Journal of Indian Geomorphology
Volume 7, 2019 ● ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

# Changing Character of River Cross Profiles Based on Optimum Cross Section Index: A Case Study of Ichamati River, West Bengal

Madhab Mondal[1] and Lakshminarayan Satpati[2]
[1]*Department of Geography, Bhowanipur S.J. Institution, Hasnabad, North 24 Parganas*
[2]*Department of Geography, University of Calcutta, Kolkata 700019*
E-mail: madhabmondal2009@gmail.com (*Corresponding author*)

**Abstract:** *The Ichamati Rriver, — a tidal stream which drains the eastern and southern part of North 24 Parganas district of West Bengal has been analysed for its changing cross sectional character. In the present paper, attention has been given to the comparative study of cross sections of the year 2012 and 2015. On this basis, the change of cross section of the Ichamati River has been discussed and the optimum size of cross sections has been estimated. Geometric characters such as, width, depth, hydraulic radius and wetted perimeter was computed based on the cross-profiles of the river. For interpretation of the form of the cross sections the Areal Difference Asymmetric Index (ADAI) has been applied and also the Optimum Cross Section Index (OCI) has been proposed to construct the optimum size of each cross section. All the techniques reveal that — i) the area of channel decreases from upstream to downstream, ii) the channel is more symmetrical in the upper reach than the lower and iii) the area of optimum channel gradually increases downstream. The river has an overall deteriorating tendency downstream.*

## Introduction

Since the Davisian concept of the 'Cycle of erosion' (1899), the river Ggeomorphologists concentrated their attention on the evolution of the longitudinal profile. Mackin (1948) was the first to draw attention on the cross section of a channel, followed by Leopold and Maddock (1953), Leopold *et al*., (1964), Richards (1982), Knighton (1998); Sinha-Roy (2001), Al-Mayahi (2011) etc. Parallelly works have been done on bank protection and management as a partial discussion of river cross section (Thorne, 1981; Lawler, 1993; Mosselman, 1998) and channel stability (Swamee *et al*., 2000; Hey, 2006; NEH, 2007), but nothing has been discussed about the optimum condition of the river cross section based on the morphological parameters such as width and depth. The concept of cross section has been shifted from general to threshold channel design technique, which was followed by Optimal Design Technique.

The changing form of cross-section is an important parameter of a river's health and one of the important vital signs of fluvial system (Lord *et al*., 2009).There are two connotations about this parameter i.e., cross section and cross profile. The geomorphic term, 'cross-section' or 'cross- profile' is the change of depth of the channel in respect to the horizontal distance from one bank to the other. River cross-sectional morphometry and characteristics is the core subject of fluvial research and river management (Lord *et al*., 2009) and it is in a three dimension form. Cross section is a set of some elements containing specific geometric character. The elements are, left bank ($B_L$), right bank ($B_R$) (both are inclined and must not be identical), bed width ($W_B$) and bank-full width (W). We can say that cross section (A) = {$B_L$, $B_R$, $W_B$, W}.

Let, $B_L$, $B_R$, $W_B$, W = a, and A ≠ {a: p (a)}, because every element has a unique identity. The bank profile (B) is the arrangement of points ($x_1$, $x_2$, $x_3$...$x_n$) which are perpendicular to the flow direction (Mondal and Satpati, 2014). So, x (1, 2, 3 ...n) € B and, B = {x: p (x)}. Bed also consists of points ($y_1$, $y_2$, $y_3$ ....$y_n$) which are horizontally oriented and parallel to flow direction. Therefore, y (1, 2, 3....n) € $W_B$ and, $W_B$ = {y: p(y)}. But there is ambiguity about the demarcation line between bed and bank. There is a gap between bed and bankfull width or, depth of water (D). As the water molecule has some velocity (v), the coordinate of any point of cross section will be $B_x$, $W_B$, v. In a dry channel (that must not be a river) the cross section will be converted into a cross profile. Cross section is a combination of two gaps, (a) horizontal gap: between two bank and (b) vertical gap: between bed and bank full width. So the cross profile only represents the horizontal gap of cross section. The set of the cross profile = {B, $W_B$}.

There are two types of hydraulic design variables, i.e. independent variables, such as discharge and channel roughness; and the other is the dependant variable, such as width (w), depth (d) and slope (NEH, 2007). A stable channel must be in equilibrium, exhibiting no systematic erosion or deposition. Under the influence of gravity, a river tends to lower its potential energy and attain a higher degree of stability (Singh, 2003). On the other hand 'a threshold channel is designed as a channel in which channel boundary material has no significant movement during the design flow. The design goal of a threshold channel design technique is to produce a channel that has positional or engineering stability (NHE, 2007).

The common cross-section shapes are rectangular, trapezoidal and circular (Merkley, 2004), but triangular section (Swamee *et al*., 2000) and compound cross-sections (Markley, 2004, NHE, 2007) are not uncommon. According to Optimal Design technique the rectangular section shows the minimum area. But, for the discussion about the projected area of open channel it should not be emphasised only on cross-sectional area, but on 'the area of free surface flows is the design of channels capable of transporting water between two locations in a safe' (Thandaveswara, 2011). From the point of hydraulic aspects, the semi-circular has the least perimeter among all sections with the same area; hence, it is hydraulically most efficient of all sections (Merkeley, 2004). But very few channels have this ideal shape (Spark, 1960).

The studied river is an irregular meandering river and vast investigations indicate that the river is going to decay downwards (Mondal, 2011, Mondal and Satpati; 2015; Mondal and Bondyopadhyay, 2014; Mondal *et al*., 2016; Basu and Howlader, 2008) losing 38% of its total potential energy, from Basirhat to Tentulia (Mondal and Satpati, 2017). The shape of the cross section of the river is highly modified by bank erosion on the concave bank and by point deposition on the convex bank (Mondal, 2011) at different rates (Mondal and Satpati, 2012). In the study area, the normal flow velocity of the river gets disturbed, helps rapid siltation, followed by sand bar formation due to the construction of bridge piers of three bridges across the Ichamati river. The bridges seemingly act as artificial local base levels (Leopold *et al*., 1964), which permit very small amount of the high tidal water to enter unto the channel (Mondal and Satpati, 2013).

The concept of cross section has been

shifted from general to threshold channel concept, which was followed by optimum design techniques. Channel cross-profile is formed as an adjustment to the dynamic equilibrium. This adjustment is the subject matter of gradation and grade channel shows maximum discharge efficiency (Spark, 1960) and this type of channel is called optimum channel.

## Objectives

The main objectives of this study are — (a) to discuss about the character of the cross-profiles of the river Ichamati based on selected geometric parameters and how the parameters change from upstream downward, (b) to propose a new technique Optimum Cross Section Index (OCI) in order to analyzse hwhether the cross section is in optimum condition or not. Till today there is not yardstick by which we can understand the deviation of the present channel to optimum one. For this a number variables at a given cross section are to be studied, i.e. width, depth, bank full discharge, bank materials, cohesiveness of bank material, vegetal character (Leopold *et al*., 1964). Among these variables, data regarding discharge, character of bank material are not always available, mainly in the third world due to the lack of river monitoring system. To overcome this problem, only two variables, viz. depth and width, have been taken into account to construct the optimum channel shape (CIVE2400, 2014; NEH, 2007; Markley, 2004).

## Study area

This study refers to Ichamati river of North 24 Parganas, West Bengal, which drains the eastern side of the North 24 Parganas district, a part of Ganga-Brahmaputra Delta (GBD). Ichamati is a tidal river and has bifurcated from the Mathabhanga Rriver, a distributary of Padma River. The river flows intowards south keeping three blocks on both sides viz. Swarupnagar, Baduria and Basirhat. The river is underlined by thick recent sediments. There is a gauging station of West Bengal Irrigation Department at Basirhat, which measures daily tidal fluctuation. The aforesaid blocks are densely populated (Swarupnagar: 1190 $Km^{-2}$, Baduria: 1587 $Km^{-2}$) (Census, 2011). Many of the distributaries of the Bhagirathi-Hugli river, transformed into sewage outlets (Rudra, 2014) and this statement was well explained by Bandyopadhyay *et al*., (2015). The Saraswati, a medieval outlets of Bhagirathi Hugli, has been converted into a seasonal river (Rudra, 2014). The Bidyadhari is connected with the upper Raymangal estuary of the eastern Sundarban (Bandyopadhyay *et al*., 2015), which gets its discharge from minor rivers (Hunter, 1875) and now converted to an agricultural land (Bandyopadhyay *et al*., 2015). Jamuna river, is another distributary, that is bifurcated from the river Hugli at Tribeni (Hunter, 1875) and detached from Hugli during 1849–55 and 1917–18 (Bandyopadhyay *et al*., 2015). The Jamuna was navigable to large trading boats but now is a feeble channel. The east flowing Jamuna met with Ichamati and was referred to as 'the Jamuna or Ichamati' by Hunter (1875).

