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Spatial Heterogeneity of Catchment Morphology and Channel Responses: A Study of Bakreshwar River Basin, West Bengal

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Abstract: *This paper synthesises the upshot of catchment topographic asymmetry on channel morphological structures and functions for the 5th order un-gauged Bakreshwar watershed. The study has revealed that, asymmetry in different physical attributes at a catchment scale explains a number of consequent channel hydro-geomorphic events. A little topographic tilting of the basin towards the north or left bank has acted as a dominant control on alignment of water flow paths, flood spreading etc. The spatially skewed nature of fluvio-geomorphic activities of the basin is manifested in (i) the tendency of rivers to migrate towards the north leaving a number of palaeochannels in the southern part of the basin, (ii) position of the thalweg closer to the left bank, (iii) concentration of erosion and stream instability in the left bank, and (iv) spread of floodwater more in the left side of the channel. However, the role of catchment geology in controlling the heterogeneity of fluvial forms of the area is a key element, which needs investigation.*

Introduction

Fluvial morphology results from the complex interplay of geomorphic processes that occur in a basin at different spatial and temporal scales (Schumm, 1988; Piegay and Schumm, 2003; Church, 2008; Schumm and Lichty, 1965; Lane and Richards, 1997). Among the variables that affect fluvial systems, catchment topography is one of the most important and have causal link to the hydrological forces, the channel network, valley form, spreading of flood water, meandering, and migration of channels (Bloschl, 2005; Rodriguez-Iturbe and Valdes, 1979; Horton, 1945; Strahler, 1964; Zevenbergen and Thorne 1987; Patton, 1988; Leopold and Wolman, 1957). Hence, it is rightly regarded that, streams are the manifestation of the landscapes that they drain (Hynes, 1975). Channels, respective to the basin topography tend towards an equilibrium state by means of changes in channel course, shape and profile through valley erosion and deposition of sediments (Montgomery and

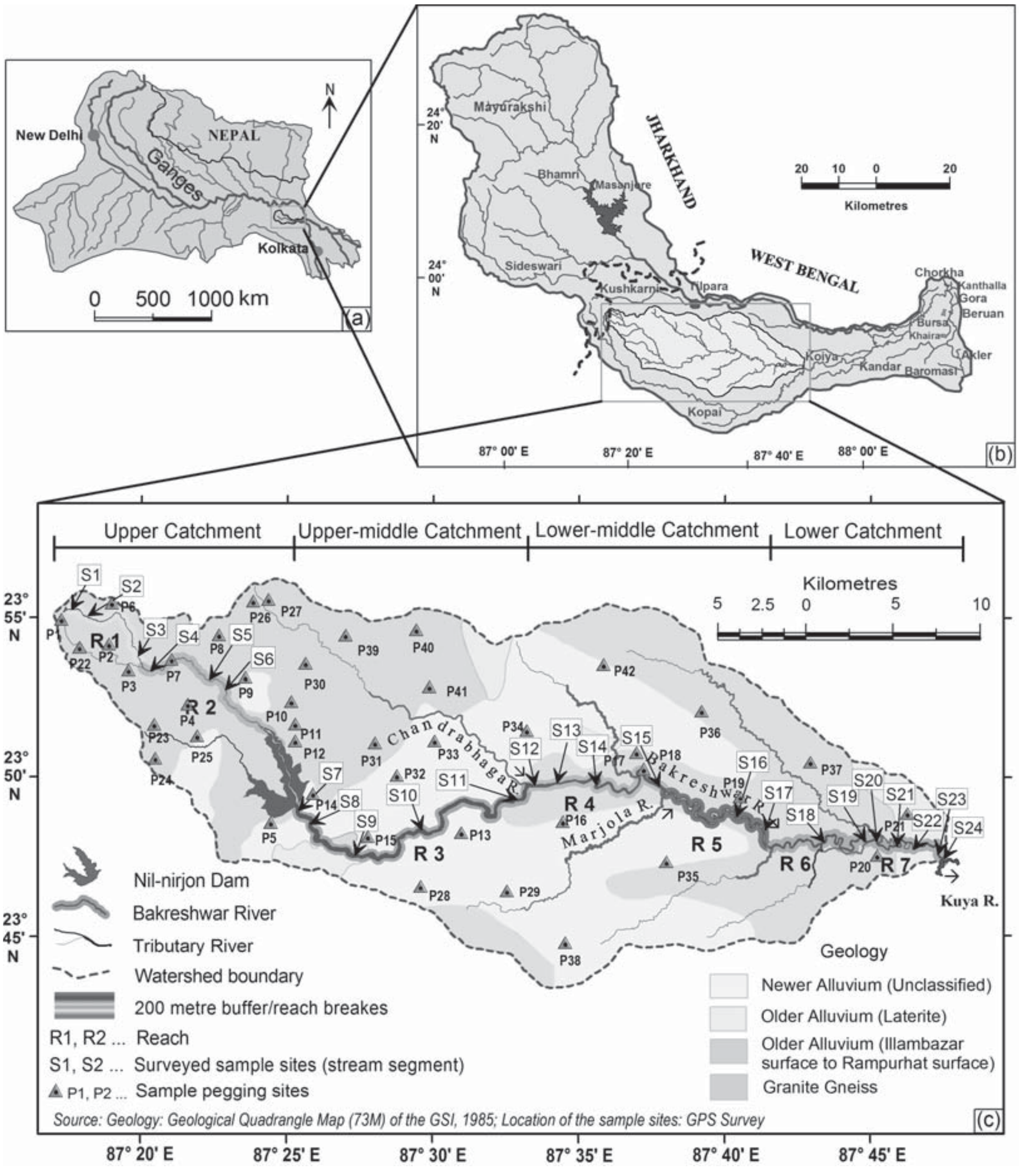

Figure 1. Reference Map: (a) The Ganga catchment, (b) The Mayurakshi river basin, (c) The Bakreshwar river basin.

Buffington, 1998). Different authors have reviewed this influence of the drainage basin on fluvial channels like, Anderson and Burt (1978), Amos and Burbank (2007); Begin (1981), Beven, *et al.* (1988), Masoud (2013) etc. Brierley and Fryirs (2005) argued that, natural channels are 'dynamically adjusted' and works within a range of 'variability set by the river style' and the 'catchment context'.

Drainage basins have long been described based on the main geomorphic processes of erosion, transportation and sedimentation (Schumm, 1977; Gregory and Walling, 1973). It is however, rather surprising that catchment topographic influence on channel hydro-morphology has received relatively little attention. In most hydrological systems of interest, this would however appear to be a difficult task because; the response time of the geomorphological systems are much longer than hydrological systems. Consequently, the channel hydro-morphology recorded today may, in most catchments, reflect responses of catchment topography in a longer time span.

