CHAPTER - 3

DRAINAGE CHARACTERISTICS OF THE KHAPRI WATERSHED

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Drainage characteristics are the significant indicator of hydrogeological conditions in watershed (Charon, 1974). It reflects the amount of precipitation that can infiltrate to ground as compared to runoff. In hard rock terrains, where groundwater movement is dominantly controlled by fractures, the drainage characteristics coupled with geology and lineaments are useful to decipher groundwater movement and recharge zones (Tomes, 1975). Therefore, it is important to develop thorough understanding of qualitative and quantitative drainage characteristics of the watershed to identify groundwater potential zones.

3.1 Introduction

The drainage characteristics of watershed can be well understood with the help of morphometric analysis[1] (Clarke, 1966, Babar, 2005). The quantitative analysis of the earth's surface, its shape and dimensions of landform is referred to as morphometric analysis (Clarke, 1966). It reflects the planimetric as well as altimetric characteristics of topography, prevailing climatic and geologic conditions of the watershed. It also provides significant information on runoff-infiltration characteristics and thereby the groundwater potential (Clarke, 1966, Eze and Efiong, 2010). Numerous studies have been carried out across the globe on hydrological modelling (Lindsay and Evans, 2008, Jahan et al., 2018, Rai et al., 2018, Prabhakar et al., 2019, Mahala, 2020) natural resource conservation and management (Gajbhiye et al., 2014, Ahirwar et al., 2019, Asfaw and Workineh, 2019), watershed prioritization (NookaRatnam et al., 2005, Thakkar and Dhiman, 2007, Patel et al., 2013), identification of groundwater potential zones (Sarkar et al., 2001, Sreedevi et al., 2005, Jasmin and Mallikarjuna, 2013) and artificial recharge sites (Zaidi, 2011, Agarwal et al., 2013) through morphometric analysis. Earlier studies related to morphometric parameters were carried out through topographic maps and field surveys (Horton, 1932), while recent studies are based on extensive application of remote sensing and GIS techniques (Sreedevi et al., 2005, Patel et al., 2012, Magesh et al., 2013, Patel et al., 2013, Yadav et al., 2014, Umrikar, 2017, Yadav et al., 2020). The use of remote sensing datasets and GIS technique have facilitated 2-D and 3-D visualization of latest spatial characteristics of terrain and provide a flexible platform for

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analysing the spatial behaviour of drainage characteristics in the watershed (Hajam et al., 2013, Fenta et al., 2017). In the present study, the morphometric parameters at watershed as well as sub-watershed level are computed to understand the hydrological regime. In addition, the spatial variation of morphometric parameters that significantly affect the groundwater potential viz., drainage density, stream frequency and drainage texture is also analysed through isopleth maps at 1 km x 1 km grid to infer the distribution of runoff and infiltration potential throughout the watershed.

3.2 Methodology

The computation of morphometric parameters and their spatial variability is carried out using remote sensing and geographical information system (GIS) tools. The Survey of India (SOI) topographic maps at 1:50,000 scale and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (https://usgs.earthexplorer.us.gov.in) of 30 m resolution are used as primary data for carrying out morphometric analysis (table 3.1). The topographic maps are georeferenced and projected using WGS-84 datum and UTM projection and are merged using mosaic tool in Arc GIS 10.4. The aerial extent of Khapri watershed is masked from the mosaic of topographic maps and DEM using extract by mask tool. Further, eleven sub-watersheds (SW-1 to SW-11) are delineated according to the micro-watershed atlas devised by Soil and Land Use Survey of India (SLUSI, 2012). The streams of Khapri watershed are manually digitized from SOI topographic maps following the Strahler's method of stream ordering (Strahler, 1957). Having ascertained the stream network and relief distribution through DEM, morphometric analysis of Khapri watershed and its sub-watersheds is carried out in three parts, linear (1-D), aerial (2-D) and relief parameters (3-D). The isopleth maps and pie diagrams of drainage density, stream frequency, drainage texture, basin relief, dissection index and ruggedness number are generated for each 1 km x 1 km grid to represent the spatial distribution (Umrikar, 2017, Yadav et al., 2020). The 1 km x 1 km grid is chosen to obtain perceptible variations in the morphometric parameters within the watershed. The grids are prepared through grid index feature of cartography tools and Inverse Distance Weighting (IDW) technique in Arc GIS 10.4. Hypsometric curve and integral are obtained from DEM derived data related to relative height and relative area in Arc GIS 10.4 to understand the basin maturity.

Table 3.1 Datasets used for morphometric analysis.

Sr. no.	Details of dataset	Source of dataset
1	SOI Topographic map 1:50,000 scale (46H/5, 46H/9, 46H/10, 46H/13 and 46H/14)	Survey of India Nakshe Portal (https://soinakshe.uk.gov.in/)
2	SRTM 1 Arc-second Global DEM (30 m resolution), 2011	https://earthexplorer.usgs.gov/

3.3 Drainage pattern of the Khapri watershed

The river Khapri is a sixth order stream flowing for 50.70 km before debouching into river Ambica. From the drainage map (figure 3.1) it is apparent that overall, the watershed exhibits dendritic to modified-dendritic drainage pattern with local pockets of trellis pattern in south-eastern and north-western extremities. The dendritic drainage pattern is characterized by irregular branching of tributaries in various directions, which join main stream at all angles (Zernitz, 1932). The presence of dendritic drainage pattern in the Khapri watershed is attributed to horizontally dispose uniform massive basaltic flows. The modified dendritic drainage pattern is the manifestation of lineaments dispensed in the watershed. Trellis drainage pattern is characterized by tributaries joining the streams approximately at right angles (Zernitz, 1932). The presence of trellis in south-eastern and north-western extremities of the watershed are mainly controlled by northwest-southeast, north-northwest-south-southeast, northeast-southwest and north-northeast-south-southwest lineaments.

3.4 Morphometric analysis

The present section discusses the detailed results of linear (1-D), aerial (2-D) and relief (3-D) morphometric parameters.

3.4.1. Linear morphometric parameters (1-D)

Linear morphometric parameters of watershed are concerned with the one-dimensional elements such as hierarchical order of streams, stream numbers and length of stream segments. It also describes various relationships that exist among them and related morphometric laws such as law of stream numbers and length. The analysis of linear parameters specifically involves, the evaluation of Stream order (Su), Stream number (Nu), Bifurcation ratio (R_b), Mean bifurcation ratio (R_{bm}), Stream length (Lu), Mean stream length (Lsm), Main stream length (L), Stream length ratio (R_L), Length of the basin (L_b) and Basin perimeter (P) (table 3.2).

