Chapter - 11

MORPHOTECTONIC ANALYSIS

The morphotectonic domain-II consists of seven major south flowing rivers. The overall drainage pattern is parallel which is consistent with the prominent regional S-SSW slope. Four of these rivers (Hiran, Singwada, Machundri and Rawal) arise in the trappean hinterlands with upper half their courses in trappean hilly region while the lower half of their courses fall in the southward sloping miliolitic terrain (Figure 11.1). The three other rivers (Somat, Sangawadi and Rupen) are comparatively shorter and flow through the miliolitic terrain only (Figure 11.1). The above mentioned two categories of rivers was found helpful in interpreting the results of morphotectonic parameters. The larger river basins covering trappean uplands and miliolitic terrain are expected to show the influence of both terrains while the relatively smaller drainage basins located almost exclusively in the miliolitic terrain will show the effect of post-miliolite i.e. late Quaternary processes.

11.1 GEOMORPHIC INDICES - RESULTS

11.1.1 Rivers originating in trappean terrain

Considering rivers originating in trappean terrain, Hiran and Singwada River largely flows towards SSW-SW, while Machundri and Rawal rivers flows along SSE trend. These large drainage basins flows through trappean hilly terrain in the upland zone and miliolite deposits in the buried pediment zone. The drainage basin area descends from west to east. The Hiran river basin covers maximum area of ~939 km^2 in the westernmost margin whereas Rawal River covers ~371 km^2 flows in the easternmost margin of this domain (Table 11.1). The watershed however shows larger perimeter i.e., ~163 km of the Singwada basin compared to Hiran River that covers more than twice the basin area (Figure 11.1, Table 11.1). This is correlated with the basin length which is the longest extent from source to convergence point near river mouth. The Singwada River shows longest basin length with highest perimeter value among all four rivers. This indicates the strong lithological control over stream network. The structural control due to presence of dyke ridges and trappean hills over basaltic terrain and geomorphic control due to E-W trending aeolianite ridges on miliolitic terrain (Figure 11.1).The main trunk channel is longest of Singwada River followed by Hiran River. The several anomalous

sinuous courses on the trappean bedrock also controlled by dykes is resulting in longest channel length (Figure 8.1, Table 8.1).However, this infers that the Machundri and Rawal River are comparatively flowing on the straight courses (Figure 11.1). The total number of streams generated from all four basins are 9022 with total stream length measured is up to 6140 km in which Hiran river basin populates with maximum tributaries (Table 11.1).

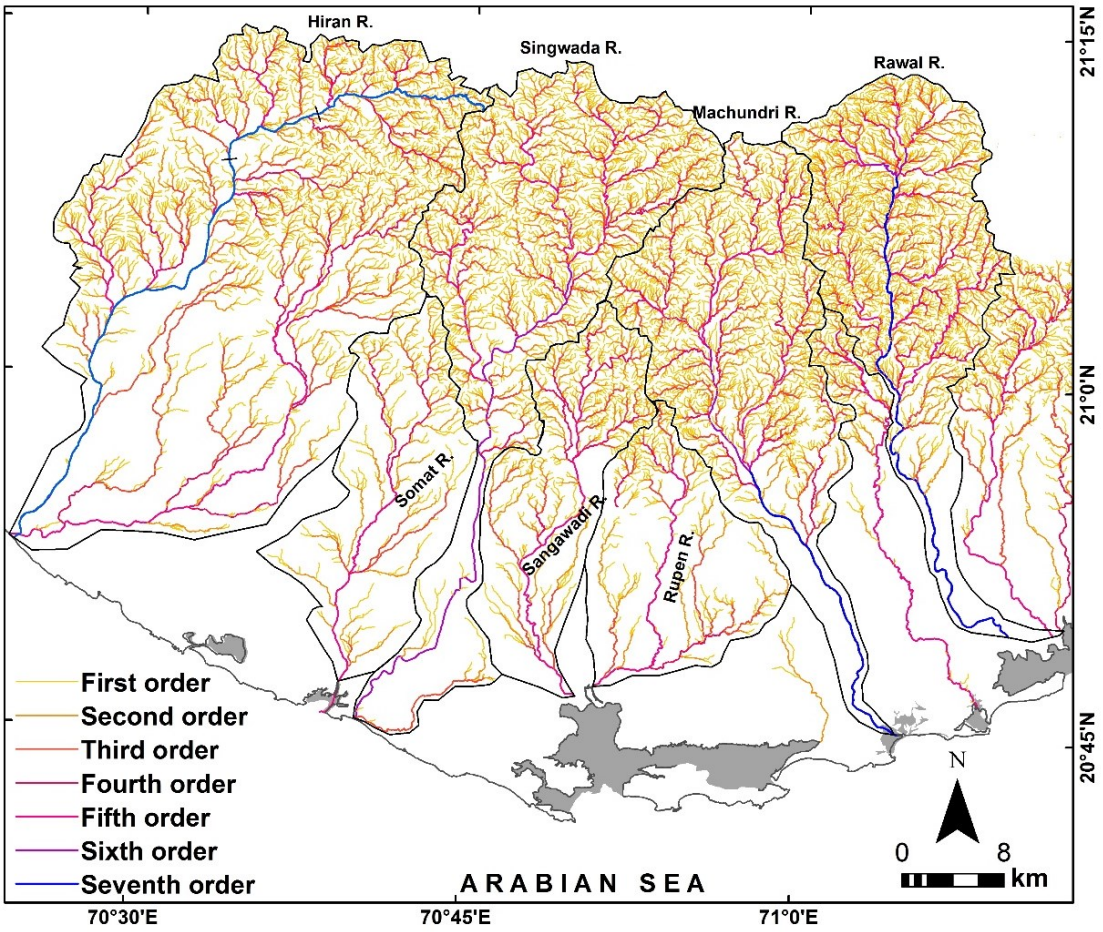

Figure 11.1 Stream ordering map of river basins in morphotectonic domain-II. Note that most part of Hiran, Singwada, Machundri and Rawal river basins (category-I) fall in trappean uplands. Somat, Sangawadi and Rupen river basins (category-II) are located mostly over Late Quaternary miliolites.

The ordering of the river basins were done for better understanding of the drainage network and its characteristics in different stream orders. The highest stream order is 7th order of Hiran and Singwada River while 6th highest order of Machundri and Rawal River (Figure 11.1, Table 11.1). The stream order map generated and number of streams measured for each order gave results about the stream bifurcation ratio of two particular stream orders. The bifurcation ratio (Rb) calculated for all four basins shows

higher value at some orders depending on the structural distortion or lithological contact. The Rb value of 3rd and 4th order stream in Hiran river is 4.21 (Table 11.2). The low order streams are originating from the high relief area thereafter merging in the channel valley. The high Rb value of these stream orders resulted due to the channel flowing in the trappean valleys forming parallel drainages confluence directly with the main channel. The drainage pattern variation and the geomorphic variation in the hilly terrain exhibited the higher Rb value inferring strong structural control. However, Singwada River shows high Rb value in 4th and 5th order streams i.e., 5.67, highest value in this category (Table 11.2).

Table 11.1 Geomorphic indices calculated for rivers originating in trappean terrain (category-I) flowing in morphotectonic domain-II.