This paper will concentrate on the influence of catchment topographical heterogeneity and asymmetry on channel morphology of the 5th order un-gauged Bakreshwar watershed. In the present work catchment topography has been considered as one significant variable to regulate the processes and the responses reflected in channel hydro-morphological nature and functions. Few observations have been incorporated in the present study, addressing the said links. However, there is yet an obvious need for collecting new field data and consider other variables that affect stream systems.

Geographic location of the study area

The Bakreshwar river is a 5th order tributary of the river Kopai (Kuya) and a part of Mayurakshi river system of eastern India. The present study area, Bakreshwar river catchment (BRC) is a part of lateritic Rarh plain region extending from 23º43′23.28″ N to 23º56′31.16″ N latitude and 87º17′1.59" E to 87º47′16.07″ E longitude. The drainage basin is covered by five Survey of India (SoI) topographical sheets — 73M/5, 73M/9, 73M/10 and 73M/13, on 1:50,000 scale. The study area lies in between the river Mayurakshi in the North and Kuya in the South. It is bounded by district boundary of Birbhum in the west while the boundary of Murshidabad district of West Bengal forms the eastern limit of the region. The river originates from a large pond (23°55'22.13"N, 87°17'18.46"E) and then flows through the hot springs of Bakreshwar (23.88°N 87.37°E) and joins river Kopai at 23°47'06.3"N and 87°48'26.09"E.

Regional settings

The Bakreshwar river basin (basin area: 714.56 km^2) is a fifth order basin having 3 fourth order, 13 third order, 54 second order and 318 first order sub-basins, all of which are rain fed with little perennial water. Total length of the river is 86.385 km. of which about 13.9 km. is perennial.

The catchment has dry, mild sub-humid and subtropical monsoon climate. As per 33 year meteorological data (1980–2013), rainfall varies with elevation from 828.8 mm to 1917.1 mm (IMD, 2013). During monsoon (June to September) advective rainfall is dominant. Presence of laterites indicates the existence of tropical wet-dry climate in this area, probably during Tertiary. Hard massive basalt of Jurassic to Cretaceous age, soft and medium hard laterite of Cenozoic age and china clay of late Pleistocene to early Eocene age (GSI, 1985) are found in different parts of the basin and at different depths (Saha, 1961

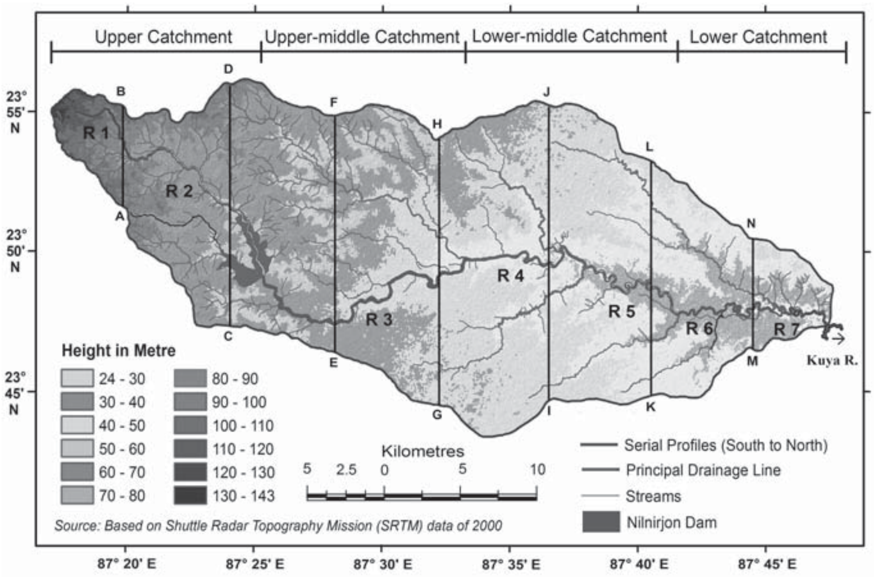

Figure 2. Relief classes of Bakreshwar river basin (based on SRTM data of February 2000)

and GSI, 1985). The area is covered mostly by reddish, loose, friable and sterile laterite soil with ferruginous concretions, locally called kankar. Owing to extreme infertility, the land is named Rarh or sterile land (O'Malley, 1910). The soil catena consists of plateau fringe and high plains with laterite soil (ultisols), adjacent slopes with sandy and loamy soils and small valley floors with older alluvial soils (ulfisols) (NATMO, 2001). Moderate to maximum physical and chemical weathering, moderate to maximum hill slope processes including sheet wash, rain splash, rill and gully erosion and laterisation are some major pedo-geomorphic processes operating in the region. The typical morphological features in the upper part of the basin include: rolling lateritic uplands with ferricrete-dominated duricrusts and deep red weathering zones, amd wide planation surfaces. Badlands and low lying flats characterise the basin's lower part. It is found that in pre-monsoon the average water level generally remains above 12 m depth (April, 2009) and in post-monsoon the average water level is near about 6 m depth (November, 2009) (SWID, 2009). Upper catchment of the basin is covered with Sal (Shoria robusta) forest but a large part of the forest is decaying rapidly.

Catchment morphological heterogeneity and asymmetry

Profile analysis of the basin

Profile indicates the nature of surface configuration and the degree of dissection of terrain (Woldenberg, 1967). 7 Serial profiles are drawn across the Bakreshwar river basin aligned North-South. (Fig. 3). One important aspect which can be ascertained from these profiles is that; the slope and relief character is not symmetric along two banks of the main river. The N-S cross profiles indicate that the slope and height in the left hand side of the catchment is relatively less, compared to the right hand side. This kind of pattern may encourage river shifting and greater spread of flood water towards the left bank of the main water course.

