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Quantification Of Areas Of Differential Rock Uplift Rates Using Steepness Index In The Lanja Region From Southern Konkan Coastal Belt, Maharashtra, India.

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Abstract:

The mega-feature of the Western Ghat located at passive continental margin of West Coast of India is considered to be neotectonic resurgence. Many geoscientists have postulated or derived sustained uplift along escarpment as well as in the Konkan lowland. The stream gradient is very sensitive to rock uplift rate. The Digital Elevation Model of the landscape from southern Konkan Coastal Belt helped us to derive quantitative estimates of spatial variation in uplift rate directly from digital topographic data. Longitudinal profiles of two major rivers (Kajali and Machkundi) and their tributaries, have been investigated to understand the spatially variable uplift rates on the concavity () of the bedrock rivers. The longitudinal profile of graded stream is typically concave-up. Areas that are undergoing faster surface uplift are identified by high normalized steepness index (Ksn) values. The study area lies under seismic zone IV. The area around Lanja had experienced few numbers of seismic events of moderate magnitude.

KEYWORDS:

Konkan Coastal Belt, longitudinal profile, profile concavity, steepness index, differential uplift

1.INTRODUCTION:

Relief is the result of interaction between climate, lithology, rock structures and tectonically induced vertical crustal movements. Landforms in active tectonic regimes are evolved as a response to interaction between tectonic uplift and surface processes. The evolution of topography reflects the balance between the tectonic uplift of rocks and their destruction by climate and slope-driven erosion and sediment transport processes (Davis, 1899; Hack, 1960). Only fluvial network consistently maintains its connection to tectonic forcing, and therefore contains potentially useful information about variation in rock uplift rates across the landscape (Wobus, et al., 2006). Mathematical modeling and field studies indicated that spatial patterns in erosion, from the local scale of tributaries to a large river valley, may influence the location of deformation in active mountain belts, (Anders et al., 2002; Stolar, et al., 2006). The bedrock streams are sensitive to tectonically imposed boundary conditions (Snyder et al., 2000) and allow estimating tectonic uplift rates where direct structural and geodetic data is not available.

In this context, longitudinal profiles in the pattern of drainage were used to infer zones of enhanced tectonic activity in area of coastal strip from southern Deccan Volcanic Province along West Coast of India (Fig.1). Quantitative measurements and geomorphic indices have been previously tested as a valuable tool in various tectonically active regimes, such as the Garhwal Himalaya and the Western Ghat regions (Tyagi, et al., 2009; Campanile, et al., 2008; Harbor and Gunnell, 2007). Kale and Shejwalkar(2008) have applied Geomorphic Indices of active Tectonics (GAT) to drainages from both

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sides of Western Ghat to identify the areas of active tectonics. They concluded with the results indicate that the Western Deccan CFB belongs to the class of relatively low tectonic activity. This paper comprises analysis and interpretation of longitudinal profile – normalized steepness and concavity of streams (Ksn and?)that have been used successfully in studies of active tectonics.

West coast of India is sutured by West Coast Fault (WCF) and this continental margin is definitive example of rifted passive shoulder type (Matmon, et al., 2002) with well-defined western (seaward) facing escarpment, the Western Ghat (Fig.1.). The formation of the present western Indian margin was initiated by the late Cretaceous separation from Madagascar (ca 88 Ma) and, finally, by a ridge-jump which detached India from the Seychelles Bank at the time of its flight over Reunion Hotspot, which also causes voluminous outpouring the Deccan Continental Flood Basalt (CFB) (ca 65 Ma), (Hooper, 1990). The Apatite Fission Track (AFT) derived ages of Deccan CFB are between 54 and 72Ma (Gunnell, et al., 2003). Formation of Western Ghat separates the CFB region into three parts from east to west are Deccan Upland, Western Ghats and coastal low land, the Konkan respectively. The Western Ghat has become drainage divide for westerly and easterly flowing major rivers. A narrow strip of coastal belt, the Konkan Coastal Belt (KCB) (average width about 50km) is characterized by westerly flowing rivers. According to Valdiya (2011) Western Ghat is mega-geomorphic feature it is not just due to isostatic uplift but can be attributed to tectonic resurgence. The variations in the dips of lava flow were attributed by Nielson and Brooks (1981) to extensional fault structure with number of rotated blocks bounded by faults / fracture zones represented by western margin of India. According to Valdiya (2011) there must be presence of blind faults along west coast of India, which are in the process of formation and have yet not reached the surface, and thus have no surface expression.

