Progress in Physical Geography 33(2) (2009) pp. 208–223

Sediment characteristics at river confluences: a case study of the Mula-Kas confluence, Maharashtra, India

Maya G. Unde* and Subash Dhakal

Department of Geography, B.P.H.E. Society's Ahmednagar College, Station Road, Ahmednagar, 414001, Maharashtra, India

Abstract: River bed and floodplain sediments are a direct reflection of river channel processes. This paper examines sediment transfer processes at river junctions, using as a case study the River Kas, a tributary of the River Mula, Godavari basin, Maharashtra, India. The study uses four cross-sections, two from upstream tributaries, one in the main confluence zone, and one downstream. Sediment samples are collected from each cross-section and adjacent banks. To understand the tributary impact on the main channel, variations in sand, silt and clay percentages and variations in the shape of sediment particles were recorded. Data suggest that the percentage of silt and clay increased away from the active channel towards banks along a cross-section, except for the mid-channel bar and the downstream segment of the confluence. The 'a axis' and 'c axis' lengths of particles increased for the samples on the confluence compared to upstream and downstream samples. Sediment characteristics between tributary and the main stream reflect both downstream distance from sediment source and the characteristics of the respective transport processes. The distribution of fine material at the tributary mouth suggests that there have been instances in the past where the mainstream flow has dominated the confluence and has led to slack water deposits on the tributary mouth. Construction of a weir for local flow regulation also affects the pattern and character of sediments. In this large, seasonal river, confluence sedimentology is a joint product of flow variation, confluence morphology and the additional effects of human activity. The study thus provides insights into confluence dynamics and characteristics which may not be revealed in the more intensively researched temperate confluences of smaller scale.

Key words: cross-section, main channel, river confluence, sediment shape, sediment size, tributary channel.

I Introduction

River confluences are integral parts of river systems. While their hydrodynamics are now well known, there is much less knowledge of the morphology and sedimentology as compared with other components of river channels such as meanders or riffle-pool sequences. Although some important

*Author for correspondence. Email: maya4unde@gmail.com

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DOI: 10.1177/0309133309338655

aspects of river confluences have been well researched, studies have traditionally been confined to the temperate rivers of Europe and North America. In India, large water resource projects are planned which will considerably alter the hydrological regimes of some river systems. The impacts of such projects are largely unexplored (Roy and Sinha, 2007).

Geologically, river confluences are locations with distinct sedimentary facies which could provide significant insights into the palaeogeomorphology of river systems. River confluences can be both aggradational and degradational, both of which may result in serious river management problems. River confluences in India are also known for their archaeological importance, and a number of ancient human settlements have been reported around Ganga-Yamuna confluence (Williams and Clarke, 1984; 1995), which are of social and mythological value. Many contemporary religious towns and institutions are also located on river confluences.

Geomorphologically, the dynamics of confluences affect the availability of water in different reaches and the pattern of sediment dispersal around the confluence point (Roy and Sinha, 2007). Several works have considered confluence dynamics, including Mosley (1976), Ashmore and Parker (1983), Best (1986; 1988), Rhoads and Kenworthy (1995), Pizzuto (1995), Biron *et al*. (1996) and Ferguson (2006). Best (1987) proposed a conceptual model of flow and sediment transport at the river confluence, which was subsequently modified by Biron *et al.* (1996). In this model, an open channel confluence consists of six different zones: zone of stagnation; flow deflection zone; flow separation zone; zone of maximum velocity; zone of flow recovery; and zone of shear. These entire zones are subjected to change in location and dimension as the junction angle and the bed elevation of the confluence change (Biron *et al*., 1996). In numerical simulations of idealized channel junctions, Bradbrook *et al.* (2001) found that the bed elevation difference at the junction significantly enhances secondary circulation due to the effects of flow separation in the lee of the bed step. There is a marked increase in lateral pressure gradients at the bed and a reduction in water surface superelevation in the centre of the tributary, with water surface depression at the downstream junction corner. Their experiment with a number of junction angles, bed discordance and velocity ratios suggests that a small (10%) reduction in tributary depth resulted in a notable increase in the intensity of localized secondary circulation. However, very little information is available for the comparative analysis of sediments and sedimentation within the confluence zone with respect to actual field characteristics. Therefore, the present paper focuses on the size and shape analysis of sediment at key points of a large-scale, natural river confluence.

The focus of this paper is the River Mula, a tributary of the River Pravara in the southwestern part of the Godavari basin, and the River Kas, a right bank tributary to the Mula (Figure 1). The Mula is a typical seasonal stream, on basalt terrain. The confluence has permanent flow during the rainy season. The seasonal stage changes provide access for the detailed study of the bed and bank materials. The characteristics of the confluences in the resistant box-shaped bedrock channel in the upper course can be directly compared to the wider alluvial confluences on the lower course of the river.

