CHAPTER-6

6. Morphotectonic Signatures of the Neotectonic Control on the Badland Formation

6.1 Introduction

The landform development and evolution are the outcomes of the coupled process of endogenic and exogenic geological dynamics (Finnegan et al., 2008; Misra et al., 2020). Tectonic forces arecontinuously changing the face of the Earth. The geological process operates externally, causes erosion and reshaping the landforms (Meliho et al., 2020; Ullah et al., 2020). The term Neotectonics was coined by Obruchev (1948) after a recent tectonic event in the Neogene and theQuaternary Period. It is defined as the study of landforms produced by tectonic processes and morphotectonics is the application of geomorphic principles to the solution of tectonic problems (Keller and Pinter, 1996; Kothyari, 2014). In India, a significant contribution has been made by Kothyari and his team on the neotectonics and geomorphology of the Himalayan region and western India.

Land upliftment is a rather slow, gradual process. Morphotectonics has emerged as a handytool for the study of neo-tectonics. Morphotectonic indicators play a significant role in indicatingactive tectonic zones and have been widely used and appreciated (Pinter and Keller, 2002; Pancholiet al., 2017; Kandregula et al., 2019). Surface features like incised valley and geo-morphological undulations provide more persuasive evidence to the picture regarding the active tectonics (Agarwal et al., 2002; Taloor et al., 2020). Tectonic geomorphology has evolved as an effective tool to study landscape evolution and identify neotectonic activities.

The present chapter aims to develop an easy approach and set of assumptions that may be helpful in neotectonic studies. This chapter focuses on

I. Morphometric data generation in a GIS environment to study the Mandakini Riverwatershed and identification, if these have neotectonics significance.
II. Classifying the parameters which have been found to be neotectonically significant bypprevious workers.
III. On the basis of significant values of such morphometric parameters, morphotectonicmaps were generated and Morphotectonic events sequencing has been attempted.

The area is located over the Faizabad Ridge and also over the peripheral bulge of the Indianshield. Ahmed (1968 and 1973), Singh (1996) and Ghosh et al. (2018) suggested that neo-tectonicactivity implies a significant role in erosion activity in the peripheral region of the Indian shield. Remote sensing and GIS applications are useful tools in morphotectonic studies. Various thematic layers are prepared with the help of satellite data in a GIS environment. The detailed morphotectonic and topographical study of the area has provided an insight into the recent tectonic influence over the region and continuously evolving landforms.

6.2 Tectonic and Depositional History of the Area

The study area is situated over the Faizabad ridge, one of the subsurface ridges in the Indo-Gangetic plain. The Indo-Gangetic plain is a foreland basin formed due to lithospheric flexing in retaliation to an orogenic load. The sedimentation and deposition process in the basin is governedby the tectonic activity in the orogen (Fraser and De Celles, 1992). The Indo-Gangetic basin is a complex system, broadly divided into five sub-basins (The Indus basin, The Punjab basin, The Ganga basin, The Bengal basin and The Brahmaputra basin), two depressions (Sarda depression and Gandak depression) and three ridges (Delhi-Hardwar ridge, Faizabad ridge and Monghyr- Saharsa ridge) (Rao, 1973; Valdiya, 1976; Parkash and Kumar, 1991) as shown in Figure 6.1 after Valdiya, 1976.

The regional-scale exploration by the Oil and Natural Gas Commission (ONGC) and Central Ground Water Board (CGWB) in search of oil and groundwater brought up many pieces of information about the basement and its complex tectonic settings in the Ganga basin. The Gangabasin is bound by Monghyr-Saharsa Ridge in the east and Delhi-Hardwar Ridge in the west. The depositional platform of the Ganga basin is over north sloping metamorphosed Precambrian Bundelkhand Gneisses and Proterozoic and Phanerozoic sediments (Singh, 1996). The Bundelkhand massif is a batholithic body that underwent faulting in the Central Ganga basin resulting in the development of one horst and two depression/grabens. These depressions are known as East and West Uttar Pradesh shelf and the horst part bounded by normal faults is known as Faizabad ridge. Gradually these depressions have become the site for sediment deposition. Thethickness of sediments near the Himalayan foothill is almost 6 Km and it gradually decreases towards the south (Rao, 1973), where the Faizabad Ridge area receives very little sedimentation. Due to the continuous deposition, sagging may be surmised to be taking place in the Ganga basin.In the study area near Chitrakoot town, the thickness of sediments ranges from 200 to 300m (Gupta et al., 2003). Most of the southern tributaries (Ken, Betwa, Ranj-bagh, Mandakini) of the

Yamuna, flowing parallel in the horst or graben system, have an elongated shape of the basin.