The KCB is characterized by westerly flowing rivers with dendritic and trellis to anastomosing drainage pattern suggesting structural control (Fig.2.). The western coast is rimmed by plateaux capped by laterite (Fig.1). The elevation of the coastal laterite (up to 200 m) together with associated development of an entrenched drainage indicates that widespread uplift has affected the margin during Late Tertiary times. Bendick and Bilham (1999) documented uplift rate at c 0.8mm/yr-1 at 13028'N latitude inferred from 14C dating of shelly deposits. Moreover, they recorded uplift rate at over 3mm/yr-1 in recent decades (1950 – 1980) with the help of tide gauge record and leveling data. They also recorded a series of Quaternary synclinal structures trending ENE on the West Indian coast between about 80N and 200N. No relative displacement can be measured in the study area due to lack of marker horizon.

2.THEORETICAL FRAMEWORK:

Stable streams are in dynamic equilibrium and called “graded”. A graded stream can have depositional and erosional events but overall the sediment transported and supplied to the stream is balanced over long periods. Disturbance of the equilibrium leads to unstable streams that are “degrading” (eroding) or “aggrading” (depositing). A stream can typically exhibit all three equilibrium states in various reaches along its channel.

When the sediment supply exceeds the transport capacity of a river, its sediment load is said to be transport-limited and aggradation of the channel bed results. Bedrock channels are commonly said to be detachment-limited as the capacity of the river to carry sediment exceeds the supply of material to the channel (Turowski, et al., 2008)The longitudinal profiles of bedrock (or mixed bedrock-alluvial) channels are more sensitive indicators of uplift rate than other morphological properties.

2.1 Stream Long Profile:

Detachment-limited incision into bedrock is modeled as a power law function of contributing area and channel gradient (Howard and Kerby, 1983; Whipple and Tucker, 1999). An equation for river profile evolution can be written as:

$$\frac{dz}{dt} = U(x, t) - KA^m S^n \quad (1)$$

Where, dz/dt is the time rate of change of channel elevation, U is rock uplift rate relative to a fixed base level, A is upstream drainage area, S is local channel gradient, K is a dimensional coefficient of erosion, and m and n are positive constants related to basin lithology, hydraulic geometry, and erosion process (Howard, 1994; Whipple and Tucker, 1999; Whipple *et al.*, 2000). Under steady-state conditions ($dz/dt = 0$), with uniform U and K and constant m and n , equation (1) can be modified to yield an expression for



equilibrium channel gradient:

$$S = \left(\frac{U}{K}\right)^{1/n} A^{-\left(\frac{m}{n}\right)}, \quad (2)$$

Equation (2) portends a power-law relationship between channel gradient and drainage area often observed in natural landscapes, of the form $S = K_{sn}A^{-\theta}$ (Tarboton et al., 1991; Sklar and Dietrich, 1998), where the coefficient $(U/K)^{1/n}$ sets the channel steepness, k_{sn} and the ratio m/n is the intrinsic channel concavity, which equals the actual concavity θ only under conditions of uniform K , U , m , and n .

Therefore, the equation (2) can be written as:

$$S = K_s A^{-\theta} \quad (3)$$

Where, k_{sn} are the steepness index and θ the concavity index. Steepness index is known to be a function of rock uplift rate, lithology and climate. The concavity index is typically in the range 0.2–0.6, (Hack, 1957; Flint, 1974; Snyder et al., 2000; Kirby and Whipple, 2001) and is apparently insensitive to differences in uplift rate, lithology and climate.