Rivers originating in trappean terrain				
Parameters	**Rawal R.**	**Machundri R.**	**Singwada R.**	**Hiran R.**
Linear aspects				
Perimeter (P) (km)	123.38	131.12	162.94	158.26
Basin length (Lb) (km)	46.80	52.51	55.62	51.28
Main trunk stream length (km)	56.45	62.16	70.70	64.93
Highest stream order	VII	VII	VI	VI
Total number of streams	2735	1939	1985	2363
Total stream length (km)	1441.2	1287.9	1429.5	1980.9
Mean Bifurcation Ratio (Rbm)	3.71	3.60	4.45	3.89
Areal aspects				
Basin area (A) (km^2)	371.04	407.93	484.99	939.02
Drainage density (Dd) ($km\ km^{-1}$)	3.88	3.16	2.95	2.11
Stream frequency (Fs) (km^{-2})	7.37	4.75	4.09	2.52
Drainage texture (T) ($km\ km^{-4}$)	28.63	15.01	12.06	5.31
Form factor (Ff)	0.36	0.16	0.15	0.17
Circularity ratio (Rc)	0.31	0.30	0.23	0.47
Elongation ratio (Re)	0.46	0.43	0.45	0.67
Basin shape index (Bs)	3.03	3.17	3.15	1.80
Relief aspects				
Basin relief (R)	494	462	611	406
Relief ratio (Rr)	10.55	8.80	10.98	7.91
Ruggedness number (Rn)	1918	1459	1800	856

The Singwada River originates from the highest elevation in this domain. The upland zone of this basin shows several lineaments formed due to the presence of multiple dyke ridges crossing trappean hills. The river bifurcation hence is seen in the 4th order stream flowing in a rectangular patterns and 5th order stream shows parallel drainages up to trunk channel (Figure 11.1, Table 11.2). Machundri river basin shows

such similar variation in 3rd and 4th order stream with Rb value 4.82 (Table 11.2). However, high Rb value in 5th and 6th order stream of Rawal basin is 4.50 which is observed in northernmost part of the basin near the upper reaches (Table 11.2). The trellis pattern in lower stream orders merges with the parallel drainages of higher stream orders. The parallel long channel of 3rd and 4th order streams follow straight courses confluence with the south flowing straight main channel (Figure 11.1). The mean bifurcation ratio of all four drainages ranges from 3.60 to 4.45 (Table 11.2). The high Rb and Rbm values clearly indicates that the upland zone is strongly controlled by dykes, trappean hills and basaltic flows. The area is structurally distorted by the structural attributes over the trappean highlands and also tectonically controlled resulting in high Rb values.

Table 11.2 Results of Bifurcation ratio (Rb) and Mean Bifurcation ratio (Rbm) calculated of rivers originating in trappean terrain in morphotectonic domain-II.

Rivers originating in trappean terrain				
Basin	**Order**	**No. of streams**	**Bifurcation ratio (Rb)**	**Mean Bifurcation Ratio (Rbm)**
Rawal R.	1	2105	4.46	3.71
	2	472	4.25	
	3	111	3.17	
	4	35	3.89	
	5	9	**4.50**	
	6	2	2.00	
	7	1	-	
Machundri R.	1	1484	4.25	3.60
	2	349	4.26	
	3	82	**4.82**	
	4	17	4.25	
	5	4	2.00	
	6	2	2.00	
	7	1	-	
Singwada R.	1	1531	4.46	**4.45**
	2	343	3.81	
	3	90	5.29	
	4	17	**5.67**	
	5	3	3.00	
	6	1	-	
Hiran R.	1	1765	-	3.89
	2	450	3.92	
	3	107	**4.21**	
	4	31	3.45	
	5	8	3.88	
	6	2	4.00	

The drainage density, stream frequency and drainage texture calculated shows higher values in Rawal basin despite of covering smaller area compared to other drainage basins. The correlation of these parameters indicates that Rawal basin shows fine to very fine drainage texture and high dissection level forming present day basin topography (Table 11.1). The drainages are originating in trappean lava flows, basaltic hills and numerous dyke ridges flowing towards southward tectonic slope. Rawal basin is sharing watershed boundary with Malan River of domain-I that flows along fault (F2). The effect of these fault zone, highly brittle shear planes in traps and varies drainage patterns are strong evidence for the fine textured densely populated streams in Rawal basin compared to other three basins.

Table 11.3 Basin shape index (Bs) values calculated and other areal parameters for rivers arising in trappean upland.

Rivers originating in trappean terrain									
Basin	**Nu**	**Bl**	**Bw**	**Bs**	**A**	**P**	**Rc**	**Ff**	**Re**
Rawal R.	2735	46.8	15.47	3.03	371.04	123.38	0.31	0.36	0.46
Machundri R.	1939	52.51	16.56	3.17	407.93	131.12	0.30	0.16	0.43
Singwada R.	1985	55.62	17.67	3.15	484.99	162.94	0.23	0.15	0.45
Hiran R.	2363	51.28	28.49	1.80	939.02	158.26	0.47	0.17	0.67

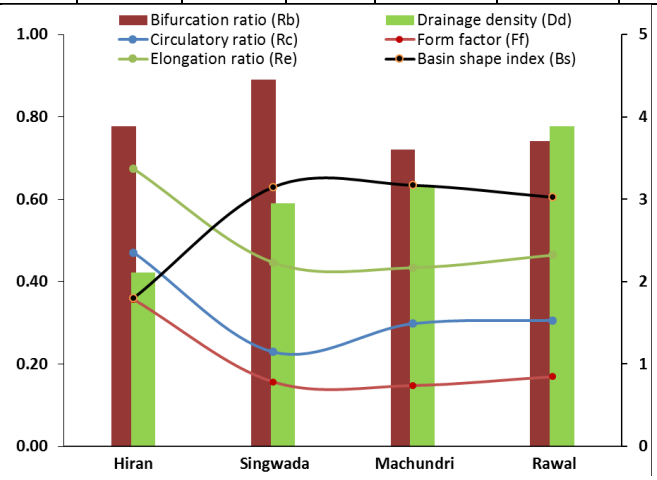

Figure 11.2 Correlation of areal parameters – Circulatory ratio (Rc), elongation ratio (Re) and Form factor (Ff) with Bifurcation ratio (Rb) and Drainage density (Dd) for rivers originating in trappean terrain. Note the Hiran river is less elongated basin with low Dd and Bs value while high Rc value.

The shape of the drainage basins in this category are almost elongated might have formed due to past tectonic events. However, continuous erosion tends to modify the basin profile with time. The elongation ratio (Re), circularity ratio (Rc) and form factor (Ff), thus calculated infers that all four basins are strongly elongated (Table 11.1). The Rc

value ranges from 0.23 to 0.47 signifies that the basin elongation with lowest value indicating very elongated basin i.e., Singwada basin (Table 11.1). The correlation of these parameters with basin shape index is plotted (Figure 11.2). The relief parameters calculated for this category suggests the Singwada basin has highest basin relief and relief ratio followed by Rawal river basin. The presence of trappean hills and dyke ridges in the upland zone and aeolianite ridges in the buried pediment zone corresponding to higher relief basin of Singwada drainage basin. The maximum elevation in Singwada basin due to basaltic hills observed in the northernmost part of the basin around channel source. However, the ruggedness number shows higher values i.e., 1918 of Rawal river basin followed by Singwada basin with value 1800.

The highly elongated basin with highest basin relief indicates that Singwada River is strongly controlled by homogenous impermeable trappean lithology in the upper half while aeolianites and sheet miliolites in the lower half of the basin. Hiran and Singwada basin is mostly controlled by highly fragmented trappean basalts in the highlands. Furthermore, coast parallel and E-W trending aeolianite ridges controls the drainage system over buried pediment zone sloping gently towards south. However, Machundri and Rawal River is strongly influenced by structural features and tectonic activity in the upland zone. This is due to the easternmost margin of this domain is bounded by fault controlled landscape and shows structurally distorted topography influencing these rivers.

