CHAPTER-5

5. Morphometric Characterisation of the Badlands

5.1 Introduction

The morphometric analysis of the landform is the mathematical analysis of earth's configurations, surficial expressions, landforms and dimensions (Clarke et al., 1966; Alqahtani and Qaddah, 2019). The quantitative geomorphological concept has been introduced by Horton (1945) over theidea of landforms as geological features. Remote sensing and GIS give a sharp edge in the morphometric analysis. Strahler (1950, 1952b) examined form in its most general two-dimensional(slope profile) and three dimensional (drainage basin) manifestations. A number of notable papersfollowed his work. Schumm's (1956) made a highly influential contribution on the evolution of badlands. Schumm established the notion that badlands might serve as the critical missing link between the laboratory and the real world. Analytically, process geomorphology has always depended much on the statistical procedures. Morphometric analysis has provided positive opportunity to correlate process with morphometric variables. It is constructive in decoding the root cause of erosion with the help of prior knowledge watershed management or prevention plansthat may be designed quite effectively (Tignath et al., 2014).

The present morphometric study has been carried out with a special reference to gully erosion andbadland formation. Badlands are the special case of fluvial action involving a chain of interrelatedinterdependent processes. The fluvial processes perform headward as well as forward erosion. They are sites of heavy loss of sediments and patterned development of stream networks (Deshmukh et al., 2011). Some crucial morphometric parameters were analyzed with respect to badland formation. Bifurcation ratio (Rb), drainage density (Dd), drainage frequency (Fs), drainage texture (Dt), relief parameters, infiltration number (If), length of overland flow (Lg) andruggedness number (Rn) are some of the fundamental parameters which can effectively define the process of badland formation.

5.2 Methodology

5.2.1 Delineation of the Watershed

The morphometric analysis of the area of the Mandakini river watershed has been carried out by using Survey of India toposheet (No. 63C/16) on the scale of 1:50000. The drainage network mapshave been generated by using the Shuttle Radar Topography Mission (SRTM) DEM (30m resolution). Data extraction and analysis is carried out by Arc GIS software (Figure 5.1). Arc Hydrology tool has been used for stream ordering (Strahler, 1964) and digitized in the GIS environment. The highest stream order is of the order six in the area of the study area. The detailedmorphometric study was carried out in 55 third-order sub-watersheds and 9 fourth-order sub- watershed (Figures 5.2a and 5.2b). After the extraction of basic parameters like, area (Au), perimeter (P), Length of the stream (Lb), number of stream (Nu), stream order (U) and average width of the watershed (W); other derived parameters are extracted (Table 5.1).

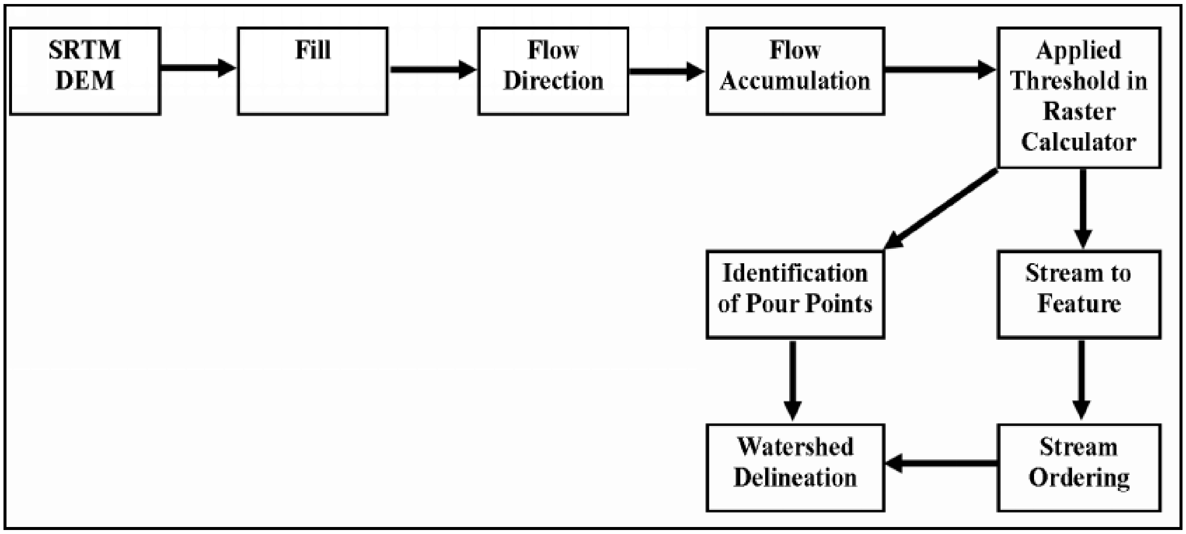

Figure 5. 1 Drainage extraction and watershed delineation methodology

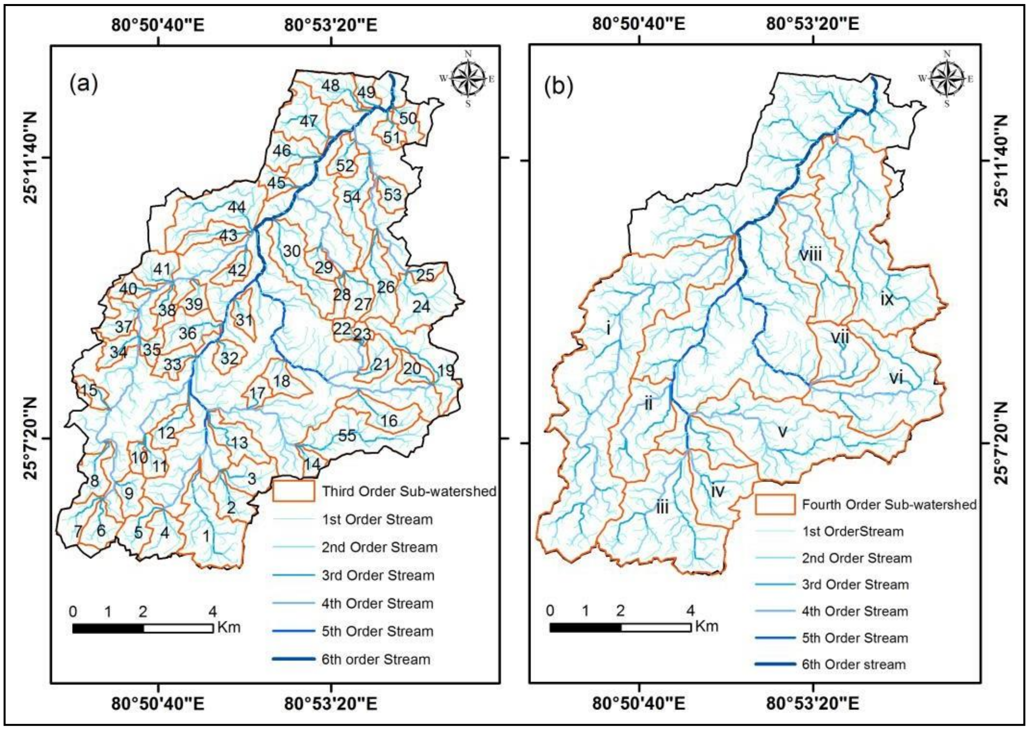

Figure 5. 2 Map of (a) Third order sub-watershed; (b) Fourth order sub-watershed

5.2.2 Description of the Morphometric Parameters

The description of the primary and derived morphometric parameters are given in the table 5.1

Table 5. 1 Table showing primary and derived morphometric parameters

Morphometric Parameters	Formula/Definition	Unit	References
Area (Au)	Plan area of the watershed, GIS software analysis	Km^2	
Basin perimeter (P)	The perimeter of the watershed GIS software analysis	Km	
Stream order(U)	Hierarchical rank	Dimensionless	Strahler (1964)
Basin length (Lb)	Length of the stream, GIS software analysis	Km	
Basin Width(W)	The average transverse distance to the master stream.		
Mean stream length (Ls)	Ls= Lu/Nu where, Ls= mean stream length Lu = total stream length of all orders; Nu = total no. of stream segments of order “u” GIS software analysis	Km	
Total Stream Length (Lu)	The sum of the length of all streams within each basin boundary	Km	Horton (1945)
Bifurcation ratio (Rb)	Rb = Nu/Nu + 1, where, Nu + 1 = no. of segments of the next higher order	Dimensionless	Schumn (1956)

Basin relief(H)	The difference in height between the highest and the lowest points (summit and the mouth) of the basin, GIS software analysis using DEM	Km	Hadley and Schumn (1961)
Drainage density (Dd)	Dd = Lu/Au, where, Lu = total stream length of all orders (km); Au = area of the watershed (km^2)	Km^{-1}	Horton (1932)
Stream frequency (Fs)	Fs = Nu/Au, where, Nu = total no. of streams of all orders; Au = area of the basin (km^2)	Km^{-2}	Horton (1932)
Drainage texture (Dt)	Dt= Nu/P, where Nu = total no. of stream segments of order “u” P = perimeter of the watershed (km)	Km^{-1}	Horton (1945)
Form factor (Rf)	Rf = A/Lb^2, where Au = area of the basin (km^2) Lb^2 = square of the basin length	Dimensionless	Horton (1932)
Circularity ratio (Rc)	Rc = 4 × π × A/P^2 where, π= 3.14 A = area of the bain (km^2) P = perimeter (km)	Dimensionless	Miller (1953)
Elongation ratio (Re)	Re =1. 128 $\sqrt{A}/L_b$, where, Au = area of the basin (km^2) Lb = basin length	Dimensionless	Schumn (1956)

Length of overland Flow (Lg)	Lg=Au/2.ΣLu, Au=Drainage Area; Lu=Total stream length	Km	Horton (1945)
Constant Channel of Maintenance (c)	C= 1/Dd Dd= Drainage density	Km	Schumn (1956)
Infiltration number (If)	If=Dd × Fs Dd= Drainage density; Fs= stream frequency		Faniran(1968)
Ruggedness number (Rn)	Rn = Dd × (H/1000), where, H = basin relief Dd = drainage density		Strahler (1964)
Dissection Index (Di)	Di = H/Ra, where, Ra = absolute relief H = basin relief or total relief	Dimensionless	Singh and Dubey (1994)

5.2.3 Statistical Methods

The detailed study is carried out in 55 third-order and nine fourth-order sub-watersheds, which includes 23 -24 morphometric parameters in third and fourth order sub-watersheds. This kind of huge data set may cause confusion in conclusion. So to avoid information overlapping from high dimensional data sets, Statistical analysis, such as Pearson correlation coefficient (Pearson, 1920)and hierarchical clustering dendrogram were carried out by using IBM SPSS Statistics 26. Pearsoncorrelation coefficient (*R*) is based on linear regression and measures the strength of correlation between two variables; varies between -1 to +1. The values of R close to zero, shows no correlation or weakly correlated variables, whereas, values close to +1 and -1 depict highly positive and highly negative correlation between variables respectively.