The coefficient K_{sn} is similar in principle to the stream-gradient index developed by Hack, (1973). In any analysis of stream longitudinal profiles, the relationships implied by equations (1) and (3):

$$\theta = m/n, \quad (4)$$

and

$$K_{sn} = (U/K)^{1/n}, \quad (5)$$

hold true if and only if (1) the river profile is in steady state with respect to current climatic and uplift conditions; and (2) both uplift rate (U) and coefficient of erosion (K) are uniform through the channel reach. Where these conditions are met, the parameters $(U/K)^{1/n}$ and m/n can be estimated directly through regressions of channel-gradient and drainage-area data.

Segments of individual profile are characterized by different values of K_{sn} and θ or both. This variation in values is helpful to extract tectonic information from landscape.

3. PHYSIOGRAPHIC AND GEOLOGIC SETTING:

The shaded relief map nicely dictates the physiographic setting of the study area (Fig. 1). The study area can be divided into three geomorphic domains, from east to west are 1) Western Ghat escarpment and Foot Hills (FH), 2) the middle low lying land (LL) and 3) tilted tableland (TT) mainly capped by laterites. Laterites found on upland are high-level laterites while those occurring in the study area are low-level laterites. Both high and low-level laterites are considered to be remnants of palaeo-surfaces (Widdowson and Gunnell, 1999).

Westerly flowing major rivers, Kajali River at north and Machkundi River at south, traverse these three domains. Though laterites encountered near the mouth of these rivers, the rivers deeply incise laterites and underlying basaltic substrate. It is better to describe these channels of both the rivers as “mixed bedrock-alluvium channels”. Bedrock channels of streams are characterized by deep and sometimes interconnected potholes, cascades, waterfalls, steep valley walls, deep incision etc.

The FH domain is characterized by high relief, trellis drainage pattern and deformed geomorphic surfaces associated with a dissected landscape. This domain has high stream gradients with low sinuosity which indicate active tectonic regime. The LL domain is characterized by low relative relief, meandering rivers with relatively low surface slope and river gradient, but high river sinuosity. Sudden increase in sinuosity of rivers in LL domain also indicates the higher vertical movement of FH domain than LL domain. Increase in sediment flux causes patchy occurrences of thin veneer of sediments in the bed. The TT domain has westerly / seaward tilted plateaux (20 to 60) with laterite capping. Sudden increase in gradient, deep incised streams and moderate relief are the characteristic of TT domain. All these features indicate that the FH, LL and TT geomorphic zones are tectonically active.

4. METHODS:

DEM, Survey of India (SOI) topographic sheets of scale 1:50,000 and field data has been used for



investigations for this study. Digital topographic data is suitable for long profile analysis. SRTM data of 30m resolution was used. The DEM data of resolution 30m was used in this study. The data was further resampled at equal intervals height (Δz) to reduce bias in regression analysis and for smoothing DEM profiles. The synthetic drainage network was extracted using the D8 algorithm with threshold drainage area set at 1km².

The digital data thus obtained was utilized to extract requisite stream profiles and their parameters. A group of built-in-functions in ArcGIS were used for flow direction and flow accumulation raster. A suit of MATLAB scripts, “profiler” was used to extract and analyze stream longitudinal profiles, knick points and logS-logA plots. Its interface with ArcGIS allows us to delineate streams and knick points on DEM.

5.RESULTS AND DISCUSSION:

Most of the tributaries join the major rivers at right angle forming trellis drainage pattern (Fig.2). The headwater of both the rivers flow towards west, but trunk channels at lower reaches of both the rivers change direction abruptly to a NNW trend near their mouth indicating structural control on these rivers.

Streams in TT domain: Though streams are at their lower reaches, deep incision occurs in this domain due to channel steepening (Fig.1). In this domain streams obey detachment-limited characters. The channels are occupied mainly by boulders, cobbles and silt. The boulders are derived from frequent occurrence of landslides in this domain.