11.1.2 Rivers flowing mostly in miliolitic terrain

Considering rivers flowing mostly in the miliolitic terrain basically originates from the trappean terrain near the trap-miliolite contact. All three rivers viz., Somat, Sangawadi and Rupen are smaller compared to rivers originating in the trappean terrain (Figure 11.1). The drainages of this category originated and flows southward up to the coast lies in between the large drainages. The traps are retreated by main channel incising up to several meters forming deep valleys upstream of trap-miliolite interface. All these rivers separately covers the basin less than 260 km^2 compared to larger basins independently occupies area almost greater than 370 km^2 (Figure 11.1, Table 11.4). This indicates the massiveness of the rivers arising in trappean uplands compared to rivers flowing mostly in miliolitic terrain. The perimeter calculated for the drainage basins shows that the watershed boundary of Rupen River is even compared to other two basins. This indicates that the streams of the Rupen River arise from the lowland areas. Somat

and Singwada River is surrounded by numerous E-W trending aeolianite ridges while Rupen River flows over planar topography consisting aeolian dune deposits.

The results of basin length and main trunk stream length shows higher values in Sangawadi drainage basin inferring the parallel drainages flowing towards southward slope. The eastward extension of aeolianite ridges are observed up to the main trunk stream of Sangawadi River. The eastern half of the river comprises of aeolian dune deposits overlying the aeolianite ridges and sheet miliolites. Several drainage anomalies are observed at the drainage divide between Sangawadi and Rupen River. For understanding the patches of the drainages influenced by topography, stream ordering and bifurcation ratio was quantified. The highest stream order for all three rivers is 5th order (Figure 11.1, Table 11.4). The bifurcation ratio ranges from 3.70 to 4.78 indicating structural distortion in the basin topography (Table 11.5). The high mean bifurcation ratio (Rbm) of Sangawadi River infers that the basin terrain shows some structural control or tectonic influence on drainage configuration.

Table 11.4 Geomorphic indices calculated for rivers flowing mostly in miliolitic terrain in morphotectonic domain-II.

	Rivers flowing mostly in miliolitic terrain		
Parameters	**Rupen R.**	**Sangawadi R.**	**Somat R.**
Linear aspects			
Perimeter (P) (km)	65	83.44	82.47
Basin length (Lb) (km)	25.67	33.10	31.21
Main trunk stream length (km)	31.96	40.74	36.99
Highest stream order	V	V	V
Total number of streams	588	588	237
Total stream length (km)	295.64	470.56	318.76
Mean Bifurcation Ratio (Rbm)	3.83	4.78	3.89
Areal aspects			
Basin area (A) (km^2)	223.83	224.84	254.36
Drainage density (Dd) (km km^{-1})	1.32	2.09	1.25
Stream frequency (Fs) (km^{-2})	0.93	2.62	2.63
Drainage texture (T) (km km^{-4})	3.47	5.47	1.17
Form factor (Ff)	0.34	0.21	0.26
Circularity ratio (Rc)	0.67	0.41	0.47
Elongation ratio (Re)	0.66	0.51	0.58
Basin shape index (Bs)	1.59	3.30	2.45
Relief aspects			
Basin relief (R)	222	287	238
Relief ratio (Rr)	8.67	8.67	7.64
Ruggedness number (Rn)	294	601	299

The shape of the basin measured by calculating Ff, Re and Rc and correlated with Bs value (Table 11.4, Figure 11.3). The Sangawadi River are showing values that are incorporated with other shape parameters inferring the strong basin elongation. Among all three rivers in this category, Sangawadi basin drainages flowing in trappean terrain shows maximum number of streams than the streams originating in aeolianite ridges. The Rc values ranges from 0.41 to 0.67 indicating elongated to circular basin shape (Table 11.4). The lower Rc values of Somat and Singwada river shows that the basin is elongated due to the presence of aeolianite ridges controlling the drainages over miliolitic terrain However, Rupen River flows mostly over aeolian dune fields where channel almost adjusted to the equilibrium showing circular basin shape (Table 11.5, Figure 11.3).

Table 11.5 Results of Bifurcation ratio (Rb) and Mean Bifurcation ratio (Rbm) for rivers flowing mostly in miliolitic terrain in morphotectonic domain-II.

	Basin	Order	No. of streams	Bifurcation ratio (Rb)	Mean Bifurcation Ratio (Rbm)
Rivers flowing mostly in miliolitic terrain	Somat R.	1	178	3.96	3.70
		2	45	4.50	
		3	10	3.33	
		4	3	3.00	
		5	1	-	
	Sangawadi R.	1	455	4.55	**4.78**
		2	100	4.00	
		3	25	3.57	
		4	7	7.00	
		5	1	-	
	Rupen R.	1	213	4.02	3.83
		2	53	3.79	
		3	14	3.50	
		4	4	4.00	
		5	1	-	

The rivers flowing in this category shows maximum elevation ranges from ~230 to ~290 m while lowest elevation from ~4 to 6.3m. The Sangawadi and Rupen River merges the intertidal zone near Diu Island several kilometers inland (Figure 11.1). However, Somat River merges up to the coastline where coastal cliff is high and the relief at the mouth of the river is ~6m. The relief parameters calculated for all three rivers shows highest basin relief in Sangawadi drainage basin (Table 11.4). However, relief ratio values of Sangawadi and Rupen basin is ~8.7 which indicating similar basin steepness resulting in equivalent intensity of channel erosion. However, the ruggedness

number of Sangawadi River is higher compared to Rupen and Somat basin (Table 11.4). This is because of Deccan traps occupying majority of the northern part of the basin and aeolianite ridges in the lower courses of streams. Four E-W trending aeolianite ridges are eroded by south flowing Somat River forming several knickpoints and narrow deep valleys in the miliolitic terrain. Sangawadi River flows in between the interface of aeolianite ridges and miliolite dune deposits incising sheet miliolites. However, Rupen River flows in the sheet miliolites incising aeolian dunes and exposing buried Tertiary deposits. The results of geomorphic indices interpreted that rivers flowing mostly in miliolitic terrain shows strong bedrock incision in the gently sloping buried pediment zone that infers post-miliolitic uplift. The basin relief, bifurcation ratio, drainage density and terrain ruggedness in Sangawadi drainage basin infers that this river is more affected by tectonic uplift and landscape changes than the other two basins.

Table 11.6 Basin shape index (Bs) values calculated for rivers mostly flowing in miliolitic terrain correlated with other geomorphic indices.

Rivers flowing mostly in miliolitic terrain									
Basin	**Nu**	**Bl**	**Bw**	**Bs**	**A**	**P**	**Rc**	**Ff**	**Re**
Rupen R.	588	25.66	16.09	1.59	224	65	0.67	0.34	0.66
Sangawadi R.	588	33.09	10.02	3.30	225	83	0.41	0.21	0.51
Somat R.	237	31.21	12.75	2.45	254	82	0.47	0.26	0.58

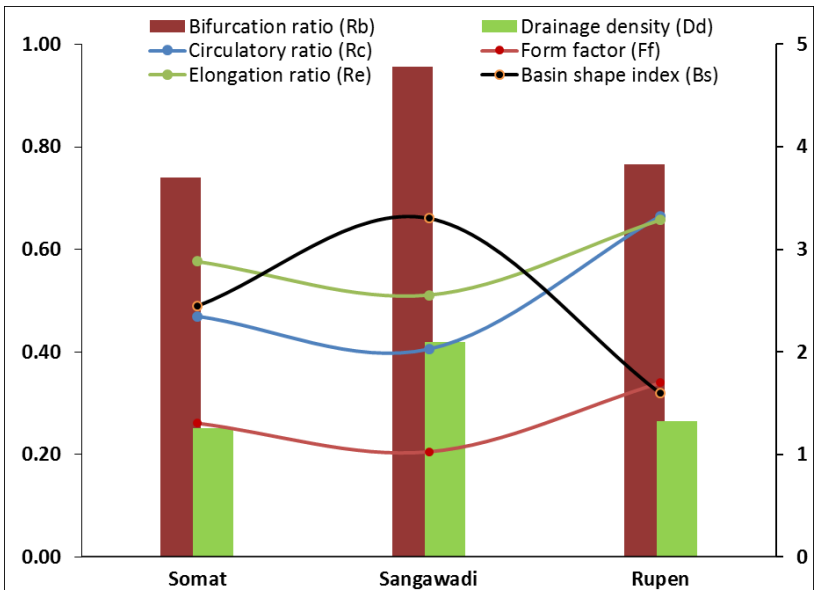

Figure 11.3 Correlation of areal parameters – Circulatory ratio (Rc), elongation ratio (Re) and Form factor (Ff) with Bifurcation ratio (Rb) and Drainage density (Dd) for rivers flowing mostly in miliolitic terrain. Note the Bs, Rb and Dd value is higher in Raidi river indicating strong structural and tectonic control on basin landscape.