Furthermore, agglomerative hierarchical clustering dendrogram was developed for the better interpretation of variables. At each step, the two most similar clusters are joined into a singlenew group. For the linkage between each cluster, the nearest neighbour method was taken for thisstudy. The distance between the two groups is defined as the distance between their two closest members. It often yields clusters in which individuals are added sequentially to a single group. Thehorizontal axis of the dendrogram represents the distance or dissimilarity between clusters. The vertical axis represents the objects and clusters.

Despite of Pearson’s correlation, the Principal component analysis is a multivariateanalysis, which is used to reduce the set of original variables to extract a small number of latent factors (principal components, PCs) for analyzing relationships among the observed variables.

5.3 Results

The quantitative analysis of the area of the Mandakini River watershed shows remarkable information about the geological processes which are operative within the watershed, of which some are observable while other only decipherable such as neotectonics, land erosion and landform development, geomorphic history and course of processes. The area is hydrogeomorphologically dynamic and is being sculpted by the Mandakini River and its tributaries. This part of the Mandakini River watershed is elongated and has a surface area of about 90.54 Km^2. The drainagepattern of the watershed gives a glimpse of the structure and lithology of the watershed. The watershed has dendritic, sub- dendritic, trellis, radial and sub-annular type of drainage pattern. This kind of wide variety of drainage pattern shows a wide range of topographic controls (Lambert,1998; Ritter, 2012). The drainage patterns of the watershed give an idea about the topography of the area; it shows buttes, dissected dome-cuesta forms, uniform topography as well as ridges. Strahler's stream ordering system has been used for stream ordering in the watershed (Strahler, 1952 and 1957). The highest stream order is sixth and third and fourth-order sub-watersheds havebeen chosen for micro-scale study.

Strahler (1964) stream ordering technique has ordered the watersheds. The watershed has been classified up to the highest order, i.e. sixth order, watershed, that has a total area of 90.54Km^2,length and perimeter of 15.17 Km and 56.1 Km respectively (Table 5.2). The total number of the stream is 1413, out of which first-order streams occupy 77% of the catchment, i.e. 1091 in number. Horton's first law i.e. "the law of stream number" (Horton 1945) says that "the number of streamsof different orders in a given drainage watershed tends to approximate an inverse geometric ratio closely". A straight line representation of log value Nu and stream orders are obtained when plottedon a normal graph (Figure 5.3a). The total length of streams, the number of streams at each streamorder may vary according to the size and shape of sub-watersheds.

Table 5. 1 Primary and derived morphometric parameters of the study area

A	P	Lb	W	U	Lu	Nu	Nu1	Nu2	Nu3	Nu4	Nu5	Nu6	L1	L2	L3	L4	L5	L6	Rb	H	Dd	Fs	Dt	Rf	Rc	Re	Lg	C	If	Di	Rn
90.54	56.1	15.17	6.58	6	406.86	1413	1091	254	55	9	3	1	203.4	100.56	51.74	32.77	10.14	8.17	3.61	0.219	4.5	15.16	25.23	0.39	0.36	0.7	0.11	0.22	70.45	0.64	1.54

Table 5. 2 Primary and derived parameters of the third-order sub-watershed

Sr. No.	Au	P	Nu	Lu	Lb	W	Ls	Nu 1	Nu 2	Nu 3	Rb 1/2	Rb 2/3	H	Dd	Fs	Dt	Rf	Rc	Re	Lg	C	If	Rn	Di
1	2.95	9.97	48	14.2	3.30	1.52	3.38	38	9	1	4.22	9	0.07	4.82	16.27	4.81	0.27	0.37	0.59	0.10	0.21	78.38	0.10	0.31
2	0.97	4.91	19	5.27	1.40	0.83	3.61	13	5	1	2.60	5	0.11	5.43	19.57	3.87	0.50	0.51	0.80	0.09	0.18	106.2	0.09	0.32
3	1.06	4.96	15	4.31	1.61	0.96	3.48	11	3	1	3.67	3	0.07	4.08	14.22	3.02	0.41	0.54	0.72	0.12	0.24	58.04	0.12	0.31
4	1.06	4.91	17	4.51	1.50	2.68	3.77	14	2	1	7.00	2	0.06	4.25	16.04	3.46	0.47	0.55	0.78	0.12	0.24	68.19	0.12	0.27
5	0.94	5.20	15	3.98	1.69	0.64	3.77	11	3	1	3.67	3	0.06	4.22	15.89	2.88	0.33	0.44	0.65	0.12	0.24	67.01	0.12	0.28
6	0.85	4.16	13	3.53	1.22	0.65	3.68	10	2	1	5.00	2	0.10	4.17	15.35	3.12	0.57	0.61	0.85	0.12	0.24	63.97	0.12	0.38
7	0.90	4.61	12	3.25	1.64	0.66	3.69	9	2	1	4.50	2	0.15	3.63	13.38	2.60	0.34	0.53	0.65	0.14	0.28	48.50	0.14	0.47
8	0.89	5.78	18	4.16	1.93	0.57	4.33	14	3	1	4.67	3	0.08	4.68	20.25	3.12	0.24	0.33	0.55	0.11	0.21	94.77	0.11	0.32
9	0.72	3.88	13	2.88	0.69	1.00	4.52	9	3	1	3.00	3	0.06	4.01	18.13	3.35	0.29	0.6	0.61	0.12	0.25	72.75	0.12	0.26
10	0.33	3.16	8	1.70	0.99	0.40	4.70	5	2	1	2.50	2	0.02	5.22	24.54	2.53	0.33	0.41	0.65	0.10	0.19	128.0	0.10	0.11
11	0.55	3.70	10	2.28	1.10	0.53	4.38	7	2	1	3.50	2	0.02	4.15	18.15	2.70	0.46	0.51	0.76	0.12	0.24	75.23	0.12	0.09
12	0.81	5.74	14	4.34	1.50	0.59	3.22	11	2	1	5.50	2	0.04	5.34	17.22	2.44	0.36	0.31	0.68	0.09	0.19	91.99	0.09	0.17
13	1.19	6.16	21	5.24	1.94	0.72	4.01	15	5	1	3.00	5	0.08	4.41	17.68	3.41	0.32	0.39	0.63	0.11	0.23	77.94	0.11	0.38
14	0.39	2.88	9	1.90	0.89	0.53	4.73	6	2	1	3.00	2	0.05	4.93	23.32	3.12	0.49	0.58	0.79	0.10	0.20	114.9	0.10	0.22
15	0.44	3.53	10	2.28	1.14	0.34	4.39	7	2	1	3.50	2	0.01	5.15	22.62	2.83	0.34	0.44	0.66	0.10	0.19	116.6	0.10	0.08
16	1.23	6.15	21	5.41	2.20	0.60	3.88	16	4	1	4.00	4	0.10	4.38	17.02	3.42	0.25	0.41	0.57	0.11	0.23	74.55	0.11	0.35

17	0.44	2.97	9	1.97	0.81	0.60	4.58	6	2	1	3.00	2	0.07	4.49	20.55	3.03	0.67	0.62	0.92	0.11	0.22	92.23	0.11	0.31
18	0.76	4.08	12	3.50	1.34	0.62	3.43	9	2	1	4.50	2	0.09	4.60	15.77	2.94	0.43	0.57	0.74	0.11	0.22	72.57	0.11	0.38
19	2.06	9.64	30	8.39	2.68	0.62	3.58	23	6	1	3.83	6	0.09	4.07	14.56	3.11	0.29	0.28	0.60	0.13	0.25	59.23	0.13	0.33
20	0.52	3.47	10	1.81	1.05	0.55	5.52	7	2	1	3.50	2	0.05	3.49	19.27	2.88	0.48	0.54	0.78	0.14	0.29	67.23	0.14	0.19
21	0.80	4.20	13	2.73	1.44	0.55	4.75	9	3	1	3.00	3	0.12	3.41	16.23	3.10	0.38	0.57	0.70	0.15	0.29	55.40	0.15	0.39
22	0.35	2.95	8	1.65	0.85	0.49	4.84	5	2	1	2.50	2	0.03	4.70	22.79	2.72	0.48	0.51	0.78	0.11	0.21	107.3	0.11	0.08
23	0.24	2.19	7	1.01	0.49	0.48	6.91	4	2	1	2.00	2	0.03	4.29	29.66	3.20	0.50	0.62	0.80	0.12	0.23	127.3	0.12	0.10
24	2.10	7.50	32	9.77	1.66	1.71	3.27	25	6	1	4.17	6	0.15	4.65	15.22	4.27	0.76	0.47	0.98	0.11	0.22	70.72	0.11	0.48
25	0.38	2.75	9	1.38	0.85	0.48	6.54	6	2	1	3.00	2	0.13	3.61	23.62	3.28	0.52	0.63	0.82	0.14	0.28	85.31	0.14	0.45
26	1.43	7.34	27	7.51	2.60	0.67	3.59	21	5	1	4.20	5	0.18	5.25	18.85	3.68	0.21	0.33	0.52	0.10	0.19	98.93	0.10	0.54
27	0.83	4.26	13	4.14	1.33	0.62	3.14	9	3	1	3.00	3	0.17	4.98	15.64	3.05	0.47	0.58	0.77	0.10	0.20	77.90	0.10	0.53
28	0.39	3.79	8	2.43	1.36	0.33	3.29	5	2	1	2.50	2	0.17	6.28	20.67	2.12	0.21	0.34	0.52	0.08	0.16	129.9	0.08	0.54
29	0.50	3.33	12	2.25	1.04	0.48	5.33	9	2	1	4.50	2	0.01	4.47	23.81	3.61	0.47	0.57	0.77	0.11	0.11	106.4	0.11	0.08
30	2.12	8.22	35	10.2	2.97	0.81	3.42	29	5	1	5.80	5	0.19	4.82	16.52	4.26	0.24	0.39	0.55	0.10	0.21	79.68	0.10	0.59
31	0.51	3.81	9	2.45	0.91	0.44	3.67	6	2	1	3.00	2	0.12	4.82	17.68	2.36	0.62	0.44	0.89	0.10	0.21	85.21	0.10	0.48
32	0.55	3.10	11	2.01	0.91	0.61	5.47	7	3	1	2.33	3	0.10	3.63	19.86	3.55	0.66	0.72	0.92	0.14	0.28	72.04	0.14	0.40
33	0.61	4.02	17	2.91	1.17	0.54	5.85	13	3	1	4.33	3	0.03	4.73	27.69	4.23	0.45	0.48	0.75	0.11	0.21	131.1	0.11	0.17
34	0.59	4.18	11	2.36	1.22	0.43	4.66	8	2	1	4.00	2	0.02	3.98	18.58	2.63	0.40	0.43	0.71	0.13	0.25	74.01	0.13	0.11
35	0.39	3.33	9	2.01	0.74	0.57	4.47	6	2	1	3.00	2	0.01	5.12	22.90	2.71	0.72	0.45	0.95	0.10	0.20	117.4	0.10	0.09
36	1.26	6.08	20	5.64	1.84	0.89	3.55	16	3	1	5.33	3	0.04	4.47	15.86	3.29	0.37	0.43	0.69	0.12	0.23	70.89	0.12	0.24
37	0.74	4.43	15	2.71	1.09	0.74	5.54	11	3	1	3.67	3	0.02	3.65	20.22	3.39	0.62	0.47	0.89	0.10	0.28	73.83	0.10	0.12
38	0.49	3.81	11	2.36	1.19	0.51	4.66	8	2	1	4.00	2	0.02	4.80	22.36	2.89	0.35	0.43	0.67	0.10	0.21	107.3	0.10	0.09
39	0.47	3.34	9	2.34	0.97	0.52	3.85	6	2	1	3.00	2	0.04	4.99	19.23	2.69	0.49	0.53	0.79	0.10	0.20	96.03	0.10	0.19
40	0.49	3.69	9	2.07	1.11	0.47	4.35	6	2	1	3.00	2	0.07	4.27	18.56	2.44	0.40	0.45	0.71	0.12	0.23	107.3	0.12	0.31