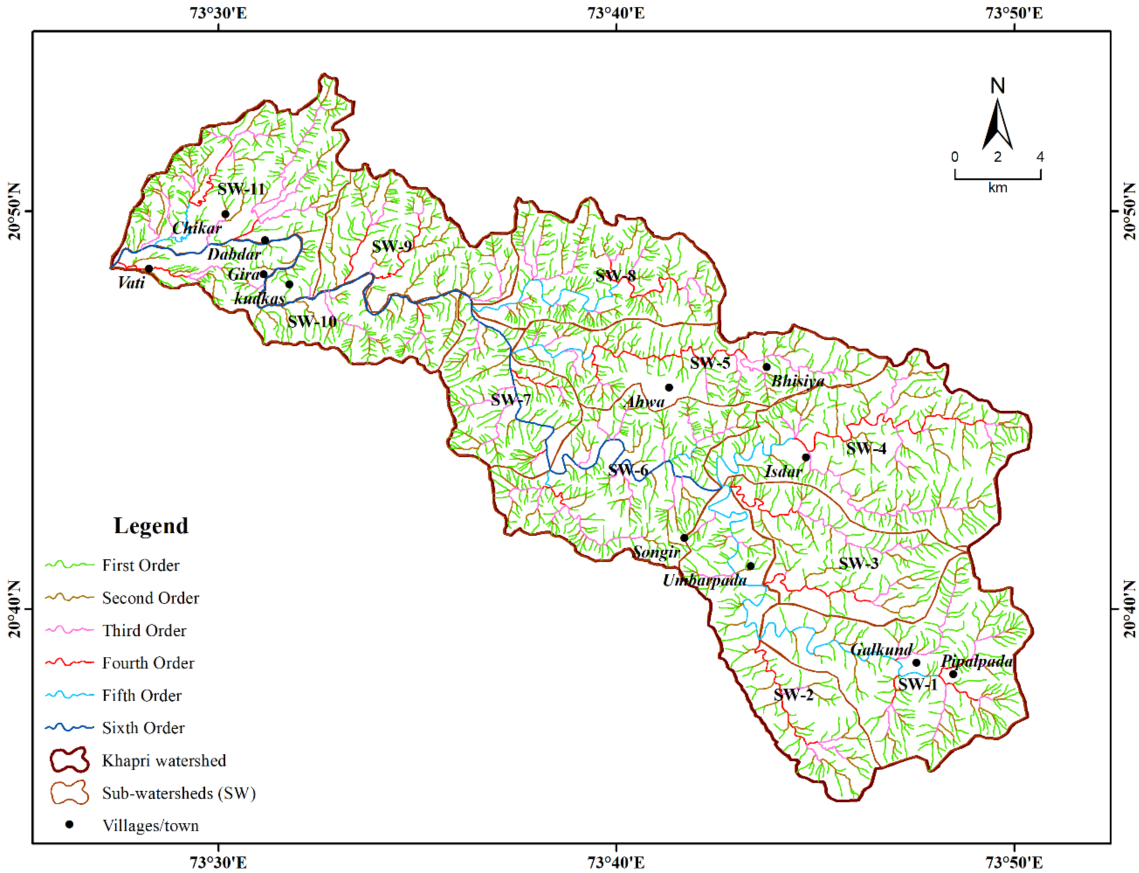

Figure 3.1 Drainage map showing stream network and stream orders for eleven sub-watersheds of the river Khapri.

Results of linear morphometric parameters for Khapri watershed and its sub-watershed are presented in table 3.3 and 3.4 respectively.

Table 3.2 Empirical formulae to compute linear morphometric parameters.

Sr. no.	Morphometric parameter	Formula	Reference
1	Stream order (Su)	Hierarchical ranking	Strahler 1957
2	Stream number (Nu)	Stream count of each order	Horton 1945
3	Bifurcation ratio (R_b)	R_b = Nu/Nu+1	Strahler 1964
4	Mean bifurcation ratio (R_{bm})	R_{bm} = Average of bifurcation ratio of all stream order	Strahler 1964
5	Stream length (Lu)	Length of streams	Horton 1945
6	Mean stream length (Lsm)	Lsm = Lu/Nu	Strahler 1964

7	Main stream length (L)	Length of trunk stream	Strahler 1957
8	Stream length ratio (R_L)	R_L = Lu of higher order/Lu of lower order	---
9	Basin length (L_b)	Longest dimension parallel to trunk stream measured aerially	Strahler 1957
10	Basin perimeter (P)	Total distance along the boundary	---

a) Stream order (Su) and Stream number (Nu)

Determining the hierarchical position of the streams within watershed is referred to as stream ordering (Strahler, 1957). Various workers have studied stream ordering schemes (Scheidegger, 1965, Woldenberg, 1967, P. Hagget, and R.J. Chorley, 1969, Lewin, 1970, Gregory and Walling, 1973). Gravelius (1914), Horton (1932), (1945) Strahler (1952) and Shreve (1967) proposed different stream ordering schemes; however, the Strahler's scheme is straightforward and trouble-free for application. According to Strahler (1952), each fingure-tip stream is assigned as 1st order stream, further at junction of two first order streams second order stream is produced and so on. Total count of streams belonging to a specific order is defined as stream number (Horton, 1945). The main stream draining the Khapri watershed attains sixth order and thereby making it a sixth order basin (figure 3.1). The lower orders streams of Khapri watershed i.e. first, second and third are much higher in number than the streams of higher order (table 3.3). Total 2455 streams are identified in Khapri watershed, of which 77.27 % (1897) are first order, 17.35% (426) are second order, 4.032% (99) are third order, 1.01% (25) are fourth order, 0.28% (07) are fifth order and 0.04 % (1) makes up sixth order stream (table 3.3). The number of streams belonging to each order is represented on logarithmic plot of stream numbers versus the stream order (figure 3.2). The plot shows a linear relationship and fits perfectly well with the Horton's law (Horton, 1945). The presence of higher number of lower order streams can be attributed to the rugged topographic setup and occurrence of hard and low permeable basaltic rocks in the watershed. Majority first order streams initiates near the drainage divide and occupies the verges of Khapri watershed. Eventually, these lower order streams merges with the higher order streams in the low-lying regions within the watershed.

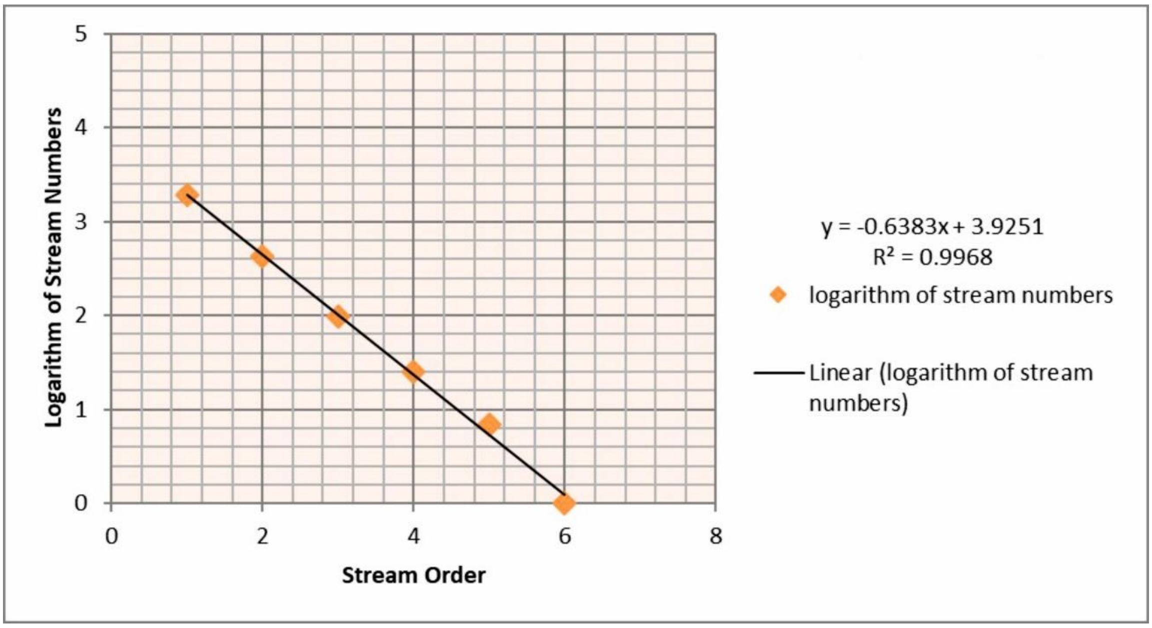

Figure 3.2 Plot of logarithm of Stream numbers versus Stream order.

b) Bifurcation ratio (R_b) and Mean bifurcation ratio (R_{bm})

The ratio of number of streams of particular order to the number of streams of subsequent higher order is bifurcation ratio (R_b) (Schumn, 1956). According to Horton 1945, the bifurcation ratio is an index of relief and dissection. The bifurcation ratio values for Khapri watershed ranges from 3.5 to 4.4 for first to fifth order streams (table 3.3). Mean bifurcation ratio (R_{bm}) is average of bifurcation ratios of all orders, which is 4.64 for Khapri watershed (table 3.3). The value of bifurcation ratio changes from one stream order to the next one, as the development of natural drainage system is dependent on climatic, geologic and ecological process (Strahler, 1964, Kadam et al., 2017). The bifurcation ratio varying from 3 to 5 indicates that the development of natural drainage system is predominantly controlled by homogenous lithology of Deccan trap and trivially by geological structures (Strahler, 1964, Kale and Gupta, 2001, Venkatesan, 2014, Babu et al., 2016). Higher value of bifurcation ratio observed for sixth order stream i.e. 7.0 indicates significant structural control (Strahler, 1957).

c) Stream length (Lu), Stream length ratio (R_L), Mean stream length (Lsm) and Main stream length (L)

Total length of all streams belonging to a particular order is referred to as stream length (Lu) (table 3.2). The stream length for different order is mentioned in the table 3.3. The minimum stream length is obtained for the sixth order stream i.e. 50.7 km, while the maximum stream length is obtained for first order streams i.e. 994.23 km (table 3.3). In general, the total length of stream segment decreases with increasing order.

