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Geomorphological Interpretation of Long-Profile Geometry of a Stream: A Case Study of Chamta Channel, Darjeeling Foothills of West Bengal, India

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Abstract: *Geometry of long-profile is the outcome of form-process relationship under fluvial environment. The longitudinal profile of the Chamta river has been considered as a case study in this paper for its geomorphic evaluation. The Chamta is a small foothill-stream, lying on the Darjeeling Himalayan piedmont zone. The long-profile of Chamta river from source to Kanyan is derived from SRTM DEM data and from Kanyan to the confluence from field survey. Linear, exponential, logarithmic and power function models have been applied to set the best-fit model over that. Each mathematical function has its own geomorphological significance for interpretation based on stream-energy and channel competency. This has been reflected through the degree of concavity of the long-profile. Logarithmic function regression model is best fitted for the entire 1.83 km longitudinal profile of Chamta river, which may bear the clue of a graded profile for the river. Application of the polynomial regression model (PRM) on long-profile of the Chamta channel, indicates the multi-collinearity among the associated controlling variables to produce such geometry. Eighty-four percent data has been explained by 2nd order polynomial through the interactions of at least 3 controlling variables. The highest Stream length gradient index (SL index) has been observed at 523 m downstream from source, where the Chamta channel crosses the Himalayan Frontal Thrust (HFT). The ratio of SL index channel and SL index total has not crossed the threshold of 2, which supports the graded condition of the Chamta channel.*

Keywords: Linear, exponential, logarithmic, power regression model, polynomial regression model, Stream Length (SL) Index, tectonic and neo-tectonic activity, Himalayan frontal thrust (HFT).

Introduction

Longitudinal profile geometry of a stream reflects the assemblage of geomorphological form-process interaction along with the tectonic activity in recent past (Ji *et al.*, 2021). Long-profile is a x-y plot showing bed elevation as a function of downstream distance (Kavitha *et al.*, 2017). It is the outcome of simultaneous adjustment of evolution of landform and the river system (Biswas *et al.*, 2021; Saha *et al.*, 2020). The long-profile reflects any kind of change in flow and/or sediment dynamics in the watershed (Sinha and Parker, 1996). An elevation of a certain point of long-profile of a stream exhibits the complex outcome of the associated controlling variables which are fully associated with the form-process relationship of channel hydraulics. However, the degree of influence of the controlling variables may not be similar along the entire long-profile of a stream, which is depicted by the spatial variation in geometry of the longitudinal profile (Lee and Tsai, 2010). Effects of exogenetic and endogenic forces over the geometry of a long-profile of a stream may not always be observable through bare eyes, and hence, needs mathematical model analysis and scientific geomorphic interpretation (Hack, 1973; Ayaz and Dhali, 2020) for the better understanding of fluvial hydro-morphology (Keller and Pinter, 2002). Ayaz and Dhali (2020) tried to establish the tectonic deformation in the Himalayan foothills by analysing the geometry of the long-profiles of the tributary network of the Teesta system within the jurisdiction of India. Kavitha *et al.* (2017) attempted to quantify the geomorphic indices coupled with mathematical models in the Thoppaiyar basin and its sub-watersheds by using the gradient index and normalised gradient index. Similar attempt has been made for the analysis of the geometry of the Chamta channel. Green *et al.,* (2013) worked on the geometry of longitudinal profile of streams of the Columbia mountains in Canada, where the stress was given on the adjustment of long-profile with the response of internal system dynamics. Troiani and Della Set (2008) applied similar methodology in smaller watersheds of Central Italy, comparable in size with the Chamta watershed. Lee and Tsai (2010) used mathematical functions to define the geometry of the long-profile and found the best fitted function for the Choushui river of central Taiwan. Brardinoni and Hassan (2007) found a good relation between the form-process relationship and its impact on a longitudinal profile. Harmar and Clifford (2007) commented that the long-profile of the lower Mississippi river reflects spatially distributed form-process feedback between all aspects of channel morphology operating at a range of poorly defined time and space scale in the presence of natural controls. The concave river profile is a property which emerges from several scales of process-form interaction. Chen *et al.* (2006) worked on tectonic activities of the central and south-western foothills streams of Taiwan and found that the tectonic intensity varies with the magnitude of Hack's profile convexity. Schumm (2005) worked on the relation between the change in geometry of long-profile and channel metamorphosis. Rice and Church (2001) commented that the exponential or quadratic functions are suitable for explaining the aggradation process in longitudinal profiles in alluvial fan environment which is unaffected by significant lateral inputs of water or sediment in the gravel-bed rivers. Similarly, the present paper deals with the geometry of long-profile of the Chamta channel and its geomorphological interpretation.