41	0.89	3.97	15	4.33	0.98	1.11	3.46	11	3	1	3.67	3	0.18	4.88	16.91	3.78	0.72	0.71	0.95	0.10	0.20	82.55	0.10	0.56
42	0.55	3.73	11	2.76	1.32	0.48	3.99	8	2	1	4.00	2	0.02	4.97	19.86	2.95	0.32	0.5	0.64	0.10	0.20	98.78	0.10	0.15
43	0.82	5.48	13	4.07	1.78	0.46	3.20	10	2	1	5.00	2	0.18	4.97	15.87	2.37	0.26	0.34	0.57	0.10	0.20	78.84	0.10	0.58
44	2.69	8.80	41	9.74	1.96	1.91	4.21	35	5	1	7.00	5	0.19	3.61	15.22	4.66	0.70	0.44	0.99	0.14	0.28	55.00	0.14	0.59
45	0.54	4.15	11	2.57	1.09	0.68	4.29	7	3	1	2.33	3	0.03	4.74	20.30	2.65	0.46	0.39	0.76	0.11	0.21	96.12	0.11	0.18
46	1.00	5.06	20	4.75	1.29	0.93	4.21	14	5	1	2.80	5	0.02	4.75	20.00	3.95	0.60	0.49	0.87	0.11	0.21	95.08	0.11	0.16
47	1.70	7.04	32	8.02	1.91	0.98	3.99	25	6	1	4.17	6	0.02	4.71	18.82	4.55	0.47	0.43	0.77	0.11	0.21	88.75	0.11	0.16
48	1.17	6.07	19	6.07	2.01	0.78	3.13	15	3	1	5.00	3	0.02	5.20	16.25	3.13	0.29	0.4	0.61	0.10	0.19	84.44	0.10	0.15
49	0.45	2.98	8	1.91	0.94	0.54	4.20	5	2	1	2.50	2	0.02	4.21	17.66	2.69	0.50	0.81	0.81	0.12	0.24	74.30	0.12	0.14
50	0.60	4.05	13	2.84	1.05	0.62	4.59	9	3	1	3.00	3	0.02	4.69	21.53	3.21	0.55	0.46	0.84	0.11	0.21	101.0	0.11	0.10
51	0.49	3.60	9	2.49	1.02	0.56	3.62	6	2	1	3.00	2	0.02	5.10	18.44	2.50	0.47	0.47	0.77	0.10	0.20	94.06	0.10	0.14
52	0.63	3.86	15	2.63	1.06	0.59	5.70	11	3	1	3.67	3	0.02	4.19	23.85	3.89	0.57	0.53	0.85	0.12	0.24	99.83	0.12	0.11
53	0.59	3.30	11	2.51	0.93	0.64	4.38	8	2	1	4.00	2	0.02	4.28	18.77	3.33	0.68	0.67	0.93	0.12	0.23	80.37	0.12	0.12
54	1.84	8.82	33	8.47	3.17	0.69	3.90	26	6	1	4.33	6	0.03	4.59	17.90	3.74	0.18	0.3	0.48	0.11	0.22	82.19	0.11	0.18
55	2.77	10.2	46	12.0	3.29	0.93	3.83	35	10	1	3.50	10	0.09	4.33	16.59	4.53	0.26	0.34	0.57	0.12	0.23	71.83	0.12	0.34

Table 5. 3 Primary and derived parameters of the fourth-order sub-watershed

Sr. No.	Au	P	Lu	Lb	W	Ls	Nu 1	Nu 2	Nu 3	Nu 4	Nu	Rb 1&2	Rb 2&3	Rb 3&4	H	Dd	Fs	Dt	Rf	Rr	Rc	Re	Lg	C	If	Rn	Di
i	16.25	30.0	60.69	10.5	1.56	4.19	196	45	254	1	13	4.36	3.46	13	0.19	3.73	15.63	8.47	0.15	0.018	0.23	0.43	0.13	0.27	58.38	0.70	0.59
ii	3.31	9.1	12.62	3.09	1.46	4.36	42	10	55	1	3	4.20	3.33	3	0.04	3.81	16.63	6.05	0.35	0.013	0.50	0.66	0.13	0.26	63.42	0.15	0.23
iii	6.92	13.9	29.43	3.48	2.32	3.50	82	18	103	1	3	4.56	6.00	3	0.08	4.26	14.90	7.41	0.57	0.022	0.45	0.85	0.12	0.23	63.40	0.33	0.35
iv	2.59	8.7	10.81	2.24	1.44	3.98	32	9	43	1	2	3.56	4.50	2	0.08	4.17	16.60	4.94	0.52	0.035	0.43	0.81	0.12	0.24	69.21	0.33	0.35
v	7.42	16.5	30.98	5.62	1.56	3.97	96	24	123	1	3	4.00	8.00	3	0.12	4.17	16.57	7.48	0.24	0.022	0.34	0.55	0.12	0.24	69.17	0.51	0.46
vi	6.21	14.6	22.25	5.32	1.56	4.05	70	17	90	1	3	4.12	5.67	3	0.16	3.58	14.49	6.17	0.22	0.030	0.37	0.53	0.14	0.28	51.87	0.57	0.49
vii	2.20	6.8	8.36	1.80	1.62	4.66	28	8	39	1	3	3.50	2.67	3	0.16	3.80	17.72	5.74	0.68	0.088	0.60	0.93	0.13	0.26	67.33	0.60	0.49
viii	3.87	11.1	15.47	3.70	1.19	4.27	52	11	66	1	3	4.73	3.67	3	0.19	4.00	17.07	5.93	0.28	0.052	0.39	0.67	0.12	0.25	68.31	0.77	0.60
ix	9.51	20.2	37.27	5.75	1.76	4.24	123	29	158	1	6	4.24	4.83	6	0.19	3.92	16.62	7.82	0.29	0.033	0.29	0.60	0.13	0.26	65.17	0.75	0.60

5.3.1 Determination of the Morphometric Parameters

The Stream Lengths (Lu) of the streams were extracted from SRTM Global DEM with the help of Arc GIS and were hierarchically ranked according to Strahler's stream ordering (Strahler, 1964).The total stream length is 406.8 Km, where first-order streams contribute about fifty percent of thetotal length. Second, third, fourth, fifth and sixth make up 24.7%, 12.7%, 8%, 2.4% and 0.07% respectively. First-order streams and their headward erosion played a key role in the formation ofbadlands.

It can be seen that such an essential piece of information or so to say a straight-line relationship obscures a conclusion by using a log variable in the plot as there is a strong correlationbetween stream order and Log Lu and Log Nu (Figure 5.3a and 5.3b) and this makes it look like a simple case of perfect mathematical relation following the noticeable natural growth and rule ofbifurcations. It is vital that with log relationships a classification must be developed taking the slope of the correlation line. On the other hand, the systems approach emphasises upon the relationships of parts with the whole. The linearized values often mask the pronounced non linearity within a natural system and specific importance of one part or the other within the system may remain ignored in assessing the behaviour of the whole. The contribution of the number of streams at the first order to the length total length of streams is such a significant indicator of badlands that can be taken as characteristic for identifying and distinguishing the badlands from other watersheds. Therefore the sub set of the first order stream in relation to the various characteristics of the whole should be properly appreciated in badlands areas.

Therefore log-values are taken to find a straight line of correlation.This masks the identification of correlation as this can only be determined if the slope of the line is classified to the class watershed with abnormal development of streams and gullies at lower order.