The ratio of total length of streams of higher order to the total length of streams of lower order is referred to as stream length ratio (R_L). The stream length ratio varies from 0.26 to 0.89. The highest stream length ratio (0.89) obtained for sixth order stream, suggests that area drained by it is relatively permeable with gentle gradients. While, the areas drained by lower order streams are relatively impermeable in nature and possess steeper gradients.

The ratio of total stream length to the stream number of the same order is mean stream length (Lsm). It is directly related with mean drainage basin area (Schumn, 1956). The mean stream length values also enable us to study the runoff and the soil erosion in the watershed (Kadam et al., 2017). The mean stream length values for first to sixth order streams varies from 0.52 to 50.7 km (table 3.3), with mean value of 10.8 km for the Khapri watershed suggesting moderate to high runoff and susceptibility to soil erosion.

The length of highest order of stream to which tributary streams join in watershed is the main stream length (L). The main stream length of 6th order Khapri watershed is 50.7 km (table 3.3).

d) Length of the basin (L_b) and Basin perimeter (P)

The longest dimension of the basin parallel to the trunk stream calculated aerially is defined as basin length (L_b). The basin length of Khapri watershed is 43.83 km (table 3.3). The outer boundary of the watershed that encompasses its area is basin perimeter (P). Khapri watershed is characterized by 147 km of basin perimeter (table 3.3).

The results of linear morphometric parameters for sub-watershed of Khapri are given in table 3.4.

3.4.2. Aerial morphometric parameters (2-D)

Analysis of aerial morphometric parameters is related to evaluation of two-dimensional morphometric parameters such as Basin area (A), Drainage density (D_d), Stream frequency (S_f), Drainage texture (D_t), Basin shape and Length of overland flow (L_o), Form factor (F), Circulatory ratio (R_c), Elongation ratio (R_e) and Constant of channel maintenance (C) (table 3.5). Results of aerial morphometric parameters for Khapri watershed and its sub-watershed are presented in table 3.6 and 3.7 respectively.

a) Basin area (A)

Basin area (A) is a two-dimensional space enclosed within the watershed divide. It is linked with the spatial distribution of various important morphometric attributes. The basin area of Khapri watershed covers an aerial extent of 523 sq. km (table 3.6).

Table 3.3 Results of linear morphometric parameters of the Khapri watershed.

Stream order (Su)	Stream number (Nu)	Bifurcation ratio (R_b)	Mean bifurcation ratio (R_{bm})	Stream length (Lu) (km)	Mean stream length (Lsm) (km)	Stream length ratio (R_L)	Basin length (L_b) (km)	Basin perimeter (P) (km)
I	1897			994.23	0.52			
		4.4				0.26		
II	426			263.13	0.61			
		4.3				0.61		
III	99			161.59	1.63			
		3.96	4.64			0.51	43.83	147
IV	25			83.31	3.33			
		3.57				0.68		
V	07			56.68	8.09			
		7.0				0.89		
VI	*01*			50.70	50.70			
Total	***2455***			**1609.64**	**10.81**			

b) Drainage density (D_d), Stream frequency (S_f) and Drainage texture (D_t)

Measure of channel lengths of all streams per unit area of drainage basin is defined as drainage density (D_d) (Horton 1945 and Strahler 1957) (Table 3.5). It indicates the equipoise between the erosive potential of overland flow and transmissible nature of the surface soils and rocks. It is directly related to the measure of stream lengths. It holds strong control on duration of concentration and magnitude of discharge. Low drainage density tends to reduce the flooding levels in the watershed; indicating presence of permeable nature of underlying material that supports infiltration and ultimately lead to groundwater enrichment (Hajam et al. 2013; Horton, 1945; Selvan et al. 2011). Overall, high drainage density value of Khapri watershed (3.07 km/km^2) (Table 3.6) is attributed to less transmissible nature of underlying rocks and hilly topography with steep slopes, leading to high runoff and increased flood potential. The isopleth map represents the spatial variation in value of drainage density; it ranges between 0.02 and 6.34 km/km^2. The drainage density is classified into 4 classes viz. very low (<1 km/km^2), low (1-2 km/km^2), moderate (2-3 km/km^2) and high (>3 km/km^2) (Figure 3.3). Pie diagram shows spread of 12.16% of very low drainage density (<1 km/km^2), 27.56 % of low drainage density (1-2 km/km^2), 39.41% of moderate drainage density (2-3 km/km^2) and 20.87% of high drainage density (3-6.34 km/km^2) of the total watershed area (Figure 3.3). An overview of drainage density in Khapri watershed suggests that around 60.28% watershed area is characterized by moderate to high drainage densities (2-3 km/km^2 to 3-6.34 km/km^2) and associated mainly with regions of steeper slopes greater than 18°. Plummet of these streams over the steeper slopes and less transmissible rocks have enforced them to get rive into numerous channels and thereby leading to moderate to higher drainage densities. Around 15% of watershed area is characterized by very low to low drainage density, associated with flat to gentle slopes (<10°) and is located in the upstream and downstream as well as along the watershed divides. The presence of competent basaltic rocks with occurrence of secondary porosity and permeability along the watershed divides, may lead to higher critical distance i.e. zone of no erosion and thereby giving rise to very low to low drainage densities (Horton 1945, Dongare et al. 2022).

Total number of stream (Nu) of all order per unit area (A) is referred to as stream frequency (S_f) (Horton 1945) (Table 3.5). Stream frequency provide us the information regarding the response of basin towards runoff process (Selvan et al. 2011). Stream frequency is dependent on lithology and is directly related to infiltration number. Higher values of stream frequency indicate presence of steep slope, higher run-off and low infiltration (Horton 1932, 1945). The stream frequency of Khapri watershed is 4.69 per km^2 (Table 3.6), suggests presence of low to moderately transmissible nature of surface and sub-surface material and moderate to high runoff in the watershed (Dongare et al. 2022). The isopleth map represents the spatial variation in value of stream frequency; it ranges from 0.62 to 5.84 per km^2 (Figure 3.4). The stream frequency is classified into 4 classes viz. low (<2 per km^2), moderate (2-3 per km^2), high (3-4 per km^2) and very high (>4 per km^2) (Figure 3.4). Pie diagram shows spread of 10.87% of low stream frequency (<2 per km^2), 35.42 % of moderate stream frequency (2-3 per km^2), 39.1% of high stream frequency (3-4 per km^2) and 14.62 % of very high stream frequency (>4 per km^2)

of the total watershed area (Figure 3.4). The moderate and very high group of stream frequencies are observed to be concentrated in the areas with notable break in slopes and shows high number of first order steams.

Drainage texture is the product of drainage density and stream frequency (D_t) (Horton 1945, Thornbury W.D. p.124) (Table 3.5). It is a measure of the infiltration capacity (Horton 1945). Drainage texture is influenced by natural factors such as climate, vegetation, rainfall, lithology, soil type, infiltration capacity, relief and stage of basin development (Smith 1950). The isopleth map represents the spatial variation in value of drainage texture; it ranges from 0.03 to 27.46. The drainage texture is classified into five classes (Smith 1950) viz. very Coarse (<2), coarse (2-4), moderate (4-6), fine (6-8) and very fine (>8) (Figure 3.5). Pie diagram shows spread of 3.44 % of very coarse (<2), 10.16 % of coarse drainage texture (2-4), 17.61% of moderate drainage texture (4-6), 22.25 % of fine drainage texture (6-8) and 46.54% of very fine drainage texture (>8) of the total watershed area (Figure 3.5). The overall drainage texture of Khapri watershed indicates presence of very fine drainage texture in the watershed (Table 3.6) leading to low infiltration.

