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Mathematical modelling of long profiles in a tectonically active area: Observations from the DEM-based geomorphometry of the Rangit River, India

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Abstract—**The longitudinal profile of a river is one of the most popular indicators for assessing the degree of tectonic and structural control in a fluvial system. Sensitive to long-term tectonic, structural and climatic regimes, long profiles have been employed all over the globe and the anomalies in the long profiles are often been interpreted as evidence of active tectonic deformation. With the advent of high-resolution DEM datasets such as, SRTM, ASTER, etc. many large rivers of the world have been studied and analysed with respect to structure and tectonics. The present study is one such attempt for the Himalayan Rangit River in Eastern India. Physiographically located in the Eastern Himalayan Division of the Himalayas, this river is a small, steep-gradient tributary of the Tista River, debouching its waters into the Tista River near Melli (27°04'47"N, 88°25'56"E). SRTM DEM (30 m) was procured for the study area and the drainage network and the watersheds of the major tributaries as well as the trunk stream were extracted using the D8 routine in ArcGIS environment. The long profiles were smoothened by the 11-point Moving Average method so as to remove all the major artefacts and spikes that may have arisen due to the inherent limitations in the SRTM dataset. This was followed by mathematical modelling of long profiles and estimation of the SL Index. Steep segments in the rivers were identified by normalizing the SL Indices and comparing with the average SL index. Finally, the shape of the long profiles was quantified from the power law regression equation between basin area and channel slope.**

Analysis of the long profiles of the Rangit River and its major tributaries reveals elevated magnitudes of most of the long profile parameters suggesting intense erosional regimes in the rivers. It is a well-known fact that the Himalayas are under active tectonic movement due to continuous collision of the Indian plate with the Eurasian landmass. Therefore, it may be concluded that the anomalous characteristics of the long profiles in the Rangit River and its tributaries may be ascribed to active tectonic deformation.

I. INTRODUCTION

Fluvial systems are characterized by extreme sensitivity of landscape. Any change in the prevailing climatic and tectonic conditions is invariably reflected by the changes in the river morphology and form. These changes are often difficult to comprehend at shorter spatial and temporal scales. Therefore, longitudinal profiles which take into consideration a river from its source to the mouth, is often used as proxies for ascertaining the degree of lithological, structural and tectonic control on the rivers [1,3,7,8,11,13,19]. The shape and form of the longitudinal profile of a river is result of the complex interplay between lithology, structure, tectonics, climate and catchment hydrology [11,14].

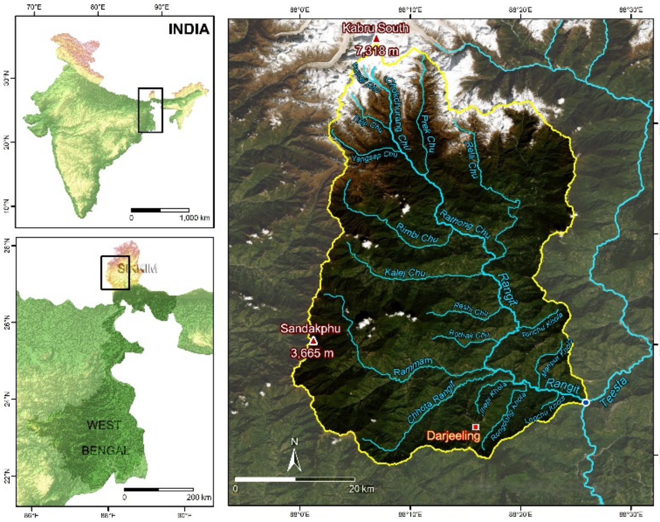

Figure 1. The Rangit Basin (delineated by yellow) along with its principal stream and tributary. The asymmetric basin is characterized by greater number of tributaries on the western side (right bank of the main channel).

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Furthermore, the role of climate and hydrological processes on the longitudinal profiles of the rivers has also been investigated [12,20]. Long profiles have also been analysed for understanding the control of lithology [1,2,5], distribution of stream power [16,18], identification of knick zones [9,10].

This paper attempts to understand the river longitudinal profiles by statistical modeling. Also, the longitudinal profile derivatives such as, Stream Gradient Index, Concavity, etc. have been quantitatively determined so as to make a broad generalization of the long profile characteristics for a tectonically active area such as the Himalayas. The present area for study—the Rangit River basin is located in the Eastern Himalayas (~2,150 km^2, Fig. 1) and characterized by its steep-gradient.

