

Tectonic Control on the Meanders Pattern of Alaknanda River in Srinagar Valley, Garhwal Himalaya, India



Sapna Semwal and D. D. Chauniyal

Abstract The present study deals with the study of tectonically regulated landform development within the meander pattern of the Alaknanda River in Lesser Garhwal Himalaya. We used high-resolution satellite imageries supplemented by field investigation to identify landform features exclusively regulated because of tectonic forces. The style of geomorphic landform and deformation pattern reveals the presence of strike-slip transverse faults within a zone of North Almora Thrust (NAT). The structural and lithological controls on the Alaknanda River system in Srinagar valley are manifested by steepness changes and deviations of drainage patterns. We identified several geomorphic anomalies such as an abrupt change in the flow direction, incised meandering, offset river channels, paleo-channels, multi-levels of terraces, knick points, and pools in the longitudinal profile associated with active tectonic in the area. Furthermore, we used morphotectonic landforms and a digital terrain model to generate a litho-tectonic map of the Srinagar valley. The results of the study show that the sinuosity index of the river is 1.34 which shows a sinuous to meandering trend. All 8 sets of meander segments are controlled by tectonic features i.e. fault, and lineaments. Six levels of terraces are the results of episodic upliftment. The meandering course is correlated with tectonic features hence it concluded that the river channel is closely controlled by structural features in the study area.

Keywords Tectonic control · Meander · Channel pattern · Structure · NAT · Transverse

1 Introduction

In the Himalayan range, the neo-tectonic movements occurred in the upper part of the Tertiary (Neocene) and Quaternary periods which have attributed to topographic development across the Himalaya (Obruchev 1948; Valdiya 2001). The

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transverse faults across the major Himalayan thrusts are providing excellent transects to understand tectonic movement during the Quaternary (Kothyari et al. 2019, 2020a, b). The reactivation of fault rejuvenated the mature geomorphology of the Lesser Himalayan very dramatically (Kothyari and Luirei 2016). The differential upliftment across the Himalaya during the Quaternary period was also responsible for crustal adjustment (Valdiya 2001; Kothyari and Pant 2007; Kothyari et al. 2017; 2019). Sati et al. (2007) are also identified geomorphic expressions of tectonic landforms in the Srinagar (Garhwal) area. In the mountainous region, rivers are extremely sensitive. The complex changes in their course are caused by tectonic activities and associated features. Tectonic effects on rivers and their resultant landforms may be a very useful tool for identifying the faulting, folding, and fractures associated with smaller-scale deformation in channel settings. Tectonic warping and faulting may result in either longitudinal (parallel to channel orientation) or transverse (normal to meanders orientation) tilting of river profiles.

In the mountain belt, several studies have been conducted in the past to determine the behaviour of river profiles and patterns of active deformation (Hack 1957; Lavé and Avouac 2001). The river terrace provides information on incision rates, where rivers are forced to cut down into rising base rocks and have abandoned numerous strath terraces in the valleys (Lavé and Avouac 2001). Duvall et al. (2004) assessed the manner and degree to which bedrock channels respond to variations in rock strength and tectonic forcing within the Santa Ynez Mountains of California. The structure also plays an important role in controlling the longitudinal profiles of channels (Kothyari et al. 2017). Channels in the Catalina-Rincon core complex are characterized by structurally controlled knick points with a wide distribution of heights and spacing's in metamorphic core complexes in Arizona (Jon and Pelletier 2009). Bedrock Rivers set much of the relief structure of active origins and dictate rates and patterns of denudation (Whipple 2003). The spatial changes in the rock-upliftment rate and rock strength in different bedrock channels and their morphological responses in the northwest Himalayan front are investigated by Allen et al. (2013), Kothyari et al. (2019).

Active tectonic control on the morphology in the Bagmati river of Bihar was observed by Jain and Sinha (2005). The active tectonic faults were characterized by the association of fluvial anomalies and morphological changes. The multi-channel pattern developed in bedrock was initiated by block or domal upliftment and its effects can be observed on the channel morphology of the stream (Kale et al. 1996). The impact of active tectonic on the characterization of the fluvial landscape has been investigated on the strike-slip fault of the Ajay-Damodar interfluves in India by Roy and Sahu (2015). Sahu et al. (2010) provided a detailed description of the Son-Ganga River to active tectonics and geomorphology in an alluvial tract of India. There are several intensive works related to the tectonic control in the Ajay-Damodar interfluves of eastern India. In the Himalayan region, Bawa et al. (2014) has investigated the natural and anthropologic controls on the spatial morphological variability of the Yamuna River. Valdiya (2018) has expressed his view that it has been qualified to the reactivation of the WNW-ESE trending faults and lineaments in the recent and sub recent time. Furthermore, it is attributed that the formation of deep gorges, uplifted

terraces, landslides, and debris avalanches along faults, anomalies in stream courses are attributed to the recent movement along North Almora Thrust (NAT) in the Lesser Himalaya (Kothyari and Pant 2008; Kothyari et al. 2017; Kothyair and Luirei 2016). Srinagar section of the NAT has been attributed to the reactivation along transverse and longitudinal faults which have been taken into consideration. The main objective of the present study is to describe the tectonic control on the meander pattern of the Alaknanda River in Srinagar valley.

