ISSN 2278-8808 SJIF 2013 = 4.194

An International Peer Reviewed & Referred

SCHOLARLY RESEARCH JOURNAL FOR INTERDISCIPLINARY STUDIES

STUDY OF RIVER CONFLUENCES FROM UPLAND MAHARASHTRA: A CASE STUDY OF RIVER MULA

Maya Unde, Ph.D. Associate Professor and Head: Department of Geography, Ahmednagar College, Ahmednagar, Maharashtra, India.

Subash Dhakal, Ph.D. Principal, Govt. Sr. Sec. School Hee-Gyathang Lower Dzongu, North Sikkim, India.

Abstract

River confluences are universal feature in all fluvial systems. It has been viewed as a point of abrupt change in hydraulic geometry (Richards, 1980), discontinuity in sediment distribution (Ferguson et al. 2000), three-dimensional patterns of flow and its dynamics (Best, 1985, Biron et, al 1996) etc. From the past experiments and studies, junction angle, discharge ratio and the geology at the confluence zone has been ascertained as the convincing factors influencing the dynamics of the confluence zone. In the present study, part of the Mula basin stretch (47 km) from Lahit Khurd (19˚ 24′00″ N and 73 ˚ 3′ 00″ 00E.) upto downstream Kas Junction (19˚ 16′ 30″ N and 74˚ 14′ 00″E) is selected. The entire left bank and the right bank stream greater than third order are chosen and their morphometric characteristics calculated [SOI 1: 50,000 (47E/15, 47I/3)]. The actual ground characteristics of these confluences are observed on the field. With the information from map and field observation, 5m × 3 m concrete flume model is prepared with five left bank tributaries and one major right bank tributary. Discharge for mainstream and each tributary are varied according to their respective stream order. Three simulations are run characterizing, low stage, high stage and flood condition in the basin. First experiment consisted of the main river and the major right bank tributary. Second experiment is configured for the main river and five left bank 3rd to 5th order tributary approximating their morphometry at the junction. Detail dynamic of confluence is noted at different time interval. The results suggested that the bed morphology and sediment entrainment though the confluence varied for different flow stages.

***Key words**: River confluences, Experimental study, flow stages, bed configuration, sediment entrainment.*

Introduction

Mosley (1976) conducted the flume experiment to understand the dynamics in the confluence zone of the river. He noticed helicoidal flow cells on the middle of the merge, where sediments were transported in two zones along the sides of the scour with no sediment movement through the center. These two zones of high sediment transport converged in a downstream direction resulting in a construction of a middle bar. Best (1987) proposed open channel confluence consists of six different zones, namely: 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). Brad brook et. al, (2000) 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 symmetrical configuration. However, these dual cell structures were limited to immediate vicinity of the junction in asymmetric configuration due to effects of streamline curvature and topographic steering. As such there are several flume experimental studies of confluences which provided significant insight to the confluence dynamics and contributed to rare literature on confluences now available. Certain aspects like sediment dynamics on the confluences needs to be studied at large. The present study tries to throw some insight on the sediment dynamics of the river confluence through a flume experiment approximating the actual ground condition.

Objective of the study

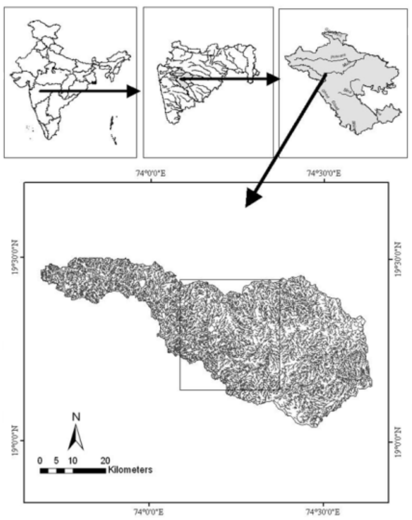
The main objectives of the present study are as follows

1. To observe the mode of sediment transportation in flume experiment model.
2. To observe and study the bed configuration in the model at different stages of flow.

Study area

Study area is the part of river Mula (33 km) from Lahit Kurd upto Abalwadi (5 km downstream from Mula – Kas confluence) extending from 19˚ 24′00″ N and 73 ˚ 3′ 00″ E to19˚ 16′ 30″ N and 74˚ 14′ 00″E. Total number of 5 left bank and 1 right bank tributary with joint watershed area of 375 km^2 is taken or study .The Mula has 6^{th} order at this stretch and the order of six other tributaries ranges from 3^{rd} order to 6^{th} order. The junction angle varies between 34 degree and 132 degree. Actual channel slope of River Mula at this stretch is 0.112 degrees and the slope of tributary channel range between 0.82 to 4.10 degrees.

LOCATION MAP OF STUDY AREA



Methodology

Following methodology are adopted for the present study:

1) Field observation and selection of the study area

163 km of River Mula is observed from its source up to Mula Dam. The main aim was to select the stretch having maximum variability in stream order, junction angle and stream slope. Based on the observation 33 km stretch between Kauthe budruk upto Abalwadi is selected.

2) Calculation of Morphometric parameters

Morphometric parameters like, stream length, basin area, order, bifurcation ratio, dissection index, absolute relief, drainage density, stream frequency and form factor is calculated. Block diagram is prepared for 50 cm × 30 cm stretch of the related area from SOI sheet 47 I/3 (1: 50,000).