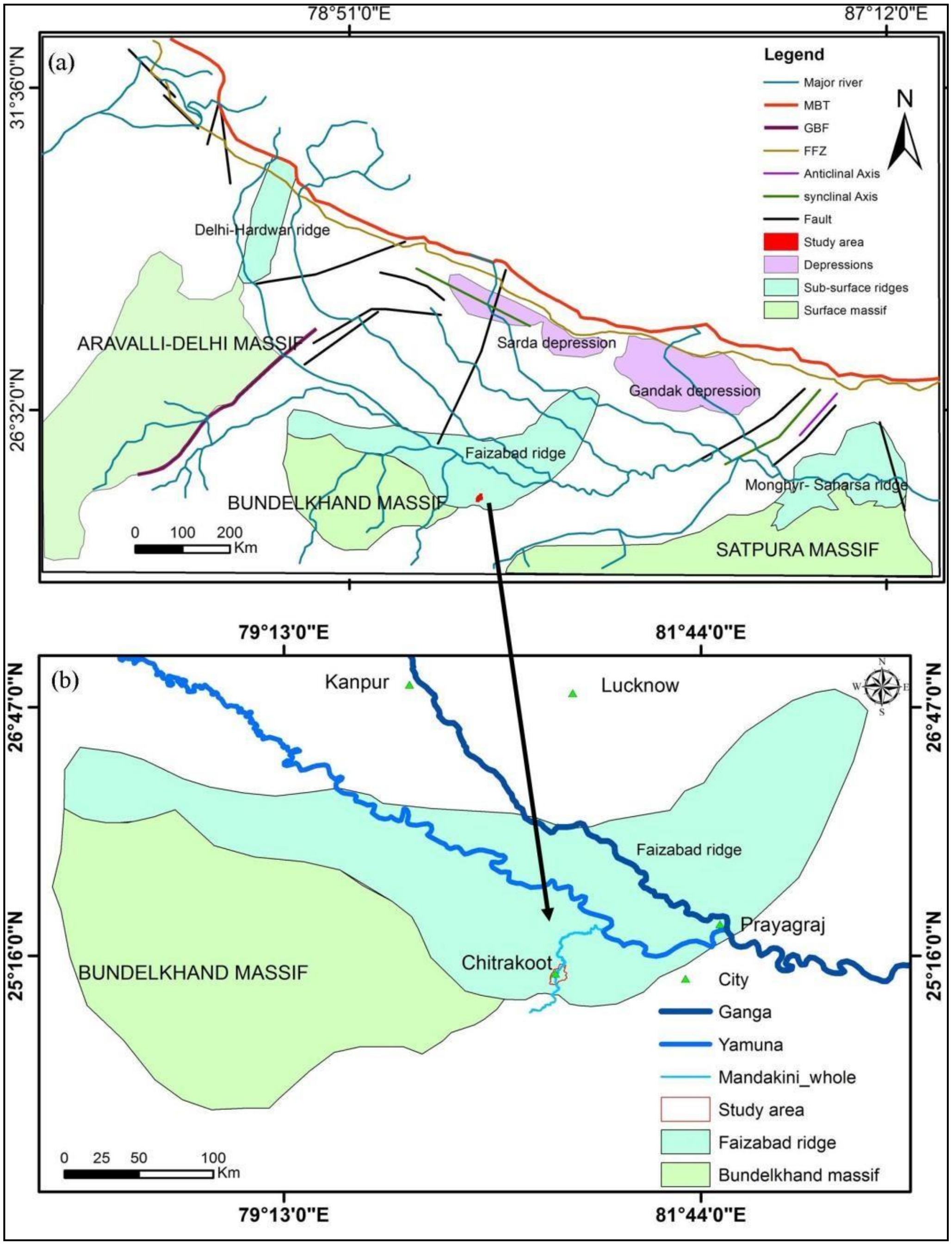

Figure 6. 1 (a) Sub-surface ridge, depression in the Gangetic basin and their surface massif (after: Valdiya, 1976); (b) Location of study area over the Faizabad ridge

Abbreviation- MBT Main Boundary Thrust, GBF Great Boundary Fault, FFZ Himalayan Frontal FaultZone

The southern part of the study area consists of Vindhyan rocks and Vindhyan rocks are known to be undisturbed and unmetamorphosed. But workers like Ram et al. (1996) and Srivastavaet al. (2009) have found evidence of tectonism in the Vindhyan synclines (Figure 6.2). Also, recentresearches assign structural nature to the Vindhyan basin and states that the sedimentation in the Vindhyan basin has started in the rift system and has the signature of multiple rift structures (Ramet al., 1996). Srivastava et al. (2009) has discussed several wrench faults in the Vindhyan basin. Except for some structural lineaments (Figure 6.3) (Source: Geological Survey of India; https://bhukosh.gsi.gov.in) , no such broad-scale fault has been reported in the study area while one large scale normal fault in the north and one large scale wrench fault in the south-east aresituated in the close proximity of about 15 and 40 km respectively.

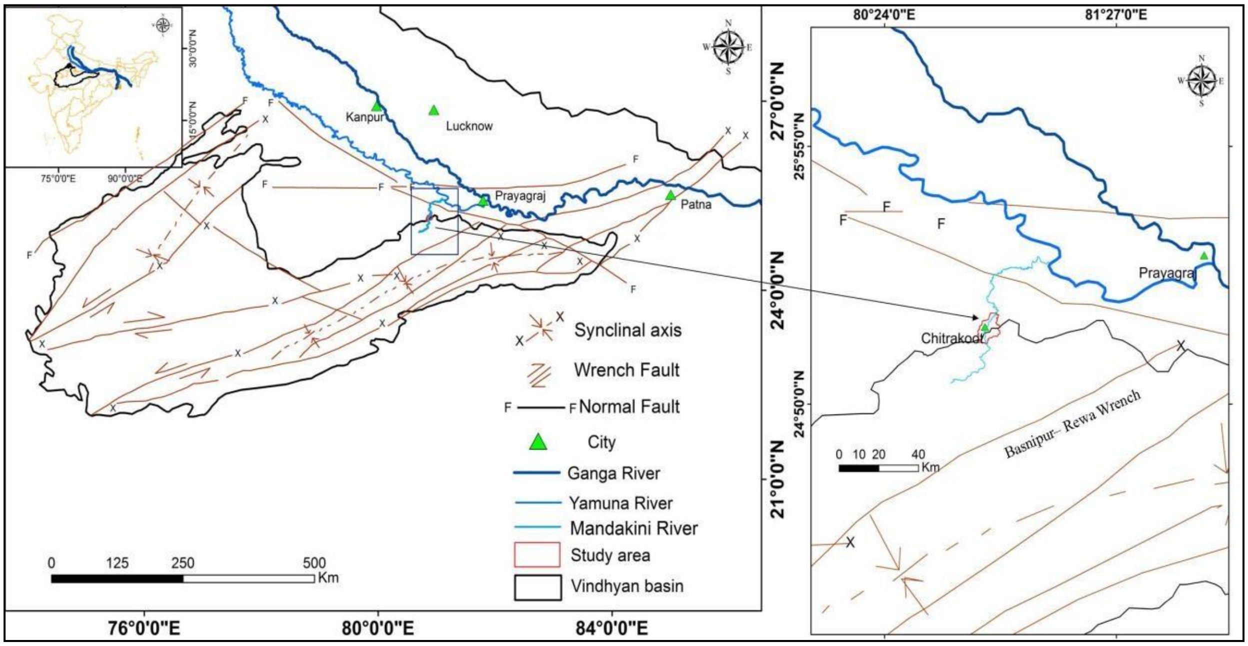

Figure 6. 2 Structural map of the Vindhyan Sedimentary basin (after Srivastava et al., 2009)adjoining to the study area

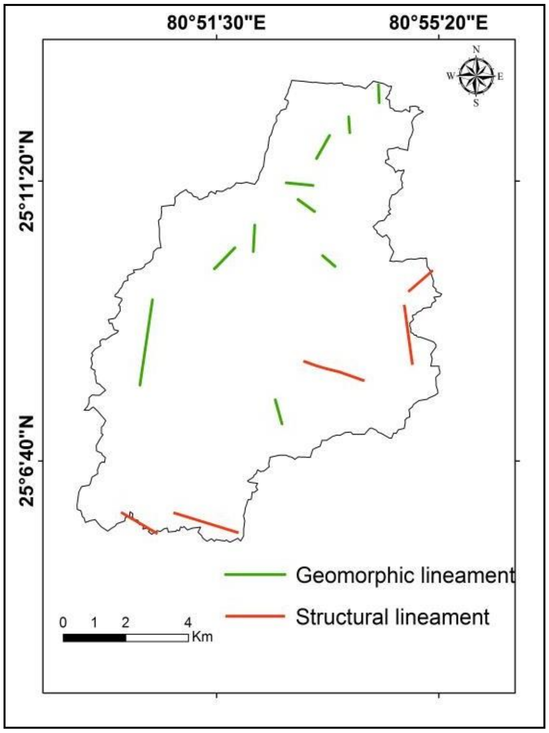

Figure 6. 3 Lineament map of the study area (Source: https://bhukosh.gsi.gov.in)

6.3 Methodology

The present work represents the influence of neo-tectonics over the study area. Neo-tectonic features may or may not appear on the surface. The morphotectonic analysis is a useful tool, whichbrings hidden pieces of information into the limelight. The present study is based on morphometricanalysis, field survey, 3D analysis and geological evidence.

For morphometric analysis, Shuttle Radar Topography Mission (SRTM) DEM was used. Morphometric parameters were derived using ArcGIS. The watershed area (A) is the areaembraced by the drainage basin boundaries and the length of the entire basin boundary is known as the basin perimeter (P). Streams are extracted and stream order has been carried out on the basis of Strahler's stream ordering system (1964) (Figure 5.2a). The streams that originate at the head are first order. Second-order stream forms when two first-orders meet and so on. The highest orderin this watershed is sixth. The area was subdivided into third-order sub-watersheds for the properevaluation of morphotectonics indicator parameters. Various parameters such as Elongation ratio (Re), Hypsometric integral (HI), Channel sinuosity(S), Basin shape index (Bs) and Asymmetry factor (AF) were determined, which have been found to be helpful in depicting the active tectonism in the study area (El Hamdouni et al., 2008).

