CHAPTER 6

DEVELOPMENT OF TWIN SCARPS-KAS HILL SECTOR

Different factors have contributed to the development of landscape over time. Among these, the contribution of rivers is believed to be the most important one, and therefore it provides vital information on the past and present activities like tectonic regime, climatic influences, fluvial processes and physical properties of the basement rock (Schumm et al., 1987; Ohmori, 1993; Burbank and Anderson 2001; Keller and Pinter 2002; Peters and van Balen 2007; Štěpančíková et al., 2008; Gloaguen et al., 2008; Kirby and Whipple 2012). Therefore, in the present study an attempt was made to examine the river geomorphic indices and longitudinal profiles with an aim to understand the role of geomorphic processes and tectonic activity in modifying the terrain of the study area to the present shape. In the recent years, a significant number of studies have been reported on escarpment deriving rivers to gather knowledge on the fluvial erosional pattern and to determine the mode of evolution and degradation of large escarpments (Kale and Shejwalkar, 2007; Harbor and Gunnell, 2007). The main objective of the present chapter is to evaluate the form and characteristics of the rivers of eastern KMF for better understanding the major controlling factor of the landscape and the evolution of Kas Hill Scarp (KHS) along KMF over time. The study also examines the DEM-derived morphometric parameters to discuss the mode of long-term geomorphic evolution of the segments of eastern KMF.

The Kas Hill sector covers major part of the eastern half of the KMF located between the villages of Nirona and Devisar in the Kachchh district. The KMF outcrops in the field as sharp lithological contact between Mesozoic and Tertiary rocks, steeply north dipping Mesozoic rocks, highly sheared rocks or in the form of scarps. The KMF zone in this reach was classified into five segments- Segment I, Segment II, Segment III, Segment IV and Segment V from west to east based on their morphotectonic characteristics and geological setting (Maurya et al., 2017) (Fig. 6.1). Each individual segment is laterally distinguished from one another by NE-SW or NW-SE striking Transverse Faults (TF). Each segment consists of one or more domal units i.e., Jhurio dome in segment I, Habo dome in

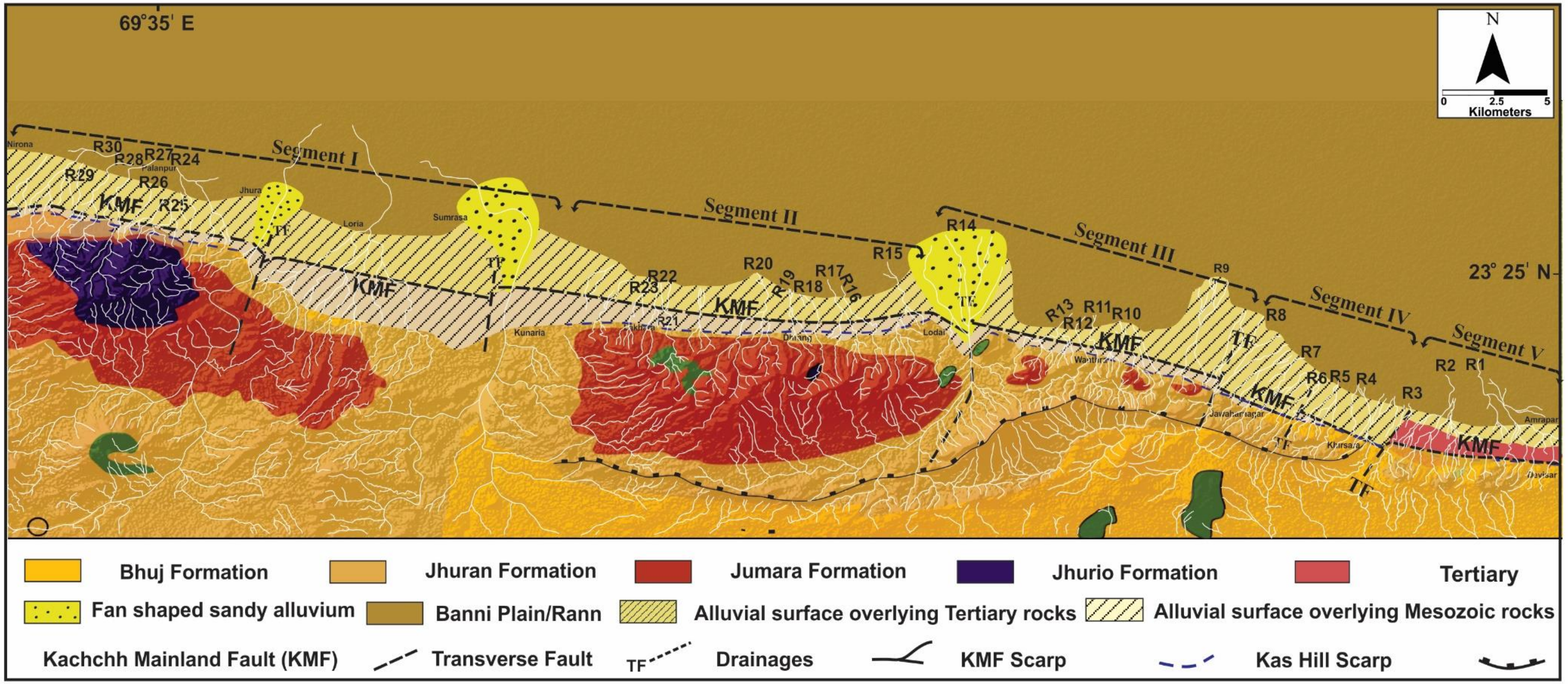

Figure 6.1 Geological map of the study area draped over the Digital Elevation Model (source: https://earthexplorer.usgs.gov and Biswas and Khattri, 2002). Major contrast in the lithologies and physiography of segments in the eastern KMF are highlighted in the map. Note that the KMF is passing between the rugged topography of NHR and flat Banni plain to the north. The narrow belt of Quaternary sediments between the KMFS and the Banni plain is also demarcated. The KMF is concealed a under thick pile of colluvio-fluvial and alluvial sediments in the eastern Kachchh. The location of the KMF was represented in the map with available Ground Penetrating Radar (GPR) data (source: Maurya et al., 2017) and field studies. Also seen are the north and south-flowing drainage systems in the footwall block of KMF. Numbers R1-R30 indicate the rivers studied in the present work. Note that the oldest Mesozoic lithology, the Jhurio Formation exposed at the center of Jhurio dome and Habo dome.