3) Construction of Model

5 m × 3 m concrete tank is constructed with horizontal flat base and 4.5 degree sloping walls. The tank is initially filled with coarse gravel at the base, followed by the layer of mixed sand and gravel, layer of coarse sand and finally Mud. Holes were drilled on the model walls at respective reduced height of the tributary source. 300 Liters plastic barrel is used as the source of the discharge which was connected with 2 inch "T" socket and2.5 inches horizontal pipe. Seven reducers were fitted with stoppage valve with pipe diameters changing as per the

stream order. 2.5cm diameter pipe was used for 6th order streams (River Mula & River Kas). 1.3 cm pipe was used for 5th order, 0.8cm for 4th order and 0.5 cm for 3rd order stream. The stoppage valve could be opened at 180 degree for full discharge. This was considered as the flood discharge for all the major streams. At 90 degree that valve could allow 50 % discharge and is considered as moderate flow and at 25 degree it allow 25% discharge and was considered low flow.

4) Setting for the channel configuration

Two settings were used for the channel configuration:

i) Type I

The first configuration consisted of two channels Mula and reduced length of tributary Kas stream from its source up to the junction. Left bank tributaries were given short length and treated insignificant source. This configuration was selected to observe the confluence dynamics of two major streams river Mula and River Kas. The Height of the channel thalweg of the river Mula at the model base is 0.59 m from the model base and same for River Kas is 0.70 m. Height at the junction is 30 cm and 1m downstream from the junction is 0.23 m from the model base. The main channel width of the Mula before the junction is 0.076 m and That of Kas 0.06 m. Maximum depth of the thalweg is 0.053m and 0.042 m respectively. Width at the junction is o.094 m with the depth of 0.041 m. downstream from the junction 0.09m and 0.043 m. Slope of river Mula up to the junction is 4.60 degrees up to the mouth is 4.47 degree. Slope of the river Kas from the Model Source up to the junction is 6.51 degree and up to the Mouth is 5.96 degree. Slope downstream from the junction is 4 degree.

ii) Type II

Model was shifted right. Main channel was dug at the place of river Kas and the tributary streams were given full length. River Kas was not included in this run.

Table 5.2 Specification for type II settings

Sl. No.	Parameters	River Mula	L. Budruk	J. Baleswar	K. wadi	S. gaon	Warandi
1.	Heigth at the Source	0.054 m	0.73 m	0.66 m	0.61m	0.58 m	0.52 m
2.	Junction Heigth		0.47 m	0.44 m	0.40 m	0.36 m	0.34 m
	Distance upto junction from source (Tributaries)		1.46 m	1.50 m	1.54 m	1.63 m	1.50 m
3	Distance of River Mula upto junction		0.67 m	1.34 m	1.98 m	2.38 m	3.03 m
4	Slope of Tributary		10. 09 degree	8.34 degree	6.29 degree	7.85 degree	6.84 degree

5	Slope of River Mula upto Junction	5.96 degree	4.28 degree	4.04 degree	4.32 degree	3. 77 degree

5. Sediments

Sediments were brought from the study area and classified into various size groups. Less than 5 mm, 5 mm - 10 mm, 10 mm – 20 mm and 20 mm – 30 mm. all the groups are painted with the oil paint. Yellow for the main stream and white for the tributary stream in type I configuration and Yellow for Mula, orange for Lahit Budruk (T_1), florescent for Jablebaleswar (T_2), white for Kangewadi (T_3), pale cream for Savargaon (T_4) and Red for Warandi(T_5) in Type II experiment.

6. Trail Run

Trail run are conducted in both the settings for absorption and infiltration of water in channel and to get acquainted with the flume Model. It was found in the trail run that, if the sediment size to the reduced scale was maintained, all the sizes were less than 5 mm in diameter and was easily washed away in the higher stages. Therefore, the maximum size of the sediment is kept at 30 mm and larger sizes are excluded to avoid blockage in the channel. The size less than 30 mm provided sufficient bed roughness and allowed the movement of finer particle in low run.

7. Actual Run

Type I

Before the actual run, the channel had sufficiently absorbed moisture from the trial run and was in the position to support the overland flow. The experiment started with the low flow and time observed. Confluence is closely monitored. Until the channel reached equilibrium at the low flow movement of the sediments were noted. When the channel reached the equilibrium stage numbered sediments ranging from 5 mm to 20 mm are introduced on the source of both streams. Second run is conducted with 50% flow from the stoppage valve. Bed configuration, sediment dynamics and the cross-sections are taken with video footage. Last run is conducted with 100% discharge of the stoppage valve. The changes in sediment position, cross-sections and the bed configuration are noted.

Type II

Similarly, this is conducted for River Mula and 5 left bank tributaries. Stoppage valve is not used for 3rd and 4th order streams.

8. Measurements

Velocity is taken for each run by floating pieces of wooden twigs. Bed configuration is measured and drawn on the plain paper at different time interval for each run. The distances travelled by the numbered sediments are measured and their three axes measured along with their weight. Distance travelled by the largest sediment of each color entrained is also noted along with their weight.

9. Analysis and interpretation

Size and shape analysis of the sediments are carried out.

Observation and analysis

A) Observation of Type I experiment

I) Low Flow

After the trial run both the channels are supplied with coarse to fine grain sand equally distributed on the bed. The bed is leveled without any undulations. Colored sediments less than 5 mm to 30 mm is distributed over the sand bed carefully avoiding the over clustering at any particular place. Larger particles are introduced towards the source and comparatively smaller are introduced nearer the junction. The bed at the junction and downstream are left with coarse sand leveled at every corner. Cross-sections at the specific sites before, on and after the confluence are taken with tape and ruler. Locations of larger particles introduced are noted. The first run is started with 25% discharge. This supposed to be the low flow condition of the experiment. The following observation is noted at different time interval:

1) Observation at 20 seconds

The tributary flow is concentrated towards the left bank before the confluence. At its mouth near confluence it takes right turn and bifurcates into two flows; one branch parallel to the right bank and the other towards the confluence of the main stream flow. This flow bifurcation leads to the formation of the tributary mouth bar extending towards downstream junction corner. The main flow enters the junction with active channel carved almost at the middle of the channel. At the confluence point, the flow immediately bifurcates into two branches. The left bank flow is parallel to the left bank downstream from the junction and the right bank flow towards the right bank to meet the right bank branch of the bifurcated tributary flow. The left bank flow again bifurcates into two branch at 50 cm downstream from the confluence where the right branch flow from the middle of the channel and the left branch follows the foot of the left bank wall. All the flow meets almost at 90 cm downstream from the confluence. Therefore, over all observation shows the condition of anabranching channels (Fig 1).