II Previous research

Zernith (1932) described several stream patterns citing typical junction angles, although no systematic measurements were made. He suggested that rectangular drainage patterns are structurally controlled by rectangular facture systems and have characteristic 90° junction angles. However, the angle of the junction of two rivers was first studied by R.E. Horton (1932: 360; 1945: 349), who noted that the angle at which overland flow enters the receiving stream is a function

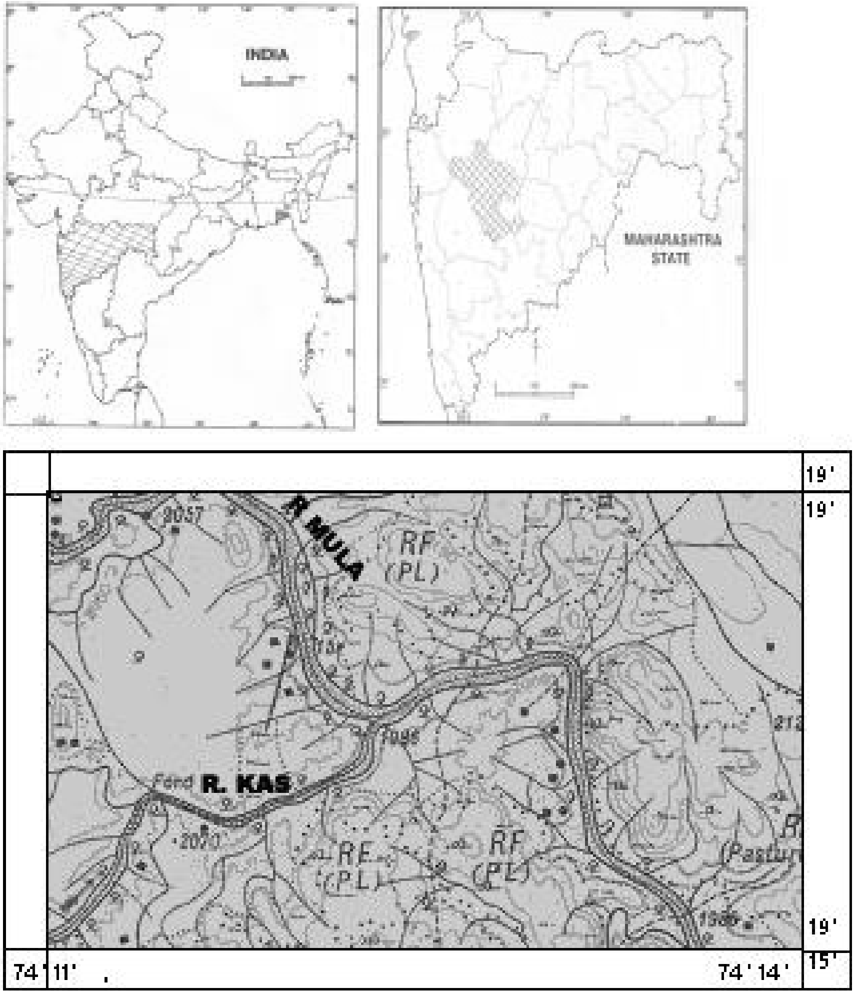

Figure 1 Location of the study area

of the ratio of channel gradient to ground slope. Mosley (1976) argued that prediction of confluence angles using the basic equations of fluid mechanics is not possible. In terms of flow process in a channel junction, confluence angle is an independent variable. In the detailed study of confluences, he presented a valuable paper on the experimental study of river channel confluences of a model channel in a flume. He noticed that water from the two tributaries remained generally separate through the zone of scour, and became completely mixed over some distance downstream from the confluence. Due to the presence of helicoidal flow cells in the middle of the junction, sediments were transported in two zones along the sides of the scour with no sediment movement through the centre. These two zones of high sediment transport converged in a downstream direction resulting in a construction of a mid-channel bar. Ashmore and Parker (1983), in their study of coarse braided streams, found that the relative scour depth was largely controlled by the angle of incidence of upstream anabranches.

Variation in the hydraulic geometry at stream junctions is also an important consideration. Leopold and Maddock (1953) introduced the notion of hydraulic geometry, whereby channel properties are treated as the continuous function of discharge downstream. Miller (1958) analysed the adjustment in the channel form occurring at tributary junctions. He stated that the width of the downstream segment after the junction is the summation of the width of tributary streams. However, more recent findings suggest that the post-junction width is less than the combined width of the two incoming tributaries, and this causes major shifts in downstream hydraulic geometry from those estimated using statistical fit. Richards (1980) found that the ratio of the widths of the downstream link and larger upstream tributary link is the product of the magnitude of the minor tributary and the ratio of the magnitude of the downstream link and larger tributary link.

Best (1988) conducted flume experiments to understand the sediment transport and bed morphology at river channel confluences. He found that flow deflection and a large zone of separated flow are the dominant fluid dynamic features within a confluence. An avalanche face at the mouth of each confluent channel is the result of sediment segregation around the centre of the junction coupled with the high velocities and the level of turbulence within the confluence. Increase in the discharge ratio and the junction angle leads to morphological consequences of larger bed scour, larger bars formed within the separation zone and the retreat of the main channel avalanche face from the junction. However, flow separation and flow deflection are minimal at very low junction angles and discharge ratios. Roy and Bergeron (1990) studied the flow and particle paths at a natural river confluence with coarse bed material. Observations were made of the spatial variation of the velocity field and movement of the particles for a range of stages. They found that, at low flow stages, the velocity was characterized by important lateral and longitudinal variation in the magnitude and direction of velocity vectors. Rhoads and Kenworthy (1995) made a more detailed investigation of flow dynamics at river confluences, in their study of flow structure at an asymmetrical confluence of River Kaskaskia and Copper Slough in east Central Illinois, USA. They point out that the structure of flow in an asymmetrical confluence is influenced by: tributary mainstream momentum flux ratio; the total discharge of the incoming flows; and the bed morphology. This was followed explicitly by Bradbrook *et al.* (2000) in their three-dimensional numerical simulation model, which examined the controls upon flow structure generation and the particular condition under which given flow structures were observed. Results demonstrated that specific dynamic field pressures were observed for symmetric and asymmetric confluences. This in turn resulted in twin back-to-back helical cells for a symmetrical configuration. However, these dual cell structures were limited to the immediate vicinity of the junction in asymmetric configurations, due to effects of streamline curvature and topographic steering.