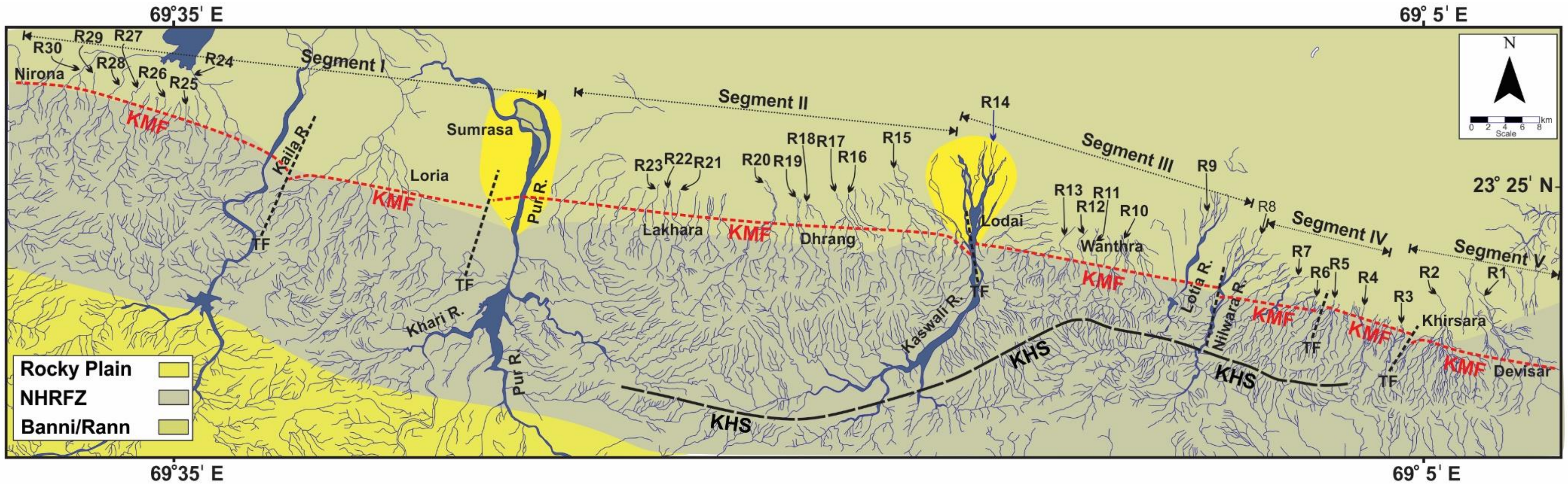

Figure 6.2 Drainage map of the study area. The rivers investigated in the present study is demarcated in the map. Note that the KHS becomes a secondary drainage divide in the segment III of the eastern KMF. Here the scarp is characterised by numerous north flowing rivers originating from the scarp face. The major geomorphic division of region is highlighted in the map.

segment II, Kas hill dome, Lotia Dam dome in segment III and Jhuran anticline and Khirsara dome in segment IV and Devisar dome in the segment V from west to east.

Here, the KHS forms a significant landform in the segment III. The Northern Hill range forms the principal watershed for the rivers of the study area. Due to the asymmetrical morphology of domes and anticlines, the north flowing rivers generally follow a parallel to sub parallel drainage pattern. At the same time, those rivers originating from the gently dipping backslope generally shows a sub-parallel to dendritic drainage pattern (Fig. 6.2). Radial to annular drainage patterns were common in the area nearby domes. The north flowing rivers of the study area show an anti-dip directional flow, while those on the southern side (back slope) follows the general slope of the beds. In some instances, rivers originating from the back slope takes a sharp turn along the base of outer cuesta ridges and flow northward. The Nilwara (River 8) and Lotia (River 9) rivers in the study area are examples of this category, where they originate from the backslope and flow northward dissecting the KHS and KMFS (Fig. 6.2). In the studied region, it was observed that majority of the north flowing rivers dissect the KMFS, thereby making it more discontinuous in appearance in the region. At the same time, the KHS was dissected only by very few rivers that includes the Lotia and Nilwara. Moreover, in segments III and IV majority of the north flowing rivers originate from the scarp face of the KHS. The KHS forms a secondary drainage divide in the region (Fig. 6.2).

The rivers draining through the study area can be classified in to lowland and coastal plain rivers based on the source elevation (Milliman and Syvitski, 1992). The lowland rivers are those with source elevation higher than 100m. Majority of the north flowing rivers that originates from the Jhurio dome, Habo dome and Kas Hill anticline can be included in this category. While the rivers that originates from the KMFS have source elevation less than 100m and therefore can be included in the category of coastal plain rivers. With the exception of a few large rivers, the rivers in the study area were generally short and with an average length of 5-6 km and average drainage area of less than 5 km^2. The domal units in the segments are separated from one another by saddle zones. The shape and size of these saddle zones also vary across the segments in the eastern Kachchh. The Jhurio and Habo dome in the western part of study area have wider saddles compared to saddle zone between the domes of the Kas Hill anticline in the eastern side. The size of the inter-domal saddles also favoured the development and nourishment of rivers in the Northern Hill range (Biswas, 1993). The larger rivers like Pur, Khari and Khaila flows through the saddle between Jhurio and Habo dome. These rivers originate from the Katrol Hill Ranges (KHR) south to the NHR. While, the larger rivers originating from the NHR includes the Kaswali River flowing through the saddle region between Habo and Kas hill dome, Lotia River flowing through the saddle between Lotia Dam dome and Jhuran anticline and Nilwara River flows between Lotia dome and Jhuran anticline (Fig. 6.2). The larger rivers like the Kaswali, Lotia and Nilwara have a drainage area of about 80 km^2, 30 km^2 and 20 km^2 and length of about 20km, 11km and 8km respectively. The Kachchh basin falls in the extreme arid climatic belt of western India with an average rainfall of less than 30cm per annum. The rivers of the region are ephemeral and remains dry throughout the summer seasons. Even though, the rivers considered for the present study remain dry during the summer season, they are characterised by well-developed fluvial landforms like deeply incised valleys, strath terraces, gorges and fan shaped alluvial deposits. Comparable size differences in the fan shaped alluvial deposits were observed for the rivers draining the eastern KMF. Among the north flowing rivers described in the present study, Kaswali River has the largest fan shaped alluvial deposition followed by the Lotia River and the Nilwara River.

LONGITUDINAL RIVER PROFILE ANALYSIS

Rivers draining through the eastern segments of KMF display variable gradients, knickpoints and convex up reaches along its course. The dimensionless curves plotted for the rivers show that the maximum concavity does not exceed 20% of the normalized distance for rivers that drains the I, II and III segments. The loss of elevation is rapid, within 20% of the total distance 70 to 80% of the elevation is lost. While the other two segments (VI and V) show maximum concavity between 35 to 50% of the normalized distance (Fig. 6.3). The highest concavity in the long profiles is observed for those rivers that originates from the center of the domal units. Also, there is a general decrease in the channel concavity or L-shaped nature of the profile from segment I to segment V. All rivers draining through the study area show strong upwarping from the ideal gradient profile in a Hack’s plot (semi-logarithmic plot). The Kaswali River (River 14) shows the highest deviation, in contrast to a river flowing the domal saddle. River draining through a saddle zone is expected to have graded profile in ideal conditions. Moreover, interdomal saddle are the region where the uplift is expected to be low in a domal structure. The convexity in the Hack’s profile signifies that disturbances produced by the external forcing on the river channels are not yet lowered to produce an equilibrium (steady) state (Fig. 6.4). This suggest that the rivers are undergoing active denudational process or fluvial erosion to cope with the externalities