11.2 MORPHOTECTONIC PARAMETERS - RESULTS

11.2.1 Stream length-gradient (SL) index

The SL index analysis was calculated for all seven south flowing drainages and the results are described into two parts – rivers arising in the trappean upland and rivers flowing mostly in miliolitic terrain. The use of toposheets 1:50,000 scale and DEM of 30m resolution to generate contour map were used to measure the SL index. These values are correlated with longitudinal river profiles that shows strong indication about abrupt slope breaks. For more precision, contour interval of 10 m were used for all seven rivers.

Rivers originating in trappean terrain

The rivers uprising from the trappean highlands are Hiran, Singwada, Machundri and Rawal. The SL values for this category ranges from 5 to 586 and these values are divided into four classes, i.e. class 1 (<50), class 2 (50-150), class 3 (150-250) and class 4 (>250). The higher class indicates sudden fall in gradient which are observed at different elevations in all four rivers. However, the SL index peaks in the graph is seen at the upland zone and at trap-miliolite interface in Singwada, Machundri and Rawal River (Figure 8.4). The highest SL index value in Hiran River is seen at miliolitic terrain around coast parallel aeolianite ridges. The SL index class 4 in Rawal basin is observed at elevation between 130 and 120m (Figure 8.4). At this elevation, the bedrock channel shows trap-miliolite interface with change in topography from rugged to southward gently sloping plane. Several other SL peaks are observed between 140 m to 60m elevation corresponds to sheet miliolite and aeolian dune deposits overlying Deccan traps (Figure 8.4).

The presence of several small rapids and knickpoints are observed at this SL class. The main channel abruptly bends with low drainage density over miliolitic terrain. However, the channel bedrock incised are trappean basalt underlain by sheet miliolites. The fault (F2) passes at around 60 m contour in Rawal river basin which is indicative of abrupt gradient change conforming to SL peaks (Figure 11.4). The channel up to coastal zone from 60 m elevation flows in a straight path with no tributaries merging the intertidal flats. The Machundri river flows towards west of Rawal river showing SL index values from 5 to 443 (Figure 11.4). The highest value in this river is observed at lithological variation of trap and miliolite forming a huge knickpoints retreating miliolites towards upstream. However, some sudden SL peaks are measured at 200, 130 and 70 m

elevation (Figure 11.4). These are due to structurally controlled dykes and trappean hills in the upland zone shaping the drainages. The small peak at 70 m interval is seen at sheet miliolite and aeolian dune deposit interface in the miliolitic terrain.

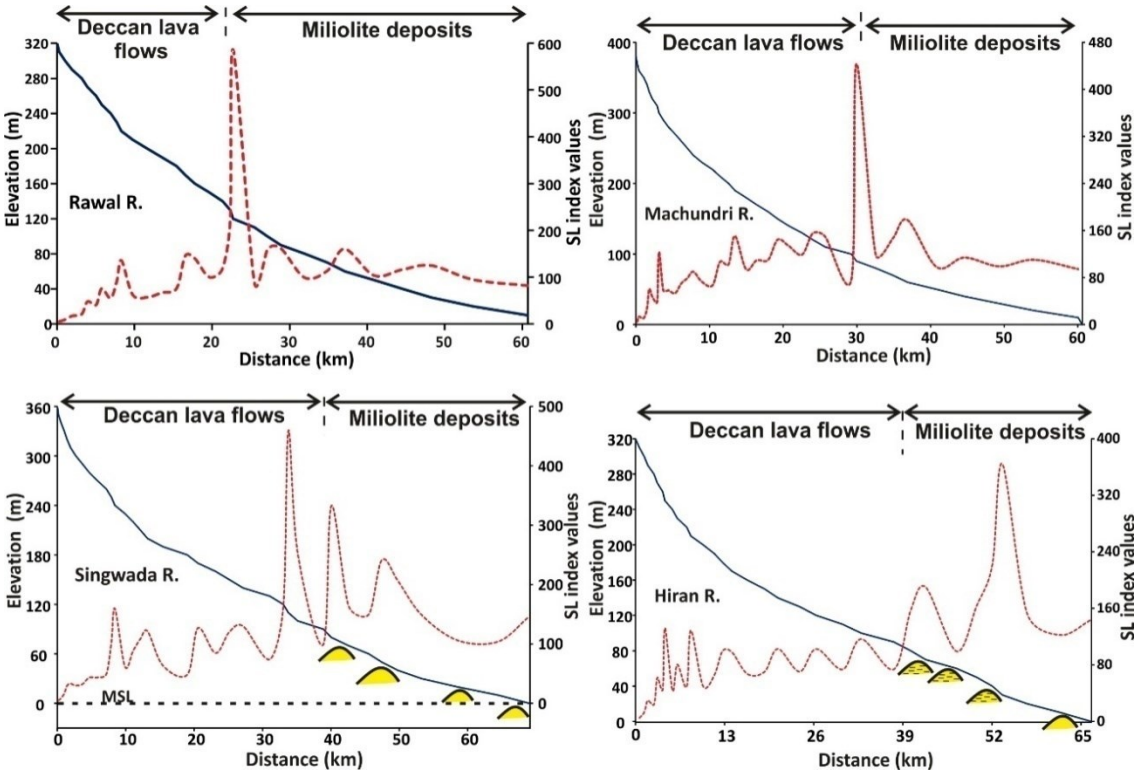

Figure 11.4 Stream length gradient (SL) index profile (red dashed line) correlated with longitudinal river profiles (blue line) showing abrupt SL peaks at sudden slope variation observed in main trunk channel bedrock. Small yellow mounds in miliolitic terrain of Singwada River and Hiran River is presence of E-W trending aeolianite ridges obstructing the main channel. Three yellow mounds with black dashed lines in Hiran River are coast parallel ridges.

In the case of Singwada River, the aeolianite ridges in the buried pediment surface plays a crucial role in gradient change over miliolitic terrain. The highest SL peak with class 4 is seen at 120, 110 and 90 m elevation with values of 459, 254 and 333 respectively (Figure 11.4). However, class 2 values are observed at 250, 130, 80, 60 and 50 m elevation. At contour interval between 120 to 90 m, trap-miliolite interface forming sharp slope change is detected (Figure 11.4). However, the drainage patterns at this elevation shows trellis and rectangular flow pattern. The lower reaches of the channel flows over the miliolite deposits consisting of E-W trending aeolianite ridges and sheet miliolites. A sharp channel curve at 70 m elevation is due to the aeolianite ridge (AR-1) obstructing the south flowing river (Figure 11.4). Formation of huge knickpoints (Jamjir

waterfall) of ~18-20 m forms gradient variation exhibiting sudden peak in the profile. The extension of aeolianite ridges (AR-2 and AR-3) merges along E-W trend around Singwada drainage basin. At 40 m elevation, another SL peak observed at sharp hook shaped meander depositing boulders eroded from these ridges (Figure 11.4). At 20 to 10 m contour interval, two ridges (AR-3 and AR-4) obstructs the river forming small meanders up to coastal zone (Figure 11.4). The presence of these ridges controls the river flowing in the miliolitic terrain.