Site, geology and tectonic setp

The Chamta river originates from the Kurseong Himalayan foothills at an elevation of 331 m, flowing through the Darjeeling Himalayan piedmont area (locally known as Terai) for 1.83 km and finally discharges into the Panchanoi channel at Sishudangi area near Siliguri town at an elevation of 212 m. The upper catchment of river falls under the jurisdiction of Kurseong block and the lower catchment under Matigara block of Darjeeling district of West Bengal (Fig. 1). The geometry of the long-profile of the Chamta channel reflects the influence of the local geological setup, lithological characteristics, geomorphological setting, and neo-tectonic occurrences. The Chamta river is one of the secondary tributaries of the Mahananda river, whose lithological arrangement can be designated after the Geological Survey of India (GSI) as well as Geological Society of America (GSA) Geological Time Scale v5.0 (Walker *et al*., 2018).

Pleistocene deposit occurs in the eastern side of the Chamta Basin. Southern portion of the basin is surrounded by Pleistocene-Holocene surface of the Quaternary period. Basement of the Chamta channel is aproned by the younger Meghalayan deposits as per the

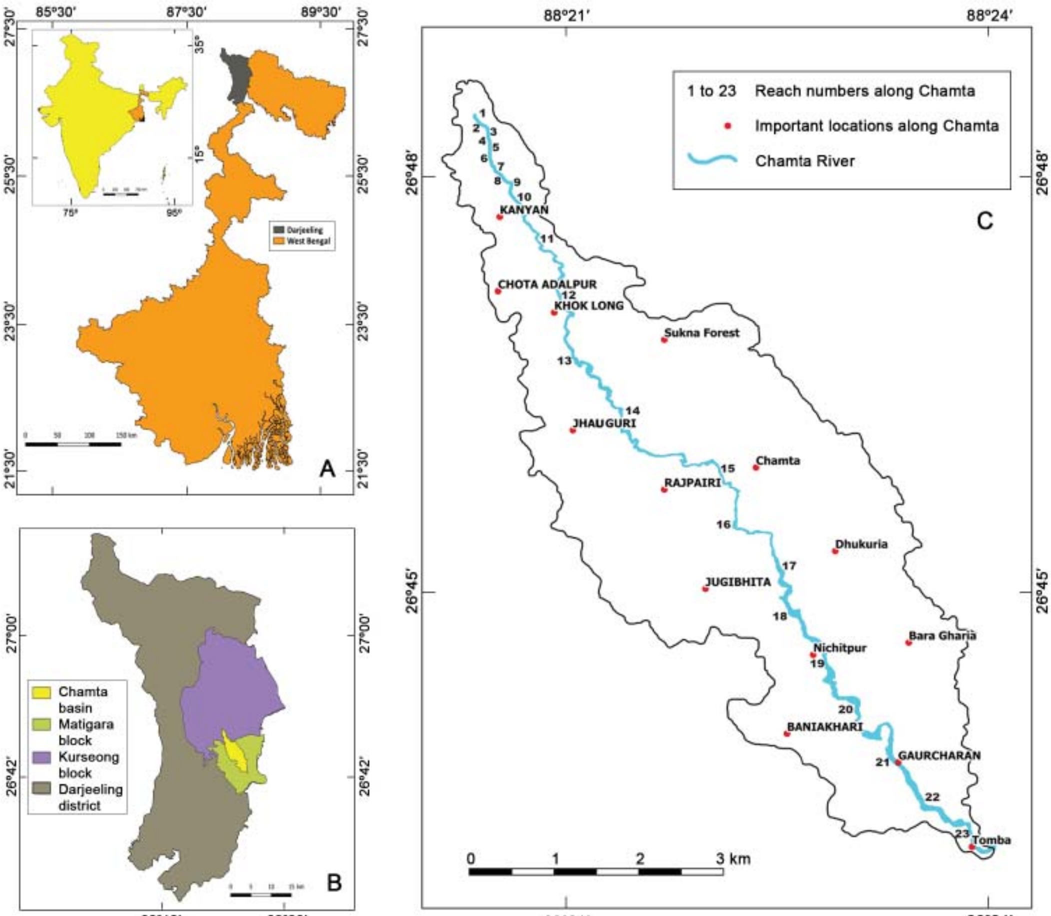

Figure 1. Location map of the Chamta basin. (A) Darjeeling district in West Bengal. The inset map is showing the location of West Bengal state in India, (B) The position of the Chamta basin in the Kurseong and Matigara blocks of Darjeeling district, (C) The Chamta river basin along with the main channel and the studied reaches numbered from 1 to 23 (red dots show the settlements along the Chamta river from Kanyan to Tomba).

The Chamta Basin is surrounded by Proterozoic surface in the north, which precedes the Permian surface of the south. Pliocene-Pleistocene surficial lobes occur in the northeast as well as in the north-west boundary of the Chamta basin, whereas the open geoscientific data site of GSI, Bhukosh (https://bhukosh.gsi.gov.in/Bhukosh/Public). The entire Terai foothill region (on which the Chamta Basin is located) comprise of unconsolidated loose Tertiary sediments, aligned horizontally on this geomorphic surface. Lower portion of Chamta basin is mostly covered by the older alluvium, whereas the upper catchment of the basin is associated with Siwalik lithological group. Differential tectonic movement along the margin of the Main Frontal Thrust (MFT) has been considered responsible for over-riding of the northern part over the southern block along the thrust plane (Nakata, 1972). The Chamta river crosses the Himalayan Frontal Thrust (HFT) within 500 m downstream from the source of the river (Fig. 2), whose presence can also be observed through the change in surface geology underlying the Chamta channel (Fig. 2). Folded rock-strata affected by the thrust movement has been recorded by GSI, which are lying under the northern tip of the upper catchment of the Chamta basin (Fig. 2). Buxa-Duars formation has been seen in the upper reach whereas the Chamta river passes through the Baikunthapur formation in the downstream area (Fig. 3). The Buxa-Duars formation is composed of a yellow weathered horizon on top of a brown top-soil that ranges in size from sand to silt. Iron-hydroxides give the weathered zone its yellow colour, whereas the combination of iron-hydroxides and organic components gives the soil its brown color (Das and Chattopadhyay, 1993). The underlying layers are mostly made up of fine to coarse sand and is strikingly comparable to the Baikunthapur formation in the eastern part of Teesta catchment area (Das and Chattopadhyay, 1993).

Siliguri and its adjacent area have received at least 250 cm annual rainfall in the span from 2011 to 2020 as per Climatic Research Unit

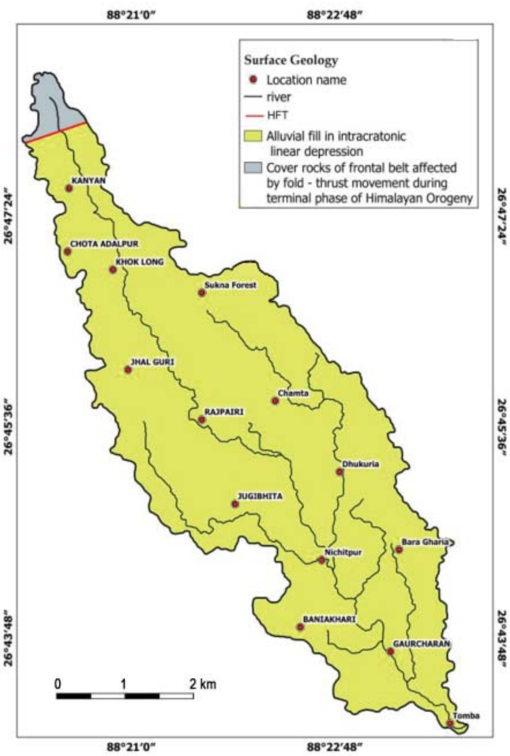

Figure 2. Surface geology of the Chamta Basin (data extracted from Bhukosh data repository, GSI and modified by authors). Location of HFT is marked by red line.