6.4 Results

6.4.1 Tectonic Parameters/Factors

The present study has been performed in the third-order sub-watersheds of the Mandakini River watershed. The third order sub-watersheds as a unit for the current study has been preferred as thethird-order sub-watersheds achieve the representative organization on one hand while on the other, they are most susceptible to changes in the geological, hydrogeomorphological and morphotectonic conditions (Doornkamp and King, 1971).

The various morphotectonic parameters of the third-order sub-watersheds were determined (Table 6.1), summarized below:

6.4.1a Elongation Ratio (Re)

It ranges from zero to one. The value zero represents a more elongated form where one shows circular. Elongation ratio closer to unit value features relatively low relief areas, whereas lower values (< 0.8) more often designates a higher relief and steep slope (Strahler, 1964). Schumm (1956) has classified Re into four classes viz. circular (> 0.9), oval (0.9 - 0.8), less elongated (0.8-0.7) and elongated (< 0.7).

The average Re value of the Mandakini River watershed is 0.7 (Table 6.2), i.e., less elongated. In the third-order sub-watersheds of the Mandakini River, Re value varies over a broader range from 0.48 to 0.99 (Table 6.1). Among 55 third-order sub-watersheds, seven are under the circular category, nine belong to the class oval, eighteen are in less elongated class and twenty-one sub-watersheds belong to the elongated category

About 52% of the Mandakini watershed lies between elongated and less elongated categories (Figure 6.5a). Re values less than 0.5 depict tectonically active terrain; it shows moderately activetectonic if Re values vary from 0.5 - 0.8 (Kale and Shejwalkar, 2008). Lower values of this parameter indicate more elongation of the watershed and less erosion and vice-versa.

6.4.1b Hypsometric Integral (HI)

It is a relative proportion of an area at different altitudes in a given area (Strahler, 1952). HI is anindicative tool used to distinguish tectonically active areas over inactive ones and hence determinethe maturity stage of the watershed.

In the sub-watersheds of the Mandakini River, the average hypsometric integral (HI) value is 0.48with a concavo-convex curve, indicating a young to nearly mature topography, stretching from southern uplands to the northern plains, respectively (Figure 6.4) (Table 6.2). In third-order sub- watershed, hypsometric integral (HI) ranges from 0.40 to 0.57 (Table 6.1) (Figure 6.5b). (El Hamdouni et al., 2008) classified hypsometric integral (HI) index into three categories HI > 0.5, 0.5 - 0.4 and < 0.4. HI > 0.5 gives a convex curve, symbolized by deep incision and little erosion from active tectonics. HI = 0.5 - 0.4 is an intermediate value that demarcates the concave-convexcurve and indicates approximate equilibrium and an intermediate stage of incision and erosion from recent active tectonics. HI < 0.4 resembles a concave curve and is distinguished by low reliefand extreme erosion.

A high value > 0.5 may indicate a younger terrain, not affected by erosion, possibly due to active tectonics. There is also a possibility of incision into a recent landscape produced by deposition. The intermediate value of the hypsometric integral (HI) shows the near-equilibrium stage; erosion occurs due to recent tectonic activity and terrain initiation is moderate. A lower hypsometric integral (HI) value indicates low relief and a higher erosion rate. Maximum number of third-order sub-watersheds have high hypsometric integral (HI) value and hence they may have higher relief as well. It is also observed that not all third-order sub-watershedsare affected by erosion.

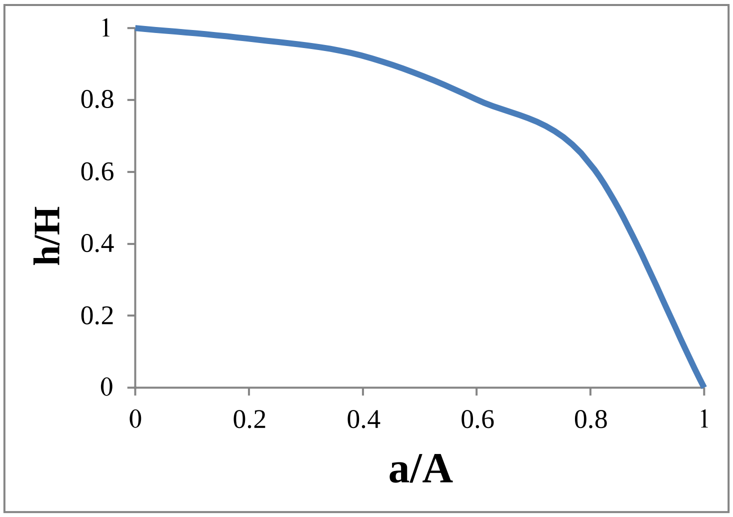

Figure 6. 4 Hypsometric curve of the Mandakini River in the study area

6.4.1c Channel Sinuosity(S)

This is the ratio of the channel length and river valley length. The role of tectonism is reflected inchannel sinuosity. Leopold (1964) has classified channel sinuosity into four classes, almost straight($S < 1.05$), windy ($1.05 \leq S < 1.25$), twisty ($1.25 \leq S < 1.51$) and meandering ($1.51 \geq S$).

The channel sinuosity of the Mandakini River (master stream) is 1.16 (Table 6.2). In third-order sub-watersheds, channel sinuosity has been calculated for the third-order streams only. Third-order sub-watersheds fall in all the classes of the classification, where fourteen belong to the almost straight class; thirty-three to windy, whereas seven are in twisty and one is a meandering class (Table 6.1) (Figure 6.5c).

6.4.1d Basin Asymmetry Factor (AF - index)

This is a vital tool to determine active tectonic tilt in the basin and the tilt direction (Zhang et al., 2019). This tool may apply to a relatively large area (Hare and Gardner, 1985).

Asymmetry factor (AF) is classified under three-class (El Hamdouni et al., 2008), Class 1($AF \geq 65$ or $AF < 35$) Class 2 ($35 \leq AF < 43$ or $57 \leq AF\ 65$) Class 3 ($43 \leq AF<57$). The asymmetricfactor value of the sub-watersheds of the Mandakini River is 55.24 (Table 6.2). In third-order sub-watersheds, fourteen sub-watersheds belong to class 1, twenty in class 2 and twenty-one falls underclass 3 (Table 6.1) (Figure 6.5d).

Asymmetry factor (AF) equal to 50 indicates no tilting, i.e., it is perpendicular to the masterstream. AF smaller and greater than 50 resembles the effects of active tectonics/ lithologic controlor differential erosion (El Hamdouni et al., 2008). The tectonically active basins are characterizedby the steep slope on the mountainside and relatively flat floors. The more precipitous sides are developed by movement of a fault line, such that the valley floor moves down relative to the surrounding margins, or, conversely, the margins move up relative to the floor. This movement results in watershed tilting and causes the river to migrate laterally and deviate from the watershedmidline. The active, moderate and low active tectonics classes are defined as classes 1, 2 and 3. The Mandakini River watersheds have an average asymmetric factor value of 55.24, indicating low active tectonics (Table 6.2). Mixed responses have been reported in the sub-watersheds.

