INTERRELATIONSHIP BETWEEN RIVER SEDIMENTATION AND MEANDERING: A CASE STUDY OF GANGA AT VARANASI

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ABSTRACT

Concave side meandering damages cities, agricultural land and hydraulic and other structures. These damages are the function of convex side sedimentation of river. The maximum height of sedimentation occurs in the zone of separation which creates the adverse longitudinal gradient in the sand bed as compared to that of the stream. The static sand bed on convex side continuously changes its friction; form and pressure drag forces responsible for increasing concave side depth of water and position of point of maximum depth at concave side. This is intensified with the increase in distance downstream. The inter-relationship between sedimentation and erosion in the case of the Ganga at Varanasi and in the laboratory flume having two 180^0 consecutive bends of the reverse order is presented. It has been found that as the depth of sedimentation increases with the increase in distance downstream the depth of maximum erosion on the concave bank side increases and its location shifts closer to the bank. Thus, the maximum depth of erosion at concave side and its location from the concave bank corresponds to the maximum height of sand bed at convex side.

Keywords: Meandering; Sinuosity; Sedimentation, Erosion; Separation zone.

Introduction

Meandering damages significant areas of valuable agricultural land. Millions of people are affected by changing courses of rivers. The main factor, responsible for molding the behavior of a river, is the sediment that is transported in the river. Erosion and deposition are related to the velocity vector. A river has bends having stable and unstable zones. In curvilinear flow secondary currents develop due to centrifugal force that acts upon the fluid filaments, and produce super elevation on the water surface. The two zones of a bend have their initiation points, termed nuclei of the zones. The nucleus of sedimentation is formed due to the formation of separation pocket, causing the variation in drag forces. On a bend, heavy deposition takes place on the convex bank, causing the deflection in the velocity vector towards the concave bank. Thus, the convex side of a floodplain is stable and the outer-half portion of the concave side is unstable. The river laterally moves on this side, resulting in meandering and valuable land is eroded. Streamlines converge near the convex bank and diverge near the concave bank. The velocity vector shifts towards the concave bank and is, thus, responsible for erosion, causing the advancement in meandering. Due to the large sedimentation and undulation in sand deposition, the deflection in velocity vector becomes more pronounced. Hence, there is a loss in the kinetic energy, causing an increase in the potential energy, i.e., flood/ inundation height on one hand and meandering the other.

In laboratory experiments conducted in a stable curved channel with two consecutive 180^0 bends, **Lawrence (1997)** found that maximum deposition took place in the region downstream of the flow separation zone. He also found that coarse sand got deposited on the convex bank side of the first bend between 90^0 and 180^0. This is the region of active secondary currents and zone of separation where sediment deposition is initiated. **Bhowmik and Choudhary (1998)** discussed that the principles behind hydraulic structures for reducing the maximum velocity occurring near the bank and diverging of concentrating stream lines were not in accord with the principle of conservation of balanced dynamics of the stream, momentum balance equation between the upstream and downstream of the structure and principle of induction of gradual resistive forces. **Kuhnle et al. (2002)** performed laboratory experiments in a channel 30 m long, 1.2 m wide, and 0.6 m deep to test three spur dike angles in order to determine the one which would yield the maximum volume of associated scour hole and minimum potential for bank erosion.

Discussing the inter-relationship between concave and convex banks **Choudhary (2003)** concluded that the increase in sand bed on the convex side of the river would increase the maximum depth of erosion on the concave side. **Choudhary and Jha (2004)** showed that the river course is the path of least resistance, the sinuosity increased with the increase in the drag force of the sand bed, and the nucleus of sedimentation was the foundation for the theory of meandering. Flood-plains of convex and concave banks of a river are interrelated, as **Choudhary et al. (1996)** showed for River Ganga at Varanasi, India.

Bank erosion consists of two processes: basal erosion due to fluvial hydraulic force and bank failure under the influence of gravity (**Jennifer, 2005).** Because the bank resistance force varies with the degree of saturation of bank material, the probability of bank failure is the probability of the driving force of bank failure being greater than the bank resistance force. Since the degree of saturation of the bank material increases with river stage, the frequency of bank failure is correlated to the frequency of flooding.

Aberle et al. (2006) stated that the stepwise increase in flow velocity is related to the rate of erosion at the beginning. Erosion is also a function of heterogeneity of the bed. Field data showed an exponential decay in the rate of erosion with time that is indicative of depth-limited erosion. **Fox et al. (2006)** showed that erosion by lateral subsurface flow was known to erode stream bank sediment at numerous geographical locations; however, the role of seepage erosion on mass failure of stream banks is not well understood. **Debnath et. al. (2007)** discussed field data on cohesive sediment erosion with particular focus on partitioning the total erosion into re-suspension and bed load.

Integration of the findings of different investigations and consideration of the order of magnitude of various parameters on erosion suggests that sedimentation defines the erosion of the river bank and the process of meandering. In the present paper, field and laboratory data relating sedimentation and meandering are presented. Employing field sediment data for maximum height of deposition and its location for different sets of bends, one can establish an empirical relationship for maximum depth of erosion and its location on the concave side. This relationship may help demarcate the meandering zone and may define conditions for sand bed meandering management.

