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Geomorphic Study of Channel Bars in Alaknanda River of Srinagar Valley, Garhwal Himalaya, Uttarakhand

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Abstract: *The main objective of the present study is to identify and classify the geomorphic characteristics of channel bars in a meandering stretch of river Alaknanda in Srinagar valley (Lesser Himalaya). The process of formation of the channel bars and their changing pattern has also been analysed. The analysis is based on CARTOSAT-1 and LISS-IV data of 2013 and 2014, Google Earth image of 2004 and 2014 and extensive field verification. Point, longitudinal, transverse, braid, lateral and mid-channel bars have been identified in the study area. Flood records show that the flood deposits of the mega-flood event of 16th and 17th June, 2013 invariably overlie the 1970 flood sediments. The mega-flood deposits provide space and material for mid-channel bar formation. These bars exhibit a complex evolutionary response to the hydrological regime in the Alaknanda river. Results show that the area of sand and pebbles bar surfaces at Sashastra Seema Bal (SSB) – Sriyantra Tapu and Srikot area increased by 31.36% and 12.55% respectively during 2013 flood. The flood affected area also increased 15.25% at Sriyantra Tapu and 11.9% at Srikot where the sand was deposited on the point and lateral bars. At Sriyantra Tapu about 9m and at Srikot 4-6m channel bed was upgraded during 2013 flood. The water channel course and pattern of bars were also changed due to the huge amount of sediments during flood in the Alaknanda River. Result concluded that the shape, size, width, and depth of dynamic bar surfaces changed according to the flood events in the study area. Bars are created by process and changes are due to the flood events. Mega flood events produced a complex alluvial morphology in the river Alaknanda.*

Introduction

Channel forms in the river course are the results of entrainment, transportation of bed, suspended and dissolved loads and sediment deposition on favourable places (Maiti, 2016). Basically, sediment deposition is a result of energy deficiency in the channel flow. Energy loss in a river is due to three reasons—reduction in gradient, fall of velocity and excess of load relative to the transportation capacity. As a result the courser materials are deposited first with progressively finer grains settling as the flow velocity continues to fall. Bar formation takes place simultaneously with the formation of meanders. These bars are not viewed as the cause of meandering, but as triggers that accelerate the meandering process as stratification of sediment startparallel and transverse to the channel bed (Knighton, 1998). The favourable sites of deposition are channel bottom, channel margins, flood plain and river mouth.

Different type of bars, pools, riffles and steps are the prominent morphological units of a channel course. Bisson *et al.* (1982) developed a detailed, descriptive classification of channel morphological units in Pacific northwest streams to quantify different types of physical habitat for salmonids. In addition, hierarchical classification of channel units and their hydraulics have been developed by various authors (Sullivan, 1986; Bryant *et al*., 1992; Church, 1982; Hawkins *et al*., 1993; Wood-Smith and Buffington, 1996). These approaches mainly use qualitative descriptions of flow (fast vs slow) and water-surface roughness (turbulent vs non-turbulent). It has been argued that channel units are the most relevant scale for relating fluvial processes (Moir *et al*., 2009). However, detailed classification of channel units for any river arguably is of more geomorphic relevance for mechanistic investigation of fluvial processes and basin function (Montgomery and Buffington, 1997).

The non-cohesive sediment creates an irregular channel surface rather than a smooth surface or a straight channel. As a result many channel patterns are developed. The reason is that, sediment transport rate depends on flow shear stress to a power higher than unity. Slight local irregularity on the stream bed causes flow deceleration and local curvature, which then leads to a relatively large local gradient in sediment transport that may grow into bed forms like bars, channels, sand waves and so on (Edmonds *et al.,* 2007). For a narrow and rock-bed channel,

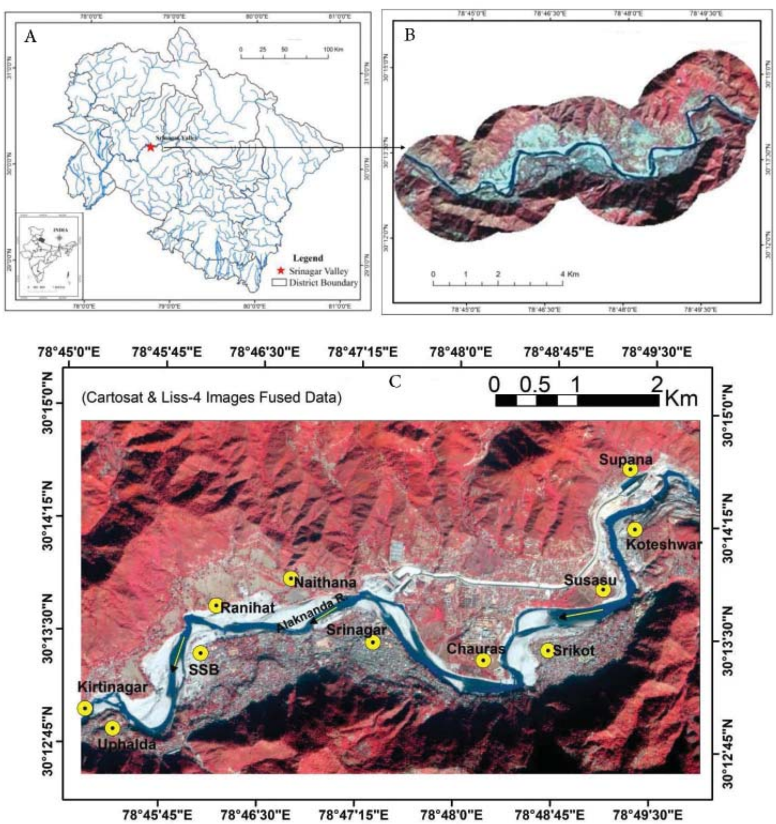

Figure 1. A) Location of the study area in Uttarakhand, **B)** The standard FCC of Srinagar Valley showing the Alaknanda river (LANDSAT ETM+, 2000) and **C)** Location of studied sites along the surveyed stretch of the river

the river flows in a straight course, and any perturbation would result in alternating bars, which grow in wide and shallow channels. At some places, mid-channel bars emerge in between the alternating bars (Crosato and Mosselman, 2009). The width : depth ratio has been used as an independent parameter in these analyses and cannot be predicted (Edmonds and Slingerland, 2007). It is also noted that if a perturbation results in altering the amplitude of the bars then a plane bed develops.