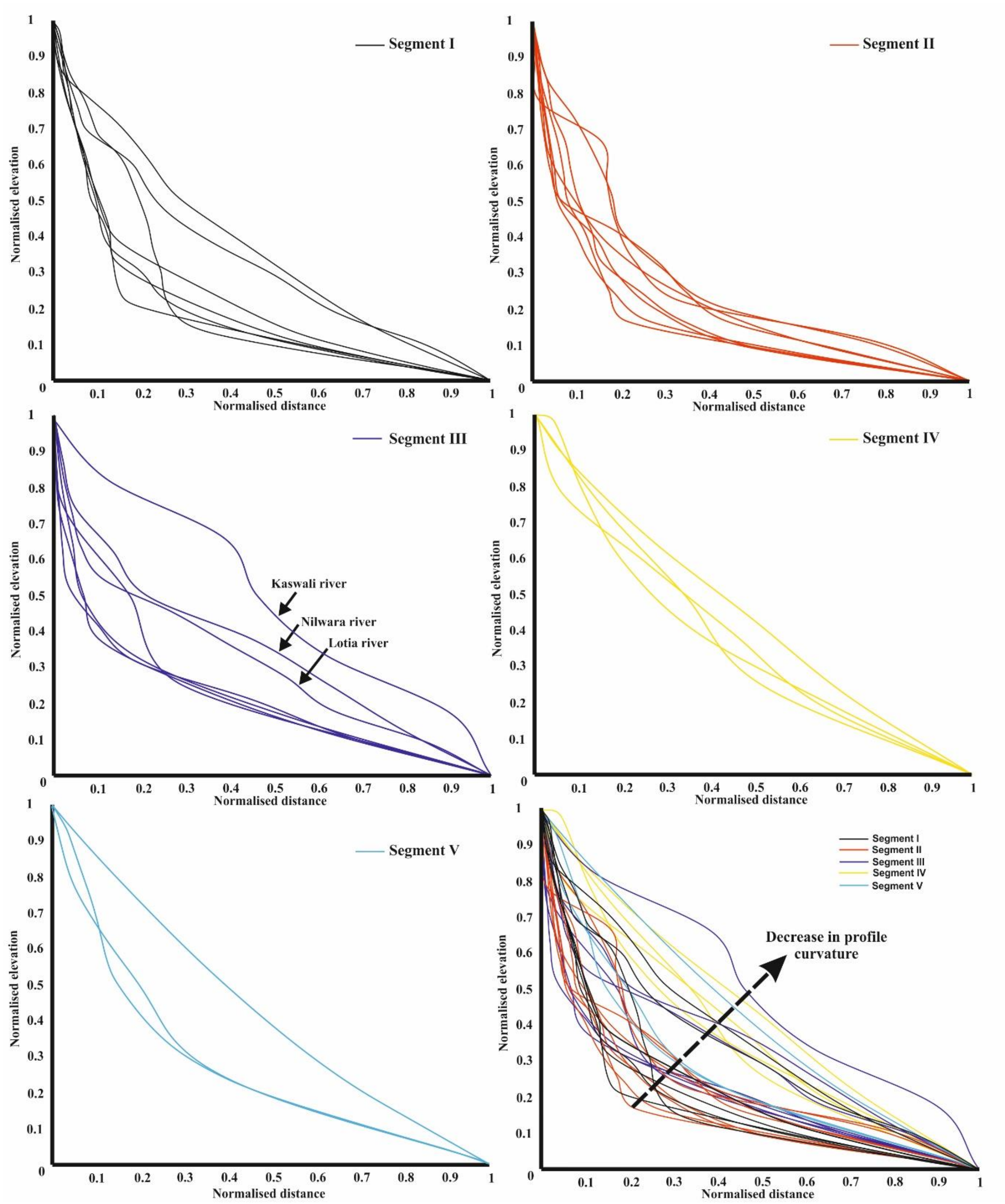

Figure 6.3 Normalized stream profiles or dimensionless curves (ratio of elevation to ratio of distance) of the major river in the study area. Note the gradually decreasing 'L' shaped nature of the long profiles towards the east. The 'L' shaped nature of the curves indicates deepening in the upper to middle portion of rivers. The rivers draining the segment I, II and III show the highest level of deepening.

(tectonics in the present case). The markedly low deviation of rivers of segment IV and V suggests low-rate tectonic disturbances or deformation in the segments. This also points to the fact that rivers experiencing comparatively lesser denudational activity or tectonic uplift in comparison to those in the segment I, II and III. Stream length gradient index (SL index) calculated for the rivers show variation throughout their length from source to mouth. However, notable change in SL values is in general confined to the upstream and the downstream of the rivers draining the study area.

Characteristics of rivers originating from Kas Hill Scarp face

The long profile studies on the scarp derived rivers are essential for determining the past and present geomorphic processes operating in the basin. Mainly rivers draining through the segment III and IV originates from the scarp face of the KHS. The majority of the rivers have a concave-up profile. The Kaswali River (River 14), Nihwara River and Lotia River behaves anomalously in comparison to the other rivers (Fig. 6.3). The rivers on the eastern side, that is those draining through the segment IV show less concavity in the profile compared to those in the segment III. The rivers in the segment III display a L-shaped profile similar to those in segment I and II. The Hack's profile of the rivers is generally convex (Fig. 6.4). The convex Hack's profile suggest that the rivers are having steep gradient and are under tectonic influences. The convex up nature of the Hack's profile also indicates that the rivers are actively undergoing fluvial erosion to cope up with the tectonic disturbance. The SL index computed for the rivers also indicates an a peak or high in the KMF zone. All these parameters of the long profile unequivocally point to the fact that the rivers in the vicinity of KHS are actively influenced by tectonic disturbances. However, there is a significant difference in the river response to the tectonic disturbances indicated by change in concavity or L-shaped nature of the profile. The more prominent concave-up or L shaped nature of the profile of the rivers in segment III is an indication that these rivers had undergone longer period of fluvial erosion and downcutting into the landscape than the rivers on the segment IV.

Characteristics of rivers dissecting the KHS

The KHS is dissected by two north flowing streams which originates from the backslope of the NHR, the Lotia and Nihwara streams. The long profile characteristics of the rivers are mentioned in the below sections.

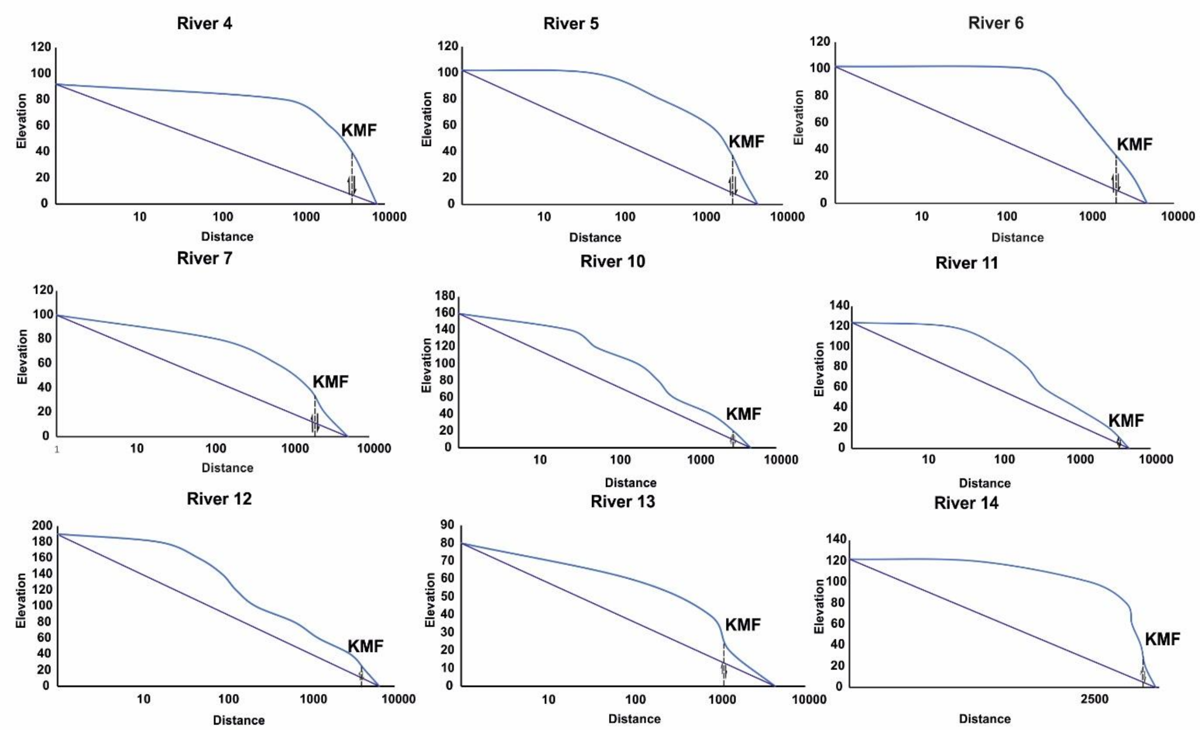

Figure 6.4 Hack profile/semi-logarithmic profiles showing the zones of major break in slope and deviation from the graded profile. Note that the rivers show a major upwarping above the equilibrium line.