Material & Methods

Field observations

A 6.58 km long curved path of the Ganga at Varanasi, India, was selected for investigating sedimentation and erosion. Whole path was divided into eleven sections. The sections and their names and the distance between bathing *ghats*- are mentioned in Table 1. All these *ghats* are situated on the concave bank of the river. *Samne Ghat* (on section (1-1)) is situated on the upstream end of the Ganga bend and *Prahlad Ghat* (on section (11-11)), is situated on the downstream end of the bend.

At each section, the depth of river and elevation of sand bed were measured with respect to water level, a line of sight was fixed approximately perpendicular to the direction of flow with the help of ranging rod. The depth was measured by traditional method in that a heavy stone piece was allowed to fall with the use of a rope. When the stone reached near the bottom, rope was tightened to ensure an accurate measurement. The length of the rope was measured with the use of a tape. The depth of river was measured along the line of sight at least 10 to 15 points at a section and graph was constructed between depth and location.

On the other hand, the elevation of the sand bed was measured along the line of sight. The staff reading of surface of water level was also noted down so as to calculate the elevation of sand bed with respect to water level and the staff intercept gives the distance of the staff station from the instrument station. The data were collected during the month of April. In this month the flow velocity becomes low; hence it was easy to have the boat stay in the flow during measurement. Cross-sectional profiles of different *ghats* are shown in Table 4.

Laboratory experimentation

Experiments were performed in the Hydraulics Laboratory of Department of Civil Engineering, IT, BHU. The laboratory channel was rectangular having two consecutive bends of the reverse order. The channel was one meter wide, 22.5 cm deep, central radius 1 m and central angle of 180^0 each. The bends were connected with a stilling basin, and the upstream straight reach 6.5 m long, a downstream straight reach 4.5 m long and side channel conveying water for recirculation into the ground tank. The water for circulation was drawn from an underground tank with a centrifugal pump. The flow depth was controlled by a tail gate over a weir at the end of the downstream reach which was so positioned as to produce roughly a uniform flow along the bends and the fixed discharge. Each cross section of the bend was identified by its respective angular position. In the upstream straight reach, it was identified by the distance from the beginning of the first bend, and in the downstream one by the distance from the end of the first bend, respectively. The schematic layout of the experimental channel with flow circulation system is shown in Fig. 1.

Sand was fed by spreading the sand uniformly to a depth of 10 cm manually. The pump was started and the water was allowed to run in the channel. Discharge in the channel was adjusted with the use of a controlled valve of the pump. Then the gate located at the downstream end of the channel was adjusted to get uniform flow downstream in the straight channel at a regular depth. The Froude number and B/h_0 ratio were found to be 0.28 and 10.0, respectively. The flow has an average velocity of 0.28 m/s and discharge of 37.8 l/s (0.0378 m^3/sec) and was observed from a graph of depth over a rectangular notch against discharge fitted at the end of the side channel. The discharge was allowed to run through channel for 4 hours. This flow condition was maintained constantly throughout the experiment. Fig. 2 shows erosion and deposition taking place in the laboratory channel.

The top of leveled 10 cm thick sand bed was measured with the help of a point gauge at 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 cm, respectively from the inner bank (i.e., convex bank for the first bend and concave bank for the second bend) and recorded for each section. The pump was started. Water was allowed to run for four hours over the mobile bed. The pump was stopped after four hours and the water was allowed to drain completely. The top level of the bed formed was measured and recorded. The difference between the top bed level after four hours of run and initial flat bed (top level of the sand bed before flow in the channel) was calculated. A positive value showed deposition and negative value erosion. Width of sedimentation at different sections was measured in radial direction with the help of scale.

Tables 2 and 3 give the values of erosion and deposition at different sections. Patterns of erosion and deposition versus width of the meandering channel at 0^o, 30^o, 60^o, 90^o, 120^o, 150^o, and 180^o are shown in Fig. 3 for the first bend and in Fig. 4 for the second bend. The concave bank is eroded and the deposition takes place on the convex bank. This phenomenon is responsible for the instability of the channel.

Laboratory Results and Discussion

Starting from 0^0 of the first bend and up to 180^0 of the second bend, data were collected from experimentation in the laboratory meandering channel. The general pattern of erosion and deposition plotted in Fig. 3(a) at 0^0 in the first bend showed that erosion was maximum near the convex side and the depth of erosion reduced towards the concave side. This is due to higher longitudinal velocity at convex side (Choudhary, 1974). From the mid point of the width onwards, deposition of outer half portion grew slowly. This pattern showed the lateral movement of the sand bed from the convex side to the concave side. This indicates the growth or development of centrifugal forces in the straight approach channel.

The general pattern of erosion and deposition at 30^0, plotted in Fig. 3(b), showed that erosion was maximum near the convex side and the depth of erosion reduced towards the concave side. From the midpoint of the width, deposition in the outer half portion grew slowly. This pattern shows the lateral movement of the sand bed from convex to concave. This indicates that centrifugal force was fully developed in the meandering channel.

The general pattern of erosion and deposition at 60^0 , plotted in Fig. 3(c), showed that on the concave side of the bend continuous deposition broke in the form of strips at 60^0. The extent of strips increases towards the convex side with increase in θ. After 60^0 the continuty of strips breaks and after 90^0 they disappear altogether and there is no further deposition on the cancave side.

From Table 2 & Fig. 3 at 90^0 it was observed that complete erosion had taken place from 50 to 100 cm of the width of channel. Deposition height near convex side increased sharply at 90^0 as compared to the previous 60^0 section and reaches from 6.6 to 12.2 cm. Further it continues to increase & becomes maximum at 180^0 (at the end of first bend) of value 14.2 cm. The width of erosion decreased from 50 cm at 90^0 (Ist bend) to 41 cm at 120^0 and width of deposition increased to 61 cm at 120^0 as compare to 50 cm at 90^0.