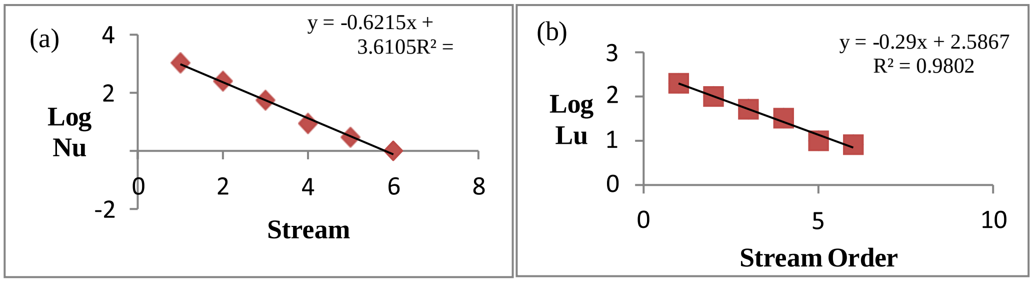

Figure 5. 3 (a) Semi-log plot of stream order and stream number; (b) Semi-log plot of stream orderand total stream length

(i) The Bifurcation Ratio (Rb) is the ratio of the number of streams of a given order to the numberof streams of the next higher-order (Schumm, 1956). The bifurcation ratio varies from a minimumof 2 in "flat or rolling drainage basins" to 3 or 4 in "mountainous or highly dissected drainage basins"(Horton 1945).

The higher value of the Bifurcation ratio ($Rb_{1\&2}$) shows control of geology over the area (Jha et al., 2009). The bifurcation ratio of the area of the Mandakini River watershedis 3.61 (Table 5.2) which indicates that the watershed has been tectonically active. The bifurcationratio ($Rb_{1\&2}$) has been calculated for the third and fourth-order watersheds as well. The value of the bifurcation ratio in fourth-order sub-watersheds ranges from 3.5 to 4.73 (Table 5.3). Among 55 third-order sub-watersheds 46 sub watersheds are having values greater than 3 (Table 5.4). Hence among third-order sub-watersheds, majority of the sub-watersheds are structurally controlled. On the whole, 85% of the watersheds belongs to the structural control category among64 sub-watersheds (Figure 5.4).

Penck (1953) suggested that erosion and upliftment both are simultaneous processes. Penck also suggested varying rate of upliftment, in the beginning, the uplift is characterized by a prolonged rate of upheaval for a long duration and after that accelerated and ultimately it declines.

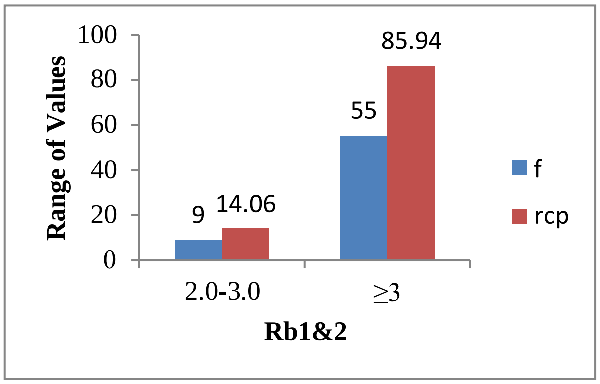

Figure 5. 4 Distribution of bifurcation ratio (Rb 1&2) in the third and fourth-order sub watersheds; f- frequency; rcp- cumulative relative frequency percent.

(ii) Drainage Density (Dd): The drainage density is the sum of stream lengths per unit area and isan expression of closeness or spacing of channels (Horton, 1932). The measurement of drainage density is a useful numerical measure of landscape dissection and runoff potential (Chorley, 1969).The drainage density is a factor determining the time of travel by water (Schumm, 1956). Drainage density is an interacting factor that controls surface runoff, but on the other hand, it is also influencing the output of water and sediment from the drainage basin (Ozdemir and Bird, 2009). It is a sensitive parameter that, in many ways, provides a bridging link between the other dependent attributes of the watershed and the processes operating along a stream course (Gregory, 1973). The drainagedensity of the watershed also reflects infiltration, runoff and discharge, land use and slope of the watershed.

The drainage density is classified as extremely low (0-1), low (1-2), Moderate (2-4), moderately high (4-6) and high (>6) (Smith 1950). The drainage density of the study area is 4.5 (Table 5.2), which represents a moderately high drainage density. In the third-order sub-watersheds, drainage density (Dd) ranges from 3.4 to 6.2 (Table 5.3). Among 55 third-order sub-watersheds, eight fall in moderate drainage density (varying between 2- 4) and forty-six fall in moderately high drainage density value (ranges from 4-6) and one sub-watershed has high drainage density (Dd) value (i.e., 6.2) (Figure. 5.5). Fourth-order sub-watersheds are showing a narrower range of drainage density (Dd) value ranging from 3.5 - 4.2. All nine sub-watershedsfall under two categories, viz. moderate drainage density and moderately high drainage density.

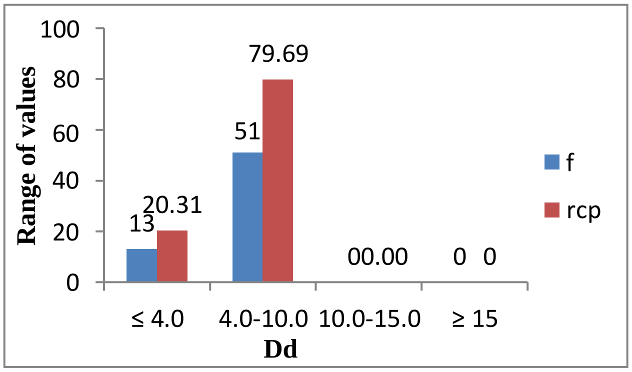

Figure 5. 5 Distribution of drainage density (Dd) in the third and fourth-order sub-watersheds; f-frequency; rcp- cumulative relative frequency percent

(iii) Drainage Frequency (Fs) stream frequency is the number of streams per unit of area. It’s the ratio of the total number of streams (Nu) in a basin to the basin area (Horton, 1945). According toHorton (1945) stream frequency is classified into five categories; low (Fs = 0 - 5 Km^{-2}), moderate(Fs= 5-10Km^{-2}), moderately high (Fs=10-15 Km^{-2}), high (Fs= 15-20Km^{-2}), very high (Fs= 20-25 Km^{2}).

(iv) The drainage frequency of the Study area is 15.61 Km^{-2} (Table 5.2). In third-order sub-watersheds, it ranges from 13.37 to 29.66 Km^{-2} (Table 5.3) (Figure 5.6), i.e., in the categories of moderately high, high and very high. In the fourth-order sub-watersheds, it varies over moderatelyhigh to high; values range from 14.48 to 17.71Km^{-2} (Table 5.4) (Figure 5.6).

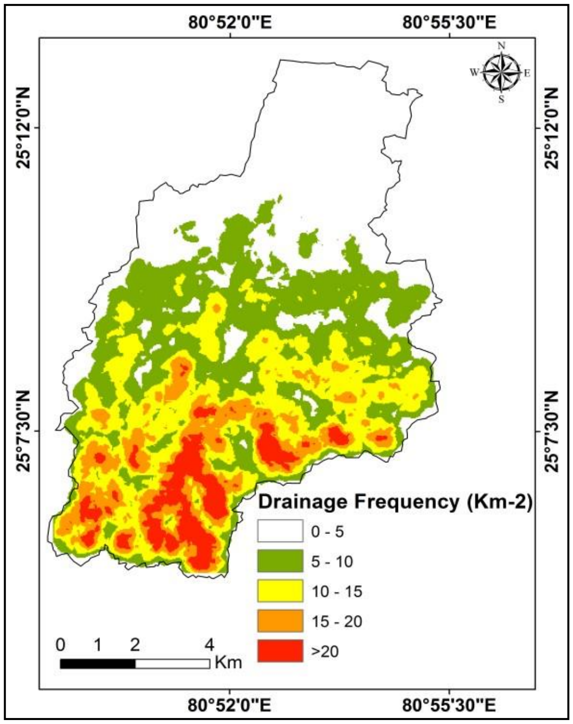

Figure 5. 6 Spatial map of the drainage frequency (Fs)

Statistically, stream frequency (Fs) and drainage density (Dd) both are positively correlatedfor both third and fourth-order sub-watersheds, which shows, stream frequency is associated withdrainage density (Magesh, 2011). A higher value of stream frequency indicates less vegetation, less permeability and relatively steeper slope. The majority of the third and fourth-order sub- watershed has high to very high drainage frequency values (Figure 5.7). The drainage frequency of the Study area is also high. Thus it is a clear indication of low permeability watershed, which has less vegetation.

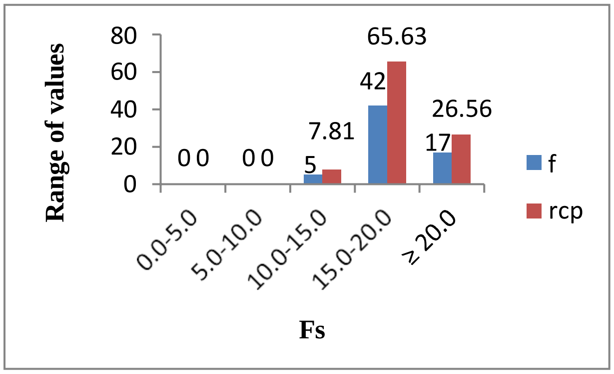

Figure 5. 7 Distribution of drainage frequency (Fs) in the third and fourth order sub-watersheds;f- frequency; rcp- cumulative relative frequency percent

(v) Drainage Texture (Dt) Drainage texture means the relative spacing of drainage lines (Smith, 1950). It is defined as the stream segment per unit perimeter of the area (Horton, 1945). Drainage texture depends upon channel spacing, rainfall, climate, lithology, vegetation, infiltration capacity,as well as relief (Smith, 1950). Smith (1950) categories drainage texture into four classes coarse (≤ 4), medium (4-10), fine (10-15) and ultrafine (>15). Drainage Texture (Dt) value of the Study area is 25.23 Km^{-1} (Table 5.2). This reflects badland topography. Drainage texture (Dt) values in third-order sub-watersheds range from 2.1 to 4.8 Km^{-1}, wherein Dt value of fourth-order sub-watershed ranges from 4.9 to 8.4 Km^{-1} (Table 5.3).

