

Entropy application to evaluate the stability of landscape in Kunur River Basin, West Bengal, India

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The river network analysis using thermodynamic entropy approach has been studied over the past several decades to decipher the behaviour of streams and landscape stability. The entropy-based study has been taken up in Kunur River Basin of eastern India to verify the level of adjustment for its present longitudinal profile to the calculated and equilibrium longitudinal profiles adopting Yang's (1971) theory of average river fall. The verification reveals that the fall ratio is less than 1, which indicates the basin has not yet reached the dynamic equilibrium phase and the whole process-response system sustains tremendous human pressure. It is inferred from the thermodynamic river profiles that there is poor agreement between observed data and the law of average stream fall, and the concave river profile emerging from several scales of process-form interaction is characterized by human interference. The present analyses also demonstrate that the lithological control, grain size and channel morphology influence the gradient in short term and climate-induced hydrological changes control the long-term stability of the total landscape.

Keywords: Dynamic equilibrium, landscape stability, longitudinal profile, potential energy, thermodynamic entropy.

CONSIDERABLE geomorphic and hydrological research on drainage network analysis using thermodynamic approach has addressed the concept of dynamic balance that guides the fluvial system¹⁻⁴. Entropy is important to understand the landscape evolution through the distribution of available potential energy. It is the only useful energy in stream morphology provided by nature that gives overland flow and converts into kinetic energy when the unit mass of water is flowing downstream^{1,3}. Using this generated kinetic energy, the flow can carve its own channel and form the stream network. During the channel formation, the river shapes up the channel pattern and the longitudinal profiles of the waterways. With continued erosion, the features of the landscape change with the change in

topography. Thus the noticeable information available on a drainage basin is its mean elevation⁴, implying the connection between entropy and potential energy. The drainage basin morphological characteristics have been analysed because the shape of all streams observed today should be the cumulated result of the distribution and expenditure of potential energy along their course of flow throughout the past. The variation and distribution of potential energy loss per unit mass of flow have a powerful effect on the stream network and it is proportional to the vertical fall between the source and the confluence. In this context, Yang³ developed the analogy equation

$$H_{\mu} = \kappa Y_{\mu}, \quad (1)$$

where H_{μ} is the average loss of potential energy by unit mass of water for all water courses of the order μ , Y_{μ} is the fall (level difference) between the source and mouth of the water course of order μ and κ is a factor for conversion between energy and fall. Adapting the concepts of thermo-mechanics analogy, i.e. the entropy variation of a fluvial system

$$\Delta S = \int dH_m/Z_m, \quad (2)$$

where H_m is the total average potential energy loss per unit mass of water from the source to the confluence of m th order stream and Z_m is the total fall from the beginning of the first-order stream to the end of the m th order stream of Leopold and Langbein¹, the law of average fall equality ($Y_{\mu} = Y_{\mu+1} = \text{constant}$) has been developed by Yang³ when a river system has reached a condition of dynamic equilibrium. Here the thermal energy in a thermal system is equivalent to potential energy for the fluvial network and the absolute temperature is equivalent to elevation in a river system. The use of this analogy in a fluvial system is considered to be an open thermodynamic system, justified and empirically established by Scheidegger^{2,5}. On the other hand, methodological base of the Yang's law of average fall equality is founded on the Prigogine⁶ theorem for a classic thermodynamic system

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as well as Lewis and Randall's⁷ statement. Prigogine⁶ assumes that entropy is an extensive property of a system, and the total entropy is equal to the sum of the entropies of each part. Alternatively, Lewis and Randall⁷ state that the most probable energy distribution in a system (here the fluvial system) in the condition of stationary regime is the one which maximizes the function with maximal entropy. Using these two above principles we get

$$\sum_{\mu=1}^m \ln p_{\mu} = \text{maximum and hence } \sum_{\mu=1}^m \frac{dp_{\mu}}{p_{\mu}} = 0, \quad (3)$$

where p_{μ} is the probability that a determined energy loss occurs in the course of order μ . Further, the sum of these probabilities of the m th order basin equals one, so we must have $\sum_{\mu=1}^m p_{\mu} = 1$, $0 \leq p_{\mu} \leq 1.0$ and hence

$$\sum_{\mu=1}^m dp_{\mu} = 0. \quad (4)$$

By applying Lagrange's undetermined multipliers method, the classical problem of determining the conditioned extreme (eqs (3) and (4)) in a stationary regime is easily solved and it can be demonstrated that the probabilities of potential energy loss (p_{μ}) of each order (μ) from 1 to m of a fluvial system should be equal ($p_1 = p_2 = p_3 = \dots = p_m$). So, it can be inferred that when a river system analogous to a thermodynamic system has reached its dynamic equilibrium condition, then the average fall in each order stream should be equal.

In this study, the theory of average river fall has been applied in the Kunur River Basin (KRB) of eastern India to derive relations between entropy and mean elevation for drainage basin network and its relations with the river profiles. The objectives are:

- To reveal the maturity of Kunur system based on equality of falls and comparison between the longitudinal profile and the equilibrium profile.
- To derive the factors controlling the longitudinal profile in a short- and long-term basis.
- To assess the evolutionary history of KRB and adjacent landscape.