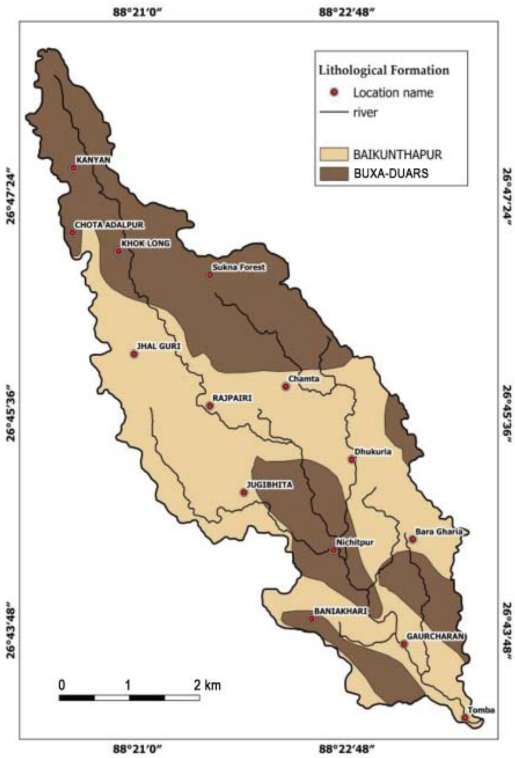

Figure 3. Lithological formation map of the Chamta Basin (data extracted from Bhukosh data repository, GSI and modified by authors)

(CRU) grid data repository (https://crudata.uea.ac.uk/cru/data/hrg/). It may indicate increase in riverine discharge in local foothills stream like the Chamta. A change in climate may enhance the capacity and competncy of the streams (Gurnell *et al.,* 2000). Darjeeling Himalayan foothills receive more rainfall than the high-altitude mountain areas of Darjeeling, which may be because of higher intensity of rainfall from the south-western monsoonal wind at the basement of Darjeeling Himalayas (Prokop and Walanus, 2017). The southern front of the Darjeeling-Bhutan Himalaya receives one of the highest annual rainfalls (3000–6000 mm) and most frequent severe rains (up to 800 mm day^{-1}) throughout the entire southern Himalayan frontier due to multi-scale interaction between monsoonal circulation and the local topography (Prokop and Walanus, 2017).

Methodology

The entire long-profile of the Chamta river, including the streth from the source to Kanyan (4.9 km from source) and from Kanyan to Sishudangi confluence (18.3 km from source) has been developed based on Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) and primary survey respectively. The upper course of the Chamta falls within the Mahananda Wildlife Sanctuary — a part of the Darjeeling Himalayan foothills, which is restricted for civilians. For this streth, the only option is to work with the DEM data to prepare the longitudinal profile up to Kanyan. SRTM DEM (n26e88-V3) data has been used here to draw the long-profile of the upper reach of Chamta river. Reduced levels (RL) have been computed from detiled field survey for the rest of the Chamta course to study the geometry of the stream. A standardised longitudinal profile of the Chamta channel has been drawn based on these two dataset from source of the Chamta to its confluence with Panchanoi (Fig. 8).

Initiative has been taken to find the best-fit curve with respect to the actual long-profile of the river Chamta by using the mathematical models. Linear, exponential, power, logarithmic and polynomial models have been tested to find the best-fit curve to predict the number of variables which are associated to produce such a long-profile geometry.

The Stream Length Gradient Index (SL index) has been used to observe the influence of structural control over the geometry of the long-profile. Difference in elevation between the highest and lowest point of a channel reach, horizontal distance of the given reach and the total length of the channel from source to the farthest point of a channel reach has been computed to calculate the SL index. The SL index has been calculated reach-wise as well as for the entire channel for assessing the intensity of structural control. The entire stretch of the Chamta river has been subdivided into 23 channel reaches in which the SL index has been calculated to observe any possible spatial variation (Fig. 8). The SL index refers to the dynamic balance between the erosion activity by the river (Hack, 1973) and neo-tectonic activities (Keller and Pinter, 2002) which can be used as useful proxy indicator to assess the tectonics movements (Ji *et al.*, 2021).

$$\text{SL index} = [\Delta H/\Delta L]/L$$

Where, ΔH indicates the relative relief a studied reach, ΔL is the horizontal distance of the given reach of the channel and L represents the total length of the channel from source to the farthest point of the given channel. Any change in channel slope is reflected in the SL index. Magnitude of fluctuation refers to possible tectonic movement, resistance of underlying rocks or topographic control over the stream (Keller and Pinter, 2002).