In the third-order sub-watersheds, 48 out of 55 sub-watersheds fall under the coarse texture. The first and second order streams are large in number (95%), which are profusely developing inthe lower reaches and directly joining a higher order stream and therefore, Dt has increased enormously without improving the order of the high-end streams. It means more significant dissection has been carried out by the first and the second-order streams joining higher-order streams representing a typical condition of badlands.

Drainage texture (Dt) increases with the increase in the stream order. Dt in fourth-order sub-watershed is more than the third order. Consecutively the Drainage Texture (Dt) value of the Study area is 25.23, i.e., ultra-fine. It refers to a badland topography or high erodible ground.

(vi) Basin relief (H) is the difference in height between the highest and the lowest points (summitand the mouth) of the watershed (Hadley and Schumn, 1961). Relief is an essential character for erosion. Erosion and upliftment, complement each other, it is a simultaneous process (Penck, 1953;Koons, 1989; Molnar and England, 1990; Avouac and Burov, 1996; Lavbe and Avouac, 2001; Joshua et al., 2015).

The Study area has a relief of 219 meters. The maximum and minimum height of the watershed is 342 and 123 meters, respectively (Figure 3.2a). The watershed is bounded by uplands(hills) and the eroded sediments are deposited in the valley side, in the Central and northern Plains.

(vii) Length of overland flow (Lg) is the length of water over the ground surface before it getsconcentrated into a definite stream channel (Horton, 1945). It is a useful parameter for thehydrological and topographical evolution of drainage watershed. The length of overland flow hasan inverse relation with drainage density. Horton (1945) signifies Length of overland flow on thebasis of its higher and lower values; more channel erosion (<0.4) and more sheet erosion (>0.7). The length of overland flow (Lg) of the area of the Mandakini River watershed is 0.11 (Table 5.2).In third-order sub-watersheds, Lg ranges from 0.14 and 0.7 (Table 5.3) and in fourth-order sub-watersheds length of overland flow varies between 0.12 and 0.14 (Table 5.4). The interpretationof this parameter corroborates and asserts the conclusion as drawn from drainage density anddrainage texture parameters. Channel erosion is dominant in the overall watershed as the overallvalue is 0.11 and for fourth-order watersheds, it ranges between 0.12 to 0.14 and further decreasesfor higher orders. This is implying that instead of an increase in the overland flow at higher-order, the present case is showing inverse behavior, i.e., possible due to the development of first and second-order streams in the lands ambilateral to the higher-order streams.

(viii) Infiltration Number (If): Faniran (1968) has explained the infiltration number (If) as a product of drainage density (Dd) and drainage frequency (Fs). Infiltration number (If) gives a glimpse of the infiltration capacity of the watershed (Mishra et al., 2003). Higher the value of infiltration number lesser the infiltration capacity of the watershed and vice versa.

The infiltration number (If) of the study area is 70.5 (Table 5.2). In the third-order sub-watersheds,it ranges from 48.5 to 131.08 (Table 5.3). In the fourth-order sub-watersheds, it varies from 51.87 to 69.21 (Table 5.4). This kind of high value of infiltration number represents very little percolationof water on the ground and very high runoff, hence cause erosion.

(ix) Constant of Channel Maintenance(C) is the reciprocal of drainage density (Dd). The constantof channel maintenance values is classified by Schumm (1956) into five categories viz. more erodible (<0.2), moderate erodible (0.2-0.3), moderately low erodible (0.3-0.4), low erodible (0.4-0.5) and least erodible (>0.5). The constant of channel maintenance value of the Study area is 0.22(Table 5.2). In the third-order sub-watersheds, it ranges from 0.11 to 0.29 (Table 5.3) and in fourth-order sub-watersheds, value ranges from 0.23 to 0.28.

By definition, the constant of channel maintenance is twice the length of overland flow asboth are derived from area length relationship. Therefore, the same implications are suggested andconcluded with this parameter here as well.

Lesser the value of constant of channel maintenance shows geological control over the areawith a surface of low permeability. Ten out of 55 third-order sub-watersheds belong to the more erodible class and the rest 45 falls under the moderate erodible category. All fourth-orderwatersheds belong to a moderate erodible category (Table 5.4) (Figure. 5.8).

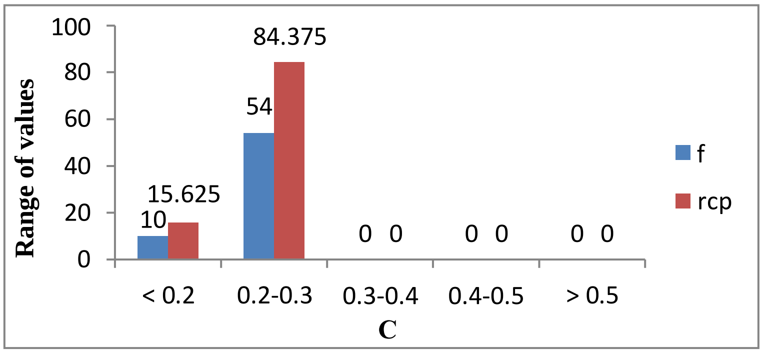

Figure 5. 8 Distribution of constant of channel maintenance (C) in the third and fourth-order sub-watersheds; f- frequency; rcp- cumulative relative frequency percent

(x) Circularity Ratio (Rc) refers to "The ratio of the watershed area (A) to the area of a circle having the same circumference as the perimeter of the watershed" (Miller, 1953). Values of Rc vary between 0 to 1, i.e., line to circle (Bali et al., 2012). Circularity ratio is affected by geologicalstructures, stream frequency, stream length, climate, land cover, slope and relief of the watershed.It's a critical parameter which embraces stages of the river basin. Rc is also indicative of the maturity level of the basin. Low, medium and high values of Rc indicate the young, mature and old stage of the geomorphic cycle of the watershed (Magesh, 2011).

The circularity ratio value of the study area is 0.36 (Table 5.2). In the third-order sub-watersheds, circularity ratio (Rc) ranges from 0.27 to 0.80 (Table 5.3). 47 out of 55 sub-watershedshave circularity ratio (Rc) values of greater than 0.6, which shows youth to mature stage of watershed development. In the fourth-order sub-watersheds, circularity ratio

(Rc) value ranges from 0.23 to 0.60. Five out of nine sub-watersheds of fourth-order embrace youth stage having

circularity ratio (Rc) value of less than 0.4; the rest of the watersheds are in the mature stage of watershed development. A higher value of Rc represents more circularity in the shape of the sub-watershed and vice-versa. Lower the circularity ratio value slower will be the discharge. The spatial distribution of gullies and ravines in the area of the Mandakini River watershed is mainly in fourth-order sub watershed, even though the circularity ratio is less than 0.40. It is because riversflow over silty alluvial. This may be due to tectonic control on the badlands forming processes.

(xi) Elongation Ratio (Re) Elongation ratio (Re) is defined as the ratio of the diameter of a circle of the same area as the watershed to the maximum watershed length (Schumm, 1956). The value of the elongation ratio gets varies from zero (exceedingly elongated) to one (circular). Either the elongation ratio values closer to one resembles low relief areas, whereas lower the value that of less than 0.8 usually shows a greater relief and steep slope (Strahler, 1964). The values of Re are grouped under four categories circular (>0.9), oval (0.9-0.8), less elongated (0.8-0.7) and elongated(<0.7) (Schumm, 1956).

The Re value of the Study area is 0.7 (Table 5.2), i.e., less elongated. In the third-order sub-watersheds, Re value varies from 0.48 to 0.99 (Table 5.3), which provides a wide range of shapes. According to classification among 55 third-order sub-watersheds , 21 sub-watersheds belong to the elongated category, 18 are less elongated, nine oval and seven falls underthe circular category. In the fourth-order sub-watersheds, Re ranges from 0.43 to 0.92 (Table 5.4).Among nine fourth-order sub-watersheds, six are elongated, two are oval and one is circular.

More than 70% of the watersheds lie in elongated to the less elongated category (Figure. 5.9). Lower values of this parameter indicate more elongation of the watershed and less erosion, while higher values indicate less elongation and high erosion. Here also, erosion is prominent in the elongated watershed and resulting in badlands conditions.

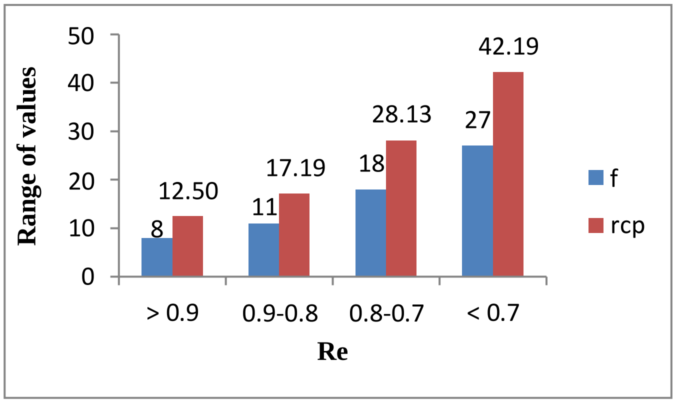

Figure 5. 9 Distribution of elongation ratio (Re) in the third and fourth-order sub-watersheds; f-frequency; rcp- cumulative relative frequency percent

(xii) Form Factor (Rf) is the representation of the shape of the watershed. Horton (1945) explainsit as the ratio of the watershed area and square of the total watershed length. Lesser the value of Rf more elongated, the watershed would generate low peak flow for a greater time duration and vice- verse. The average form factor (Rf) of the area of the Mandakini River watershed is 0.39(Table 5.2). Among 55 third-order watersheds, 39 has a form factor (Rf) value of less than 0.5 and16 stands between 0.5-0.8, whereas in fourth-order sub-watershed six out of nine watersheds are having a value of less than 0.5 and rest has higher values (Figure. 5.10).

