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Human intervention on river system: a control system—a case study in Ichamati River, India

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Abstract

With the advancement of human civilization, the river cascading system has been converted into a control system and man has a significant role in it. This paper has examined how the rivers, flowing across the highly populated Ganga–Brahmaputra Delta, are being obliterated due to the close contact of human civilization, as is an example of Ichamati River, an important distributary channel in the district of North 24 Parganas, India. The Ichamati River drains the east and south sides of the North 24 Parganas district and is covered by deep Quaternary sediments produced under tropical monsoon climate in India. The district is densely populated. GIS and a detail field investigation along with two case studies have been incorporated to extract the relationship between man and river, as a control system. This study significantly will draw the attention how the river has modified itself against imprudence human attitude towards environment without any proper river management. This paper has examined the human interventions over river, as a control system, and has discussed about the associated changing characters of river behaviour as the response, e.g. (1) longitudinal profile has been changed temporally due to human impact; (2) the characters of cross profiles have been changed due to the impact of bridge and other human influences; (3) the tidal discharge of the river has been changed downstream upward due to intake of water for different purposes. The primary objective of this article is to examine the role of man as an important controlling element of a river system.

Keywords Cascading system · Control system · Land use · Biological element · Negative feedback

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1 Introduction

Human intervention over the river is well studied (Fuller et al. 2003; Rinaldi 2003; Brookes et al. 1983), which belongs to 'system analyses'—a fundamental basis for the investigation (Chorley 1962) of river management. The origin of the word 'system' goes back to the seventeenth century and is derived from the French 'systeeme' or the Latin, 'systema' and Greek, 'sustema'. The word 'sustema' has been derived from two words, sun- with + histanai- 'setup' (Oxford Advanced Dictionary, 7th ed.). The definition of the word 'system' is thus 'a set of objects together with the relationship between the objects and between their attributes' (Bertalanffy 1969; Hall and Fagen 1956; Chorley 1962). Here, two technical terms have been used, such as, '*set'* and '*relationship*'. The term '*set*' denotes the collection of conceived as a whole, different and independent of order, well-defined objects; therefore, the river is a cascading system which is defined by the path followed by throughputs of energy and mass (Ahlawat 2013; Strahler 1980). If we consider the river system as a set (R), it is a union of three different elements, i.e. energy (E), mass (m) and form (F) (Buffington et al. 2003; Montgomery and Buffington 1993), and human activities (H) that promote degradation or aggradation (Ashworth and Best 1994; Peakall 1995) or extrinsic variable (Schumm and Lichty 1965). The set can be formulated as $R = \{E, m, F, H\}$. The first element is energy (E), and $E = $(Ke U Se). Energy is the sum of kinetic energy (Ke), latent in the water, which is transformed from potential energy (Richards 1982; Leopold et al. 1964) and solar energy (Se) (Evans et al. 1998). The second important term is 'relation'. The basic concepts of relation are: 'order pair' and 'Cartesian product set'. Here, the term relation denotes a binary relation. A ('a' is the element of A) set R is a binary relation if all elements of R are order pairs, i.e. $a \in R$. In such a way, in a set 'z' there are two element, x and y, such that $z = (x, y)$ or $x. R. y$. We can say x is in relation R with y. When the character of the element in a set changes, the relation between the objects obviously changes. If the character of any element of a system changes, this changes also influence another element and that influence is denoted as a relation. And it is reflected by the behaviour (i.e. output—it may or may not be) of the system. According to the character of binary relationship, we can describe the river system as follows: R *(river system)* $= \{E, w, L, Cp, Lp\}$. In a unit river, the total energy is always dissipating (Langbein and Leopold 1964). Water and load belong to mass (m), which is the proper subset of R. The character of load changes from source to mouth, and thus, L = {LU, LL}, LU: load in upper stream {bolder, pebbles, etc., big particles (a): belong the character p}; LL: load in lower stream {sands, silts, etc., small particles (b): belong the character q} (mass elements) (Church 2006). Therefore, we can write LU = {a: a (p)} and LL = (b: b (q)}. In a cascading system such as a river system, the shifting from LU regime to LL regime is a gradual but continuous process without a pause of threshold demarcation. In an undisturbed (i.e. external influence) river system, there is a consistency in the relationship among the elements of different sets. In a single river system, the shifting of one regime to another is adjusted by energy management. It is a homoeostasis or negative feedback system, and output is the formations of different types of landforms (Yilmaz 2006). The third major proper subset of the river system is a form element and $F = \{Y, X\}$ (Mondal et al. 2018). We can represent the set concept of the river system as follows (Fig. 1).

The river is a process response system (Charlton 2008; Chorley et al. 1984a, b), and it also reflects s self-regulatory mechanism or negative feedback system (Leopold and Wolman 1960). When the process response system is interrupted by human intervention, it is called as control system (Hillman and Brierley 2005; Bischoff et al. 1997) and the total

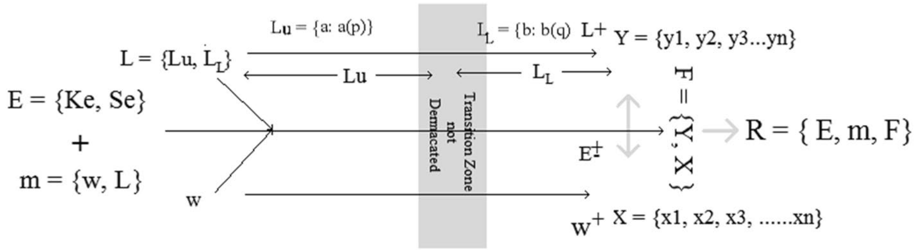


Fig. 1 Different elements of a river system: W+ means the increase in water, E+ indicates an increase in energy, and L+ indicates an increase in load. Source: authors