2) Observations at 58 seconds

The bifurcated tributary flow flowing towards the confluence point shows the sign of braiding. Mid channel bar can be noticed upstream from the junction on the main stream. After the junction the bifurcated left bank flow seems to close and the greater flow is concentrated on the right branch. It flows downstream for 50 cm and strikes the right bank wall and reflects to cut the channel from the larger elongated bar creating a broken point bar at the left bank which extends 50cm from the junction. Another such bar is seen at the right bank extending 50 cm to 90 cm downstream from the junction.

3) Observations at 3 minutes

The bifurcated left bank branch immediately downstream from the junction becomes active again. The broken point bar by the right branch joins again and becomes elongated mid channel bar. Therefore, at this point of time there are two major flows downstream from the junction with higher discharge on the right branch (Fig 3).

4) Observations at 10 minutes

The left bank branch downstream from the confluence becomes active with maximum discharge. The mid channel bar is converted into series of slanting sub-bars aligned to the tributary flow with minor rills separating them to join the activated left branch flow. Series of four parallel sub bars are noticed on the middle of the channel downstream from the junction. A minor part of the distributed right branch flow follows the right bank wall for almost 80 cm length downstream from the junction. This flow detaches the point bar extending 50 cm to 70 cm downstream from the junction and aligns the point bar to the slanting bars. This gives an impression that the size of these slanting bars increases downstream from the junction. Therefore there are total of five slanting bars.

5) Observations at 15 minutes

At this point of time some dynamics were observed at the tributary mouth. The right branch bifurcated flow at the tributary mouth is now closed creating the single tributary flow to meet the main flow at the junction. This creates the typical downstream junction bar at the downstream junction corner. The discharge to the bifurcated right branch flow remarkably reduces. Interestingly the total of five slanting bars is reduced to three larger bars with same alignment. Now the right bank flow has only two distributaries to join the left bank active flow. The amount of the discharge at the left bank flow increases than before.

6) Observations at 17 minutes

The width of the tributary flow before meeting the main flow increase eroding the bulge of the downstream junction bar. The eroded materials are not carried away rather deposited on a narrow strip across the right branch flow downstream from the confluence. This leads to total closure of this branch. Now there is only single flow downstream from the junction. Only the remnants of the rills are noticed on the elongated bar developed along the right bank (Fig 4).

7) Observations at 20 minutes

The flow seems to approach towards the equilibrium bed configuration at this constant low flow. At this point of time we can notice the following confluence characteristics: a) two major proximal flows converging to the junction. b) a triangular shape bar at the upstream junction corner 11 cm in length. c) elongated right bank bar form the right bank of the tributary mouth up to 90 cm downstream from the confluence. d) a narrow strip of a point bar formed at the right bank 50 cm downstream from the confluence

9) Observations at 50 minutes

No major changes took place for 26 minutes from the last dynamics. A mid channel bar could be noticed 20 cm before the confluence on the main channel (fig 10). A development of the bar 50 cm downstream from the confluence increased the channel width at that point. However the position of the two bars downstream was intact.

10) Observations at 2 hours

The channel reached almost at an equilibrium stage with the clear water flow. No major changes were observed. Slight widening of the channel took place at the position of the bar 50 cm downstream from the confluence. Bar at 70 cm downstream from the junction migrated 7 cm downstream followed by development of another minor bar at 87 cm downstream from confluence (Fig 5).

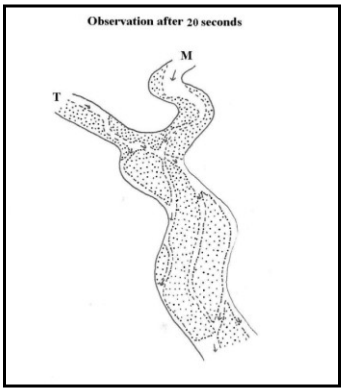


Fig. 1

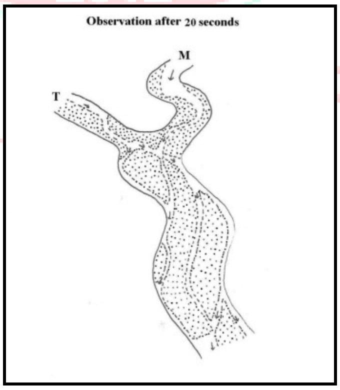


Fig. 2

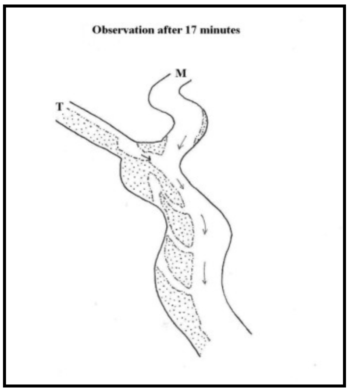


Fig. 3

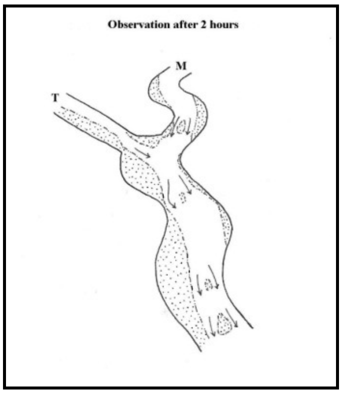


Fig. 4

11) Sediment dynamics at the low flow

Movement of the colored sediment less than (5 mm-30 mm) at the main stream and white (5 mm-30 mm) at the tributary stream is monitored during the run. Only the sediment less 5 mm diameter was seen entrained during the flow. Sediment greater than this diameter remained intact on their launched positions. Observation on the final bed configuration after two hours revealed following:

1. 16 cm bar at the upstream junction corner is composed of fine sediment mostly fine sand and clay. This did not show much change in shape at the constant low flow for two hours.