Conceptually, formation of bar depend upon the nature of channel and configuration of channel bed. In this way ‘free bars’ grow from perturbations and they migrate with changing size, while ‘force bars’ grow from change in curvature of the channel (Edmonds and Slingerland, 2007). Free and forced bars are not entirely mutually exclusive and mixed forms exist in low sinuosity channels (Seminara and Tubino, 1989). Generally, forced bars are more common than free bars. Most channel-unit classifications focus on the wetted channel, generally excluding bars, but a detailed classification of bar types and associated physical processes has been developed by Church and Jones (1982).

This study takes into account an 11 km stretch of the Alaknanda riverwhich falls within the Srinagar valley, but, the focus of the study remains on the meandering reaches. Although meander is the most common type of channel pattern, it is understood the least due to its ‘lack of sterile order and its undecipherable disorder’ (Ikeda, 1989).

Study area

In this paper, an attempt has been made to identify and classify channel bars of Alaknada river in Srinagar valley. The Alaknanda is one of the parental streams of the Ganga in Garhwal Himalaya. The area investigated lies in the lower Alaknanda valley between Supana to Kiratinagar of Garhwal Himalaya. Geographically, the valley is bounded by 78°45′16″ E to 78°49′43″ E and 30°12′36″ N to 30°14′47″ N, which covers 41.29 km^2 area. The maximum altitude is at Khola Top (1456 m) and the minimum altitude of 520 m is seen at Kiratinagar. In this reach the river Alaknanda flows for 11.5 km within the 2.5 km wide Srinagar with bow shaped meanders (Fig. 1).The Srinagar Township is located on the left bank terrace of the river.

Objectives

The main objectives of this study are:

- To identify the pattern of channel migration in relation with the movement of sand and gravels.
- To document and classify the types of channel barsusing remote sensing data and identify their process of formation within the Alaknanda river system in Srinagar valley after the big flood event of 2013.

Methodology

One of the easiest ways to assess channel and gravel bar features and their movement is with large scale satellite data. The base map was prepared on 1:50000 scale. Cartosat-1 and IRS P6 LISS IV data of 2013 and 2014 and Google earth image 2004 and 2014 have been used for identification, classification and digitisation of the channel boundary and gravel bars in order to quantify the lateral migration of the stream and also the downstream migration of gravel bars. A 500m buffer was demarcated along the main channel from Supana to Kirtinagar. The morphological features identified from satellite images were digitised in ArcGIS (v10.1) platform, and the attributes were added as per requirement. The GIS and RS integration in monitoring the movement of the stream and its gravel bars is of much importance to resource planners and park managers for its time and cost efficiency. The study of Srikot and Sriyantra Tapu meander bars has been supported by intensive field verification.

Results and discussion

Results indicate: (1) characteristics and types of channel bar (2) changing pattern of bar, and (3) valley location and morphology of channel bar.

A riverine bar is an elevated region of deposited sand or gravel within the river valley, typically found in the low velocity, shallowest parts of rivers and streams (Strahler, 1996) and are often parallel to the bank, occupying the area farthest from the thalweg. The locations of bars are determined by the geometry of the channel and the flow regime. On the basis of the process of formation, location, channel pattern, nature of meander, bank material etc. bars have been classified by the past workers in different part of the world (Ritter *et al*., 1995; Reinfelds and Nenson, 1993; Lattman, 1960; Morisawa, 1968).

The bars are oscillatory bed features; with regular spacing, finite width and depth and are scaled to the dimension of the channel. They reflect the sediment supply conditions and systematically change downstream as water discharge, velocity and sediment supply change.

Channel bars in Srinagar valley

A classification of channel reach morphology in mountain river valley synthesises stream morphology into the following distinct types of bar surfaces (Fig. 2 and 3).

POINT BAR

Point bars are formed as the materials eroded from the convex bank of the channel are laterally moved by sweeping or rolling across the floor of the stream and deposited below the slip-off slope. Point bars are found in abundance in mature or meandering streams. They are crescent-shaped and located on the inside of a stream bend, being very similar to, though often smaller than, towheads, or river islands. Point bars are composed of sediment that is well sorted and typically reflects the overall capacity of the stream. They have a very gentle slope and gain elevation very close to the water level. Since they are low-lying, the flood water often overrides the bars and driftwood and other debris can accumulate on them during high water levels. Owing to their low elevation the point bars are vulnerable to overtopping during flash floods

Some prominent point bars are found in the valley at Surasu (Fig. 4), Srikot (Fig. 7), Chauras suspension bridge and Sriyantra Tapu. At Surasu village and Chauras suspension bridge, the point bar shows stratified deposition of course boulders, gavels, fine gravels and sand (Fig.8). The

Figure 2. Longitudinal, lateral and point bar along with pool and riffle from Ghasiya Mahadev to Naithana bridge (Field photograph, 2014 facing N).