Streams in LL domain: This middle domain exhibits varieties of stream channel patterns (Fig.1). Streams exhibit patches of thin veneer of alluvial deposits and can be classified as mixed bedrock-alluvial channel. Increase in sinuosity, presence of ponding and trellis drainage pattern of tributaries is characteristic of major rivers in this domain mainly due to decrease in gradient (Fig.2). Dhokachi tributary increases its sinuosity because of uplift zone at its lower reaches. Frequent land sliding and subsidence occur along the channel of Dhokachi stream. A channel of Dhokachi is characterized by presence of boulders and cobbles derived from landslide, series of interconnected potholes, and four knick points. River piracy is indicator of active tectonics. The drainages of tributary Indavati are captured by Panhale stream. The piracy occurred because the capturing stream (Panhale) is a shorter distance upstream from the Machkundi river base level, at the point of capture, than the captured (Indavati) stream (Fig.2). The knick zone of Panhale stream must have been migrated to its upstream to accommodate larger river. Headwater erosion of the shorter and steeper Indavati stream was fostered by the knick points.

Streams in FH domain: The streams in this domain are characterized by narrow valley width and good hydraulic scaling indicating active uplift zone. Valley sides are steep and narrow. Few numbers of tributaries meet major rivers at right angles. Kajali exhibit broader basin width at its upper reaches than the basin width shown by Machkundi at its head.

5.1 Long-Profile:

Equation (3) has been used to generate long-profiles using “Profiler” suit in MATLAB with ArcGIS interface. Long-profiles of two major rivers as well as their 14 tributaries and their corresponding concavity and steepness were used to characterize tectonics, uplift pattern and knick zones. A reference concavity $\gamma_{ref} = 0.45$ is considered for interpretation of steepness values, because K_{sn} and γ are determined by regression analysis. Long-profile of channels are segmented and regressed to know the gradual change in the steepness indices of a channel. Distribution of normalized steepness indices for all tributaries in the catchment can be extremely useful tool for delineating tectonic boundaries (Kirby et al., 2003; Wobus et al., 2003).



Table 1: Steepness and concavity indices of Kajali and Machkundi rivers and their tributaries.

	K_{sn}^i (range)	q		K_{sn}^i (range)	q
Kajali River	52.1 (44.4-59.7)	0.72±0.043	Machkundi River	40.2 (33.5-46.9)	0.59±0.22
Agav	9.1 (5.18-13)	0.57±0.18	Bhandar	19 (16.8-21.2)	0.3±0.21
Dugva	22.4 (17.4-27.3)	0.064±0.11	Panhale	10.4 (8.48-12.4)	0.44±0.14
Murshi	35.9 (31-40.9)	0.63±0.054	Hardkhale	40.4 (32.2-48.5)	0.85±0.24
Palu	39.2 (34-44.4)	0.63±0.061	Indavati	12.2 (5.28-19.2)	0.023±0.44
Panval	15.1 (12.8-17.4)	0.34±0.14	Mandav	9.38 (8.45-10.3)	0.42±0.086
Salpe	27.5 (22.9-32.1)	0.64±0.059	Vilavade	8.25 (7.25-9.24)	0.45±0.056
Thorli	16.3 (14.9-17.7)	0.3±0.096	Dhokachi	10.5 (4.79-16.2)	0.039±0.3

The long-profiles of the Kajali river is found to have relatively smooth and concave curves for much of its length suggesting a condition in which the rivers have equilibrated with local rock uplift. Kajali River has attained their steady state. (Fig. 3 and 4) Machkundi River shows convexities at segments along their long profiles. Machkundi River is likely to be undergoing transient response to tectonics. The convexities at upper and lower reaches indicate higher uplift rate.

Pronounced change in increase in the steepness and concavity indices in the FH domain has been observed. The long-profile of streams in this zone dictates increase in convexity (Fig 3 and 4).

The pattern of uplift is best developed in the TT domain. Convexities in long profiles of tributaries of Kajaliriver such as Panval, Agav, Dugva and Thorli and tributaries of Machkundi river such as Dhokachi, Indavati, Southern stream of Panhale, Mandavkar and Bhandar indicate these streams are in transient state because of high uplift rate. All of these tributaries are flowing in TT domain. All rivers and their tributaries show pronounced increase in steepness and concavity indices in TT domain (Table1). The presence of knick points dictate transient long profiles with short over steepened reach separating old and new equilibrium states of these streams (Fig. 3 and 4)

In the LL domain the streams exhibit increase in their sinuosity. The gradient and grade of incision of streams also decrease. The increase in rate of uplift at lower reaches of streams across this domain is responded by streams by increasing their sinuosity.