system falls into a chaos (Kesel 2003). This chaos leads to the system towards a deteriorating condition (Brookes and Shields 1996; Dudgeon et al. 2006). In a river system, character and functional attitude of every element change from one regime to another in their own context. For example, we can say that boulder, pebbles are predominating elements in the upper or mountainous region of a certain river and silt; sands are predominating elements in the lower portion of the river. The character of load changes in a gradual way. Not only loads, energy, a gradient of longitudinal profile also changes from one regime to another. The locations of such 'regime-change' have been indicated as '*transition zone'* (Rowntree and Dollar 1996) (Fig. 1). In a river system, there are different transition zones, i.e. energy transition zone, slope transition zone, bed load transition zone, Froude number transition zone, specific energy transition zone, etc., which collectively make the river a complex system. In an uninterrupted river, the shifting of one transition zone to another is systematic, whereas there is abruptness of such shifting in a disturbed river. Human intervention on large river is not uncommon (Nilsson et al. 2005; Schumm 2007; Fathy 1956; Eschner et al. 1986; Livesey 1963; Somogyi 2000; Hadfield 1986; Collier et al. 1996; Warner 2000). Human beings continuously exploit the river (Wallick et al. 2007), and it is important to re-examine the role of man, as a biological element, on river system. The Ichamati River is an irregular meandering course which is in a gradual decaying condition. A vast studies have been conducted on Ichamati River in the recent past, e.g. significance and geomorphic effect of bank erosion (Mondal 2010); character of long profile and impact of bridge (Mondal 2011a, b); management of bank erosion (Mondal 2011a, b); mechanism and nature of bank erosion (Mondal 2012); evaluation of the character of long profile vis-a-vis discharge pattern (Mondal and Satpati 2013, 2014); changing character and decaying pattern of the long profile with the help of best-fit curve method (Mondal and Satpati 2015); character of pool-riffle sequence (Mondal and Satpati 2016); hydrodynamic character (Mondal and Satpati 2017); and changing character of cross section (Mondal et al. 2016). Mondal et al. (2018) derived an index (i.e. OCI) to indicate an optimum cross section of river channel based on studies of the Ichamati River; its channel shifting, sinuosity index, physical and chemical properties, turbidity index, etc., have also been highlighted by Mondal and Bandhyopadhyay (2014a, b); changes of hydrodynamic pattern (Mondal et al. 2016) and water quality of Ichamati River (Mondal et al. 2016), etc. But all of these have approached with more or less singular aspects, and none have discussed about the river response. In this study, the Ichamati River has been selected for a holistic discussion. The river is indiscriminately used by the people living on the riverside in various ways. This study may be considered as the first scientific investigation on this important river in the context of response of the river to human intervention. Our aim is to discuss about the changing pattern of the geomorphic character of the Ichamati River over space due to human intervention under similar physical environments along its course. The principal objectives of the present paper are: (a) analytical discussion about the land-use pattern along the river and different modes of use of river, as external stimuli; (b) the behaviour of the river or the response of the river in connection with these stimuli as a control system or how the river reacts with human behaviour. Mention may be made that the river has experienced a number of floods occurred in the past, i.e. in the years of: 1802, 1823, 1838, 1857, 1859, 1867, 1871, 1885, 1890, 1936, 1938, 1952, 1955, 1959, 1966, 1970, 1971, 1978, 1984, 1999, 2000 and 2004 (Basu and Howlader 2008; Mondal et al. 2018), severe bank erosion at different locations (Sarkar 2004), which brings about huge monetary and as well as loss of life. This paper seeks to understand the behaviour of the river in the context of human intervention.

2 Methodological issues

2.1 Study area

Geographically, the study area is located between 22°10′N and 23°11′N of latitudes and 88°37′E and 89°E of longitudes (Fig. 2). It refers to Ichamati River of North 24 Parganas, W. B., which drains to eastern side of the district North 24 Parganas, a part of GBD, and more than half of the area is lying below 3-m contour line and with the mean sea-level 'zero' lying along the coastline (Bagchi and Mukherjee 1978). The river is a linkage between the 'Nadia group of the river' in the north and Sundarban in the south (Mondal and Bandyopadhyay 2014a, b). Concerning the position of the river, it should be noted that it is a tidal river, which has been bifurcated from the Mathabhanga River, a distributary of the Padma River. The river flows southward along a gradually increasing salinity (Mondal et al. 2018), keeping three blocks on both sides, i.e. Swarupnagar, Baduria and Basirhat. The Ichamati River is underlined by thick recent sediments deposition and characterized by silt and clay. The aforesaid blocks are highly populated (Swarupnagar: 1190/sq. km, Baduria: 1587/sq. km) (Census report-2011). Referring to some rivers, a few preliminary remarks are necessary to contextualize this work, namely Bhagirathi-Hugli River, western side of the study area has been transformed into a sewage (Rudra 2014), and this statement has been well explained by Bandyopadhyay et al. (2015). The Saraswati River, a mediaeval outlet of the Bhagirathi-Hugli, has been converted into a seasonal river (Rudra 2014). The Bidyadhari River in the south-western side of the study area is connected with the upper Raymangal estuary of the eastern Sundarban (Bandyopadhyay et al. 2015), which is used to get its discharge from few minor rivers (Hunter 1875a: p. 25) and now seems to be an agricultural land (Bandyopadhyay et al. 2015). Another example is the Jamuna River that was bifurcated from the Hugli at Tribeni (Hunter 1875a: p. 25) and got detached from the Hugli during 1849–1855 and 1917–1918 (Bandyopadhyay et al. 2015). Earlier, the Jamuna was navigable by large-size trading boats, but now it is a narrow and feeble channel. The east-flowing Jamuna meets with the Ichamati, which was referred to as 'the Jamuna or Ichamati' by Hunter (1875a, pp. 24–26). Concerning the position of these rivers, it should be noted that the Ichamati River is very important in this region, but it is going to be decaying very fast, and it may be lost forever if proper river management is not undertaken. Mention may be made that there is no climatic and geological variations in this region, as it is characteristically under the humid tropical climate with mild winter

