Identifying areas of differential uplift using steepness index in the Alaknanda basin, Garhwal Himalaya, Uttarakhand

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In this paper an attempt has been made to identify places of high surface uplift in the Alaknanda valley using the steepness index method. Locations that are undergoing faster surface uplift are marked by convex river profile and high steepness index (k_s) values. Conventionally, the Main Central Thrust (MCT) is known to be the zone of high uplift (incision), which accords well with our analyses. The second zone of relatively higher surface uplift is identified south of the MCT around Chamoli, Nandprayag and Karnprayag. These locations are traversed by the Chamoli, Nandprayag and the Alaknanda faults respectively. Our preliminary study suggests that for future earthquake risk evaluation, detailed geomorphological and seismotectonic studies should be undertaken in this area.

Keywords: Alaknanda basin, differential uplift, river profile, steepness index.

EVOLUTION of landscape in tectonically active mountain regions is intrinsically related to the combination of endogenic (crustal deformation) and exogenic (surface) processes. In such areas, rivers play an important role due to their ability to incise, which ultimately sets the rate of lowering of a landscape and therefore mass removal in actively rising mountainous regions[1]. Two major factors that modulate bedrock incision rate are climate and tectonics. In a steady state condition, when climate (the long-term sediment supply and transport capacity are balanced) and the rate of uplift is equal to the rate of incision, the longitudinal profile of a river would be graded[2]. However, if the river bed uplift rate exceeds the incision capability, then the convex longitudinal profile develops[3]. Therefore, in order to ascertain the fluvial response to terrain instability (stability), longitudinal river profile provides a first order approximation towards the role of endogenic and exogenic processes. Towards this, empirical studies were found quite useful[4–6] to assess the spatial variability in surface uplift (endogenic) in active orogen. The general equation for the river profile evolution can be written as[4,6,7]

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

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where dz/dt is the rate of change of channel elevation, U is rock uplift rate relative to fixed base level, K is erosion coefficient, A is channel drainage area, S is channel gradient, and m and n are the constants depending on the basin lithology, river channel geometry and erosion process.

In such studies (for steady state condition), erosion is balanced by uplift, and the longitudinal profile of a river can be represented by a power law function in which the local channel slope (S) of a stream is a function of the stream drainage area (A) and can be represented as $S = k_s A^{-\theta}$.

Here k_s is the steepness index and θ is the concavity. If there is no differential uplift, the value of k_s should remain constant for a given stream. However, if the river basin is undergoing differential uplift, k_s may change from one segment to another[4]. Considering that the channel slope is inversely proportional to drainage basin area, therefore, as the drainage area increases, the slope of the river profile decreases. However, in areas where differential uplift is going on, the proportionality of drainage area and slope does not hold. The areas where differential uplift is higher, oversteepening of the river profiles should occur, and can be ascertained by changes in k_s.

However, in this equation, it is assumed that the role of lithology, channel geometry and sediment variability has limited influence. This is reasonable considering that in the study area there is no significant lithological variation, river dominantly flows on the bedrock, and hence variable sediment supply may not have much influence on erosion coefficient. Therefore, changes in k_s can be used to ascertain the variation in the uplift. Here we would like to mention that the equation can be used in areas where insignificant variations in lithology, sediment supply and channel width exist. In the Himalayas a good correlation exists between erosion-resistant lithology and high river gradient and vice versa, implying that the role of differential erosion is secondary to the role of tectonics in shaping the profiles of Himalayan rivers[2]. Further, channel geometry and sediment supply would have insignificant influence on the river profile development because of the confined nature of river channel and bedrock-dominated flow characteristics. In the present study, longitudinal profile of the Alaknanda river in the Central Himalaya was investigated using the given expression in order to identify areas of differential uplift. The Alaknanda river drains through three major lithologies, from north to south; these are the Trans-Himalayan Sedimentaries (THS), the Higher Himalayan Crystalline (HHC) and the Lesser Himalayan Metasedimentary rocks (LHM)[8]. The orographic and lithological discontinuities are differentiated by the Trans-Himadri Fault (THF) and the Main Central Thrust (MCT) respectively. In addition to this, the Alaknanda river traverses the MCT at Helong, the Alaknanda fault (AF) at Karnprayag and the North Almora Thrust (NAT) at Srinagar before meeting the Bhagirathi river at Devprayag in the Lesser Himalaya[9,10]