Knick points in multiple rivers and streams are found at different points in the basins but nearly constant elevation (Fig. 2). Domains TT and FH can be ascribed as knick zones as only few number of knick points occur in the domain LL.

Gradient-area (logS-logA) data analysis of channel profiles can be a powerful quantitative tool even without a complete understanding of fluvial incision process (Whipple, 2004). The slope-area data presented along with long profile in figure 3 and 4 also support the transient response of rivers and their tributaries to uplift rate by changes in their regression (dashed lines in each plot).

Panval, Thorli, Bhandar, Indavati and Dhokachi streams, loaded with knick points, exhibit extremely low concavity ($\theta = <0.4$) is due to increase in their incision rate, indicative of their transient state (Table 1.). Moderate concavity ($\theta = 0.4 - 0.7$) is shown by Agav, Murshi, Palu, Salpe, Panhale, Mandav and Vilavade streams is suggestive of uniform rock uplift. Kajali River and Hardkhale stream exhibit high concavity ($\theta = 0.7 - 1.0$) and are associated with downstream decrease in uplift rate.

The increase in gradient, steepness and convexity in the long-profile occurs above the topographic contour 120 in TT domain while the same trend occurs in FH domain above the topographic contour 220.

6.CONCLUSION:

Results of morphotectonic analysis of part of KCB region dictate a geomorphology and landscape dominated by active tectonics. The tectonic activity is superimposed on the drainages in the study region. The fluvial response to uplift is based on the fact that the area has experiencing uniform lithology and climatic conditions.



Pattern and intensity of tectonic activity in the KCB regime has been exploited with the help of morphotectonic indices. The longitudinal profile of the streams seems to be very useful in understanding the relationship of uplift rate and its consequences on drainages.

- Increase in steepness and concavity in western (TT) and eastern (FH) domain indicate they are undergoing higher uplift rate than the middle domain (LL).
- The wave of tectonic resurgence transmitted in the area and is reflected by the drainage pattern and their adaptation with it by increase in incision. The major rivers Kajali and Machkundi attained state of equilibrium with the higher uplift rate. The tributaries of these rivers are in transient state as a response to their conflict with tectonic imbalance. Geomorphic processes driving erosion by tributaries are lagging behind the tectonic processes that have driven the rock uplift. This result emphasize the importance of lag times a landscape may digest to transform the tectonic conditions to another.

Signals transmitted by tectonic disturbances are reflected in the drainages patterns as well as physiography of the study area. Higher uplift rate in domains TT and FH is also reflected in physiographic setting of the study area. Deep incision by rivers, presence of narrow and deep valleys and increased gradient indicate high uplift zone. The middle domain LL experiencing low uplift rate than the adjacent domains is dictated by increase in sinuosity and sediment flux, river piracy and absence of relief features. The visual interpretation of shaded relief map derived from DEM also supports the spatial variation in uplift zone and rate.

There are no previously inferred faults or fault zones in the study area. We interpret the presence of graben structure formed due to extensional tectonic activity as in rifted CFB margins of other parts of the world. Morphotectonic studies coupled with other structural signatures would help to build a conclusion leading to presence of extensional tectonics.