The Kunur River system: geographic and litho-tectonic setting

Draining through diverse geological units (Archaean and lateritic formation in extreme west and the land-locked alluvial valley in the east), the Kunur River in West Bengal is a unique river system of the Bhagirathi–Hooghly Basin (BHB), which occupies part of the still wider structural basin in Bengal (Figure 1). It is notorious in nature causing devastating floods, which affect large areas of

Barddhaman district, West Bengal. Rising near Bansgara (elevation ~ 100 m) in the Faridpur area of Barddhaman district, the Kunur River (between 23°25'N and 23°40'N lat., 87°15'E and 87°54'E long.) is a fifth-order (after Strahler stream order), non-perennial, monsoon-influenced river traversing a total distance of 112 km (ref. 8) and merging into the river Ajay at Kogram (23°32'30"N, 87°54'E). It is a right bank tributary of the river Ajay and both are part of the Bhagirathi (a distributary of the Ganga) in the western boundary of Ganga–Brahmaputra Delta (GBD). The river has a special status as most part of the river lies within the canal command of Damodar River Basin covering 277 villages and three urban areas located either partly or fully within the basin^{9,10}. With a perimeter of 174 km and dominated by semi-dendritic and sub-parallel drainage pattern, the elongated basin area from source to confluence is 826.5 km² and basin elevation varies from <43 to 100 m from mean sea level (Figure 1). The study area experiences tropical climate characterized by warm wet summers and cool dry winters. About 90% of rainfall occurs in this basin due to the southwest monsoon and the rest 10% of rainfall occurs due to northwestern in the summer and western disturbance during winter. On an average, the eastern and western parts of the basin receive 1275 mm and the central part receives 1225 mm of rainfall annually. The maximum rainfall or about 80% of the precipitation occurs from June to October⁹. During the monsoonal months, the Kunur River gets adequate water from its catchment areas that generally contributes to the occurrence of flash floods and bankfull discharge which affects about 19,328 population of 9 villages (area = 16.63 km²) and damages the *kharif* crops near the Ajay–Kunur confluence^{11,12}. In addition, when the water level of Ajay rises, the Kunur fails to discharge into the Ajay and due to back pressure

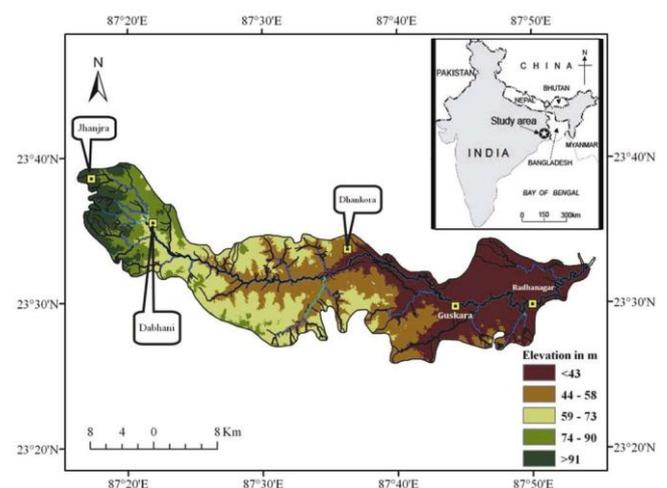


Figure 1. Physiography of the Kunur River Basin (KRB), West Bengal based on SRTM-DEM (version 4). The locations of surveyed stations are shown. (Inset) Map showing the location of KRB in India.

RESEARCH ARTICLES

Table 1. Interrelationship among geomorphic forms, processes and geological units in and around Kunur River Basin, West Bengal

Broad geomorphological unit	Subunits	Geologic units	Predominant structure, lithology	Predominant geomorphic processes	Geomorphic features	Age
Alluvial plain	Alluvial plain lower	Kalna Formation	Alluvium of sub-recent to recent origin	Fluvial processes—riverine erosion and deposition	Younger terraces and flood plain, levee	Late Pleistocene to Holocene
	Alluvial plain upper	Sijua Formation/ Kusumgram Formation	consists alternate beds of compacted clay, silt and sand			
Dissected lateritic upland (DLU)	DLU lower	Upper Lalgarh Formation (Worgram Formation)	Laterized pebble, cobbles and boulders	Chemical weathering—laterization; gully erosion, sheet wash; Fluvial processes—riverine erosion and deposition	Table land with surrounding gently sloping terrain, laterite-capped aggradational plain	Early Pleistocene
	DLU upper	Lower Lalgarh Formation (Santiniketan Formation)				
Dissected Gondwana upland		Supra Panchet Formation Panchet Formation Raniganj Formation Barren Measure Formation Barakar Formation	Typical sandstone—shale—coal cyclothem sequence	Soil creep, gully and rill erosion, sheet and surface wash	Rolling topography and mounds, badlands, residual hillocks	Mesozoic (Permo—Triassic)

inundates its entire flood plain stretching from the railway embankment below Guskara. During the 1959 flood, the level of Ajay was higher than that of Kunur by 3.1 m and the flood slope of the river Ajay was about 0.3788 m/km whereas that of Kunur was 0.18939 m/km. In 1968, within a year, there were abnormal numbers of reported flood events, nearly 14, from the Kunur River¹³.

The landscape of KRB has a great diversity in terms of physiographic, geological and pedological conditions experiencing different geomorphic processes (Table 1). The most remarkable feature is its dynamism, caused by heavy seasonal downpour (monsoon rainfall) on the fragile geologic and tectonic base. The salient geomorphic and fluvio-environmental characteristics, including lowest drainage density (0.85 km⁻¹) amongst all sub-basins of the Ajay River System, high bifurcation ratio (4.66), low relief ratio (0.0009) and ruggedness number (0.0079) suggest that the catchment area has more infiltration capacity compared to surface run-off; composed of alternating outcrops of yielding and resistant lithologies; and mature terrain^{14,15}. Moreover, high bifurcation ratio further indicates a substantial extension of the tributaries that the sub-basin has undergone due to intense rainfall, thick soil cover and deep weathering on a more or less lateritic tract.

Tectonically, the region is disturbed by a series of basin-deep normal strike faults trending NNE–SSW/NE–

SW arranged in an en échelon pattern¹⁶. The fault zone runs through Jalangi–Debagram, Barddhaman–West Ghatal areas on the shelf zone, which is possibly reflected in the NNE–SSW course of the Kunur River and Ajay River near Mongalkote. The geological characteristics in this area exhibit Gondwana Supergroup overlain by Quaternary formations from west to east, where most of the alluvial deposits belong to the older alluvial formations of Pleistocene upland (Figure 2) composed of argillaceous beds or coarse materials, pale reddish-brown in colour, containing calcareous limonite and pisolitic ferruginous concretions occupying higher positions^{17–19}. In the context of stratigraphy, the oldest unit is represented by lateritic boulders and conglomerates, which mark the beginning of Quaternary sedimentation over the planation surface of Mio-Pliocene rocks in the eastern fringe of the shield area^{20–22}. The morpho-lithology of KRB manifests that most of the watershed area comprises yellow, oxidized sand and clay. It has moderately dissected alluvial tract covering the highest grounds above the occasional and usual flood level in the alluvial landscape of the Ajay Basin. The relief zone between 20 and 40 m elevation has pedocal soil (containing calcium carbonate and magnesium carbonate) with alluvium, the marker between the older and newer alluvium zone covering the maximum surface area²³.