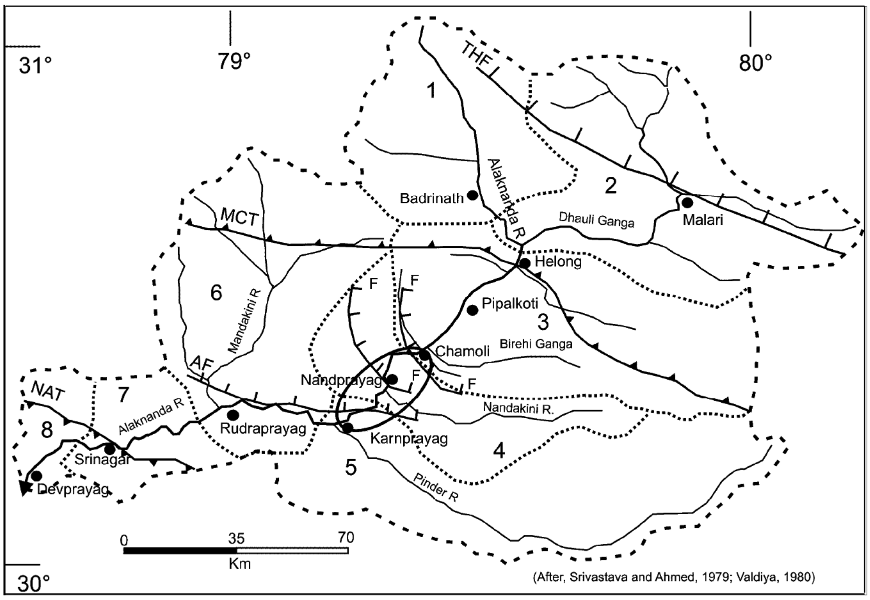

Figure 1. Basin map for Alaknanda valley with sub-basins. 1, Badrinath; 2, Helong; 3, Chamoli; 4, Nandprayag; 5, Karnprayag; 6, Rudraprayag; 7, Srinagar and 8, Devprayag. THF, Trans-Himadri fault; MCT, Main Central Thrust; AF, Alaknanda fault, NAT, North Almora Thrust and F, F fault. Dotted line indicates the sub-basin boundaries. Elliptical circle marks the zone of high uplift after the MCT.

(Figure 1). On the basis of exposure age dating, Vance *et al.*[11] have calculated the average erosion for the Upper Ganga Catchment (Bhagirathi and Alaknanda river basins) and suggested that the erosion rate in the Trans-Himalaya is around 1.2 mm per year, this increases to around 2.7 mm per year in the Higher Himalaya and again decreases to around 0.8 mm per year in the Lesser Himalaya. In addition to this, focused incision rates obtained using the dating of terraces suggest that in Lesser Himalaya it varies from 4 mm per year around AF[12] and near Devprayag the estimate ranges from 2.3 to 1.4 mm per year[13]. These estimates indicate a spatial variability in the incision (uplift) along the course of the Alaknanda basin.

The subtle expression of differential movement is expressed by the longitudinal river profiles in an active orogen[2,3]. Using the conventional geomorphological technique supported by stream profile analyses, a preliminary attempt has been made to identify areas in the Alaknanda basin that are currently undergoing differential uplift.

SRTM data along with the Survey of India (SOI) topographic map was used for delineating the catchment of Alaknanda river. Eight sub-basins of Alaknanda river were demarcated using the watershed boundaries and major tributary rivers draining into the Alaknanda basin. The georeferenced data of SRTM was exported with image format. The area estimation of the sub-basins and Alaknanda catchment was done using the ERDAS IMAGINE software with fixed common boundaries (Figure 1). Longitudinal profile of the Alaknanda river from the source to its confluence with Bhagirathi river at Devprayag was made using the SOI topographic map at 1 : 50,000 scale (Figure 2). The profile was drawn by measuring the length of line segment between two points where the consecutive contours (contour interval 40 m) were intersecting the river using ERDAS IMAGINE software.