6.4.1 e Basin Shape Index (Bs)

This is the horizontal projection of a basin; the elongation ratio may also describe it. Comparatively, younger basins are under active tectonic influence and tend to be elongated in shape, parallel to the mountain slope. As the effect of active tectonic decreases, elongated basins are gradually transformed into circular ones (Bull and McFadden, 1977). Since streams have a higher gradient in tectonically active areas and their basin widths are much narrower, followed bya down-cutting abrasive stream. Basin shape index (Bs) is the ratio of the basin's length to the basin's width at its widest point. Basin Shape index (Bs) has been grouped into three classes as Class 1 ($Bs \geq 4$), Class 2 ($3 \leq Bs \leq 4$) and Class 3 ($Bs \leq 3$) (El Hamdouni et al., 2008).

The Basin shape index value of the Mandakini River sub-watersheds is observed to be 1.6(Table 6.2), which shows that the Mandakini River watershed is influenced by low active tectonics. In third-order sub-watershed, fifty-two among fifty-five sub-watersheds belong to class 3, two belong to class 2 and one to class 1(Table 6.1) (Figure 6.5e).

Table 6. 1 Derived values of morphotectonic parameters of the third order sub-watershed

Sub watershed No.	**Re**	**HI**	**S**	**Bs**	**AF**
1	0.587	0.500	1.182	1.778	47.46
2	0.796	0.500	1.044	1.354	41.19
3	0.720	0.500	1.240	1.488	48.34
4	0.776	0.500	1.027	1.605	60.38
5	0.647	0.502	1.306	1.920	41.31
6	0.849	0.436	1.181	1.290	64.58
7	0.653	0.503	1.121	2.093	36.68
8	0.550	0.428	1.210	2.693	46.57
9	0.610	0.500	1.139	0.627	35.15
10	0.650	0.453	1.306	2.359	45.40
11	0.762	0.500	1.052	1.730	68.42
12	0.677	0.500	1.141	2.039	59.29
13	0.633	0.505	1.305	2.134	60.19
14	0.791	0.500	1.037	1.469	62.69
15	0.658	0.500	1.073	2.791	70.14
16	0.569	0.530	1.062	3.304	53.97
17	0.924	0.467	1.544	1.172	49.77
18	0.737	0.491	1.000	1.794	48.49
19	0.603	0.479	1.244	2.803	17.18
20	0.778	0.510	1.162	1.449	47.40
21	0.700	0.495	1.388	1.808	51.19
22	0.782	0.532	1.114	1.165	60.40
23	0.800	0.410	1.152	1.067	29.66
24	0.980	0.500	1.397	0.800	70.38
25	0.815	0.504	1.118	1.590	38.06

26	0.519	0.518	1.087	0.379	54.61
27	0.773	0.487	1.125	1.958	49.46
28	0.515	0.499	1.133	4.124	48.58
29	0.773	0.500	1.089	1.588	37.90
30	0.553	0.481	1.180	2.868	70.32
31	0.887	0.408	1.030	1.774	43.81
32	0.920	0.476	1.136	1.144	63.00
33	0.754	0.471	1.075	1.465	44.95
34	0.709	0.500	1.021	1.797	33.78
35	0.954	0.500	1.036	1.189	78.12
36	0.687	0.500	1.159	1.815	51.86
37	0.889	0.500	1.213	1.768	81.00
38	0.666	0.500	1.127	1.805	61.38
39	0.792	0.485	1.018	1.419	57.26
40	0.710	0.419	1.047	1.238	38.35
41	0.950	0.479	1.030	0.816	40.92
42	0.636	0.500	1.027	2.411	70.22
43	0.574	0.437	1.098	2.502	50.67
44	0.994	0.579	1.376	1.697	48.26
45	0.763	0.513	1.094	1.069	65.50
46	0.874	0.474	1.060	1.174	56.40
47	0.771	0.500	1.253	1.380	40.59
48	0.608	0.500	1.286	1.682	53.46
49	0.805	0.500	1.036	1.520	34.00
50	0.836	0.500	1.011	1.273	42.72
51	0.770	0.510	1.135	1.210	48.16
52	0.848	0.500	1.042	1.412	63.75
53	0.931	0.500	1.006	1.096	71.16
54	0.483	0.500	1.121	3.122	34.49
55	0.571	0.505	1.216	2.330	53.39

Table 6. 2 Summary of morphotectonic analysis of the study area

Parameter	Value	Description
Elongation Ratio (Re)	0.7	Moderate active tectonic
Hypsometric integral (HI)	0.48	Moderate active tectonic
Channel Sinuosity(S)	1.16	Moderately high active tectonic
Basin Asymmetry Factor (AF)	55.24	Low active tectonic
Basin Shape Index (Bs)	1.6	Moderate active tectonic

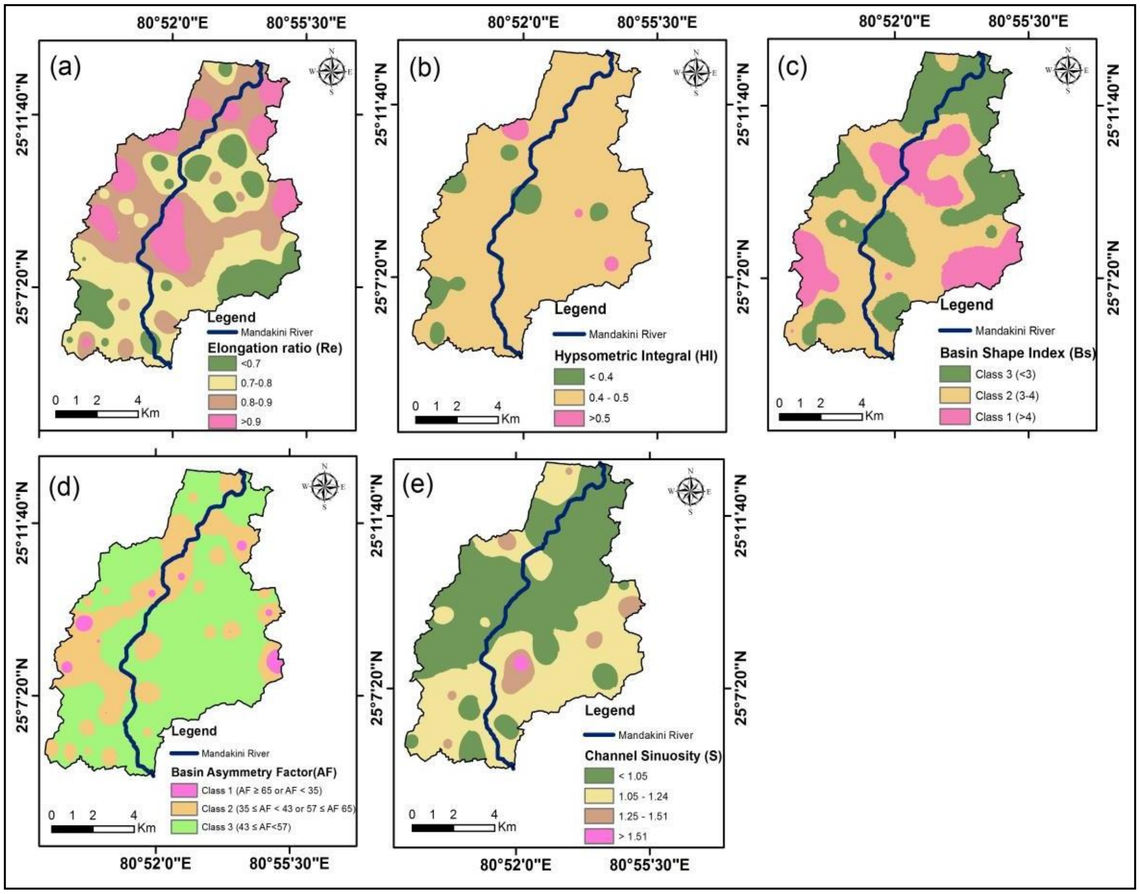

Figure 6. 5 Spatial map of (a) Elongation ratio (Re); (b) Hypsometric Integral (HI); (c) Basin Shapeindex (Bs); (d) Basin Asymmetry Factor (AF); (e) Channel Sinuosity (S) in the study area

