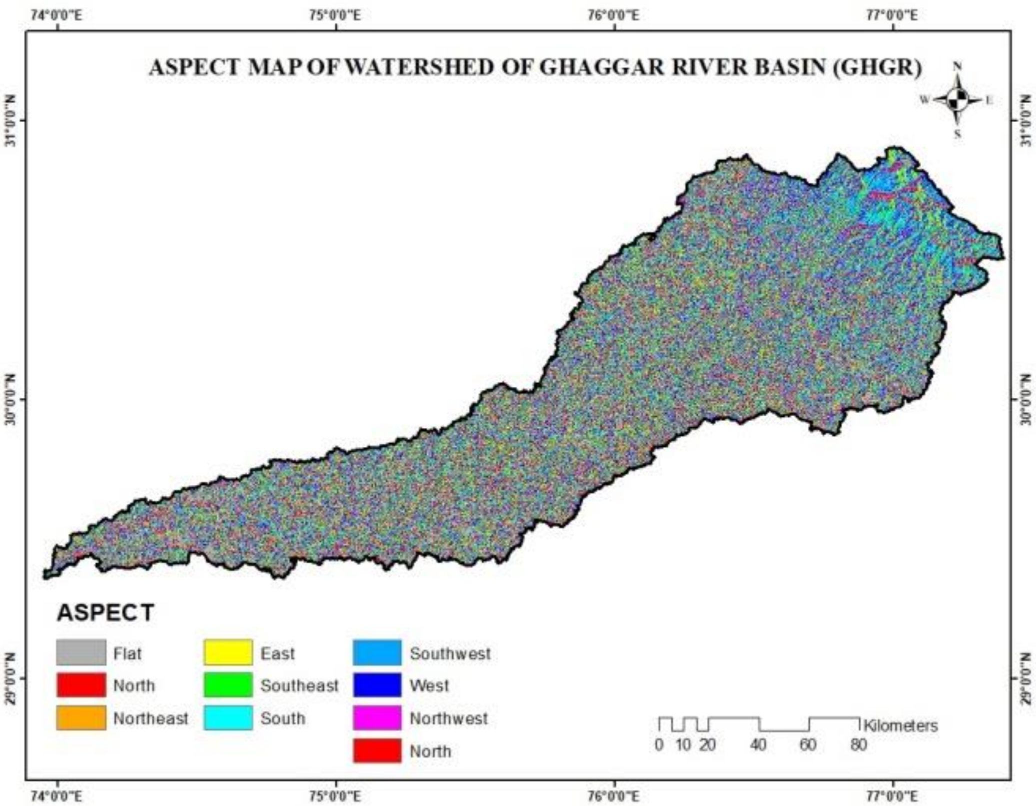

Fig. 3 Aspect Map of the Basin

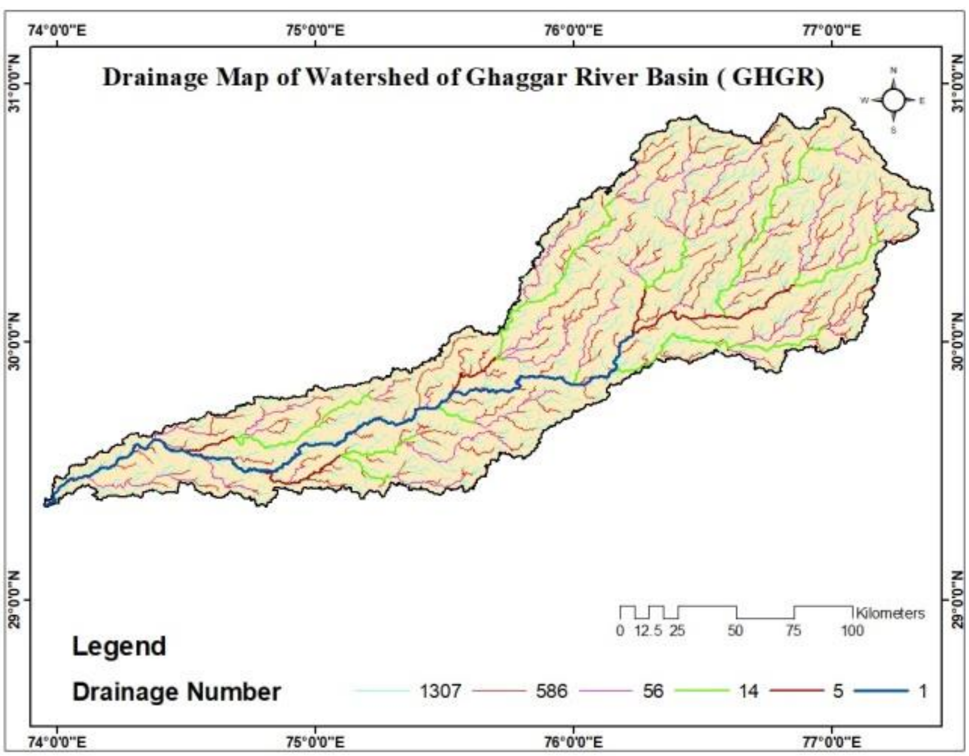

Fig. 4.Drainage Map of the Ghaggar River Basin

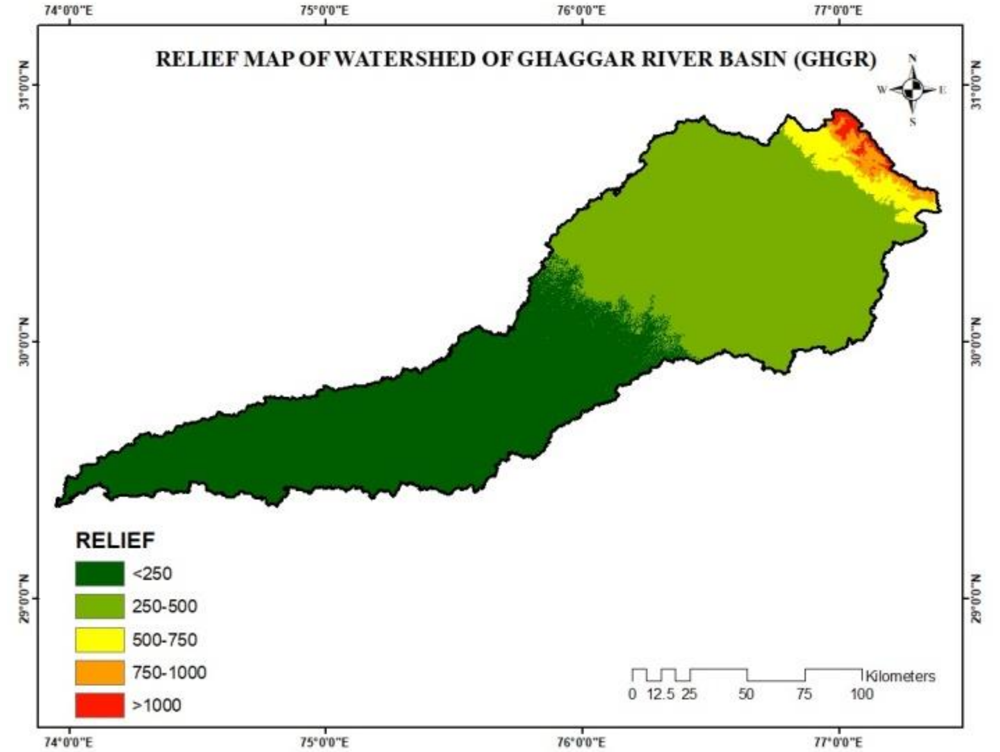

Fig. 5. Relief Map of the Ghaggar River Basin

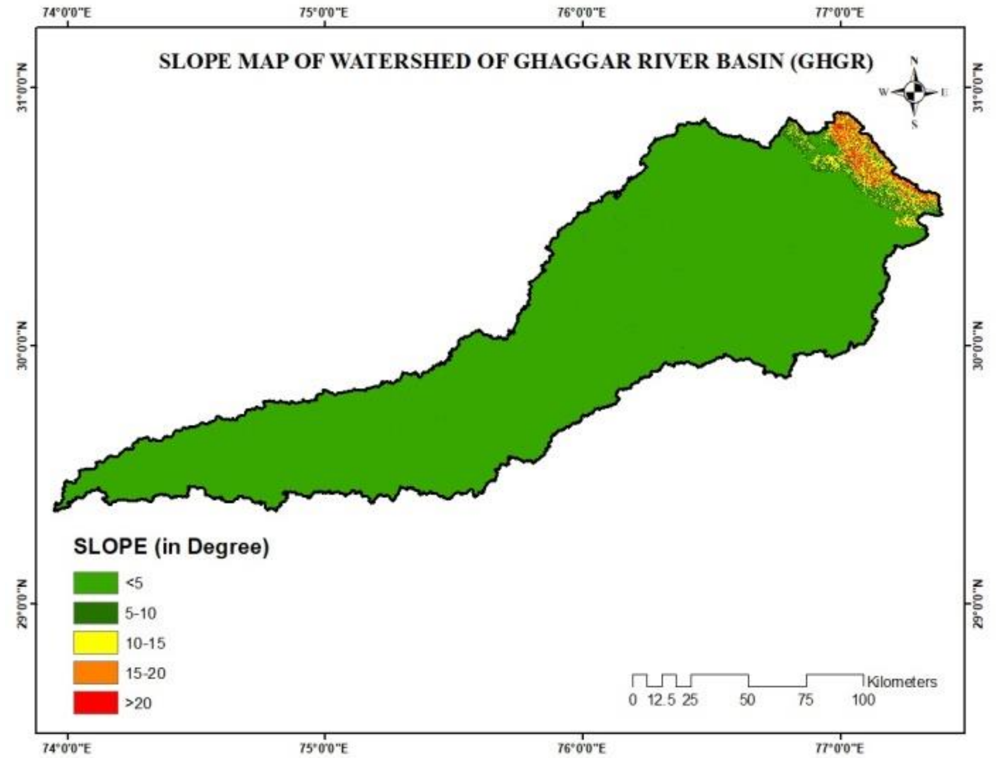

Fig.6 Slope Map of the Ghaggar Basin

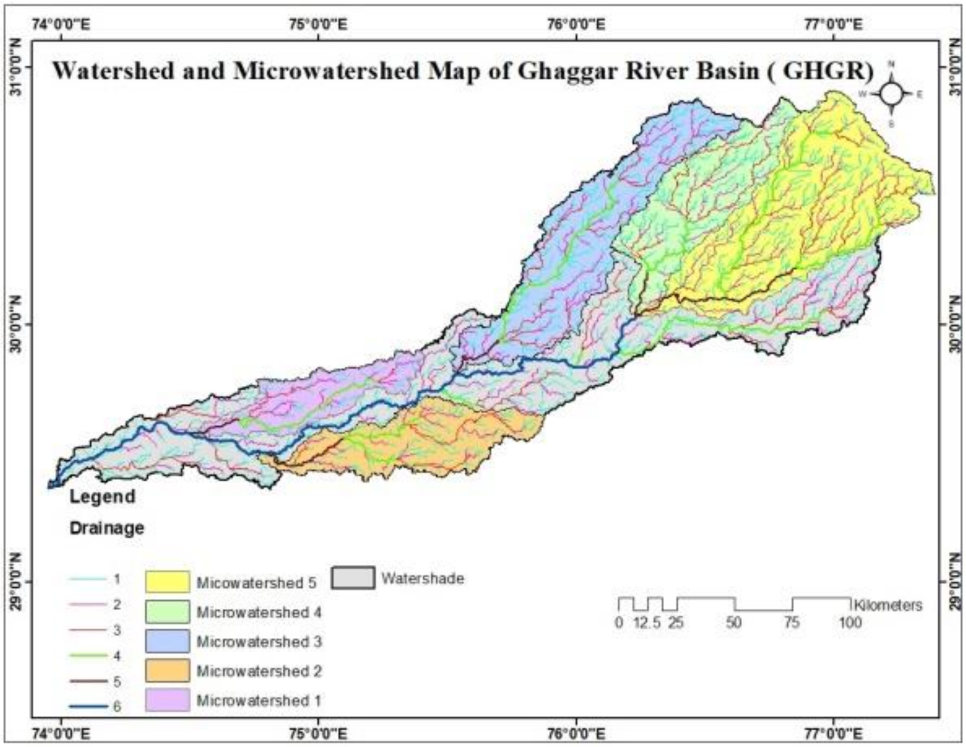

Fig. 7. Micro watershed Map of the Ghaggar River Basin

The dendritic to sub-dendritic drainage pattern and sixth order streams (Fig. 4) are indicative of basin homogeneity, uniform resistant lithology (metamorphic and sedimentary rocks) and less structural control that amounts for a large quantity of stream flow (Withanage et.al, 2014).

The major linear morphometric parameters quantified for the basin including total stream length, mean stream length, stream length ratio, bifurcation ratio each stream order are summarized in Table II. Similarly, major areal morphometric parameters include area, perimeter, drainage density, stream frequency, drainage texture, length of overland flow, constant of channel maintenance, form factor, circularity ratio, elongation ratio, shape index and infiltration number are presented in Table II. The major relief aspect parameters viz. basin relief, basin length, relief ratio, ruggedness number, gradient ratio, Melton ruggedness number, channel gradient and basin slope are presented in Table II.