The catchment area and slope for individual segments were calculated using the expression $S = k_s A^{-\theta}$, a regression analyses of log (S) vs log (A) (Figure 3), which provide the values for concavity (θ) and the steepness index (k_s) for eight segments (Figure 4; Table 1). It was observed that in active orogen, value of θ varies between 0.35 and 0.60 (refs 1, 14 and 15) hence in some cases an intermediate value of 0.45 was also considered[16,17]. Compared to this, the value of steepness index changes in accordance with the surface upliftment rates[1,18–21].

In order to estimate the value of k_s we have calculated the value of θ which was obtained from the log (S) vs log (A) regression analysis for the Alaknanda river profile, and also for $\theta = 0.45$ as used in the earlier studies (Figure 3). We obtained $\theta = 0.38$ for the Alaknanda river which was employed for computing the k_s for eight segments. The maximum value was obtained for Helong (230.6) followed by Karnprayag (205.3) whereas a minimum value of 131.3 was obtained for Devprayag (Figure 4). Similarly, using the intermediate value of concavity ($\theta = 0.45$) the k_s values are 622.3, 1131.3, 998.4, 1037.7, 1079.9, 900.6, 781.8 and 704.4 for Badrinath, Helong, Chamoli, Nandprayag, Karnprayag, Rudraprayag, Srinagar and Devprayag respectively (Table 1). In both cases ($\theta = 0.38$ and 0.45), maximum value of k_s was observed around Helong (proximal to MCT) followed by Karnprayag (proximal to AF) (Figure 4).

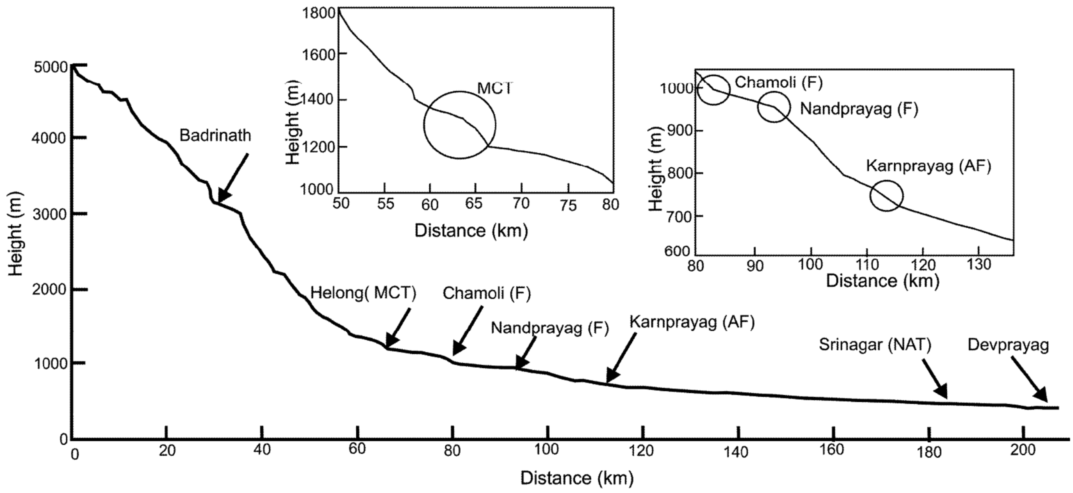

Figure 2. Alaknanda river profile from origin to its confluence at Devprayag. Insets show the convexity in the river profile at Helong (proximal to MCT), and between Chamoli and Karnprayag.

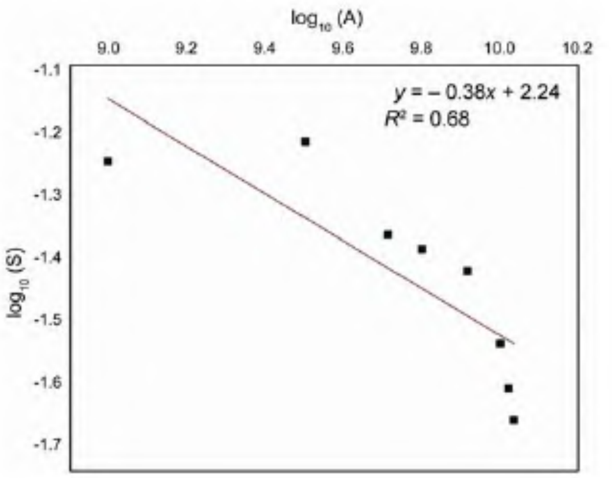

Figure 3. Regression analysis for Alaknanda river profile for eight segments provided $R^2 = 0.68$. The moderate value of regression coefficient signifies that the longitudinal profile experiencing differential uplift.