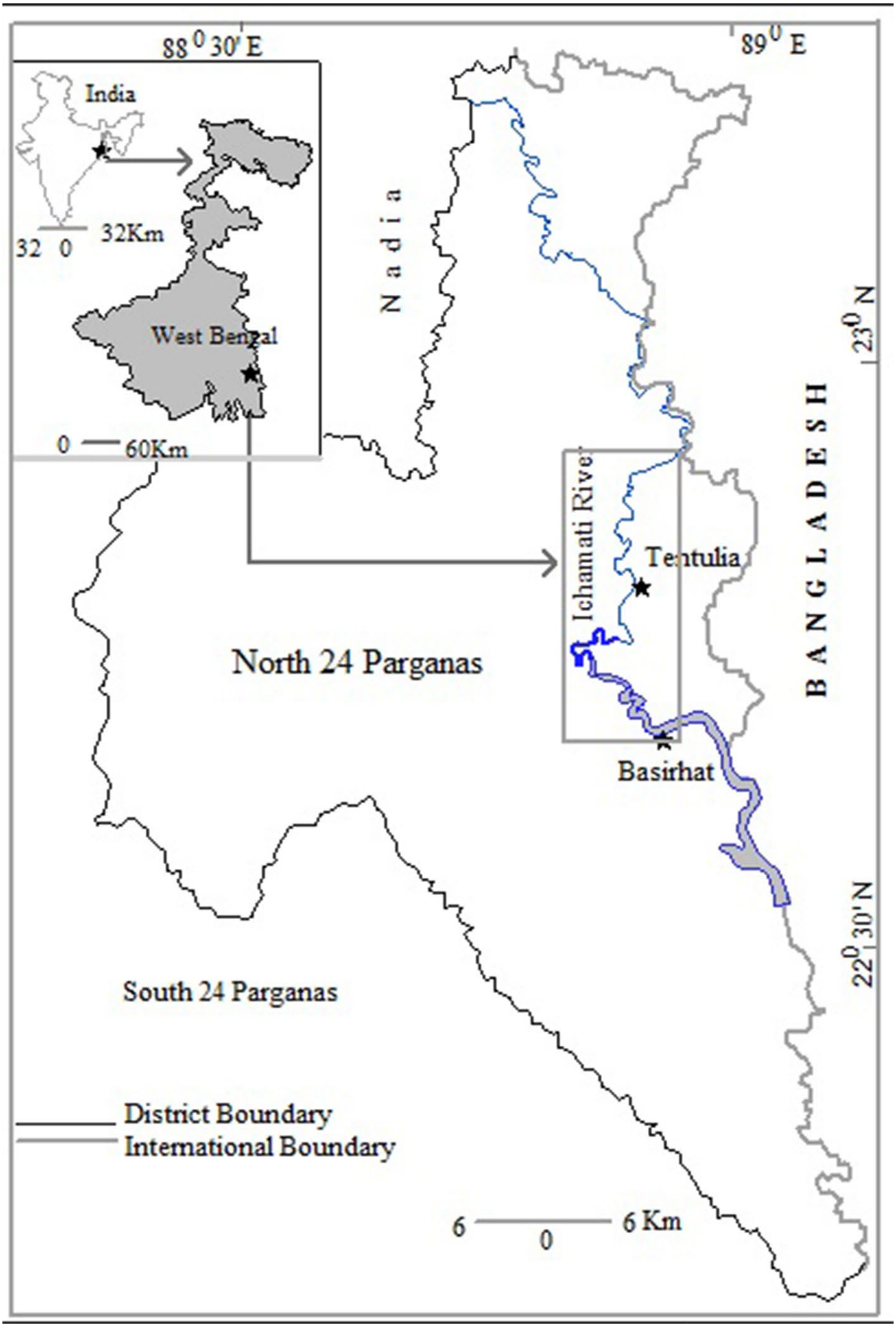


Fig. 2 Location of the study area—the selected reach of the Ichamati River

from November to January. The Bengal delta is formed by a chain of fluvio-tectonic actions operating over the neo-miogeosyncline of the Bengal Basin (Sengupta 1966). Geological investigations reveal that the subsurface geology is completely blanketed by the quaternary sediments comprising a succession of silty clay, sand of various grades and sand mixed with occasional gravels and thin intercalations of silty clay (Sikdar and Sahu 2009). Early reports on the hydrology of the area suggest that there are interconnected, shallow semi-confined to confined conditions' aquifers (12–15 m below ground level) in the upper plain. There is generally a south-easterly gradient of the water surface sub-parallel to the general slope of the area (Basu and Sil 2000; Chakraborty et al. 2009). The district of North 24 Parganas of West Bengal is located in the southern part of the Bengal Basin. The Basin is actually a pericratonic basin and comprises of Ganga–Brahmaputra Delta (GBD) (Basu 1981). The Ganga–Brahmaputra and other river systems bring huge sediments from the Himalayas, and the surrounding Indian shield area has converted the basin area as one of the biggest modern delta systems in India (Roy et al. 2010). The study area belongs to the semi-active mature portion up to the Sundarban from the south of the moribund delta (Bagchi 1944). Therefore, the present landscapes of the study area are: (a) 3-m interval map shows that the study area more than half area is lying below 3-m contour (Bagchi and Mukherjee 1978); (b) it is often similar type of flat landform assemblages as is seen across the zones, only with different absolute heights (Bandyopadhyay 2007); (c) all of these areas are dotted with human settlements, agricultural lands, ponds, etc. These make the morphological characterization of the different deltaic zones rather difficult (Bagchi and Mukherjee 1978); and (d) 1-m SRTM elevation data and multi-resolution satellite images reveal that the study area belongs to deltaic lowlands and cannot be classified according to relief but the availability of tidal intrusion or not (Bandyopadhyay 2007).

2.2 Field methods

2.2.1 Data collection and construction of longitudinal and cross profiles

A 55-km alluvial reach of the Ichamati River between Kalanchi and Basirhat was surveyed in 2012 and 2015, through both traditional pole-method (upper study area: Tentulia) and modern eco-sounding method (lower study area: Basirhat) (Fig. 3). The cross-sectional profiles of any river are useful for documenting changes in vertical (i.e. bed) and lateral (i.e. bank) stability. Before measuring the cross-sectional profile, we have selected different benchmarks at different locations (4 m: Tentulia (Swarupnagar), 3.14 m: Baduria, and 3.14 m: Basirhat) (Ogdahl et al. 2014). In total, 22 cross sections have been measured in the study area and 8 cross sections [which were spaced at irregular basis at lower reach of the Ichamati River (Fig. 3)] among them were surveyed by eco-sounder–GPS collaboration method at the lower reach of the river. The survey, therefore, provides a high-resolution data set to study the cross profile as well as the long profile (Harmar 2004). Models of the longitudinal profiles, using simple mathematical functions, are made considering four functions for describing the form of longitudinal profiles: the linear function $Y=a-bX$, the exponential function $Y=ae^{bX}$, the power function $Y=ax^b$, the logarithmic function $Y=a \log X$, where Y is elevation ($H/H0$); X is the length of the river ($L/L0$); and a, b are coefficients independently determined for each profile (Rädoane et al. 2003). In this paper, conventional regression analysis, $y=a+bx+cx^2$, has been used to construct the long profile.