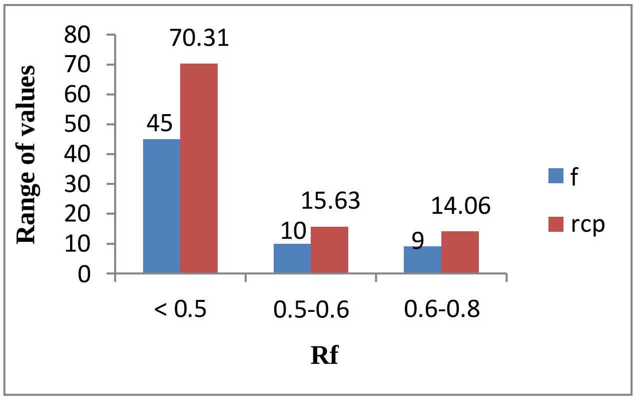

Figure 5. 10 Distribution of form factor (Rf) in the third and fourth-order sub-watersheds; f-frequency; rcp- cumulative relative frequency percent

(xiii) Ruggedness Number (Rn) it is the product of watershed relief and drainage density (Strahler,1968), Rn is a dimensionless parameter. For the higher value of ruggedness number (Rn), drainagedensity and relief value should both be higher and in the case of the slope, it should be steeper andlonger both. (Farhan et al., 2015) have classified Rn into five categories subdued morphology (<0.1), slight morphology (0.1-0.4), moderate morphology (0.4-0.7) and sharp morphology (0.7- 1.0). Extreme morphology indicates badland topography, i.e., high erosion-prone area. In third-order sub-watershed, Rn varies from 0.079 - 0.149 (Table 5.3) and in fourth-order sub-watershed, it ranges from 0.15-0.77 (Table 5.4) and most of the sub-watershed is coming underthe class of slight rugged terrain (Figure 5.11).

The ruggedness number (Rn) of the Study area is 1.54 (Table 5.2), which indicates extremegeomorphic processes, long and steep slopes with sudden breaks due to rejuvenation processes, which implies high soil erosion-prone area with the mass movement.

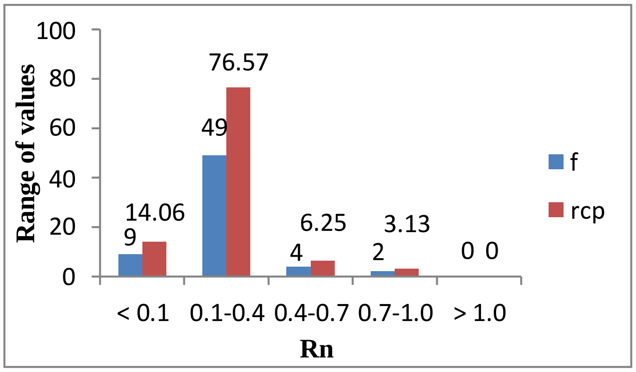

Figure 5. 11 Distribution of ruggedness number (Rn) in the third and fourth-order sub-watersheds; f- frequency; rcp- cumulative relative frequency percent

(xiv) Dissection Index (Di) is the ratio of watershed relief and absolute relief. It shows the level ofdissection or vertical erosion and the stage of landform development in any given watershed (Singhand Dubey, 1994). Values vary between zero to one. According to the degree of dissection, Di is classified under five categories flat-undulating (< 0.1), rolling (0.1-0.4), moderately dissected (0.4-0.7), highly dissected (0.7-0.9) and extremely dissected (>0.9).

Dissection Index (Di) of the Study area is 0.64 (Table 5.2). In the third-order watersheds, it varies from 0.08 to 0.59 (Table 5.3). Among 55 third-order sub-watersheds, six shows flat, undulating features, 37 sub-watersheds have rolling topography and 12 belong to moderately dissected terrain. In fourth-order sub-watersheds, six are showing moderately dissected feature andthree belongs to rolling topography.

More than 90 % of the watershed belongs to rolling and moderately dissected topography(Figure 5.12). Hence it is apparent that vertical erosion is affecting the terrain and continuously reshaping the landform.

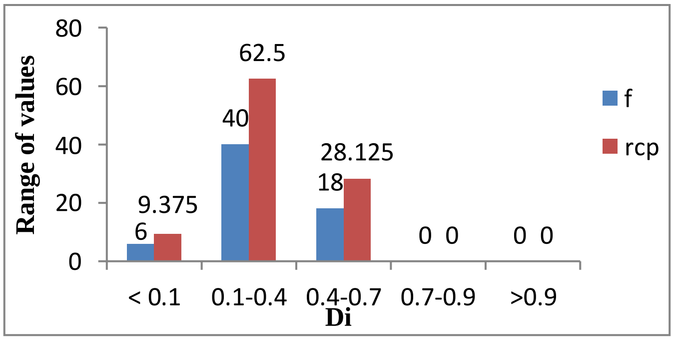

Figure 5. 12 Distribution of dissection index (Di) in the third and fourth-order sub-watersheds; f-frequency; rcp- cumulative relative frequency percent

5.3.2 Statistical Analysis

5.3.2a Pearson's Correlation Coefficient

In the study area, total number of streams (Nu) is very significantly related with the lengths of thefirst order L1 (95.9), the second order L2 (76.4), the third order streams L3 (91.4) and the total stream length of all orders Lu (97.8) in 'third order sub-watersheds'. So also in 'fourth order sub-watersheds' the length of the first order L1 (99.94), the second order L2 (89.15), the third order L3 (95.35), the fourth order streams L4 (94.39) and total stream length of all orders Lu (99.44), very significant correlations exist (Table 5.5 and 5.6).

Another test of the efficiency of the development of the system as the number of streams increases all the parameters are accordingly increased is reflected in the rigidity of the parameter of the number of streams per unit area i.e. stream frequency. The stream frequency does not haveany significant correlation with any primary parameters in general as the sensitivity of primary parameters shows such changes so as to maintain the ratio of derivative parameter and therefore

stream frequency (Fs) is stable near-constant as does not show correlation changes (Table

5.5 and5.6).

Length parameters are strongly correlated with each other and so also with the area. This is again the signature of a sensitive system that tries to maintain its form parameters and other ratios such as drainage density with which it has no significant correlation values (Rc versus L1 (-43.4), L2 (-25.8), L3 (-58.6)) (Lu versus Dd (6.56)) (Table 5.5).

Table 5. 5 Pearson’s Correlation Coefficient (= r × 100) for 55 third-order sub-watersheds of the study area

	Au	*P*	*Nu*	*Lu*	*Lb*	*W*	*Ls*	*L1*	*L2*	*L3*	*H*	*Dd*	*Fs*	*Dt*	*Rf*	*Rc*	*Re*	*Lg*	*C*	*If*	*Di*	*Rn*	
Au	100	96.01	98.23	98.21	87.24	58.77		97.15	78.51	91.27	37.68			73.16				9.27	9.98		40.55	9.27	*Au*
P		100	95.01	95.87	94.06	46.25		92.68	71.88	93.43	33.60	0.92		60.77					2.47		36.58		*P*
Nu			100	97.77	87.14	54.99		95.88	76.41	91.37	30.60			80.31				3.04	4.10		33.05	3.04	*Nu*
Lu				100	89.46	55.16		97.85	78.23	92.41	36.68	6.54		72.19							39.21		*Lu*
Lb					100	30.89		83.80	64.09	90.75	32.92	6.61		50.74							35.96		*Lb*
W						100		60.10	52.60	35.16	22.60			56.81	21.12	0.76	20.83	14.30	16.62		25.86	14.30	*W*
Ls	-43.9	-49.7	-34.9	-50.2	-50.4	-27.2	100						77.82	4.26	29.75	38.30	32.00	39.76	32.44	33.29		39.76	*Ls*
L1							-50.4	100	79.89	87.23	43.72	4.75		73.28							45.52		*L1*
L2							-40.8		100	64.94	36.57			61.85					0.61		38.38		*L2*
L3							-43.9			100	34.72	4.82		59.08							36.33		*L3*
H							-38.9				100	1.56		17.13				8.25	9.96		98.06	8.25	*H*
Dd	-8.8		-3.9			-16.6	-45.6		-0.47			100	18.90							65.74			*Dd*
Fs	-53.5	-53.5	-40.2	-50.3	-50.6	-40.4		-52.5	-45.6	-44.5	-46.8		100		16.32	14.84	17.13			83.76			*Fs*
Dt												-16.3	-5.41	100	12.60		10.97	11.61	7.23		17.97	11.61	*Dt*
Rf	-22.3	-39.0	-23.3	-27.4	-58.9			-16.5	-10.1	-42.7	-6.3	-23.9			100	60.63	99.50	16.80	18.55			16.80	*Rf*
Rc	-44.9	-63.7	-47.4	-49.3	-64.1			-43.4	-25.8	-58.6	-6.4	-38.6		-3.1		100	62.00	37.09	27.77			37.09	*Rc*
Re	-24.2	-41.3	-25.4	-30.0	-61.5			-19.2	-10.9	-44.3	-9.1	-26.7					100	19.84	20.49			19.84	*Re*
Lg		-0.2		-5.9	-4.6			-4.7	-2.5	-0.7		-94.2	-22.0					100	83.30		11.08	100	*Lg*
C				-3.7	-3.1			-6.8		-0.3		-86.1	-26.0						100		13.48	83.30	*C*
If	-46.3	-40.9	-34.2	-36.4	-35.6	-40.4		-39.0	-37.4	-31.6	-34.2			-16.9	-2.0	-11.1	-2.5	-64.4	-63.5	100			*If*
Di							-42.6					-2.0	-53.0		-7.1	-6.4	-10.0			-40.2	100	11.08	*Di*
Rn		-0.2		-5.9	-4.6			-4.7	-2.5	-0.7		-94.2	-22.0							-64.4		100	*Rn*

Abbreviations: Au- Area of the basin; P- Perimeter of the basin; Nu- Total number of streams; Lu- Total stream length; Lb- Basin length; W- Width of the basin; Ls- Mean stream length; L1- Length of first order streams; L2- Length of second order streams; L3- Length of third order streams; Rb- Bifurcation ratio; H- Basinrelief in (Km); Dd- Drainage density; Fs- Stream frequency; Dt- Drainage texture; Rf- Form factor; Rc- Circularity ratio; Re- Elongation ratio; Lg- Length of overland flow; C- Constant channel of maintenance; If- Infiltration number; Di- Dissection Index; Rn- Ruggedness number.