Kennedy (1984), from data obtained from 100 confluences, concluded that a high proportion of junctions were discordant. Discordant junctions have tributary beds higher than those of the main channel. This was attributed to differences in channel-forming discharges and varying geology and sediment calibre of bed and the banks (Kennedy, 1984). Best and Roy (1991), from their experiments on unequal depths, showed that vortices at the mixing-layer interface were deformed at discordant junctions and this can affect the sediment entrainment, bed morphology and sediment characteristics at river confluences (Biron *et al.*, 1993). Biron *et al.* (1993) studied the spatial and temporal variations in the bed geometry and bed material size of a sand-bed river confluence with unequal depths in Montreal, Quebec. Three important morpho-sedimentological zones with distinct grain size, sediment structure and bedform characteristics were observed: an upstream junction corner, where the sediments were finer than the mean; a maximum depth zone with coarser than average particles; and a bar at the downstream junction corner where the grain size is finer than the mean is and which decreases downstream. In a more detailed and systematic paper on bed discordance (Biron *et al.*, 1996) the effect of the discordance are examined focusing on the key flow dynamics in four regions: flow deflection, flow separation, maximum velocity zone and the mixing layers. De Serres *et al*. (1999) confirmed most of the above findings from experimental studies in their study of three-dimensional flow structure at a natural discordant confluence of the Bayonne and Berthier Rivers, Montreal, Quebec.

A characteristic of sediment entrainment in the river junction is another important area of investigation. Various studies have indicated that the smooth downstream trend of fining of sediments is punctuated due to the lateral inputs from the river tributaries. Such a characteristic was observed along the Peace River in British Columbia (Church and Kellerhals, 1978), numerous upland streams in England (Knighton, 1984), part of the Sunwapta River (Dawson, 1988), Standing Stone Creek (Pizzuto, 1995) and Pine and Sukuna Rivers in British Columbia (Rice and Church, 1997; Rice, 1998; 1999). Sternberg (1875) noted the importance of tributaries for disrupting downstream sediment fining. Sawtooth patterns of punctuated downstream fining are typical, therefore, with fining sequences along 'sedimentary links' (Rice, 1999) separated by upturns where coarse sediment is added from the lateral sources (Church and Kellerhals, 1978; Knighton, 1980; Rice and Church, 1997). This punctuated fining is associated with the discontinuity in slope, which resembles a 'knick point' (Rice and Church, 2001). Knighton (1980) argued that the mainstream bed could become coarser after a junction if a tributary supplies a substantial flux of relatively coarse bed. Pizzuto (1995) applied a network-based model to determine how spatial variation in sediment supply influences the rates of downstream fining in a small watershed in Central Pennsylvania. Rice (1998) in his study of Pine and Sukuna Rivers, attempted to identify the significant lateral sources which would interrupt the downstream fining. He concluded that a source close to the link head is more likely to redefine the mainstream grain size population, produce a textural discontinuity, and delimit the new sedimentary link. Ferguson *et al*. (2006) investigated the mainstream response to the lateral inputs using a one-dimensional sediment routing model with multiple grain size fractions. Benda *et al*. (2004) evaluated 167 confluences and 730 km of streams to study the confluence effects on rivers. They found that the distance between geomorphologically significant confluences increases with the increasing drainage area of the main stream. Heart-shaped and pear-shaped basins containing dendritic networks favour increasing tributary size and hence greater confluence effects downstream (morphological changes at confluences), compared with rectangular basins containing trellis or parallel networks, which do not.

The above review suggests that most research has considered perennial rivers in temperate regions, often for smaller and less dynamic stream systems. The confluence dynamics of seasonal streams has not been investigated. Furthermore, there are relatively few detailed descriptions of the sedimentology of river junctions. The purpose of this paper is to understand the sediment transfer process at a highly seasonal, large-scale river confluence, using the case study of the Mula-Kas junction in the state of Maharashtra, India.

III Study area

The study area used in this paper is the Mula-Kas confluence zone, located at 74° 10' east and 19° 20' north latitude, near Aklapur, east of the Pune–Nashik Highway, India.

The River Mula is the major tributary of the River Pravara, which is, in turn, the main tributary of the Godavari basin. The River Mula has its source on the eastern slopes of the Harishchandra Range in Ahmednagar district. It is a seasonal river, with much of its flow concentrated during the months of June to September. The total catchment area is just over 1152 km^2. The total length from its source to its mouth (Pravara-Mula confluence) is 199.89 km (Figure 1).

The River Kas is a right bank tributary of the River Mula. It is situated approximately 95 km from the Mula source. The junction is symmetrical, with a junction angle of 53°. The Kas is a sixth-order stream and drains an area of 182.66 km^2. The maximum length of the tributary trunk stream is 35.5 km. It has a drainage density of 3.01 km/km^2. Stream frequency is 5.29 streams/km^2. Horton's form factor 'R' is 0.23. Absolute relief is 1060 m and relative relief is 469 m. The dissection index is 55.75%. Scabland features characterize the channel upstream of Bota. Bretz (1923) suggested that scabland erosion is a result of plucking rather than abrasion. The river originates on the hills surrounding Karandhi village north of Brahmanwada. The minimum annual rainfall in Brahmanwada during the past five years was 425 mm in 2003, and the maximum was 753 mm in 2006. Although the stream is seasonal, the flow in the rainy season is more consistent compared to the extremely seasonal downstream tributaries of the Mula.