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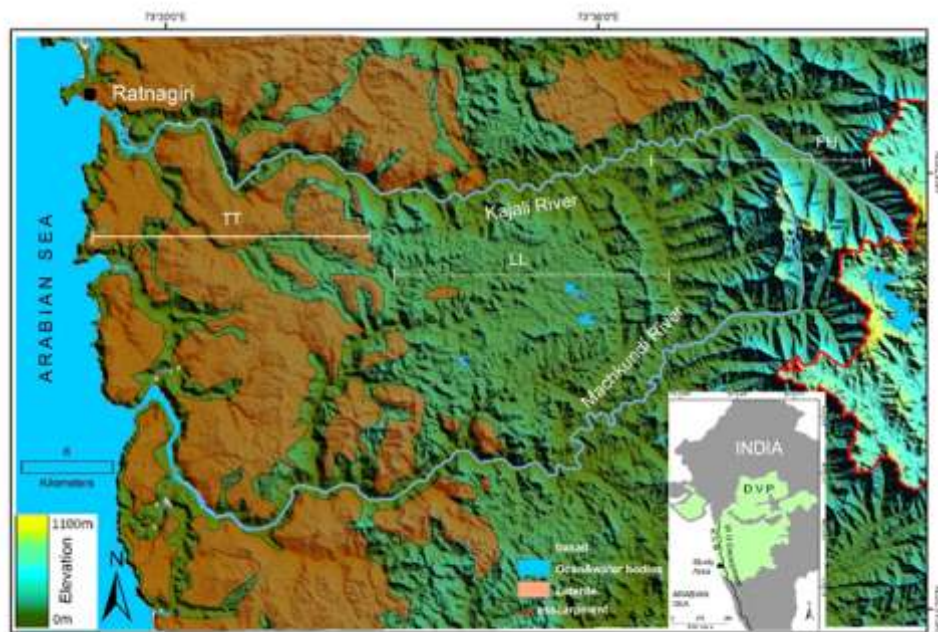


Fig. 1: Location and geologic map of the study area. The domains are marked by TT (Tilted Tableland), LL (Low lying Land) and FH (Foot Hills).

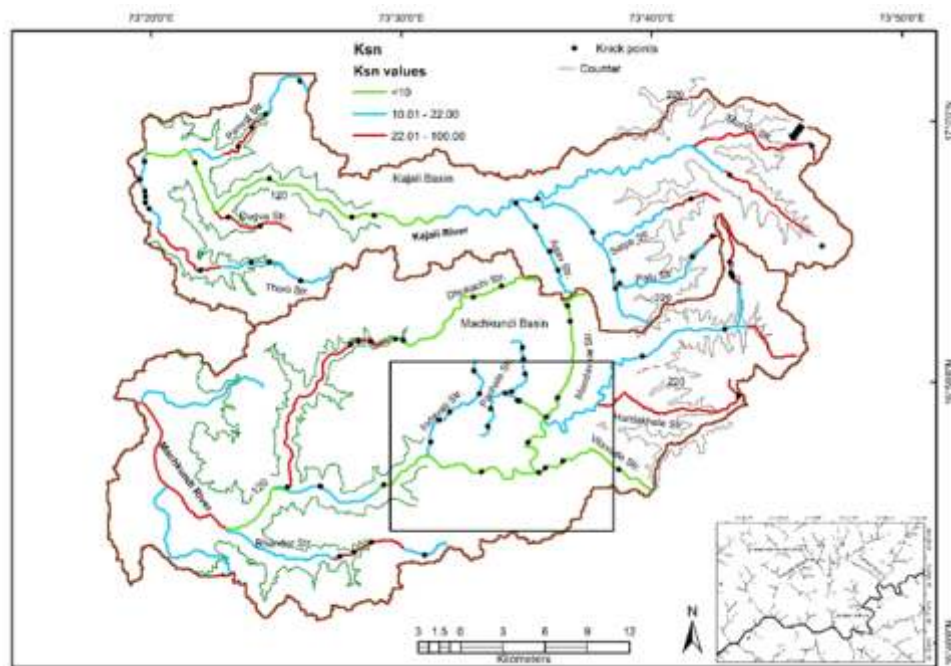


Fig.2: Drainage map of the study area showing Ksn values along segments of stream. Dots on the stream show knick points. Inset shows Indavati stream captured by Panhale stream.