Table 5. 6 Pearson’s Correlation Coefficient (= r × 100) for 9 fourth-order sub-watersheds of the study area

	Au	*P*	*Nu*	*Lu*	*Lb*	*W*	*Ls*	*L1*	*L2*	*L3*	*L4*	*H*	*Dd*	*Fs*	*Dt*	*Rf*	*Rc*	*Re*	*Lg*	*C*	*If*	*Di*	*Rn*	
Au	100	99.44	99.69	99.58	96.46	22.46		99.66	90.94	95.58	94.01	45.06			89.85				20.97	20.97		50.48	43.02	*Au*
P		100	99.49	98.86	97.56	15.38		98.90	91.43	94.34	93.77	49.29			87.98				21.88	21.88		54.95	47.47	*P*
Nu			100	99.44	96.21	19.41		99.54	89.15	95.35	94.39	47.08			90.52				18.92	18.92		52.87	45.58	*Nu*
Lu				100	94.65	27.35		99.50	91.01	96.08	91.50	42.30			92.33				12.66	12.66		48.81	41.24	*Lu*
Lb					100			95.09	91.61	86.88	95.01	49.97			81.14				34.07	34.07		54.15	46.83	*Lb*
W					-0.15	100		22.91	25.58	40.94			33.58		45.04	38.45	6.07	30.60						*W*
Ls	-20.3	-18.4	-16.3	-25.9	-9.86	-60.9	100				7.58	35.56		70.70		2.45	28.99	2.65	56.02	56.02	12.54	26.12	31.55	*Ls*
L1							-20.4	100	88.30	94.85	94.40	46.20			89.60				16.48	16.48		52.09	44.77	*L1*
L2							-38.6		100	85.56	77.27	39.66			83.97				21.85	21.85		44.90	37.18	*L2*
L3							-26.6			100	84.26	32.72			92.39				15.16	15.16		38.05	30.93	*L3*
L4						-2.8					100	53.59			77.32				37.15	37.15		56.33	50.31	*L4*
H						-25.0						100		10.08	35.27				38.74	38.74		98.82	99.21	*H*
Dd	-20.6	-21.7	-18.9	-12.3	-33.7		-59.5	-16.3	-19.9	-14.8	-37.9	-39.9	100	14.60		36.74	8.82	42.03			72.05			*Dd*
Fs	-42.7	-40.7	-36.1	-42.3	-40.4	-48.7		-39.1	-64.0	-45.9	-23.4			100		31.87	40.44	37.17	79.02	9.48	15.09			*Fs*
Dt							-27.0						-1.1	-34.7	100				1.18	1.18		41.87	36.04	*Dt*
Rf	-62.8	-68.7	-63.4	-60.5	-77.9			-59.3	-71.1	-52.4	-64.1	-40.6			-50.0	100	83.10	98.26			43.20			*Rf*
Rc	-84.0	-88.8	-84.6	-84.0	-87.5			-82.9	-84.8	-77.7	-75.6	-49.8			-69.5		100	84.67			32.37			*Rc*
Re	-71.4	-76.4	-71.7	-68.8	-85.3			-67.5	-79.2	-61.5	-71.4	-39.7			-57.2			100			50.40			*Re*
Lg						-31.3							-99.8	-18.8		-36.7	-9.2	-42.3	100	100		26.50	27.37	*Lg*
C						-31.3							-99.8	-18.8		-36.7	-9.2	-42.3		100		26.50	27.37	*C*
If	-43.1	-42.0	-37.4	-37.7	-48.9	-15.7		-38.0	-56.7	-42.2	-40.3	-16.9			-26.0				-74.9	-74.9	100			*If*
Di						-21.9							-27.6			-43.6	-57.6	-42.3			-9.7	100	99.52	*Di*
Rn						-23.9							-28.7			-38.4	-50.1	-36.3			-6.5		100	*Rn*

Abbreviations: Au- Area of the basin; P- Perimeter of the basin; Nu- Total number of streams; Lu- Total stream length; Lb- Basin length; W- Width of the basin; Ls- Mean stream length; L1- Length of first order streams; L2- Length of second order streams; L3- Length of third order streams; L4- Length of fourth order streams; Rb- Bifurcation ratio; H- Basin relief (in Km); Dd- Drainage density; Fs- Stream frequency; Dt- Drainage texture; Rf- Form factor; Rc- Circularity ratio;Re- Elongation ratio; Lg- Length of overland flow; C- Constant channel of maintenance; If- Infiltration number; Di- Dissection Index; Rn- Ruggedness number.

5.3.2b Hierarchical Clustering Dendrogram

The morphometric analysis points towards the fact that the badlands are systems of more or so of *self-enhancing nature*. Due to the increase in Infiltration number (If) drainage frequency (Fs) andstream length (Ls); (strong correlation between If, Fs and Ls), channel erosion is initiated and landscape transformation is enhanced (the strong relationship between Lg, C and Rn).

The representative dendrogram cluster based on the Pearson correlation coefficient also shows the same result for the watersheds (Figure 5.13 and 5.14). There are three significant clustersof derived parameters with higher similarity viz. If-Fs-Ls-Dd, C-Lg-Rn and Re-Rf-Rc (dendrogram of third-order basins). In the dendrogram of fourth-order sub-watersheds, the result is also the same with higher similarity between the above discussed parameters (Figure 5.14). Thisindicates an influence of slope and lithology on badland formation. Due to steep slope and low permeable terrain, the rain gets quickly drained into the stream channels hence drainage frequencyand drainage density increase and causes erosion and landform transformation in the form of rillsand gullies. These rills and gullies go on spreading and can lead to soil loss and deterioration of land until geomorphological, sedimentological or hydrogeological controls are practiced.

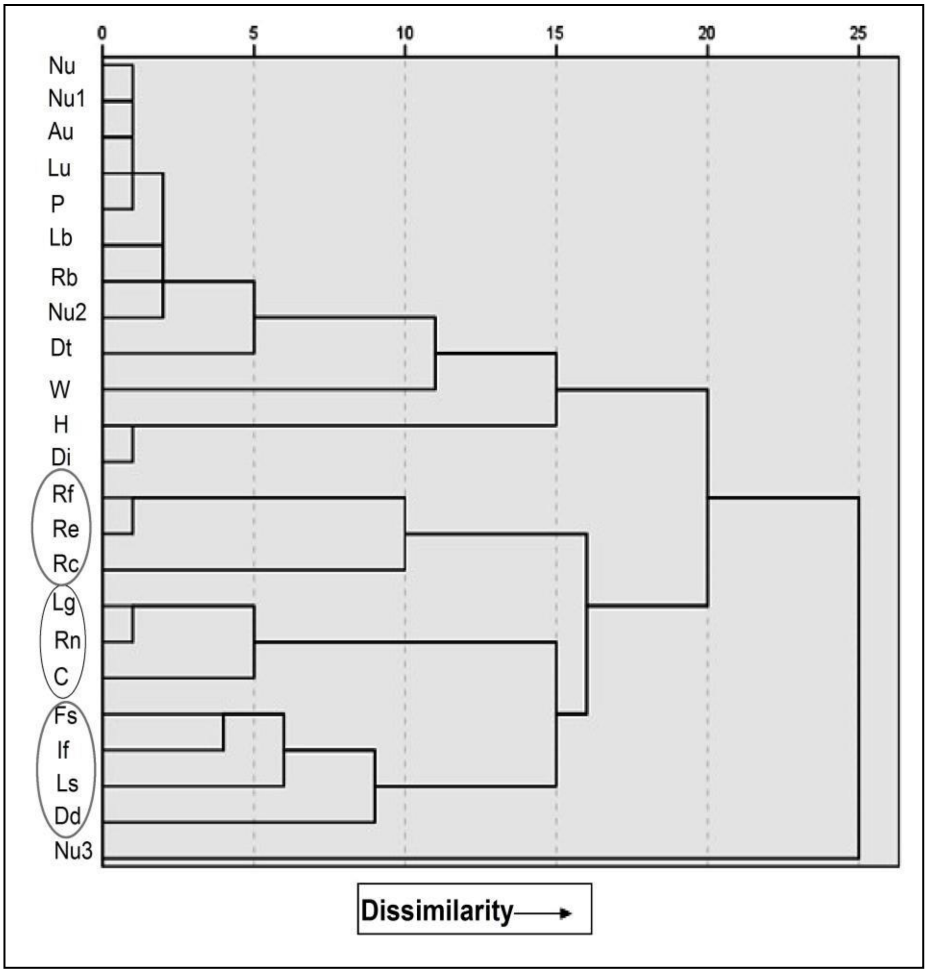

Figure 5. 13 Hierarchical clustering dendrogram of morphometric parameters of third-order sub- watershed of the study area

Abbreviations: Au, area of the basin; P, perimeter of the basin; Nu, total number of streams; Lu, total stream length; Lb, basin length; W, width of the basin; Lu, total stream length; Nu, total number of stream segments; Nu1, total number of first-order streams; Nu2, total number of second-order streams; Nu3, total number of third-order streams; Rb, bifurcation ratio; H, basin relief; Dd, drainage density; Fs, stream frequency; Dt, drainage texture; Rf, form factor;Rc, circularity ratio; Re, elongation ratio; Lg, length of overland flow; C, constant channel of maintenance; If, infiltration number; Rn, ruggedness number; Di, dissection index