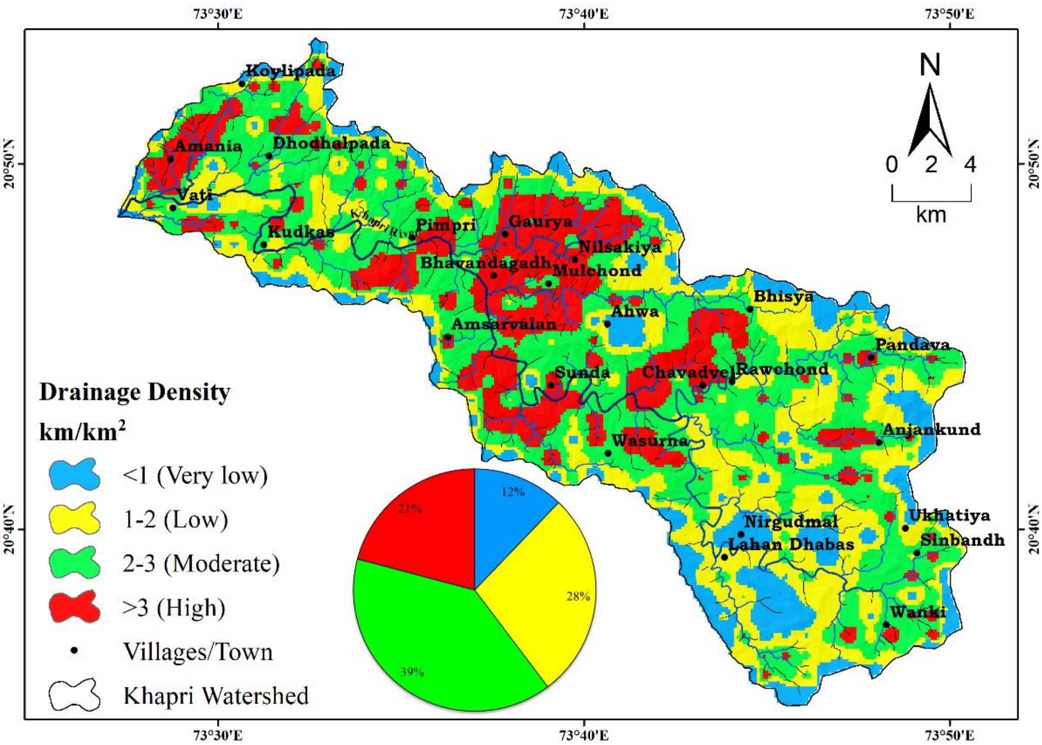

Figure 3.3 Isopleth map of Drainage density. Inset pie diagram represents the percent aerial coverage of different drainage density classes.

			Stream number (Nu) of different Stream order (Su)							Bifurcation ratio (Rb) Rb = Nu/Nu+1					Mean bifurcation ratio (R_{bm})
Sub-watershed	**Length (L_b) (km)**	**Perimeter (P) (km)**	**1**	**2**	**3**	**4**	**5**	**6**	**Σ Nu**	**1/2**	**2/3**	**3/4**	**4/5**	**5/6**	
SW-1	12.1	39	162	41	09	04	01	-	217	3.9	4.5	2.25	4	-	3.6
SW-2	15.3	41	116	30	08	03	01	-	158	3.8	3.7	2.6	3	-	3.3
SW-3	10.4	30	102	24	05	02	-	-	133	4.2	4.8	2.5	-	-	3.8
SW-4	14.3	41	221	51	08	02	01	-	283	4.3	6.3	4	2	-	4.1
SW-5	16.4	40	181	38	09	02	01	-	231	4.7	4.2	4.5	2	-	3.8
SW-6	9.6	40	243	59	14	02	02	01	321	4.1	4.2	7	1	2	3.6
SW-7	9.0	26	137	30	07	02	02	01	179	4.5	4.2	3.5	1	2	3.5
SW-8	11.0	33	206	43	14	03	01	-	267	4.7	3.0	4.6	3	-	3.8
SW-9	8.8	32	137	25	06	02	-	01	171	5.4	4.1	3	-	3	4.2
SW-10	14.8	48	160	38	07	02	-	01	208	4.2	5.4	3.5	-	2	4.3
SW-11	10.5	45	238	48	12	04	01	-	303	4.9	4	3	4	-	3.9

	Length of stream (Lu) of different Stream order (Su)						Mean stream length (Lsm)						Stream length ratio (R_L)				
Sub-watershed	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**2/1**	**3/2**	**4/3**	**5/4**	**6/5**
SW-1	107.67	24.11	15.34	5.83	12.49	--	0.66	0.58	1.70	1.45	12.49	--	0.22	0.64	0.38	2.14	--
SW-2	67.12	17.25	8.95	7.35	13.3	--	0.58	0.57	1.11	2.45	13.3	--	0.26	0.52	0.82	1.81	--
SW-3	62.38	17.24	9.89	12.15	--	--	0.61	0.71	1.97	6.07	--	--	0.28	0.57	1.23	--	--
SW-4	126.3	37.78	19.85	13.31	7.93	--	0.57	0.74	2.48	6.65	7.93	--	0.3	0.53	0.67	0.59	--
SW-5	90.42	18.45	15.55	11.22	4.5	--	0.5	0.48	1.72	5.61	4.5	--	0.2	0.84	0.72	0.40	--
SW-6	122.12	29.92	22.30	2.15	2.99	13.63	0.5	0.50	1.59	1.07	1.49	13.63	0.24	0.75	0.1	1.39	4.56
SW-7	70.85	15.9	9.09	3.08	10.16	--	0.52	0.53	1.29	1.54	--	--	0.22	0.57	0.34	3.29	--
SW-8	94.74	22.28	14.25	7.02	10.73	--	0.46	0.51	1.01	2.34	10.73	--	0.24	0.64	0.49	1.58	--
SW-9	66.9	26.08	7.38	8.27	--	--	0.49	1.04	1.23	4.13	--	--	0.39	0.28	1.12	--	--
SW-10	76.38	23.46	9.17	5.43	--	--	0.48	0.61	1.31	2.71	--	--	0.31	0.39	0.59	--	--
SW-11	108.97	30.25	29.08	7.31	4.32	--	0.46	0.63	2.42	1.82	4.32	--	0.28	0.96	0.25	0.59	--

Table 3.4 Results of linear morphometric parameters of the Khapri watershed at sub-watershed level.

Table 3.5 Empirical formulae to compute aerial morphometric parameters.

Sr. no.	Morphometric Parameter	Formula	Reference
1	Drainage density (D_d) (km/km^2)	$D_d = Lu/A$	Horton 1945
2	Stream frequency (S_f) (1/km^2)	$F_s = Nu/A$	Horton 1945
3	Drainage texture (D_t) (1/km)	$D_t = D_d \times F_s$	Horton 1945
4	Form factor (F)	$F = A/L_b^2$	Horton 1932
5	Circulatory ratio (R_c)	$R_c = 4\pi A/P^2$	Miller 1953
6	Elongation ratio (R_e)	$R_e = 1.128 \sqrt{A}/L_b$	Schumm 1956
7	Length of overland flow (L_o)	$L_o = 0.5 D_d$	Horton 1945
8	Constance of channel maintenance (C)	$C = 1/D_d$	Strahler 1957

Table 3.6 Results of aerial morphometric parameters of the Khapri watershed.

Basin area (A) (km^2)	Drainage density (D_d) (km/km^2)	Stream frequency (S_f) (1/km^2)	Drainage texture (D_t) (1/km)	Form factor (F)	Circulatory ratio (R_c)	Elongation ratio (R_e)	Length of overland flow (L_o)	Constance of channel maintenance (C)
523	3.07	4.69	14.39	0.27	0.30	0.58	0.16	0.32