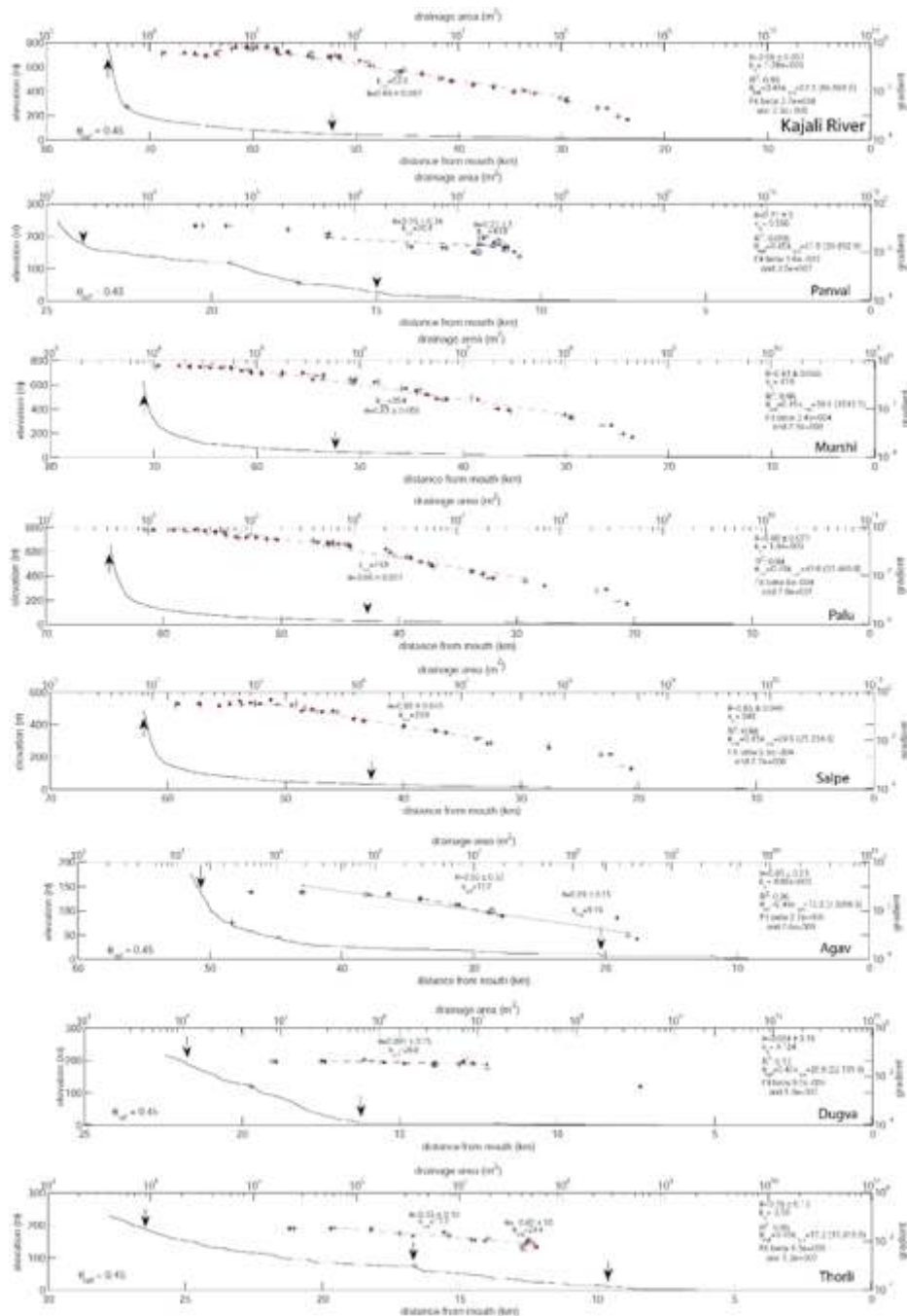


Fig.3: Long profile and slope-area data from 30m resolution digital elevation data model (DEM) of Kajali River and its tributaries. The plus marks along the profile indicate the locations of user-specified knickpoint positions. Arrows above and below long profiles show regression limits for slope-area fits. In all plots dashed lines are fits to data with $\theta_{ref}=0.45$. Squares are slope-area data using log-bin averaging method; crosses are data using 200m smoothing window to calculate channel slopes. Open circles show the locations of the knickpoints as plotted on the long profile.