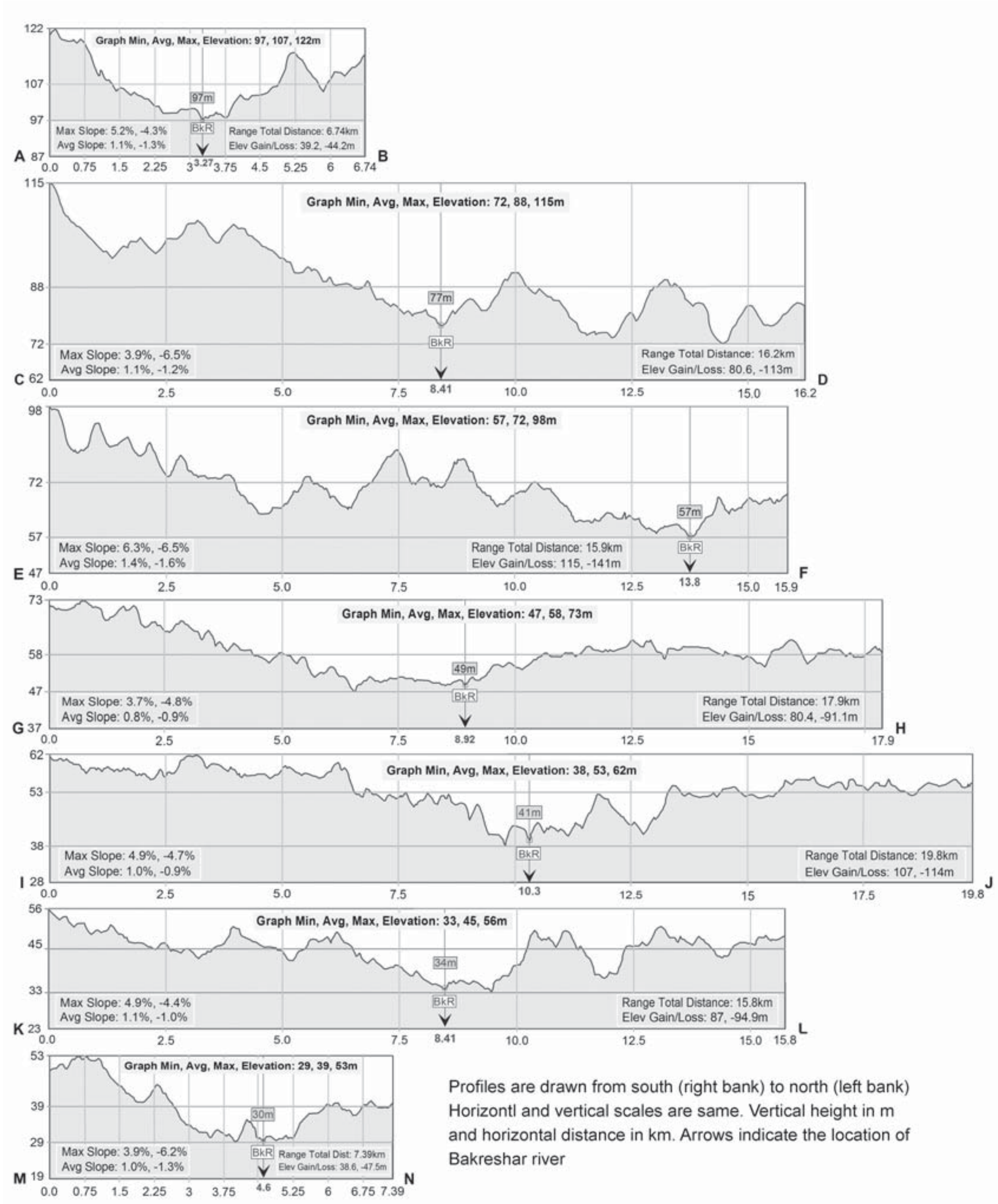

Figure 3. North–South profiles across Bakreshwar river basin from upstream to downstream at an interval of about 6.5 km. Note the pointer indicating the basin mid points (Based on ASTER DEM of February 2012).

Table 1. Indices used for basin asymmetry assessment.

Basin asymmetry indices	Formula/Derivations	Reference
Areal Asymmetry Index (AAI)	$AAI = \frac{Al}{Am}$ Where, *Al* denotes one side of the main stream having less area and *Am* denotes one side of the main stream having more area.	Das, P. *et al.*, 2014
Stream Number Asymmetry Index (NAI)	$NAI = \frac{N\mu l}{N\mu m}$ Where, *Nµl* = One side of the main stream having less total number of stream; *Nµm* = One side of the main stream having more total stream number.	Das, P. *et al.*, 2013
Stream Length Asymmetry Index (LAI)	$LAI = \frac{L\mu l}{L\mu m}$ Where, *Lµl* = One side of the main stream having less total stream length; *Lµm* = One side of the main stream having more total stream length.	Das, P. *et al.*, 2013
Composite Basin Asymmetry Index (CAI_B)	$CAI_B = \frac{\sum_i^n \mathrm{PAI}}{N}$ Where, *N* = Number of parameters and *PAI* = Parameter Specific Asymmetry Index. Here, *∑PAI = (AAI+NAI+LAI)/3* ***Or*** $\sum_{i=1}^{n} PAI = [\frac{Al}{Am} + \frac{\mathrm{N\mu l}}{\mathrm{N\mu}m} + \frac{\mathrm{L\mu l}}{\mathrm{L\mu}m}]/3$ PAI_B values range from 0-1. '0' means high asymmetry and '1' means symmetry.	Das, P. *et al.*, 2013
Transverse Topographic Symmetry Factor (TSF)	TSF = Score has been obtained by dividing proportion of length in two sides of the principal drainage line when the drainage basin is divided into sections by the straight line traversing the main river at 90^0 angle.	Moglen, G.E. and Bras, R.L., 1995.
Catchment Front Sinousity Index (SIcf)	$SIcf = \frac{Lcf}{Ls}$ Where, *SIcf* = Catchment Front Sinuosity Index *Lcf* = straight line distance along a contour line, *Ls* = true distance along the same contour line.	Bull, W.B., and McFadden, L.D., 1977

ASSESSMENT OF BASIN ASYMMETRY: From profile analysis it is found that the river has a tendency to shift towards its left bank which can be attributed to greater erosion and higher flood sprawl on the left side by southeast-oriented streams. So, there is a need to investigate the contrasts that exists between the left and right side of the trunk stream of

Table 2. Input database and basin asymmetry results of Bakreshwar river

Basin Asymmetry Parameters	Left Side of the Master Stream	Right Side of the Master Stream	Basin Asymmetry Indices (PAI_B)	CAI_B
Basin Area	404.31 km^2	310.25 km^2	0.767	0.734
Number of Stream	228	185	0.81	
Length of Stream	337.38 km	210.77 km.	0.625	

the basin, their relative status and some inherent characteristics of the studied river basin. These investigations will help to provide useful information to explain the lopsided tendency towards the left with a larger proportion of area in the left side than on the right side. All Parameter-specific Asymmetry Indices (PAI) show almost the