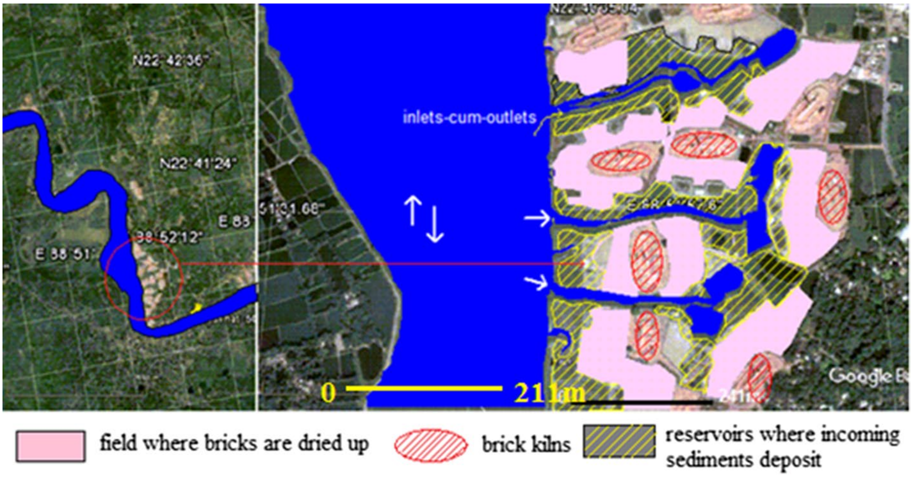


Fig. 3 Brick-making process. These identified places have been marked on a satellite image (collected from Google Earth Pro version-2015) after field survey. During the high tide, the tidal water enters (white arrow) into the nearby reservoirs through inlets-cum-outlets which are followed by gradual sedimentation. Later, the sediment is used for making the bricks

2.2.2 Velocity measurement

Velocity is one of the most important parameters of river morphology which has been measured by using a current meter, on a new moon day (15/8/2015), at Basirhat. The Price AA current meter has a wheel of six metal cups that revolve around a vertical axis. A five-volt cell provides the power for the work of the wheel. An electronic signal is transmitted by the meter on each revolution allowing the revolutions to be counted and timed. Because the rate at which the cups revolve is directly related to the velocity of water, the time of revolutions is used to determine the water velocity. This current meter is designed to be attached to a steel wire for measuring the depth of waters. During the measurement, the weather condition was calm and the wind was mild. We measured depth at each site with a reading stuff and took velocity at different depths, i.e. surface, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 4 m and 5 m (Diebel 2003). The Ichamati River is characterized by diurnal fresh and tidal water. The upper reach (Tentulia) is dominated by freshwater, and the lower reach (Basirhat) is dominated by tidal inflows. We have measured the total revolution of the cup of the current meter in 30 s. After that, we have applied the formula, velocity $(v) = 0.0069 + \text{RPS}$ (revolution per second) 0.0838. It may be noted that data pertaining to groundwater recharge or discharge, evaporation rate, previous information of the velocity and discharge of the Ichamati River are not available here. On the field, we have collected the hydrological data in three sessions, i.e. pre-monsoon (April to May), monsoon (June to September) and post-monsoon (October to March).

2.2.3 Calculation of the tidal prism

A number of research paper, works on tidal river, indicated that there is a relationship between tidal river and tidal prism (O'Brien 1969). There is a relationship between the observed tidal prism and the minimum cross-sectional flow area, as, i.e. Ac = C P n, where

Ac = the minimum inlet cross-sectional area in the equilibrium condition, C = a coefficient, P = the tidal prism and n = exponent. We have applied the equation, with Ac = 43.42. P. 0.9985 (Shampa and Pramanik 2012) to calculate the tidal prism.

2.2.4 Extraction the data of land-use land cover

Collection of land-use land cover (LULC) was completed using field surveys supplemented with remote sensing (RS) data of the study area. RS data of IRS P6 LISS III have been used. The IRS P6 LISS III provides data in four spectral bands: green, red, near infrared (NIR) and short-wave infrared (SWIR), with 23.5-m spatial resolution and 24 days repeat cycle. The spatial resolution is suitable for 1:50,000 scale mapping. The study area is covered in 13 IRS LISS III scenes. Two data sets have been used: one acquired during April/May and another is acquired during November/December. These data were used to capture the change of LULC in the study area during the pre-monsoon and the post-monsoon seasons, respectively. The data have been extracted on both sides with 500-m buffer area along the banks of the river (Fig. 4).

3 Results

3.1 Changes of land-use pattern

Spatial changes in land use have been investigated in relation to alterations of the channel process (Lach and Wyzga 2002). Land use is the ramification of footprint of human beings on a virgin land, and thus, it is important throughout the world, because of its relationship with different human activities. It helps us to understand the human perception regarding its immediate natural surroundings and the relationship between man and the natural environment (Tripathi and Vishwakarma 1988), 'the use of 'land cover' by human society, politics or cultural 'function' of land cover' (Aspinall and Hill 2008), and 'the term land use relates to the human activities associated with specific piece of land, features present on the earth surface' (Lillesand and Kiefer 1987). The variations of land-use pattern throughout the river basin suppose to keep a great impact on the river system (Brierly 2008; Sartz 1973). The significance of variations of land-use pattern has be identified as in: the first zone (0–20 km) (1–3 segment) with length of the river course: 20 km, area of the river channel: 438.25 m^2; the second zone (20–35 km) (3–8 segment) with length of the river course: 15 km, area of the river channel: 888 m^2; and the third zone (35–55 km) (7–12 segment) with length river course: 25 km, average area of the river channel: 2390.4 m^2 (Fig. 5). In the first zone, the classified area is 31,303 m^2, whereas the area that belongs to the river is 1753 m^2 that covers 5.6% of the total first zone. The other important land cover in this zone includes agriculture (911,862 m^2 or 37.89%), open land (7814 m^2 or 24.96%), inland water body (1658 m^2 or 5.29%), brick kilns (278 m^2 or 0.88%), open land (7814 m^2 and covers 24.96%) and natural vegetation (8025 m^2 or 25.63%). The total area of the second zone is 23,674 m^2, which comprises of river (2664 m^2, that is 11.25%), agriculture (5196 m^2 and 21.9%), open land (3728 m^2 or 15.74%), inland water body (1236 m^2 or 5%) and brick kilns (931 m^2 or 3.9%). The area of the third zone is 42,282 m^2. The area of the river is 11,952 m^2 (28.26% of the third zone), which is followed by natural vegetation (6697 m^2 or 15.83%), open land (6390 m^2 or 15.11%), agricultural land (5600 m^2 or 13.24%) and brick kilns (4066 m^2 or 9.61%) within this zone (Fig. 5).