Table 1. Values for steepness index (k_s) calculated using $\theta = 0.38$ and 0.45 for locations between Helong and Devprayag

Location	Length of individual segment (m)	Steepness index (k_s) $\theta = 0.45$	Steepness index (k_s) $\theta = 0.38$
Badrinath	22881.9	622.3	138.1
Helong	35084.0	1131.3	230.6
Chamoli	6936.4	998.4	196.4
Nandprayag	11648.5	1037.7	201.2
Karnprayag	40066.1	1079.9	205.3
Rudraprayag	30161.1	900.6	168.8
Srinagar	25483.8	781.8	146.1
Devprayag	22881.9	704.4	131.3

Late Quaternary reactivation of faults in the Alaknanda basin is eloquently expressed by the impounding of streams, deflection in river courses, development of strath terraces and deep gorges[22,23]. Majority of the rivers originate from the north of the Higher Himalaya including the Alaknanda River. These rivers are characterized by steep gradient through the Higher Himalaya and relatively gentle gradient in the Lesser Himalaya. This is adequately expressed in the longitudinal profile of the Alaknanda river (Figure 2). First major break in profile was observed near Badrinath which is due to the change in valley morphology caused due to the glaciation and activity along the Pindari Thrust[24]. The second major discontinuity was observed around MCT which delimits HHC from LHM rocks around Helong. Following this, an appreciable change in the profile could be seen between Chamoli and Karnprayag (Figure 2). MCT which defines the topographic boundary between the Higher and Lesser Himalaya passes through Helong and is known for thrust earthquakes[2]. According to Valdiya[25], there is more than 10 times increase in normal gradient and is attributed to the uplift on the fault plain delimiting the base of Higher Himalaya (MCT). Steepness index value also indicates that the terrain around MCT is indeed active which is consistent with the earlier studies, suggesting that the MCT is an active structure[2,10,16]. However, in addition to this, relatively higher steepness index values and convexity in the river profile around Chamoli, Nandprayag and Karnprayag (Table 1, Figure 2) suggest that the rate of uplift in the inner Lesser Himalaya is exceeding the rate of incision[3].

In the outer Lesser Himalaya (south of Karnprayg), graded river profile (absence of knick point) and low value of steepness index suggest that uplift and erosion are in equilibrium[2]. In this segment the only major structures is the south dipping, WNW–ESE trending North Almora Thrust (NAT) which traverses the Alaknanda river near Srinagar[22,25–27]. The structural elements of NAT suggest a movement of SW–NE direction along the almost vertical plane[9]. This is further indicated by eastward deflection of the streams while crossing the NAT (Figure 5). It is because of the dominance of horizontal movement in the vicinity of NAT, the longitudinal river profile and the steepness index do not show any variation.

Conventionally, it is believed that the Lesser Himalayan basins are in a steady state, that means differential uplift is balanced by differential erosion, the profile should have been graded as discussed above. This is also indicated by the presence of mature and rolled topography[10]. This may be true at a regional scale, however, locally the terrain may be responding differently as indicated by the present study. Kayal *et al.*[28] have suggested that the complex fault systems to the south of the MCT are triggered/activated to generate the aftershocks of the 1999 Chamoli earthquake. According to them, earthquakes of magnitude 4 to <5 occurred between the MCT and the AF. In this study we also observed that after MCT, this is the zone of high steepness index values (Table 1; Chamoli, Nandprayag and Karnprayag). An indirect evidence of the activity particularly along the AF is also suggested by the high incision rate (~4 mm per year) by Barnard *et al.*[12]. Though some information exists on the nature of AF fault, however its seismic status is still uncertain. Kumar[29], and the subsequent study by Kumar and Agarwal[9], suggests that it has a cross-cutting relationship with the older structures implying its geologically recent origin. According to Valdiya[25], AF is a dextral wrench fault. Interestingly, Kayal *et al.*[28] suggested that the above earthquake was caused by activity at the depth where AF meets the detachment plane. Considering the above, it can be suggested that the faults that traverse the Alaknanda river near Chamoli, Nandprayag and Karnprayag are active structures, as a result, activity along these faults is outpacing the erosion. Since the Central Himalaya lies in high seismic risk zone, it is important that a systematic morphotectonic study of the faults that lie immediate south of the MCT particularly the AF should be undertaken in order to ascertain its seismotectonic status. The present study, though preliminary in nature, indicates that in conjuncture with the longitudinal river profiles, empirical method can provide an insight to the differential incision and upliftment in areas that are otherwise considered seismically dormant in the Central Himalaya.