2 Study Area

2.1 Location

The area investigated lies in the lower basin of Alaknanda River between Supana to Kirtinagar of Garhwal Lesser Himalaya. Srinagar valley is formed by the River Alaknanda in Lesser Himalaya. Alaknanda rises from the snout of Satopant Glacier at the height of 3760 m and after traveling 191 km it joins the Bhagirathi River at Devprayag (442 m). The average gradient of the river is about 17.3 m/km from source to mouth (Nand and Kumar 1989). After passing the distance of 161 km downstream from the source it enters in 11.5 km long and 2.5 km wide sinuous meandering river valley of Srinagar (Fig. 1). Geographically the valley is bounded between $78^{\circ} 45' 16''$ E to $78^{\circ} 49' 43''$ E Long and $30^{\circ} 12' 36''$ N to $30^{\circ} 15' 47''$ N Lat. which covers 41.29 km² area. About 600^m contour line demarcates its valley bottom. Out of the total area, about 13.27km² is occupied by Quaternary sediments. The River Alaknanda flows in the centre along with bow shape meander. The average gradient of the river is very low (0.0054) from Supana to Kirtinagar. After passing 11.5 km (channel length) distance further it enters a narrow shape gorge at Kirtinagar in the west (Fig. 1).

2.2 Structural Setting and Geology

The study area is located in the central portion of the tectonically active Lesser Himalayan domain. The Lesser Himalaya lies between the Main Central Thrust (MCT) in the north and the Main Boundary Thrust (MBT) in the south. It has made an extremely rugged landscape characterized by complex topography. This terrain is made up of Precambrian rocks older than 540 million years in age (Valdiya 1980, 2001). The North Almora Thrust (NAT) is one of the major tectonic units in the Lesser Himalaya which passes through NW to SE direction near Srinagar (Fig. 2). This regional thrust is also known as Tons Thrust (TT) and Srinagar Thrust (Valdiya 1980) or NAT (Kumar and Agarwa 1975; Srivastava and Ahmed 1979). Within the NAT zone because of the horizontal and vertical shear stress, a large number of

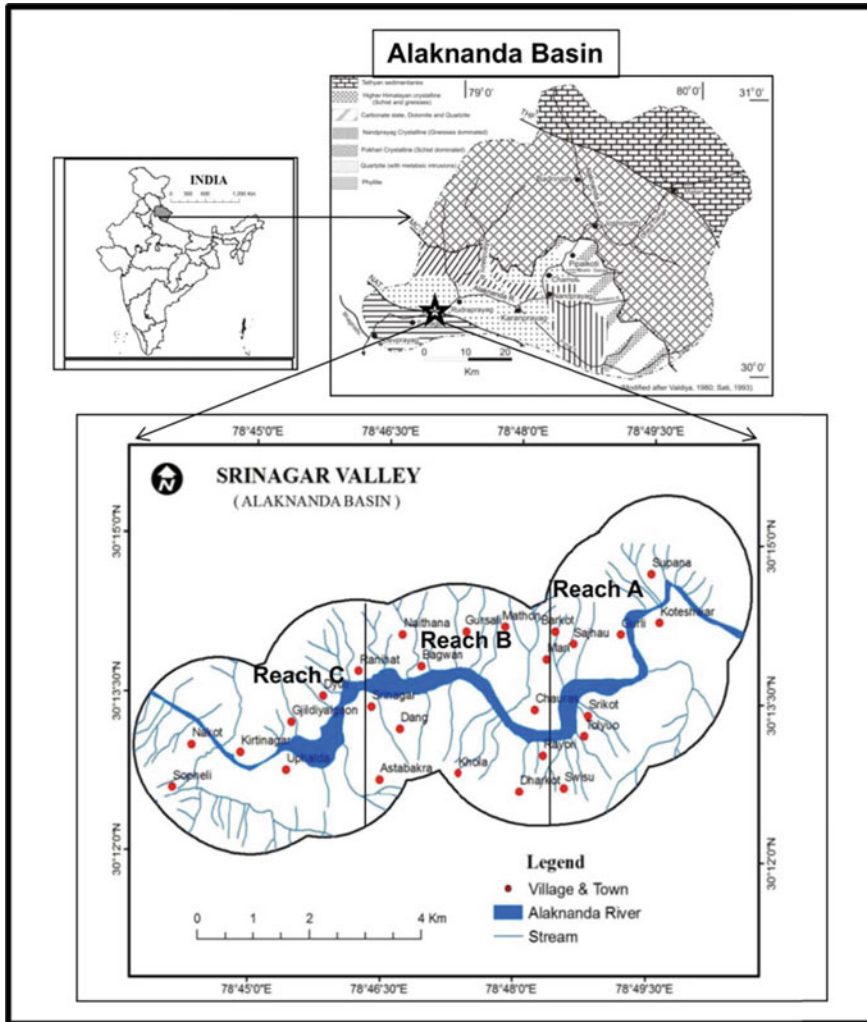


Fig. 1 Location map of the Srinagar valley along with reaches (a, b, and c) and geological map of Alaknanda basin in Garhwal Himalaya

transverse and oblique faults have been generated. Out of those two local faults/lineaments, the SCKF Fault in the centre and Dhobi ghat-Kirtinagar-Maletha Faults (DKMF) in the SW also exist in the study area. The Dhobighat-Kirtinagar-Maletha Fault is inferred from lineaments viewed in aerial photography on a local scale (Sati et al. 2007) (Figs. 2 and 3).

The NAT separates the Garhwal group of rocks in the north from the Chandpur group of rocks in the south (Kumar and Agrawal 1975). The Chandpur phyllite is predominant in the present study area. Upper proterozoic rocks on both sides of