Nihwara River

Longitudinal profile of the stream displays only marginal variation in the gradient associated uplift or tectonic disturbances along the KMF. A close examination of the longitudinal profiles of the Nihwara River and its tributaries was done to understand the channel characteristics of the region. The river originating from the backslope of NHR has a source elevation of 190 m. The river flows north dissecting the NHRFZ and finally disappears into the Banni plain. The Nihwara River, from its origin to the lowest flow point, shows varying profile characteristics like concavity, convexity, and stepped profile segments (Fig. 6.5 a and b), indicating transient stage of the river in response to variations in lithology or tectonic processes. Considering the general form of the profile it can be assigned a concave-convex shape. Two major zone of knickzone (numerous minor knickpoints) was identified in the river channel. The first zone of knickpoint was identified in the upstream side, where it forms a series of knickpoints in the Bhuj Formation. The second zone of knickpoints was close to the KMF zone. Presence of such multiple knickpoints in the vicinity of KMF zone clearly suggests the rejuvenation of KMF during the recent past. The SL index calculated for the same stream segments used to generate longitudinal profiles. After generating SL indices, a comparative plot was drawn with the longitudinal profile of the corresponding stream. There are three major peaks or change in the SL index curve identified in the Nihwara River,

1) Upstream of the river
2) Lithological contact between Bhuj and Jhuran Formations.
3) KMF zone.

The variation in SL index confirms that the river is presently in a transient state. An in-depth study that incorporates the field verified lithology data suggests that the lithology has also played a significant role apart from the tectonic influence in the present transient nature of the river.

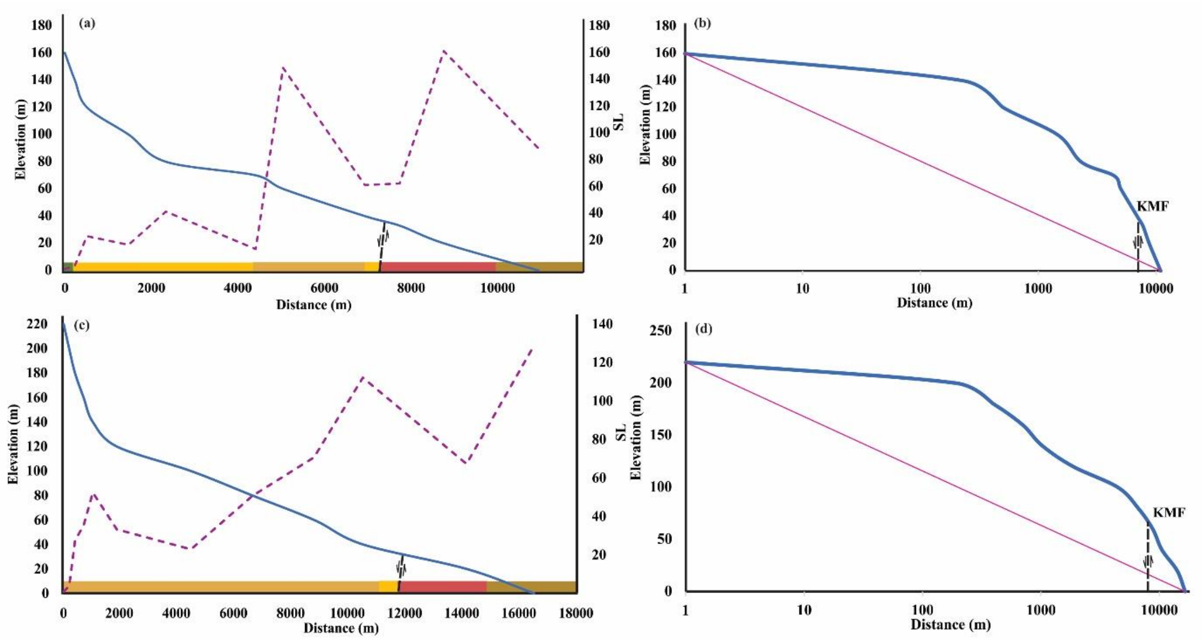

Figure 6.5 (a) Longitudinal profile of Nihwara River with SL index. Note that the rivers show significant variation at the zone of KMF and at the lithological contact between Bhuj and Jhuran Formation. (b) Hack profiles/semi-logarithmic profiles of Nihwara River. (c) Longitudinal profile of Lotia River. Note that significant change in the SL index at zone of KMF and upstream side. (d) Hack profile/semi-logarithmic profiles of Lotia River. Note that both the rivers show a major upwarping above the equilibrium line.

Lotia River

Lotia River flows northerly dissecting the KHS similar to the Nihwara River. The long profile analysis of the Lotia River shows prominent breaks and convexities along its course (Fig. 6.5 c, d). These breaks are indicative of rejuvenations forming knickpoint which is strong indication of influence of tectonic activity in the landscape evolution. Moreover, the convex-up segments in the profile are typical of disequilibrium stage or transient stage of the landscape, which is characteristic of tectonically controlled terrains. Variation in channel gradient, presence of numerous knickpoints and convex Hack's profile indicate that the rate of tectonic uplift exceeds the rate of incision as a result of continuous tectonic adjustment along KMF. Tectonic uplift overrides river erosion, and therefore the Lotia River could not develop an equilibrium profile, similar condition of the river could be seen elsewhere (Ambili and Narayana, 2014). In this study, an attempt has been made to understand whether the knickpoints in the Lotia River basin is controlled by lithology or by base level changes associated with active tectonism. For a better understanding SL index was calculated for same stream segments used to generate longitudinal profiles (Fig. 6.5 c). After generating SL indices, a comparative plot was drawn with the longitudinal profile of the corresponding stream. Knickpoints/knickzones were marked and compared with the underlying lithology to have a better understanding of the break in physiographic slope in the profile. The plot shows two major peaks or zone of variation in the SL index plot.

1. Contact on between Bhuj and Jhuran Formation.
2. KMF zone

The variation in the SL correspond to the lithologic variation as well as tectonism (faulting). Therefore, it can be confirmed that both tectonism and lithology have a coupled effect on the drainage profile and behaviour. Field investigation on the river confirms that knickpoints associated with river is controlled by lithology as well as faulting activity. The river forms multiple set of knickpoints and deeply incised gorge like landform in the Bhuj Formation exposed at the zone of KMF. Above evidences suggest that continuous adjustment of the river in the Quaternary period has sculpted the present-day transient river profile.