Table-II Values of morphometric parameters in the study

Parameters	Sub-basin1	Sub-basin 2	Sub-basin 3	Sub-basin 4	Sub-basin 5	Basin
Linear Parameters						
Perimeter, P (km)	308.28	374.71	529.76	341.008	443.925	1290.286
Stream Length, Lu (km)	518.562	855.826	1482.991	1076.002	2116.345	8885. 64

Mean Stream Length, Lsm (km)	4.14	4.17	4.57	4.95	4.96	4.512
Stream order, Su	5	5	5	5	5	6
Stream Number, Nu	125	205	342	217	426	1969
Basin length,L (km)	96.237	111.739	155.616	109.475	127.803	499.535
Bifurcation Ratio	2 to 7.2	2 to 10.66	2 to 11.66	2 to 12	3 to 9	2.23 to 10.46.
Stream Order	1	2	3	4	5	6
Stream number, Nu	1307	586	56	14	5	1
Aerial Parameters						
Area, A (sq.km)	1302.19	2055.58	3438.58	2334.24	4618.2	20454.08
Drainage Density, Dd (km/sq.km)	0.398	0.416	0.431	0.461	0.458	0.434
Stream Frequency,Fs (sq. km)	0.0959	0.0997	0.0994	0.0929	0.0922	0.096
Drainage Texture,T(km)	0.038	0.041	0.043	0.042	0.042	0.417
Length of overland flow, Lg (sq.km/km)	0.199	0.208	0.211	0.231	0.229	0.217
Form Factor, Ff	0.14	0.164	0.142	0.195	0.283	0.155
Constant of channel maintenance (km2/km)	2.513	2.404	2.32	2.17	2.183	2.304
Circulatory Ratio, Rc	0.172	0.184	0.154	0.252	0.294	0.154
Relief Parameters						
Basin relief, R (km)	44	48	105	376	1650	1716
Relief ratio, Rr	0.457	0.429	0.674	3.43	12.91	4.72
Elongation Ratio, Re	0.423	0.458	0.425	0.498	0.5997	0.333
Ruggedness Number, Rn	0.018	0.02	0.045	0.173	0.755	0.745
Melton Ruggedness Number, MRn	1.219	1.059	1.79	7.782	24.28	11.998
Asymetry Factor, AF	0.355	0.623	0.516	0.468	0.343	0.474

The total length has been observed to be longest (518.56 km) for the stream of first order and shortest (8885.64 km) for the stream with sixth order as shown in Table II. This means that the total stream length is inversely proportional to the stream order which lies in conformity with the existing research findings (Horton, 1945, Singh et.al, 2014). Also, an increasing trend is observed in the mean stream length from first order (4.14) to sixth order (4.9) which implies that the streams of the first order although short are numerous in number, whereas for the sixth order stream is just one but longer in length. This too is as described by Strahler (1945, 1964). The slope of the basin (Fig. 6) is also showing decreasing trend from the divide line to the outlet of the basin, which indicates that the basin is in its mature stage. Moreover, longer stream length is indicative of flatter gradient (Withanage etal., 2014).

The bifurcation ratio (Rb) varies with varying stream orders. The Bifurcation ratio of the basin ranges from 2.23 to 10.46, which is indicative of variation in geological and lithological development of the drainage basin (Strahler,1964; Singh etal.,2014). Bifurcation ratio more than 5 means lithology under the drainage basin is not uniform, streams exhibit systematic branching with numerous streams of different orders, and more structural controls for drainage pattern in the basin (Bedi et. al., 1978; Strahler,1964; Chandrashekar etal.,2015; Das et. al, 2018).

Drainage area and perimeter of the basin 20454.08 sq. km and 1290.286 km, respectively, characterize the study area as large. Drainage density, drainage texture, stream frequency and length of overland flow 0.434 km per sq.km, 0.417 km, 0.096 sq.km and 0.217 sq.km per km respectively are strongly correlated (Horton, 1945, 1957) and indicate that the basin has low drainage density, fine texture with high permeable lithology and longer flow path with high rate of infiltration and minimum run off (Bhardwaj et. al., 2014; Chandrashekar et. al.,2015).