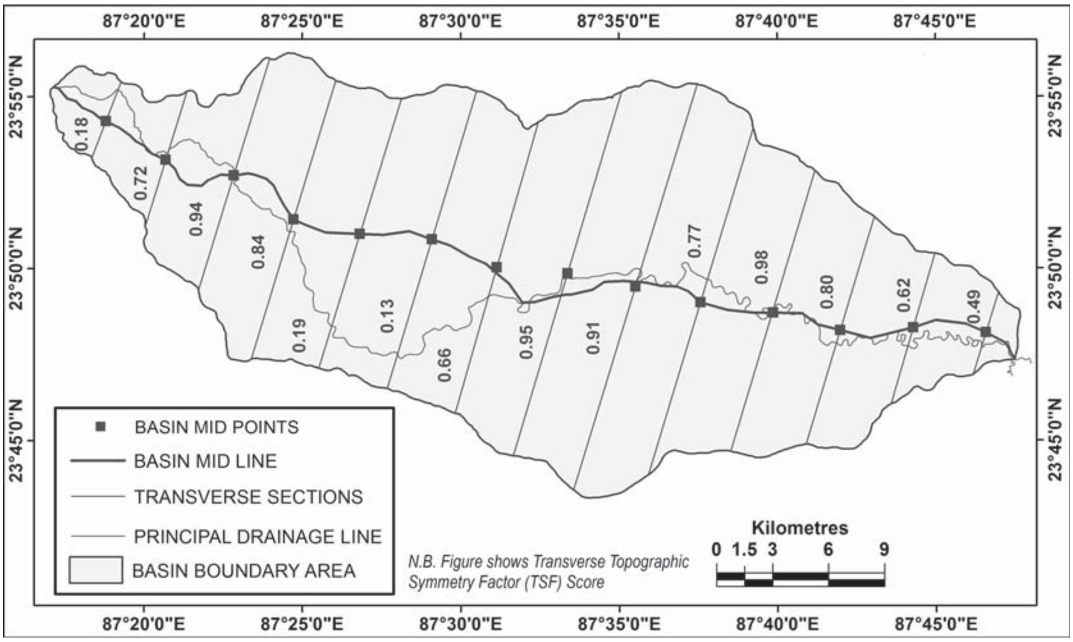

Figure 4. Transverse Topographic Symmetry Factor (TSF) Map of Bakreshwar River Basin

structural control on the hydrological behaviour of the watershed.

COMPOSITE BASIN ASYMMETRY INDEX (CAIB): For Bakreshwar river basin is 0.734, means that the basin is on an average 27% away from achieving accordant distribution of the selected parameters as a whole between left and right part of the basin. The basin has same tendency as like areal asymmetry. Stream length asymmetry of 0.625 indicates that, out of total stream diversity of the basin, left side of the catchment explains 62% and right side explains only 38%. Higher relief, slope and lesser number of associated streams can explain the low percentage of stream diversity on the right side of the basin.

Table 3. Catchment front sinuosity index

Contour height	Length of contour at the Left side of the main stream		$SIcf_L$	Length of contour at the Right side of the main stream		$SIcf_R$	Total length of the contour		$SIcf_B$
	Actual	Straight		Actual	Straight		Actual	Straight	
120	5.314	2.218	0.417	8.461	2.848	0.337	13.775	4.399	0.319
100	32.349	9.385	0.29	32.693	9.026	0.276	65.042	13.482	0.207
80	89.594	12.69	0.142	41.683	11.534	0.277	131.277	12.649	0.096
60	50.036	21.339	0.426	19.182	10.852	0.566	69.218	21.223	0.307
40	50.254	18.077	0.359	46.861	14.684	0.313	97.115	5.247	0.054
Avg.	45.509	12.742	0.327	29.776	9.7888	0.354	75.285	11.4	0.197

TRANSVERSE TOPOGRAPHIC ASYMMETRY (TSF): Is widely used for determining the possible tilt direction (Bull and McFadden, 1977). Perfect symmetric basins have value of TSF as 1 — as the asymmetry increases TSF decreases and approaches the value of zero. The result varies between 0.13 and 0.98. The upper part of middle catchment indicates more asymmetry where TSF values are as low as 0.13 and 0.19 (Fig. 4).

CATCHMENT FRONT SINUOSITY INDEX (SICF): Is based on the observation that catchment front of a river basin, demarcated by contour line are more patchy over a asymmetric landscape than over the region where landscape is relatively symmetric. The morphology of a catchment front depends upon the degree of exogenic activity like erosion. Active fronts will show straight profiles with lower values of SIcf and less active fronts are marked by

Table 4. Selected basin morphometric parameters

Sl No.	Morphometric variable	Methodology	Sl No.	Morphometric variable	Methodology
1	Stream frequency (Df)	Horton, 1945	9	Maximum relief (Ab/Rmax)	Smith, 1935
2	Drainage density (Dd)	Horton, 1932	10	Minimum relief (Rmin)	Smith, 1935
3	Drainage texture, (Dt)	Horton, 1945	11	Average relief (Ra)	Smith, 1935
4	Length of overland flow (Lo)	Horton, 1945	12	Relative relief (Rr)	Smith, 1935
5	Constant of channel maintenance, (CCM)	Schumm, 1956	13	Dissection index (Di)	Dov, Nir, 1957
6	Drainage intensity (Di)	Faniran, 1968	14	Ruggedness number (Rn)	Patton and Baker, 1976
7	Infiltration number (In)	Faniran, 1968	15	Average slope (θ)	Wentworth, 1930
8	Frequency of stream junction points (Sjf)	Smith, 1935			

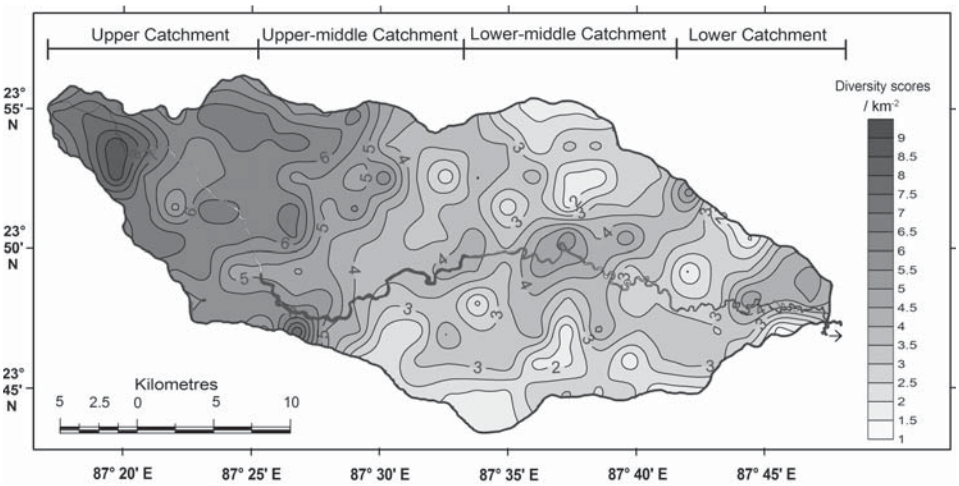

Figure 5. Basin morphometric diversity map
(based on composite score of Df, Dd, Dt, Lo, CCM, Di, In, Sjf, Ab/R_{max}, R_{min}, Ra, Rr Di, Rn and θ)

irregular or more eroded profiles, with higher SIcf values (Wells *et al.,* 1988).