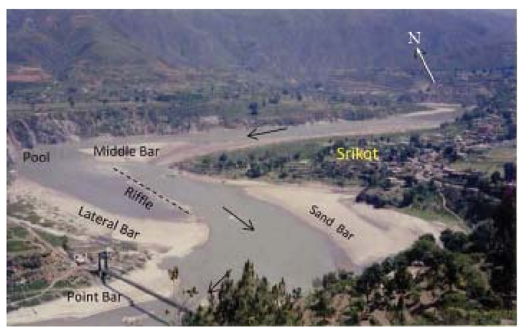

Figure 3. Middle, lateral, point bar along with pool and riffle at Srikot meander bend (Field photograph, 2014 facing NE).

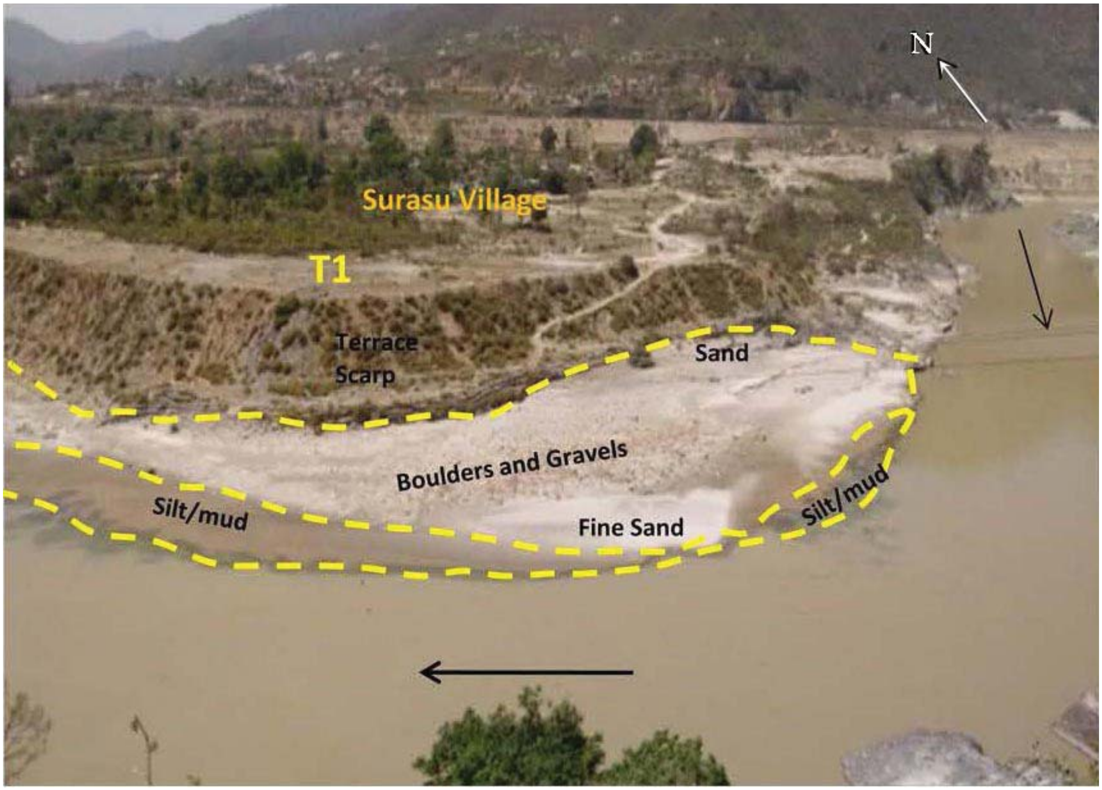

Figure 4. Point bar at Surasu Village (Field photograph, 2013 facing NE)

other morphological features and flow properties associated with the point bar are —avalanche face, inactive area, erosion prone cliff, edge of scroll bar, submerged bar edge, main current, secondary current etc. Back-bar chutes can be formed at inside edge of point bars when the flood water overtops the bar.

Fig. 4 shows that the formation of point bar at a meander bend are due to (i) super elevation of the water surface against the concave bank, (ii) transverse current directed towards the outer bank at the surface and towards the inner bank near the bed results in secondary circulation, (iii) maximum velocity current moves from the near inner bank at the bend entrance to near the outer bank at the bend exit, crossing the channel

Figure 5. Longitudinal bar near Ghasiya Mahadev (Google Earth Image, 2013)\

Figure 6. Longitudinal Bar in front of Kilkleswar (Google Earth Image, 2013)

through the zone of greatest curvature.

LONGITUDINAL BAR

Longitudinal bars are common in streams with gravel and sandy gravel beds.These bars are developed relatively straight, parallel to the flow direction where the gradient is insufficient to transport the sediment (Fig. 5). The horizontal stratification is well developed and accretion takes place on the margins of the channel (Galloway and Hobday, 1983). Best example of longitudinal bar is observed just downstream of Ghasiya Mahadev (Fig. 5).Three parts of the bar can be recognised as the (i) bar head, (ii) riffle and (iii) bar tail. The head of the bar is sharp, conical shaped which extend towards the flow direction. Due to sudden change in the gradient by riffle formation, the channel is divided into two parts and sediment deposited near the bifurcation, along the channel. In between the two diverging channels a long tail of gravels developed. This bar also bears characteristics of a mid-channel bar. Other examples of longitudinal bar are found at Srikot and just in front of Kilkileswar Naur (Fig. 6).