6.4.2 Neo-tectonic Features in the Study Area

Badlands have been developed on unconsolidated sediments, namely of sand, silt and clay. Strongseasonality with extended dry periods with little or no vegetative cover and tectonic uplifts contribute significantly to the formation of badlands (Ramakrishnan and Vaidhyanadhan, 2010). The Mandakini River cut a deep incision into the valley. It indicates that the river has been receiving sufficient water flow through precipitation and groundwater recharge that it was able tomake a deep incision in the hard Vindhyan rocks all through the Holocene and late Pleistocene time. The climatic conditions do not seem to have vastly shifted in intensity and pattern in recent times of a few hundred years. Nevertheless, periods of wet and dry conditions are indicated withinthe alluvium cover. Multiple layers of calcretes have been noticed, which indicates a change in theclimatic conditions from wet to dry periods. The calcretes are much earlier to the setting up of badlands conditions. Tectonics influence over a terrain can be identified in the fluvial channel andlandforms. The study area is placed in marginal sites of the Peninsular Shield. The terrain is composed of Vindhyan rocks and peneplain and pediment complexes. The cliff's height goes up to 10 - 40m with a maximum slope of 20 degrees (Figure 6.6a, 6.6b, 6.7 and 6.8) and the river cutsacross recent alluvial. Ahmad (1968) attests that due to the peripheral bulge of the Peninsular Shield, discontinuous incision patterns may develop, which can be attributed to the differential rate of disturbances. This kind of incision can easily be recognized in the southern and central regions of the river course. The Mandakini River shows small cascading along its course throughChitrakoot townships. The course of the Mandakini River does not form meanders and the bends are asymmetric, irregular and non-harmonic in nature. There are no segments of buried channels or oxbow lakes related to meandering shifting. The bends are more of tectonic nature rather than of meandering process. This spreads across a considerable length of 300 - 1200 meters and a relief of 5 - 20m (Figure 6.9). These undulations are very prominent in the entire marginal plain and lookmore like drumlins of the periglacial regions (Singh et al., 1996; Agarwal et al., 2002; Sinha et al.,2002) (Figure 6.10).

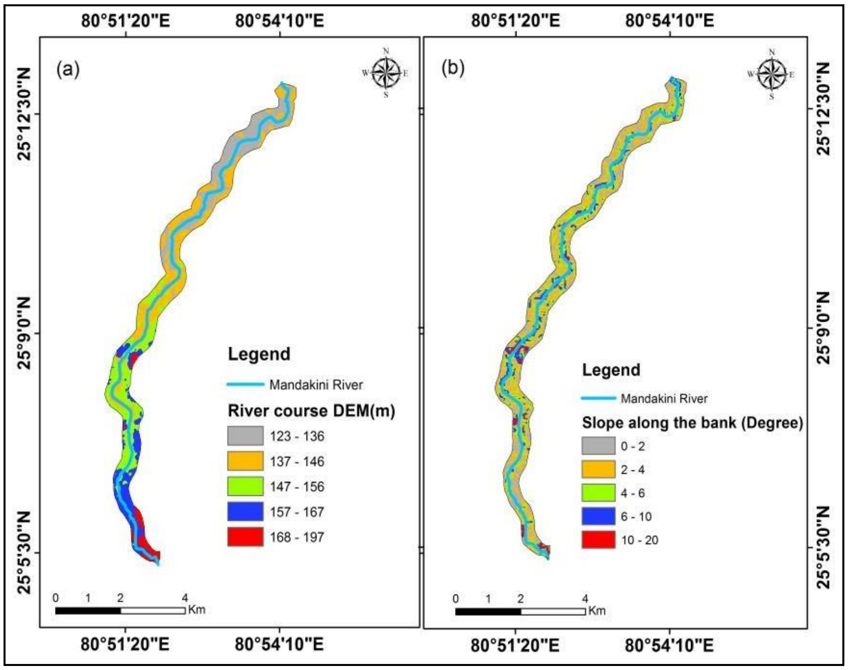

Figure 6. 6 (a) DEM (Digital elevation model) of the river course; (b) The slope along the river course (width of the river course varies from 300-600m)

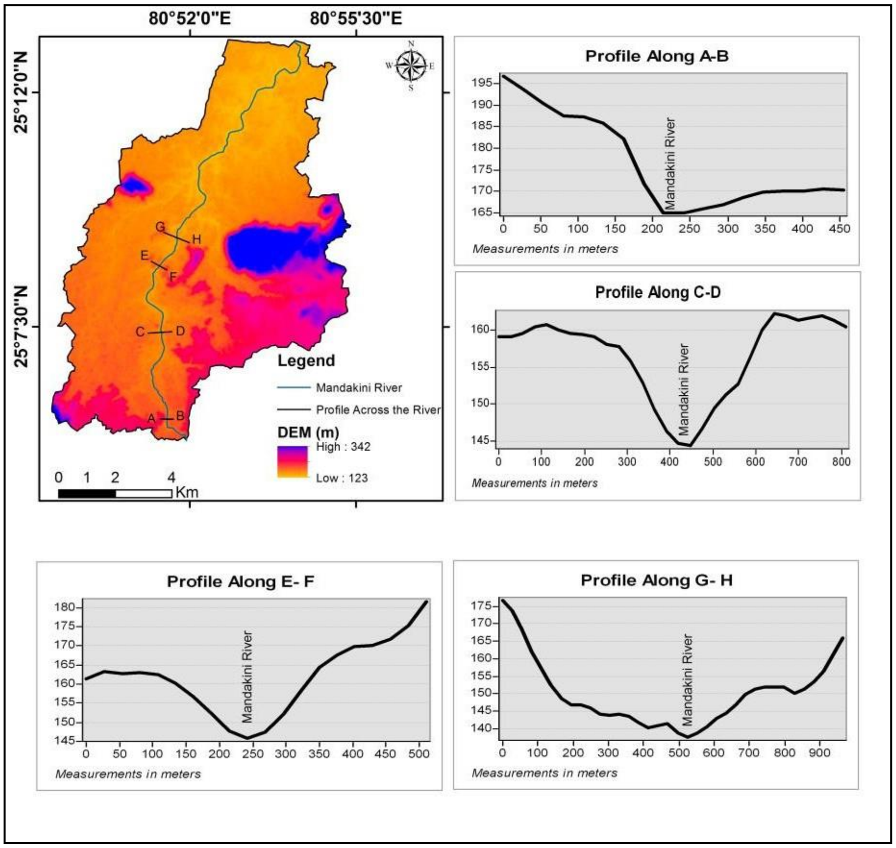

Figure 6. 7 Different River profiles along the Mandakini River (master stream) in the study area