2. The bar at the downstream junction corner is composed entirely of white sediments less than 5 mm from the tributary channel at its upper half towards the tributary mouth. Downstream from the junction the sediment composition of two point bars and the minor mid channel bars showed heterogeneous composition of the sediments ranging from fine sand to the colored material.

II) Moderate flow

Moderate flow in the present flume experiment is supposed 50% discharge from the stoppage valve. As the potentially of the entrainment of the sediment increases at this flow, the entire channel is marked by flags at 20 cm distance. Green flags are used on the left bank and pink flag on the right bank from the model source to the mouth. The equilibrium bed of the 2 hr low flow condition is left undisturbed for the moderate run. In addition, numbered sediments ranging from 5 mm to 30 mm is introduced at the distance of 0 cm-20 cm in the source of both the channels.

1) Sediment dynamics

At the moderate flow sediment size between 5 mm and 15mm are entrained past the junction. The similar flow condition, similar size of the material and similar order of the stream, most of the aforesaid sizes flowed past the junction and is drained out of the model. However, at the later stages the input of the material from the tributary channel is comparatively less due to less channel width compared to the mainstream. Most of the sediment is trapped upstream in the tributary channel. However, there is dominant movement of aforesaid sizes from the main stream. The entire bed configuration is remarkably reduced and the eroded material drained out of the model.

2) Measurements

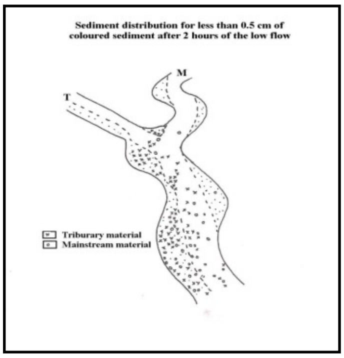
The distances travelled by the numbered sediments are noted along with their three axes.

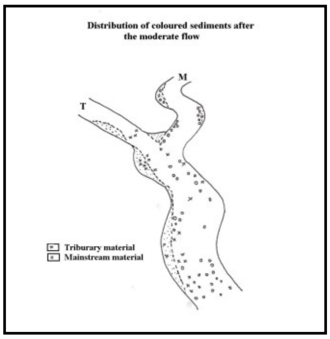
III) High flow

The equilibrium channel bed of 14 min moderate flow is left undisturbed. Flood flow in the present experiment is considered as the discharge from 2.3 cm diameter input pipe when the stoppage valve is fully open. The flow lasted for 4 min. sediment sizes ranging from 5 mm to 25 mm are entrained. Point bar at the main channel and the tributary channel before the confluence are formed of coarse sediments. Elevated flow is seen 70 cm downstream from the confluence due to the formation of mid channel bar. In spite of high velocity, the downstream junction corner is characterized by back circulation of water. This zone is characterized by deposition of fine material. Similar bar is noticed on the left bank downstream from the confluence. There is flow constriction on the confluence and marked increase in velocity. The flow velocity reduces 7 cm downstream from the confluence and bifurcates due to mid channel bar formed of coarse material. Unlike the low flow 80 cm bar was seen this time on the left bank. The maximum width of the bar is 16 cm and it is characterized by deposition of the fine material for first 50 cm of its length and heterogeneous coarse material for the next 30 cm. maximum with of the downstream bar is 13 cm with the width of constricted flow 11 cm. junction width id 26cm. width of the channel upstream from the channel at mainstream is 17 cm and tributary channel is 16 cm the length of the upstream junction corner reached to 9 cm and it becomes attached to the point bar formed on the main stream at the mouth of the junction .

1) Sediment dynamics

High proportion of the material is entrained to the junction of all the introduced sizes. The largest yellow material entrained past junction and deposited at the bar has diameter 2.51 cm and weight 124 gms. The largest white material entrained from the tributary channel deposited on the point bar downstream from the confluence is 2.9 cm weighted 186 .5 gms. Both yellow and white material of all the size are seen clustered at the 30 cm stretch of the point bar downstream from the confluence at the left bank . Huge quantities both yellow and white but smaller than sizes deposited at the bar is entrained out of the model. The active channel flow is shifted to the right bank contrary to the left bank active flow of moderate and the low stage.





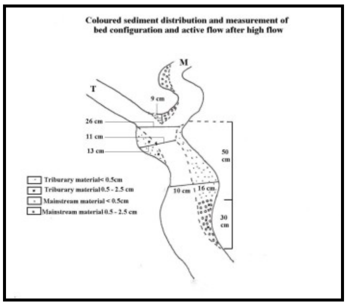


Fig 5 Fig. 6 Fig 7

2) Measurements

Measurement is taken for the velocity downstream from the junction, before the junction and for the full length from model source to end. Distances travelled by numbered sediment are noted.

IV) Shape analysis of numbered sediments

A group of sixty colored sediment samples random in shape but between 0.5 to 3 cm diameters are introduced to tributary stream and the main stream before the run. The entire channel is graduated with flags 20 cm apart (Pink flags for the left bank and Green flags for the right bank). During the low flow samples less than 0.5 cm diameter are entrained. There is no movement of numbered samples from both the channels.