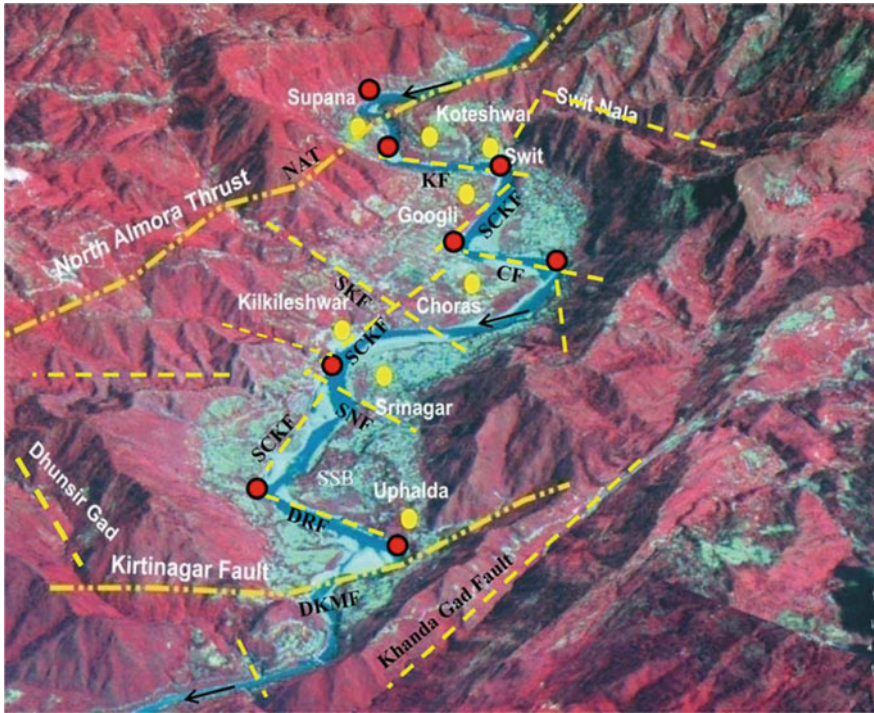


Fig. 2 Tectonic setting of the Srinagar valley along North Almora Thrust (NAT). Red dots are showing the meander bends, yellow dots are localities and dashed lines are faults and lineaments. Faults DRF = Dhobighat-Ranihat-Fault, SCKF = Sweet–Chauras-Kilkileswar Fault, SNF = Srinagar-Naithana Fault, SKF = Srinagar-Badkot Fault, CF = Chauras Fault, DKMF = Dhobighat-Kirtinagar-Maletha Fault. SCKF is a longitudinal lineament/fault parallel to NAT but displaced by transverse faults in places

the thrust are directly overlain by quaternary deposits consisting of boulder and gravel beds along with sandy and clayey horizons, contained in several depositional terraces. The phyllite is tightly folded, fractured, and weathered in nature. Enter bedded flaggy quartzite between phyllite is very common near Chauras suspension bridge and Kirtinagar locality. The study area is situated very near to NAT so that it is characterized by a wide shear zone (Kumar and Agrawal 1975).

3 Material and Methodology

The present research work is essentially based on the interpretation made on a topographical map, large-scale aerial photographs (1/40000 scale), Digital Elevation Model, Satellite image LISS III, Google images, and field investigations. The base map of the study area has been prepared on 1:50,000 topographical sheets.

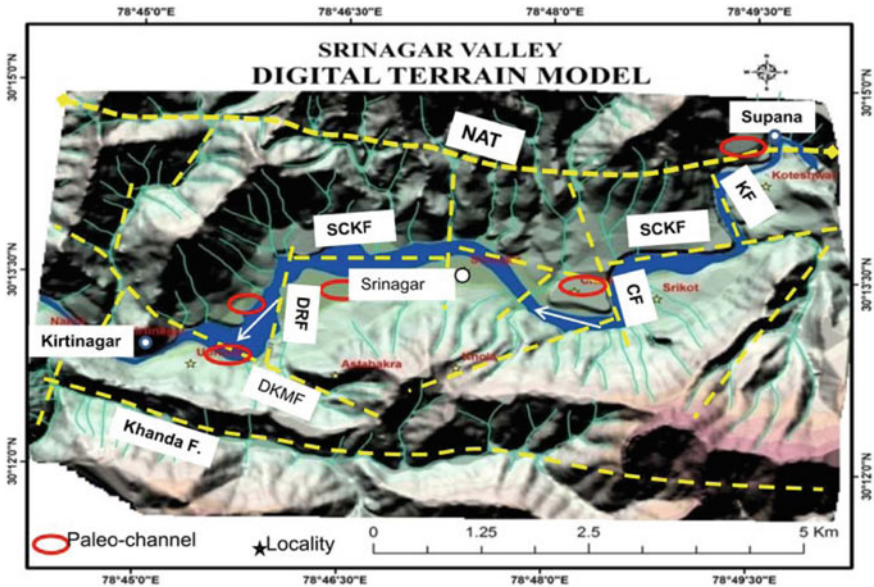


Fig. 3 Digital Terrain Model is showing the location of meander bends control by transverse faults in the Srinagar valley. The longitudinal lineament in the center is displaced by transverse faults. Red oval-shaped marks are showing the location of paleochannels. Meander bends are showing the hogback features from Supana to Chauras

The survey of India (SOI) topographical sheets and satellite images were georeferenced in Arc GIS 10.1. The terraces are demarcated by large-scale 1:40,000 aerial photographs. Thrust, faults, major and minor lineaments are marked based on satellite imageries, SOI map, DTM, and drainage pattern using the software ARC GIS and datum system. Furthermore, geomorphic anomalies such as terrace scarps, faulted cliffs, offset drainage, hogback and rapids are identified during longitudinal and transverse field traverses. A dumpy level, plane table, and GPS surveys have been conducted for the measurement of meander bends and stream gradient. The depth of pools has been measured by measuring tape and rope in the deepest portion of the pool. The depth of pools upward and the downward stream is less than the deepest portion.