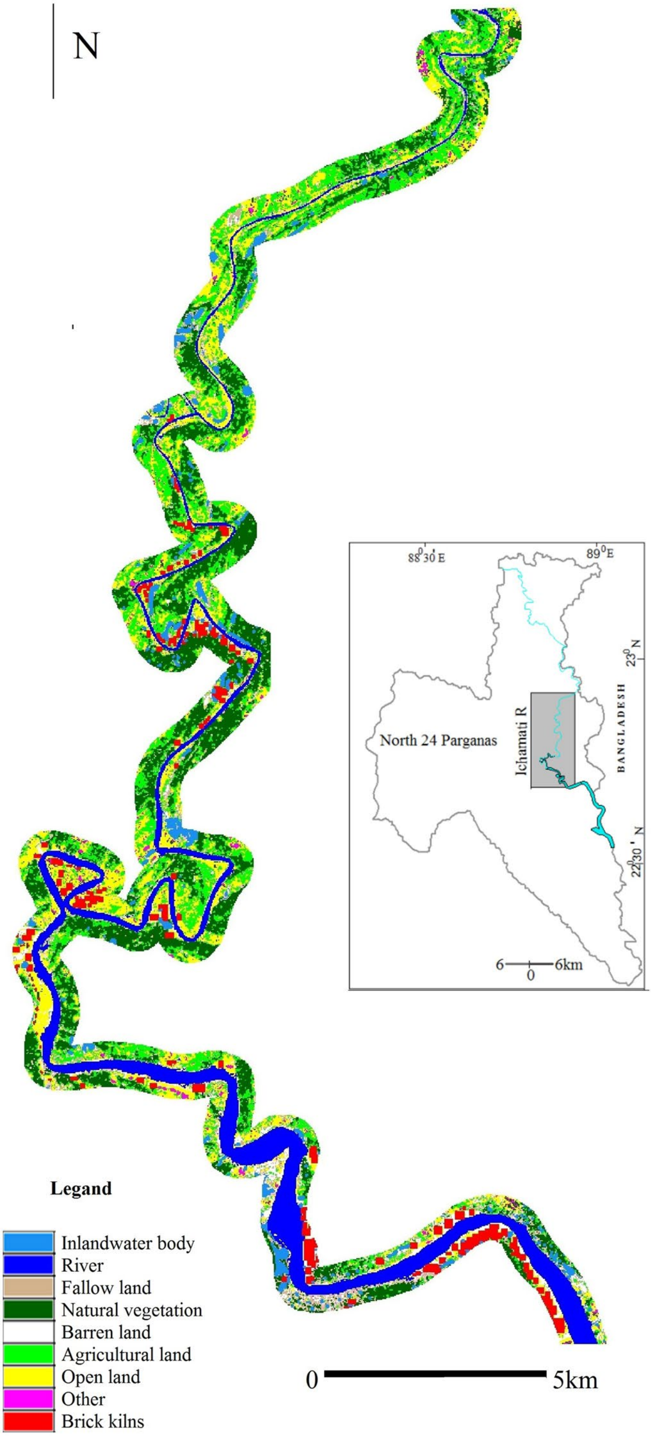


Fig. 4 Land-use pattern in the Ichamati basin, demarcated by 500-m buffer on both sides of the river banks

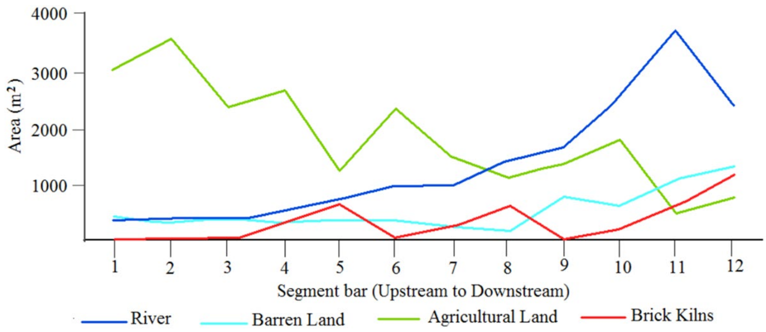


Fig. 5 Change of land-use pattern: area of agricultural land has decreased, but the area of the river, barren land, brick kilns have increased gradually from upstream downwards

The channel area of the Ichamati River has increased from upstream downwards (correlation coefficient: $r = 0.89$, coefficient of determination: $r^2 = 0.79$ (Fig. 6a). The area of the river and the area of the brick kilns both have increased from upstream downwards: $r = 0.57$, $r^2 = 0.33$ (Fig. 6b). In the lower reach, the area of the river is enough to provide a huge amount of sediments to the nearby brick kilns for making bricks. Though the coefficient of determination (r^2) shows an insignificant result, the equation has been considered in the sense that the brick kilns only have concentrated at the lower reach of the river, but have a great impact on its hydrodynamics. On the other hand, the relationship is highly negative: $r = -0.75$, $r^2 = 0.56$ between agricultural land and channel area (Fig. 6c). Because

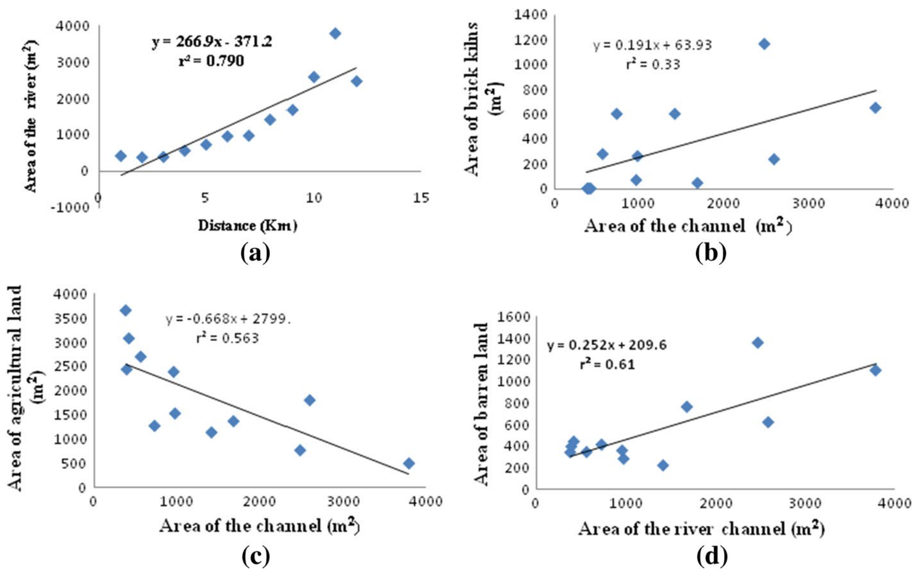


Fig. 6 **a** River area has been increased with distance; **b** area of brick kilns has been increased with river area; **c** area of the agricultural area has been decreased with river area; **d** area of barren land has been increased with channel area

in the lower reach, the river is characteristically saline that is unfavourable for agriculture. In the lower reach, the extensive sandy point bars create the barren land which gradually decreases in size with the river area towards upstream (Fig. 6d).