During moderate run some movement though not significant is observed. On the tributary channel, 18samples remained in the launched position between 0 cm-20 cm. 29 samples travelled to 20 cm-40 cm distance, 4 samples between 0.5 cm and 1 cm diameter reached 60 cm-100 cm distance.

Similarly of the Main stream, out of 60 numbered samples, 33 samples of all sizes (0.5 – 3 cm) remained in the launched position on 0 cm-20 cm distance. 7 samples between 0.5 cm and 1 cm travelled to 80 cm to 100 cm distance. No samples reached the confluence zone. However, no measurements were taken.

During the high stage, significant movements of the numbered samples are noticed. Therefore all the sediments are measured and detailed analysis carried out (fig 10 & 11).

From the following conclusions can be drawn from the observation

1. Out of 60 numbered samples of random shape and diameter between 0.5 and 3 cm only four samples from the tributary channel is entrained past the junction whereas 27 samples

from the main stream crossed the junction. This is due to sediment trapped at the turn on the tributary channel 160 – 200 cm distance. Secondly, the width of the tributary channel is less than the main stream. The greater width allowed the main stream material to move freely.

2. The Mean diameter of the mainstream numbered samples that travelled past the junction from the main stream is 1.2 cm and that of the tributary stream also is 1.225 cm. This shows there is not much difference. However, the largest unnumbered white coloured sample (tributary) collected from the point bar 70 cm downstream from the confluence has diameter 2.9 cm and weighted 186.5 grams in spherical shape. The largest unnumbered Yellow colored (Main stream) sediment collect from the same location had diameter of 2.5 cm and weighted 124.5 grams in spherical shape. This showed in spite much larger sediment trapped at the turn at 160 to 180 cm distance tributary stream had more competence than the main stream.

3. Out of total samples that flowed past the junction from the tributary stream all the samples are in spherical and roller shape. However, out of total samples that flowed past the junction from the main stream 18 samples are spherical, 6 samples are of disc shape, 2 roller and1 bladed.

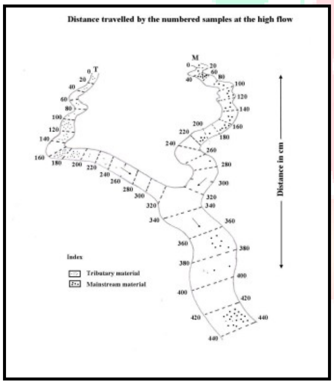
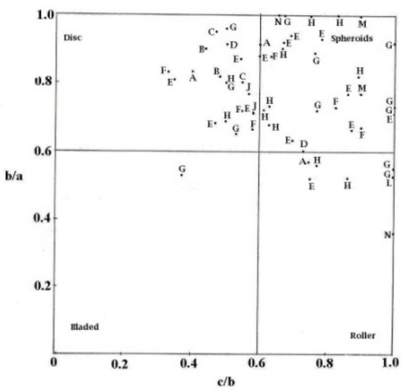


Fig. 8 Distance travelled by numbered sediments



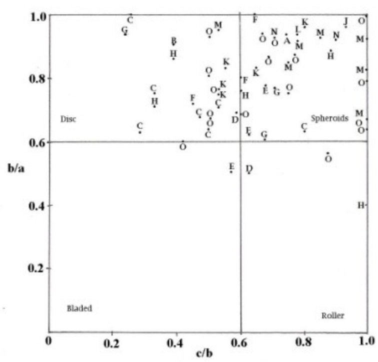


Fig. 9 Shape analysis of Tributary Sediments Fig. 10 Shape analysis of Mainstream Sediments

V) Findings and Discussions

The first experimental study of dynamics on the river confluence revealed following facts

1. The channel took exactly one hour to reach the equilibrium condition after the low flow. After which there is no change in bed forms at constant low flow.

2. Maximum transportation of materials is observed at the moderate flow. The size of the bed forms on and after the confluence reduced in size.

3. Bars at the confluence are formed at the opposite bank during the high stage. At the similar junction angle and similar channel geometry, albeit at the reduced scale, we can conclude that the bar observed at the Mula-Kas confluence towards the left bank downstream from the confluence is formed by the flood discharge. The coarseness of the bar materials increased. Stretches' of exposed bank and alternative deposition of coarse materials is observed at the stretches before the confluence signifying the pool riffle sequence.

4. Typical flow characteristics at the confluence zone cited in the literature by Best et al, (1987, 1988, 1996 etc.) is observed at the high flow.

5. The observation of sediment entrainment revealed that the tributary channel had higher competence at the high flow due to increase channel gradient (inferred from the largest white material collected from the bar downstream from the confluence zone). Due to greater channel gradient but less width at the source of the tributary, spherical samples were more easily entrained than the tabular ones. Main stream due to greater width had the greater capacity than the tributary and proportionally entrained materials of all shapes and sizes but lesser in size than the largest tributary material collected from the bar downstream from the confluence.

VI) Limitations

1. Due to the smaller size of the source tank (300 liters), we could not sustain the moderate and high flow discharge for longer duration.

2. Due to lesser channel width of the tributary channel most of the material remained on the channel upstream from the confluence and became saturated at the turn upstream from the confluence. Therefore, no materials were entrained from the tributary channel after sometime in the high flow.

3. The flow from the smaller tributaries was not incorporated.

4. Due to drastic reduction in the scale small distance in the model means large distance at the field. This could not explain the exact field condition in the model.