Result and discussion

Spatial variation of the magnitude of SL index has been estimated along the long-profile of the Chamta river. The magnitude of the SL index for the entire channel is 219. The reach-wise magnitude of SL index has also been estimated, which does not exceed the threshold of 100 except the representative site located at 477 m downstream from source of river Chamta, where the SL index is 421. The surface geology map of the studied basin (Fig. 2) shows the existence of the Himalayan Frontal Thrust (HFT) across the Chamta channel Chamta at 477 m downstream from source.

The ratio of SL index-channel reach and SL index-total (Magar and Magar, 2016) has been estimated for every reach of the Chamta channel (Fig. 4). SL index-total refers to the average of the SL indices measured from the representative reaches along the long-profile of a river. The magnitude of this ratio does not exceed the threshold of 2. Highest magnitude (1.92) occurs at HFT (Fig. 5), which is significantly larger than the values derived from the downstream portion of river Chamta. This can be considered as a proxy indicator which reflects the existence of the HFT across the Chamta channel. Relation beteen distance from the source and SL index does not show a bi-linear relationship, but 62% data can be explained (Fig. 6) through the 4th order Polynomial Regression Model (PRM).

The break of slope in long-profile may indicate the change in lithology and/or structural control along the channel (Ayaz and

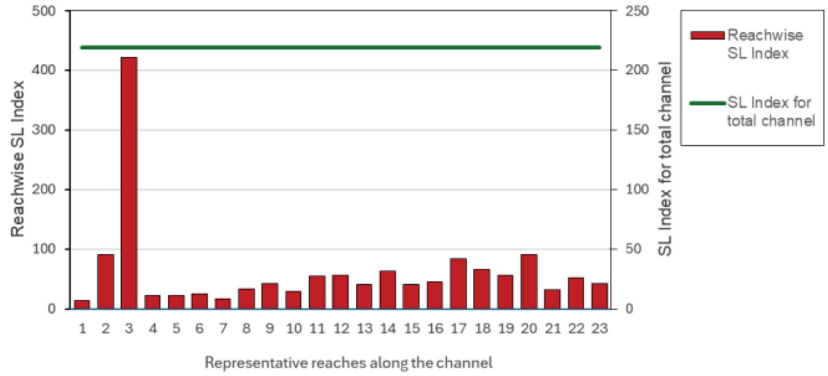

Figure 4. Spatial variation of channel reach-wise SL index along Chamta and SL index along the total Chamta channel

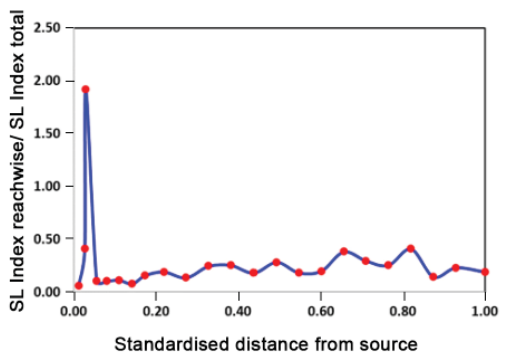

Figure 5. Spatial variation of the ratio between channel reach-wise SL index and SL index along the total Chamta channel with the change of standardized distance from source.

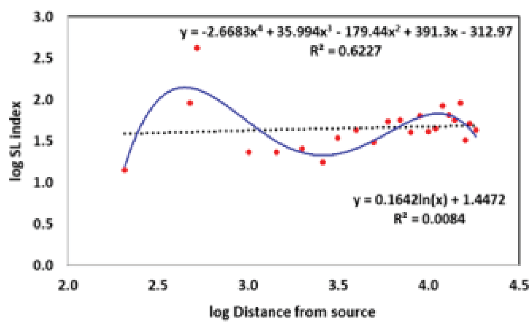

Figure 6. Relationship between the distance from source of Chamta channel and SL index through logarithmic regression model and polynomial regression model.