II. METHODOLOGY

In all, the longitudinal profiles of 16 major tributaries of the Rangit River as well as the profile of the main channel in the Eastern Himalayas were extracted and analysed in ArcGIS platform. For extracting the longitudinal profiles of these streams, the 30 m resolution SRTM DEM was downloaded from the official website. The DEM was terrain corrected and imported in the ArcGIS environment. To generate the long profiles of the rivers from the DEM data, the following procedure was adopted:

The depression-less DEM was subjected to the ‘Hydrology’ Routine in the ArcGIS software to get the stream segments. These streams were divided into segments of 60 m length. This is in accordance with the resolution of the SRTM data (30 m) so as to ensure that the same cell was not extracted for two points. These stream segments were converted into points and only the end points of each segment were extracted to the newly created point file. The elevation of each point along with its x-y coordinates were extracted by the “Feature to DEM” routine of ArcGIS. The data obtained were exported to the Microsoft Excel software for further analysis. Using the distance formula (Eq. 1), the distances of the extracted points from one another was computed.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad (1)$$

where, d = distance between points x1 and x2, x1 = x-coordinate (in meters) of point x1, y1 = y-coordinate (in meters) of point y1, x2 = x-coordinate of point x2, y2 = y-coordinate of point y2

The distances were then cumulated taking the source as origin (zero) and then the distances of all the points from the source of the river were obtained.

Due to stepping in adjacent elevations and the effect of water bodies (dams) the long profiles derived from DEM are not as smooth and accurate as those produced from other techniques [4,18], especially for low-gradient reaches. In the present study, first the artificial spikes were deleted and smoothing of the long profiles using a 11-elevation points moving average (5 points upstream and 5 points downstream), was carried out. Then the long profiles were obtained by taking the distance on the horizontal axis and elevation on the vertical axis. Further analysis involved the following:

A. Description of the long profile forms:

The form and characteristics of the river long profiles were studied and compared with the concave=up profile of a river under steady-state equilibrium [6,13].

B. Normalized Long Profiles:

There is a possibility that the slight to noteworthy differences in the long profile shapes is because of the difference in basin relief and size (surrogate for power and discharge). Therefore, the long profile length and relief were normalized to minimize the effects of these two variables and highlight the effects of tectonics and/or lithology. The elevations and distances were divided by the head (i.e. maximum basin relief) and the total stream length, respectively to normalize the long profiles [8,15].

C. Mathematical Modeling: Curve Fitting

To describe the form of the long profiles simple linear, logarithmic, exponential and power-law regression models were fitted to the elevation versus distance data in the Rangit River and its tributaries.

The best fit model is one which minimizes the sum of squares of residuals and which also gives the minimum standard deviation of residuals [17]. It is also indicated that when the channel bed grain size is greater than the capacity of the river for transportation, the long profile shows a low degree of concavity and hence a better linear function fit [8]. As the transportation and deposition of channel sediment approaches dynamic equilibrium, the long profile better fits the exponential function. As the system approaches the graded profile, the channel sediment grain size will decrease downstream and hence the long profile fits more suitably for the logarithmic function. With further increase in the profile concavity, the power function becomes more appropriate. Thus, the evolution sequence should be linear followed by exponential, logarithmic and power [8].

D. Semi-logarithmic Profiles

Generally, the long profiles of the rivers are plotted on a semi-logarithmic paper in order to neutralize the exponential increase in the distance from the headwaters [2,13]. A river under graded condition is expected to be in a state of balance between uplift and erosion rate and hence the long profiles of such rivers would plot as a straight line on a semi-logarithmic paper. Such linear plots are generally observed for areas of uniform lithology or under relative tectonic stability. On the other hand, if a river flows through a tectonically active area characterized by uplift exceeding denudation or over resistant rocks, its long profile displays convexity. Therefore, the long profiles of the rivers under consideration were plotted on the semi-logarithmic graph paper with distance on the logarithmic scale.

E. Stream Gradient Index:

The gradient of a graded river usually decreases downstream as the discharge increases, and the longitudinal profile of this river can be often approximated by a straight line on a semi logarithmic plot [6]:

$$H= C - K\ln L \tag{2}$$

Where, H = elevation, L = distance from the source, and C and K are constants. K, the slope of this idealized profile, is called the stream gradient index [6] and can be evaluated by:

$$K = Hi - Hj / \ln Li - In\ Lj \tag{3}$$

Where, i and j refer to two points along the river profile. The SL Index can be used to characterize a relatively short reach (segment) of the river as well as the entire profile. By comparing the river long profiles to the ideal semi-logarithmic profiles, the significance of anomalous gradients can be evaluated in the context of the discharge increasing downstream.

F. Identification of steep segments/zones:

It is known fact that a segment of the river with anomalously high SL Index has high stream energy corresponding to resistant rock area (control of lithology) or differential uplift zone (control of tectonics) [2,8]. For this purpose, an index called Normalized Stream Gradient Index (NSL) was proposed [13]. The SL Index of each reach or segment of the river is divided by the idealized gradient index (k), which is the slope of the graded river profile, to obtain the NSL for each reach or segment of the river [13].