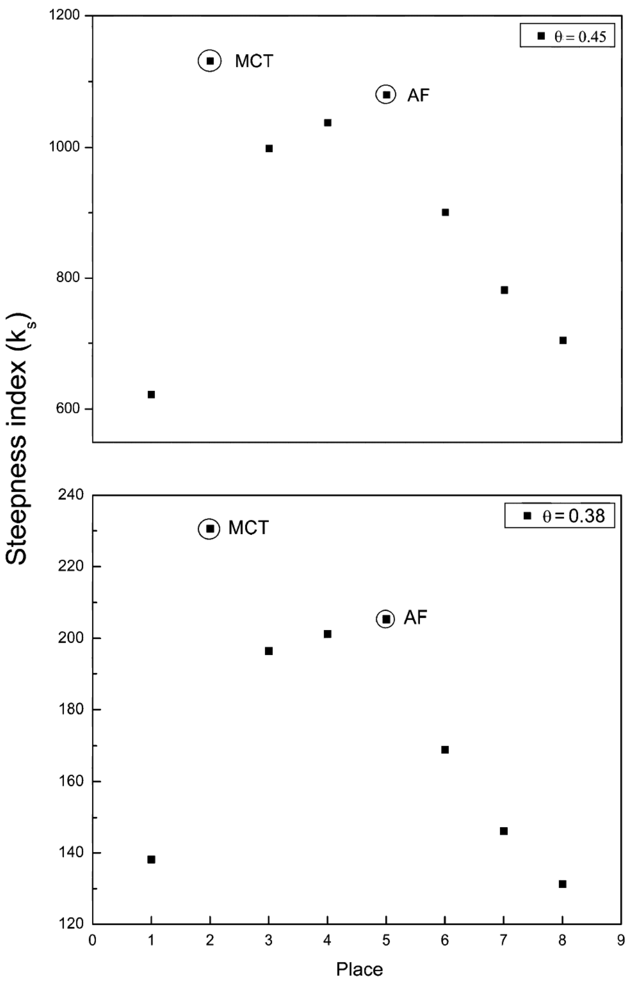

Figure 4. Locations with steepness index for the river profile analysis using concavity 0.45 and 0.38. A value of 0.38 was obtained from the slope of log (*S*) – log (*A*) regression analysis for Alaknanda river at Badrinath, (1), Helong (2), Chamoli (3), Nandprayag (4), Karnprayag (5), Rudraprayag (6), Srinagar (7) and Devprayag (8). Maximum value of steepness index can be seen near Helong (2) followed by Karnprayag (5).

Figure 5. Field photograph showing the trend of North Almora Thrust (NAT) and the eastward deflection of streams caused due to horizontal (strike slip) movement.

Appendix 1

The rate of change in channel elevation is a function of rock uplift rate (*U*), drainage area (*A*) and local channel gradient (S). The equation for river profile can be written as[4,6,7]

$$\frac{dz}{dt} = U(x,t) - KA^m S^n. \qquad (1.1)$$

Here K is dimensional coefficient of erosion, and m and n are positive constants which are related to the basin lithology, river channel geometry and erosion process. In eq. (1.1) first term represents the rate of uplift and second term represents the rate of erosion. For steady state condition, rate of uplift is balanced by rate of erosion and hence for steady state condition

$$\frac{dz}{dt} = 0, \qquad (1.2)$$

and therefore eq. (1.1) can be modified as

$$S = \left(\frac{U}{K}\right)^{1/n} A^{-(m/n)}, \qquad (1.3)$$

and this can be written as

$$S = k_s A^{-\theta}. \qquad (1.4)$$

Here S is local channel gradient (change in elevation/ change in length), $k_s = (U/K)^{1/n}$ and $\theta = (m/n)$ and are called as steepness index and concavity.

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