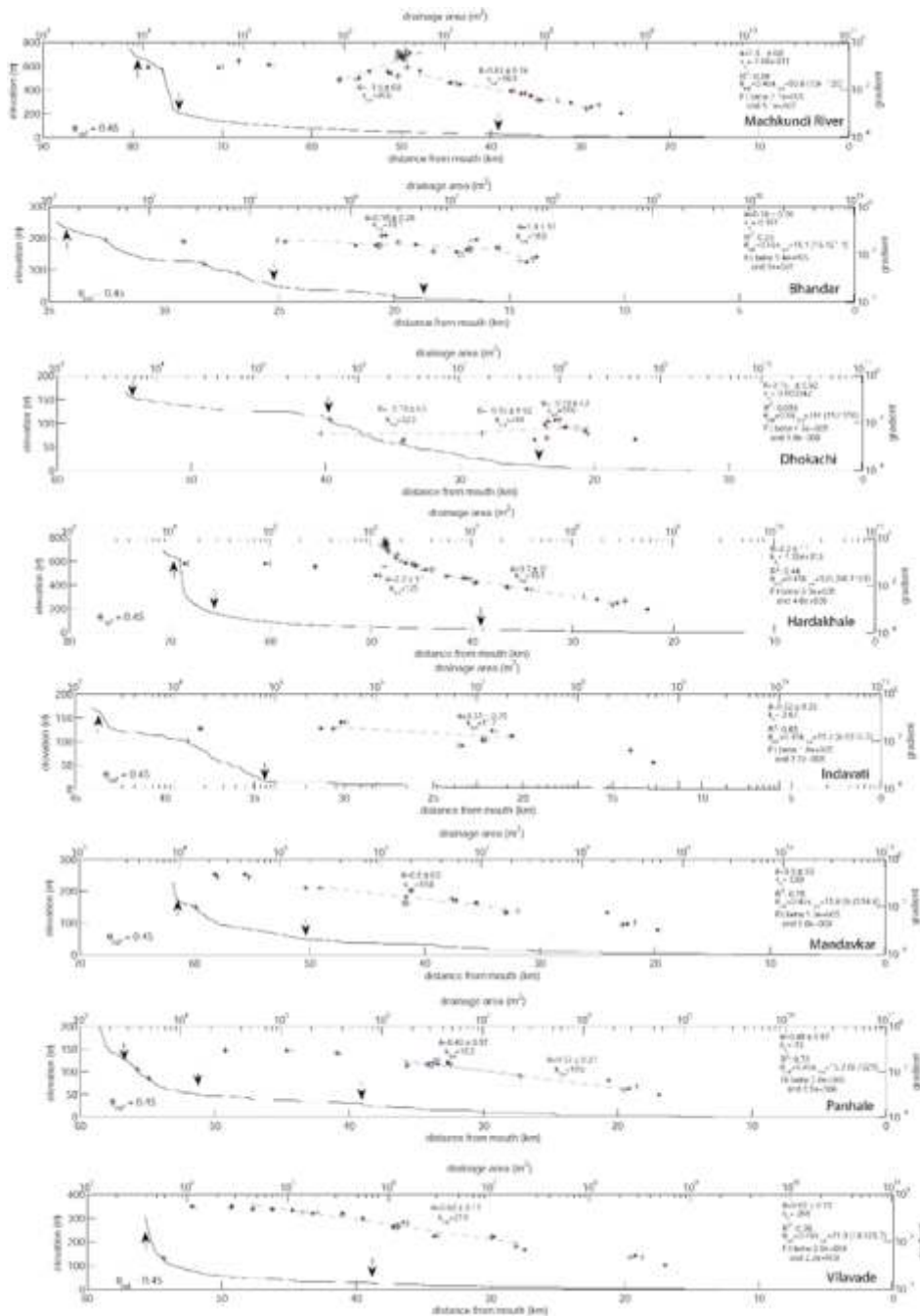


Fig.4: Long profile and slope-area data from 30m resolution digital elevation data model (DEM) of Machkundi River and its tributaries. The plus marks along the profile indicate the locations of user-specified knickpoint positions. Arrows above and below long profiles show regression limits for slope-area fits. In all plots dashed lines are fits to data with $\theta_{ref}=0.45$. Squares are slope-area data using log-bin averaging method; crosses are data using 200m smoothing window to calculate channel slopes. Open circles show the locations of the knickpoints as plotted on the long profile.

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