Moreover, the elongation ratio, form factor and circulatory ratio of the basin are 0.333, 0.155, 0.154 respectively have strong correlated with each other (Soni, 2016; Strahler, 1964) and these low values indicate that the basin is elongated in shape, has low run-off potential (Strahler,1964; Singh etal.,2014). Constant of channel maintenance is the measure of drainage area that is needed for the maintenance of a unit length of the channel and defines the topography, vegetation cover, the degree of resistance offered by the underlain material and erodibility (Altaf et. al., 2013; Bharadwaj et. al., 2014). The constant of channel maintenance for the Ghaggar River basin has been computed to be 2.304 sq. km per km, which means that the 2.304 sq. km basin is needed for sustaining 1 km of the drainage channel.

The relief aspect parameters indicate the overall steepness, erosional process, morphology of the terrain and denudational characteristics (Hadley& Schumm, 1961; Bali et. al. 2011; Tejpal,2013; Altaf et. al., 2013; Oruonye et. al. 2016). The basin relief, relief ratio, ruggedness number, Melton ruggedness number and asymmetry factor are computed to be 1716 m.s.l, 4.72, 0.745, 11.998 and 0.474 respectively. These indicate that the river flows longer distance in smooth topography with slight tilting towards the right side, low erosive power of run-off, high potential for transporting water and sediment dominated by bed loads (Strahler,1957; Melton, 1965; Cox, 1994; Wilford et. al., 2004,).

The study of morphometric parameters have been demonstrated to be of immense importance in the mapping of palaeochannels, elucidation of groundwater potential zones for water resource planning and sustainable development, flood risk assessment and mapping (Rao et. al. 2009; Upadhyay et. al, 2020; Upadhyay et. al, 2021; Pandey et. al, 2020).

The basin morphometry is firmly associated with the physiography and hydrology. Major hydrological behavior of the Ghaggar river basin such as topography, geology, lithology, soil erosion, flooding and groundwater recharge can be well inferred from the quantitative morphometric analysis of various parameters.

The morphometric relief parameters such as basin slope, gradient ratio, basin relief, relief ratio, ruggedness number and melton ruggedness number define the characteristics of the topography of the basin (Cox, 1994; Melton, 1965; Tejpal, 2013; Singh et. al, 2014; Soni, 2016; Uniyal et. al, 2018). The low values of these parameters indicate that the Ghaggar river basin is less susceptible to severe soil erosion.

The morphometric parameters such as the mean stream length, drainage pattern, constant of channel maintenance and bifurcation ratio help in inferring the geology and lithology underlying the given basin (Bedi & Bhan, 1978; Mahala, 2020). These parameters clearly indicate that the Ghaggar river basin is underlain by alluvium and have high groundwater recharge potential.

The basin area, length, elongation ratio, form factor, drainage frequency and drainage density determine the flood status of the basin (Miller, 1953; Palanivel et. al, 1996; Delta et. al, 2004; Soni, 2016; Das & Pardeshi, 2018). Medium drainage density, medium drainage frequency and elongated basin account for minimum peak run off, more infiltration and absence of severe flooding.

The basin morphometry such as basin length, stream frequency, drainage texture and density, basin configuration, infiltration number and length of overland flow determine the groundwater recharge potential (Dinesh et. al, 2012; Tejapl, 2013; Soni 2016). The Ghaggar river basin has high infiltration capacity and thus high groundwater recharge potential and potential groundwater resource.

CONCLUSION

Morphometry governs the dynamics of a river basin. The quantitative morphometric analysis of the Ghaggar River basin as tabulated has been executed with the help of remote sensing and GIS and mathematical approach. The derived morphometric parameters viz. linear, areal and relief reveal that the basin has lack of structural control, geology and lithology uniform in major part of the region which means that it is prone to flooding in the lowland part during heavy rainfall as the river is ephemeral in nature. Further, the run-off and transportation is slow in the basin, which means there is ample time for infiltration and groundwater recharge which increases the groundwater potential of the basin and demarcation of effective rainwater harvesting sites that could alleviate the problem related to water scarcity in the region as it is devoid of any major river. Moreover, the analysis of the morphometric parameters has extensive scope in formulating soil erosion studies, watershed planning and management, groundwater potential zone assessment, flood-risk assessment and mitigation. The study will be helpful in future watershed prioritization and management, hazard management studies, groundwater potential zone mapping, better groundwater governance, soil erosion studies and delineation of effective rainwater harvesting sites. The morphometric analysis can also be applied to seasonal river basins across the globe.

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