Mathematically, the statement can be represented as:

$$NSL = SL / k \tag{4}$$

Where, NSL = Normalized Gradient Index for a given reach or segment, SL = stream gradient index for the given stretch, and k = slope of the idealized Hack's graded profile.

Segments having $SL/k \geqslant 2$ are regarded as significantly steeper, whereas the reaches with $SL/k \geqslant 10$ are classified as extremely steeper reaches [13]. These attributes are characteristically associated with the areas undergoing uplift. In the present study, the points characterized by anomalously high SL values were identified using the criterion $SL/k \geqslant 10$.

G. Long Profile Concavity:

This was derived from the power logarithmic regression relationship between upstream drainage area and channel slope. The upstream drainage area is considered as a proxy for discharge [8,10,16,20]. The relationship that has been used to calculate the long profile concavity and steepness is described below:

$$S = K_s A^{-\theta} \tag{5}$$

Where, S is the channel slope, A is the basin area, θ is the concavity and Ks is the steepness index.

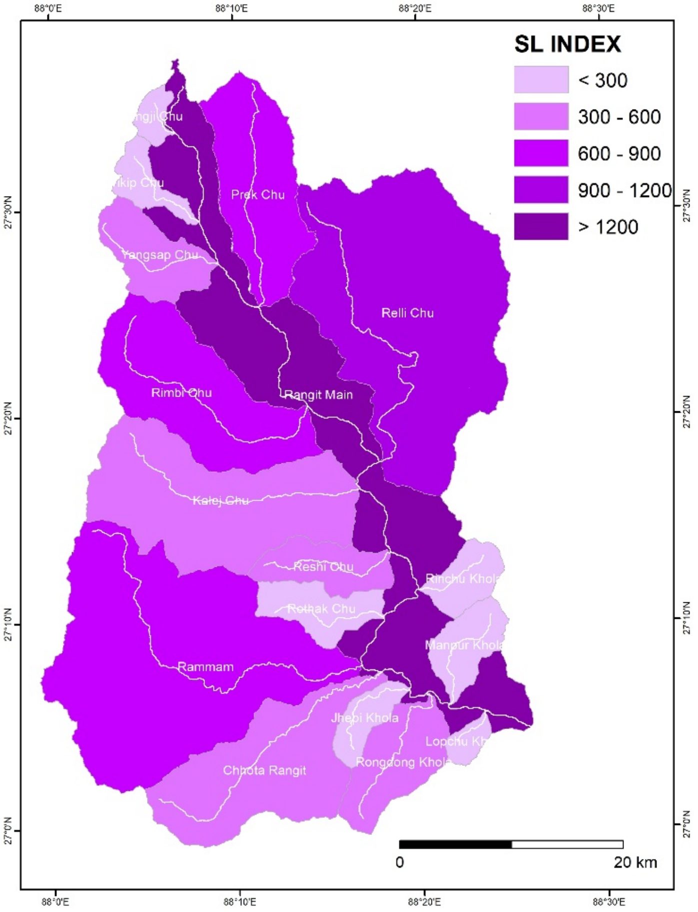

Figure 2. The SL index map of the Rangit Basin. The higher values of SL index imply steep gradients, often associated with the areas undergoing recent tectonic deformations.

III. RESULTS AND CONCLUSIONS

The long profiles reveal that none of the rivers in the Rangit Basin display the typical concave-up profile which one would associate with a river under uniform lithology and long-term tectonic stability. Rather, as expected for a tectonically active region, the long profiles are, more or less, characterized by steep upper segments. Similarly, the semi-logarithmic profiles of the rivers under review do not exhibit the straight line. In fact, all the profiles display above-grade conditions suggesting intense erosional regime. Most of the long profiles display the best fit for exponential equation. This means that the system has not yet reached the steady-state and is approaching the condition of dynamic equilibrium with channel bed grain size greater than the capacity of the river for transportation [8]. However, in the upper reach of the river, the tributaries display best fit for linear model which implies that the upper reach of the rivers are characterized by elevated erosion rates.

The stream gradient (SL) indices of the rivers range from 300–1200 which implies tectonic resurgence (Fig. 2). An important observation is that the left bank tributaries displaying higher values of SL index. Furthermore, analysis of the maps displaying the Normalized SL Index (NSL) reveals that a number of steep segments are predominantly concentrated in the upper reach of the Rangit River. Also, in the lower reach such steep segments are found. An important characteristic in the lower reach is that there are a number of barbed drainages, an important signature of drainage reorganization due to tectonics.

Finally, it can be concluded that geomorphometry can be a very efficient tool in deciphering the morphological adjustments of the rivers due to tectonics and lithology. The Rangit River, located in the Eastern Himalayas, display ample evidence of a river under active tectonic deformation. High values of SL Index supplemented by the right-skewed asymmetry of the river and high SL Indices of the right bank tributaries points out possibilities of the river gaining more are to the right at the cost of left.

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