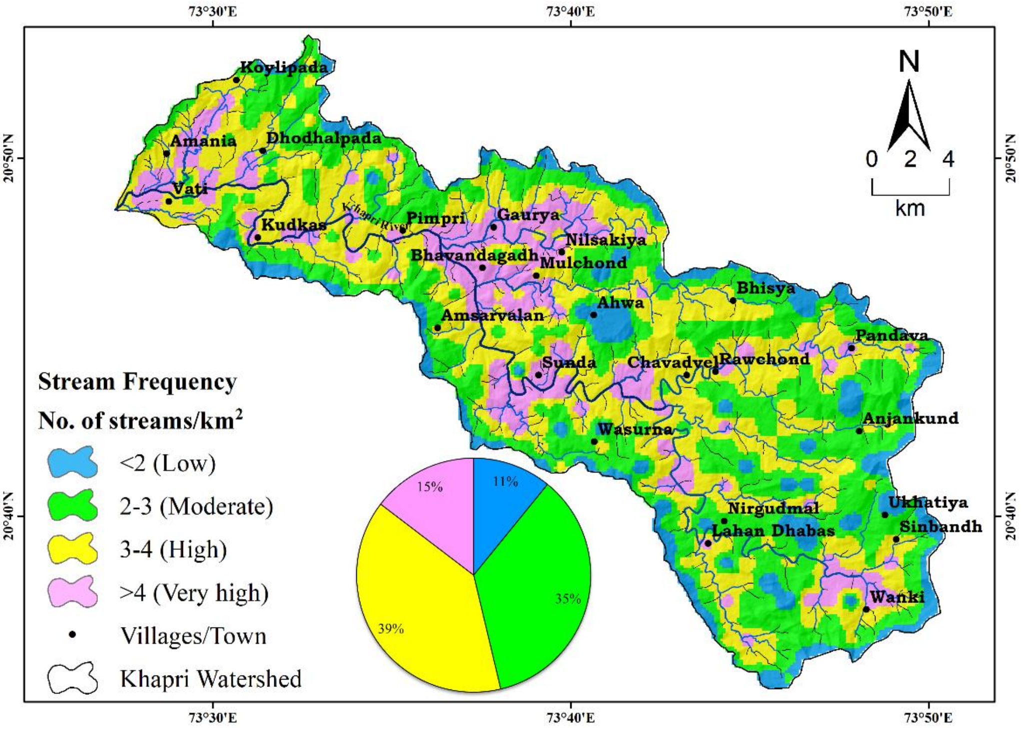

Figure 3.4 Isopleth map of Stream frequency. Inset pie diagram represents the aerial coverage of different stream frequency classes.

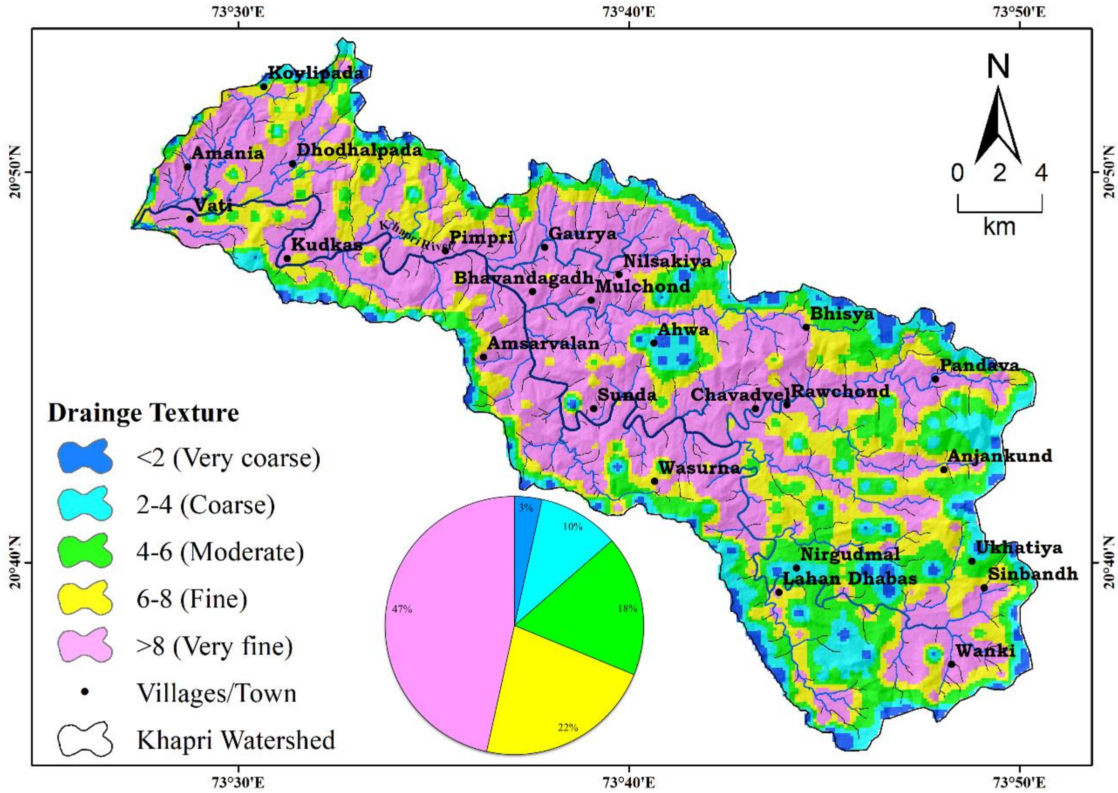

Figure 3.5 Isopleth map of Drainage texture. Inset pie diagram represents the aerial coverage of different drainage texture classes.

c) Form factor (F), Circulatory ratio (R_c) and Elongation ratio (R_e)

Horton (1932) defined form factor (F) as the ratio of basin area to square of the basin length (table 3.5). The value of form factor ranges from 0 to 1. Smaller values of form factor are indicative of relatively elongated basin. Thus, higher values of form factor indicate high peak flow for shorter duration in drainage basin and vice versa. The value of form factor obtained for Khapri watershed is 0.27 (table 3.6), which indicates watershed is slightly elongated in shape and flat peaks of flow for longer durations (Venkatesan, 2014, Dongare et al., 2022).

Miller (1953) defined circulatory ratio (R_c) as the ratio of the basin area to the area of the circle with same circumference as the perimeter of the basin (table 3.5). Factors like length and frequency of streams, geological structures, land use/land cover, climate, relief and slope of the basin influences the circulatory ratio (Chopra et al., 2005). The value of circulatory ratio varies from 0 to 1. The values close to zero suggest the basin is relatively elongated and vice-versa (Miller, 1953, Umrikar, 2017). The Value of circulatory ratio obtained for Khapri watershed is 0.3 (table 3.6), which suggest that basin is not circular (Venkatesan, 2014).

Ratio of diameter of a circle having the same area as the basin to the maximum basin length is elongation ratio (R_e) (Schumn, 1956) (table 3.5). Elongation ratio varies from 0 to 1. Lower values are related to highly elongated shape, while the higher values close to 1 indicate circular shape of the basin. Elongated shape of basin is associated with areas having high reliefs, steeper slopes, and defencelessness towards head-ward erosion (Strahler, 1964, Yadav et al., 2020). The value of elongation ratio obtained for Khapri watershed is 0.58 (table 3.6), which indicates elongated nature of the basin with moderate to high reliefs and steeper slopes (Dongare et al., 2022).

These values of shape factors suggest elongated nature for the Khapri watershed that shall manifest flat peaks of flow for longer durations (Venkatesan, 2014). The flat and longer flow durations due to elongated nature of Khapri watershed is increasing possibility of water discharge to infiltrate and probably enrich the groundwater. This elongated nature of watershed is taking care of high runoff from lower order streams (Dongare et al., 2022).

d) Length of overland flow (L_o)

The distance for which water travels on the ground surface before entering into the stream channels is referred to as length of overland flow (L_o) (Horton, 1945). Length of overland flow ($L_o = 0.5\ D_d$) (table 3.5) controls hydrologic and physiographic development of the drainage basin (Horton, 1945). It is inversely proportional to average of channel slope and is approximately half of the reciprocal of drainage density (Horton, 1945). Low value of L_o (0.16) for Khapri watershed (table 3.6) indicates presence of high relief and rapid run-off in the watershed (Dongare et al., 2022).

e) Constant of channel maintenance (C)

According to Schumn (1956), the inverse of drainage density is referred to as constant of channel maintenance (C) (table 3.5). The value of constant of channel maintenance is an expression of the relative size of the landform unit in a drainage basin (Gabale et al., 2015). In other words, it provides us the measure of square km of watershed surface necessary to sustain one linear stream channel of 1 km. Channel of constant maintenance is affected by slope of basin, geological setting and vegetation cover (Yadav et al., 2020). Generally, the lower values of constant of channel maintenance are associated with impermeable nature of rocks and vice versa (Yadav, 2018 and Yadav, 2020). The constant of channel maintenance value obtained for entire

Khapri watershed is 0.32 (Table 3.6), which implies that an average 0.32 km^2 of surface area is required to maintain 1-km length of the stream channel and suggests less transmissible nature of the underlying rocks.

The results of aerial morphometric parameters for sub-watershed of Khapri are given in table 3.7.

3.4.3. Relief morphometric parameters (3-D)

Relief morphometric parameters of the watershed are concerned with three dimensional features and consider altitude as third dimension of landforms. Relief parameters include the analysis of the relationship between area and altitude, basin relief, relief ratio, dissection index, slope and ruggedness number (table 3.8). Results of relief morphometric parameters for Khapri watershed and its sub-watershed are presented in table 3.9 and 3.10 respectively.