The sediment deposition pattern demarcates the zones of erosion as well as deposition of the sand bed found in the bend region. This demarcation is due to the well developed radial components of velocity from outer bank side to the innner bank side in the bottom region responsible to get the sediment accumulated near the convex side. Direction of radial component of velocity from outer bank side to the innner bank side in the bottom region is due to lateral hydrostatic pressure created on account of the rise in the water surface on the concave bank side (Choudhary (1974), Choudhary et al. (1977)).

Enhancement in the deposition after 90^0 of the first bend indicates the more active role of low or reversed flow zones developed and situated at 150^0 near convex side of the first bend. The zone of seperation affects upstream as well as downstream sections of the first and second bend. In the case of river this is the zone of erosion at concave side. The deposition on the convex bank up to 30^0 of the second bank does not occur because the sediment deposited on the convex bank side of the first bend and the adjacent concave bank of the second bank generate high momentum in the fluid moving around the convex bank of the second bend.

Results and discussion of field observations

Cross-sectional Profile

The cross-sectional profiles of river at Section1-1(Samne Ghat) and Section11-11(Prahlad Ghat) are shown in Figs. 5 and 6. The river width, the maximum water depth with respect to water level and its location from the concave bank, the maximum elevation of sand bed with respect to water level, the distance of maximum elevation of sand bed from convex bank, and the width of sand bed are shown in Table 4. These results reflect stream line convergence on the convex bank side and the consequent growth in centrifugal forces, resulting in a lateral shift of the maximum depth towards the concave side.

Maximum river depth versus maximum sand bed elevation

Figure 7 shows the variation of sand bed elevation vs. maximum river depth from Samne Ghat to Prahlad Ghat. It shows that as distance increased in downstream height of sand bed increased. In the beginning the rise in elevation had a lower gradient but as the sand bed entered in the high degree curvature zone the growth in sand bed elevation rose at a faster rate. As the distance approached the downstream end portion the rate of sedimentation became highest. This zone of the Ganga at Varanasi exists between Dasaswamedha Ghat to Prahalad Ghat. In between Gai ghat and Prahalad ghat the sand bed had maximum R.L.

This result shows that a zone of separation existed in the vicinity of Prahalad Ghat section on the convex side. Thus the complete result of sedimentation showing the adverse gradient in the sand bed is a function of separation pocket located at the downstream end of the river bend on the convex side of the floodplain. As the distance increases from this zone in the upstream side the sand bed slope & height decreases and the R.L. of sand bed decreases. Thus, the separation zone in general is setting up the condition for the adverse sand bed gradient and its different slopes. The figure further shows that as the height of the sand bed increases on the convex side proportionately the depth of water on the concave side also increases. Also the position of the maximum depth of water in a section becomes closer to the concave side. Near Prahlad Ghat the point of maximum depth of water is closest to the concave bank and its value is 16.2 m. On the same section the R.L. of the sand bed was found to be maximum.

Maximum river depth versus the distance of maximum depth from concave bank

In Figure 8 the maximum depth of water and its location from concave bank side is presented. The maximum depth of water increased with the distance in downstream and its location became closer to the concave bank. This may be attributed to the growth in sand bed causing deflection in streamlines from the convex side to the concave side. Strength of secondary circulation increased. Longitudinal velocity also became higher. As the distance increased in downstream the deflection became more pronounced due to the residual action. The maximum depth recorded was 16.20 m and it was located at 45m from the concave bank. The outer half portion of the concave side was subjected to intense bank erosion, and was thus the meandering pocket.

Maximum depth of river versus longitudinal distance between sections

The variation in maximum depth with longitudinal distance in Figure 9 indicates that at the beginning of bend the enhancement of depth was less, but the distance grew in curvature the rate of increase in depth grew. This can be attributed to the increase in strength of spiral currents and growth in the sand bed.

Maximum elevation of sand bed versus longitudinal distance between sections

In Figure 10 the variation in maximum elevation of sand deposition with longitudinal distance has been plotted. This figure shows that with the increase in distance in downstream the height of sand bed and depth of water followed the same pattern as that of Fig. 7.

Comparison of the field investigation with laboratory investigation

Cross sectional shapes of the Ganga at different ghats of Varanasi obtained from the field investigation and also the profile of the sand bed formed in the flood plain area match qualitatively with the experimental data obtained in the meandering channel:

1. Sand is eroded from the concave bank side, indicating the maximum depth of water on this side. As flow advances downstream, the maximum value of this depth shifts nearer to that bank.
2. Sand is deposited on the convex bank side indicating less water depth on that side and the rising slope of the sand bed in transverse direction with distance downstream.
3. The sand bed form in the flood plain area expands laterally and increases in height as flow proceeds downstream.
4. The maximum height of sand bed is found near the zone of flow separation (near Prahlad Ghat). In the laboratory experimentation also the maximum deposition took place in the zone of separation.