## Methodology

Cross sectional survey was done at 22 locations (P1 to P22) in the year 2012 and 2015. It may be noted that the study area has three local bench marks—4m at Tentulia (Swarupnagar), 3.14 m at Baduria, and 3.14 m at Basirhat (P22). In every case, the bench mark has been referred during profile survey. In the upper reaches measurements have been done, taking the distance from the bank and the elevation of the bed with the help of rod/ tape intercept. In the lower reaches of the river Ichamati 8 cross sections, spaced at irregular interval were surveyed by echo sounder. Positions were marked by GPS. The survey provides a high resolution data set to study the cross profiles as well as the long profile (Harmer, 2004).

The change in channel profile have been determined by calculating the difference in elevation and distance from bank for features like riffle, bank height, edge of water etc. on different sampling days (Rosgen, 1996).

*Construction of cross profile*

The data collected by echo sounder have been used to construct the cross profiles with the help of Microsoft Excel 2007, which have been calibrated with the help of surface heights taken by Dumpy Level survey, based on local Bench Marks. The surveyed reach of the river, has been divided into two windows (first window: 0–26 km, second window: 26–55 Km), based on the bed contour pattern, bank profile, width-depth ratio (Mondal and Satpati, 2016), character of long profile (Harmar and Cliford, 2007) including parameters as, concavity, gradient, pool-riffle

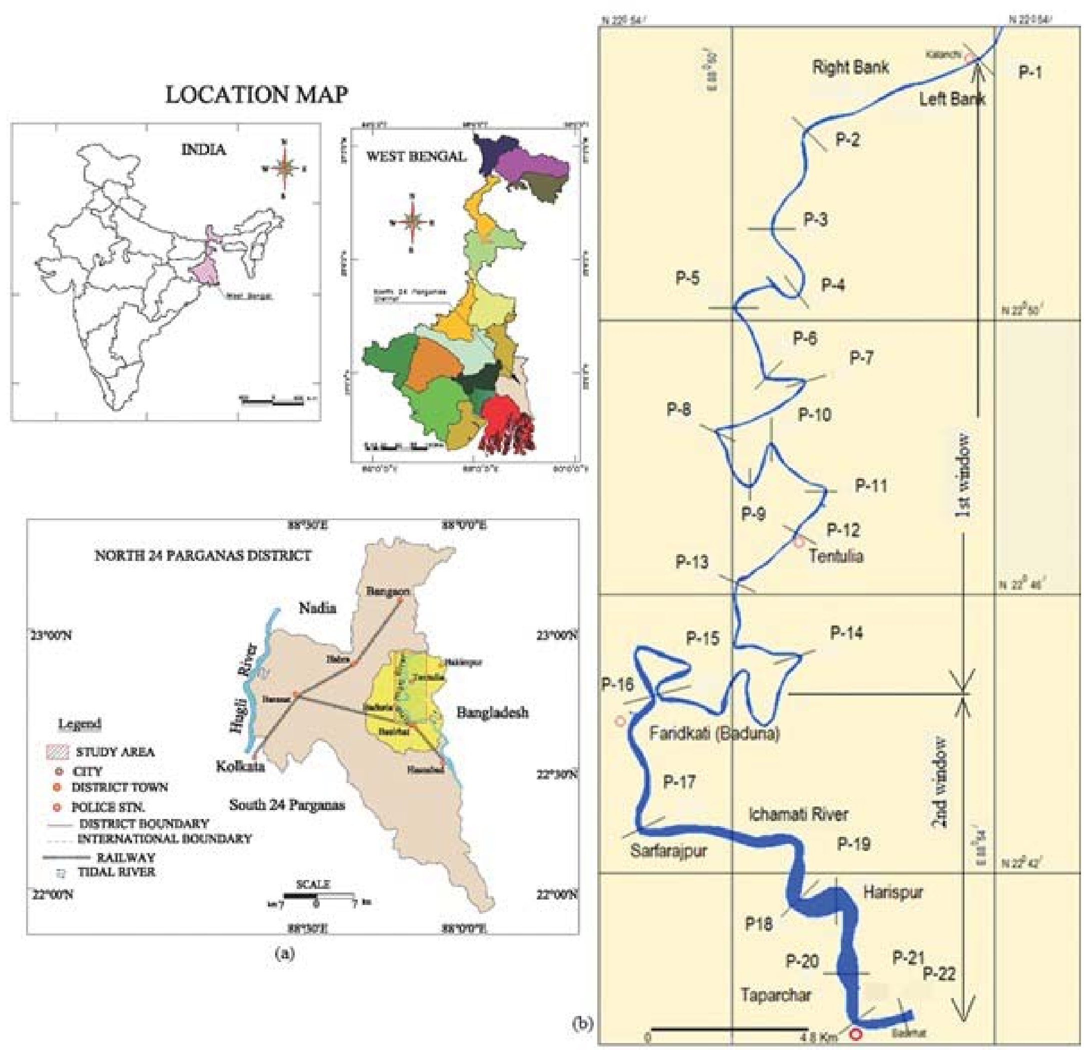


**Figure 1**. (a) Location of the study area and (b) positions of the cross-sections of Ichamati river in the study area (1st window: P1 - P15, 2nd window: P16 - P22)

sequences (Mondal and Satpati, 2015, 2016). Here the term 'window', has been used to denote the two different river reaches.

*Construction of river bed map*

DL,A non-traditional 'river bed map' has been presented to visualise the contour pattern of the riverbed at a glance. In this case, 0.0 m has been selected as datum. The mid-point of each cross-section has been plotted on the Y-axis (which represent the river length), whereas the X-axis represents the horizontal distance between one bank to another. The point O, represents the mid-point of the cross section. OX and OX′ represents the left bank and right bank of the cross sections respectively (Mondal *et al*., 2016).

*Application of ADAI*

To obtain the channel cross-sectional symmetry, the 'Arial Difference Asymmetry Index' (ADAI) technique has been used (Framhingham and Brown, 2002). This techniques compares cross-sectional area on either side of the channel centre line,
$A^{*}=A_r–A_\ell / A$;
where $A_r$ is area to the right of channel centreline, $A_\ell$ = area to the left of channel centreline, and A = total counted area (to find out the symmetrical form of the river cross-section the value of $A^*$ has been calculated as 0.01–0.08 m).

*Construction of bank profile*

The construction of bank slope includes the study of gradient, slope alignment, slope aspect, and composite features. A slope is measured by gradient over some distance. It is known that gradient changes at every point along the profile. If the angle of slope $\Delta y \rightarrow 0$, is a dependent variable changes in respect of horizontal distance $\Delta x \rightarrow 0$, that is independent variable, the gradient will be $\Delta y/\Delta x$, Let $x \rightarrow 0$, here the equation is $y = f(x)$. In this study, we have taken the average value of slope angle with the help of clinometers. Then we have measured the slope length and calculated the bank height applying the 'tan θ' formula. If, the coordinate of two points on a curve are (x, y) and (x +*d*x, x + *d*y), the slope (m) of the point (x, y) will be:
$m = (y + dy) – y / (x +dx) – x = dy/dx$ or, $\theta = dy/dx$ (Fig. 2).