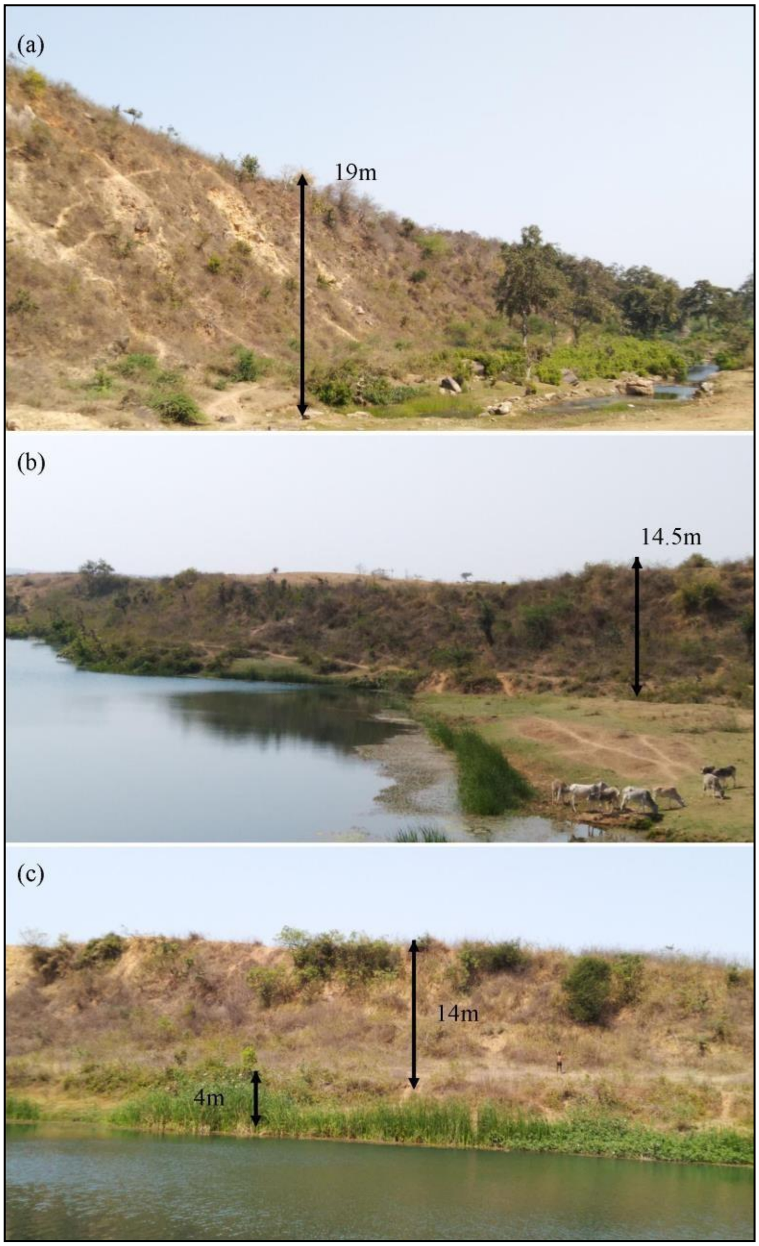

Figure 6. 8 Field photographs (a) (b) (c) showing high cliff in the study area

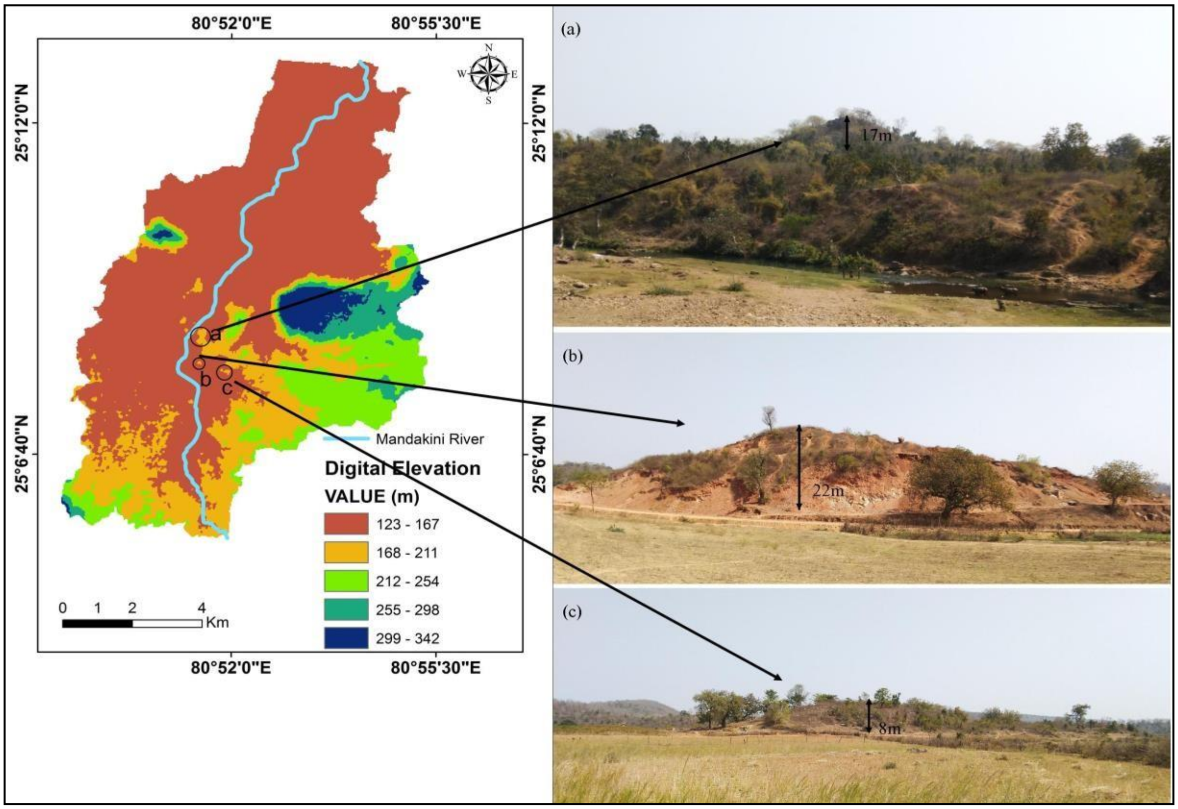

Figure 6. 9 Field photographs (a) (b) (c) showing undulation in topography (drumlin shape structure) in the study area