The Hiran River shows very distinct SL peaks along with the longitudinal river profile. The SL index values are highly irregular that matches with the uneven river profile in the upland and buried pediment zone. The highest peak between 40 and 30 m interval is due to the presence of coast parallel ridges extending from the northwest up to the Saraswati River, major tributary of Hiran River (Figure 11.4). At the coastal zone, the high SL value indicates the presence of E-W trending aeolianite ridge (AR-1) extending from the east. The Saraswati River flows along this ridge up to the confluence with Hiran River near the small intertidal zone. The drainage basin topography of Singwada and Hiran River is largely controlled by aeolianite ridges in the miliolitic terrain. Whereas Machundri and Rawal River is mostly occupied by structurally controlled trappean dykes and hills. Overall, the formation of all the slope breaks are suggestive of structurally controlled dykes, trap-miliolite interface, variation in different phases of miliolite deposits, and trappean hills, tectonic uplift or presence of fault/deep seated fault.

Rivers flowing mostly in miliolite terrain

The SL index values of Somat, Sangawadi and Rupen River ranges from 5-109, 5-124and 5-117 respectively (Figure 11.5). These values are thus divided into four classes viz., class 1 (<30), class 2 (30-60), class 3 (60-90) and class 4 (> 90) where class 4 being highly active zone. The Rupen River flows towards east and abruptly curves towards south along the regional slope. At 10 m elevation, river flows along E-W trending aeolianite ridge (AR-4) towards west and merges with the mudflats (Figure 11.5). From 60 to 20 m elevation, the river flows in a lees gentle southward slope compared to the upland zone (Figure 11.5). This resulted in a large concave downward SL peak sue to the presence of aeolian dune field deposits over sheet miliolites.

The highest SL index value is at the coastal zone of the drainage basin due to the presence of aeolianite ridges incised by Rupen River exposing underlying Tertiary

deposits in the channel bedrock. The Sangawadi River shows several peaks belonging to class 4 at 70 to 50 m elevation and 20 m to the minimum elevation of the basin near river mouth (Figure 11.5). The trap miliolite interface around 70 m elevation results in sudden gradient change corresponds to the retreat of sheet miliolites from the downstream. The aeolianite ridge (AR-1) extending from the Veraval coast abruptly terminates around this elevation. At 60 to 50 m elevation, the SL value is 101 due to extension of two aeolianite ridges merging together forming a single ridge (Figure 11.5). These ridges control the drainage patterns and bedrock topography of Sangawadi River at the middle reaches. However, aeolianite ridge (AR-4) passes from the river mouth extending further eastward up to Machundri River (Figure 11.5).

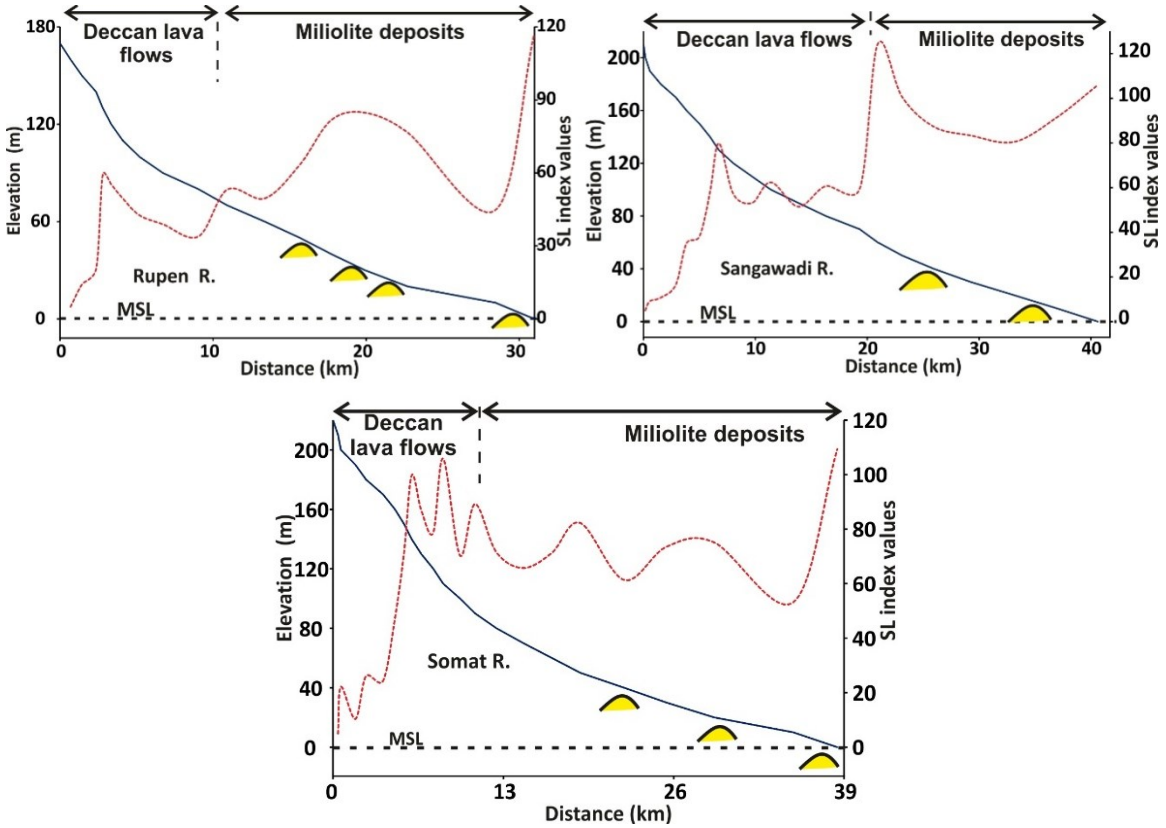

Figure 11.5 Stream length gradient (SL) index profile (red dashed line) correlated with longitudinal river profiles (blue line) for rivers flowing mostly in miliolitic terrain. Abrupt SL peaks indicates sudden slope change in channel bedrock. Small yellow mounds in miliolitic terrain are E-W trending aeolianite ridges hindering the main channel. Note the highest peaks are observed at the aeolianite ridge obstruction with channel.

The SL values of Somat River, however, shows five abrupt peaks. The maximum drainage basin area is occupied by aeolianite ridges and sheet miliolite deposits. The highest peak is observed at the mouth of the river where aeolianite ridge (AR-4) is

incised by the south flowing river. The other two peaks are also associated with the presence of aeolianite ridges (AR-2 and AR-3) eroded by the Somat river forming several knickpoints and narrow incised channels (Figure 11.5). Several abrupt peaks in the trap-miliolite interface shows SL values of class 4 (Figure 11.5). This infers that the Somat basin is controlled by miliolite ridge topography. In this category, all three rivers shows significant gradient change prominently at two places. The high SL values observed very near to the upper reaches of the stream are due to the trap and miliolite lithological contact. However, the rivers also show change in flow after this particular altitude due to the geomorphic changes of the irregular topography to gently sloping pediment surface because of aeolianite ridges. Another noteworthy observation regarding the high SL values indicates the tectonically active terrain of Quaternary miliolite deposits.

11.2.2 Valley floor width-to-height ratio (Vf ratio)

For the calculation of Vf ratio, locations from the main channel were selected from the upland zone and few in miliolitic deposits. The cross-sections shows U-shaped and mostly V-shaped valleys in upland zone and also over miliolitic terrain. Overall, the Vf ratio value ranges from 0.38 to 7.58 (Table 11.7) where value <1 is suggestive of tectonic uplift forming deep incised valleys and gorges.