3.2 Existing hydrodynamic problems of the Ichamati River

The incoming high tidal water is comparatively denser and enters landward like a rotating screw. This type of incoming tidal current excavates the river bed and produces a huge amount of suspended sediments. Characteristically, the Froude number of river flow is between 0.14 and 0.26 (Mondal et al. 2018), so the flow of Ichamati river is supposed to be non-turbulent or laminar type (Moriswa 1985), which has been matched with our own experiment. The incoming volume of silt accumulation is 277,589.92 m^3/month, and rate of sedimentation during the monsoon period is 16,328.82 m^3/month and 11,109 m3/month in the non-monsoon period (Mondal et al. 2018). If the river is undisturbed, the returning low tide further excavates the river bed; thus, a balance between erosion and deposition is maintained. As there is hardly any input of non-monsoon discharge from its parent river, the balance between deposition and erosion is disturbed and the river has turned into the ground of sedimentation. Out of 6% annual silt deposition, 5% silt deposition took place between June and October and rest deposition took place during the month of November and May (Mondal et al. 2016). The turbidity of suspended sediment load is shown of the lower stretch average value 600–700 NTU (turbidity unit) (Mondal et al. 2018).

These zones are characterized by regular influxes of tidal water through the Ichamati River twice a day. The tidal bore of morning time is stronger than the time of evening/afternoon. The morning tide increases the water level of Ichamati River by above 1.5 to 2.5 m, while the evening tide increases the tidal level by about 1 to 2 m daily. In the monsoon, during the rain, the impacts of these two tides are felt less due to the input of freshwater flow of the discharge of the Ichamati River. In the pre- or post-monsoon period, in the absence of rainwater, the impact of tidal effects is enhanced and the tidal water reaches up to Kalanchi. It is surprising that the distinct inward flow of tidal water into the Ichamati River is never prominent. The duration of the high tidal period is much longer than the ebb period. The high tidal period lasts for about 7 h daily, which is considered to be a great hurdle for the load transfer of the Ichamati River. The river is not able to transport the bed load due to the short period of ebb phase and lack of strong undercurrent. The maximum velocity zone (0.6–1.0 ms^{-1}) occurred at about 4 m depth from the surface ($r^2=0.636$). The injection of saline water by tides into the upstream sweet water of the Ichamati River has an indirect but more lasting effect on the load–movement behaviour of the Ichamati River. After reaching its maximum path, i.e. the specific point in the tidal reach of the river, as the wedge of salt water approaches this point from downstream, the tidal flow, upon meeting this saltwater wedge, lost its velocity. For this reason, the coarse particles of the suspended load will settle down as per the Stoke's law. But very fine sediments get deposited very slowly or may not settle down at all, while particles subject to electrochemical reaction flocculate upon contact with the salt water (Basu and Howlader 2008). For this, the clay particles coagulate to form egg-sized 'mud balls'. Such heavy mud balls can, in no way, be transported by the feeble discharge of the Ichamati River. As such, these get deposited on the river bed in the form of shoals (Basu 1981). Thus, the during the freshets, the net drift of sediment carried by the river Ichamati is seawards, whereas during the dry season in the upper reach of the Ichamati River, landward redistribution takes place due to stronger tidal flood currents. The dry season redistribution of sand is in excess of the freshet improvement and every year the capacity of the river channel decreases gradually in the study area. The relative transport capacity of tidal current is high up to Tentulia (mean velocity = 0.67 ms^{-1}), after which the transportation capacity of the river decreases progressively, e.g. at Kalanchi the mean velocity = 0.14 ms^{-1} (Mondal et al. 2016).

3.3 Human activities as an element of the river system

3.3.1 Use of river water in the brick kilns

It should be noted that there is the agglomeration of brick kilns at the lower reach of the river (Fig. 4) due to the lowering of transport capacity of the river. These brick kilns collect coarse grain sand, which is very essential for making brick, from the river in two ways, e.g. (a) indirect way and (b) direct way. The river receives $12{,}705{,}984 \times 10^3$ L of total tidal water in a day. The coarse grain sand is collected indirectly from the lower reach of the river. Many canal-like reservoirs have been built in the brick kilns, where silt and sediments (i.e. 6 × 106 m^3 or $421{,}875 \times 10^4$ L water that is 33.2% of total discharge) get deposited during high tides as the reservoirs are joined with the river through inlets-cum-outlets. These channels run parallel to the river. During high tides, huge amount of tidal water (23,437,500 L day^{-1} that is 0.18% of daily discharge) gets diverted through these inlets (Fig. 3). Secondly, the coarse sand is collected directly from the river bed as well as from the point bar deposition during low tide level and transported towards upstream by boat. The stream is not competent to carry such coarse sand upstream during high tides.

3.3.2 Diversion of river water into the agricultural fields

There are twenty-five river pumps of HP 24.5 on both sides of the river between Tentulia and Kalanchi. At Tentulia, the tidal input is $292{,}896 \times 10^4$ L day^{-1}. The pumps collectively draw $10{,}071 \times 10^5$ L day^{-1} of water from the river. Total input of the water at Tentulia is $292{,}896 \times 10^4$ L. The total water intake in agriculture land is $10{,}071 \times 10^5$ L (34.38%), and water remain in the channel is $192{,}186 \times 10^4$ L.

3.3.3 Interruption to the river flow: pillars of the River Bridges

In the study area, there are three bridges on the Ichamati River, namely Kalanchi Bridge (22°53′42″N, 88°53′6″E) in Gaighata area, Tentulia Bridge (22°47′06″N, 88°51′18″E) at Swarupnagar area, and Basirhat bridge (22°39′04″N, 88°52′30″E) at Basirhat town. These bridges are resting on several pillars erected on the river bed, and its impact is enough to obstruct the tidal currents, where there is a homogeneous geological structure, such in the Bengal Basin. As a result, the normal flow velocity gets disturbed, helps rapid siltation, followed by sandbar formation. Consequently, the river becomes shallower with time. The bridges seemingly act as artificial local base levels (Leopold et al. 1964), which permit the very small amount of the high tidal water to enter into the upstream direction (Mondal and Satpati 2013).