MORPHOMETRIC ANALYSIS

Segment I

The north flowing rivers originating from the Jhura dome of segment 1 are characterised by 3rd or 4th order channels. The segment also has few larger rivers like Pur, Kaila and Khari that are flowing through the eastern fringe of the Jhura dome. These rivers are generally characterised by higher drainage area and have 5th and 6th order channels. Large number of streams in a drainage basin is a general characteristic of an erosional topography (Zaidi, 2011). Moreover, the occurrence of large number of first order streams in contrast to the arid climatic condition prevailing in the region perhaps is a manifestation of the tectonic activity to which region is subjected. The drainage density calculated for the segment ranges between 3.3 and 3.5 (Table 6.1). According to Strahler (1957) and Smith

(1950) the region possesses a course drainage density. The stream frequency value ranges between 4.4 and 5.9. The relatively higher stream frequency is an indication of the ongoing tectonic activity in the segment (Horton, 1932). The bifurcation values calculated for the rivers is in the range of 3.25 and 5.4, with mean bifurcation ratio of 2.64. The values obtained for the studied segment suggest a prominent role of structural control in distorting the drainage pattern of the region (Strahler, 1964). The structural control on the river networks in turn attributes to the tectonic active nature of the segment. The river basins in this segment are elongated with values ranging between 0.6 and 0.38. The hypsometric curves obtained are concave up with integral values ranging between 0.25 and 0.48. The lower elongation ratio and lower hypsometric integral suggest that the rivers are actively undergoing headward erosion in a longitudinal fashion.

Segment II

The rivers flowing through this segment are mainly 3rd and 4th order channels similar to the rivers in the segment I. The segment is characterised by a coarse drainage density, with values ranging between 3.5 and 4.7 (Table 6.1). The drainage density values are slightly higher compared to the Segment I. The stream frequency calculated for the segment has values that ranges between 4.49 and 6.68. The stream frequency also shows slightly higher values in comparison to the segment I. The bifurcation ratio is in the range between 2.23 and 4.58 suggesting a prominent structural control in the river basins. The basins are generally elongated with values ranging between 0.4 and 0.58. The hypsometric curve of these rivers is concave up with integral values arranging between 0.17 and 0.40. The lower hypsometric integral and elongation ratio suggest headward erosion of the channel similar to that in the previous segment. The morphometric analysis along the segment suggest that the river basins are tectonically controlled and are actively undergoing fluvial erosion.

Segment III

The rivers that drain the segment are generally 3rd, 4th or 5th order ones. The Kaswali is the largest river draining through the segment followed by the Nihwara (River 8) and Lotia (River 9). Similar to the previous segments, the segment III is having a coarse drainage density with values ranging between 3.34 and 5.58 (Table 6.1). Stream frequency ranges between 4.22 and 10.11. The relatively higher stream frequency than the previous segments is suggestive of a higher or more recent tectonics activity in the segment. The higher stream frequency are identified for those streams originating from the KHS. The bifurcation ratio calculated for the rivers are ranging from 2.35 to 5.37, indicating the structural control on the drainage networks. The river basins are elongated with values ranging between 0.46 and 0.64. The Kaswali River and an unnamed river originating the KHS have relatively moderate elongation ratio. The hypsometric curves of the river basins are generally concave with slight difference in the curvature in comparison with the previous segments. The hypsometric integral values are in a range between 0.28 and 0.38 suggesting highly eroded river basins. Generally, the low hypsometric integral and elongation ratio are characteristics of headward advancement of river networks, however a few rivers that originates from the KHS display a moderate elongation. The moderate elongation of rivers suggest that the rivers are increasing the drainage area laterally in the region. However, the difference are not that significant.

Segment IV

The segment is characterised by rivers of 3rd and 4th order. Segment has a coarse drainage density with values ranging between 3.97 and 5.6 (Table 6.1). The stream frequency of the rivers ranges between 4.76 and 7.02. The bifurcation ratio of the rivers are in a range between 2.58 and 5 suggestive of structural control similar to the other segments of the study area. The river basin is elongated with values between 0.44 and 0.63. The hypsometric curve of the rivers shows less concavity in comparison with the rivers draining through the previous segments. The rivers draining the segment IV shares a curve that lies between the convex up and concave up suggesting that the basins are younger in comparison to the previous segments. The rivers have an integral value between 0.34 and 0.46 suggesting that rivers basin have undergone less erosion in comparison with that of the previous segments.

Segment V

Rivers draining through the sector are of 3rd, 4th and 5th order and its drainage density ranges between 3.1 and 5.95 (Table 6.1). The stream frequency calculated for the rivers are is in the range of 3.93 and 9.4. The bifurcation ratio of the river networks are between 1.63 and 3.16. Rivers flowing through this segment are generally elongated having values between 0.49 and 0.78. The River 2 draining the segment has slightly circular drainage basin. The hypsometric curve of the rivers is concave up with integral values ranging between 0.34 and 0.48. This suggest that river basin is comparatively young similar to those in the segment IV.

Table 6.1 Summary of various morphometric parameters calculated for the rivers in the study area.

Segment	River	Basin area	Order	Drainage density	Stream frequency	Bifurcation ratio	Hypsometric integral	Elongation ratio
Segment V	River 1	10.92	4th	3.1	3.93	3.11	0.34	0.69
	River 2	11.93	5th	5.95	9.4	1.65	0.39	0.78
	River 3	2.72	3rd	4.87	5.16	3.16	0.48	0.49
Segment VI	River 4	6.84	3rd	4.63	6.58	2.58	0.46	0.53
	River 5	4.91	4th	4.94	6.1	2.78	0.41	0.63
	River 6	5.12	4th	5.6	7.02	3.54	0.34	0.62
	River 7	3.89	3rd	3.97	4.76	5	0.35	0.44
Segment III	River 8	19.90	4th	3.46	5.53	4.68	0.38	0.54
	River 9	30.03	4th	3.57	6.09	5.37	0.37	0.50
	River 10	5.47	4th	5.58	9.86	2.35	0.28	0.64
	River 11	2.72	3rd	5.23	9.19	4.5	0.28	0.48
	River 12	3.95	3rd	4.89	10.11	3.05	0.32	0.46
	River 13	3.37	3rd	5.01	7.7	4.58	0.28	0.54
	River 14	79.61	5th	3.34	4.22	3.54	0.34	0.63
Segment II	River 15	4.61	3rd	4.07	5.63	4.58	0.24	0.58
	River 16	4.45	3rd	3.71	4.49	4.16	0.33	0.52
	River 17	4.72	4th	4.725	6.348	2.83	0.17	0.52
	River 18	3.48	3rd	3.93	5.44	5	0.39	0.46
	River 19	2.95	3rd	4.21	5.08	4	0.24	0.49
	River 20	10.79	4th	3.65	6.68	3.73	0.40	0.58
	River 21	3.97	4th	3.76	6.29	2.23	0.36	0.45
	River 22	2.44	3rd	3.45	2.87	2.5	0.29	0.44
	River 23	2.28	3rd	4	5.69	3.5	0.29	0.49
Segment I	River 24	10.51	4th	3.5	4.7	5.1	0.25	0.60
	River 25	2.41	4th	3.42	4.50	4.25	0.26	0.58
	River 26	0.94	3rd	3.5	5.58	5.2	0.30	0.38
	River 27	5.27	3rd	3.3	3.978	4	0.48	0.46
	River 28	3.39	4th	3.75	4.48	5.4	0.23	0.48
	River 29	4.47	3rd	3.51	5.816	4.5	0.42	0.47
	River 30	6.90	4th	3.71	5.94	3.25	0.38	0.59

Overall, the morphometric studies carried in the river networks of the study area suggest that the rivers are in an early to late mature stage of evolution (Table 6.1). The western segments (Segments I and II) have undergone higher degree of fluvial erosion in comparison with the eastern most segments. The major controlling fault that regulates the baselevel for rivers in the area is the KMF which is located north of the study area and at present, concealed under the recent Rann sediments. The present morphometric studies carried out in the study area rule out the control of minor fault systems (secondary faults) in the present morphology of the landscape. This is evident from the calculated morphological parameters of the rivers that are not showing any significant changes when crossing these minor structures.