In addition, the vertical and lateral extent of the previous (2013) flood level was also identified on the ground. Paleo-valleys were identified and differentiated from terraces, based on their morphology and association with incised bedrock. For the analysis of channel pattern and meander geometry, the 11.5 km long Alaknanda River channel course in Srinagar valley is divided into hierarchical geomorphic units. A geomorphic unit is a portion of the river that shows different forms of physical features that can be summarized by properties. On the basis of uniform gradient, shape and width, the geomorphic unit is classified into three reaches (Fig. 1c). The reach is a section of geomorphic unit in which not only the river shape and energy

flow are relatively uniform but also other conditions such as meandering pattern, bank properties and bed sediments. Each river reach can contain one to several meander segments. Thus on the basis of meander pattern and morpho-tectonic characteristics, three reaches are further classified into 8 meander segments (Table 1). A single segment includes one or several hydraulic elements such as rapids, pools, point bars, sediment particles, bank erosion etc. On the basis of 1:50,000 SOI map sinuosity index and other geometrical parameters such as length, width, depth, amplitude, radius and w/d ratio (Table 1) have been measured according to Leopold (1964), Leopold and Wolman (1957). Stream sinuosity means deviation channel course from the straight channel. It is the ratio of channel length and valley length. A Digital Elevation Model of the Srinagar valley is constructed using 20-m contours from SOI topographical maps (Fig. 3). Extensive longitudinal and transverse field traverses were carried out to identify and check the morpho-tectonic features.

4 Neotectonic Movement and Channel Evolution

4.1 *Morpho-Tectonics and Channel Evolution*

The mountainous region of Garhwal is influenced by Himalayan tectonics. Large-scale morpho-tectonic activities occurred in the south of NAT during the Quaternary (Kothyari and Pant 2008; Luirei et al. 2016; Kothyari et al. 2017, 2018). Evidence suggests that the Srinagar Thrust (ST) is a subsidiary branch of NAT was reactivated during the Late Quaternary (Sati et al. 2005). Quaternary episodic movement along the tectonic plan has rejuvenated the old mature topography of the Lesser Himalayan terrain. The horizontal and vertical shear and stress to the south of the NAT are responsible for recent active deformation in the region (Valdiya et al. 1992). The major and minor longitudinal and transverse faults and lineaments indicate that the area was passing through differential upliftment. Dhobighat-Kirtinagar-Maletha Fault (DKMF) and Sweet-Chauras-Kilkileswar-Ranihat Fault (SCKF) are two longitudinal linear features parallel to NAT in the study area (Fig. 3). After crossing NAT at Supana village the general trend of Alaknanda valley is an east–west direction parallel to NAT (Fig. 3). It shows that the river was followed the trend of SCKF lineament from Supana to Kirtinagar. Due to the continuous episodic upliftment and shear and stress, strike-slip/ transverse faults were activated. The incision of the valley along these lineaments was more active and simultaneously river followed the trends of transverse faults. Numbers of tributaries streams are also developed along these fault lines on both sides of the river. The prominent streams are Sweet Gadhera along with SCKF, Badkot Gadhera along with CF, Naithana Gadhera along with SN, and Dhobighat along with DKM, Nauli Gad, Dhundir Gad and Khanda Gad (Figs. 2 and 3). The N-S transverse faults or lineaments are the second and third-generation deformation features which displaced the earlier linear features at

Table 1 Channel morphological parameters

Reach	Segment	Meander width ratio	Meander length ratio	W/D ratio	Wave length (km)	Amplitude (km)	Radius (km)	Sinuosity Index	Width (m)	Depth (km)
A	Supana	7.0	20.0	1.43	1.0	0.35	0.38	1.18	10	7
	Koteswar	4.67	11.67	3.33	1.25	0.8	0.43	1.4	30	9
	Surasu	6.67	16.67	2.86	1.5	1.0	0.4	1.43	20	7
	Srikot	2.29	7.14	6.25	1.5	0.8	0.43	1.29	50	8
B	Chauras	5.5	15.0	2.73	1.25	1.15	0.5	1.41	30	11
	Srinagar	2.8	10.0	4.37	1.75	0.8	0.4	1.18	35	8
C	SSB	2.12	6.25	8.33	1.5	0.9	0.4	1.25	50	6
	SriyantraTapu	1.9	5.0	9.17	1.5	1.0	0.5	1.34	55	6
Average	Alaknanda (Supana to Kirtinagar)	4.12	11.47	4.83	1.4	0.86	0.43	1.34	35	7.25

Source The table generated from 1/50000 SOI topographical sheet by the authors

the junction (Fig. 2). The prominent transverse and strike-slip faults/lineaments are shown in Figs. 2 and 3.

Srinagar valley has a tectonic origin between NAT and Dhobighat-Kirtinagar-Maletha fault (DKMF) because of the flexure slip faulting (Sati et al. 2007). Few Quaternary tectonic features are reported by Sati et al. (2005) in the Srinagar valley. The presence of unpaired terraces preserved along the Sweet Nala-Chauras-Kilkleswar Fault (SCKF) is considered to be uplifted along with the NAT (Semwal 2018). The Alaknanda River flows through a bow-shaped meandering course in Srinagar valley and meander bends are either controlled by transverse fault or lineaments (Figs. 2 and 3). Juyal et al. (2010) have also identified that most of the meander bends are control by tectonic features in the Srinagar valley. At the junctions of morpho-tectonic features, landslide, undercut by river, terrace scarp, and talus cone are prominent features (Photo 5 A and B) while channel bars, boulder bed, pools, and riffles are channel bed features along the river course.

In the Himalayan terrain, the evolution of streams/rivers and their pattern are characterized by episodic upliftment, litho-stratigraphy, and steepness of the terrain, water discharge, and sediment load. These factors have been interpreted as indications of the presence of structure in the region bounded by thrust and faults. The sinuosity index of the Alaknanda River is calculated at 1.34 which advocated a sinuous to the meandering pattern. Based on tectonic features and sinuosity index, it can be inferred that fault pattern, sinuous to meander pattern, and straight pattern of the three reaches are found in the study area. From Supana to Srikot (reach A) the river formed a sinuous to meanders pattern controlled by faults and lineaments in which the sinuosity index is 1.4. From Chauras to Ranihat (reach B) the river formed nearer to the straight pattern which the sinuosity index is 1.18 while Ranihat to Kirtinagar (reach C) sinuosity index is 1.33 which shows sinuous to meanders pattern. Similarly, the sinuosity index of 8 meander segments has been calculated to range from 1.18 to 1.43 (Table 1).