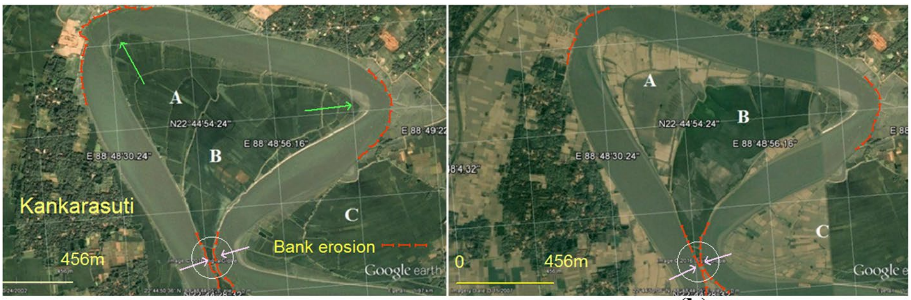
3.4 Location-specific case studies of human interventions

3.4.1 Kankarasuti–Faridkati in Baduria police station

Kankarasuti in the western part of the Ichamati River, in Jurisdiction List (J.L.) no. 29 under Baduria Block, and Faridkati (eastern side of the river) has been selected for the case study. The river has created an acute loop that is characterized by completely vested land within it (Fig. 7a, b), separated by a narrow neck of about 17 m (white circle in Fig. 7) to cut off (Fig. 8: P15 and P16). The river has been found to be shifted towards the west, transferring the erosional land mass eastward into the loop. The vested land was used for the purpose of agriculture and subsequently for brick kilns by the people coming from Faridkati through the neck passage. It becomes difficult for the people of Kankarasuti to set their foot upon the vested land, crossing the river and as the people create the active resistance against this intrusion. In this zone, the river channel frequently changes its position except for the neck (Fig. 9) due to constant anti-erosion activities. If there is a neck cut-off, the river will flow through a new course, leaving the loop as well as the vested land behind and now it would be easier for the people of Kankarasuti to take over it.

The river is not able to perform the neck cut-off due to the anti-erosion activities taken by the people of Faridkati; the people of Kankarasuti always try to cut this neck. Thus, this narrow neck of about 16 m between the two bends plays a significant role on both the river and the social environment of this area. Therefore, the people of Faridkati always pay great importance on the neck to keep control over the vested land. The satellite images of four consecutive years, such as 2002, 2007, 2012 and 2017, show a gradual but slow change of land use in the study area. The first image (Fig. 7a) (24 December 2002) shows the total land within the loop (552,303.9 m2) was completely under agriculture (winter paddy: Aman). The second image (Fig. 7b) (15 March 2007) shows the total land (567,338 m^2) was characterized by Rabi and Boro cultivation. The third image (Fig. 10a) (18 November 2012) shows a remarkable change in land-use pattern. The plot 'A' and the plot 'C' are under the Rabi crops (October to February), but the plot B has been shifted into brick kilns (226,816.59 m^2). The fourth image (Fig. 10b) (13.01.2015) shows that the loop area has been increased due to point bar deposition (632,452.56 m^2) and that has been completely changed into brick kilns.

The production of bricks is always more profitable than the traditional crop in the study area. The import of coal for brink making and export of bricks take place by the



(a) (b)

Fig. 7 **a** Land use in 2002, **b** land use in 2007; A, B, C indicate agriculture-dominated land use

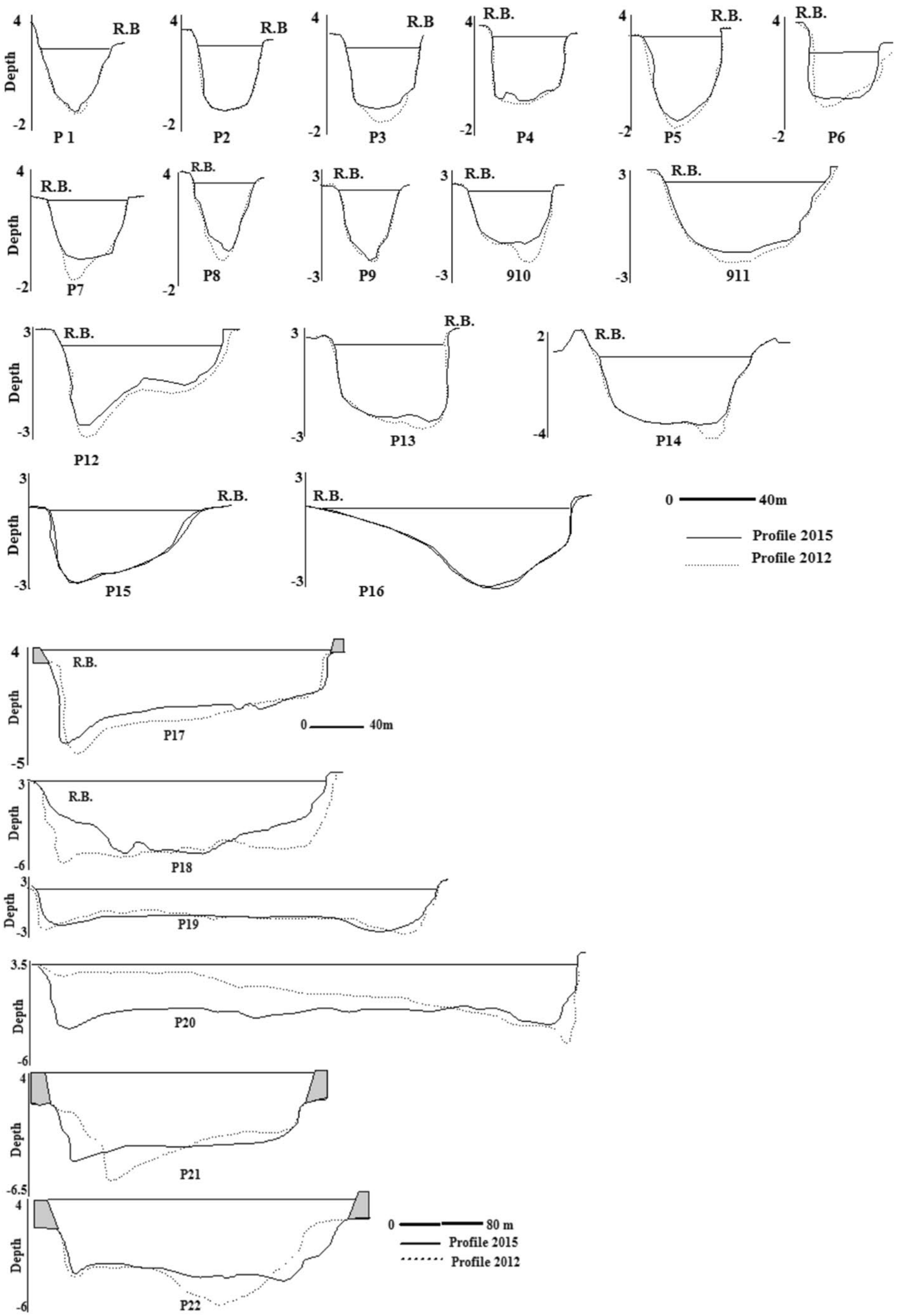


Fig. 8 Changing positions of the profiles (P1–P22)