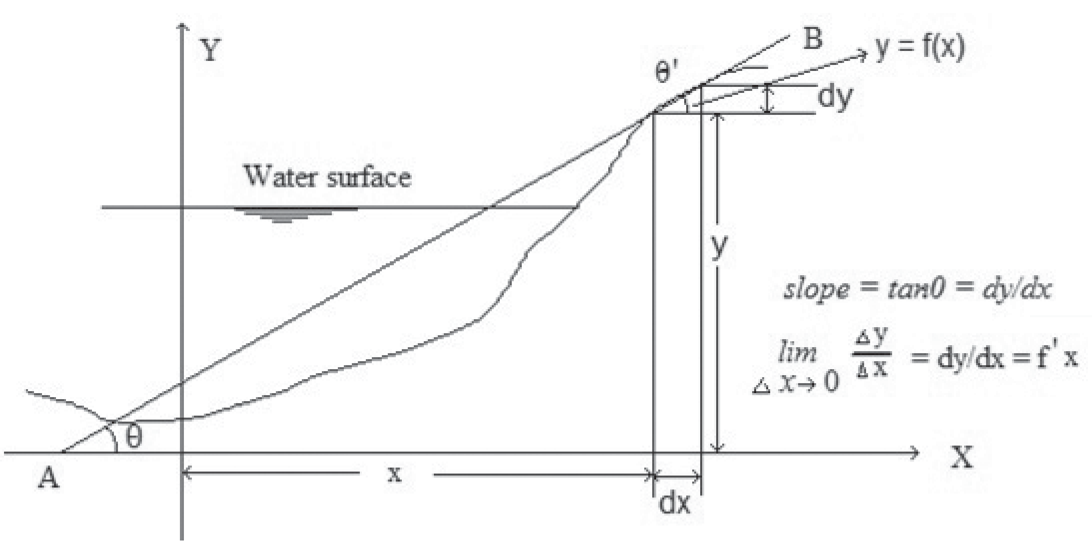


**Figure 2**. Change of height along horizontal distance from one point to another. Computation of the optimum cross section

*Computation of the optimum cross-section*

The under mentioned equations have been followed to preparefit different shapes of cross sections.

TRAPEZOIDAL CROSS-SECTION

Rectangular cross-sections are just special case of trapezoidal sections. Trapezoidal cross-section can be symmetrical and non-symmetrical. The parameters of a trapezoidal cross-section are: top width of flow (T), bottom width (b), regular side slope ($m_1$) and inverse side slope ($m_2$). The inverse side slope (H:V) is usually between zero and 2.0. High inverse side slope is more stable and may require less maintenance, normal bank length ($\omega_1$) and inverse bank length ($\omega_2$), bank height or water depth (h).

SYMMETRICAL CROSS-SECTION

The symmetrical cross-section is identically same of the two halves. The important characters of such section are area (A), top width (T), wetted perimeter ($\omega_p$) etc. Area is the function of water depth (h), bottom width (b) and side slope (m).

$A = b.\ h + (\frac{1}{2}\ m.\ h + \frac{1}{2}\ m.\ h)$

$= b.\ h + \frac{1}{2}\ (2m.\ h) = b.\ h + m.\ h$

$= h\ (b + m)$ .......................... Equation 1

Top width of the flow (T) denotes the maximum width of a cross section which is an easily measurable element.

$T = b + (m.\ h + m.\ h)$

$= b + 2m.\ h$ .............................Equation 2

Using the following equation we can get the bottom width,

$b = T - 2m.\ h$ ............................. Equation 3

Wetted perimeter ($\omega_p$) is the length of the wetted surface measured normal to the direction of flow.

$\omega_p = b + 2h\ [\sqrt{m^2} + \sqrt{1}]$ .................. Equation 4

Side slope (w) actually represents the bank properties. There are two types of side slope, inverse side slope and high inverse side slope. The inverse side slopes occupy less area. The high inverse side slopes are more stable. It is easier to climb out. In this case the side slope of the cross section is symmetrical. The equation

$w = h\ [\sqrt{m^2} + \sqrt{1}]$ ..............................Equation 5

NON-SYMMETRICAL CROSS-SECTION

This type of trapezoidal cross section is characterised by two different inclined side slopes i.e., $m_1$ and $m_2$. When the areas to the right and left of the channel centreline are not equal is called non-symmetrical cross section (Knighton, 1981). The equations used to quantify of some important parameters of such cross sections are as follow:

$A = h\ [b + 0.5(m_1 + m_2)\ h]$ ..........Equation 6

$T = b + (m_1 + m_2)\ h$ ..................... Equation 7

$\omega_p = b + h\ \{[\sqrt{m_1^2} + \sqrt{1}] + [\sqrt{m_2^2} + \sqrt{1}]\}$

.......................................... Equation 8

$w_1 = h\ [\sqrt{m_1^2} + \sqrt{1}]$,

$w_2 = h\ [\sqrt{m_2^2} + \sqrt{1}]$ ........................Equation 9

For the most efficient trapezoidal section, m = 1/ tan 60° ($m_1$) = 0.557, tan 60° ($m_2$) =1.73, or tan 45° = 1. But the slope angle; depends on slope material (Merkeley, 2004; Thandaveswara, 2011; Mondal *et al.*, 2016)

SEMI-CIRCULAR CROSS-SECTION

For semi-circular cross-sections the equations to quantify the components of hydraulic geometry are as follows:

$r = D/2$ .................................Equation 10

$T = D \sin(\beta/2)$ ........................Equation 11

$A = D^2/8\ (\beta - \sin\beta)$....................Equation 12

$\omega_p = \beta.\ D/2$ ............................Equation 13

Where β = angle of radius and D= diameter of the circle.

*Calculation of Optimum Cross-section Index (OCI)*

OCI is the ratio between total computed area of the optimum cross section and total computed area of the observed channel; OCI = total computed area of the optimum cross section / total computed area of the observed channel, OCI >1, indicates the channel is far from optimum condition and OCI =1, indicates the channel is in optimum condition (Mondal *et al*., 2016).

## Result

*Bed configuration*

A river-bed map, has been prepared based on the data of 2015 survey, maintaining continuity beyond the study area (Fig. 3). On the basis of the width parameter and contour value, the studied reach of the river has been divided into two windows — 1st window (width 30 m to 70 m), and the 2nd window (width 70 m to 500 m). The –1.4m depth contour separates these two windows. The contour pattern of individual windows has been discussed indicating the datum line as 0.0 m.

BED CONFIGURATION OF THE FIRST WINDOW (LENGTH: 0–26 KM)

Here, the orientation of the leading contour lines (–1m, 0.0 m and +1.5 m) are symmetrical and parallel with the riverbank. Most of the area from the central point to the left bank is occupied by the 0.0 m and 1.5 m contour lines. But in the right side of the main channel, the river bed is represented by 1.5 m and –0.15 m contour. The 0.0 m contour line runs through the central position of the channel, before it swings towards left and merges ultimately with the left bank (Fig. 3).

BED CONFIGURATION OF THE SECOND WINDOW (LENGTH: 26–55KM)

The leading contours of –1 m, –1.4 m, –1.7 m and –3 m are symmetrically orientated and run transverse to the channel cross-section. The –1.4 m and –1.7 m contour lines run across from one bank to another. The contour pattern shows that the bed level in the second window is much lower than the datum level of the first one (Fig. 3).

*Relation between width and depth*

It was observed during the repeat-field investigation in 2015 that the surveyed sites of 2012 became shallower at majority of the locations. In the first window, the average width of the channel is 40–80 m, whereas the average width of the second window is 200 m. The width abruptly increases from the section P16 downwards. Area is the product ($A= w \times d$) of mean width (w) and mean depth (d). The discussion about the changing character of cross-sectional area is also based on the data of 2012 and 2015 (Fig. 4). The data in 2012 indicates that the area of the river channel increased with distance downstream. The 2D form of the cross section in the lower reach is asymmetric at the bends. The asymmetric form is due to the existence of prominent point bars at each convex bend, with coarse sediment. In the upper reaches of the river, the point bars are seldom noticed. The Hydraulic radius (HR) of a stream channel is defined as the cross sectional area of the flow in a channel divided by the wetted perimeter (Summerfield, 1991). Higher value of the ratio indicates better efficiency of the river (Sparks, 1960). Not only the HR but also the channel shape and size are the other important factors of stream capacity. The variation of HR has been discussed from three perspectives — (i) variations of HR with distance, (ii) Variation of HR with area and (iii) variations of the ratio between HR and area with distance.

The bank characteristics viz. bank height, slope and length vary in the two windows. The bank slope has been divided into three classes based on the slope angle — (a) low angle slope (0°–30°), (b) medium angle slope (30°–60°) and (c) high angle slope (60°–90°).