Database, methodology and limitations

The work was carried out on five available $15' \times 15'$ scanned Survey of India (SOI) topographical sheets (nos $73^M/6$, $73^M/10$, $73^M/11$, $73^M/14$, $73^M/15$) of various editions with scale 1:50,000 from which the morphometric data (see Supplementary Table S1; see online) regarding hierarchy of the drainage network, length, drainage area and perimeter were derived using ERDAS Imagine (v. 9.0) and ArcGIS (v. 9.3). For reckoning the number of stream segments of a given order, Strahler's stream order was followed because it is consistent with the concepts of entropy and dynamic equilibrium²⁴. In addition, to find out the average vertical fall data of each stream order, freely available version 4 of Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of 3 arcsec (ca. 90 m resolution) with geographic projection was also used (source: <http://srtm.csi.cgiar.org>). The processed SRTM data with a reported vertical accuracy of 7.58 m for Phuket Island, Thailand and 4.7 m in the Catskills Mountains, USA²⁵ are most reliable and have been supplemented with auxiliary DEMs to fill the data voids²⁶. The data are used in 3D analysis tool on ArcGIS platform and the extraction process of elevation data related to source and mouth of each order was carried out. Before that the DEM data were re-projected to UTM grid with WGS84 datum for performing the analysis. The above data are needed for the purpose of computing the Horton–Strahler equations and construction of the graphs, calculating the Yang's equations and construction of thermodynamic longitudinal profiles of Kunur River; analysing the terrain characteristics and geomorphic indices. The computation was carried out employing the following methodology.

Application of Horton–Strahler's empirical laws

Adopting Strahler's²⁷ water courses ordering (μ), Horton's²⁸ laws concerning the number of channels (N_μ), the

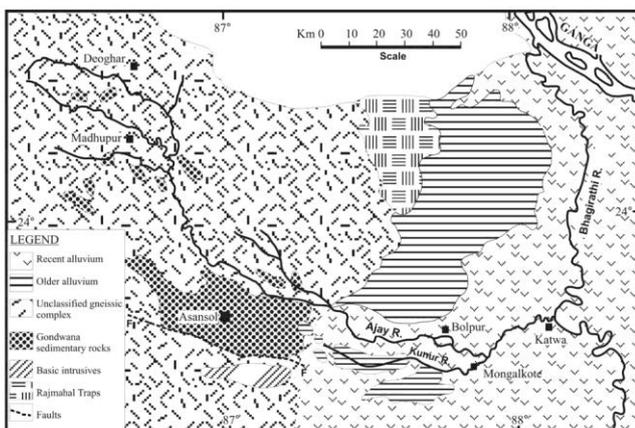


Figure 2. Geologic and tectonic map of the study area (modified after Bhattacharya⁵⁶).

average length (\bar{L}_μ) and the average stream slope (\bar{S}_μ) can be described as follows

$$\ln N_\mu = A - B\mu, \quad (5)$$

$$\ln \bar{L}_\mu = C - D\mu, \quad (6)$$

$$\ln \bar{S}_\mu = E - F\mu. \quad (7)$$

Plots of eqs (5)–(7) based on derived drainage basin data for the river Kunur in semi-log paper are usually referred to as Horton–Strahler straight lines (Figure 3). These equations were used to derive the bifurcation ratio of stream number $e^B = N_\mu/N_{\mu+1}$, stream length ratio $e^D = \bar{L}_\mu/\bar{L}_{\mu+1} + 1$, concavity of the course profile of order μ , $e^F = \bar{S}_\mu/\bar{S}_{\mu+1} + 1 = (Y_\mu/\bar{L}_\mu)/(Y_{\mu+1}/\bar{L}_{\mu+1} + 1)$ and ultimately find the interesting parameter, i.e. stream fall ratio

$$(e^D e^F) = Y_\mu/Y_{\mu+1}, \quad (8)$$

which is important for understanding a stream network. The advancement of the maturity of the basin (to reach its dynamic equilibrium condition) can be evaluated by the equality of the falls (eq. (8)) and in this case the stream fall ratio must be unity, i.e. $e^D e^F = Y_\mu/Y_{\mu+1} = 1$. The stream fall ratio not only provides an index of the maturity of the stream system, but also indicates in general whether the river valley should aggrade or degrade in the future³.

Longitudinal stream bed profile by thermodynamic approach

Previous studies indicate that most empirical plots of longitudinal profile were obtained only for the main stream within a drainage system. This longitudinal profile

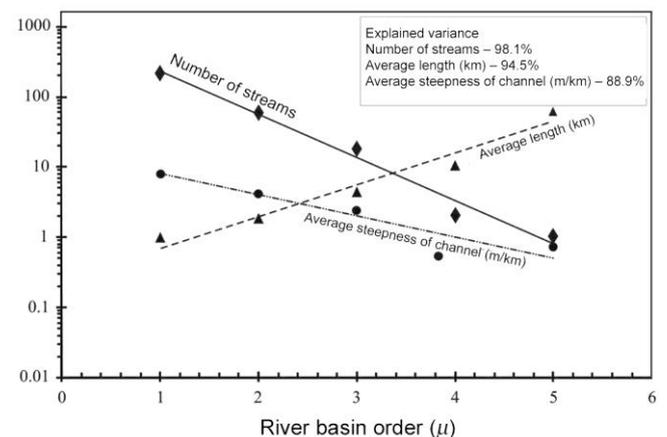


Figure 3. Relationship among number of streams, average length, average steepness of channel and Strahler's stream order for the KRB.

of the main stream was considered to represent the characteristics of the entire river system without using the other parameters. However, to understand the evolution of the young landscape of any river basin applying the thermodynamic entropy principle based on Yang's³ (eqs (9)–(11)), all the drainage basin parameters need to be considered for all stream orders.