Generally, in tectonically active terrains a youthful nature of topography is imminent. However, the rivers in the study area according to Strahler (1964) are in late mature to early mature stage of evolution. During the period of higher tectonic uplift, the uplift overrides the denudational process and results in overall growth of topography followed by exhumation of the topography during the period of lower tectonic uplift. Geological setting of the present study area shows that the older Jhurio Formation are exposed at the center of Jhurio dome and Habo dome in the western side, which is absent in the eastern domes. In the eastern domes, the younger Jhuran and Bhuj Formations are exposed at core of the domes (Biswas 1993, 2016b). This suggests that the western segments, i.e., Jhurio and Habo domes have experienced higher net uplift in comparison with the eastern domes (Fig. 6.1). The difference in magnitude of uplift could impact the river networks and result in changes in fluvial erosional processes and maturity of the landscape.

INTERPRETATION OF RESULTS

1. Role of tectonics

The spatial and temporal pattern of tectonic uplift can interfere in the basin and landscape evolution in different ways (Bloom, 1998; Jordan, 2003; Bishop, 2007). In the study area rivers originating from similar altitude have different gradients. These gradient changes associated with rivers are not fully linked with the lithological changes, though such gradient changes associated with lithology change is seen in few rivers. The long profiles and Hack’s profiles of the major north flowing rivers clearly point to the tectonic control in the region. In comparison with the western KMF (Jara-Jumara sector) the rivers show sharp gradient changes at the zone of KMF. The gradient change could be linked to the reactivation of eastern KMF in the recent times. The Lotia River and Nihwara River in the segment III have developed multiple knickpoints at the downstream side near the vicinity of KMF. The multiple set of knickpoints and severe incision in the fault zone are few supplementary evidences for the Late Quaternary reactivation of KMF in the region. Furthermore, the colluvio-fluvial deposit seen along the eastern Kachchh suggests the interplay of three major episodes of Late Quaternary tectonic activities in the region (Maurya et al., 2022). The first episode of tectonic uplift occurred during 100ka, followed by a tectonic disturbance during 50-35ka. The third phase during Holocene to recent (Maurya et al., 2017). The north flowing rivers incise through the Late Quaternary colluvial and alluvial deposits suggesting continuation of the tectonic activity to the present time.

The present study on the drainage networks also suggests a strike variation in magnitude of tectonic uplift in the eastern KMF. The nature of long profile verifies the degree of fluvial development in a topography. The shape and curvature of a long profile is believed to be the outcome of rock uplift and erosion in a landscape (e.g., Whipple and Tucker, 1999; Snyder et al., 2000; Singh and Awasthi 2010; Giaconia et al., 2012). Here, the L-shaped nature of the long profile of the north flowing rivers indicates a progressive decrease in curvature towards the eastern segments. The present trend shown by the north flowing rivers can be linked to the strike variation magnitude of tectonic uplift. The drainage basin area advances either laterally or longitudinally in a setting depending on the external and internal forces that were in operation. In a normal terrain with the advancement in fluvial processes, Hypsometric integral (HI) will approach value close to zero and the basin geometry will evolve more circular (Schumm, 1956). However, in tectonically active terrains the rivers have the tendency to increase the basin area longitudinally in headward direction and become more elongated. Here a plot of hypsometric integral *versus* elongation ratio was constructed to understand the fluvial erosional process and concurrent basin area advancement in the NHR (Fig. 6.6). The presently adopted method is widely used in understanding the catchment evolution and its relation to escarpment retreat (Kale and Shejwalkar, 2007). In the present study area, all rivers were falling in the same portion of graph where the rivers have moderate hypsometric integral and moderate elongation ratio. This suggests that the rivers are in geomorphologically active phase and were increasing drainage area longitudinally in the headward direction rather that lateral advancement. The present nature of the river has an important connection with the scarp retreat and erosion in the investigated region. A direct linkage existing between footwall scarp erosion and evolution of catchments was demonstrated in similar tectonic settings (Elliot et al., 2012).

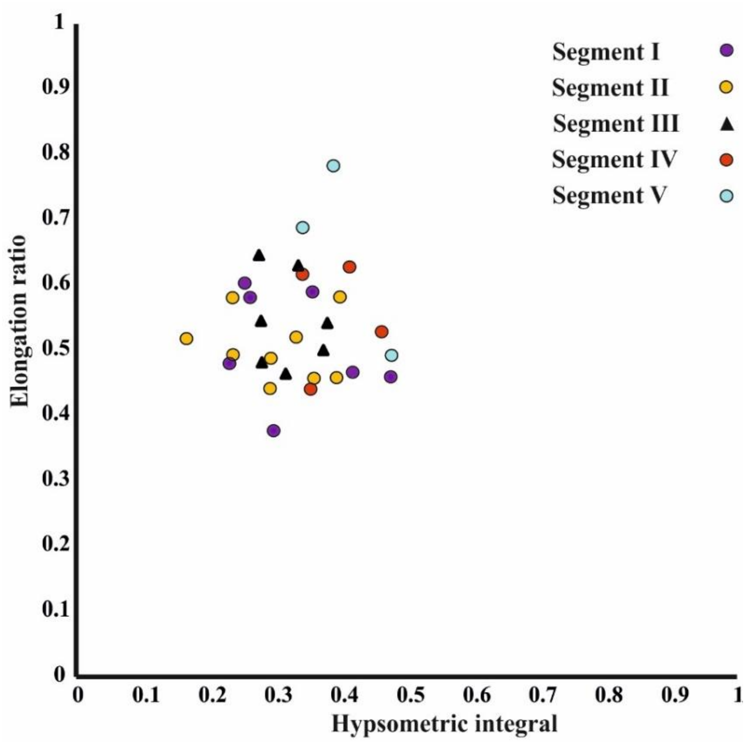

Figure 6.6 Relationship between hypsometric integral (HI) and elongation ratio (Re). The parameters indicate that the drainage basins are increasing their basin area longitudinally rather than laterally. The present nature of the north-flowing river basin in the study area has an important connotation in the retreat of the scarp in the region.

The episodic tectonic perturbation brought by the KMF in the channel intensified the amount of footwall erosion in the landscape.

2. Role of lithology

Lithological variation can potentially affect the results of morphometric analysis, so it is important to have a regional wide assessment of lithological factor (Schumm et al. 1987; Whipple and Tucker 1999; Snyder et al., 2000). Moreover, the lithological factor can intervene in the evolution of landscape in different ways. The harder, resistant lithology with high erosional resistance will result in a lithologically controlled knickpoint or knickzone causing a transient stage for the rivers. Presence of thick and resistant litho-units at the upstream side of the catchment can decrease the hypsometric integral and vice versa (Walcott and Summerfield, 2008). Laure (2008) also reckoned the fluctuation in the river channel slope with the lithological change. In the present study, the rivers mainly flow through sedimentary successions of Mesozoic era, of which, the Jumara, Jhuran and Bhuj are the major lithology exposed in the NHRFZ. The SL index calculated for the river networks changes with the lithological variation. For example, Nihwara River draining the segment III shows sharp variation or peaks in the SL value at the contact of Bhuj Formation and Jhuran Formation. This peak in the SL value are associated with large knickpoints interfered by field investigation (Fig. 6.5 a and c). Similarly, the Kaswali River and Lotia River also show such variation in the SL index associated with lithological change. The Kaswali River flows entirely through the Jhuran Formation. However, the river displays changes in the SL values at the contact of upper and lower Jhuran Formation. The Jhuran Formation as mentioned in the previous chapter, can be classified further into upper, middle and lower Jhuran. The lower Jhuran is composed of relatively softer lithologies of sandstone and shale intercalations. While the upper Jhuran rock units are hard and resistant to erosion (Biswas, 1977,1993). These evidences suggest that the region has a secondary influence of lithology in landscape evolution other than tectonics. Therefore, the influence of lithological control has to be taken into consideration while proposing a landscape evolutionary model for KHS.