BANK CONDITION IN THE FIRST WINDOW (LENGTH: 0–26 KM)

Here, the bank profile of both sides represent a unit profile. The bank height

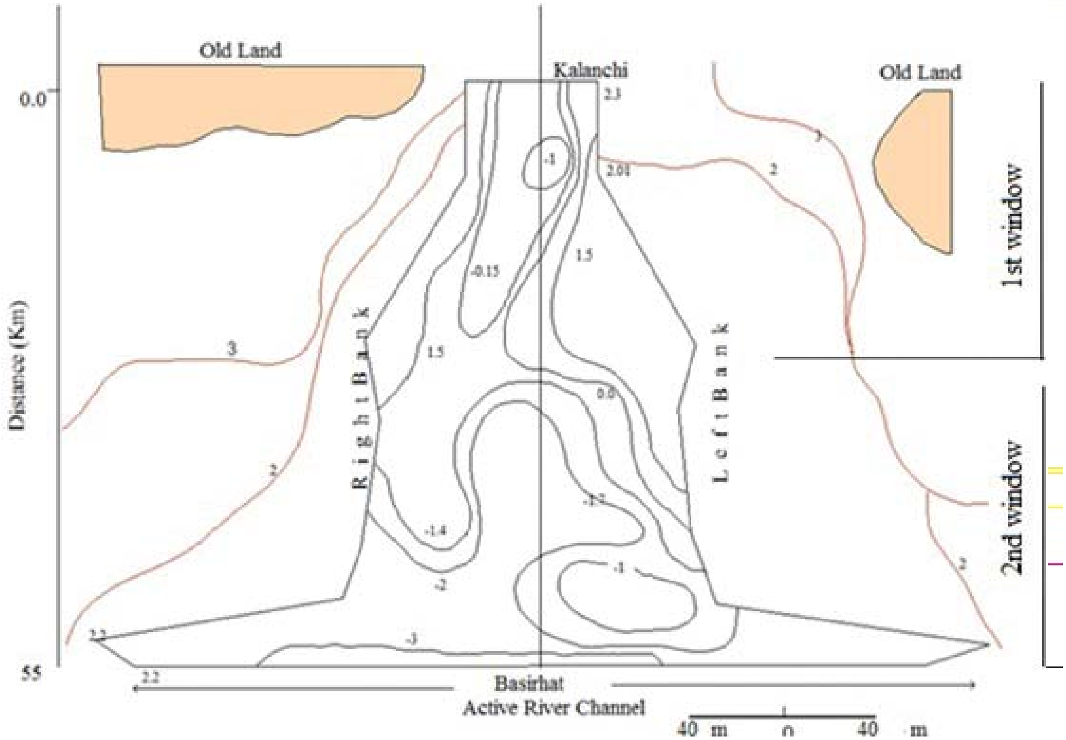


**Figure 3**. Contour pattern of the bed of the Ichamati river (Mondal et al., 2016).

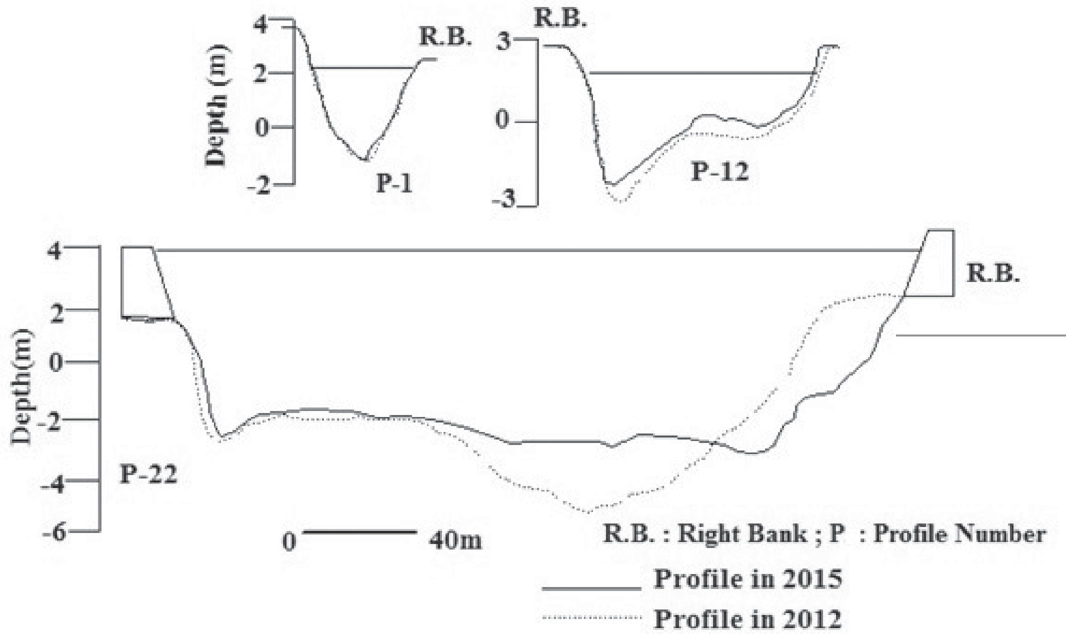


**Figure 4**. Changing cross profiles (2012–2015)

does not exceed more than 1 to 1.5 m at any place. The slope is of medium and high angle type. In this region, the steepness of slope can be maintained due to smaller height and cohesiveness of the bank material.

### BANK CONDITION IN THE SECOD WINDOW (LENGTH: 26–55 KM)

In this window there are point bars at allmost every convex bend of the bank which consists of a number of segments. The upper segment of the bank often shows a wash slope, formed by fine sediment and are usually muddy. On the other hand, the concave slope represents erosive bank which represent a single segment of the profile. The convex bank profile mostly consist of three segments. The first segments are of low angle type, which are inundated during high tidal period and are covered by grass. The second and third segments are medium and low angle type. The variations in the angle of the point bars indicate the different sedimentation regimes in different seasons. The angle of the concave side is high formed due to slope failure by helical flow. At some places there are two segments on the concave bank. The first segment of the profile is formed during the high tidal period, and the second segment is formed durinng the low tidal period.

### *The Areal Difference Asymmetrical Index (ADAI)*

This index has been used to discuss about the form of the cross sections. This Index helps us to quantify the shape asymmetry of the river cross sections. In the cross sectional area on either side of the centre line the value of ADAI will be zero. Greater value of ADAI indicates the difference in the cross sectional areas on two sides of the centre line. The following discussion is a comparison of the ADAI in 2012 and 2015.

### ADAI OF 2012

The total cross sections surveyed in 2012 have been classified into four classes according to the value of ADAI — highly symmetric (0–0.19), moderate symmetric (0.19–0.38), moderate asymmetric (0.38–0.57) and highly asymmetric (> 0.57) (Table 1).

In the entire surveyed reach 63.63% of the sections are highly symmetric, 18.18% are moderately symmetric, 13.63% are moderately asymmetric and only 4.54% is highly asymmetric. A significant meander

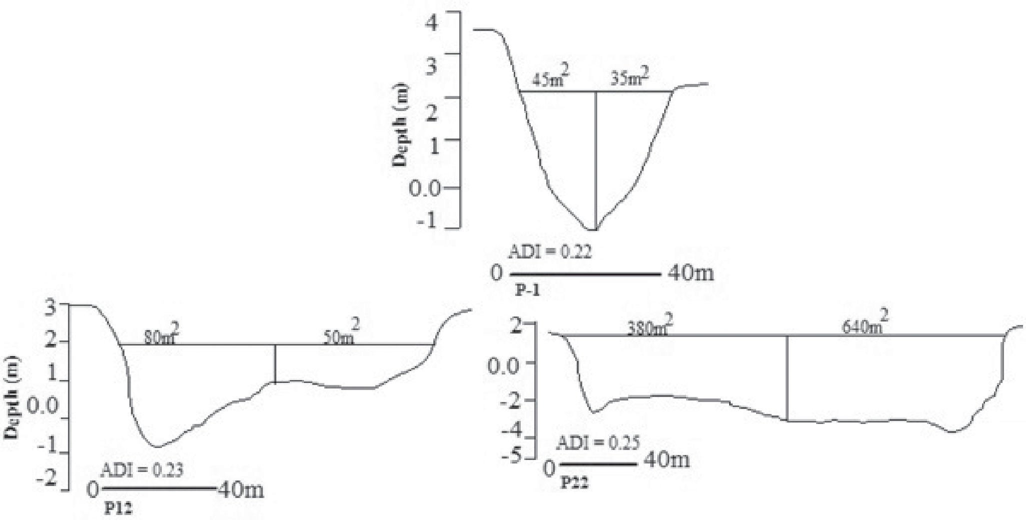


**Figure 5**. Symmetrical assessment of cross-sections of 2015

loop has been noticed at Faridkati (22°44.35′ N, 88°48.33′ E and between 35 km to 40 km). The length of the loop is 4.03 km. The distance between the two bends of this loop is only 17 m. The two successive profiles have been surveyed (P-15 and P-16) here. The values of the ADAI at these two sections are the same.