In eqs (9)–(11), the total fall measured from the beginning of the first-order stream to the end of the *m*th order stream should be

$$Z_m = \sum_{\mu=1}^m Y_{\mu} \text{ or } Z_m = e^{(C+E)} \sum_{\mu=1}^m e^{-(D+F)\mu}. \quad (9)$$

From the empirical laws, the total horizontal length measured from the beginning of the first-order stream to the end of the *m*th order stream should be

$$X_m = \sum_{\mu=1}^m L_{\mu} \text{ or } X_m = e^C \sum_{\mu=1}^m e^{-\mu D}. \quad (10)$$

When the stream system has reached its dynamic equilibrium condition, an equal average fall in each stream order should exist. Then equation becomes

$$Z_m = me^{(C+E)}. \quad (11)$$

The calculated profile and equilibrium profile are described by eqs (9) and (11) with the same values of total horizontal length ($\sum_{\mu=1}^m L_{\mu}$) obtained by eq. (10). The construction of a graph from the above-mentioned equations gives the longitudinal profiles of the drainage network. The stability of the basin can be evaluated by the equality of the falls and by comparing the calculated longitudinal profile of the basin with the equilibrium profile.

Terrain analysis and geomorphic indices

Further, to probe into the present-day controlling factors which influence the gradient of Kunur River and the adjacent landscape, analyses of terrain and geomorphic indices have been done. Terrain analysis includes the analyses of topographic profiles and river longitudinal profiles and their derivatives, followed by calculation of geomorphic indices conducted using DEM. In the present study, we use Hack's²⁹ semi-logarithmic profile to know the diversity of geomorphic work throughout KRB. In order to find the controls on landscape, an exponential and a fourth-order polynomial curve that achieved best fit for Kunur River (see [Supplementary Information online](#)) has also been superimposed on the long profile curve of the Kunur River. To reduce the effects of variable basin relief, normalized profile is also used because of the large

number of data points for each profile and the integer stepping in adjacent elevations on the DEM, which is smoothed^{30,31}. Geomorphic indices, including stream length-gradient index (SL) and concavity index (CI) were calculated, which are sensitive to natural and anthropogenic forcings. In the longitudinal profile equation of Hack²⁹, the constant κ is referred to as the stream gradient index by Hack³². It is the proxy to identify areas of anomalous uplift within a landscape because uplift zones are indicated by anomalously high SL values with a specific rock type and within a particular drainage segment^{31,33,34}. SL is calculated here with longitudinal profiles to infer the lithological or tectonic controls on channel slope as follows^{32,35}

$$SL(\kappa) = \frac{H_1 - H_2}{\log_e L_2 - \log_e L_1}. \quad (12)$$

CI of the river profile is calculated in order to find out the influence of sediment on channel gradient³⁶. For quantifying index of concavity, the following equation is used: Concavity = $2(A/H)$, where *H* is the total fall and *A* the height difference between the profile at mid-distance and a straight line joining the end points of the profile.

Plan form morphology, hydrology and grain-size analysis

In addition to the terrain analysis, the results of channel morphological analysis, hydrological information and grain-size distribution of bed sediment are also presented to emphasize on the causal factors shaping river profiles as well as drivers of landscape stability. The plan form characteristics of Kunur River were studied through measurement of sinuosity for three different reaches following the parameters defined by Friend and Sinha³⁷ and inferences based on Schumm³⁸ with proper ground check. The analysis was carried out on window-based classification of river reaches using digital remote sensing data (Figure 4) of Landsat TM sensor (spatial resolution 30 m). The digital data are available from the Global

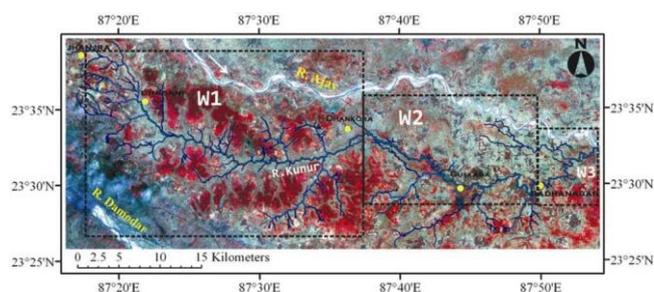


Figure 4. Contrast in planform parameters of Kunur River in three windows is remarkable on Landsat TM image (path/row – 139/044) of November 2006. The northern side of the river is confined by the wide Ajay River Valley, whereas the southern side forms a Damodar valley.

Land Cover Facility site hosted by the University of Maryland, USA (<http://glcfapp.umiacs.umd.edu>). In addition, extensive field observations have been an integral part of the study to collect reach-wise sediment samples from the river bed, finding the overall channel forming discharge, and consolidating the results obtained from the analyses. The collected sediment samples from the river beds of different reaches show that the bed materials are mostly composed of varying proportions of medium and coarse sand, with only the occasional presence of fine granules. In the field, measurements of the channel cross-section were made using a Dumpy level, measurement tape (metric), Global Positioning System (Model eTrex®H Garmin) during October 2011–2012 from the right to the left bank side at four different sites. These are Jhanjra village (0.640 km from the source), Dabhani village, Guskara and a site about 15.15 km downstream of Radhanagar village (Figure 1). The survey points of this cross-section were selected considering the uniformity of bedform and roughness where large vegetated channel bars do not exist and width (from one bank top to another) of the riverbed is comparatively uniform. The implication of such hydro-morphological and sedimentological diversity and variability will also be discussed later.