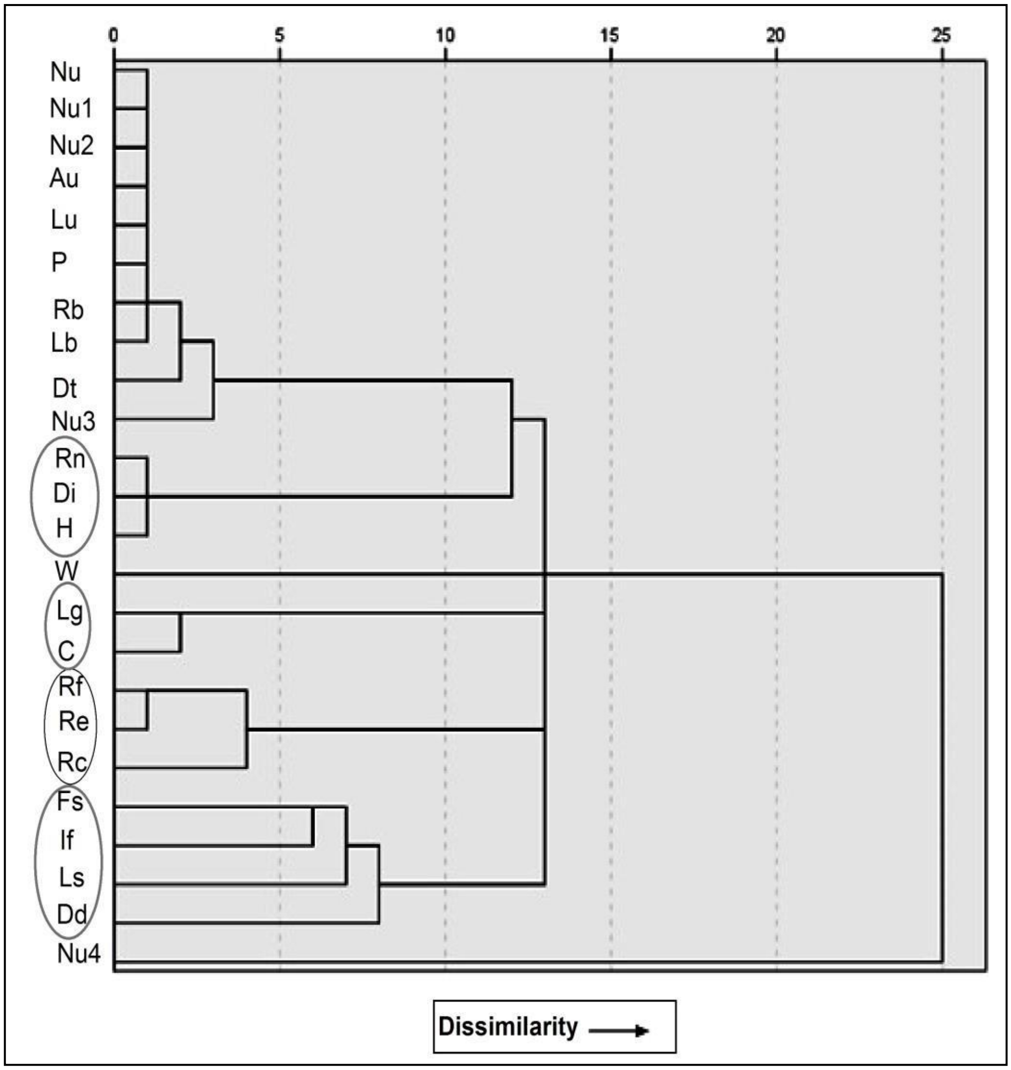

Figure 5. 14 Hierarchical clustering dendrogram of morphometric parameters of fourth-order sub-watershed of the study area

Abbreviations: Au, area of the basin; P, perimeter of the basin; Nu, total number of streams; Lu, total stream length; Lb, basin length; W, width of the basin; Lu, total stream length; Nu, total number of stream segments; Nu1, total number of first-order streams; Nu2, total number of second-order streams; Nu3, total number of third-order streams; Nu4, total number of fourth-order streams; Rb, bifurcation ratio; H, basin relief; Dd, drainage density; Fs, stream frequency; Dt, drainage texture; Rf, form factor; Rc, circularity ratio; Re, elongation ratio; Lg, length of overland flow; C, constant channel of maintenance; If, infiltration number; Rn, ruggedness number; Di, dissection index

5.4 Discussions

The morphometric analysis of the Mandakini River watershed plays an anchor role in the study ofthe badlands in the region. Quantitative, qualitative and statistical analyses of derived morphometric parameters show significant information retarding watershed evolution. In the study area, the number of first-order streams is high in number (about 50%). The first order L1(99.94), the second-order L2 (89.15), the third-order L3 (95.35), the fourth-order streams L4 (94.39) and total stream length of all orders Lu (99.44) (Table 5.5 and 5.6), very significantly correlated. This very significant correlation in length parameters indicates that the length is nearlyuniform and increases due to appearance of more stream segments. This highly sensitive relationship suggests that the two primary parameters are forming a very sensitive system where space available to stream segment is generated. A badlands system is a self-augmentative erosivesystem (Tignath et al., 2005; Deshmukh et al., 2011) that extends with headward erosion bifurcating upward at a certain space interval. This system can only operate with a high correlationof the total number of the streams (Nu) with length parameters of the streams, length parameters of the watershed, drainage texture and area. All these primary parameters should be strongly correlated with the stream number. This indicates the badlands process that goes on with stream bifurcation upwards.

The bifurcation ratio of the study area is high (3.6) in the watershed, showing a structural control over the area. The bifurcation ratio is also kept high in third and fourth-order sub- watersheds; almost 70% of sub-watershed has higher value and belong to the structural control category. The drainage texture of the study area shows a moderately high (4.5) drainage texture. The drainage frequency of the study area depicts a high value of

15.61Km^{-2} and both of these values are gradually increasing in the higher-order sub-watersheds. Both of these parameters having moderate to high value show a low permeability terrain with less vegetation. These conditions are suitable for high drainage texture. The drainage texture value of the study area is 25.23.

The drainage density is an indicator of the linear scale of landform element in stream eroded topography and defines as the total length of stream of all orders/drainage area and maybe an expression of the closeness of spacing of channels (Horton, 1932). It is the computation of drainage texture. The high drainage density (Dd) assists relatively incompetent rock or impermeable substratum in the basin and vice-versa. The drainage density (Dd) of the area is high(Table 5.2) and it has a robust negative co-relation with Lg, C and Rn (Table 5.5). A more moderatepositive correlation was observed with the infiltration number (If). These correlations provide a well-figured observation of the sub-watershed that due to the increase in the infiltration number (If), the drainage density (Dd) also increases. Obviously, it leads to augmentation in channel cutting and erosion rates (low Lg and C value). The correlation coefficient of the Ruggedness number (Rn) is moderately low, signifying that the alluvial thickness above the base level of Mandakini River is not enough only for the formation of single-story badlands, unlike the Chambalregion.

Circularity ratio (Rc) is affected by geological structures, stream frequency, stream length,climate, land cover, slope as well as relief of the watershed. It is a key parameter which embracesstages of the river watershed. Circularity Ratio (Rc) also indicates the maturity level of the watershed. Low, medium and high values of Rc indicate the young, mature and old stage of the geomorphic cycle of the sub-watershed (Magesh, 2011).

Elongation ratio (Re) is defined as the ratio of the diameter of a circle of the same area as the sub-watershed to the maximum watershed length (Schumm, 1956). The value of the elongationratio varies from zero (exceedingly elongated) to one (circular in shape). The elongation ratiovalues closer to 1 resemble low relief areas whereas lower values of less than 0.8 usually show agreater relief and steep slope (Strahler, 1964).

Form Factor (Rf) is the representation of the watershed shape. Horton (1945) explains it asthe ratio of the watershed area and square of the total watershed length. The lesser the value of Rfmore elongated the watershed would be and lowers the peak flow for a greater interval of time andvice-versa (Nautiyal, 1994). The Rc value of the study area is 0.36 and Re and Rf are 0.7 and 0.39,respectively (Table 5.2). In the PCC statistical analysis, Rf is positively correlated with Re and Rc.Results show that the sub-watershed is in shape with a low peak flow for a longer duration of time.

This interpretation further creates an enigma with gullies present in the sub-watershed. Thenumber of lower-order streams and their occurrence in lower down the slope with headward erosion supports the reason that erosion is also possible in elongated watersheds. It is clearly seenthat in these systems at the fourth-order level, the correlation with the rigid parameters improves.This indicates that there are chances of accommodation of more primary parameters in those regions that are inter-watershed of the third-order watersheds. It again suggests that the work of badlands formation has either been counteracted by land management activities such as agriculture or the area is quite low/down and flat.

5.5 Conclusions

I. The morphometric analysis is an important method for understanding the badlands. Although, purely by observing data without any direct identification, it cannot be said the area is essentially a badlands as such yet it can certainly be ascertained that the area has higher development of erosional system and has been suffering excessive sediment loss. Once it is known that the area is an alluvial landscape then it can be said with certainty thatthe data set belongs to badlands conditions. Moreover, once the identification is made that the land belongs to badlands then the morphometric analysis can be used in deciphering controlling factors and evolutionary events which may include Neotectonism. The elongated watersheds might have multiple controlling factors such as structures, differential lithology in terms of resistance, groundwater table depletion and tectonic influence. The morphometric study and the correlations between different parameters within the space and time dictate an operative stage of *self-enhancing* process of badlands formation in the watershed.

II. The majority and cumulative length of the first-order stream is quite very high (50%). First-order streams and their headward erosion play a significant part in the formation of badlandformation. Badland's system can only operate with a high correlation of the total number of the streams (Nu) with length parameters of the streams and the watershed, the drainagetexture and the area. All these primary parameters should be strongly correlated with the stream number. This is indicative of the badlands process which goes on with stream bifurcation upwards.

III. With the depletion of the groundwater table, calcretes may precipitate in the soil horizons. Calcretes restricts the vertical movement of water and hence promotes horizontal flows. The runoff erodes a considerable amount of soil particles very easily because of its non- cohesive nature.

IV. Origination of gullies and their headward development mark the onset of an erosive system in the hydrogeomorphological setting, which naturally had wetland conditions. Neotectonism and later overgrazing history destroyed the wetlands and laid out the ways for the erosive agency. Hence this is a complex superimposition of positive feedback loopof the erosive system over the positive feedback loop of wetland conditions.

V. Continuous overgrazing has been well established to be one of the major causes of triggering gullying as soils lose their fertility and are depleted in various constituents whichin turn changes the soil texture etc.

VI. This all-impacts infiltration and run-off dynamics. Luxuriant grasslands with availability of surface water must have been favourite grazing grounds for large number of livestock over long periods. Tignath et al. (2005) have found badlands areas were related tosettlements of shephards and interestingly found such names of villages which indicate sheep herds or like. It is obvious that the barren badlands of today cannot sustain large number of herds as they must have been the places of abundant fodder. However, more researches on various badlands with historical perspective need to be carried out to establish that badlands were old wetland areas.

VII. Despite lack of large data of various such places to make a general statement of relation between wetland area and badland area, this area does have signatures of wetlands in the form of presence of calcretes. Calcites have been related to presence of wetlands conditionsas these have been related to fall in water levels therefore indicate much higher water levelsnearly close to ground surfaces and badlands which have shallow calcretes horizons can besaid to have been wetlands in past.