The variation of ADAI has also been discussed, based on the different river reaches — First reach (Kalanchi to Tentulia: 0–25 Km), Second reach (Tentulia to Faridkati: 25–35 Km) and Third reach (Faridkati to Basirhat: 35–55 Km). In the first reach 77.77% of the cross sections are highly symmetrical and 22.22% cross sections are moderately symmetrical. In the second reach 71.4% cross sections belong to the highly symmetrical and only 28.57% of the cross sections are moderately symmetrical. But in the third reach the picture is different, where 50% cross section is highly asymmetrical. The lower portion of the river is more dynamic and the river is capable of modifying its channel according to its hydrodynamic character. Therefore, in the lower portion, at the bend, a well developed point bar and pool have been noticed which give an asymmetrical form to the river channel.

### ADAI of 2015

In 2015, the value of ADAI has decreased than that of 2012. The range of the value is 0 to 0.29. In this year the highly symmetrical cross sections has not changed (63.63%) but the moderate symmetric cross section has increased from 18.18% in 2012 to 40.9% in 2015 (Table 1). In the first window the picture is same as of 2012. In the second window, the percentage of highly symmetrical cross section has been decreased to 57.14% from 71.4% in 2012. But in the third window moderately symmetric sections have increased abruptly from 16% to 66%. In this window, the percentage of highly asymmetrical sections has decreased from 50% to 0%.

### *The optimum cross section or projected cross section*

Traditional channel design methods for fixed boundary channels focus on efficient flow conveyance where water surface velocity is of primary importance. Some selected cross-sections have been shown in Fig. 6 along with their optimum cross-section. The semi-circular form of profile is usually non-existent in reality. On the other hand, trapezoidal cross-sections are more close to reality and are best-fit with the actual cross-sections. Only at Kalanchi, the form of the river cross-section is symmetrical. Here, the symmetrical trapezoidal form is a better fit than the optimum semi-circular form. In this form, the present river bed attains the optimum channel bed (Fig. 6). Moreover,

**Table 1**. The variation of ADAI in the different reaches of the Ichamati river

| Classes of cross-section based on ADAI | % of class (unit reach) | | % of class (segmented reach) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1st window 0–20 Km | | 2nd window 20–40 Km | | 3rd window 40–55 Km | |
| | 2012 | 2015 | 2012 | 2015 | 2012 | 2015 | 2012 | 2015 |
| 0–0.19 Highly symmetric. | 63.63 | 63.63 | 77.77 | 77.77 | 71.4 | 57.14 | 33.33 | 33.33 |
| 0.19–0.38 Moderately symmetric. | 18.18 | 40.9 | 22.22 | 22.22 | 28.57 | 42.85 | 16.66 | 66.66 |
| 0.38–0.57 Moderately asymmetric. | 13.63 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| >0.57 Highly asymmetric | 4.54 | 0.0 | 0..0 | 0.0 | 0.0 | 0.0 | 50 | 0.0 |

this form is efficient for accommodating the discharge. The rest of the cross-sections are asymmetrical. The deepest point of every cross-section usually attains the level of the bottom width and relatively little mass have to be excavated from the side of the channel bank. The amount of the projected mass, which will be excavated, would be decreased with increasing distance from upstream downward.

## Discussion

*General form of the cross-sections*

Different parameters have been taken into account to find out the relationship among the cross-sectional parameters of the Ichamati river viz. width (w), depth (d), area (A), discharge (Q), wetted perimeter ($w_p$), hydraulic radius (HR), width of the bed ($w_b$), width-depth ratio, and asymmetry (Knighton, 1998).

WIDTH-DEPTH RELATION

To denote depth (d), maximum depth has been used. Two linear regression lines have been used to represent the relationship in the data set of two years (2012 and 2015). The regression line reflects that the relationship of these two parameters is negative (y2012 = –0.018x –2.183 and y2015 = –0.012x –1.833). The relationship is stronger in 2012 than the year 2015 (2012: r = –0.55, $r^2$ = 0.3, 2015: r = –0.52, $r^2$ = 0.2). This relation indicates that the river is on its way to decay.

RELATION BETWEEN DISTANCE AND WIDTH: DEPTH

The relation has slightly deviated from 2012 to 2015. Though the two regression lines (y2012 = 1.776x –118.8, y2015 = 2.01x –141.0) show the positive results but the relation has become slightly stronger in 2015 (2012: r=0.42, $r^2$=0.17, 2015: r=0.43, $r^2$=0.18). Development of a fluvial erosion system is sometimes analogous to the growth of organism. This fundamental growth principle is known as the ‘law of allometric growth’. According to this law, the growth rate of an organ is a constant fraction of the relative rate of growth of the whole body. Similarly, a fluvial system is comparable to an organ of an organism and the rate of erosion in the fluvial system increases according to the allometric growth law (Strahler and Strahler, 2004). The rate of allometric growth of the river channel is not same throughout the reach. The scenario of downstream increase of width

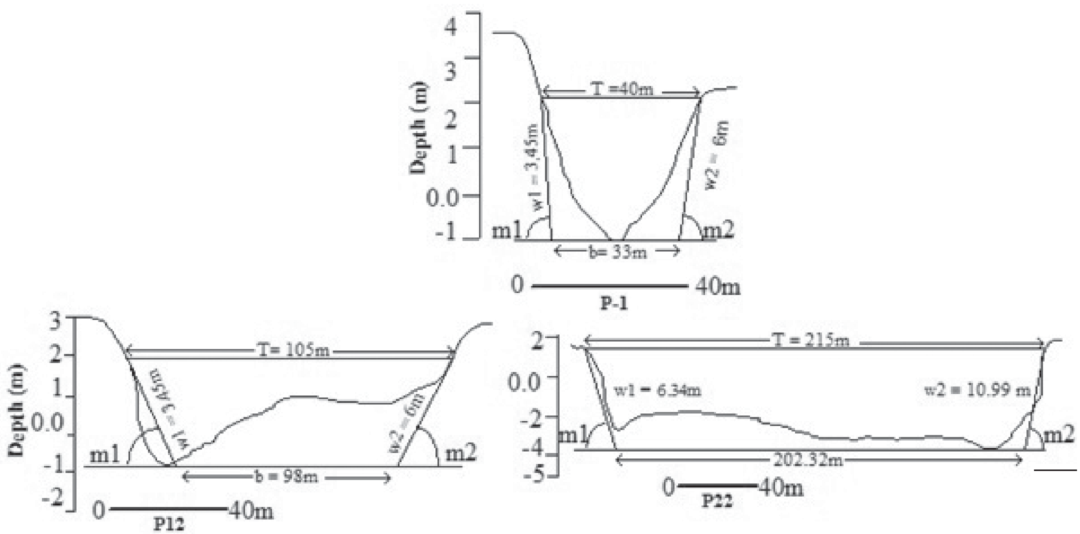


**Figure 6**. Optimum area of some selected cross sections

with distance is not same in 2012 and 2015 (2012: r = 0.85, $r^2$ = 0.72, 2015: r = 0.78, $r^2$ = 0.63). The width and depth both abruptly increase downstream of 40 km, but the rate of increase of the width is 2450% whereas the rate of increase of depth is 340%.

### CROSS-SECTIONAL AREA (A) OF THE CHANNEL

Cross-sectional area is the product of mean width (w) and mean depth (d) i.e. A= w.d). The linear regression (Fig. 7) indicate that the channel cross-sectional area increases with distance downstream (y2012 = 22.82x –258.6; y2015 = 27.97x –346). The diagram shows the correlation between: following (a) the actual value of each cross-section area and the corresponding distance and (b) the rate of change of cross-sectional area in percentage with distance. In the case of (a) the relation is very strong ($r_{2012}$ = 0.881, $r^2_{2012}$ = 0.777). In 2015, the regression line deviates from that of 2012 after 30 km which indicates that cross-sectional area has been increased substantially in the lower reaches (Fig. 7). In 2015 also the correlation between actual cross-sectional area and distance is strong ($r_{2015}$ = 0.84, $r^2_{2015}$ = 0.709).