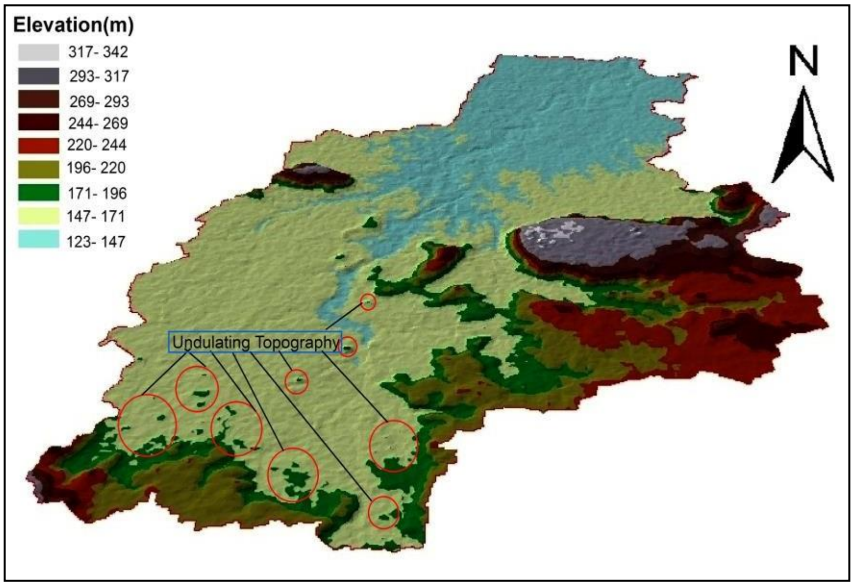

Figure 6. 10 3-D DEM model of the study area, manifesting undulating topography

6.4.3 Morphotectonic Events Sequencing

The principle of ergodicity can be applied by surrogating time for spatial facts of larger areas (Thorns 1988). On the basis of strong discord in the sub-watershed and relatively sudden variationsof the morphometric parameters' indicators of neotectonics, four assumptions have been formulated to classify the area with varying degrees of neotectonic events interfered with hasteningthe already continuing process.

Assumptions:

I. Tectonic impacts can be considered uniform for a small area with the same geological, hydrological and meteorological conditions.
II. Therefore, the spatial variations over a small area would be imprints of a sequence of eventsreflected in the basin parameters especially related to tectonics history in time.
III. The older event should be found as inclusions; hence the event which includes all older events is the currently active phase.
IV. Morphotectonic parameters of different tectonic phases show varied responses in terms ofreadjustment with the changed tectonic conditions. Hence their spatial distributions show unequal changes in the superimposition of different phases.

The morphotectonic parameters such as Hypsometric integral, Asymmetric factor, Basin shape index (El Hamdouni, 2008), Sinuosity index (Leopold, 1964), Elongation ratio (Schumm, 1956) have been found to be confidently correlated with high, moderate and low tectonic activities (Figure 6.11a, 6.11b, 6.11c, 6.11d, 6.11e). Their values help in classifying the intensity of the tectonic activity. Following the fourth assumption, an overlay analysis of the parameters would decidedly indicate the spatial distribution of the tectonic activities

(Figure 6.11f). Once the spatial distribution map is found by overlay analysis showing the commonality of the area of similar phases among the above given five morphotectonic parameters, it is possible to apply assumptionnumber three.

These periods of tectonic activities have been categorized as suggested by El Homdouni (2008), namely, High activity, Moderate activity and Low or no activity. Their superimposition may be in any order. The picture would be more complicated if the events of the same intensity are repeated over time. It will not be then easy to decipher and differentiate them only on the basisof morphotectonic parameters.

However, the task of deciphering unequal intensity events is comparatively simple on the basis of morphotectonic parameters. Then, the sequence may be any of the following if only unequal tectonic categories, namely High Tectonic Activity Phase (HTAP), Moderate Tectonic Activity Phase (MTAP) and Low Tectonic Activity Phase (LTAP) are present:

HTAP - MTAP -
LTAP- HTAP -
LTAP - MTAP-
MTAP - LTAP -
HTAP- MTAP -
HTAP- LTAP-
LTAP- MTAP -
HTAP- LTAP -
HTAP- MTAP-

Their sequence, duration and time distance from the present are important for the basin to retain and obliterate previous events' signatures. There may be more than three phases, also.

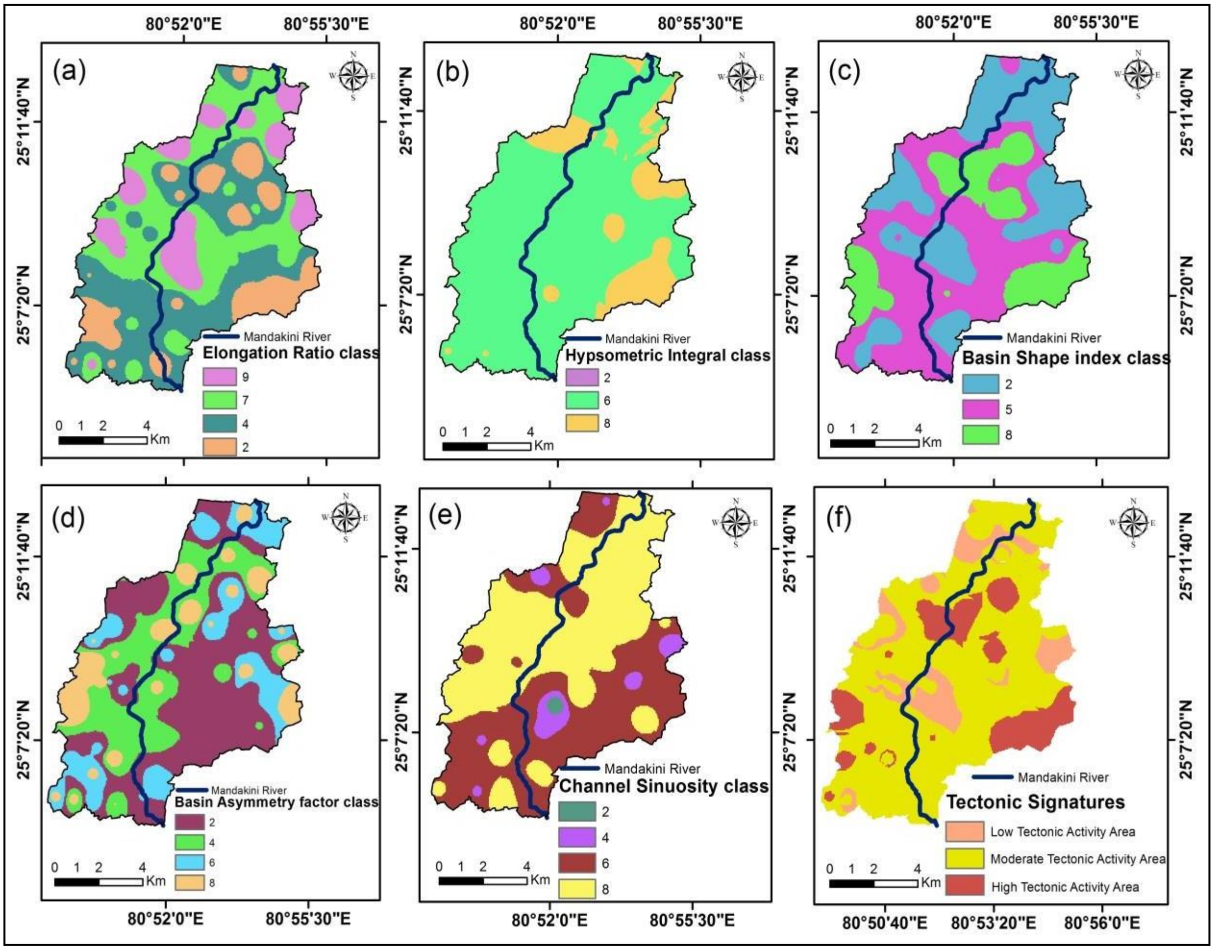

Figure 6. 11 Spatial map showing assigned classes for overlay analysis of (a) Elongation ratio (Re); (b) Hypsometric Integral (HI); (c) Basin Shape index (Bs); (d) Basin Asymmetry Factor (AF); (e)Channel Sinuosity (S) in the study area; (f) Spatial map of Tectonic signatures in the study area.