Srinagar valley is well known for its intermountain-wide basin with a multi-level of terraces and ingrown meanders develop along the longitudinal course of the Alaknanda River. The aerial photo interpretation shows the development of six levels of fluvial terraces preserved along the longitudinal course of the Alaknanda River. Genetically debris fill, valley fill, and strath three types of terraces are identified in the Srinagar valley (Juyal et al. 2010). The sequence of six-generation terraces and their sub-levels are demarcated at Chauras localities (Fig. 4a, b).

4.2 *Tectonic Control in the Formation of Meander*

Regional seismic records indicate that the Garhwal region is tectonically very active. Transverse faults have played a significant role in the recurrence of seismic events along with the NAT (Valdiya 1976; Dasgupta 1987). These tectonic movements have also influenced the fluvial dynamics in the region. A large number of evidence of geomorphic expressions associated with tectonic activity has been documented along

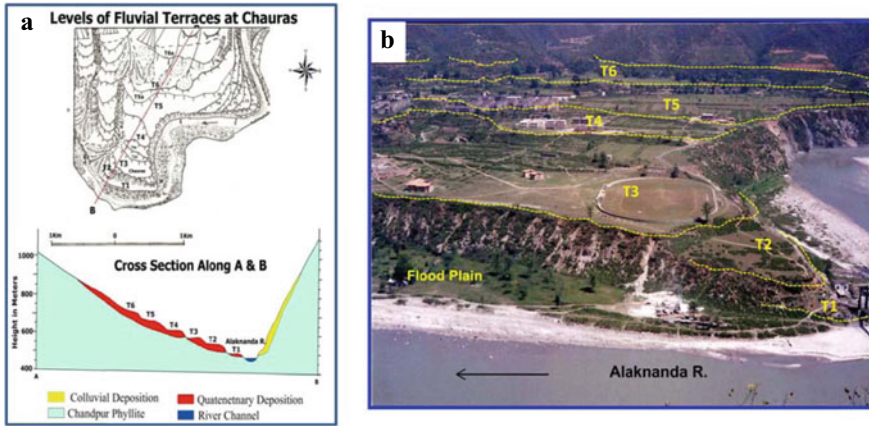


Fig. 4 a A geomorphological map at Chauras locality is showing the sequence of six levels of river terraces and their schematic cross section along a–b. The cross section is also showing unpaired terraces and asymmetrical valley. b Field photograph is the true evidence of 6 levels of terraces at Chauras locality

the Alaknanda River. These geomorphic expressions are 6 levels of river terraces (Fig. 4a, b), fault scarp (Fig. 5a) offset drainage (hogback) (Figs. 2 and 3), deformation of earlier generation fault and lineament (Fig. 2, SCKF), valley incision in undercut side (pools), tilting of beds (Fig. 5b) and landslide on terrace scarp (Fig. 5a, b). The most remarkable geomorphic expressions are associated with tectonic activity.

During the reactivation of the NAT, numbers of longitudinal and transverse faults, fractures and lineaments have been formed along with the thrust. Simultaneously major and minor drainage lines were also developed with these structural features. Tectonic control is reflected in the formation of meanders of the Alaknanda River

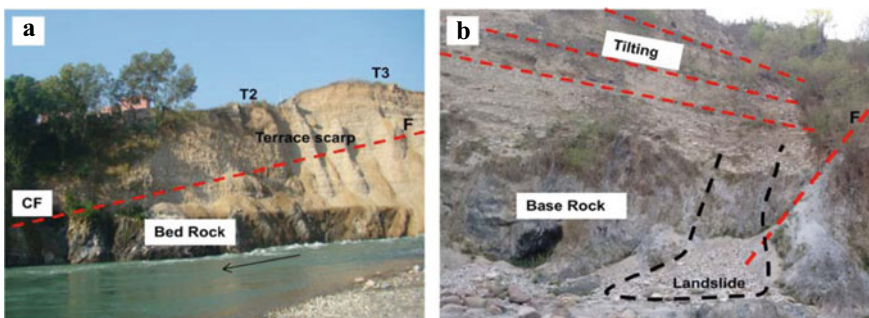


Fig. 5 a Active fault (CF) scarps extending from N-S along with landslide on terrace scarp at Chauras. It was exposed during the 2013 Kedarnath flood. b Quaternary sedimentary beds are tilted eastward on terrace scarp which inferred the active tectonic along the transverse fault. It is an undercut side of the river which is prone to landslides. The newly generated fault is showing the displacement of Quaternary beds and bedrock near the transverse fault (CF)

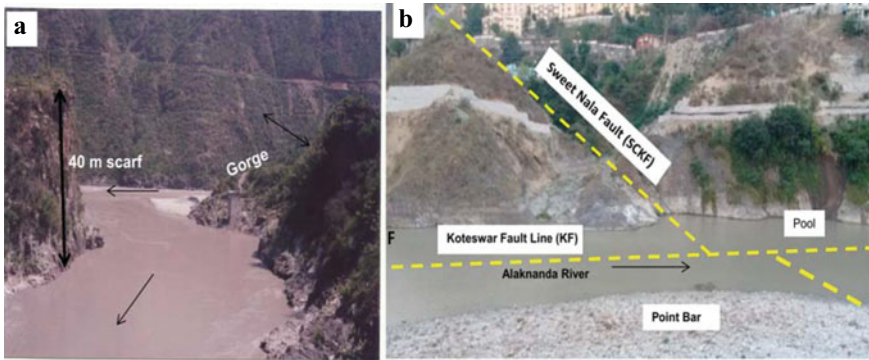


Fig. 6 The River suddenly changes her direction at Supana and is flowing through a narrow passage (a). Here the river formed a hogback feature along with a 40 m vertical rocky fault scarp. (b) Field photograph is showing the junction of Koteswar fault and the Sweet Nala fault. The Alaknanda River formed a 10 m deep pool (b) and hogback feature at the junction point