IMPLICATION FOR SCARP DEVELOPMENT

The Kas Hill Scarp is a prominent feature and drainage divide in the eastern part of KMF. The present location of the scarp, its lateral continuity and episodic colluvial deposits serve as a prime example of a landscape generated by long-term erosion in a tectonically active environment. The colluvio-fluvial deposits at the mouth of the river indicates the predominance of fluvial erosion in the scarp. In a tectonically active basin like Kachchh, the reactivation of faults is the prime factor responsible for the landscape development (Biswas, 2016a; Maurya et al., 2017). Previous studies carried out around the region suggest that the eastern part of Kachchh is more active during the Late Quaternary period in comparison with the western counterpart. The colluvio-fluvial deposits along the north flowing rivers, which date to the Late Pleistocene are direct indicator for episodic reactivation of the KMF (Maurya et al., 2017). The previous chapters, it is clear that the KHS is much older when compared to the KMFS. Also, the KHS has undergone minimum three major phases of enhanced degradational process corresponding to tectonic reactivations during Late Pleistocene to recent.

Exhumation of landforms in semiarid setting can be driven by fluvial erosion related to regional uplift (Formento-Trigilio and Pazzaglia, 1998). The long profile analysis and other morphometric studies carried on the eastern KMF suggest that the fluvial network has a significant role in controlling the regional denudation rate and in carving the present morphology of a region. The Hack's profile of the scarp deriving rivers is convex up in nature, which suggests the dominant role of tectonics activity and fluvial erosion in the landscape. The observation is further substantiated by the occurrence of incised Quaternary deposits and knickpoints in the rivers draining the eastern KMF. For example, the incised Quaternary sediments in the downstream portion of the Lotia River (River 9) and Falay River (River 20). Normalized profile of those rivers that originate from the segment III are generally L-shaped in nature. (Fig. 6.3). The nature of the long profile analysis indicates the severe deepening of rivers in the upper segments of the rivers and also specifies that the erosion is concentrated in the scarp face. The long profile of rivers originating from the KHS is similar in shape of the river originating from the JMS, however the gradient change and steepness of the rivers originating from KHS are comparatively higher. In short, critical analysis on the basins can lead to the following interpretations (a) the region has undergone uplift during the Late Cenozoic period which is well supported by present convexities in the river profiles b) the headward erosion and growth of drainage area occurred in the upstream direction c) L shaped river profile indicating severe downcutting and channel deepening in the scarp face d) the Kaswali river and rivers flowing the segment III and II contributed to the overall erosion of KHS.

The hypsometric analysis carried out on the river basins based on Strahler cycle of landscape evolution suggest that the rivers are on the early to late mature stages of landscape evolution. To have a better understanding on the fluvial erosional process and stage of geomorphic cycle the average hypsometric curve for each segment was computed (Fig. 6.7). The rivers in the segment I and II have a smooth concave up average hypsometric curve in comparison with segments III, IV and V. The segment III displays a S shaped average hypsometric curve whereas, the segments IV were having straighter average curve. This generally points to the fact that the segments of the study area are in different geomorphic stages of evolution. This difference in the geomorphological stages can be directly linked to the difference in tectonic activity along different segments of the eastern KMF. Studies conducted in the Japanese mountains show that a region which undergoes concurrent episodes of tectonic uplift and denudation will not strictly follow the Strahler's model of geomorphic cycle. The Strahler's hypsometric model was on the concept of Davisian scheme in which the mountain area rapidly uplifted with no serious denudational process and when the uplift ceases the denudation comes into play, lowering the relief by erosion. One of the biggest setbacks in this model was that the stages do not advance once the surface