TRANSVERSE BAR

Transverse bars are produced in areas of flow line divergence due to channel widening. In sandy braided streams transverse bars are more common than in the gravelly streams and are extensively developed in the distal part of a braided reach (Reineck and Singh, 1980). Transverse bars commonly occur in braided streams where the gradient is insufficient to remove the sediment. Although the transverse and lateral bars are similar, transverse bars tend to migrate downstream while lateral bar tend to accrete laterally into the channel. Jackson (1976) describes transverse bars from the meandering Wabash river of USA. Martini (1977) discussed that in tight bends of a stream helicoidal flows are important in shaping transverse bars. The prominent example of transverse bar in the study area is at Sriyantra Tapu (Fig. 7). There are number of transverse bars which are attached to the channel margin and show some similarity to point bars as they develop by lateral migration. Due to insufficient gradient to remove high sediments load, there is loss of channel competency and braiding starts at this point. Fig. 7 shows that the flow of water has formed a complex

Figure 7. Transverse/ braid bar at Sriyantra Tapu (Source: Google earth image, 2017)

pool at the outer bend of the meander and in the inner part of the meander there is a wide expanse of deposited material. As a result, the main channel has divided into a number of distributaries towards the inner margin to form a transverse bar.

BRAID BAR

A braided channel pattern is usually characterised by a wide and shallow channel divided by many unstable mid-channel bars. Braid bars or channel bars are found in the Sriyantra Tapu meander bend in the Alaknanda River (Fig. 7) .These bars start to form when the discharge is low and the river is forced to form multiple channels to follow the route of less resistance. During times of extremely high flow, the bars may become covered by water; only to re-surface when the water recedes. Their formation starts when the river begins to erode the outer edges of the bar. The water level decreases even more as the river laterally erodes the less cohesive bank material resulting in a widening of the river and a further exposure of the braid bar. As the discharge increases, material may deposit around the braid bar. Most braid bars of the study area are not stable or in one location. They are commonly composed of sand or gravel. Owing to the rapid and frequent shift of the thalweg, mid-channel bars cannot remain stable.

MIDDLE BAR OR MID CHANNEL BAR

Mid-channel bars are common in zones of rapid deposition of coarse bed load accompanied by channel widening. Mid-channel bars are found in between the two divergent channels at Srikot (Fig. 8), Kilkileswar and at Sriyantra Tapu (Fig. 10). After the sudden change in thalweg gradient and flow velocity, the channel deposited all sizes of bed load at the zone of bifurcation.The bar height is approximately maximum, where there is a transition from flow convergence to divergence. A model for mid-channel bar growth is presented that helps to explain the long-term development of the confluence-diffluence unit (Leopold and Wolman, 1957). The shape, size and morphology of middle bar of Srikot meander bend is shown in Fig. 8. In between the two diverging channels

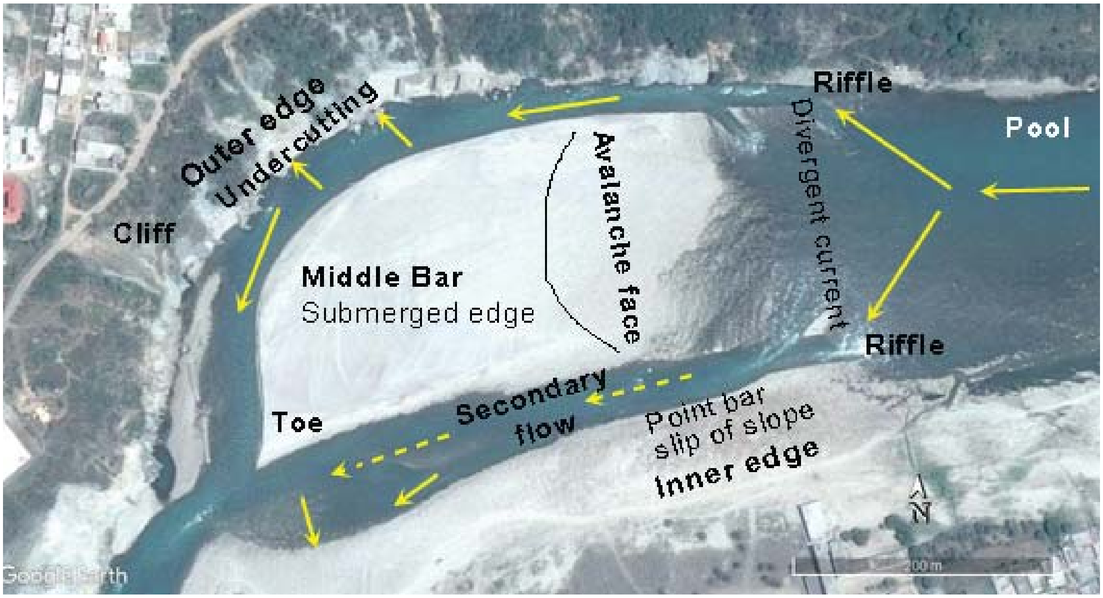

Figure 8. Bar morphology at Srikot (Source: Google earth image, 2013)