Probable error in measurements

Utmost care was taken during digitization of stream network, but still errors may have occurred. This is mostly while digitizing the stream line from the old topographical maps. Again error may occur in identification of stream order where the delineation of first-order stream is difficult in such a small river basin. Necessary care was taken at the time of extraction of elevation data with fixed distance from SRTM DEM, but errors could not be avoided completely. As remotely sensed data contain systematic and non-systematic errors³⁹, when we import Cartesian coordinates (X , Y and Z) from projected SRTM DEM and calculate the distance from X to Y using Euclidean geometry, the cumulative total distance is not exactly equal to the length of the main stream.

Results

Thermodynamic profiles and equilibrium state

The analysis carried out for KRB indicates that it follows the Horton–Strahler's equations (eqs (5)–(7)) very well. Hence Yang's³ approach has been chosen to check and decipher the behaviour of the present-day stream. It is apparent that the equilibrium profile is far from the calculated profile (Figure 5), indicating that the analysed fluvial system has not reached the dynamic equilibrium condition, since the fall ratio ($e^D e^F$) of the river Kunur is

smaller than one (0.176). From the small value of stream fall ratio <1 , we infer that there is poor agreement between observed data and theories and ultimately the present stream system is a disturbed system either controlled by external physical forcings and/or anthropogenic activities. As the stream fall ratio is smaller than unity, it implies that the stream bed should aggrade. Since the theoretical longitudinal profile represents the average profile of whole river system, the profile agrees with observed stream profile along the main river in part of middle and lower portions, but not in the upper and middle parts of the stream (Figure 5). It provides an indication as to what physical constraints exist along this particular course of the stream. The equilibrium profile, having a curvature at the source below the calculated profile, corroborates the trend already observed in the basin, namely accelerated erosion. This characteristic can therefore explain the trend in the studied basin, i.e. occurrence of gullies (Table 1).

Analysis of topographic profiles

The two topographic cross-sections (AB and CD) in Figure 6 *b* and *c* aligning SW–NE across the Ajay–Kunur Basin (AKB) show the highly variable relief that corresponds closely to the structural framework of AKB. Dissected lateritic upland is conspicuous in the southwestern part of both the profiles (Figure 6 *a*). The northeastern valley margin is extremely flat and merges with the floodplain of Ajay River in case of C – D transect. On the other hand, in case of A – B transect, its northeastern part is bounded by lateritic uplands. The two representative sections also reveal sharp contrasts in elevation among the segments. The interfluvial zone between Kunur and Ajay rivers attains maximum elevation in A – B section

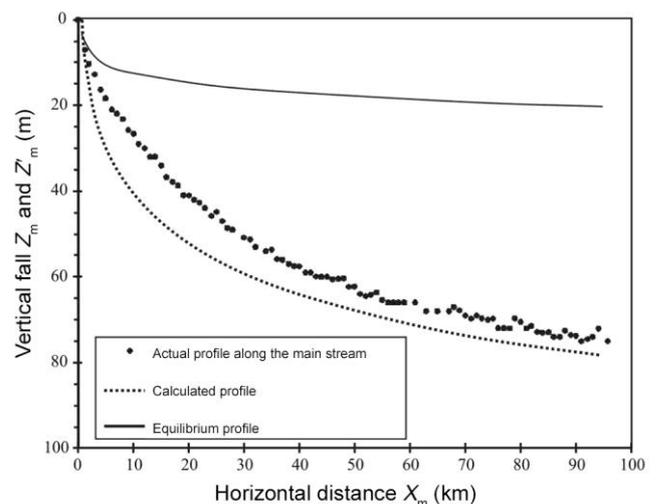


Figure 5. Longitudinal bed profiles of the Kunur River using thermodynamic approach.