Table 3.7 Results of aerial morphometric parameters of the Khapri watershed at sub-watershed level.

Sub-watershed	Basin area (A) (km^2)	Drainage density (D_d) (km/km^2)	Stream frequency (S_f) (1/km^2)	Drainage texture (Dt) (1/km)	Form factor (F)	Circulatory ratio (R_c)	Elongation ratio (R_e)	Length of overland flow (L_o) (km)	Constance of channel maintenance (C)
SW-1	61	2.7	3.5	9.4	0.4	0.5	0.7	1.3	0.3
SW-2	45	2.5	3.5	8.7	0.1	0.3	0.4	1.2	0.4
SW-3	38	2.6	3.5	9.1	0.3	0.5	0.6	1.3	0.3
SW-4	72	2.8	3.9	10.9	0.3	0.5	0.6	1.4	0.3
SW-5	44	3.1	5.2	16.1	0.1	0.3	0.4	1.5	0.3
SW-6	58	3.3	5.5	18.1	0.6	0.4	0.8	1.6	0.3
SW-7	31	3.5	5.7	19.9	0.3	0.5	0.6	1.7	0.2
SW-8	43	3.4	6.2	21.0	0.3	0.4	0.6	1.7	0.2
SW-9	36	3.0	4.7	14.1	0.4	0.4	0.7	1.5	0.3
SW-10	38	3.0	5.4	16.2	0.1	0.2	0.4	1.5	0.3
SW-11	54	3.3	5.6	18.4	0.4	0.3	0.7	1.6	0.3

Table 3.8 Empirical formulae to compute relief morphometric parameters.

Sr. no.	Morphometric parameter	Formula	Reference
1	Elevation of watershed mouth (h)	----	----
2	Elevation of watershed source (H)	----	----
3	Basin relief (R)	R = H-h	Schumm 1961
4	Relief ratio (R_r)	$Rr = R/L_b$	Schumm 1956
5	Dissection index (D_i)	D_i = R/ (max. absolute relief)	Nir D 1957
6	Slope of watershed (S)	----	----
7	Ruggedness number (R_n)	$R_n = R \times D_d$	Schumm 1956

a) Basin relief (R) and Relief ratio (R_r)

The difference between the highest and lowest points of the watershed is defined as basin relief (R) (table 3.8). It is a significant variable that allows us to understand the erosional and mass movement process in the watershed (Schumm and Hadley, 1961, Yadav et al., 2014, Das et al., 2018 and Yadav et al., 2020). The south-east direction of Khapri watershed is characterized by highest point of 1083 m above mean sea level which lowers down in the north-west direction reaching to 86 m amsl near the confluence with river Ambica (figure 3.6). The basin relief of Khapri watershed is 997 m (table 3.9). The isopleth map of relative relief displays the spatial variation in the relief, which ranges from 172 m to 590 m in watershed (figure 3.7). The pie diagram shows that low and moderately low classes of relative relief spreads around 60% of the watershed area, while moderate, high and very high classes of relative relief spans about 40% of the watershed area (figure 3.7).

Table 3.9 Results of relief morphometric parameters of the Khapri watershed.

Elevation of watershed mouth (h) (m)	Elevation of watershed source (H) (m)	Basin relief (R) (m)	Relief ratio (R_r)	Dissection index (D_i)	Ruggedness number (R_n)
86	1083	997	0.02	0.9	2.73

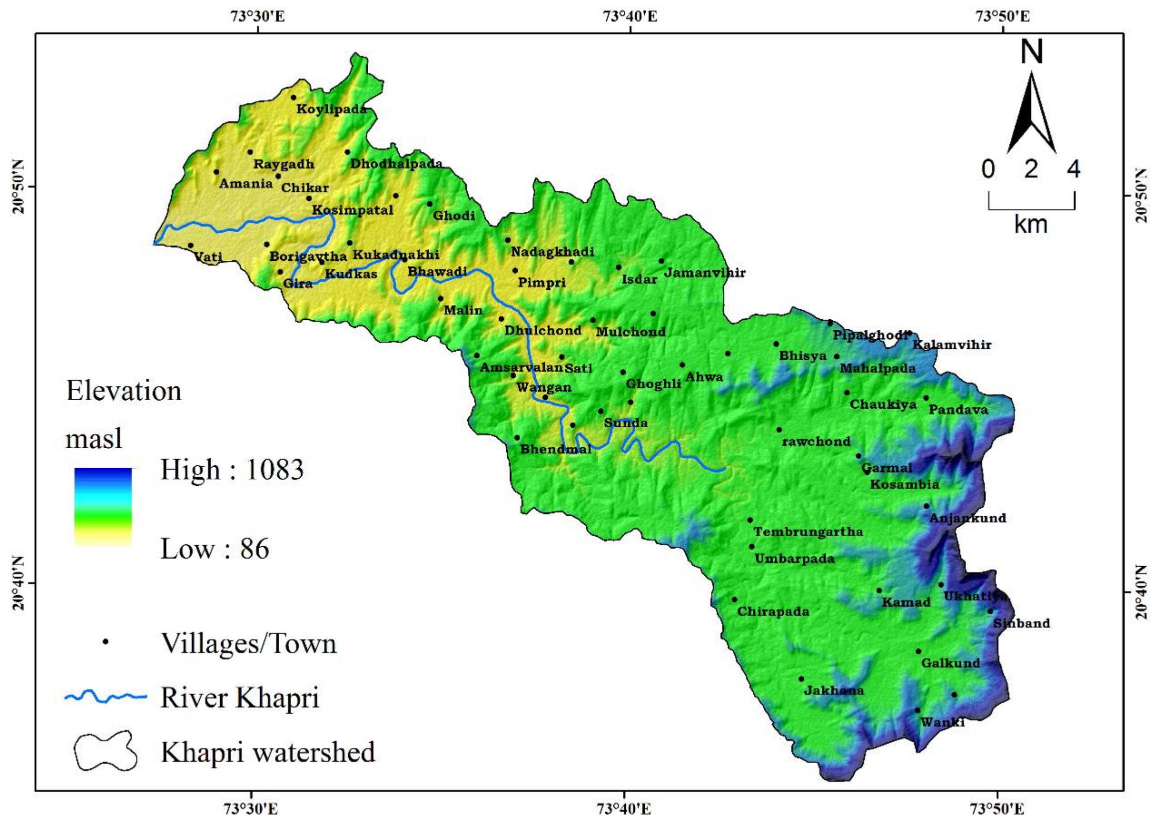

Figure 3.6 SRTM - Digital Elevation Model (30 m) representing highest elevation of 1083 m asl in southeastern to 86 m asl in northwestern direction of Khapri watershed.

Relief ratio (R_r) is the ratio of the maximum relief of the watershed to the horizontal distance along the longest dimension of the basin essentially parallel to the principal drainage line (Schumn, 1956) (table 3.8). Measurement of overall steepness of the basin can be done using relief ratio. It indicates the intensity of the erosion process actively occurring on the slope of the drainage basin. Relief ratio is inversely proportional to the basin length (Gottschalk, 1964). The relief ratio of Khapri watershed is 0.02 (table 3.9). The values of relief ratio suggest the presence of steeper slopes in the Khapri watershed.