IV Field surveys, methods and results

Results here represent a combination of cross-section survey, field description of flow and morphology, and laboratory sediment analysis. Sediment analysis of samples from each cross-section were used to infer the dynamics of flow through the confluence. Finer materials usually carried in suspension are generally deposited in the places of markedly reduced velocity, or can be derived from the lithified unleached sections from the banks. Coarse sediments may be found on the areas of high velocity, where much of the finer materials are carried away in suspension or the weathering of the indurated compact material from the banks.

Sediment samples were collected from different locations on the cross-section from both the banks and the bed. Samples were dried and 50 g from each sample were mechanically sieved in the laboratory to sort the sediment into different size groups. The sieve sizes used for the present analysis were 2.36 mm (upper plate), 0.6 mm, 0.3 mm, 0.15 mm, and 0.09 mm (bottom plate). The weight of each size group was calculated and converted into a percentage by weight. Cumulative percentage graphs were plotted for each sample on probability graph paper. Phi values were calculated for the statistical analysis. For the present analysis, the weight of the sediment samples less than the 0.09 mm sieve size was taken for the silt plus clay group (although the silt group is normally taken from less than 0.06 mm sieve size). These sizes of material can be easily carried in suspension by upland rivers. The materials with sieve size between 2.36 and 0.09 mm were taken as sand. Based on the above criteria, the percentage of silt plus clay and sand from each 50 g sample was calculated.

Particle-size analysis was accompanied by the measurement and analysis of the three particle axes that define the three-dimensional shape of a particle. The analyses of particle sizes and particle shape parameters were based on the length of three mutually perpendicular particle axes: the *longest* (a axis), the *intermediate* (b axis), and the *shortest* (c axis) axis. The size of a particle can be determined in three different categories: the actual b axis length, the nominal diameter, and the particle-sieve diameter. Particles were classified into four basic shapes according to the ratios of the three particle axes. The particle shape of a disc is characterized by its small c axis. The degree of disc shape is quantified by the axis ratio c/b (Krumbein, 1941). A sphere-like particle, in turn, has almost identical a, b and c axes. A bladed particle is thin and long, ie, it has small ratios of c/b and b/a, whereas a rod-like particle is long, which is quantified by a small b/a ratio.

1 Cross-sectional characteristics

The first cross–section was taken nearly 100 m above the confluence on the Kas tributary which has a maximum bank full width of 70 m and maximum depth of 3.5 m, with a cross-sectional area of 245 m^2 (Figure 2, CS-1). The annual average discharge here was estimated to be 191 m^3/sec. This was estimated by measuring velocity on the cross-section at different time intervals during the rainy season. The measured velocity was multiplied by the cross-sectional area and the annual average taken. The right bank is a vertical wall with a moderately wide flood plain on the top, whereas the left bank is steep with precipitous slope. The lower levels of both the banks are cohesive with a disturbed bed following human interference (Figure 3).

The second cross-section was taken 100 m before the confluence zone but on the main Mula stream. The channel is U-shaped with maximum depth and active flow towards the right bank. The channel width is 114 m and the depth 5.0 m. The cross-sectional area is 570 m^2, with an estimated average discharge of 470 m^3/sec (Figure 2, CS-2). Here, the right bank is nearly vertical, forming the base of the water divide. The left bank gently slopes and forms the terrace of old deposits, which is presently agricultural land.

The third cross-section at the Mula-Kas confluence has a maximum bank full width of 130 m. Maximum depth is 5 m, with the cross-sectional area 650 m^2 (Figure 2, CS-3). The right bank is formed of cohesive materials and forms thick deposits supporting trees and shrubs. The active channel is bifurcated into two parts, one tributary channel with coarse deposits towards the right bank, and an active channel towards the left bank with a pool and deposits of fine sand. The left bank comprises a steep vertical rock wall. The middle portion of the confluence is occupied by a mid-channel bar. The top of the bar comprises almost lithified heterogeneous deposits supporting vegetation growth.

The fourth cross-section occurs approximately 100 m downstream from the confluence, and forms a gently concave shape with the width–depth ratio 1:30. The maximum width is 126 m and maximum depth 5.5 m, yielding a cross-sectional area of 693 m^2 (Figure 2, CS-4). The velocity at this cross-section seems to reduce drastically due to a low-height local dam constructed across the river a few hundred metres down stream from the present cross-section. This is mostly used for the seasonal storage of water for local use. It is locally called the KT weir or Kolhapuri-type weir, as it was first developed in Kolhapur, Maharashtra state, India. Pebbles characterize the bed, with gravels mixed with clay also occurring due to the backwater effect. The left bank is a vertical wall of resistant rock, whereas the right bank has a near-vertical cohesive wall beyond which it forms a terrace used for human settlement and agriculture.

2 Confluence characteristics

This is an important confluence, which possesses key characteristics of varying confluence morphology. The tributary channel at the initial stage is rectangular with resistant bedrock. After Bota, gravel beds along with the bank-eroded materials at the meander bends characterize the tributary channel. Upstream from the confluence, the tributary channel bed is characterized by loose alluvium with a mixture of pebbles and coarse granules. For constructional activities, local people collect large cobbles and gravels from the bed surface. Fine cohesive sediments with ample vegetation growth characterize the right bank. On the other hand, the left bank is formed by sun-dried colluvial material on the interfluve. A well, constructed at the mouth of the tributary, shows a thick deposit of fine to coarse alluvium with the bedrock following this layer. This is evident from the shallow water level in the well (Figure 3).