in Srinagar valley. The offset drainage pattern is clearly indicating the displacement and deformation (Figs. 2 and 3). Reconstruction of channel configuration indicates that the river followed east–west along longitudinal SCKF line parallel to the NAT prior to the meandering course in the Srinagar valley. SCKF is one of the earlier generated longitudinal lineaments parallels to NAT. In the latter episodic stages, this was deformed and displaced by a number of north–south trending transverse faults and lineaments in the area. Just after crossing the NAT at Supana village the river turns towards the southwest direction and formed a hogback feature (Figs. 2 and 3). The sinuosity of the meander bend is calculated at 1.18 while the width and depth ratio is 1.43. The 40 m deep narrow gorge on the quartzite rock indicates that the river has been shifted toward the left along the transverse fault plane (Fig. 6a).

At the right bank near Supana village, a paleochannel also proofs the fact that the river shifted towards the left along the newly activated fault line (Fig. 2). After flowing a half km distance it further follows the pattern of the Koteswar fault (KF) which extended from north to south direction up to Sweet Nala (Fig. 6b). The important lithology of the area is phyllite and inter-bedded quartzite which is folded in many places (Srivastava and Ahmad 1979). The sinuosity of the Koteswar meander is 1.4 which width and depth ratio is 3.33. It is compressed by the Koteswar fault. At the junction point of the Koteswar Fault (KF) and Sweet Nala Fault (SNF), the river suddenly turns towards the west direction along longitudinal lineament (SCKF) and forms a hogback feature (Fig. 6a). The offset drainage pattern is attributed due to differential tectonic movement in the region. Mostly junction of two lineaments becomes the unstable part that tends to fast vertical and lateral erosion. It advocated that the valley incision was deepest near the junction point where a 10 m deep pool is formed at the meander bend (Fig. 6b). The Surasu meander segment is compressed by Koteswar Fault (KF) and Sweet-Chauras-Kilkileswar fault (SCKF) (Fig. 7). The sinuosity index of the Surasu meander is 1.43 which indicates the sinuous to the meandering pattern.

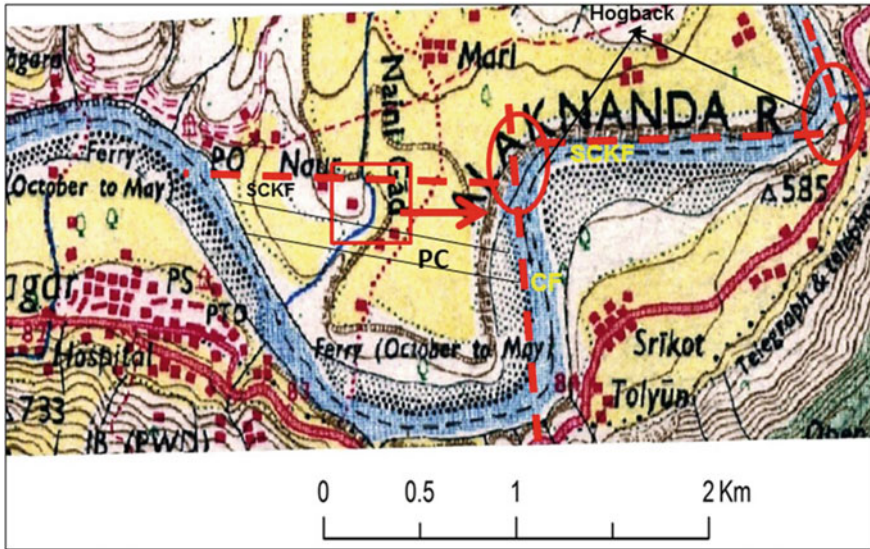


Fig. 7 Topo map is showing the faulted pattern of the river (SCKF and CF). Earlier generation fault SCKF (red dashes lines) displaced by latter generation transverse fault CF at Chauras. Red circles are showing the meander bends and hogback feature control by faults. The red square is showing the deflection of Nauni Gad towards the east direction. Two black parallel lines are showing the buried paleo-channel (PC) course under T3 at Chauras

Opposite of the Chauras bend the Alaknanda River formed a prominent Srikot meander (Figs. 2 and 3) which is compressed between SCKF and CF. At Chauras E-W flowing Alaknanda River suddenly turned towards the south direction along the younger generation Chauras transverse fault (CF). Hogback feature is advocating the offset drainage pattern (Figs. 7 and 8). Paleo channel course is also one of the evidence of shifting of the river. The paleo-channel (PC) was identified during field observation which was exposed during the 2013 Kedarnath flood by undercutting at Chauras terrace scarp (Fig. 7). It was 1.25 km long and 0.75 km wide. Potholes and polished rock surfaces on quartzite rocks are the ground evidence in the exposed paleo channel course. The sinuosity index of the Srikot meander is 1.29 which shows sinuous to meandering pattern of which the width/ depth ratio is 6.25. Here the valley is quite wide with numerous channel morphological features (Pools, riffles, braided channel and knick points) (Fig. 8). Channel morphology in this segment confirms to hydrological characteristics and therefore, external control such as active tectonic is implied. The detailed characteristics of the meander geometry are given in Table 1. After running 500 m south direction, the river further turns to south-west direction through 154 m narrow rocky passage at Chauras suspension bridge (Fig. 8). Opposite of this bend there are 6 levels of river terraces (Fig. 4).