CONCLUSIONS

From the study of inter-relationship between erosion and deposition in the river & the laboratory curved channel the following conclusions are drawn: (i) Sand is eroded from the concave bank side indicating the maximum depth of river on this site. The maximum depth of river was 16.20 m and the maximum elevation of sand bed was 7.10 m. They both occurred at Prahlad Ghat section where separation zone exists near convex side. (ii) The maximum width of river occured at Samne Ghat section and it was 536 m and the minimum width was Dasaswamedha ghat section and it was 253 m. (iii) Sand width is proportional to lateral movement of the maximum erosion pocket from the central portion to concave side. (iv) Lateral position of the maximum erosion pocket becomes closer to the concave bank as the flow advances in the downstream direction. (v) As more and more sediment gets deposited in the flood plain of the convex bank, the maximum depth of erosion on the concave bank side increases. (vi) The sand bed formed in the flood plain area expands laterally and also in height as the flow proceeds downstream. (vii) Bank slope of the river is steeper towards the concave bank and is mild towards the convex bank at a particular section. (viii) The longitudinal bed slope and the bank depth of river increases in the downstream direction. (ix) The transverse slope of flood plains increases with the increase in the downstream distance. (x) There are two important zones of erosion, viz., the concave side of the first bend after $60^0$and the concave side of the second bend after 90^0(fig.3). (xi) The maximum height of sand bed is found near the flow separation zone (near Prahlad Ghat). In laboratory experiments also the maximum deposition takes place in the separation zone. (xii) The laboratory experimental data simulates (to a certain degree) qualitatively with the characteristics of River Ganga at Varanasi obtained by the field investigation.

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Table 1. Distance between Ghats

S.No.	Section between	Distance in meter (Convex Side)
1	Samne Ghat to Bhagwan Ram Ghat	440
2	Bhagwan Ram Ghat to Ravidas Ghat	700
3	Ravidas Ghat to Assi Ghat	540
4	Assi Ghat to Harishchandra Ghat	1080
5	Harishchandra Ghat to Dasaswamedha Ghat	1080
6	Dasaswamedha Ghat to Marikarnika Ghat	560
7	Marikarnika Ghat to Sankata Ghat	440
8	Sankata Ghat to Brahma Ghat	440
9	Brahma Ghat to Gai Ghat	360
10	Gai Ghat to Prahlad Ghat	940

Table 2: Erosion and deposition in meandering channel (1st bend)

Distance from the convex side (cm)	Depth of deposition at lateral sections of various angles (cm)						
	0^0	30^0	60^0	90^0	120^0	150^0	180^0
0	2.2	3.0	6.6	12.2	12.5	13.8	14.2
10	3.0	2.6	5.0	10.7	12.8	13.6	14.1
20	2.5	2.2	4.3	7.3	11.5	13.5	14.0
30	2.7	2.0	2.4	6.9	10.8	11.7	13.3
40	3.3	3.3	2.1	5.1	10.3	8.2	9.1
50	2.3	3.4	3.1	0	3.9	5.5	6.1
60	4.6	3.6	2.5	0	0	1.2	5.2
70	5.6	6.3	4.1	0	0	0	3.6
80	5.8	6.9	5.4	0	0	0	0
90	7.4	8.8	7.2	0	0	0	0
100	7.5	7.1	6.1	0	0	0	0
Width of Erosion (cm)	0	0	0	50-100	59-100	61-100	76-100

Table 3: Erosion and deposition in meandering channel (2_{nd} bend)

Distance from the convex side (cm)	Depth of deposition at lateral sections of various angles (cms.)						
	0^0	30^0	60^0	90^0	120^0	150^0	180^0
0	14.2	12.3	9.5	0	0	0	0
10	14.1	11.9	8.4	0	0	0	0
20	14.0	9.8	8.2	4.4	0.6	0	0
30	13.3	8.5	8.0	4.7	0.4	0	0
40	9.1	7.8	5.1	4.1	0	0	0
50	6.1	3.1	1.2	1.3	0	2.6	5.7
60	5.2	0	0	0	2.9	7.5	9.3
70	3.6	0	0	0	2.8	9.0	10.4
80	0	1.1	0	0	3.1	9.5	11.0
90	0	0	0	0.8	6.6	10.5	11.4
100	0	0	0	3.3	10.8	10.9	12.2
Complete Erosion (cm)	76-100	56-74 and 84-100	54-100	0-11 and 52-88	0-14 and 32-56	0-46	0-49

Table 4. Cross-sectional profile characteristics of different Sections

No.	Ghat	Width (m)	Depth of Water at Concave Side		Sand bed on the convex side		
			Maximum depth (m)	Distance (m)	Width (m)	Maximum depth (m)	Distance (m)
1	Samne	536.00	3.65	160.00	210.00	0.86	100.00
2	Bhagwan Ram	482.00	4.12	146.00	320.00	1.21	160.00
3	Ravidas	398.00	4.60	113.00	222.00	1.57	113.00
4	Assi	335.00	5.02	288.00	640	1.82	288.00
5	Harishchandra	257.00	7.65	72.00	690.00	2.15	302.00
6	Dasaswamedha	253.00	3.30	65.00	720.00	3.30	240.00
7	Manikarnika	289.00	12.40	59.00	600.00	3.95	206.00
8	Sankata	312.00	13.70	55.00	570.00	6.15	176.00
9	Brahma	331.00	14.20	52.00	490.00	6.70	135.00
10	Gai	356.00	15.30	49.00	350.00	6.95	115.00
11	Prahlad	393.00	16.20	45.00		7.10	92.00