In the case of (b) in 2012, the rate of change of cross-sectional area with distance in percentage shows a poor correlation ($r_{2012}$ = 0.038, $r^2_{2012}$ = 0.001). Similarly in 2015, when the rate of change of area is considered in percentage with distance, the relation is about the same of 2012 ($r_{2015}$ = 0.038, $r^2_{2015}$ = 0.02). This means that the rate of increase of area do not show a systematic pattern. But when,

The cross-sectional area of the river Ichamati shows marked changes from 2012 to 2015 (Fig. 4). If the entire reach of the river Ichamati is considered, the relationship between the change of cross-sectional area and distance does not show strong relation (r = 0.367, $r^2$ = 0.135). When the river reach is divided into two segments, the upper segment shows comparatively better correlation (r = 0.155, $r^2$ = 0.024) than the lower one (r = 0.02, $r^2$ = 0.0) (Fig. 8). This indicates that the change of area in the upper portion is not significant, but the lower portion of the river shows a reverse scenario. The rates of change of cross-sectional areas are not same throughout the river in 2012 as well as in 2015. In the upper portion (0–40 Km) of the river, the rate of change is more or less homogeneous (y = 0.852x –10.79, r = 0.41, $r^2$ = 0.169), but in the lower portion of

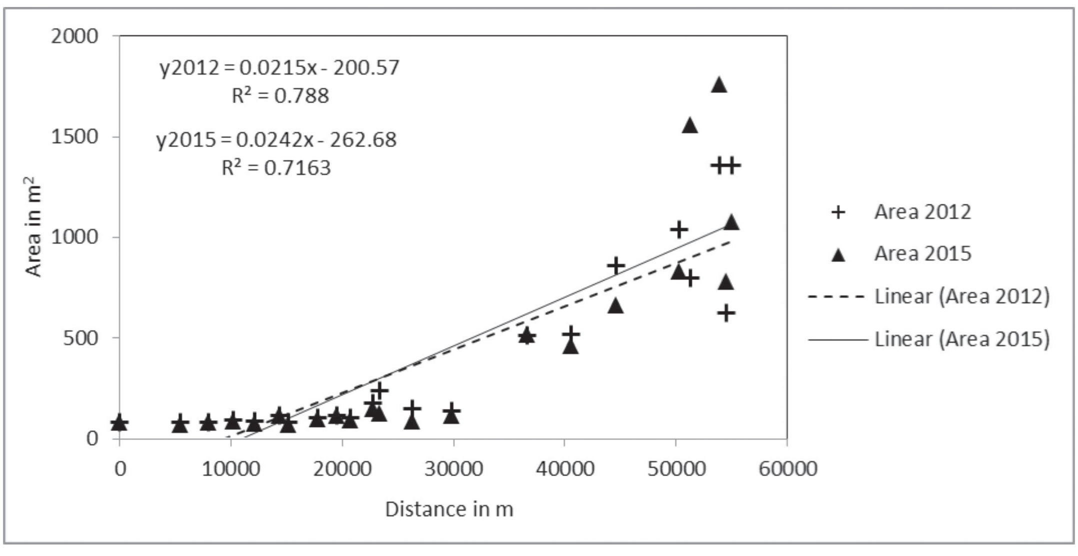


**Figure 7**. Relation between area and distance for the entire river as in the years of 2012 and 2015

the river (40–55 Km), the rate of the change of the cross-sectional area is not regular ($y = –4.927x + 304.9$, $r = 0.06$, $r^2 = 0.003$) (Fig. 8). Moreover, the rate of change has decreased with distance downwards. This indicates that, though the lower reach of the river is in better condition than the upper reach, but gradually it is going to decay with the river bed raised at the rate of 12.5cm $y^{-1}$ (Mondal and Satpati, 2015).

*Variations in hydraulic radius*

The hydraulic radius (HR) of a stream channel is defined as the cross-sectional area of the channel divided by the wetted perimeter (Summerfield, 1991). Higher value of the ratio indicates better channel efficiency (Spark, 1960). Not only the HR but also the channel shape and size are the other important factors of stream capacity.

VARIATIONS OF HR WITH DISTANCE

The distribution of HR shows that the value of HR gradually increases with distance towards downstream. The HR has a strong positive correlation with distance ($y = 0.057x + 0.442$, $r = 0.77$, $r^2 = 0.601$). This indicates that the efficiency of the stream gradually increases downstream. There is a notable demarcating line at 31.4 Km distance which divides the entire HR distribution into two different scenarios. The first scenario is of the upper reach (0–31.6 km) and the second one is of the lower reach (31.6 Km–55 Km), which corresponds to the two windows discussed earlier. If the upper reach and the lower reach of the river are analysed individually, a different picture comes out. In the upper reach the relation is marginally positive ($y = 0.009x + 1.094$, $r = 0.212$, $r^2 = 0.045$), because de-siltation was carried out frequently as a part of the river bed program within 2005–2007 (IWD, 2009). The lower reach of the river shows a different situation. The relation is negative and its magnitude is greater ($y = –0.050x + 5.961$, $r = –0.225$, $r^2 = 0.192$) than the first reach. This is because, the water from the river is diverted for various purposesdirections . In the upper reach the total input of tidal discharge is $292896 \times 10^4$ litres $day^{-1}$ whereas, the total water intake in agriculture land is $10071 \times 10^5$ litres (34.38 %) (Mondal and Satpati, 2017). Besides these, it is very common in the study area that the free tidal flushing has been interfered with by reclamation of spill areas for brick kilns and agricultural land by means of earthen embankments (Mandal, 1999).

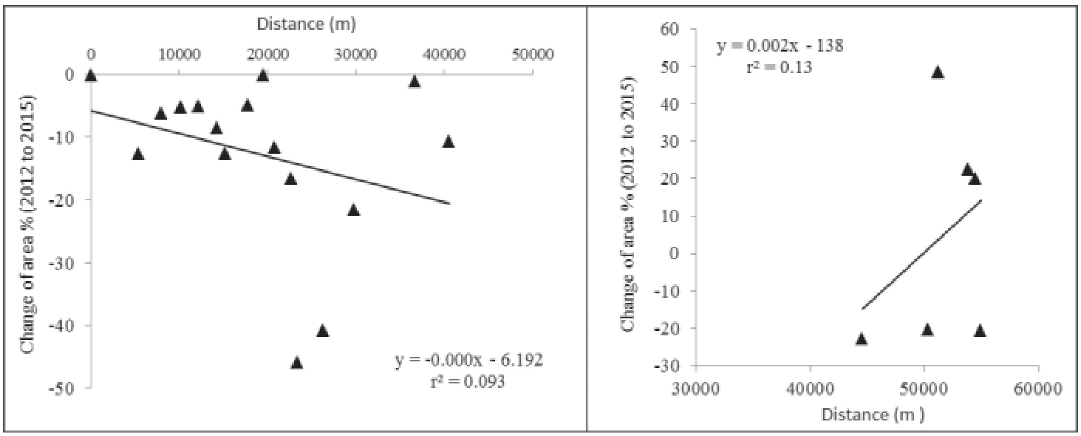


**Figure 8**. Rate of change of area and distance in the upper (0–40 km) and lower portion (40–60 km) of Ichamati (2012 to 2015).

As a result, sedimentation occurs during the slack period. Theses constructions not only force the river to deposit sediments within the channel which raise the river bed, but also reduce its tidal prism. All these events represent a lexical example of negative feedback system. This means that the circuit of changes has the effect of dampening down the first change (Chorley, 1962). In the upper reach, the Ichamati Rriver has reduced its channel area as per the availability of the discharge (Fig. 9).