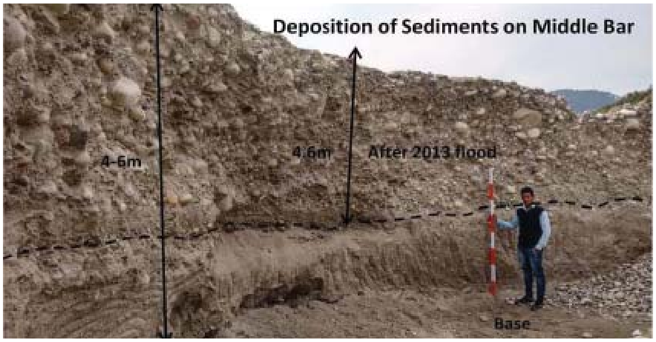

Figure 9. Thickness of the sediment on meddle bar at Srikot

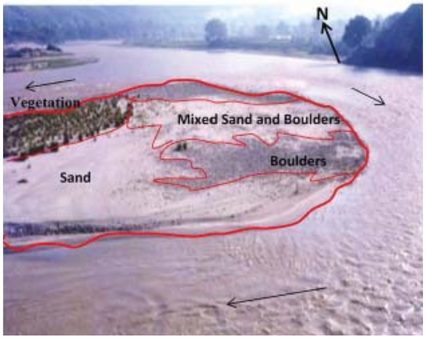

Figure10. Morphology of middle bar at Sriyantra Tapu

boulders, gravels and sand is deposited in a crescentic shape. According to Dietrich and Smith (1983) the crescentic shape was due to the helical flow experienced during the peak flood. The thickness of the sediment is 4 to 6 m from the water level as per field measurement (Fig. 8). Being the largest middle bar in the valley it is 1.12 km long and on an average 183 m wide. The tail of the bar is very sharp with a zigzag shape. There is a pool at the outer edge and point bar at the inner edge of the meander.

LATERAL BAR

Lateral bars are elongated features attached to banks along relatively straight channels which commonly alternate from bank to bank. These are sometimes the extension of point bars. Lateral bars are found along the Alaknanda river at Naithana bridge, between Nathan and Ranihat villages (Fig. 11 and 12).

ISLAND BAR

Island bars are commonly developed at the riffle locations and subsequently emerge above the water with receding water level. This bar, near SSB developed as the coarse

Figure 11. Lateral Bar along Alaknanda river at SSB Srinagar

Figure 12. Lateral bar between Naithana and Ranihat village

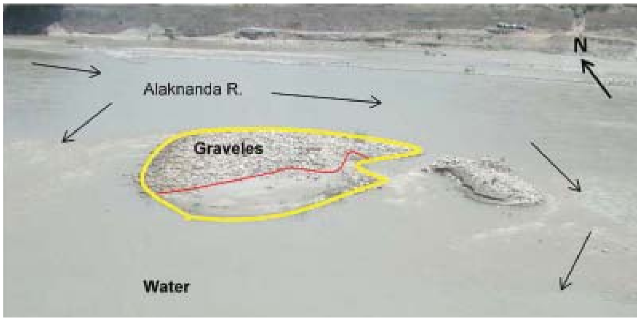

Figure 13. A view of Island Bar near SSB

bed material comprising of boulders, pebbles and gravels were deposited at the bottom of the channel due to low gradient and was later exposed with the decreasing flood water level (Fig. 13).

Classification of bars on the basis of bed material

The studied reach of the Alaknanda may be considered as both sand-bed and gravel-bed river. Thus on the basis of the material deposited, the bars can be classified into — (i) boulder bar, (ii) gravel bar, (iii) sand bar and (iv) mixed bar.

The *boulder bars* are generally found on the slip-of-slope and mid channel locations where the Alaknanda river enters the study area after passing through a narrow valley. The coarse materials are sorted out when the gradient suddenly decreases. The large-sized boulders are deposited on the channel bed near Srikot. *Gravel bars* are found on the point and lateral bars throughout the river. However, most of the point bars and lateral bars have mixed material at different layers. Eddy motion stratifies the material into different layers. The upper layer consists of boulders and pebbles, successively underlain by sand, silt and clay. The fine materials are deposited by the secondary flow during the peak discharge. Most of the mid channel bars are composed of mixed material. Prominent examples of sand bars are observed south west of Srikot and Sriyantra Tapu. These bars grow by deposition of sediment eroded from the immediately upstream bank. Single or multiple rows of bars have steeper downstream faces and migrate in the same direction. Bank erosion and channel widening leads to increase in channel-width and subsequent drop in water level. When water level drops, the highest parts of the bars become emergent.

Changing pattern of bars

Alaknanda is extremely dynamic in nature, originating at a distance of 190 km and draining the 11332 km^2 area of Ganga catchment up to Srinagar. During monsoon season flash floods are very common in Alaknanda. During the flood the river transports huge quantity of sediment flushed by the river. Two past events of mega flash floods in. 26 August 1894 and 20 July 1970 are well documented (Nand and Prashad, 1973 and Pal, 1986). According to Wasson *et al*., 2008) all the large floods in the Alaknanda river appear to be the result of landslide dam burst and these are likely to continue and possibly worsen as the monsoon intensifies over the next century (Rana and *et al*., 2013).

Recent major flood events occurred on 16 and 17 June 2013. This flood records show that the 2013 flood deposits unconformably overlie the 1970 flood sediment at an elevation of 536 m at ITI in Srinagar (Rana *et al*., 2013). The major floods of 1984, 1970 and 2013 changed the channel morphology of the Srinagar valley completely. Drastic changes in channel morphology and bar surfaces have been found in the Alaknanda river at Srinagar valley. Lateral migration is a common geomorphic process that involves the alluvial river channels flowing across the floodplains (Bierman and Montgomery, 2013). Typically with reference to meandering streams, the process of channel migration is mainly driven by the composition of bank material, deposited over time. When referring to channel migration, the bars are closely associated with meandering streams, depending on the channel gradient. The major changes observed in the study area after the 2013 flood have been tabulated in Table 1 and represented in Fig. 14 A and B.