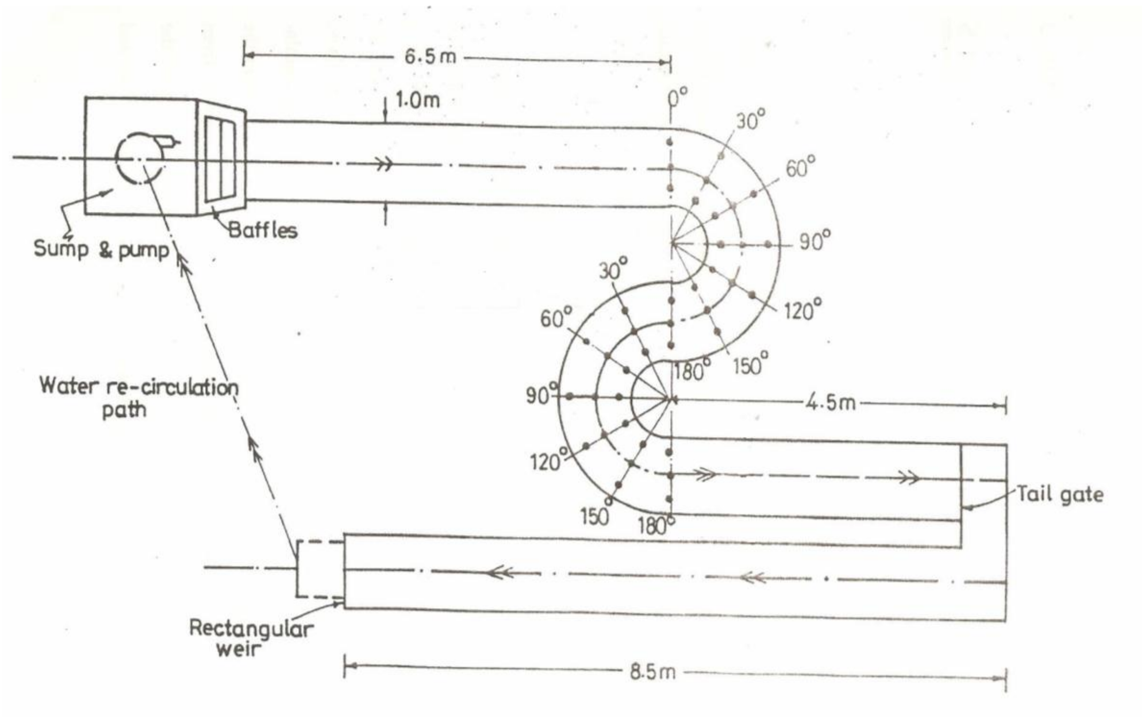

Fig. 1. Meandering channel set-up in the laboratory

Figure 2: Photograph showing the erosion and deposition taking place in the meandering channel