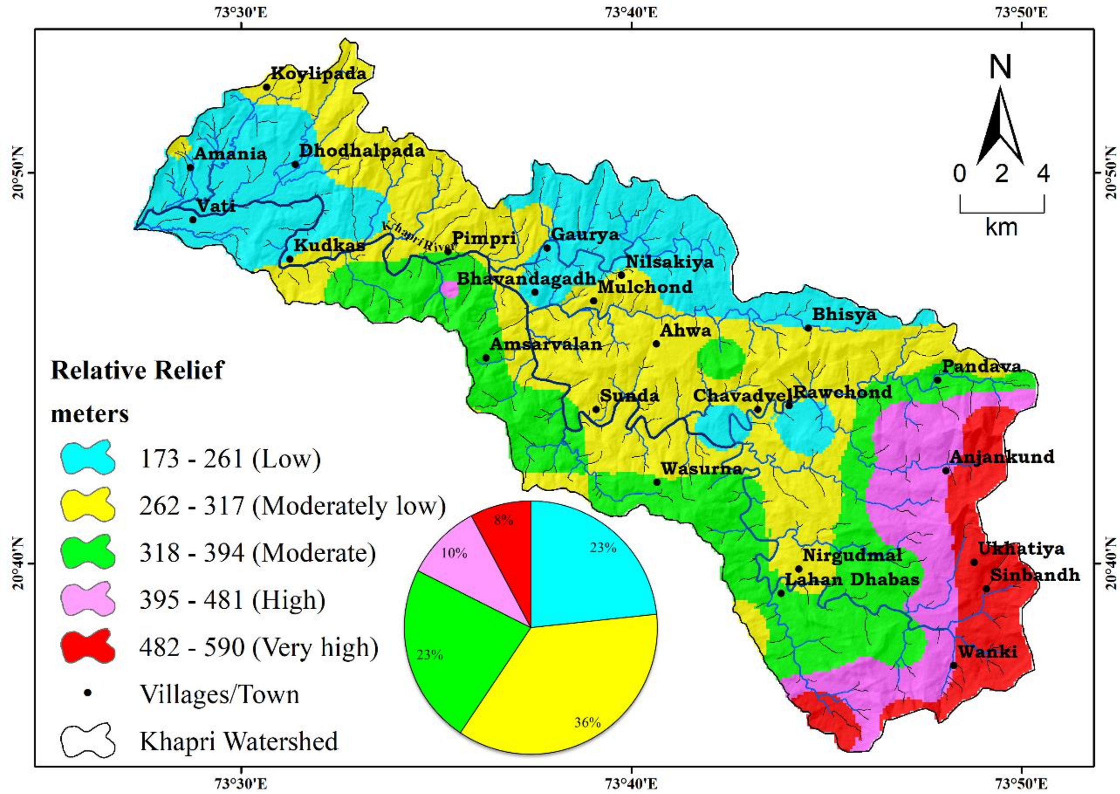

Figure 3.7 Isopleth map of Relative relief. Inset pie diagram represents the aerial coverage of different relative relief classes.

b) Dissection index (D_i)

Dissection index is the ratio of basin relief to absolute relief (Nir, 1957) (table 3.8). It is an important morphometric tool that indicates the nature and magnitude of dissection with respect to vertical exaggeration of terrain. The value of dissection index ranges between 0 and 1. Value zero indicates terrain where erosion is not prominent and hence terrain is flat. In contrast, value one indicates very high erosion and dissection leading to vertical cliffs and escarpments. The overall value of dissection index obtained for Khapri watershed is 0.9 (table 3.9) suggesting significant dissection of the landscape and also implies the ruggedness. Isopleth map of dissection index of Khapri watershed varies from 0.3 to 2.6 (figure 3.8). Pie diagram shows spread of 38.17% of low dissection index, 38.52% of moderate dissection index, 13.54% of high and 9.75% of very high dissection index (figure 3.8).

c) Ruggedness number (R_n)

The product of drainage density (D_d) and basin relief (R) is ruggedness number (R_n) (Strahler, 1958, Babu, 2016 and Prakash et al., 2019) (table 3.9). It is an expression of both slope steepness and length (Strahler, 1958, Babu, 2016, Prakash et al., 2019).

Higher values of ruggedness number occur when the drainage density and relief of watershed are higher along with steeper and longer slopes (Strahler, 1958). The isopleth map shows that ruggedness number of Khapri watershed ranges from 0.01 to 2.73 (figure 3.9). Pie diagram summarizes spread of 18.59% of low ruggedness, 41.31% of moderate ruggedness, 30.57% of high and 9.54% of very high ruggedness of the total watershed area (figure 3.9). The overall higher value of ruggedness number (2.73) for Khapri watershed (table 3.9) suggests the presence of rugged topography and susceptibility to soil erosion in the watershed.

The results of relief morphometric parameters for sub-watershed of Khapri are given in table 3.10.

Table 3.10 Results of relief morphometric parameters of the Khapri watershed at sub-watershed level.

Sub-watershed	Highest elevation (H) (m)	Lowest elevation (h) (m)	Basin relief (R) (m)	Relief ratio (R_r)	Dissection index (D_i)	Ruggedness number (R_n)
SW-1	1081	359	722	0.05	0.6	1.9
SW-2	1022	266	756	0.04	0.7	1.8
SW-3	993	274	719	0.06	0.7	1.9
SW-4	1083	266	817	0.05	0.7	2.3
SW-5	657	187	470	0.02	0.7	1.4
SW-6	666	208	458	0.04	0.6	1.5
SW-7	648	177	471	0.05	0.7	1.6
SW-8	545	176	369	0.03	0.6	1.2
SW-9	480	137	343	0.03	0.7	1.0
SW-10	587	89	498	0.03	0.8	1.4
SW-11	474	86	388	0.03	0.8	1.2

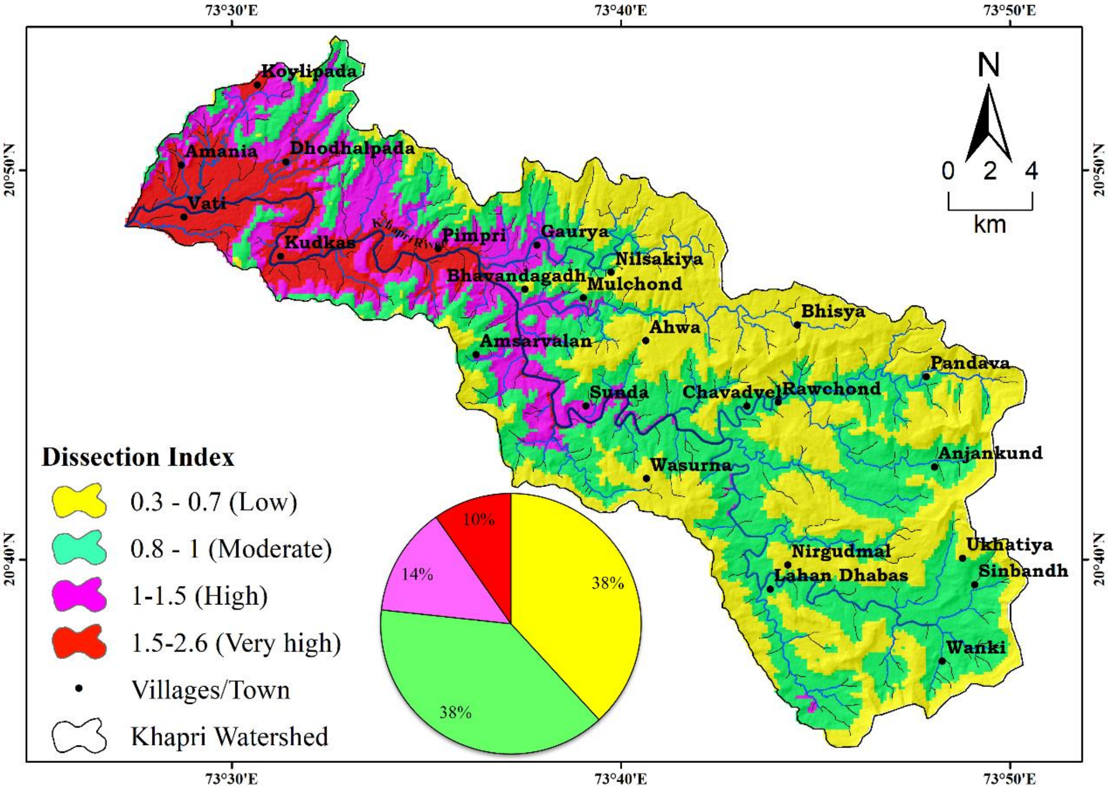

Figure 3.8 Isopleth map of Dissection index. Inset pie diagram represents the aerial coverage of different dissection index classes.