Changes in bar surface

The formation of new bars, their shape and size all are analysed from the pre (2004) and post (2014) images of Cartosat-1, IRS-P6

Table 1. Pre and Post flood changes in channel morphology

	Pre Flood (January 2013)		Post Flood (December 2013)		
Land use class	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Change (%)
Scrub land	0.48	9.76	0.27	5.49	– 4.27
Rocky banks	0.01	0.20	0.01	0.20	0.00
Flood effect area	0.11	2.24	1.68	34.15	31.91
Wasteland	0.49	9.96	0.17	3.46	– 6.50
Sand bar	0.79	16.06	0.80	16.26	0.20
Back swamp	0.07	1.42	0.01	0.20	1.22
Shallow water	0.06	1.22	0.00	0.00	1.22
Agriculture land	0.13	2.64	0.04	0.81	–1.83
Vegetation	0.45	9.15	0.31	6.30	–2.85
River channel	1.25	25.41	1.32	26.83	1.42
Settlement	0.19	3.86	0.11	2.24	–1.62
Dam material	0.86	17.48	0.18	3.66	–13.82
Fallow land	0.03	0.61	0.02	0.41	– 0.20
Total	4.47	100	4.92	100	4.88

LISS IV and Google earth images. It is observed that there are noticeable changes in the shape, size and formation of bars after 2013 flood. The bar area has increased around 90% after the 2013 flood episode. The morphology of the bar surface is changed at Srikote, Kilkileswar, SSB and Sriyantra Tapu.

The most significant change in river morphology took place in the inner bank of the channel at Srikot-Chauras meander bend of the studied reach. Fig. 15 (2004) is showing the Google earth image of the river course in 2004 at Srikot meander bend. The river was forming a pool at the head of the meander and followed a straight course from north to south. The toe of the point bar at the slip-of-slope was cut by the river. In the western bank there was a sizable lateral bar. After 2010 flood, the channel morphology changed completely. Fig. 15 (2011) shows that the river formed a lateral bar in the same place where the pool existed.

In Fig. 15 (2011) the river was flowing between the lateral bar and point bar from northeast to southwest direction. That was the effective flow path of the channel which changed significantly in 2013 flood. Before 2013 no mid-channel bar or longitudinal bar existed in the channel, but after 2013 major flood, the channel course shifted towards the outer bend of the meander and undercut the Chauras terrace scarp. It is calculated that the channel length increased about 220 m than the length in the previous year. Here the channel divided into two branches (Fig.16, 2014). After sudden reduction in velocity with decreasing gradient, sediments were deposited in the middle of the channel. As a result the channel diverted into two branches, though the outer branch is more active in comparison to the inner branch. In between these two branches there is a crescent-shaped

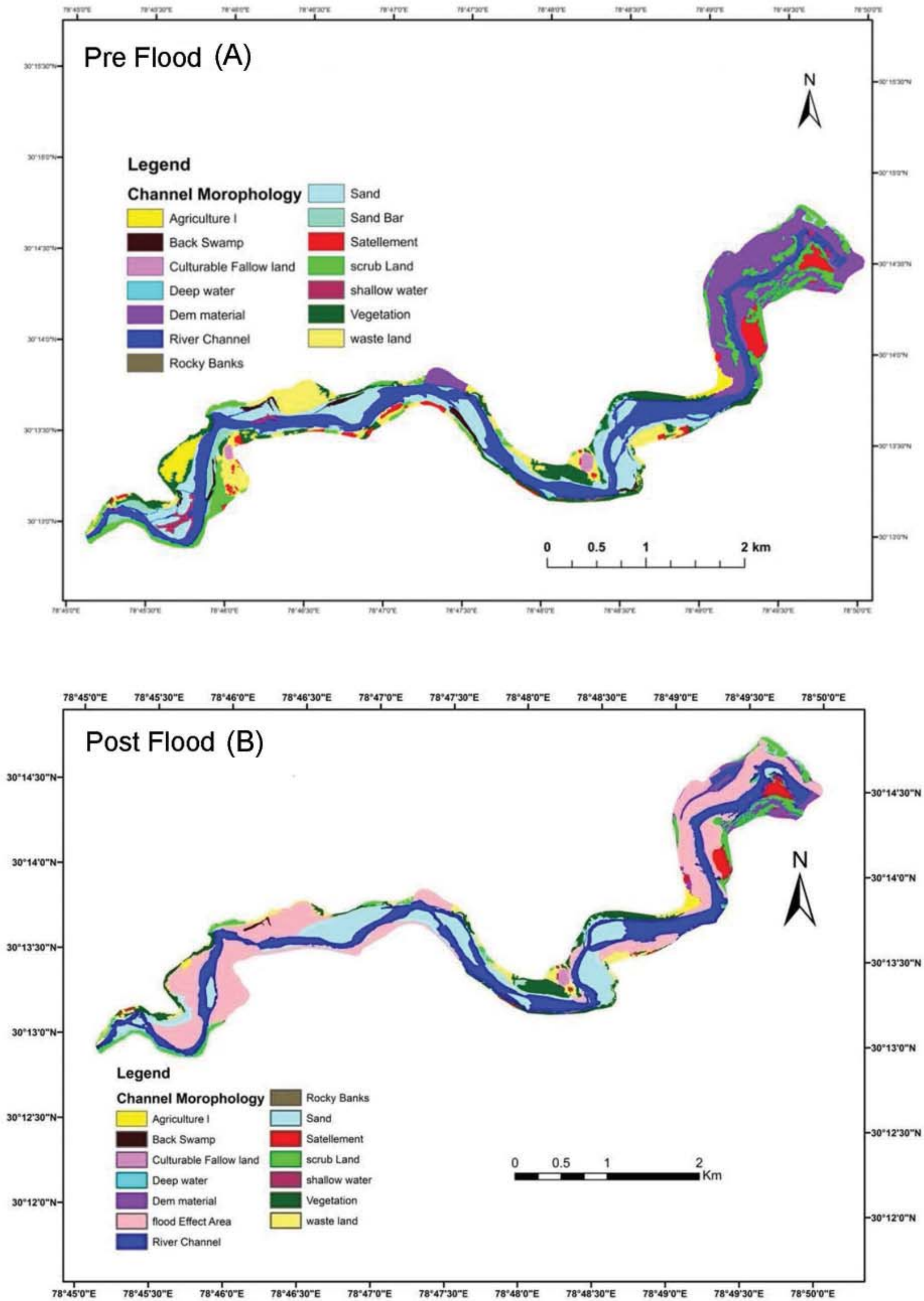

Figure 14. (A) Pre and (B) Post 2013 flood changes in channel morphology

Figure 15. Changing pattern of bars at Srikot in 2004, 2011 and 2014

mid-channel bar at Srikot. The changes in land use and land cover have been shown in Table 2 and the changes in the channel morphology is shown in Fig. 16 (2004 and 2014).