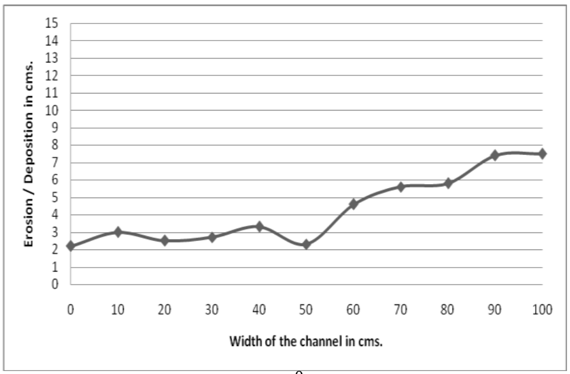

Fig. 3(a) 0^0 Section

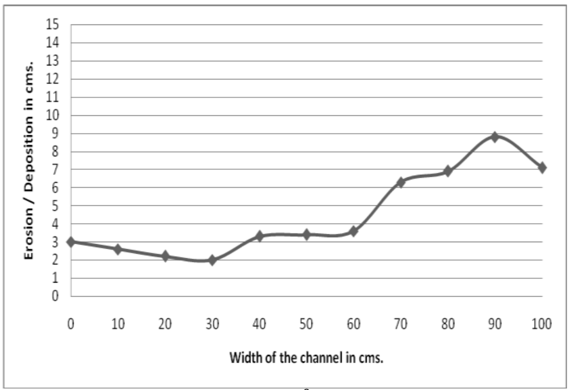

Fig. 3(b) 30^0 Section

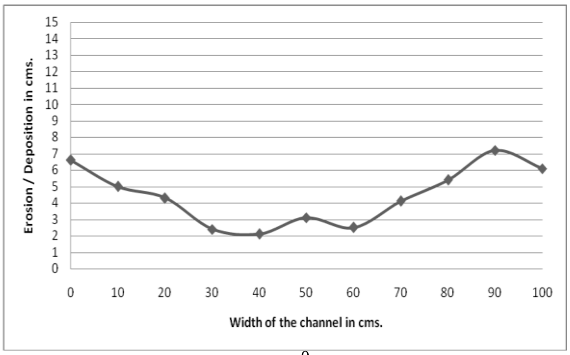

Fig. 3(c) 60^0 Section

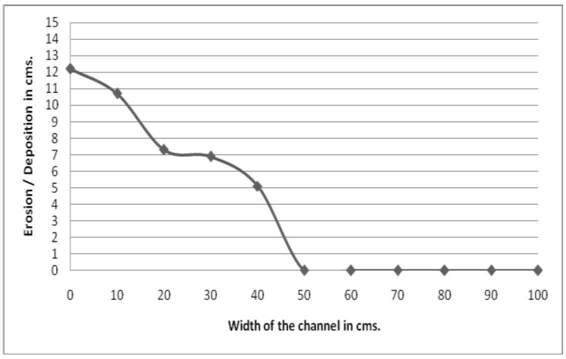

Fig. 3(d) 90^0 Section

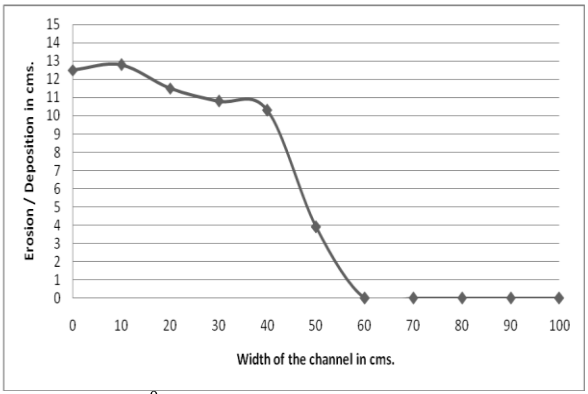

Fig. 3(e) 120^0 Section

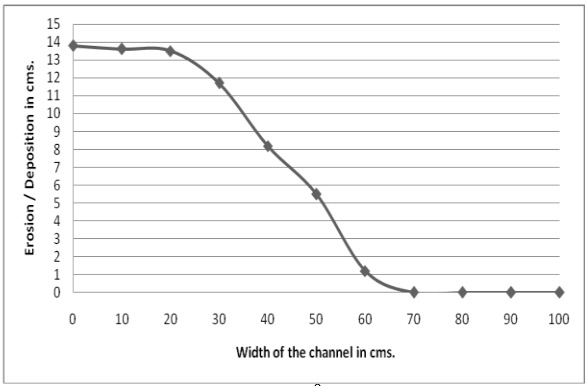

Fig. 3(f) 150^0 Section

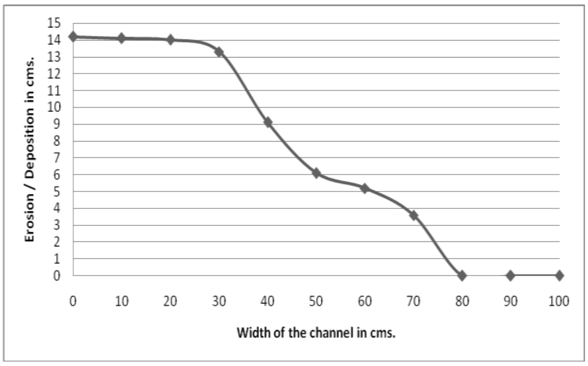

Fig. 3(g) 180^0 Section

Fig. 3 Erosion/Deposition versus width of the channel (First Bend)