Figure 7 reveals that earlier generation east–west trending longitudinal fault (SCKF) is displaced by north–south trending transverse fault (CF). As the latter generation transverse fault reactivated continue due to the episodic upliftment, the

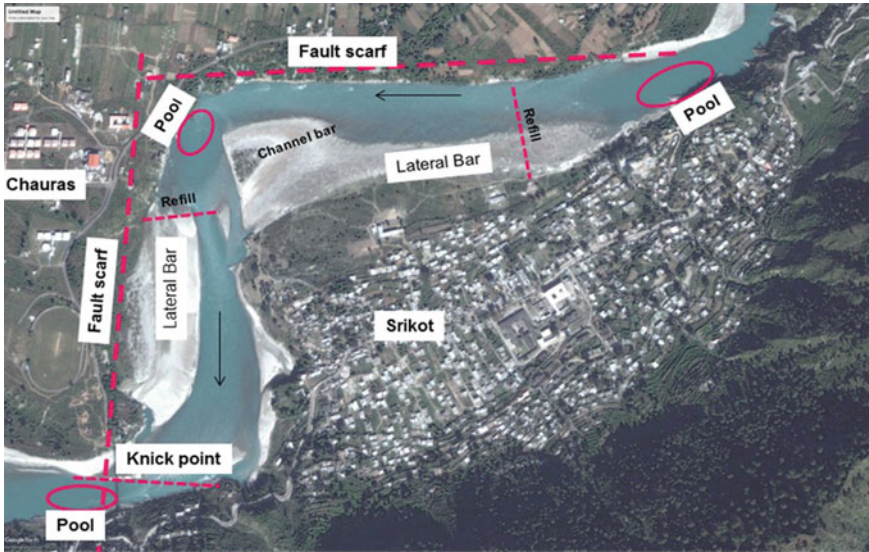


Fig. 8 Google earth image is showing the tectonic (faults and fault scarps) and channel morphological features (lateral and channel bars, pools knick points and refills)

river followed the trend of that lineaments and shifted eastward. In addition, the channel course of Nauri Gad a small tributary rivulet of Alaknanda is also deflated towards the east direction (Fig. 7 in box) which manifested that the deflation force was from W to E direction by the differential rate of upliftment). It also indicates that that episodic upliftment is not rejuvenated the main river but also tributary streams in the area that manifested in the epigenetic gorges, knick points (Fig. 8) and steepness of gradient in the streams,

Srinagar and SSB meander segments are also controlled by tectonics. Srinagar-Gorsali Gadhera lineament is passing from N to S direction and formed a Srinagar wide meander bend. The sinuosity of the meander bend is very low (1.18) and higher width and depth ratio (8.33) which indicates a straight course to a sinuous course. SSB meander is formed between Naithana Gadhera and Dhobighat-Ranihat (DRF) transverse faults. The low sinuosity index (1.25), high width and depth ratio (8.33) braided channel and aggradations of the meander indicates the wide meander segment (Table1).

Sriyantra Tapu meander segment displays a number of features that are suggestive of tectonic control in the development of meander and channel pattern. This investigation was supplemented with topographic sheet, Google earth image and field verification (Fig. 9a, b). At Ranihat village the Alaknanda River suddenly change its flow direction toward the south which seems to be the manifestation of a fault pattern. Reconstruction of channel configuration in this area shows that the river followed the usually east–west course prior to following the trend of DRF (Fig. 9a, b). The abandoned channel course is 500 m long, 125 m wide and 25 m above the present

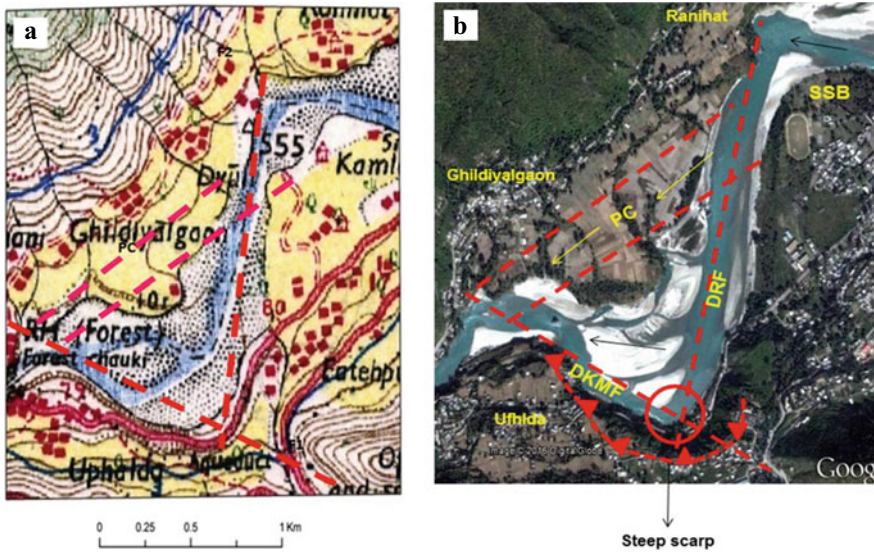


Fig. 9 Topo map (a) and Google earth image (b) both are showing the two faults line DRF and DKMF along the Alaknanda River by red dashes line. Red circle showing the junction of two faults line and meander bend of Sriyantra Tapu. It is the most sensitive zone and prone to landslide in concave undercut side (B). PC is showing the paleo channel. The general trend of the river valley is showing east–west direction but due to the activation of DRF the river followed the trend of fault from north to south. Similarly river followed the trend of DKMF and forming a 60 m steep faulted site at the undercut site

river level. Two sets of river terraces are clearly identified at the Gildiyalgaon. This proves that as well as the fault reactivated up, the river continued to shift along the fault line by incision of the river. Latter on old river channel course has been filled by mega-flood events and remained as a buried channel. Rounded quartzite and granite boulders exposed polished rock surfaces with potholes are the field evidence on the paleochannel course. A major flood can be generated during the interglacial period and phases of deglaciation because of the very high transport capacity and steep gradient of the Alaknanda River (Chodhary et al. 2015). The fault notch is the most sensitive zone prone to landslides and, undercutting by the river. The high sinuosity index (1.34) of the meander segment is showing the tight bend compressed by DRF and DKMF. The high width and depth ratio (9.17) indicates a wide channel course in which braided channel, lateral and channel bars are identified in different shapes and sizes. (Fig. 9a, b).