In the present study SIcf values have been computed for five major contour lines viz,, 120, 100, 80, 60 and 40 metre according to Bull and McFadden (1977). SIcf values less than 0.15 indicates more asymmetric areas, between 0.15 and 0.4 indicate moderately asymmetric areas and SIcf values greater than 0.4 indicate areas with low topographic asymmetry (Table 3). This study concludes that, topographic asymmetry is higher in the middle catchment than rest part of the Bakreshwar river basin.

Assessment of basin morphometric diversity

Here grid (1 km^2) specific individual standard scores, SC (SC=Xi/XMax; where, XMax=Maximum value of column and Xi=variable) of 15 morphometric parameters, which have been added to get composite basin morphometric diversity score and mapped accordingly (Table 4).

In the uppermost zone the diversity score is highest where high relief, greater slope and several lower order streams are the important landscape elements. In the lower catchment the diversity zones are fragmented in patches. In the middle catchment the patches are distributed in clusters and the composite score reflects the heterogeneity of the area. The middle and lower catchment shows the most complex landscape character and the greatest diversity.

Some observation of channel hydro-morphology

Field survey sites

The Bakreshwar river was surveyed during 2011–14 at 24 sites having reasonably homogenous hydro-geomorphic traits along the stream corridor. Table 5 shows the locations of the survey sites.

Bank wise width variation from thalweg: There is obvious disparity in the distribution of width from thalweg to the banks. The average width of the left bank from thalweg is 25.73 m. while it is 27.97 m. in case of right bank. This indicates that the thalweg of the River is closer to the left bank (Fig. 6). The average cross sectional width increases downstream, with consequent increase in the

Table 5. Survey site locations and distances from the source of the main river

Name of the sites	Site ID	Distance from source (in km)	Location	
			Latitude (N)	Longitude (E)
Babupur-I	1	0.97	23º 55′ 17.25″	87º 17′ 50.45″
Babupur-II	2	1.03	23º 55′ 15.62″	87º 17′ 54.004″
Banshbuni-I	3	7.67	23º 53′ 30.4″	87º 19′ 57.1″
Banshbuni-II	4	7.71	23º 53′ 28.5″	87º 19′ 58.0″
Bakreshwar-I	5	13.18	23º 53′ 7.4″	87º 22′ 20.7″
Bakreshwar-II	6	13.44	23º 53′ 4.3″	87º 22′ 33.6″
Nilnirjon	7	23.55	23º 49′ 3.87″	87º 25′ 19.99″
Sagar	8	24.11	23º 48′ 50.6″	87º 25′ 18.7″
Pirijpur	9	29.11	23º 47′ 31.65″	87º 27′ 26.45″
Jostabad	10	34.3	23º 48′ 23.5″	87º 29′ 31.7″
Kanspai-I	11	44.14	23º 49′ 47.6″	87º 33′ 17.8″
Kanspai-II	12	44.27	23º 49′ 47.8″	87º 33′ 18.4″
Palsita	13	46	23º 49′ 51.7″	87º 34′ 5.2″
Hatikra	14	49.39	23º 49′ 46.9″	87º 35′ 35.4″
Patharghata	15	55.12	23º 49′ 40.33″	87º 37′ 46.96″
Julntha	16	63.2	23º 48′ 52.0″	87º 40′ 17.4″
Tekadda	17	67.56	23º 47′ 56″	87º 41′ 35.1″
Babna	18	73.92	23º 47′ 58.5″	87º 43′ 37.8″
Khagradanga-I	19	77.51	23º 48′ 01.3″	87º 44′ 43.3″
Khagradanga-II	20	77.6	23º 48′ 01.17″	87º 44′ 45.9″
Dhangara (Kendla)	21	80.9	23º 48′ 00.1″	87º 46′ 15.2″
Shekhampur (Dwimohini)	22	82.87	23º 47′ 53.919″	87º 46′ 21.651″
Milonpur-I	23	86.16	23º 47′ 06.7″	87º 48′ 26.3″
Milonpur-II	24	86.21	23º 47′ 06.1″	87º 48′ 27.3″

Note: 1. Rainfall on 19 September 2000 (River Research Institute, Kolkata)

width from thalweg to the bank. The width is maximum in the middle stretch (Figure 6).

Bank wise variation of slope

There is significant variation in bank side slope of each site and on an average left bank top to foot slope as well as top to thalweg slope is comparatively more than the right bank. This again has confirmed that river bank erosion is more in the left bank. Shifting tendency of the thalweg towards the left bank caused variation in the channel geometry. The slope of the banks in selected survey sites is quite steep at the head, gradually decreasing downward, again increasing in the middle and lower middle stretch. Catchment