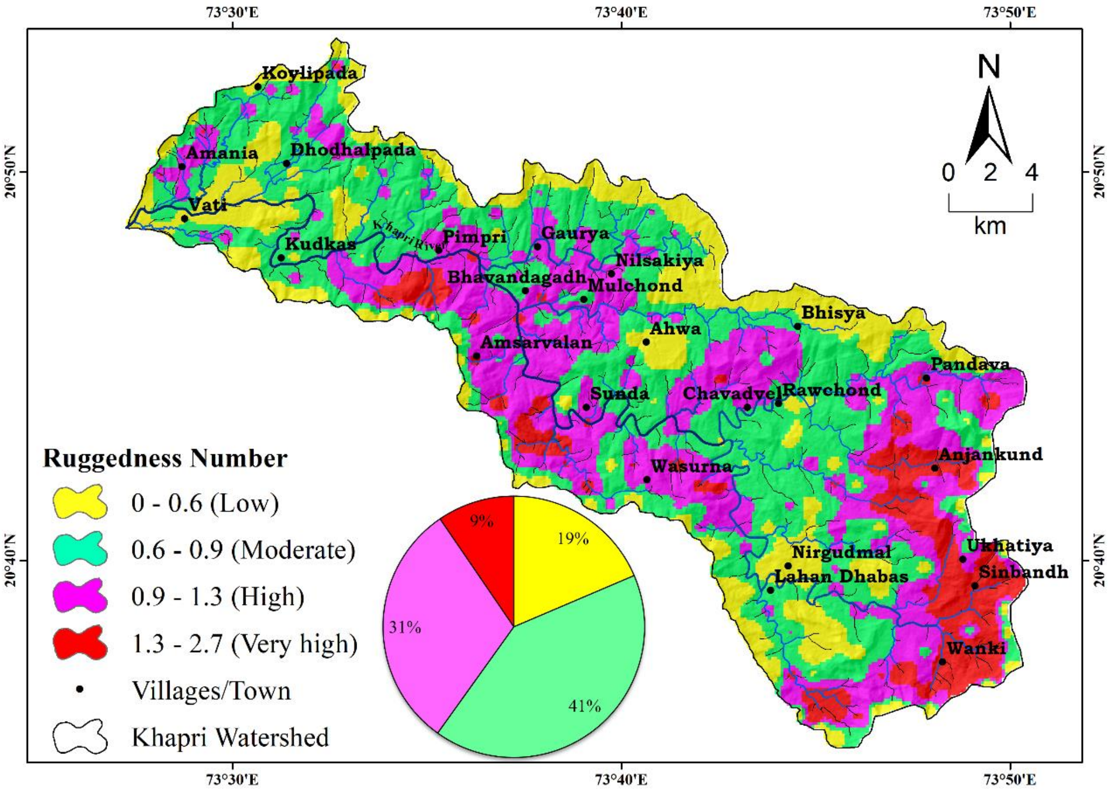

Figure 3.9 Isopleth map of Ruggedness number. Inset pie diagram represents the aerial coverage of different ruggedness number classes.

3.5 Hypsometric curve and Hypsometric integral

Hypsometry analysis involves the measurement and analysis of relationships existing between area and altitude of the watershed. It allows us to understand degree of dissection, stage of erosion cycle and hence is useful in determining watershed developmental stage (Strahler, 1952, Gardner et al., 1990). Hypsometric curve represents the proportion of area of the surface at various elevations above and below a datum (Alka Gautam, 2000). It is generated by plotting the proportion of total basin height (h/H) against the proportion of total basin area (a/A). Hypsometric integral is the ratio of the area below the hypsometric curve to the total area of the watershed (Umrikar, 2017, Yadav et al., 2020) and therefore it is correlated with the shape of hypsometric curve. Convex-up hypsometric curve represents youthful stage of watershed, S-shaped curve represent moderately eroded regions, and concave curve represents monadnock phase of watershed. Hypsometric integral enables us to understand the erosion that has taken place in watershed during geologic time because of hydrologic process (Bishop et al., 2002). Besides, it provides a simple morphological index to predict surface runoff from watershed (Vivoni et al., 2008). Hypsometric integral is expressed as:

HI = mean elevation – minimum elevation / maximum elevation – minimum elevation

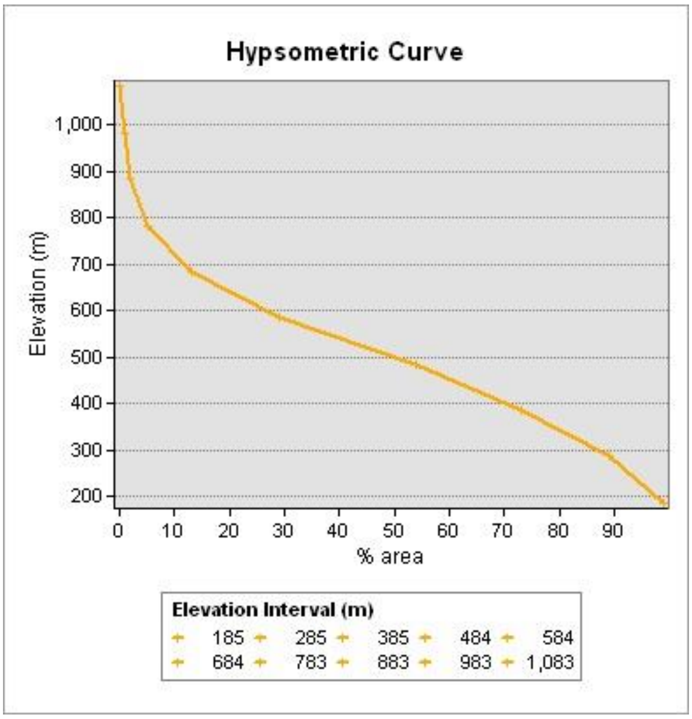

Figure 3.10 Hypsometric curve indicating the mature stage of geomorphic evolution of Khapri watershed.

The sigmoid shaped hypsometric curve obtained for Khapri watershed (figure 3.10) is concave upwards at higher elevations and convex downwards at the lower elevations; indicates the equilibrium or mature stage of geomorphic evolution of watershed. The value of hypsometric integral obtained for Khapri watershed is 0.5, also supports the association of watershed with mature or equilibrium stage of geomorphic evolution. The hypsometric integral of Khapri watershed indicates moderate to high surface runoff.

3.6 Epilogue

The integrated use of remote sensing and GIS enables quantifying and analysing the spatial variations in drainage characteristics throughout the watershed. The isopleth maps and pie diagrams are useful guide to the spatial variation and percentage spread of significant hydrological morphometric parameter respectively. The results are useful for identifying suitable locations for water harvesting and recharging structures, also for the exploration of probable groundwater potential zones in the watershed. Khapri watershed is the sixth order basin characterized by 98.6% of lower than fourth order streams (table 3.3). This higher number of lower order streams can be attributed to the rugged topographic setup and occurrence of hard and low permeable basaltic rocks in the watershed. The linear plot of stream number versus stream order shows inverse relationship and follows Horton’s law. The bifurcation ratio values for Khapri watershed ranges from 3.5 to 4.4 for first to fifth order streams, is the result of homogenous lithology of Deccan trap with less significant structural control. The higher bifurcation ratio value of 7 for the trunk stream indicates significant structural control. The lower stream length ratios (0.26 to 0.68) obtained for first to fifth order streams suggest that they are draining over relatively less permeable rocks on steeper slopes. Compared to lower order streams, the sixth order stream having high stream length ratio (0.89) flows over relatively more permeable rocks with gentle slopes. Overall, the fine drainage texture of the Khapri watershed also suggests the low to moderately transmissible nature of underlying lithology. The value of drainage density reveals the less transmissible nature of underlying lithology. Within the watershed, areas with high drainage densities are closely associated with steeper slopes, while the low drainage density is associated with gently sloping regions. The presence of competent basaltic rocks with occurrence of secondary porosity and permeability along the divides of watershed shows very low to low drainage densities suggesting less runoff and more infiltration in this region of the watershed. Moderate to high classes of stream frequencies spreads around 85% of the watershed area. These are in association with the significant break in slopes and are characterized by numerous first order streams suggesting higher runoff and low infiltration for this region of the watershed. The fine drainage texture of the Khapri watershed also suggests the less transmissible nature of underlying lithology. The analysis of shape factors indicates elongated shape of Khapri watershed. In addition to joints and fractures the elongated shape of the watershed increases the possibility of infiltration. More than 60 percent of watershed possesses appreciably steep slopes, suggesting its significant control over drainage characteristics. The higher value of dissection index and ruggedness number suggests presence of steeper and longer slopes with rugged topography. The hypsometric integral (0.5) and the hypsometric curve of Khapri watershed indicate the mature stage of geomorphic development. Thus, the morphometric analysis and resultant isopleth maps have revealed the spatial distribution of morphometric parameters governing the hydrological regime of Khapri watershed. It indicates the watershed is characterized by steep slope, less transmissible nature of underlying rocks, high drainage density, fine drainage texture leading to high runoff and less infiltration in major part of the watershed.