VARIATION OF HR WITH CROSS-SECTIONAL AREA

The relation between area (A) and the hydraulic radius (HR) of the Ichamati river shows overall high positive relationship ($y = 0.001x + 1.359$, $r = 0.668$, $r^2 = 0.446$). The reach of the Ichamati river can be divided into three different zones according to spatial variation of HR values. In the first zone (0–31.4 Km or within 150 $m^2$ cross sectional area) 63.63% of the cross-sections are concentrated. The correlation is positive ($y = 0.005x +0.686$, $r = 0.45$, $r^2 = 0.205$). The next 18.18% cross-sections are concentrated within 31.4–49.5 Km or 150 to 800 $m^2$ cross-sectional area. The relationship is highly negative ($y = –0.008x +8.489$, $r = –0.93$, $r^2 = 0.883$). The third zone possesses 18.18% cross-sections and the limit of this zone is between 49.5–55 Km. This zone shows a marginally negative relationship ($y = –0.000x +3.730$, $r = –0.25$ and $r^2 = 0.021$). The second and the third zones are highly modified by human activities and are indiscriminately used for brick kilns and fisheries. People construct artificial embankments on both sides of the river as an extra protection against incursion of saline tidal water. For this reason the cross sectional area of the river is artificially increased. But the wetted perimeter remains the same.

*Symmetrical assessment of cross-sections*

The Areal Difference Asymmetrical Index (ADAI) has been used to discuss about the form of the cross sections.

ADAI OF 2012

Asthe sameThe Pearson's method has been applied to find out the correlation between the ADAI and distance. The relation is moderately strong ($r = 0.57$). To find out the correlation determination the linear regression line has been used. The form of the

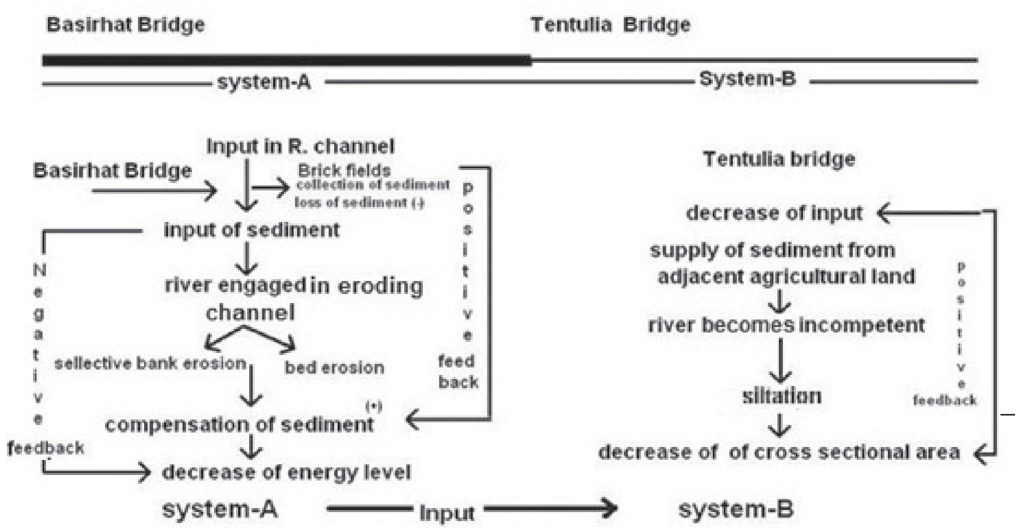


**Figure 9**. Human activities and fluvial process-response system (stimulus a: sand collection, stimulus b: agriculture).

equation is y = 0.005x + 0.020 and $r^2 = 0.327$.

ADAI OF 2015

The relation between the ADAI and distance is marginally positive (r = 0.2178). The value of the correlation of determination ($r^2$) is 0.047 (Fig. 10). The form of the linear equation is y = 0.001x + 0.012. These values indicate that the relationship between these two variables is not strong, which means that distance may not be an important factor for variation in ADAI. The inherent determining factor is actually discharge of the river. In case of river Ichamati, discharge is decreasing due to various human interventions and thereby decreasing stream energy also. Due to the lack of energy the river is going to be symmetrical gradually.

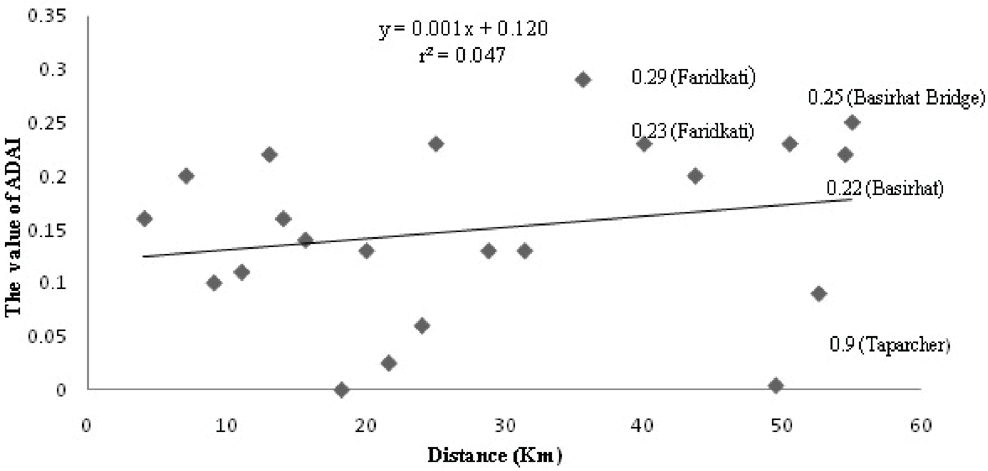


**Figure 10**. Relation between ADAI and distance in 2015

*The optimum cross section or projected cross-section*

The values of the index indicate that the cross-sectional areas in the downstream portion are not being able to maintain their optimum area in respect of their widths. The result of the relationship between OCI and distance is highly negative (y = –0.007x + 7.34, r = –0.76, $r^2 = 0.46$). However, the relationship cannot be generalised for the entire river. There are some cross sections like P-12, P-14, P-18 and P-20) which have been highly modified by sedimentation due to unwanted obstruction of river flow by nearby brick kilns and also the obstruction of the Basirhat bridge. So, these places show high OCI values. Barring these particular cases, the scenario will show a marginal negative trend (r = –0.03, $r^2 = 0.00$).

*The OCI and the geometric character of the Ichamati river*

The sinuosity index (SI), radius of curvature (Rc) are the important parameters of the channel geometry. There are two contradictory relationships between OCI to SI and OCI to radius of curvature (Rc). There is a marginal positive relation (r = 0.3, $r^2 = 0.09$) between Rc and OCI. Whereas there is a marginal negative relationship (r = –0.26, $r^2 = 0.06$) between the SI and the OCI. Though there is a negative relationship (r = –0.34, $r^2 = 0.12$) between SI and Rc on channel symmetry but OCI is independent to these geometric factors.

## Conclusion

The investigation shows that the relationship between width and depth shows better correlation in the second reach of the river (26–55 km). The w:d ratio does not increase at a fixed rate towards downstream. In the upper reach (0–26 km) the w:d ratio varies between 9.5–20, whereas in the second reach the maximum value of w:d is 83.33. In this reach the change in the area of cross-section is more or less homogeneous (r = 0.41), but in the lower reach the change of the cross sectional area is not regular (r = 0.06). The hydraulic radius also increases from upstream to downstream (r =0.77). The 2012 results show that 77.77% of the cross-sections in the upper reach are symmetrical; while 71.4% of the cross-sections are highly asymmetrical in the middle reach and 50% of the cross-sections are highly asymmetrical in the last reach. The value of OCI indicates that the upper reach of the river is in better condition but field evidences does not substantiate that. In the lower reach the river is not able to maintain its depth as per its top width. This is due to human intervention in the form of construction of bridge, brick kilns etc. But due to active tidal flushing, the lower reach of the river greaterexhibits some dynamism. As a whole these results indicate that the river is showing signs of degeneration.

## Acknowledgement

My thanks specially go to Prof. Lakshminarayan Satpati and Prof. Sunando Bandyopadhyay, Dept. of Geography, Calcutta University, for initiating two bathymetric surveys on the Ichamati river. I am also grateful to the students of the department of Geography who helped in numerous ways during the survey. The helpful comments and suggestions of the anonymous reviewer is acknowledged. I am also thankful to the Irrigation and Waterways Department, Government of West Bengal for their valuable suggestions.

## References

Al-Mayahi, D.S.B. (2011) A quantitative analysis of transverse river profiles and its applications for morphotectonics: a case studying Shatt Al-Arab River, Southern Iraq, *Mesopot. Journal of Marine Science*, 26 (1): 15–24.