Table 2. Land Use/Land Cover changes in Srikot and Sriyantra Tapu localities

Land use/ land cover class	Srikot (Area in %)			Sriyantra Tapu (Area in %)		
	2004	2014	Change	2004	2014	Change
Sand and boulders	29.89	42.44	12.55	24.58	55.93	31.36
Rocky bank	1.39	2.40	1.01	1.69	1.69	0.00
Back swamp	0.00	0.00	0.00	2.54	0.85	– 1.69
Flood affected area	0.00	11.91	11.91	0.00	15.25	15.25
River channel	44.10	43.26	-0.84	32.20	26.27	– 5.93
Agriculture land	0.00	0.00	0.00	10.17	0.00	–10.17
Built up area	0.76	0.00	-0.76	4.24	0.00	– 4.24
Vegetation and open land	23.87	0.00	-23.87	24.58	0.00	– 24.58

Table 2 reveals that 12.55% area of sand and boulder bar surfaces and 11.9% flood affected area were increased after 2013 flood in the Srikot meander bend. Besides this 0.84% channel length decreased and 0.76% built up area was affected in the Srikot locality.

The thalweg line follows a path very close to the north western outer bank (Fig. 16, 2014) and then shifts towards the western bank and undercuts the Chauras terrace scarp.

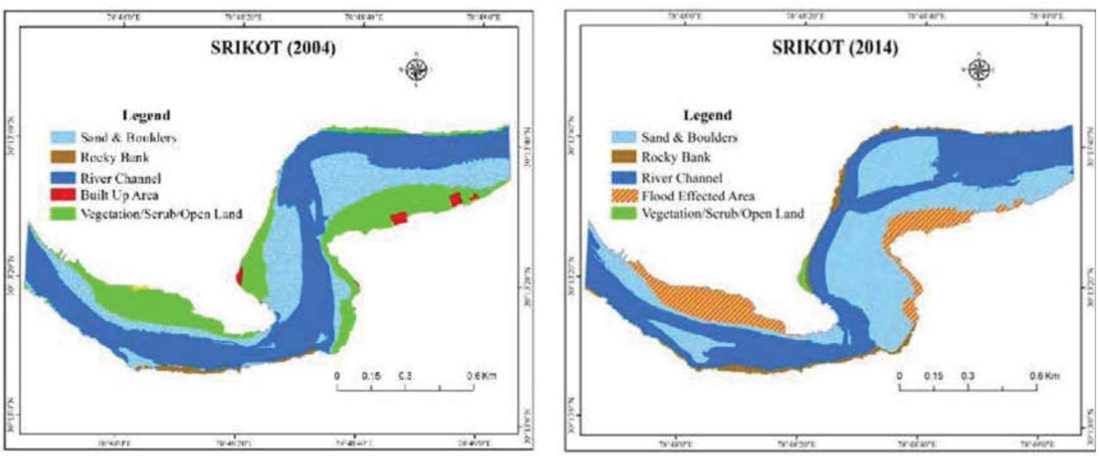

Figure 16. Changes in land use and land cover along Srikot-Chauras meander bend in 2004 and 2014

It is a very steep landslide-prone cliff which still remains vulnerable to bank erosion. The position of the thalweg line has changed significantly after 2013. The most significant change occurred in the river thalwage and channel morphology because of huge amount of discharge with high velocity transported a large quantity of sediment from Kedarnath flood in Mandakini River.

If Fig. 16 (2004) is compared with Fig. 16 (2014) then it can be observed that there is a significant change in the bar morphology. The point bar converted into lateral bar in both the banks of the river and the river flows between two lateral bars. Outer bank lateral bar was completely eroded by the river in 2010 flood and a new lateral bar was formed at the inner bank of river. Pool at the outer meander bend was silted-up in 2010. It shows that channel bars are highly dynamic and their stability depends upon the nature of flood discharge and sediments transported by them.

Figure 17. The changing pattern of bar and channel at Kilkileswar locality

The second prominent example of changes in bar formation was observed from Ganga Darshan to Naithana Bridge near Kilkileswar. Fig. 17 A shows that before 2013 flood, the main river channel flew just besides the Kilkileswar temple and formed a point bar feature just opposite the temple. The main channel flowed right of the point bar. After 2010 flood, the channel divided into two branches and in between the two branches a longitudinal bar was formed (Fig. 17 B). The flow gradually increased in the southern branch and there was reduction of flow in the northern branch. After 2013 flood the longitudinal bar converted into a lateral bar (Fig. 17 C).