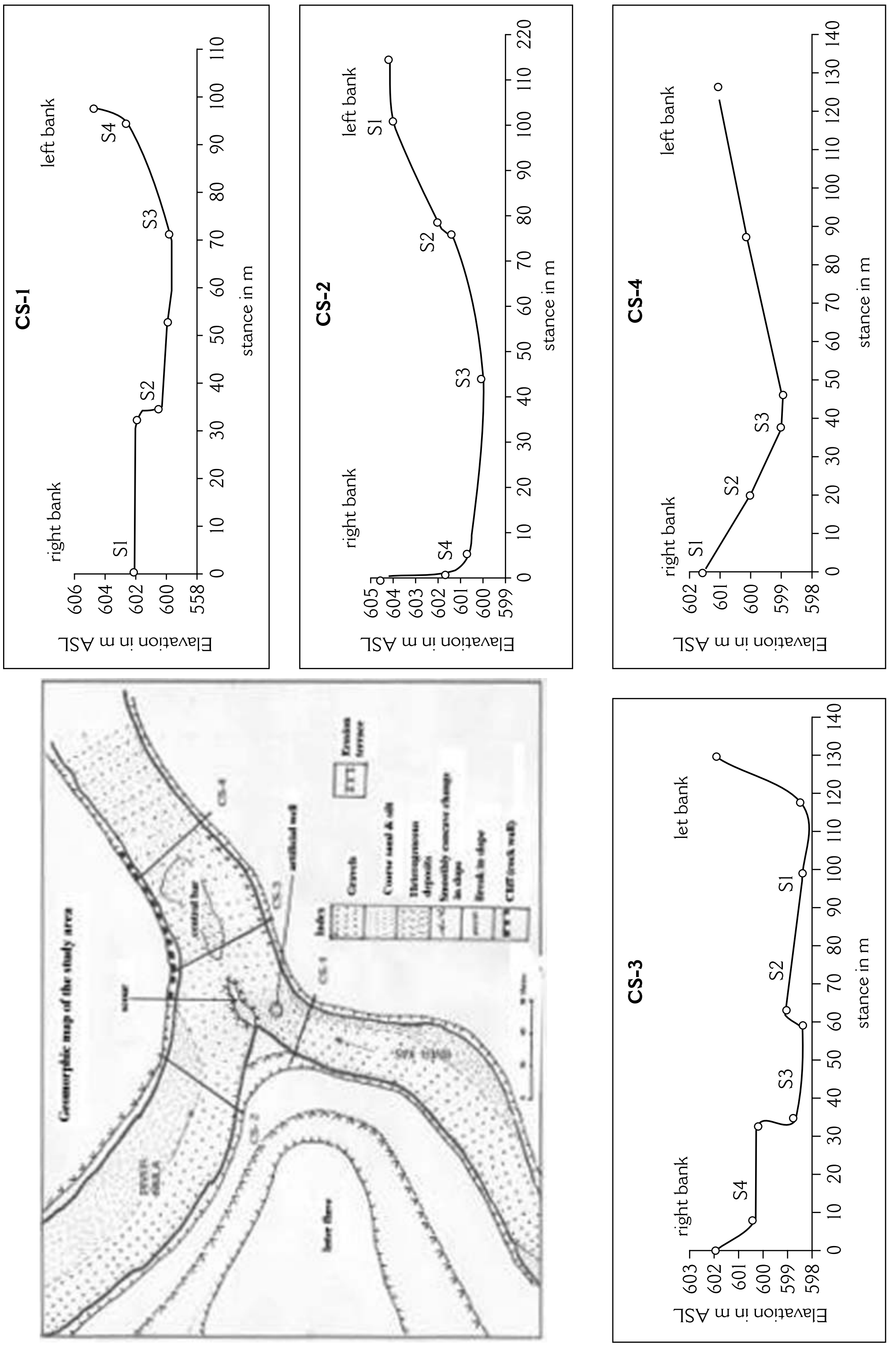

Figure 2 Cross-section diagram with location of sediment samples

Figure 3 View of a well, constructed on the mouth of the tributary. The fine materials are deposited as the slack water deposits by the Mula channel

The River Mula before the confluence has an asymmetrical channel with the active flow towards the right bank. Coarse pebbles and cobbles characterize the bed. The right bank is a steep rise of dry, and eroded, bare colluviums. The left bank consists of coarse sand and granules (newer alluvium) followed by clayey sand and mixed desiccated old alluvium at the terrace supporting vegetation.

The within-confluence characteristics are: flow deflections, a shallow scour zone elliptical in plan from the upstream junction corner, a mid-channel bar and point bars on both banks where the separated flow meets after the mid-channel bar (Figure 4). The tributary continues its flow on the right bank of the main channel up to 70 m downstream from the junction, with well-rounded pebbles and a gravel bed. The mid-channel bar is composed of partially buried gravels in fine silt and clay. The bar has been a permanent feature for a couple of years, which eventually has led to a growth of grasses over it. The left bank channel is a pool section of the mainstream active flow. The two separated flows meet after the central bar terminates in the downstream direction. After this, the channel is characterized by single flow with point bars on both the banks. Downstream from the confluence, the impact of the tributary stream is superimposed upon the backwater effect of the KT weir constructed after the confluence zone. The backwater effect is seen far beyond the central bar, as evidenced by the mixture of gravels saturated with the clay.