Dhali, 2020). The geometry of the long-profile can be better explained geomorphologically by using several mathematical models. Linear, exponential, logarithmic and power models are popular for the explanation of long-profile geometry (Lee and Tsai, 2010). Best-fit linear regression model (LRM) refers to the low degree of concavity, logarithmic regression model (LORM) represents a graded condition, whereas the transitional geomorphic stage is denoted by the exponential regression model (ERM). The best-fit power regression model (PORM) indicates the further increase in channel profile concavity (Lee and Tsai, 2009). The best-fit regression model is determined by the degree of association between the regressor and regressand. These four models have been tested on the long-profile of river Chamta to find the best-fit one (Table 1 and 2; Fig. 7).

The magnitude of R^2 is largest for the LORM (0.9051). It indicates that the Chamta is passing through the graded condition where the river is neither in eroding nor aggrading stage at any point along its course. The concavity of the long-profile drawn along the thalweg of the Chamta channel favours the downward transport of the sediment load, only during the high discharge monsoon days. The long-profile geometry of the upper catchment of the Chamta river up to Kanyan (5 km downstream from source) has been tested using the mathematical regression models. Here also the LORM is found to be best-fitted with 82% explained variation. The observed long-profile of the Chamta channel also denotes a graded condition.

Polynomial regression model (PRM) has been applied (Table 2) on the Chamta channel to get an idea about the number of controlling variables which are associated in a complex system to develop such geometry of the longitudinal profile. 84% (3 possible controlling variables), 88% (7 possible variables), 91% (15 possible variables) and 93% (31 possible variables) data can be explained through the 2nd, 3rd, 4th, and 5th order PRM respectively.

Percentage of explained variation often increases with the increase of the polynomial

Table 1. Association between distance from source and elevation of thalweg of Chamta channel through mathematical models

Mathematical model	Regressor	Regressand	Equation	Explained variance
Linear regression model (LRM)	Distance from source of Chamta (m)	Elevation of thalweg (m)	$y = -0.0081x + 231.54$	75.1%
Exponential regression model (ERM)			$y = 234.29e^{-5E\text{-}05x}$	88.4%
Logarithmic regression model (LORM)			$y = -33.19\ln(x) + 455.16$	90.5%
Power regression model (PORM)			$y = 709.25x^{-0.169}$	85.1%

Table 2. Association between distance from source and elevation of thalweg through polynomial regression model

Mathematical model	Order	Regressor	Regressand	Equation	Explained variation (%)
Polynomial regression model (PRM)	2nd	Distance from source of the Chamta (m)	Elevation of thalweg (m)	$y = 0.5938x^2 - 0.9711x + 0.7634$	84.7%
	3rd			$y = -1.4914x^3 + 2.6283x^2 - 1.6587x + 0.8073$	88.4%
	4th			$y = 5.2539x^4 - 11.305x^3 + 8.3388x^2 - 2.7515x + 0.8508$	91.4%
	5th			$y = -18.818x^5 + 49.993x^4 - 48.45x^3 + 21.011x^2 - 4.3389x + 0.8941$	93.7%

order. In the present case of Chamta, the long-profile geometry follows the same trend, but the rate of increase in explained variance is not the same. Highest magnitude of change in explained variance occurs from 2nd to 3rd order polynomial model (3.7%). Long-profile of Chamta river shows an overall concavity. Upper reach up to Kanyan is more concave than the downstream reach of the channel. The surface geology map (Fig. 2) shows that the Chamta channel is lying over the alluvium, deposited at intra-cratonic linear depression (as per Bhukosh repository) after crossing the Siwalik mountain front. The Chamta channel finds its path through the Buxa-Duars formation (now-a-days used for tea plantation) which has been partially eroded and washed out by fluvial erosion. The eroded, but elevated middle terrace or upper terrace of Mahananda river exists in the form of oxidized remnants of Buxa-Duars formation. The lower catchment of Chamta basin consists of the youngest Baikunthapur formation (Fig. 3).