Rivers originating in trappean terrain

The cross-sections from the selected location for calculating Vf ratio in Rawal, Machundri and Singwada river are one in upland zone, one at the trap-miliolite interface and one in the miliolitic terrain over buried pediment zone. However, Hiran basin is comparatively large and wide mostly over the miliolite deposited topography. Therefore, four locations of Vf ratio were measured, where two locations are over miliolitic terrain a and two over trappean upland zone. The value of Rawal river ranges from 0.63 to 4.00 as observed from upland to coastal zone which indicative of widening of channel as we go towards downstream (Table 11.7). The structurally controlled upland trappean terrain in Rawal and Machundri basin shows lowest Vf ratio due to the presence of very deep V-shaped valleys amidst hill range and dyke ridges. However, Machundri River shows V-shaped valley at the lower reaches incising sheet miliolites overlying Deccan traps up to ~12 to 15m (Table 11.7). The V ratio at trap-miliolite contact also shows lower values suggestive of ongoing incision of miliolites retreated towards the upland zone. The Vf ratio values for Singwada river ranges from 0.38 to 1.95 with lowest value is measured at

the middle reaches of the channel (Table 11.7). This zone of Singwada river shows anomalous river bends in south flowing straight channel. This is due to the presence of aeolianite ridges obstructing the channel flowing along the regional southward slope. The formation of deep V-shaped valleys and huge waterfalls are observed at this location. The Hiran River shows Vf ratio values ranges from 1.11 to 7.58 which comparatively displays more U-shaped valleys (Table 11.7). However, the highest values are taken from the miliolitic terrain around the coast parallel aeolianite ridges.

Rivers flowing mostly in miliolitic terrain:

The Vf ratio of Somat, Sangawadi and Rupen river shows lowest values around trap and miliolitic lithological contact. The south flowing rivers retreated the sheet miliolites from the buried pediment zone up to the trap-miliolite interface with the presence of steep gradient. The SL peaks are also prominently shows the higher values at this zone. The V-shaped valleys are observed mainly in Sangawadi and Somat River due to the obstruction of aeolianite ridges forming river to sharply meander. The Rupen River, however, shows more wide valleys over the gently sloping buried pediment zone. The values are > 7 which indicates very wide U-shaped valleys eroding the aeolian dune deposits and sheet miliolites (Table 11.7). Such wide valleys with less incision is only observed in the lower reaches of Rupen River.

11.2.3 Basin Asymmetric Factor (AF)

All the seven drainage basins show strong tectonic tilt with the AF values ranges from 0.31 to 0.58 (Table 11.7). The shifting of the main trunk stream towards the tectonic slope with rivers flowing along regional slope is evident in all the drainage basin.

Rivers originating in trappean terrain

The asymmetric factor calculated for all four rivers in this category shows very significant interpretation about the tectonic slope in the study area. The values indicates that the Hiran, Machundri and Rawal basin shows west to southwest ground tilt (Figure 11.6). However, Singwada River, alone, shows southeast basin tilt indicated by the shifting of main channel towards ESE (Figure 11.6). Considering overall trend of the basin by looking at the basin length, Machundri and Rawal River shows SSE while Hiran and Singwada river shows SW to SSW trend (Figure 11.6). The Singwada River is the most elongated basin with several anomalous channel meanders, deep incised V-shaped valleys, knickpoints, huge waterfalls and SSE basin tilt. However, Hiran River shows

high AF value i.e. 31 (looking upstream) indicating the westward channel shift and major tributaries like Saraswati River flowing along the aeolianite ridge towards west confluence at the coast (Figure 11.6, Table 11.7). These values indicate that the overall regional slope is towards south to southwest. However, the tectonic tilt calculated through AF indicates ongoing neotectonic activity over the upland and buried pediment zone resulting in strong variation in ground slope.

Table 11.7 Valley floor width to height ratio, Asymmetric factor and Hypsometric integral calculated for river flowing in morphotectonic domain-II.

Basin	Vf ratio	Basin area (A) km^2	Area of a part of a basin on the right of the main stream (looking downstream) km^2	AF %	Maximum elevation (m)	Mean elevation (m)	Minimum elevation (m)	Hypsometric Integral
Rivers originating in trappean terrain								
Rawal R.	**0.63**	371	142.18	38	507.40	213.95	13.5	0.41
	1.38							
	4.00							
Machundri R.	**0.45**	408	192.48	47	467.70	165.51	5.5	0.35
	1.73							
	0.87							
Singwada R.	1.20	485	283.31	58	610.80	195.74	0.2	0.32
	0.38							
	1.95							
Hiran R.	3.57	939	293.11	31	405.90	127.82	0.1	0.31
	1.11							
	7.58							
	7.06							
Rivers flowing mostly in miliolitic terrain								
Rupen R.	1.10	24	103.09	46	228.70	56.75	6.3	0.23
	7.58							
	7.06							
Sangawadi R.	2.45	25	127.82	57	291.20	87.78	4	0.29
	0.89							
	2.73							
Somat R.	1.40	54	122.48	48	244.20	67.55	5.9	0.26
	1.60							

Rivers flowing mostly in miliolitic terrain:

The AF values measured for the rivers in this category shows Sangawadi basin as highly asymmetric while Rupen basin shows very low symmetry (Figure 11.6). The values indicates that the Sangawadi River shows ESE to SE channel shift while flowing

along the southward regional slope. However, Rupen and Somat drainage basin shows low asymmetry with basin tilt towards southwest (Figure 11.6). The Sangawadi River flowing amidst Singwada and Rupen River. However, the shape, drainage characteristics and tectonic tilting of Rupen and Sangawadi River shows variation. Singwada and Sangawadi rivers show ground tilting towards right (facing upstream) while all other basins show westward basin tilt (Figure 11.6). This indicates that these rivers are highly affected by tectonic activity resulting in the inconsistency of all the parameters results compared with other drainage basins (Figure 11.6).