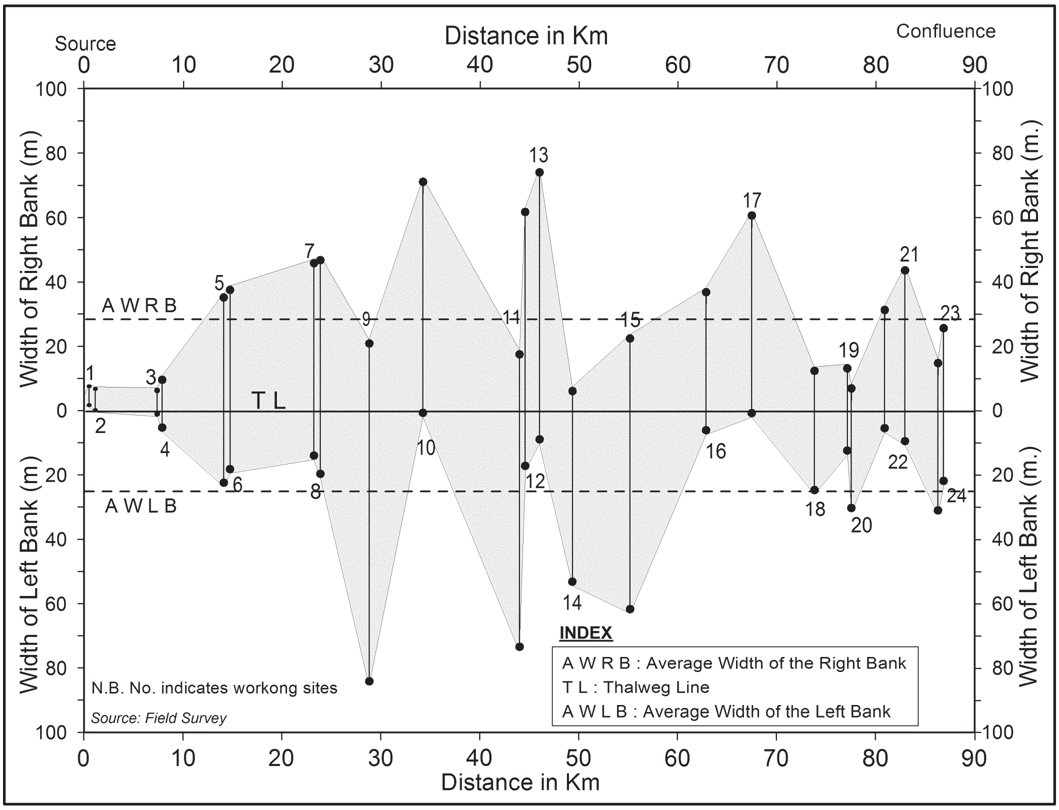

Figure 6. Variations in width from thalweg to channel banks at different sections across the Bakreshwar at 24 survey sites shown in Table 5.

morphological heterogeneity explains this overall trend of slope.

Assessment of bank erosion

In the present section, attempts have been taken for quantitative assessment and prediction of Stream Bank Erosion Hazard Potential (SBEHP) at 24 selected segments along the Bakreshwar river using the Bank Erosion Hazard Index (BEHI) of Rosgen, (2001).

The values of BEHI decrease marginally downstream. It means the erosion rate as well as probability of channel modification decreases downstream. Factors that are responsible for SBEHP in the upper catchment area are largely due to catchment morphological responses. From source to mouth it has been noticed that the rate of erosion is slightly more on left bank of the river. Such unequal rate of erosion between left and right bank indicates the erosional vulnerability of the left bank.

Assessment of the flood affected area The spatial flood coverage area during last 6 flood years since 1978 has been detected based on field survey data and from the data-base of Ankur Patrika, 2002; Dasgupta, 2002; Anonymous, 2000, 2002; Govt of West Bengal, 1992, 1999, 2000, 2007, 2009, 2011 and 2014 (Table 6). It is also significant to

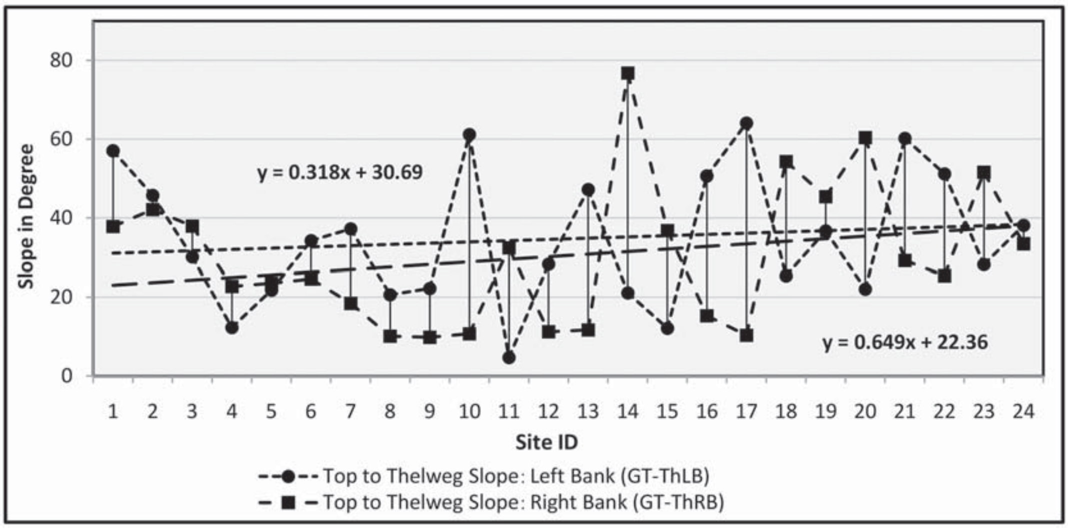

Figure 7. Bank top to foot slope at different cross sectional sites across the Bakreshwar river

note that (Fig. 10) in most of the flood affected years, the flood sprawling is more in the left hand side of the main river.

Detection of channel meander migration
There is a definite influence of catchment morphology on the rate and direction of channel migration. (Hooke, 1980; Lawler *et al.*, 1999, Nanson and Hickin, 1986, Mac Donald, 1991, Biedenharn *et al.*, 1989, Petts and Gurnell, 2005). The evidences are visible in the present river also. Identification of palaeochannels was done based on SoI topomaps (79M/5, 9, 10 and 13, surveyed in 1916-17 and 1968-69), Landsat-8 OLI image of 26 April 2013 (path 138, row 44) and

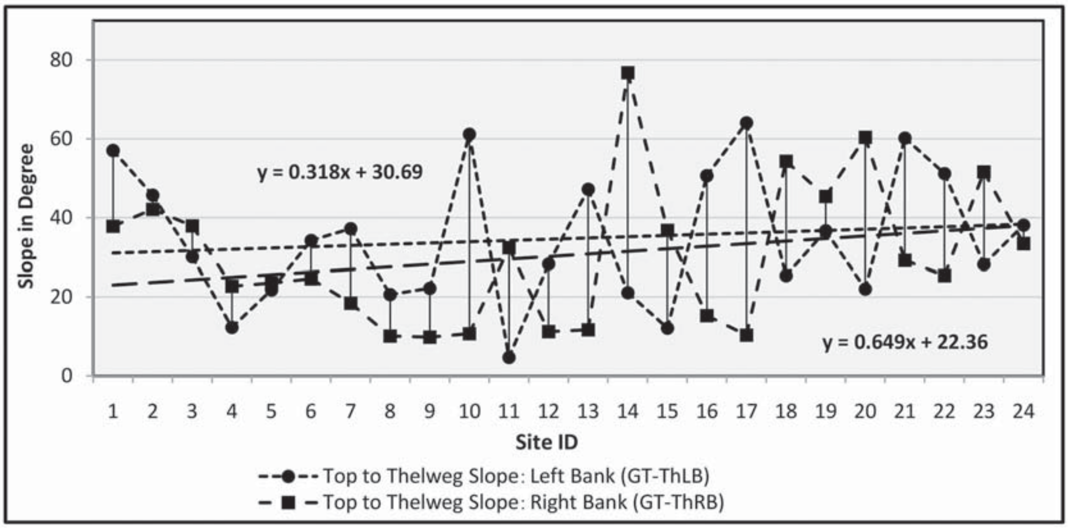

Figure 8. Bank top to thalweg slope at different cross sectional sites across the Bakreshwar river