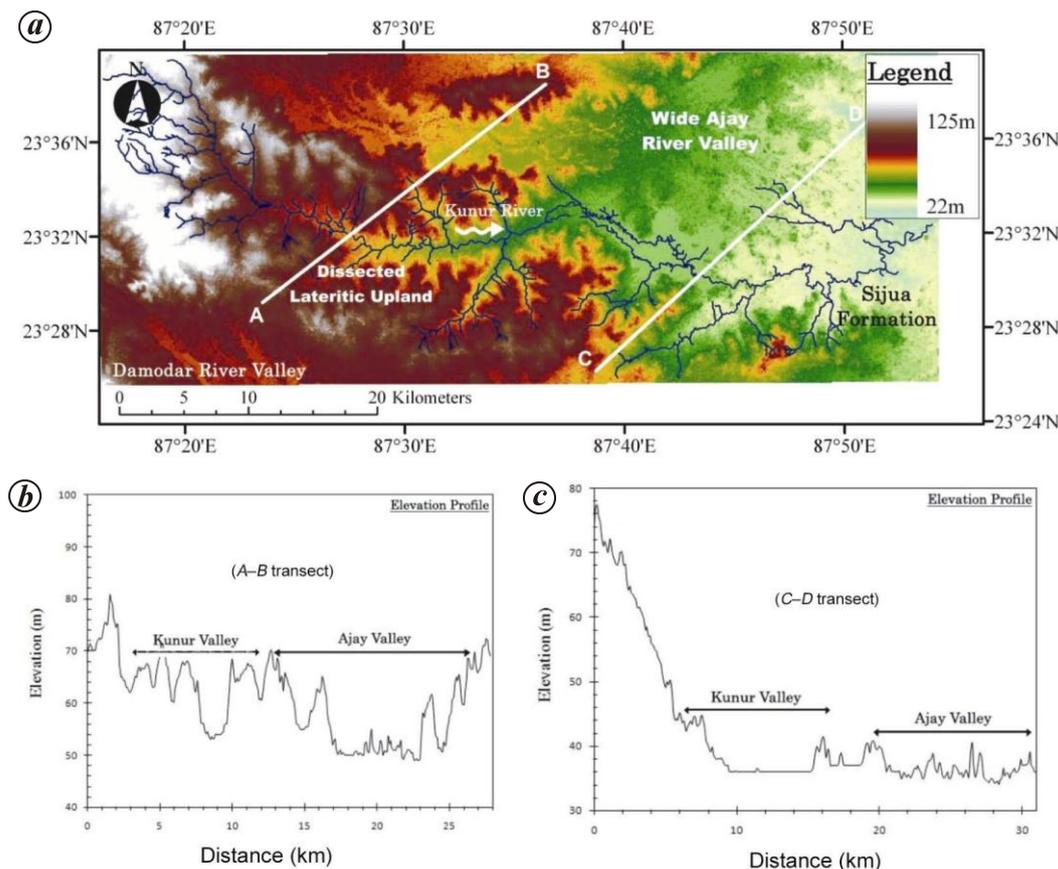


Figure 6. a, Digital elevation model (DEM) derived from the SRTM data. b, Elevation profile along A–B transect. c, Elevation profile along C–D transect.

whereas in C–D it is relatively subdued, which denotes a low-land surface (Figure 6 a). The width of the asymmetric valley of Kunur River is variable, ranging from 6 to 10 km, but the active channel belt is close to 2 km wide in most reaches.

Variation of river profile forms: curve fitting and regional characteristics

The channel slope measurements through longitudinal profile analysis by various curve fitting methods of the Kunur River in its 112 km reach are presented in Figure 7. Plotting of longitudinal profile of the Kunur River using Hack’s equation (Figure 7 a) results in a curve, more or less regular, typically convexo-concave and does not show a straight line, i.e. the river is not graded. The upper segments, parts of the middle segment and extreme lower segments below the equilibrium line are inferred to result from the fluvial deposition and human intervention. Similar scenario is revealed while comparing the observed and theoretical entropy profile in the upper and middle parts of the basin, which suggests that the present channel flow in these segments does not perform any signi-

ficant geomorphic work for shaping the river profile (Figure 5). On the other hand, the middle and parts of the lower segment of the profile are above the graded profile reflecting incised valley, which suggests an abnormal condition within a river reach. The break-in-slope (knick points) cannot be easily inferred from Hack’s profile, so the long profile length and relief were normalized, which displays three major knick points at 54, 41 and 33 m elevation and two minor knick points at 49 and 28 m elevation (Figure 7 b). The major knick points 2 and 3 are supposed to be a response to alterations in local lithology^{40,41} (Figures 2 and 7 b). The normalized profile shape suggests severe deepening in the upper-medial portion of the profiles; three inflection points and the lower segment appear to be close to the regional base level of erosion. The minor knick point 2 is inferred to be generated due to hydrological effect of major trunk of river Ajay during floods within AKB, as already discussed in previous section. The fitting results of mathematical function using exponential and fourth-order polynomial curve (Figure 7 c) indicate that the fourth-order polynomial function explains a high proportion of the total variance of the series ($R^2 = 0.99$). It also indicates that the Kunur River profile is better fitted for fourth-order polynomial

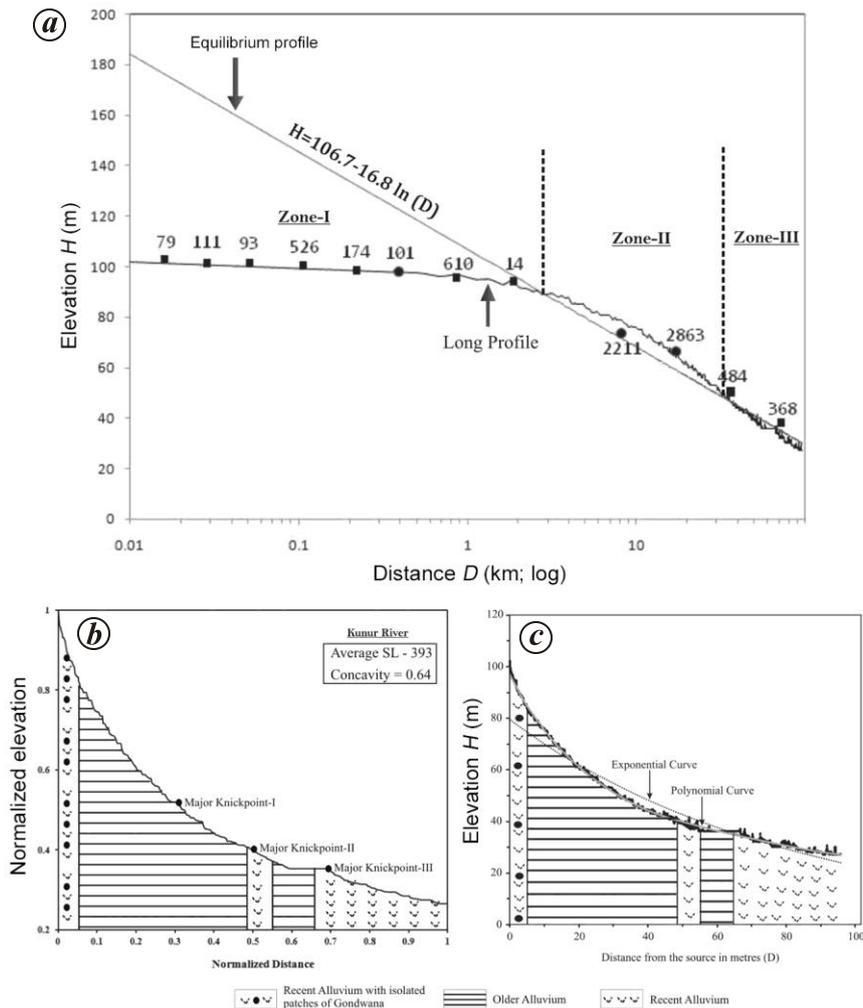


Figure 7. Longitudinal stream profiles. (a) A semi-logarithmic profile of the Kunur River. The straight line represents the graded or equilibrium profile. The source has been set at 0.01 km due to problem of zero distance on logarithmic scale. Numbers on the observed profile (curve) represent stream gradient index (SL) values. (b) Normalized stream profile/dimensionless curve with average SL index and Langbein's³⁶ index of concavity of the Kunur River. Curve is normalized by its maximum elevation and maximum distance. Note the location of major knickpoints in the vicinity of the boundary between two lithologies. (c) Solid line is the fourth-order polynomial curve fitted to the long profile of the channel and dotted line is exponential trend. Elevations have been extracted from the SRTM DEM at regular 200 m intervals.

function and steep sections in the lowermost portions support the presence of minor knick point 2 (Figure 7 b). Profiles approach an exponential form ($R^2 = 0.95$), which implies that grain size decreases downstream under conditions of low sediment transport and near constancy of other major controls.