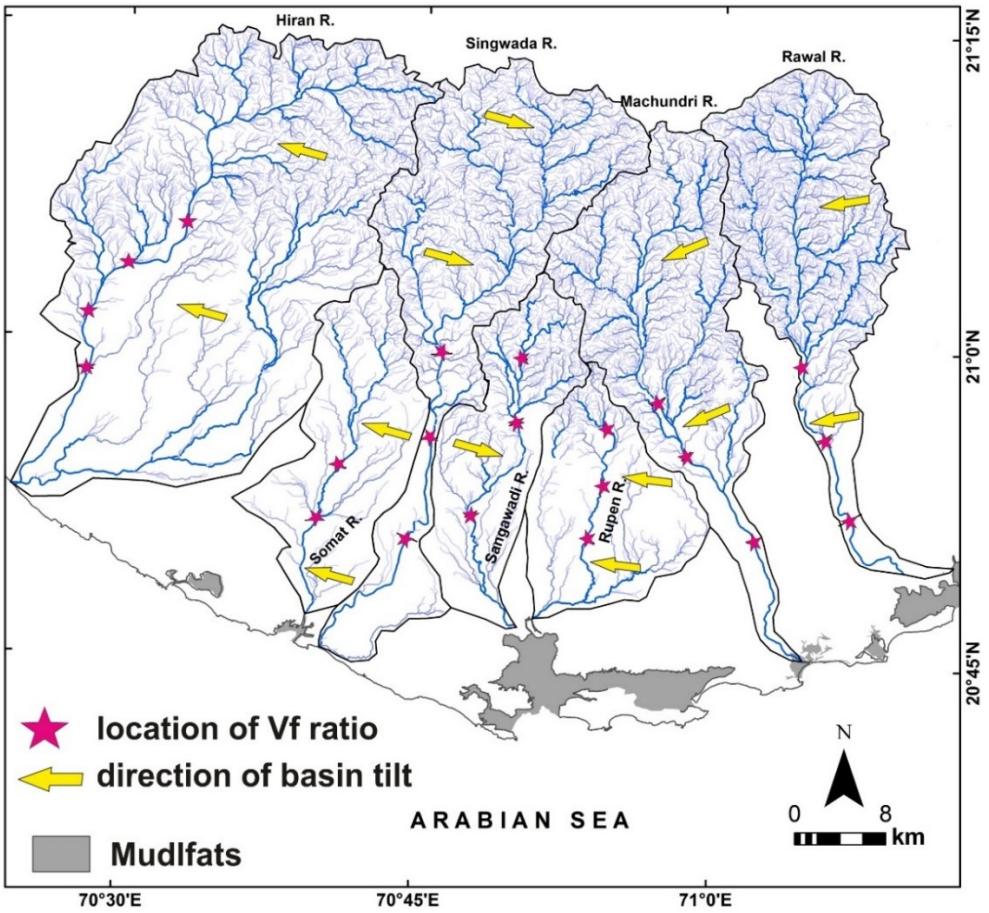

Figure 11.6 Drainage map showing locations of Vf ratio calculated and direction of basin tilt showing drainage basin asymmetry. Pink star represents the location of cross-sections taken for Vf ratio. Yellow arrow suggests the direction of the tectonic tilt resulting in shifting of the main trunk stream towards the slope. Note the Singwada and Sangawadi River showing eastward basin slope while others are towards west.

11.2.4 Hypsometric Integral (HI)

Rivers originating in trappean terrain

The basin topography of Rawal and Machundri River is high relative to its mean elevation showing high HI values. As most of the drainages are flowing in the upland

zone, the trappean rocks are highly dissected and eroded by south flowing channels resulting in irregular dissected landscape. The high integral values are also suggestive of very young stage of channel erosion (Figure 11.7). The rivers originating in the upland zone are at youthful stage described by undulating relief with deep incising valleys and gorges in the trappean terrain (Figure 11.7). The landscape evolution of these drainage basins needs long time to obtain the equilibrium.

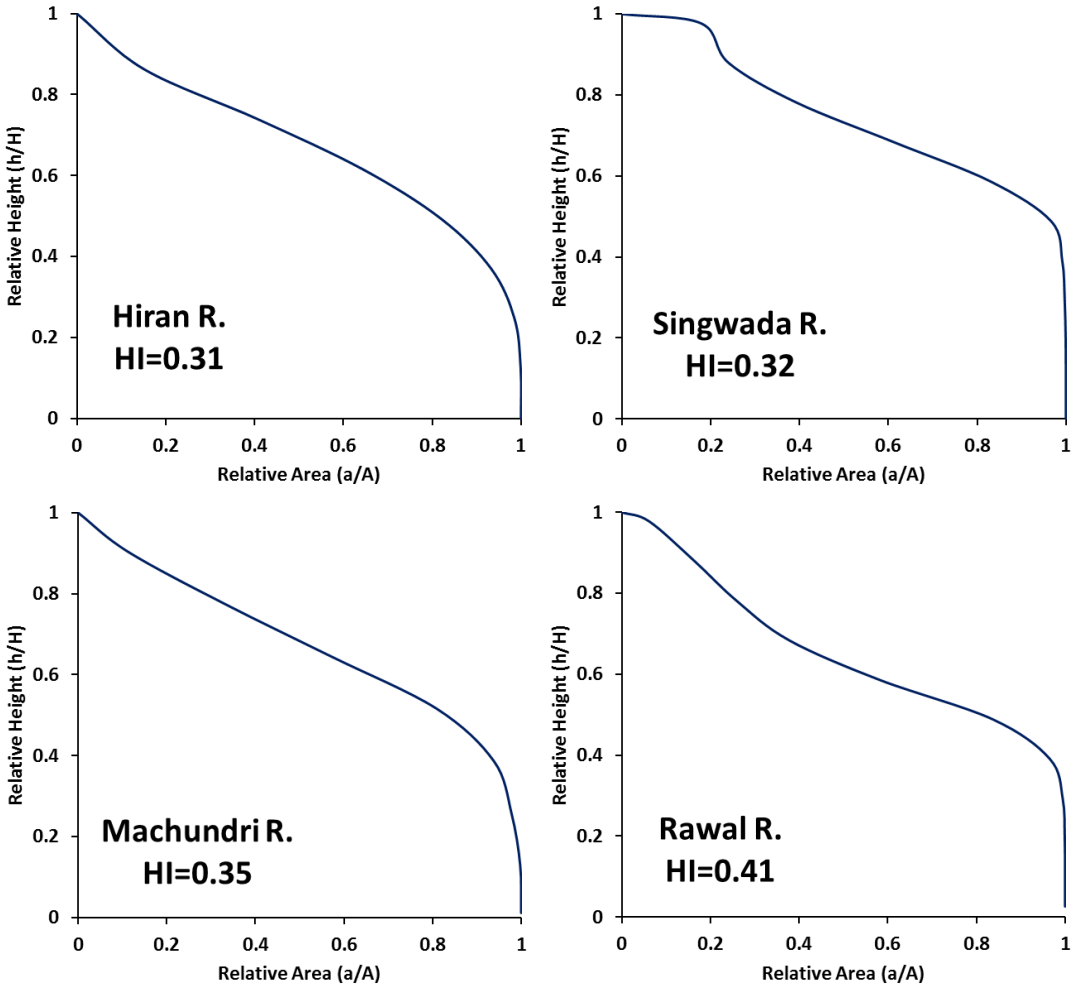

Figure 11.7 Hypsometric curves of river arising in the trappean upland. Convex upward to almost sigmoidal shaped curves indicating youthful to moderate stage of basin development. Note the higher HI value of Rawal River inferring to very young erosional stage.

Rivers flowing mostly in miliolitic terrain:

The values of hypsometric integral of Somat and Rupen River basin is indicative of evenly dissected terrain by south flowing parallel drainage over gently sloping planar topography forming broad valleys (Figure 11.8). However, at few places, deep channel incision is observed in these rivers due to the presence of aeolianite ridge. The straight

course towards coast is still denudating the Quaternary miliolites. Rupen River incising aeolian dune deposits and sheet miliolites shows lowest Hi value inferring very high degree of erosion in this domain. Due to the tectonic tilt towards west and southwest, the channel incise strongly the trappean dykes and aeolianite ridges forming deep incised valleys. The stage of channel development for all the rivers are measured by plotting hypsometric curve.