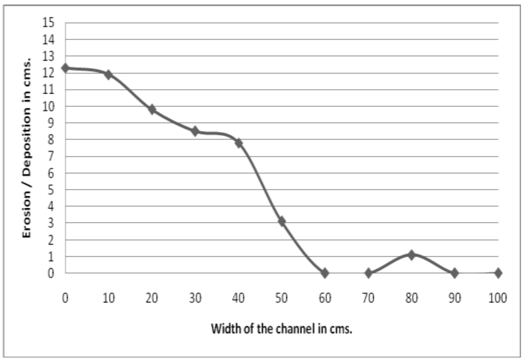

Fig. 4(a) 30^0 Section

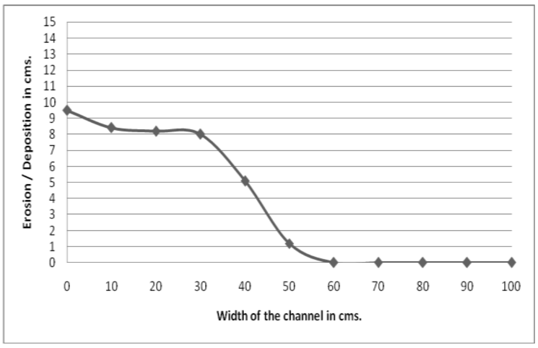

Fig. 4(b) 60^0 Section

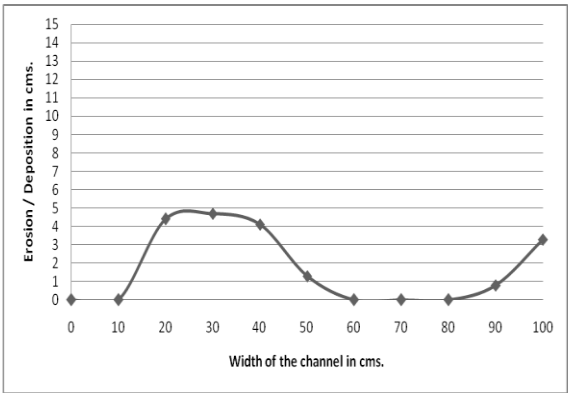

Fig. 4(c) 90^0 Section

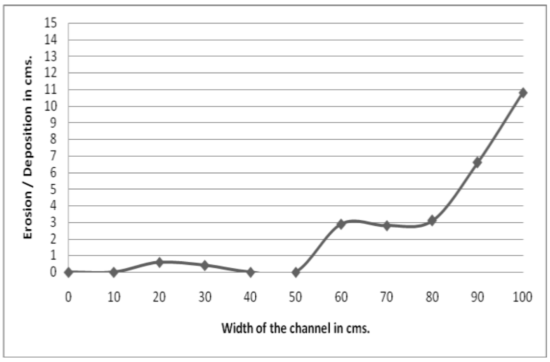

Fig. 4(d) 120^0 Section

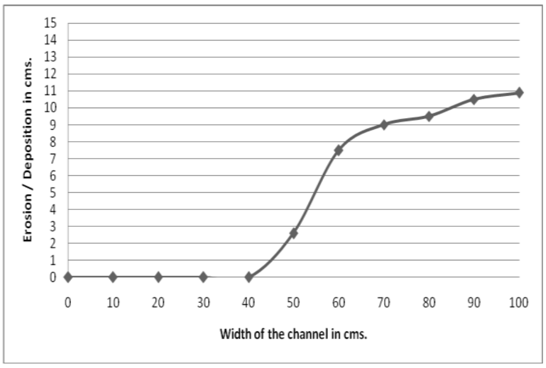

Fig. 4(e) 150^0 Section

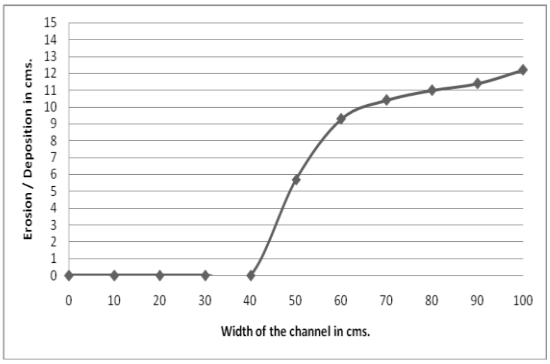

Fig. 4(f) 180^0 Section

Fig. 4 Erosion/Deposition versus width of the channel (Second Bend)

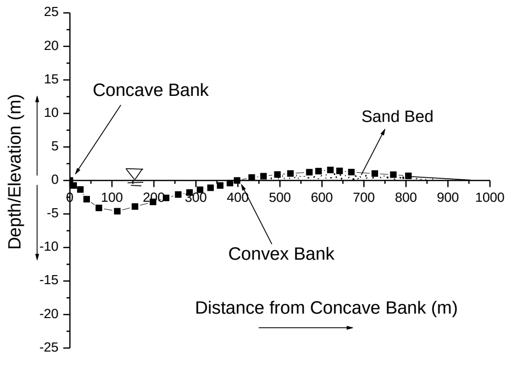

Fig.5. Cross-sectional profile of the Ganga at section (1-1) i.e. Samne ghat

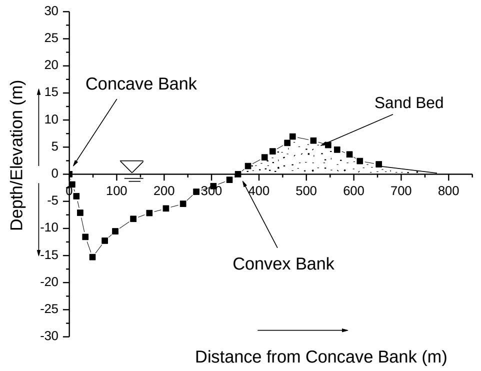

Fig. 6. Cross-sectional profile of the Ganga at section (11-11) i.e. Prahlad ghat