Stream length-gradient index and concavity index

In order to discriminate the results of SL indices (eq. (12)), Hack's trunk stream profile of KRB has been divided into three zones (Figure 7 a). Overall, the abrupt variations of SL values from source to confluence indicate that the longitudinal profile is not smooth, much irregular. Zone-I shows relatively low to intermediate SL

values between 14 and 610, with two abnormally high SL values (526 and 610). These high values correspond to the steep channel gradient developed within the alluvial reach. The anomalous values of SL (2211 and 2863) occur at the channel segment of the 48–92 m elevation between Guskara and Radhanagar village that coincides with the older and newer alluvium contact, which has also been observed in longitudinal profiles. A similar distribution of SL-like zone-I is also observed in zone-III. However, there is a gradual decrease in the SL values from upper to lower part in zone-III. The SL value of 393 represents the average for the entire river.

The ubiquitous concavity of the profile of rivers can be ascribed to several causes, including increasing discharge, decreasing size of bed material in the downstream

Table 2. Vertical fall for calculated profile and equilibrium profile

Order	$e^{-(D+F)_\mu}$	$\sum_{\mu}^5 e^{-(D+F)\mu}$	$e^{(C+E)} \sum_{\mu}^5 e^{-(D+F)\mu}$	$Z_{\mu} - Z_{\mu+1}$	Calculated fall (Z_m) $\sum (Z_{\mu} - Z_{\mu+1})$	Equilibrium fall $Z'_m = me^{(C+E)}$
1	1.525	20.272	77.804	5.792	5.792	3.838
2	2.326	18.763	72.012	8.747	14.539	7.676
3	3.547	16.484	63.265	13.21	27.749	11.514
4	5.409	13.042	50.055	19.942	47.691	15.352
5	8.248	7.846	30.113	30.113	77.804	19.19

direction³⁶, or more complex causes like climate³⁰. The CI is determined over the full channel length of Kunur River. The high concavity index (0.64) can be explained by the downstream decrease in grain size and long-term climate change. KRB shows much variation in the grain size of the thalweg part from the upper reaches to the confluence. It is also observed that the high concavity of the basin is a determining factor regarding the formation of channel networks. The differences in base level and climate change may be also the causative factors for high concavity index values, which can be deciphered from river falls and the distribution of potential energy dispersion along the course of the rivers (Table 2).

Plan form analysis

The channel morphological analysis reveals that the sinuosity of the Kunur River channel is variable in three windows ranging from 1.3 to 2.1 (Figure 4). Geological study of the basin indicates that the causes of sinuosity are different in three different segments of the channel. The segment in window-1 (~48.5 km), that is mostly the upper catchment, exhibits a low sinuosity index (sinuosity 1.36) and near straight channel (Figure 8 a), probably because of rapid percolation of water through the riverbed making subsurface flow. This segment is characterized by suspended-load channel, carries a small load of sand and gravel, has low width–depth ratio and high degree of gradient (1 : 1010). The high sinuosity (2.065) with less stable mixed-load in the middle part of the river, in window-2, is mainly attributable to factors like gentle slope (1 : 2262), high flood discharge, high rate of sediment deposition from suspension and bank erosion. The last 16 km reaches up to the confluence with Ajay River in window-3 having low sinuosity channel (sinuosity 1.94) in the highly dynamic and frequently inundated flood plain part where the gradient is almost flat (1 : 2759). The width–depth ratio of the Kunur River shows that the channel shape changes from a narrow and deep section in the upper and middle parts (average *w/d* 3.09 and 5.24 respectively) to a wide and shallow section (average *w/d* 5.86) near the confluence point.

Discussion

Factors controlling channel gradient

The analysis of aggregated data indicates a wide range of possible factors influencing channel gradient and landscape architecture of KRB⁴². Such changes are apparent from the thermodynamic profiles which show disturbances in the basin along with the stream fall ratio implying aggradation within the landscape. Analysis of longitudinal profiles with SL index of the main channel reveals that the local-scale geologic factors such as resistance to weathering and lithologic variation determine the shape of the longitudinal profiles. Prominent contrast in valley configuration (Figure 6 b and c) and plan form morphology, such as low sinuous channel in dissected lateritic upper reach (Figure 6 a) and high sinuosity in unconfined region (Figures 4 and 8 a) show the intricate connection between the underlying lithologic controls and surficial geomorphic processes. Additionally, the three other important factors which affect the long-term balance between aggradation and degradation in a graded or equilibrium channel are (i) increasing sediment delivery, (ii) changes in the sediment: stream flow ratio and (iii) base-level changes in the lower reaches of a river⁴³⁻⁴⁵. Since sediment load data are difficult to obtain, empirical analysis tends to focus towards effects of grain size in the load on channel slope in this study⁴⁶. This quantification of grain-size indicates that predominant sediment sizes in three different locations towards downstream are (i) upper reach ranging from >4 to 1 mm (Figure 8 b), (ii) middle reach ranging from 1 to 2 mm and (iii) lower reach ranging from 0.2 to 0.5 mm. The reach-wise distribution of grain size with respect to intensity of geomorphic work shows no direct relationship, as human activities result in significant changes in the landscape of KRB. But, the discharge values allow the comparison of stream gradients with CI and the results indicate that discharge gradually increases downstream from 347.47 to 551.28 cumecs, which demonstrates the significant relation. In addition, from the Hack’s profile, the present-day zone of erosion with abruptly high SL values manifests the insignificant expression in the longitudinal profile which may be due to the dredging activities in the channel.