6.4.4 Interpretations

The maps generated in the study have been interpreted in light of the above-mentioned assumptions and understanding thereof.

The morphotectonic features such as Hypsometric Integral, Asymmetric factor, Channel Sinuosityindex, Elongation ratio and Basin shape index have been undergoing unequal modifications and adjustment to the nature of the periods that operated in the area. Therefore, an overlay analysis ofthese parameters shows intensity-wise common areas for all the parameters (Figure 6.11f).

In order to know the operative phase at present from the overlay analysis (Figure 6.11f),assumption three has been applied. It shows that the basin is under the control of the Moderate Tectonic Activity Phase (MTAP). In contrast, partly, there are inclusions of signatures of the HighTectonic Activity Phase (HTAP) and the Low Tectonic Activity Phase (LTAP). In terms of area, the MTAP has a clear influence over approximately 64 Km^2 (71.11%) of the total area, whereas HTAP and LTAP are reflected in 14 Km^2 (15.6%) and 12 Km^2 (13.3%). The current activity and surface erosion dynamics belong to Moderate Tectonic Activity Phase (MTAP). The smallinclusions of high and low tectonic activity are relicts of older phases.

The High Tectonic Activity Phase (HTAP) must be the oldest and the Low Tectonic Activity Phase (LTAP) followed after that; therefore, we have relicts of low or no tectonic activitypreserved. Otherwise, should the LTAP have preceded the HTAP, then the signature of the Low Tectonic Activity Phase must have got completely obliterated by now as HTAP would have imprinted completely on the then-existing LTAP. If any inclusion would have survived the HTAP,then the following MTAP that nearly obliterated even the HTAP to remain only 15% would havecompletely consumed the LTAP. Thus, in that case, the sequence would have been like LTAP- HTAP-MTAP. In such a case, the Low Tectonic Activity Phase area would not have been equal to that of the High Tectonic Activity Phase even after imprints of High Tectonic Activity Phase followed by Moderate Tectonic Activity Phase.

It firmly establishes that the Low Tectonic Activity Phase (LTAP) followed the High Tectonic Activity Phase (HTAP). Thus, the sequencing of Tectonic phases must be HTAP-LTAP-MTAP.

6.5 Discussions

The study area has a tectonic history, as it situated over the Faizabad ridge. The surface expressions like higher cliffs and undulating topography also depicts an influence of tectonics over the region.The regional structural map further shows that there is no such structural features present in the study area; but wrench faults are present in a close proximity of the area, which can influence thefluvial process of the watershed.

Since the study area is situated over a sedimentary terrain, it is hard to preserve tectonic remnants at the top of the surface. Further, the place is quite far from the active margin of the Indian plate. So, it is rare to have active structures (like fold faults etc,). These kind of conceal tectonics can be caught by morphotectonic analysis, as the river responses in the presence of neotectonisms.

The result shows that the less elongated (Re = 0.7) shape of the Mandakini River watershed,Hypsometric integral (HI= 0.48) and basin shape index (Bs= 1.6) and the windy channel are indicative of moderately active tectonism in the watershed. Although the watershed is more or lesssymmetrical in some parts, the basin asymmetry factor (AF) is 55.24, which again indicates thereis a partial impact of low active tectonics on the watershed under the study area. Sub-watersheds at the third order-level show significant variations of these morphotectonic indicator parameters observed through the sub-watersheds of the study area. In this regard, it is also of significant consideration that the spatial orientations of several sub-watershed show strong discords from thegeneral orientations of the rest of the sub-watersheds at the third-order level and as such, they occur as morphometric 'inliers' in the current scheme of the current drainage processes. Continuous, uninterrupted geomorphic processes cannot account for this discord and in the absence of any significant anthropogenic interference, these could only be correlated to aggravating impacts of neotectonics interventions. On the basis of significant values of the morphometric parameter indicative of neotectonism and spatial discord of the sub-watershed, a division of zones has been attempted here, showing a degree of neotectonic interference during thesustained erosive phase of badlands formations. The values are found to be ranging from High Tectonic to Low tectonic signatures of different tectonic activity phases. Although the tectonic influence in the watershed is moderate, yet soil erosion in the watershed is prominent. The width of the gullies may be further widened at few sites. This may be because most of the horizons in the watershed are alluvium, consisting of sand-silt.

6.6 Conclusions

I. Badlands are reported to develop on unconsolidated sediments, namely of sand, silt and clay. Strong seasonality with extended dry periods with little or no vegetative cover and tectonic uplifts contribute significantly to the formation of badlands. The Mandakini Rivercut a deep incision into the valley. It indicates that the river has been receiving sufficient water flow through precipitation and groundwater recharge that it was able to make a deepincision in the hard Vindhyan rocks all through the Holocene and late Pleistocene time. The climatic conditions do not seem to have vastly shifted in intensity and pattern in recenttimes of a few hundred years.

II. Periods of wet and dry conditions have been noted within the alluvium cover. Two layers of calcretes have been noticed, which indicates a change in the climatic conditions from wet to dry periods. The calcretes are much earlier to the setting up of badlands conditions.Tectonics influence over a terrain can be identified in the fluvial channel and landforms.

III. Deeply incised valley, higher cliffs, deep gullies and undulating topography all indicate anunstable subsurface. In the southern part of the watershed, the cliffs are steep and high andthe topography's undulation is visible. Gullies can also be noticed in every part of the watershed. These neotectonic signatures show the tectonic history of the area.

IV. The results show that the shape of the Mandakini River watershed is less elongated (Re = 0.7), which shows moderate active tectonics. Hypsometric integral (HI= 0.48) (young to nearly mature topography) and Basin Shape Index (Bs= 1.6) also signifies moderate active tectonics in the watershed. The windy channel of the watershed denotes that it is influencedby moderate active tectonics. The watershed is more or less symmetrical and the Basin Asymmetry Factor (AF = 55.24) hints that some parts of the watershed are under low activetectonics.

V. The overlay analysis of the morphotectonic parameters shows that all three categories of tectonic signatures, namely High Tectonic Activity Phase (HTAP), Moderate Tectonic Activity Phase (MTAP) and Low Tectonic Activity Phase (LTAP), are present.

VI. The MTAP is currently the dominant phase, whereas HTAP and LTAP are relicts of olderphases. The sequence of events is HTAP-LTAP-MTAP, as deciphered in the study.

VII. Although the tectonic influence in the watershed is moderate, yet soil erosion in the watershed is prominent. The width of the gullies may be further widened at few sites. Thismay be because most of the horizons in the watershed are alluvium, consisting of sand-silt. Thus, it can be comprehended that a joint act of neo-tectonics and geology plays over the region, emphasizing its extensive soil erosion activity.

VIII. Neotectonism is an external agent that influences the base-level rise and provides a platform for erosion. The gully clusters, those are located in the high and moderate active tectonic regions, should prioritize more while making the management practices.