Bandyopadhyay, S., Das, S. and Kar, N. (2015) Discussion: ‘Changing river courses in the western part of the Ganga–Brahmaputra delta’ by Kalyan Rudra (2014)’, *Geomorphology,* 227: 87–100, *Geomorphology.* [DOI 10.1016/j.geomorph.2015.02.037]

Basu, S. R. and Howlader, K. (2008) Some considerations on the process of sedimentation in the Ichamati tidal channel, *Geographical Review of India*, 70(4): 369–380.

Census of India (2011) Office of the Registrar General, India, 2A, Mansingh Road, New Delhi-110011, India.

Chorley, R.J. (1962) Geomorphology and General Systems Theory. *Geological Survey Professional Paper*, 500-B: 1–10.

CIVE: Civil Engineering Materials 2400. (2014) Open Channel Hydraulics. In *Fluid Mechanics*. www.efm.leeds.ac.uk/CIVE/FluidsLevel2 *(retrieved on 2014-05-31)*

Davis, W.M. (1899) The Geographical Cycle, *The Geographical Journal*, Blackwell Publishing on behalf of The Royal Geographical Society, 14(5): 481–504.

Framhingham, K.M. and Brown, N. (2002) Objective Identification of pool and riffles in human- modified stream system, *Middle States Geographer*, 35: 52–60.

Harmar, O. P. (2004) *Morphological and Process Dynamics of the Lower Mississippi River. Unpublished* PhD thesis, University of Nottingham: 409p.

Harmar, O.P. and Clifford, N.J. (2007) Geomorphological explanation of the long profile of the lower Mississippi river, *Geomorphology*, 84: 222–240.

Hey, R.D. (2006) Fluvial geomorphological methodology for natural stable channel design, *Journal of the American Water Resources Association*, 42(2): 357–386.

Hunter, W.W. (1875) *A statistical account of Bengal*: *Districts of 24 Parganas and Sundarbans*, Trübner and Co. London. 404p. https://archive.org/details/astatisticalacc06kiscgoog (retrieved on 2014-12-10).

IWD: Irrigation and Waterway Directorate (2009) *Survey Report*, Government of West Bengal.

Knighton, A.D. (1981) Asymmetry of river channel cross-sections: Part I. Quantitative indices, *Earth Surface Process and Landforms,* 6: 581–588.

Knighton, D. (1998) *Fluvial Forms and Processes*, Oxford University Press, Inc., New York, USA: 383p.

Lawler. D.M. (1993) The measurement of river bank erosion and lateral channel change: a review, *Earth Surface Processes and Landforms*, 18(9): 777–821.

Leopold, L.B. and Maddock, T. (1953) The Hydraulic Geometry of Stream channels and some Physiographic Implications. *U. S. Geological Survey. Professional Papers* 252: 57p.

Leopold, L.B., Wolman, M.G. and Millar, J.P. (1964) *Fluvial Processes in Geomorphology*. Eurasia Publishing House (Pvt.) Ltd., New Delhi 55 by arrangement with Messrs. W. II. Freeman & Co., San Fransisco, U.S.A.: 552p.

Lord, M.L., Germanoski, D., and Allmendinger, N.E., (2009) Fluvial geomorphology: Monitoring stream systems in response to a changing environment. In Young, R., and Norby, L. (eds.) *Geological Monitoring*, Boulder, Colorado, Geological Society of America: 69–103. (DOI: 10.1130/2009. monitoring (04).

Mackin, J.H. (1948) Concept of the graded river, *Geological Society of America Bulletin*, 59: 463–511.

Mandal, D.K. (1999) Ichhamati-Bidyadhari interfluve: A study in the perspective of drainage evolution with the help of remote sensing techniques. In Jha, V.C. (Ed.) *Geomorphology and Remote Sensing*, ACB publication, Kolkata: 413p.

Markley, G.P. (2004) Irrigation conveyance and control. In *Flow movement and Structure Design*, Biological and Irrigation Engineering Department, Utah State University, Logan, Utah: 180–190.

Mondal, I. and Bondhyopadhyay, L. (2014) Morphodynamic change of the Ichamati river and land use / land cover changes through space and time using remote sensing and GIS techniques, N24 Parganas, Bagdah, Bongon, Gaighata and Swarupngar Block, West Bengal, India. In *Proceedings of the International Symposium on Operational Remote Sensing Applications: Opportunities, Progress and Challenges*, Hyderabad, India December 9–12.

Mondal, I., Bondhyopadhyay, L. and Paul, A.K. (2016) Estimation of hydrodynamic pattern change of Ichamati river using HEC ARS model, West Bengal, India*, Modelling Earth System and Environment* 2: 125. https://doi.org/10.1007/s40808-016-0138-2

Mondal, M. (2011) Bank erosion of the Ichamati river: the hazard, its management and land resource development in Swarupnagar and Baduria CD blocks of North 24 Parganas District, West Bengal, *Geographical Review of India*, 73(4): 391–399.

Mondal, M. and Satpati, L.N. (2012) Morphodynamic Setting and Nature of Bank Erosion of the Ichamati river in Swarupnagar and Baduria blocks, 24 Parganas (N), West Bengal, *Indian Journal of Spatial Science*, 3(1&2): 35–43.

Mondal, M. and Satpati, L. N. (2013) Evaluation of the character of long profile vis-à-vis discharge patterns of the river Ichamati in a selected stretch of North 24 Parganas District, *India, Indian Journal of Power and River Valley Development*, 63(11-12): 183–188.

Mondal, M. and Satpati, L.N. (2015) Long profile analysis of Ichamati river with the help of best fit-curve, India, *Indian Journal of Geomorphology*, 20(2): 109–124.

Mondal, M. and Satpati, L.N. (2016) Changing character of pool-riffle sequence: a quantitative representation of long profile of Ichamati, India, *Indian Journal of Power and River Valley Development*, 66(1&2): 14–21.

Mondal, M. and Satpati, L.N. (2017) Hydrodynamic character of Ichamati: impact of human activities and tidal management (TRM), West Bengal, India, *Indian Journal of Power and River Valley Development*, 67(3-4).

Mosselman, E. (1998) Morphological modelling of rivers with erodible banks, *Hydrological Processes*, 12: 1357–1370.

NEH: National Engineering Hand Book (2007) Basic Principles of Channel Design, US Department of Agriculture, Natural Resources Conservation Service, Chapter 7, Part 654: 1–12. OpenNonWebContent.aspx?content= 17783.wba (retrieved on 2014-3-13).

Richards, K. (1982) *Rivers, Form and Process in Alluvial Channels*, Methuen, London and New York: 358p.

Rosgen, D.L. (1996) A Stream Channel stability Assessment Methodology. In Proceedings of the Seventh Federal Interagency Sedimentation Conference, Volume I, Stream Restoration: 18–26. (retrieved on 2012-03-13).

Rudra, K. (2014) Changing river courses in the western part of the Ganga-Brahmaputra Delta. *Geomorphology*, 227: 87–100.

Singh, V.P. (2003) On the theories of hydraulic geometry, *International Journal of Sediment Research*, 18(3): 196–218.

Sinha-Roy, S. (2001) A new approach to the changing of transverse river valley profile and implications for morphotectoinics: a case study in Rajasthan, *Current Science*, 81(1): 106–111.

Sparks, B.W. (1960*) Geomorpohology*, Longmans Green, London: 371p.

Strahler, A.H. and Strahler, A. (2004) *Physical Geography: Science and Systems of the Human Environment*, 3rd edition John Wiley and Sons. Inc. New York: 816p.

Summerfield, A.M. (1991) *Global Geomorphology*, Pearson, Education. Ltd., Edinburg gate, Harlow, England: 547p.

Swamee, P.K., Mishra, G.C. and Chahar, B.R. (2000) Comprehensive design of minimum cost irrigation cannel sections, *Journal of Irrigation and Drainage Engineering*, 200: 322–327.

Thandaveswara, B. S. (2011) *River flow measurements*. http://nptel.iitm.ac.in/courses/IIT-MADRAS/Hydraulics/pdfs/Unit4/4 (retrieved on 2014-6-10)

Thorne, C.R. (1981) Field measurements of rates of bank erosion and bank material strength. In *Erosion and Sediment Transport Measurement* (Proceedings of the Florence Symposium), IAHS Publication 133: 503–512.

Date received : 2 April 2019
Date accepted after revision: 3 December 2019