Figure 8. *a*, Field photograph showing low sinuous channel of Kunur River in the upper reach at Dabhani. Two levels of terraces developed downstream along the right bank of the river. *b*, Sediment sample site characteristics in the upper reach. Growth of the bar in the area indicates aggrading stage of the channel (flow direction is towards south-west).

Evolution and stability of the landscape

The rates of topographic decay and landscape denudation are essentially controlled by relief and the landscape is gradually sculpted in the midst of some of the controlling factors like climate, rock erodability, sediment flux, etc.⁴⁷. Although there are numerous tectono-structural, Quaternary base-level histories and palaeoclimate studies regarding GBD evolution, the present study attempts to link the geomorphology of modern landscapes through quantitative river longitudinal profile analysis with climate, palaeohydrological conditions and understanding of past landscape dynamics in AKB. The results of thermodynamics stability profile, supporting topographic profiles, SL distribution on Hack's profile, knick points identification from normalized profile, polynomial and exponential curves are insightful to identify the controlling factors (topography, channel morphology, hydrology, sediment characteristics, human activities) of channel slope which can be correlated with the evolutionary history and stability of the region. As the study area is situated in the vicinity of the stable shelf zone¹⁶, tectonic influences on geomorphology may be insignificant. Hence there exists a consistent relation between channel slopes and channel morphology drivers, and the differences are related to

evolutionary history and stages of drainage development. An insignificant relationship is observed between hydro-morphometric parameters in this region, which suggests that the present channel flow is not guided by tectonics, but lithology in most part and to a lesser extent, human activities. In addition, the high concavity ratio and the steeper channel gradient suggest that the supply of the erosional products in response to climate has determined the longitudinal profiles of the rivers. The thermodynamic profiles reflect a long-term instability of the geomorphic landscape in this part of BHB during the Holocene. Some geoarchaeological studies and Quaternary stratigraphic framework in recent years have strengthened our inferences and revealed that climate-induced hydrological changes and changes in sea level in late Quaternary period controlled the past landscape. The geoarchaeological studies suggest that the Terminal Pleistocene (22–16 ka) was characterized by relatively dry climate, erratic and reduced fluvial activity, whereas during the mid to late Holocene (<3 ka), there have been some changes in the bed elevation and channel gradient in response to aggradational and erosional modes of the GBD. Rajaguru *et al.*⁴⁸ summarized the palaeoflood dynamics of GBD from the buried site of Balupur on the river Kalindri and indicated that there was evidence of three successive palaeoflood deposits on the brownish silty clay (~35 cm thick) virgin layer up to 12th century AD. The first flood deposits containing pellets of iron–manganese oxides and calcretes indicate that pedogenesis under hydromorphic conditions occurred at about 1.2 ± 0.2 ka. But after 12th century AD, except the early 16th century flood, no large floods for the next ca. 700 years have been able to disturb the thick cultural layer. The present level has been reached by the stream at beginning of the last century and changed to an incisional mode. In AKB, the chalcolithic and late medieval (ca. 16th and 18th century AD) settlements are relatively undisturbed by floods, whereas the early historic (2.5 ka) and early medieval (ca. 8th–12th century AD) settlements are relatively disturbed by the low energy overbank type of flood⁴⁹, known as 'nuisance' floods⁴⁵. All these evidences indicate that the distinct period of smaller floods or no floods was between ca. 13 and 19 century AD in GBD and BHB. Similar palaeofloods are recorded from six large Indian rivers⁵⁰ and southern Europe⁵¹, suggesting the influence of regionally widespread Little Ice Age reducing the intensity of the southwest monsoon, around 600 years ago between 1300 and 1850 (refs 52, 53). Aggradational nature of Kunur River through alluvial filling can be dated as early to mid Holocene⁴⁹, which reflects the decreasing level of precipitation established by carbon isotopic composition⁵⁴. On the other hand, erosional mode of Kunur continued from the chalcolithic to the medieval period⁵⁵, which includes gully development through flux of rainwater. In the context of extent and magnitude of these changes, it can be inferred that these

fluctuations in fluvial regime have substantially affected the river equilibrium in the long term.

Conclusions

This quantitative work adopting entropy approach studies longitudinal channel profile in monsoon-dominated fluvio-deltaic plains transmitting signals of change across the landscape of KRB due to interplay of climate, lithology, exogenous geomorphic characteristics and eustatic changes in long timescale and human disturbances in short-time scale. This interpretation is consistent with deviations of observed long profile and thermodynamic profile from the equilibrium profile which represents the disruption of this basin due to anthropogenic activities like land-use practices, canal construction and river dredging. The results of our study also indicate that the influence of lithology, climate, inherited morphology, recent and contemporary geomorphic processes and anthropogenic effects collectively influence the architecture of Kunur valley and floodplain.

In addition, the entropy concept signifies 'inside change' which reflects that the behavioural pattern of a basin is controlled by the rivers draining within it. The inside change takes place in order to maintain equilibrium of the system. The basinal equilibrium is maintained either through incorporation of the sediment load or through spilling it out of the basin. However, in order to do so it may not be possible for the system to return to equilibrium instantaneously and this results in over spilling and hence the floods. With this viewpoint, the present study has impact on the prediction of recurrence of floods and their possible control. First, if proper monitoring of any flood-prone basin is done prediction can be made for the flood events in future. With regard to the second aspect, it needs to be mentioned that improper constructions of canals, dams and retention walls as well as unplanned dredging render the basin to become flood prone. These unplanned attempts destroy the fertile floodplains by sand incursions as the riverbed rises owing to such reprehensible drainage confinements, which results in huge long-term economic loss. Though a proper study of the basinal equilibrium parameters, appropriate planning could be made to control the flood waters and divert them for useful purposes.

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