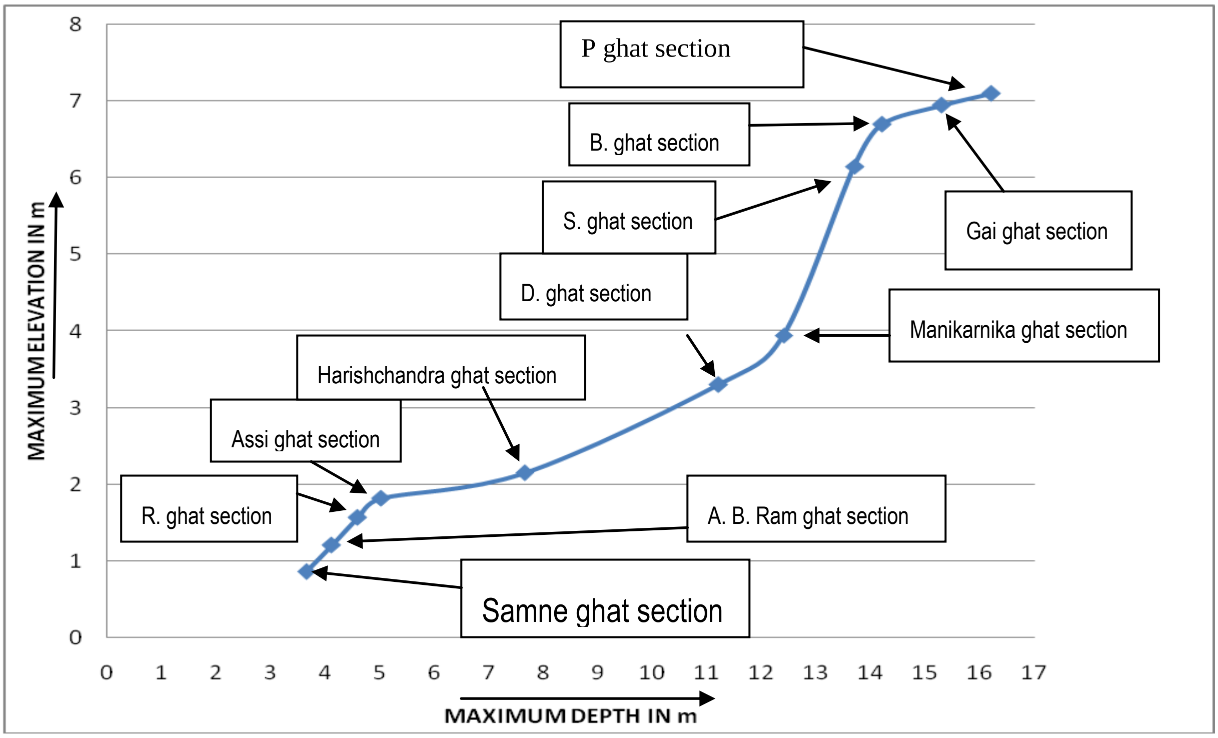

Fig. 7. Graph between maximum depth of river Vs maximum elevation of sand bed

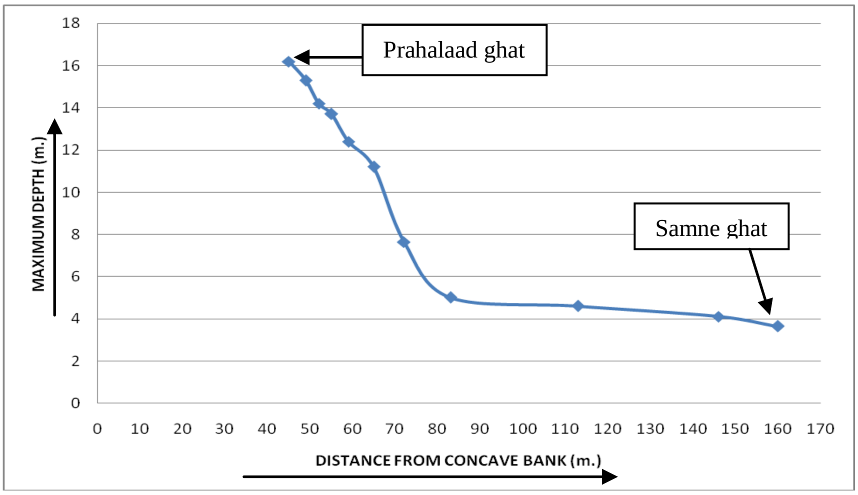

Fig. 8. Graph between maximum depths of river Vs distance of maximum depth from concave bank

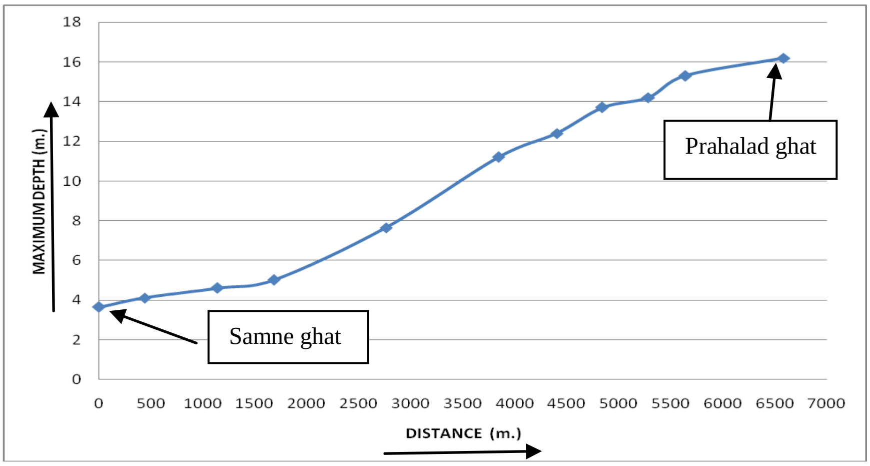

Fig. 9. Graph between maximum depth of river Vs longitudinal distance between sections

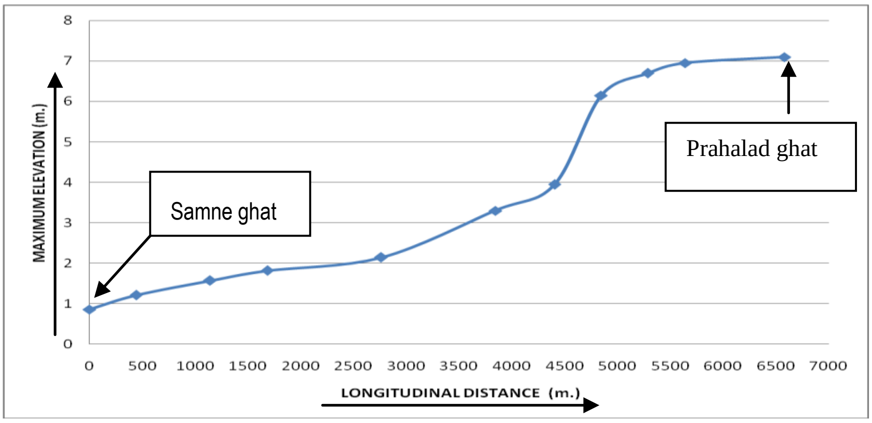

Fig. 10: Graph between maximum elevation of sand bed Vs longitudinal distance between sections