B) Observations of Type II experiment

Channel configuration settings were changed during the type II experiment. It was configured approximating the channel characteristics of River Mula and its five left bank tributaries (3rd order to 5th order) with varying junction angle and channel gradients observed on the field upstream of Mula Kas junction. River Kas is not included in this experiment. The main objective was to notice the formation of tributary mouth bars and slack water deposits at the mouth of these lower order minor confluences. Controlled discharge was operated for the main stream and the 5th order tributary, whereas the discharges for 3rd and 4th order streams were left constant due to smaller pipe diameter. Similar to experiment I, trial runs were conducted for channel stabilization. Starting from the source different coloured sediments are introduced upstream form the junction for all the channels. As the number of junctions is increased to five, minute observation like experiment I was impossible at a time. Possible major changes are noted at the junction at different time interval.

I) Low flow

As these seasonal tributary streams contributes negligible impact to the junctions at low flow, less and constant discharge was operated. Similarly, the mainstream and the 5th order tributary are also adjusted to low flow (25 % discharges). Following changes are observed at different time interval.

1) Observation at 3 minutes

Bar is formed at the downstream junction corner, at the confluence of tributary 1 (T_1). Similarly, the tributary deposits spread in fan shape on the main stream at confluence of tributary 2 (T_2). Mid channel bars are formed on the main stream downstream from the T3 and T4 confluences zone. No dynamics occur at confluence of T_5.

2) Observation at 5 minutes

Bar at the downstream junction corner is eroded at T_1 confluence with the formation of mid channel mouth bar and flow bifurcation at the mouth. The fan shaped mouth bar earlier observed at T_2 is eroded from the left bank with the formation of bar attached to the upstream junction corner with more of its extension towards the tributary channel. Now a significant mouth bar is noticed at the confluence of T_3 followed by the formation of point bar on the main stream opposite to the bar at the main channel. This led to the constriction of main channel flow. The mid channel bar formed downstream from the T_3 confluence on the main stream migrates towards the mouth of T_4 almost blocking the tributary flow. No dynamics occur at T_5 confluence.

3) Observation at 10 minutes

The mid channel mouth bar at the confluence of T_1 disappears. There is again formation of mouth bar at the T_2 junction along with the elongated point bar on the mainstream opposite to the junction. The size of the mouth bar at the T_3 junction grows in size, which leads to the erosion of the point bar opposite to the junction which slightly migrates upstream. A significant mouth bar is now noticed at T_4 junction. Large point bar is noticed before T_5 junction constricting the main channel flow towards the tributary mouth.

4) Observation at 15 minutes

Channel width at the downstream segment of T_1 junction increases in size with the narrow lateral bars on either side of the channels. The attached mouth bar with the left bank lateral bar segregates itself to the tributary mouth with the erosion of extension towards the main channel. Mouth bar at the T_3 junction remains unaffected; however, the point bar opposite to the mouth bar on the right bank increases in size. This results in the constriction in the width of the active flow at the mouth of T_3 junction. Mouth bar at the T_4 junction slightly reduces in size due to erosion of its extended segment by the main flow. Large laterally spreading mouth bar is noticed on T_5 junction and immediately starts to be eroded by the constricted main flow due to bar opposite to the junction.

5) Observation at 20 minutes

There is downstream migration of the right bank point bar downstream T_1 junction; however its left bank counterpart remains unaffected. The back water deposits at the mouth of T_2 junction is again eroded by the tributary flow from the left bank. Part of the bar remains as the upstream junction bar and eroded material are deposited as lateral bar extending downstream from the downstream junction corner. The Mouth bar at the T_3 junction drastically reduces in size. Also there is erosion of extended point bar opposite to this junction. This increases the earlier constricted flow at this channel position. The mouth bar noticed at the mouth of T_4 junction is eroded from the left bank. This lead to the formation of an extended upstream junction bar tapering downstream towards the confluence. The mid channel bar earlier noticed slightly upstream from the junction at this point migrates to the downstream direction. The tributary mouth of T_5 junction disappears with the mid channel bar at the downstream segment.

6) Observation at 25 minutes

The confluence zone of T_1 appears to be almost stable with the clear water flow. The eroded material from the right bank point bar deposits as the mid channel bar exactly at the T_2 junction. Therefore, the main channel flow is bifurcated at this point. An upstream junction bar attached to the narrow left bank lateral bar of the main stream is again noticed at T_2 junction. An elongated point bar is formed opposite to T_2 junction. Small upstream junction bar is noticed at T_3 junction. All the materials at the mouth noticed earlier are carried downstream and joins the upstream junction corner of T_4 increasing its size. A mid channel bar is noticed on the main stream at T_5 junction.

7) Observation at 30 minutes

The mid channel bar and the dynamics observed at the T_2 junction all disappears. There is slight migration of the point bar downstream formed opposite this junction in earlier observation. The elongated upstream junction bar slightly increases in length at T_4 junction. Series of Mid channel bars noticed past T_4 junction.

8) Observation at 45 minutes

Erosion of the right bank of the main stream is noticed at T_1 junction due to the formation of the mid – channel bar extending to the confluence zone from the upstream. The minor left bank bifurcated flow meets the tributary flow and the major flow of the mainstream follows right bank. Major point bar is formed opposite to T_2 junction with the mainstream flow flowing from the left bank. This leads to the slack water deposits at the mouth of the T_2 junction. Smaller point bar is noticed before T_3 junction on the right bank of the main stream.

Bar at the downstream junction corner extends downstream from the T_3 junction and the merges with the upstream junction bar of T_4 junction. The earlier noticed extension of this bar reduces in length. Similarly the bar at the downstream junction corner at T_4 tributary merges with the upstream junction bar at T_5 junction. The formation of this bar leads to the migration of the confluence zone almost 20 cm downstream from the junction point.