Conclusion

Sudden irregularity in the variation of SL index at a particular point of long-profile may indicate the influence of structural control. Similar trend has been followed by the Chamta channel at the mountain front. The significant break-of-slope at this point of long-profile supports this inference. The ratio of reach-wise

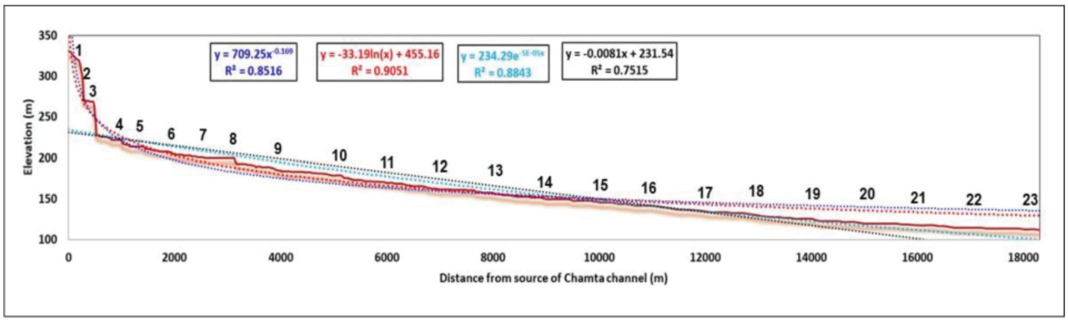

Figure 7. Longitudinal profile of Chamta river from source to confluence (actual curve) with its expected trend lines (black represents linear, sky-blue dotted line represents exponential, red represents logarithmic and deep blue represents power). The upper segment of this profile up to Kanyan is drawn based on SRTM data and rest the profile is drawn based on field survey data (presence of pools and riffles are represented by the sequential pattern of micro level relief variation. Numerical values (1 to 23) along the Chamta long-profile refers to the reaches within which the SL index is calculated by authors.

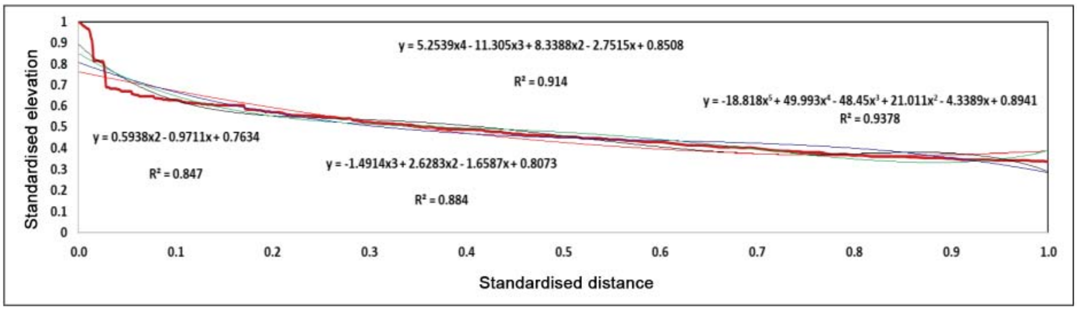

Figure 8. Standardized longitudinal profile of Chamta river from source to confluence (brown curve represents the actual curve) with its expected polynomial regression model (black, sky-blue, red and deep blue curve represents 2nd, 3rd, 4th and 5th order polynomial geometry respectively).

SL index and SL index of the total channel does not exceed the threshold of 2, which indicates a graded profile for the different reaches along the longitudinal profile of Chamta river. 62% data has been explained through the 4th order PRM, which refer to structural influence over the long-profile geometry of Chamta. The geometrical shape of the long-profile cannot be explained by linear regression model. It is best explained but the 5th order PRM, where at least 15 known or unknown variables impact to generate the geometric output of the long-profile. The highest noted magnitude of association of logarithmic regression model (0.9017) indicates that the sediment grain size of the Chamta channel decreases in downstream direction and the Chamta channel has adjusted itself in a stage where the river neither executes erosion nor degradation. The channel has established a graded long-profile as it reaches the local base level. The PRM, indicates that the number of variables associated with the system which produces such a geometry of long-profile is (2^n–1). Here, 'n' denotes the respective order of PRM. There are some known variables like tectonic control, lithology, geology, channel gradient, rainfall, temperature, flow velocity, discharge, sediment discharge, channel capacity and channel competency, which have direct impact over the geometry of the long-profile of the Chamta; whereas there are a few unknown variables which have some minor impact on the same. The overall concavity of the long-profile of the Chamta river reflects a progressive decrease in channel gradient and progressive increase in channel discharge in the downstream direction. More or less uniform SL index (<100), except at HFT refers to the homogeneous lithological setup along the Chamta channel after crossing the HFT.

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