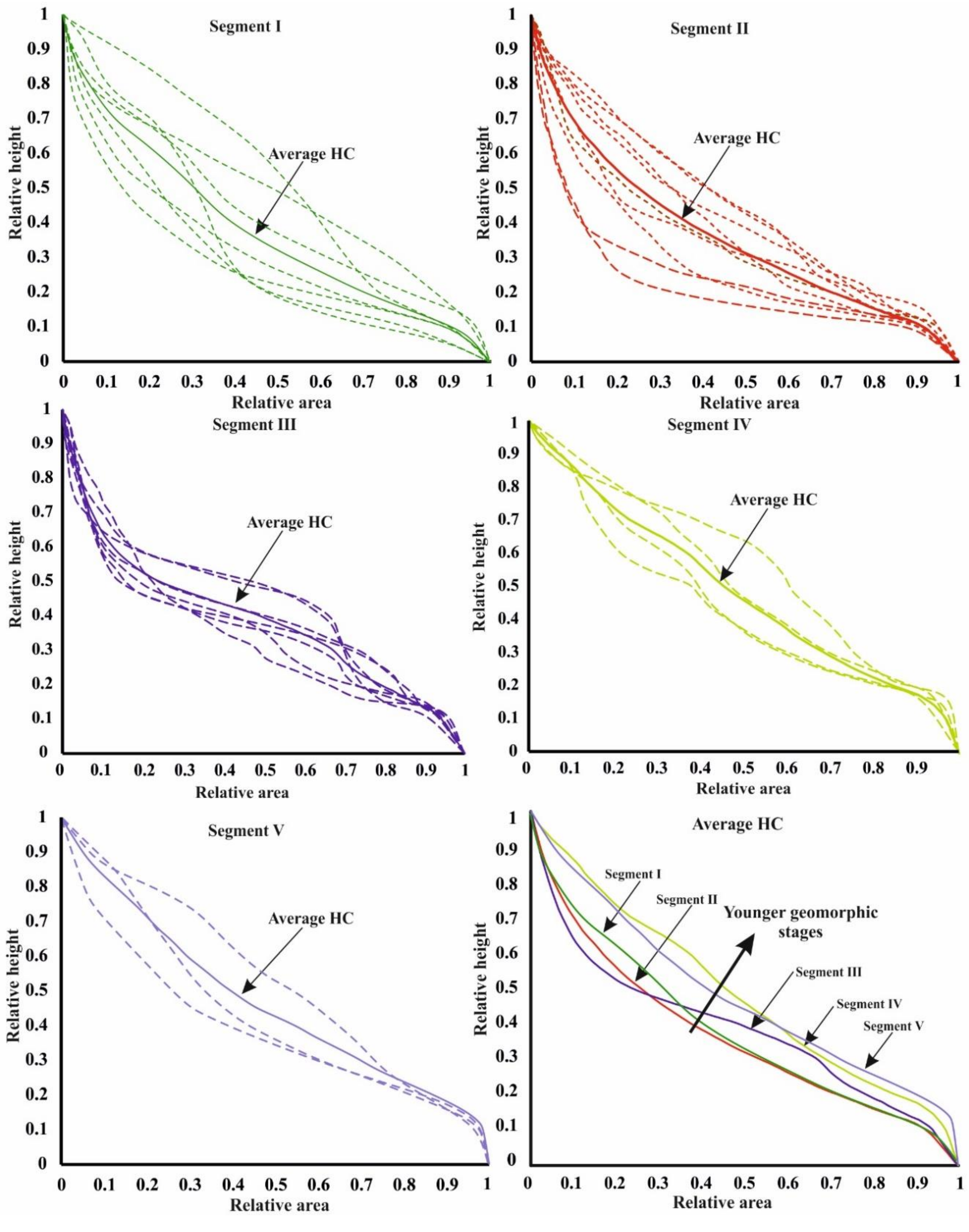

Figure 6.7 Hypsometric curves of rivers in the study area. In segment I and II, concave up average hypsometric curves (solid line) can be seen, while in segment III a S-shaped curve, indicative of an early to late developing stage in the geomorphic cycle is seen. The western segments (Segment I and II) have experienced greater net uplift and tectonically induced fluvial erosion than the eastern segments. The segments IV and V are more straight, indicating that the topography is in a youthful stage of development.

wears down (Ohmori, 1993). Therefore, the resultant hypsometric curve will not be sufficient to explain the stage of geomorphic cycle in the studied terrain where concurrent tectonics and denudational process owe at work. The Ohmori's model is therefore more dependable and relevant for terrain like the Kachchh basin, which experienced prolonged periods of episodic tectonic uplift and denudation. Ohmori (1993) classified the geomorphic cycles mainly into three stages (i) developing stage (ii) culminating stage (iii) declining stage. In contrast to Strahler (1957), in Ohmori (1993) model the initial landform starts from an old or monadnock phase of Strahler's diagram and with advancement in stage due of concurrent tectonic and denudation in operation, the hypsometric curve will shift from concave to S-shape. The previous studies in the basin also supports the view that the basin had undergone several spells of tectonic and denudational events in the past (Biswas, 1993,2005). Hence, in the present study, the model of Ohmori (1993) has been followed to explain the landform evolution of the region. The concave curve obtained for the segments I and II indicates that the rivers are in the early developing stage of geomorphic cycle. This suggests that the rivers have eroded the basins to the base levels, at the same time reactivation of the KMF resulted in the advancement in the relief and further commencement in fluvial processes. This finding obtained from the hypsometric analysis matches well with the L- shaped and sharped gradient changes associated with the rivers in the segment I and II. Altogether, the present analysis for segments I and II suggest that the segment has responded to long-term tectonic deformations and quiescence. Whereas, the S-shaped average hypsometric curve of the segment III indicates that the segment is in late or latest developing stage of landscape evolution. This may be because of the recent tectonic movements that have occurred in the segment. The average hypsometric curve of segments IV and V are of straight type as these terrains are in the younger stage of geomorphic cycle. Overall, a progressive decrease in the maturity of geomorphic stage towards east, i.e., from segment I to V is noticed in the study area.

The present finding along with findings in the previous chapters corroborate the strike variation in the magnitude of tectonic reactivation of KMF during the post-deccan inversion phase. The variation in tectonic uplift and lithological resistance has important influence in the landscape degradation and preservation. Uplift induced fluvial erosion and drainage rejuvenation is continuing along the NRHFZ as indicated by the evidences form the present chapter and the previous chapters. The data generated from the drainage analysis supports the strike variation in the tectonic activity and maturity of the landscape. The segment I and II have undergone higher degree of tectonically induced fluvial erosional processes when compared with the segment III, IV and V. The sharp L-shaped profiles of the rivers are an indication of the same. The finding is well supported by the stratigraphic offset along the segments of eastern KMF. The Jhurio dome has the highest stratigraphic offset along the entire KMF and in the study area. The dome outcrops the Jhurio Formation as an inlier. Considering the domes in the segments (II-V) and lithologies exposed as inliers, a progressive trend of younger lithologies is observed. This further supports to the conclusion that tectonic deformation varies along the strike direction. As mentioned in the previous chapter, the fundamental processes responsible for the evolution and degradation of the hillslopes are downwearing and backwearing (Dikau, et al., 2004). In addition to tectonics, lithology is a significant component that influence the rate and pattern of landscape degradation. The presence of hard and resistant lithological unit will favor the process of backwearing than downwearing. In the present study, the rivers show a significant variation in the calculated parameters at the contact between the lithological units. The arenaceous units of Bhuj and upper Jhuran Formation are hard and resistant to the erosion. The scarp of the KHS is mainly formed in the upper Jhuran Formation, however comparatively softer lithologies are exposed at the base of the scarp. The hard sandstone unit exposed at the scarp face will favor backwearing process.

The morphometric parameters like drainage density, bifurcation ratio and stream frequency do not vary significantly in the segment III and IV when compared to the segment I and II. The parameters are indicative of the prominent role of tectonics and fluvial erosion in controlling the landscape development. Accordingly, the plausible explanation for formation of the KHS is the erosional exhumation of the paleo scarp bounding KMF. However, the rate and magnitude of the tectonic reactivation was different in the segments. The higher degree of fluvial dissection into the topography and higher concavity of average hypsometric curve are indications of higher frequency of tectonic reactivation and deformation that have happened along the segment I and II. Considering the computed river parameters on the Kas Hill sector and adjoining segments of eastern KMF, it can be concluded that formation and preservation of the KHS in the segment III and IV could be because of three possible reasons. First, the strike variation in the uplift and uplift induced erosion in the Cenozoic period. The western segments went through much longer period of tectonically induced erosion or exhumation when compared with the eastern segments. The higher frequency of uplift in the segment I and II led to growth in the relief and tectonically induced exhumation. Comparatively, lesser tectonically induced erosion led to preservation of the paleo scarp in the segments III and IV. Second, the stronger and more resistant lithology of the upper Jhuran sandstone led to the preservation of the scarp. The presence of resistant lithology in the escarpment top could favour backwearing or parallel retreat of the scarp (Shejwalkar, 2007). Third, the major rivers of the study are following a general trend of increasing the basin area longitudinally by headward erosion. However, the Re *versus* Hi plot of the Kaswali River and the other rivers arising from the scarp face of KHS show a tendency to increase the drainage area laterally than longitudinally. The lateral increase in the drainage area results in the parallel retreat of the slope face (Kale and Shejwalkar, 2007). The factor coupled to degradation, retreat and preservation of KHS in the present topography of Kachchh.

The tectonic framework of the Kachchh basin comprises of episodic uplift along the E-W trending intrabasinal fault systems including the KMF (Biswas 2005, 1993, 1987; Maurya et al. 2017), during the Cenozoic period. Flexure zones with steep north dipping scarp faces developed, when there was a major change in the stress pattern from extension to compression due to Indian-Eurasian plate collision. The periodic reactivation of the KMF thereafter led to increase in the asymmetry of the domes and the faulted limbs attained steep to vertical dips (Maurya et al., 2017). The slope produced by episodic reactivation of the KMF provided the energy for the river systems to cut through the episodically uplifting flexure zones as evidenced by the anti-dip flow directions of the rivers. Phases of reactivation of KMF in the Late Cenozoic induced changes in the basin relief and created non-equilibrium condition for the rivers, which is clearly reflected in the present profile of the rivers. Episodic nature of the uplift facilitated the rivers to continuously adjust to tectonic uplift and maintain their northward flowing courses. The strike variation in the tectonic activity and fluvial incision led to the parallel retreat and preservation of the KHS.