9) Observation at 50 minutes

Mid channel bar at T_1 junction is eroded and joins the lateral bar and leads to the formation of minor bars downstream from this junction. A Mid channel bar is now seen upstream of T_2 junction which bifurcates the flow equally into two parts. The bifurcated Left bank flow meets the tributary flow. This flow enters the tributary mouth and leads to slack water deposits along with small bar extended downstream from the corner of T_2 junction. A slack water deposit is seen also at T_3 junction. The dynamics of T3 and T4 remains unchanged.

10) Observation at 2 hours

This observation is taken after 2 hours when the channel was totally stable at the given discharge condition. The final channel configuration at the two hour runs are as follows:

1) No mouth bar formation except the slack water deposit at the left bank mouth of T_1 confluence. **2)** A mid channel bar 8 cm × 9 cm upstream from the junction at the mainstream and the extended downstream junction bar (21 cm) towards downstream direction in T_2. Width of the active flow at the junction is 7 cm. Slack water deposits are noticed. **3)** Point bar is noticed in opposite side of T_3 junction with 21 cm length along with Slack water deposits. **4**) 15 cm × 6cm tributary mouth bar is formed at T_4 junction with10 cm width of the active main flow.**5)** Extended upstream junction bar 14.5 cm from the upstream junction corner of T_5, along with 21 cm × 7cm point bar on the opposite side of the junction. Width of the active flow is 11 cm.

II) Moderate flow

The moderate flow is operated with the 50% discharge of the main stream and 5th order tributary. However, the discharge for the tributaries with 3rd and 4th order is kept constant. There is more movement of mainstream material and the material from the 5th order tributary. There is maximum transportation of material from the main channel. Two mouth bars are noticed at T_2 and T_3 junctions with junction angle 90 degree and 105 degree respectively. Sediments up to 1.5 diameters are entrained up to the model end. All the transported materials are deposited downstream from the T_5 junction. The links between the tributary junctions become clear of sediments with exposure of bed.

III) High flow

The high flow is operated with 100% discharge of the mainstream with the constant tributary discharge. The run lasted for 10 minutes. All the colored materials launched at the source are entrained. Much of this coarse material up to 3 cm diameter is tapped by the extension of mouth bars formed at T2 and T3 junction. However the bed of the main stream at T_4 and T_5 junction seem to be lowered due to erosion therefore the tributary material remained on the bed higher than the main stream bed. All the material entrained are deposited at the bar formed downstream of T5 junction.

IV) Discussion and findings

As there is only major variation in discharge of the mainstream, much of the materials entrained are from the main stream. The tributaries are given low and constant discharge. The material entrainments from the tributaries are only noticed at low flow condition until their channel reached in equilibrium condition. At the constant flow, their channel became stable for moderate and high flow run; therefore, no sediments were entrained. This is the actual condition at the field were the main River Mula dominates the channel discharge during the flood (with its source at the high rainfall zone of Maharashtra) and tributaries towards the east falls on the rain shadow area supporting very less discharge. At this normal condition the tributary channel remains dry and sediment laden. Slight increase in rainfall in the catchment due to local disturbances may produce flash flood where the tributary material is deposited as the extended mouth bar at the junction (T_2 and T_3 junction in the experiment). When this is followed by the higher discharge condition on the main stream these mouth bar obstructs the main flow which may result in the formation of the pool upstream from the junction. This typical condition is noticed at the Palshi junction on the field.

The overall findings of the Type II experiment are as follows.

1) The complex system of channel adjustment is noticed when considered for series of junctions in downstream direction. Formation of mouth bars and its disappearances, migration of point bars, and their dynamics in size revealed that the material brought by the tributaries are first deposited as the mouth bar or the downstream junction bar. The bar noticed at the upstream junction corner is the broken attachment of the tributary mouth bar. All the materials brought by the tributary are not deposited only at the downstream junction bar, however, at the lateral bar formed downstream from the downstream junction corner. These material stay semi-permanently on these lateral bars and are subsequently eroded and deposited to the mid channel bar downstream.

2) The slack water deposits are occurrences noticed at the junctions with greater than 90 degree junction angle. However, all the asymmetrical junctions with greater than 90 degree junction angle may not experience slack water deposits. The possible conditions for slack water deposits as observed in the experiment are as follows;

i) Formation of the mid channel bar before the confluence with flow bifurcation and the major flow towards the bank where the tributary joins the main stream. This constricted flow has greater velocity and enters the tributary mouth at the point of the angle at the downstream junction corner. Some flows enter the tributary stream which later on circulates back with the tributary flow. This portion of the flow entering the tributary flow deposits the main stream material (mostly finer) leads to slack water deposits at the upstream segment of the tributary mouth from the downstream junction corner.

ii) Formation of point bar on the main stream on the opposite side of the junction. When this point bar erodes due to flow dynamics from its upstream end, detached material laterally deposits to its downstream segment. This increases the width of the point bar towards the main channel. The increase in the width of the point bar opposite to the junction constricts the main channel flow and directs the flow towards the tributary mouth where some flow enter the tributary mouth and deposit the material. However, in former, if the major bifurcated flow is away from the tributary mouth the chances of slack water deposits diminishes.

iii) It is formed if there is a flood condition on the mainstream and insignificant flow on the tributary channel. Sudden increase in the width at the confluence zone may allow greater transportation of material from the confluence which might temporally increase the bed elevation at of the mainstream at the confluence. This allows the mainstream material to enter the tributary mouth. However, this unstable condition is quickly adjusted by the deposition of tributary material at the mouth and upstream to attain the new equilibrium at the temporally elevated main stream bed. The lower stages of the flow at the mainstream cuts the deeper channel or channels to abandoned the flood course as the bar surface.