Figure 4 An upstream view of the Mula-Kas confluence (note the confluence scour zone)

In the confluence zone, the flow deflection of the tributary towards the right bank results in bank cutting which adds some material to the deflected channel flow of the tributary. By contrast, the deflected flow of the main channel has little scope for bank cutting because of the resistant left bank rock wall. A survey of the junction from the downstream segment revealed that the downstream channel thalweg was more aligned to the tributary channel than to the main channel thalweg. The main channel flow seemed to enter the junction with a slight right turn. This is the result of rapid right bank cutting by the tributary flow. The confluence reveals some important morphological features discussed in the literature. However, the material dug on the tributary mouth suggests slack water deposits in the main channel. This supports the inference that, during past years, there have been spells of much lower variation in discharge; alternatively, this could be the result of the lateral shifting of the scour–slackwater zone.

3 Cross-sectional size analysis of sediment samples

For the present study, samples from the active channel were expected to be composed of coarser material, with an increase in the proportion of fine material towards the banks. At the first cross-section, on the tributary channel (the Kas), 100 m before the confluence, four sample points were selected starting from the right bank (Figure 2, CS-1). The first sample from the right bank terrace was composed of 30% silt plus clay and 70% sand. The percentage of fine materials decreased to 17% in the sample taken on the bed–bank wall corner on the right bank. The thalweg on the middle of the channel was 5% silt clay, which increases to 16% on the left bank wall (Table 1). Thus, there was a distribution of coarse and fine material as expected.

The second cross-section was taken 100 m before the confluence on the main stream (Figure 2, CS-2). Similarly, from the right bank, four sample points were selected. The percentage of fine material varied between 10% at the right bank wall, 6% at the thalweg 6%, and 20% at the left bank (Table 1).

The third cross-section is taken in the confluence zone. All the materials were collected from the right bank up to the bed–water line on the mainstream active channel (Figure 2, CS-3). The sample from the central bar comprised 40% silt plus clay, which is reduced

Table 1 Cross-section-wise analysis of sediment samples for the Kas-Mula confluence

CS no.	Sample no.	Bank	Location	Distance from thalweg to sample points in right/left bank (m)	% Sand	% Silt + clay
1	1	Right	Terrace	60	70	30
	2	Right	Bed–bank wall corner	45	83	17
	3	–	Thalweg	0	95	5
	4	Left	Bed–bank wall corner	25	84	16
2	1	Left	Terrace	58	80	20
	2	Left	Bed–bank wall corner	33	94	6
	3	–	Thalweg	0	95	5
	4	Right	Bank wall	38	90	10
3	1	Right	Bed–water line	10	95	5
	2	Right	Bar	39	60	40
	3	Right	Bed of tributary channel flow	65	98	2
	4	Right	Terrace	98	85	15
4	1	Right	Terrace	3	80	20
	2	Right	Bank wall	20	85	15
	3	Right	Bed–water line	40	60	40

Note: Thalweg for CS-3 is taken as thalweg of the main channel flow.

to 5% towards the main channel bed and to 2% on the bed of the continuation of the tributary channel. The right bank terrace sample is composed of 15% fine materials (Table 1).

The fourth cross-section, taken 100 m downstream from the confluence, exhibited different characteristics. The near-bed sample on the right bank is composed of 40% fine material, which reduces to 15% on the bank and increases to 20% at the right bank terrace (Figure 2, CS-3). This unusual increase in the near-bed sample in the downstream cross-section is due to the backwater effect of the KT weir constructed 200 m downstream from the confluence.

4 Particle shape analysis

Shape analysis of samples for the tributary stream upstream of the confluence revealed that 65% of the sediment samples are spherical, 23% are rods, and 12% are disc-shaped. Before the confluence on the main stream, 53% of the sediment samples are disc-shaped, 29% are spheroids, 1% are bladed and 14% are rods. At the confluence, 51% samples are disc-shaped, 44% spheroids, 1% bladed and 1% rods. After the confluence, 42% samples are disc-shaped, 34% spheroids, 6% bladed and 8% rods (Figure 5). This indicates that the tributary stream supplies a greater proportion of spherical materials to the mainstream.

Before the confluence, on the tributary stream (Kas), maximum frequencies of the length of the a and b axes varied between 10 and 16 cm. Variation for the c axis occurred between 10 and 14 cm (Figure 6a). For the proximal mainstream (Mula), the length of the a axis ranged between 4 and 14 cm, with