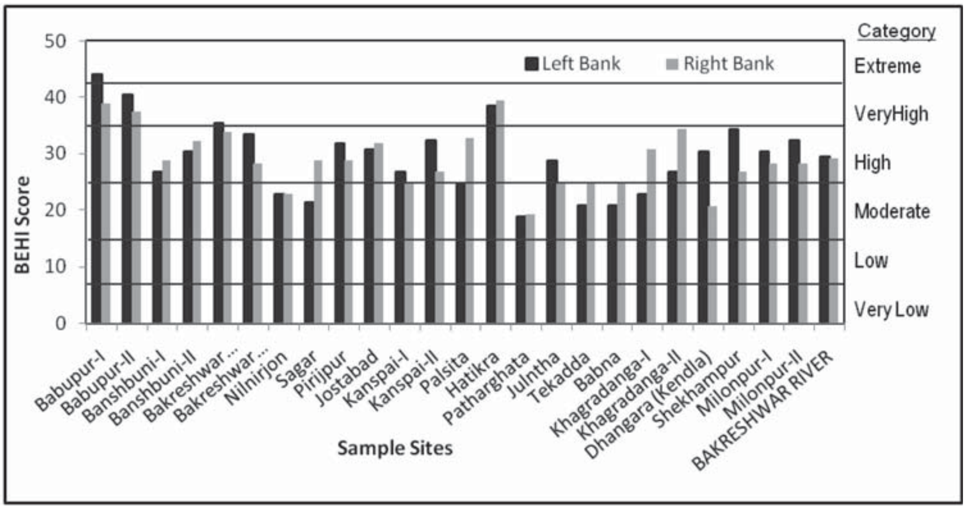

Figure 9. The BEHI score for individual banks of the survey sites along the Bakreshwar river

Google Earth images (2013). Field survey and interaction with the local residents was also done for exploring the ground reality. Some of the major sites of channel meander migration along the river have been shown in Figure 11.

The pattern of meander migration of Bakreshwar river brings out several facts. First, The leftward shifting tendency of the main river course is validated by the positions of the palaeochannels, which are mostly at the right hand side of the main course (Fig. 11) Second, Higher elevation of the southern (right hand) side of the catchment acts as a buffer zone against free migration or extension of the river course. This pushed the

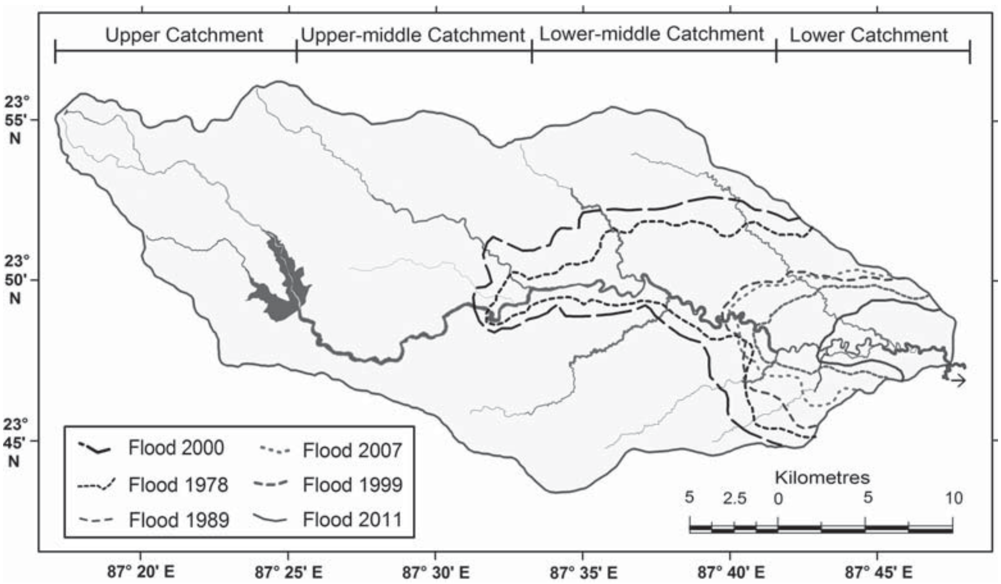

Figure 10. Maximum flood limits in different flood years in Bakreshwar river basin