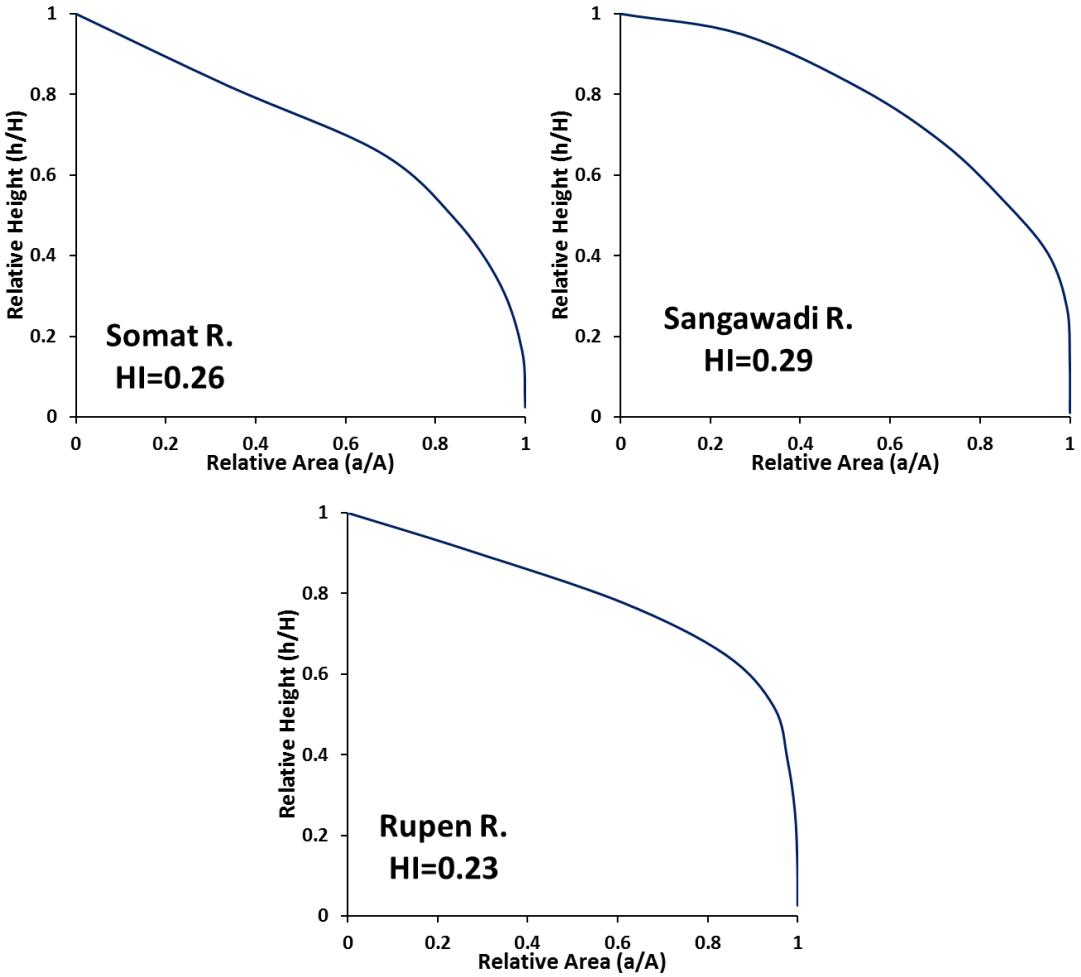

Figure 11.8 Hypsometric curves with hypsometric integral values of rivers flowing mostly in miliolitic terrain. Note the highest HI value of Sangawadi river and convex up curve indicating youthful basin development stage.

11.2.5 Hypsometric curve

Rivers originating in trappean terrain

Almost all the rivers are showing high to moderate values of hypsometric integral which indicate the youthful stage of basin landscape development. However, hypsometric curve gives a clear indication about the erosion cycle and present day basin topography. The convex upward hypsometric curves observed in all the rivers except Rawal and

Singwada basin showing sigmoidal shape curve. The S- shaped curve of river Singwada and Machundri with HI values 0.47 and 0.53 respectively shows that these two river basins are moderately eroded with presence of valleys, knickpoints and the basin is still developing (Figure 11.7). While Rawal river basin with HI value 0.68, shows sigmoidal shaped hypsometric curve which clearly indicates that the basin is moderate stage of basin development (Figure 11.7).This analysis is helpful in the present study to understand the tectonically active zones as these profiles are sensitive to landscape evolution.

Rivers flowing mostly in miliolitic terrain:

The convex upward shape of all three basins is suggestive of youthful stage of basin (Figure 11.8). The river flowing mostly in miliolitic terrain infers that Sangawadi River is structurally and tectonically controlled by either deep seated faults over Quaternary surface or tectonic uplift. The Somat River has incised strongly the aeolianite ridges showing very deep incised valleys in the gently sloping miliolitic terrain (Figure 11.8). However, Rupen River is showing almost s-shaped hypsometric curve indicating that the river is going to moderate erosional stage which is evident by wide meandering channels over the buried pediment zone (Figure 11.8). The Sangawadi River is at very youthful erosional phase where the ruggedness and uneven dissected topography is observed (Figure 11.8).

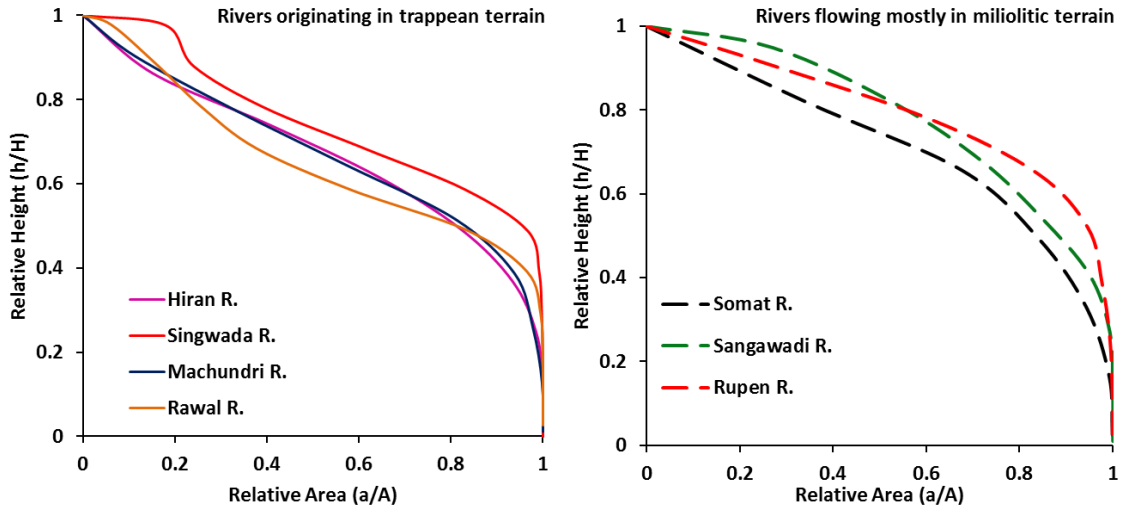

Figure 11.9 Hypsometric curve with hypsometric integral values. Rivers originating in trappean terrain shows s-shaped curves representing moderate erosional stage. Rivers flowing mainly in miliolitic deposits convex up curves signifies youthful basin topography.

Comparing the hypsometric curves of rivers in both the categories infers that the rivers flowing mostly in miliolitic terrain are at very youthful stage of basin development (Figure 11.9). The deep incised V-shaped valleys and bedrock erosion of miliolite deposits deduces post-miliolitic uplift and ongoing neotectonic activity. However, the rivers arising from trappean highlands shows evenly dissected trappean landscape showing s-shaped curves. The HI values shows intermediate to high values for all seven drainages and youthful to moderate erosional stage in morphotectonic domain-II.

Considering the geomorphic indices and morphotectonic analysis results of major rivers arising in trappean upland and small rivers flowing mostly in miliolitic terrain, Singwada River and Sangawadi River shows distinct characteristics in drainage characteristics, incised channel valleys, basin asymmetric factor and abrupt gradient changes. The tectonic tilt of these two rivers shows significantly towards east and southeast showing very youthful basin development stage. This indicates that the presence of strong structural and tectonic control in morphotectonic domain-II is observed near Singwada and Sangawadi river basin. However, post-miliolitic tectonic uplift is inferred in all seven rivers which is evident from the outcomes of morphotectonic parameters. The presence of deep incised valleys, sharp anomalous channel bends, knickpoints, rapids, abrupt gradient change, sudden change of river course and drainage adjustment to the gently sloping miliolitic terrain infers that the area is affected by either coastal uplift, subsurface structures or earthquake swarm activities.