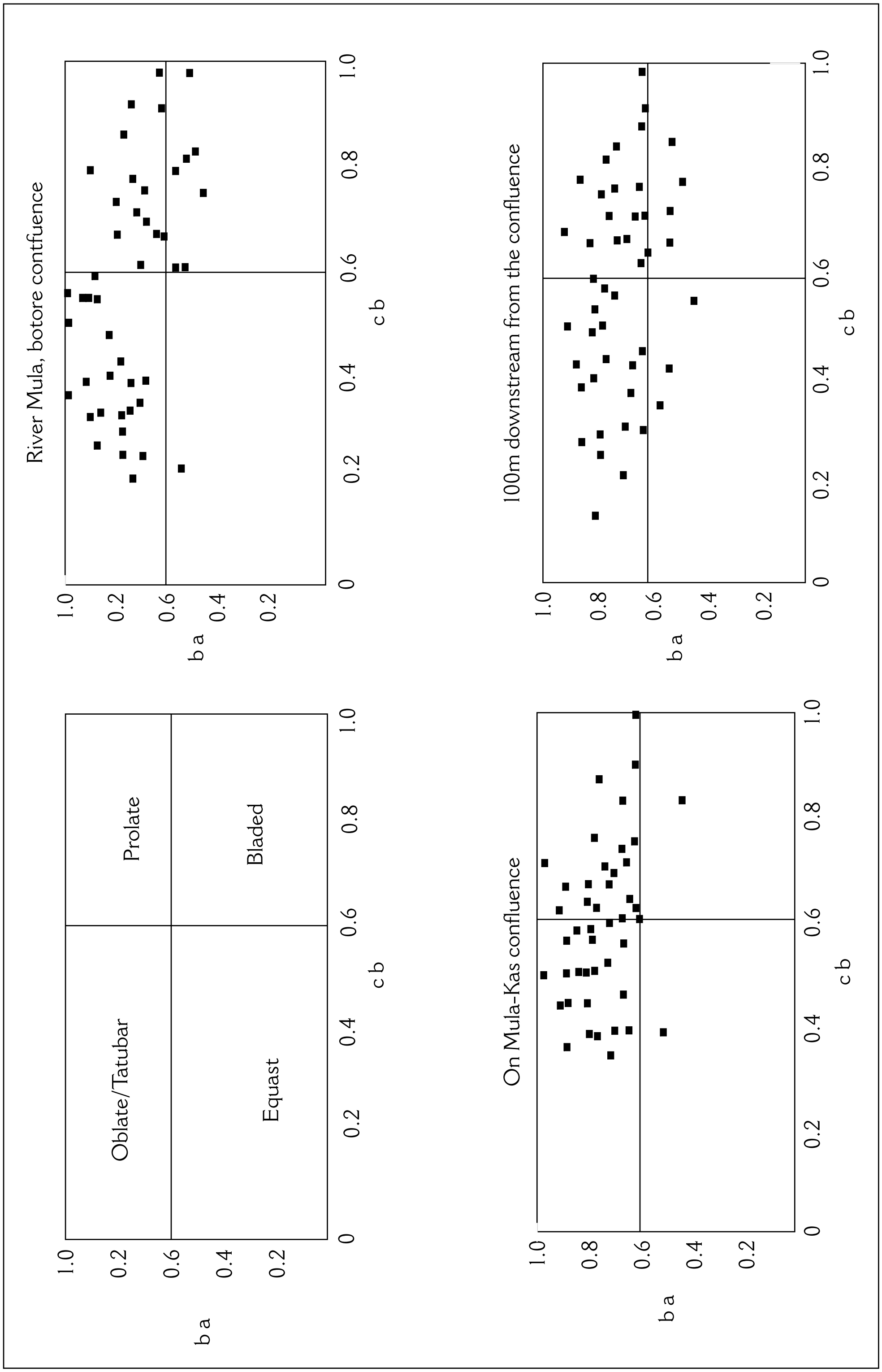

Figure 5 Shape classification diagram for shape analysis of the Mula-Kas junction

the maximum frequency in the 6–8 cm class. Similarly, the length of the b axes varied between 6 and 16 cm, with the maximum frequency in the length class 8–10 cm. The length of the c axis ranged between 0.5 and 10 cm with a maximum frequency in the 4–6 cm class (Figure 6b).

At the confluence, the length of the a axes varied between 4 and 18 cm, with the highest frequency in the 8–10 cm class. The length of the b axis varies from 2 to 12 cm, with the maximum frequency in the length class 4–6 cm. Similarly, the length of the c axis varies between 6 and 24 cm, with the maximum frequency in the 10–12 cm class (Figure 6c). Downstream from the confluence, the a axis length of sediment samples ranged from 4 to 18 cm with the highest frequency in the length class 6–8 cm. The length of the b axis varies from 0.5 to 10 cm with a maximum frequency between 2 and 6 cm. The c axis varies between 4 and 22 cm with the highest frequency in the 8–10 cm class (Figure 6d).

Therefore, from the analysis, there is an increased proportion of samples with longer a and c axes in the confluence zone, which is also noticed for the Kas stream upstream from the confluence zone (Figure 6, a and c). The mean sediment size of sediment samples ranges from ø 0.02 to 1.20. The sorting value ranges from ø 0.71 to 2.22, which implies moderately to poorly sorted. Skewness is positive for the banks and negative for the bed except in the fourth cross-section. The positive value means fine sediments and the negative value means coarse sediments. The kurtosis index is less than three, suggesting a platykurtic distribution.

V Discussion

First, sediment data suggest that the tributary sediments impact on the main stream, thus punctuating the downstream trend in sediment size decrease as found in most other studies (Miller, 1958; Moss *et al.*, 1973; Knighton, 1980; Troutman, 1980; Rhoads, 1987; Dawson, 1988; Ichim and Radoane, 1990; Rice, 1998; Ferguson *et al.*, 2006). When considering the sediment size decrease on a longitudinal profile of a river, major tributary inputs can cause a saw tooth variation in the sediment distribution curve. Thus, the real downstream decrease in sediment size suggested by a particular exponential trend value would be valid only for a stretch of stream between two links (two junctions).

Second, the size of the tributary is an important factor for tributary impact on the main stream. If the tributary is too small, it conveys little sediment flux that would make a difference to the relatively large flux of the main stream. Similarly, if the tributary is too large (almost equal in size to the main stream) it is likely to have similar slope and calibre, again making little difference in the sediment distribution. Therefore, intermediate size tributaries with large basin areas and greater slope are most likely to have the greatest sedimentological effect (Knighton, 1980; Rice, 1998; Ferguson *et al.*, 2006).

Third, the geology at the confluence zone is an important factor influencing the morphology of the confluence. The River Kas had straightened its course downstream towards the confluence by eroding the right bank. This has resulted in widening of channel towards the right bank in the confluence zone.

Fourth, particle size decreased from the active flow bed towards the banks and bars. However, downstream from the confluence, this characteristic was reversed, due to the backwater effect of the KT weir.