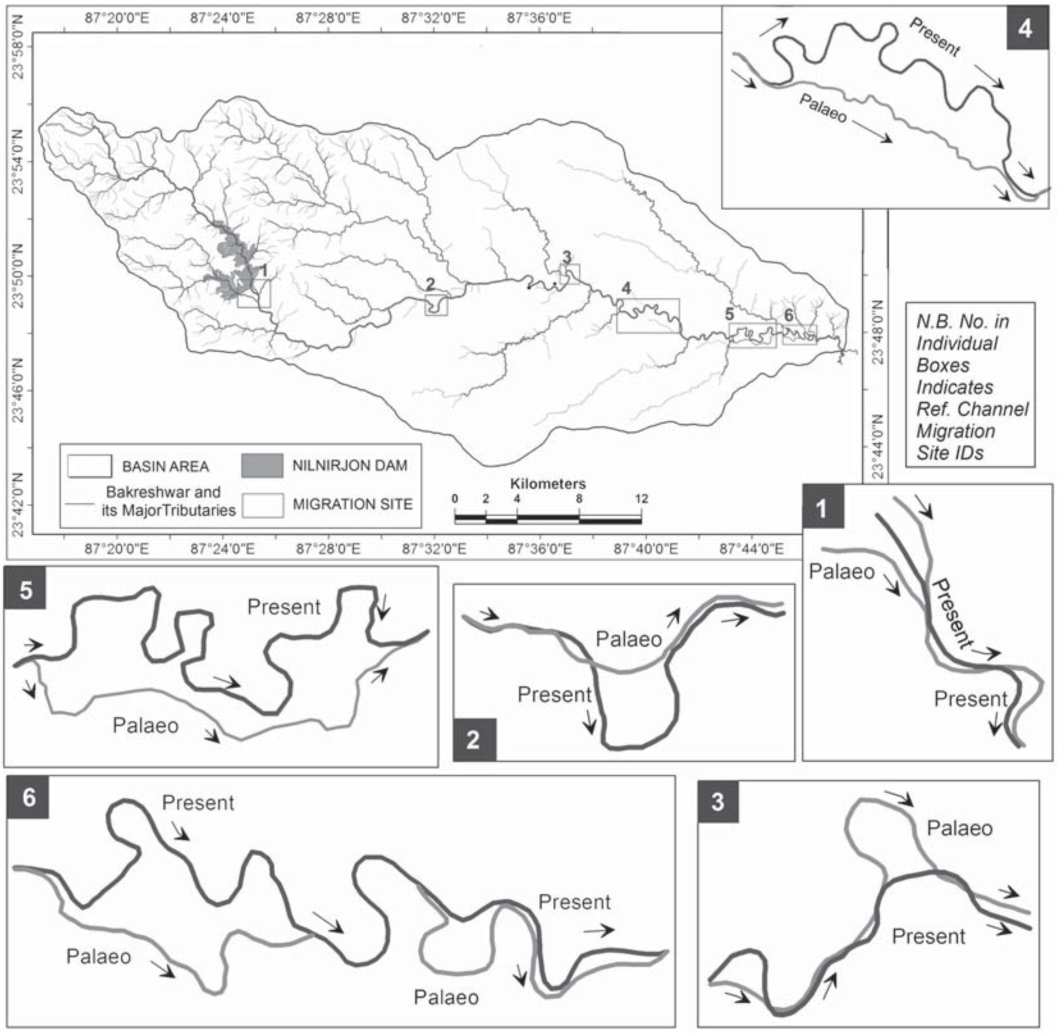

Figure 11. Major Palaeochannels of Bakreshwar river. 1: Nilnirjon dam, 2: Muradpur, 3: Hatikra, 4: Kusumjatra, 5: Babna, 6: Dhangara and Shekhampur

river course to the north, making the left bank more unstable. Third, Both lateritic middle catchment and alluvial lower catchment facilitate migration of the river. However, the rate is more in the alluvial lower reach. Greater discharge in the lower reach of the river energises its migratory motion.

Estimation of surface lowering

Surface lowering rate has been measured at 42 sites over the entire basin through wooden pegging operation since February 2011 to February 2014 to relate catchment morphology and the surface lowering status. The average annual surface lowering rate has been shown in figure 12. From this isoerodent plot an estimation of the catchment lowering rate and volume of eroded material has been attempted (Table 6).

Average rate of surface lowering for the entire basin is 6.63 mm yr^{-1}, though there are considerable spatial variations. The annual

Table 6. Catchment specific annual surface lowering rates and estimated erosion volume

Catchment	Area (km^2)	Average lowering rate (mm yr^{-1})	Volume of eroded material (m^3 yr^{-1})
Upper	78.03	12.5 (8-17)	$78.03\times10^{6}\times12.5\times10^{-3}$ = 975,375
Upper-Middle	216.69	8 (6-10)	$216.69\times10^{6}\times8\times10^{-3}$ = 1,733,520
Lower-Middle	341.44	4.5 (3-6)	$341.44\times10^{6}\times4.5\times10^{-3}$ = 1,536,480
Lower	79.4	1.5 (negligible)	$79.4\times10^{6}\times1.5\times10^{-3}$ = 119,100
Whole Basin	714.56	6.63	$714.56\times10^{6}\times6.3\times10^{-3}$ = 4,737,532.8

Source: Based on Field Survey during 2011–14

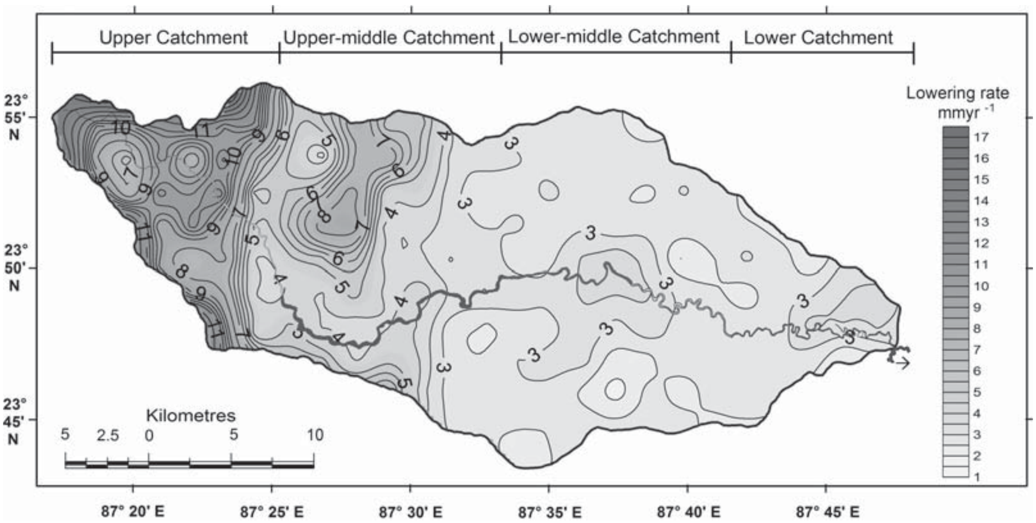

Figure 12. MAnnual average surface lowering rate of Bakrshwar River Basin (based on field measurements during 2011-2014).

surface lowering rate ranges from 8 mm to 17 mm yr^{-1} in the upper catchment, 6–10 mm yr^{-1} in the upper-middle catchment and 3–6 mm yr^{-1} in the lower-middle catchment. Lowering rates in the lateritic tract are exceptionally high. The low-lying undulating surface in the lower catchment shows negligible surface lowering.

One can easily relate rate of annual surface lowering with the catchment topographic diversity. In spite of good coverage of forest land in the upper part of the basin, erosion rates are high because high relief, steeper slope and several lower order streams accelerates the erosion rate. Erosion rate are also high in areas near lateritic badlands. In these areas one can also observe relatively high diversity scores (Fig. 5).

Conclusions

This work brought out two important interrelated areas of catchment topographic response. First, the watershed inclination effects on the channel orientation, bank erosion, thalweg as well as channel shifting, and spreading of floodwater towards less elevated areas. Second, the spatial changes in catchment topographical components (slope, elevation etc.) regulate the variations in stream association and soil erosion across the catchment.

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