3) At the lower junction angle (34 degree in case of T_5) a parallel bar starting from the upstream junction corner or the continuation of the point bar of the main stream merged with the upstream junction corner is formed extending downstream from the confluence, which separates the tributary and the main flow for some distance downstream the junction before the flow merges. This condition is noticed for T_5 junction at low and moderate flow.

V) Limitations

1. It was very difficult to observe the dynamics at all the junctions at a time when considered for series of junctions downstream. The dynamics at one junction affected the channel downstream.

2. Sediment dynamics could not be observed as the tributaries became stable at the constant flow for higher stages of the main river.

REFERENCE

Ashmore, P.E. 1993: Anabranch confluence kinetics and sedimentation process in gravel bed streams. Publication of geological society of London 75, 129-146.

Ashworth, P.J. 1996: Mid channel bar growth and its relationship to local flow strength and directions. Earth surface process and landforms, 21, 103-23.

Benda, L., Andras, K., Miller, D. and Bigelow, P. 2004b: Confluence affects on rivers: interactions of basin scale, network geometry, and disturbance regimes. Water Resources Research, 40, W05402.

Best, J.L. 1986: The Morphology of river channel confluences. Progress in Physical Geography, 10, 157-74.

Best, J.L. 1988: Sediment transport and bed morphology of river channel confluences. Sedimentology, 39, 797-811.

Biron, P.M., Best, J. L., Roy, A.G. 1996: Effects of bed discordance and flow dynamics at open channel confluences. Journal of Hydraulic Engineering, 122, 676-682.

Biron, P., Roy, A.G., Best, J. L. and Boyer, C. J. 1993: Bed morphology and sedimentology at the confluence of unequal depth channels. Geomorphology, 8, 115-129.

Bradbrook, K.F., Lane, S. N, and Richards, K.S. 2000: Numerical simulation of three-dimensional, time-averaged flow structure at river channel confluences. Water resources research 36, 2731-2746.

Bradbrook, K.F., Lane, S. N., Richards, K.S., Biron, P.M, and Roy, A.G. 2001: Role of bed discordance at asymmetrical river confluences. Journal of Hydraulic Engineering, 127, 351-368.

Ferguson, R.I. and Ashworth, P.J. 1991: Slope induced changes in channel character along a gravel bed stream; the Allt Dubhaig, Scotland. Earth Surface Process and Landforms, 16, 65 -82.

Ferguson, I.R., Cudden, R.J., Hoey, B.T. and Rice, P.S. 2006: River system discontinuities due to lateral inputs: generic styles and controls. Earth Surface Process and Landforms, 31, 1149 – 1166.

Gupta, A. 1975: Stream characteristics in eastern Jamaica, an environment of seasonal flow and large floods. American Journal of Science, 275, 825 – 847.

Joingxin, Xu. 2001: Adjustment of mainstream – tributary relation upstream from a reservoir: An example from the Laohahe River, China. Z. Geomorph. N. F, 45, 359-372.

Kale,V. S. 2002: Fluvial Geomorphology of Indian Rivers, Progress in Physical Geography, 26, 400-433.

Knighton, A.D. 1973: Variations in width – discharge relation and some implication for hydraulic Geometry. Bulletin of Geological Society of America, 85, 1069 – 76.

Knighton, A.D.1975a: Variation in at a station hydraulic Geometry. American Journal of Science, 275, 186-218.

Komar, P. D. 1987: Selective gravel entrainment and the empirical evaluation of flow competence. Sedimentology, 34, 1165-1176.

Lane, S. N. and Richards, K. S.1995: Morphological estimation of the time integrated bed load transport rate. Water Resources Research, 31, 761-722.

Leopold, L. B. and Maddock, T. 1953: The hydraulic geometry of stream channels and some physiographic implications. United State Geological Survey Professional Paper, 252, 56.

Leopold, L. B. and Miller, J. P. 1956: Ephemeral streams – hydraulic factors and their relation to drainage network. United States Geological Survey Professional Paper, 282 A, 36.

Lubowe, J. K. 1964: Stream junction angle in the dendritic drainage pattern. American Journal of Science 102, 325-339.

Mosley, M.P.1976: An Experimental Study of Channel Confluences. Journal of Geology, 84, 535-62.

Mills, H.H. 1979: Downstream Rounding of pebbles – A Quantitative Review, Journal of Sedimentary Petrology, 49, 295-302.

Morisawa, M. E, 1962: Quantitative geomorphology of some watersheds in the Appalachian Plateau. Bulletin, Geological Society of America, 73, 1025-1046.

Mosley, M.P. and Schumm, S.A. 1977: Stream junctions – a probable location for bedrock placers. Journal of Economic Geology, 72, 691-697.

Osterkamp, W. R. 1978: Gradient, discharge, and particle size relations of alluvial channels in Kansas, with observation on braiding. American Journal of Science, 278, pages 1253-1268.

Rhoads, B.L. 1987: Changes in stream channel characteristic at tributary junctions. Physical Geography, 8, 346-361.

Rhoads, B. L. and Kenworthy, S. T. 1995: Flow structure at an asymmetrical stream confluence. Geomorphology, 11, 273-293.

Rice, S. 1998: Which tributaries disrupt downstream fining along gravel-bed Rivers? Geomorphology, 22, 39-56.

Rice, S.1999: The nature and controls of downstream fining within sedimentary links. Journal of Sedimentary Research, 69, 32-39.

Richards, K. S, 1980. A note on changes in channel geometry at tributary confluences. Water Resources Research, 16, 241-244.

Roy, A. G. and Bergeron, N. 1990: Flow and particle paths at a natural river confluence with coarse bed material. Geomorphology, 99, 99-112.

Roy, A.G. and Woldenberg, M.J.1984: A model for changes in river form at channel confluences. Journal of Geology, 94, 402-411.