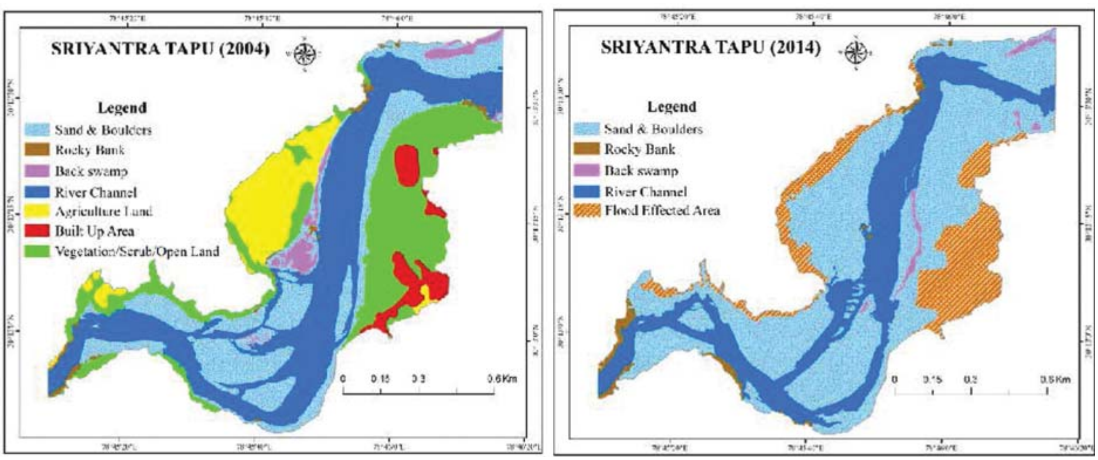

Figure 18. Change detection of land use and land cover of Sriyantra Tapu Meander Bend (2004 and 2014)

The third example of channel bar changes was observed at the reach of SSB and Sriyantra Tapu in the lower part of the study area. About 31.6% bar surface area increased after 2013 flood in comparison to 2004 (Table 2) in the SSB-Sriyantra Tapu reach. The flood affected area increased about 15.3% in which sand and silt deposited at ITI and Sakti Vihar. Beside this about 24.6% riparian vegetation and 10.2% agricultural land was washed out during the major flood of 2013 and boulders, pebbles and sand was deposited at Dewali village. About 4% built up area was submerged during flood at Sakti Vihar. Changes of land use and land cover of 2004 and 2014 are shown in Fig. 18. On the right bank of Alaknanda river about 7–9 m height new bar terrace formed on the slip-of-slope site of Sriyantra Tapu meander. The field surveys indicate that the river bed was upgraded about 9 m in comparison to previous years.

The formation of bar in the mountain river channel is due to the sudden changes in stream gradient, damming of channel, higher amount of water discharge and sediment supply, stream power and bed load transport during high flood. As the gradient of the river course decreases, the valley becomes wide rather than deep. Lateral erosion is more than valley incision and channel water spreads over the wide channel bottom and sediment start to settled down in different parts of the river. Primarily point bars, lateral bars and mid channel bars are formed. The changing sequences of bars are shown at Sriyantra Tapu meander bend in the study area (Fig. 17).

As the flood water level recedes, island bars appear in the bank full channel (Fig. 13). After that the island bars are converted into mid-channel and braided bars (Fig. 10 and 7). Here the river channel becomes broad and shallow. Braided rivers have complex and unpredictable flow paths and sediment size tends to vary among the different branches. Massive amount of sediment creates multiple stream channels within the flood plain. Anastomising river channels also create mid-channel bars; however they are typically vegetated bars, making them more permanent than the bars found in a braided channel which record high rates of channel shifting because of the deposition of large amounts of non-cohesive sediment, lack of vegetation and high stream power found in braided river channels (Schuurman *et al.*, 2017). The gradient being insufficient to remove the sediment, lateral bars commonly change over to braided bars. Although the transverse and lateral bars are similar, transverse bars tend to migrate downstream while lateral bar tend to accrete laterally into the channel (Fig. 7).

Conclusion

Examination of channel bars has produced a typology of bar and channel features for gravel-bed river of Alaknanda. The river bed of the Alaknanda is infested with bars, pools and riffles. Bar indices reflect changes in flow, sediment supply and channel morphology. Basically five types of bar are classified namely point, longitudinal, lateral, braid and middle bar which have complex depositional sediments (boulders, grabbles and sand) attached to river channel and bank in the mountain channel. The major changes in the formation of bar surfaces and channel course recorded during the mega flood of 2010 and 2013 in Alaknanda valley. Drastic changes were observed at Srikot, Kilkileswar and SSB-Sriyantra Tapu. On an average 21.45% area of the channel bars and 13.6% flood affected areas increased after 2013 flood in the Alaknanda river. The shape, size and depth of bar surfaces also changed after the flood event. River bank erosion and deposition of gravels and sand on bar surfaces changed the river course at Chauras, Kilkleswar, and SSB. Changing patterns of bar formation also show that island bars change with reducing flood water to middle bars and middle bars are converted to longitudinal bars. The channel bed aggraded for about 9 m at Sriyantra Tapu and 4.6 m at Srikot. Floods during monsoon season are the major causes of upgrading of the channel bed. A major result of this work is demonstration of the critical role that channel bars play in linking the flood process with the process of sediment transfer in the river. Though bars are created by the fluvial process the changes are the result of the flood events. Mega flood events produce complex alluvial morphology in the river and are demonstrated particularly clearly in the studied reach of the river.

Glacial lake burst, cloud burst and intensive rain in the catchment of Alaknanda River are the recent incidents of disasters. Through the major flood events of 1894, 1970 and 2013 in Alaknanda river, Nature has warned us not to venture into flood-prone areas. The flood events have been subsequently followed by different types of channel disturbance and loss of property. Since the characteristics of channel disturbance and bar deposition vary from one stream to another, signatures of channel disturbances in Alaknanda river can be compared with streams having similar river valley characteristics. This can help us to understand the spatio-temporal characteristics of channel migration and gravel deposition, and such knowledge can help in selection of sites for infrastructural development, pilgrimage, bathing ghats, waste dumping, camping, boating and other recreational activities. The knowledge will be very useful for the Namami Ganga Project run by Government of India as well.

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