5 Discussion

Detection of structural features and geomorphic anomalies in the Alaknanda River has provided tools for recognizing the tectonic control in the meandering pattern of the study area. The trends of closely spaced transverse faults along the major thrusts are sufficient to relate active tectonic movements in the Himalayan terrain (Fig. 2). This approach using remote sensing imagery and DTM coupled with repeated field observations have provided information on the nature of the fault (Figs. 2 and 3). River response to neo-tectonics depends upon the nature and rate of vertical movement and the trend of faults with respect to the direction of flow of the river. In the Srinagar valley, most of the transverse faults are across the Alaknanda River channel near the North Almora Thrust (Figs. 2 and 3). Differential movements along the strike-slip faults have produced river terraces, tilting of Quaternary sediment beds (Fig. 5b), hogback features, faulted scarp, and shifting of river channel course. Out of these features riverbank erosion, aggravation behaviour of the channel, channel pattern, channel widening, overbank flooding, and channel morphology are also some of the geomorphologic expressions of tectonic control in the meander pattern of the Alaknanda River. Most of the transverse faults are identified in the Srinagar valley where the Precambrian phyllite of Chandpur formation is the main lithology. One of the longitudinal lineaments parallel to NAT in the center of the valley is displaced by latter generation transverse faults or lineaments which are responsible for turning of river channel course, formation of terraces, paleochannels, and other morpho-tectonic features.

The formation of compressed meanders is due to the two closely related faults i.e. Koteswar fault (KF) Sweetnala-Chauras-Kilkileswar fault (SCKF). SSB and Sriyantra Tapu meander segment zone are characterized by flooding because of lowering the channel gradient. Typical geomorphic signature of tectonic movement and shifting of the river along the faults can be seen in the Supana, Chauras, Ufald, and Ghildiyalgaon localities. Paleo channels are the results of upliftment of the terrain, valley incision, and shifting of the river towards active tectonic faults. At Supana village the river crosses the North Almora Thrust (NAT) and enters the Srinagar valley. Here the paleochannel is 400 m long parallel to the present river course. The incision phase has been inferred that the Supana paleo channel formed around 8 Ka (Chaudhary et al. 2015). A typical paleo channel pattern is observed at Chauras. The buried paleo-channel was exposed during the 2013 Kedarnath flood. It was parallel to the SCKF but after the activation of CF, the river shifted toward the newly generated fault line by the valley incision. At Ufald village, there are two sets of paleochannels extending from NE to SW direction lie at an elevation of 35 m and 55 m above the river bed respectively. The narrow bedrock passages are carved by fluvial action. It shows that the river shifted northwards along the Dhobighat-Kirtinagr-Maletha fault (DKMF). An isolated erosion-resistant rock mass in the middle of the channel bed at Sriyantra Tapu also indicates the river shifted towards the north along with the active tectonic fault (DKMF) (Fig. 9b). Below the Ufald village, the river crosses the DKMF and enters into a narrow bedrock gorge. At Kirtinagr the Srinagar valley becomes closed.

Another important point that emerged from this study is the development of 6 sets of river terraces at Chauras locality. The paleochannels and river terraces are closely associated with transverse faults. At Chauras 6 levels of fill, terraces are well exposed along the transverse fault which is formed during -15, 8 Ka valley aggradations (Juyal et al. 2010). It can be inferred that the Paleo channels are formed due to the turning of the river eastward along the transverse faults by the action tectonic movements (Fig. 7). Supana, Chauras, Ghildiyalgaon, and Ufhlda are prominent examples of paleochannels along a transverse fault in the study area. The digital elevation model of the valley area has been generated for comparison of tectonic setting, the slope of the terrain, and direction of flow. The major tectonic landforms identified in the study area are associated not only with tectonic activities related to NAT, but are modified by the recent tectonic activities of the latter-formed transverse fault. Therefore, we must take into account the role of transverse tectonics while analysing the neotectonics in the Himalayan region. The results obtained from the tectonic control on the meanders pattern of Alaknanda River in the Srinagar Valley and confirmed with field evidence indicating that the transverse faults along the North Almora Thrust (NAT) is tectonically active. The drainage pattern of the region is controlled by thrusts, faults and lineaments.

6 Conclusion

Based on the above geomorphic investigations following conclusions have been drawn.

- 1 The present study reveals that the landform development and the deformation pattern within the NAT zone are a result of the late Quaternary tectonic movement.
- 2 Further, based on geomorphic anomalies we strongly argued that the transverse faults play a significant role in the development of landforms as evident from the offset drainage patterns, meandering of the river, paleochannels, knick-points, and steeping of river gradient.
- 3 However, a river that follows the transverse faults in substrate rock display a sudden change in river profile form. The channel morphological features such as paleochannel, knick points, refills, pools, undercut sites; meander scars; and hogback all are associated and controlled by tectonic activities.
- 4 Based on detailed satellite data interpretation and geomorphic analysis we infer the presence of NW–SE oriented strike-slip faults, genetically associated North Almora Thrust.
- 5 The present course of the Alaknanda River in the Srinagar valley is being deflected in many places by tectonic forces. Meanders' patterns, size, and shape are controlled by different phases of tectonic activities.
- 6 Channel incision under differential upliftment rate and slope gradient display sinuosity indices is consistent with the channel pattern. The Alaknanda River

in the study area appears to adjust both gradient and width in response to the increased tectonic moment.

- 7 Finally, it is concluded that the structure plays an important role in controlling the river riches, meander segments and longitudinal profile of rivers in the study area.

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