Fifth, analysis revealed that well-rounded large pebbles and cobbles dominated the tributary inputs, and semi-rounded tabular and smaller sediments dominate the main stream. Both sources are supplied from basaltic weathering. Cobbles occur in the tributary channel due to steeper slopes and shorter distances of transport. However, while mainstream sediments travel a greater distance than the tributary material, and are thus smaller, they are transported in phases by flash-type floods. In this process of transportation, sediments are dragged along the bed or eroded on the exposed part of the

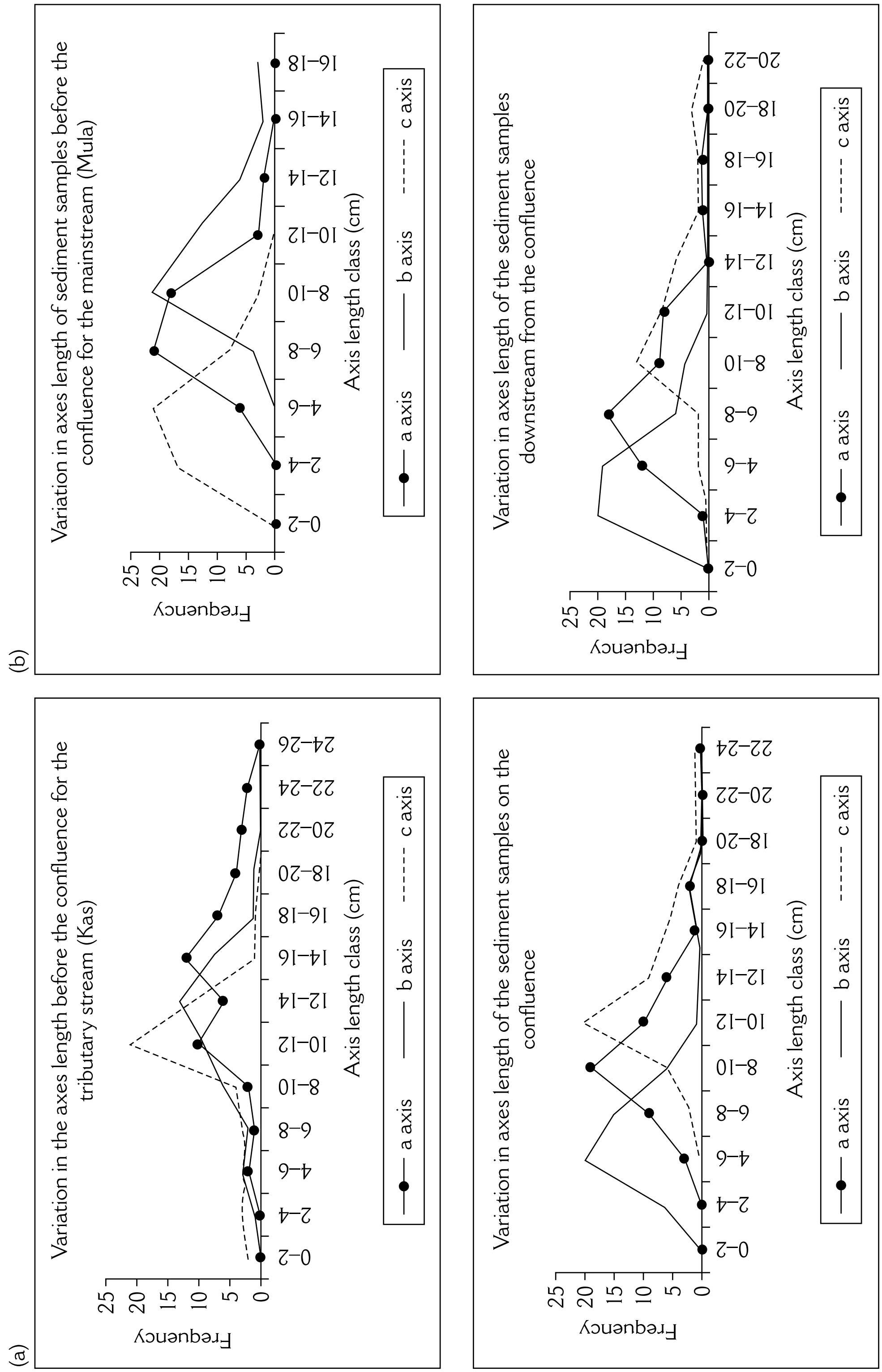

Figure 6 Frequency graphs for variation of axis length (a/b) before, (c) on, and (d) downstream from the confluence

partially buried sites on bars and bed, and it is this which causes their tabular shape.

VI Conclusion

Although the study is not meticulously supported by flume or numerical models, the analysis does throw light on the actual variation of sediment size and shape over a cross-section at key points through a large-scale, seasonal and natural confluence. The present study reveals the fact that the tributary streams are characterized by larger and more spherical material, compared to the tabular material of the mainstream, despite common geological sources. These differences are the result of differing transport distances, and different transport processes, between the main river and the tributary inputs.

However, the impact of the tributary stream downstream from the junction may not be generally applicable due to the backwater affect of the KT weir. Artificial flow regulation such as the KT weir in this study may be of general significance in influencing the natural characteristics of river channels in the seasonal rivers of semi-arid Maharashtra, since these are common, providing much-needed water and constructional materials. The bars formed on these seasonal confluences form more stable features compared to perennial streams because of the very low frequency of the channel-forming discharge. Therefore, the larger confluences are more likely to display permanent mid-channel bars with vegetation growth.

The present case study thus supports earlier works that confluences define zones of discontinuity in sediment characteristics along the long profile of rivers. However, when studying seasonal streams, one has to also consider factors such as differential flooding and the impact of humans on these channels.

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