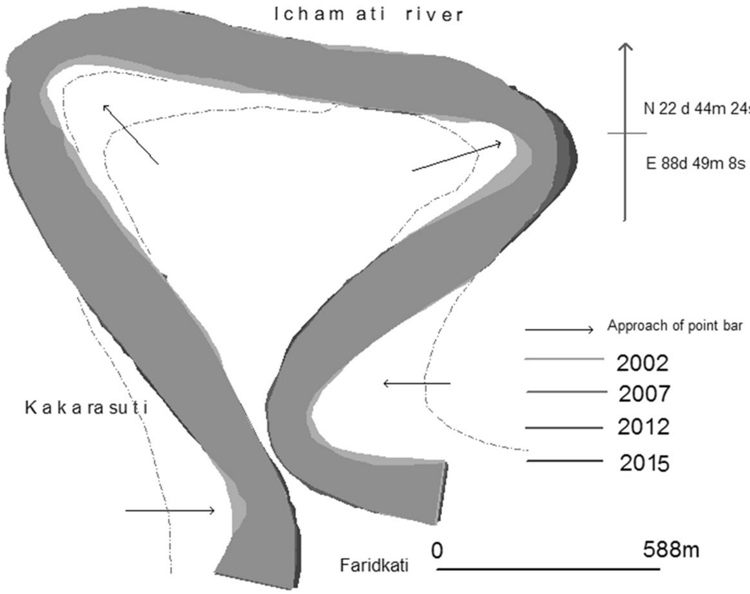


Fig. 9 Shifting of Ichamati River channel during the period 2002–2015

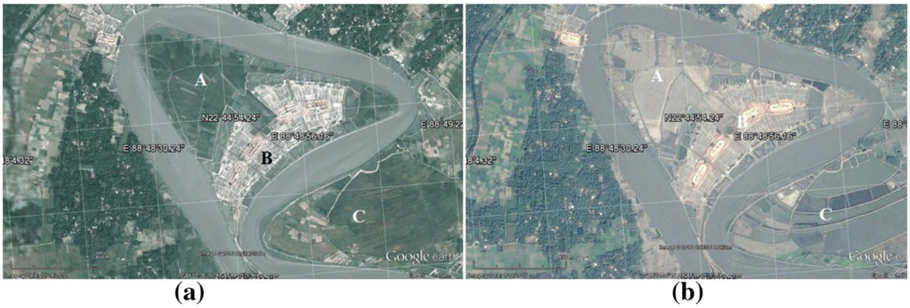


Fig. 10 **a** Land use in 2012. A and C indicate agriculture-dominated land use. **b** Land use in 2015. A and C indicate agriculture-dominated land use but B indicates the area under brick kilns

road formed on the neck. If the neck cut-off is taken place here, the river will find its new course avoiding the extra 1943 m.

Being isolated from its original infrastructures (roads and markets) and source of sediments, the brick kilns will be collapsed. If the loop becomes isolate from Faridkati by the newly formed river channel, the people of Faridkati would lose control over it. As the owner of brick kilns invested a huge amount of capital in the brick-making industry, and therefore, they are not interested about neck cut-off and trying their level best to protect this neck by taking different types of anti-erosion measures.

3.4.2 Impact on the long profile

The above-mentioned anthropogenic factor resists the river to neck cut-off which leads the river to flow the extra 1943 m. This factor has flattened the gradient of the long profile of the river. The gradient of the long profile (in 2015) is 0.000025 m/m (Fig. 11). If the neck cut-off is allowed, the gradient of the long profile will be steeper as estimated 0.0058 m/m.

3.4.3 Impact of the bridge at Tentulia

The Tentulia bridge was constructed in the 1970s. The bridge was situated on three columns. Two columns of these were on both banks of the channel, and the third one was in the middle of the river. The tree lines on both sides of the river are about sixty years old. The old tree line and the witness interviews of the local old people reveal that the width of the active river channel was about 160 m (Fig. 12). But after the construction of the bridge, the river gradually went to be emaciated. That the first pillar (situated near the right bank—upstream downward) was on the bank of the river channel (Fig. 12b) which has been silted up gradually and is approaching towards the second pillar which is in the mid-channel position. A strip-like continuous elongated point bar has been formed along the right bank of the river, and the present width of the river is only 50–60 m.

We have taken three cross sections to discuss the impact of Tentulia bridge on the river channel. One of them is at upstream direction (Fig. 12a) from the bridge. Another is at downstream direction (Fig. 12c) and the third one at the base of the bridge (Fig. 12b). After the construction of the bridge, the tidal current has been interrupted by the pillars which are followed by rapid siltation on both sides on the channel. The point bar at the bend of upstream direction has been increasing gradually and is converted to an elongated point bar along with the right-side river bank. Thus, ultimately the cross-sectional area of the river has been decreasing. For example, the area of the cross section in 2012 was 240 sq. m, which has been reduced to 130 m^2 in 2015, at the rate of 45.83%.

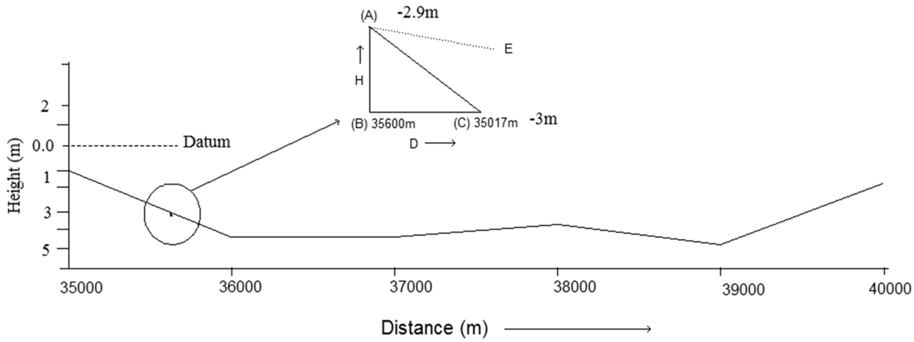


Fig. 11 Impact of brick kilns on long profile at Faridkati: A–E: the present profile; AC: the projected profile; A: the upstream end of the meander loop (Fig. 8, P15); C: the downstream end of the meander loop (Fig. 8, P16); BC: the horizontal distance between A and C (P15 to P16) (17 m); and the circle indicates the actual gradient between A and C

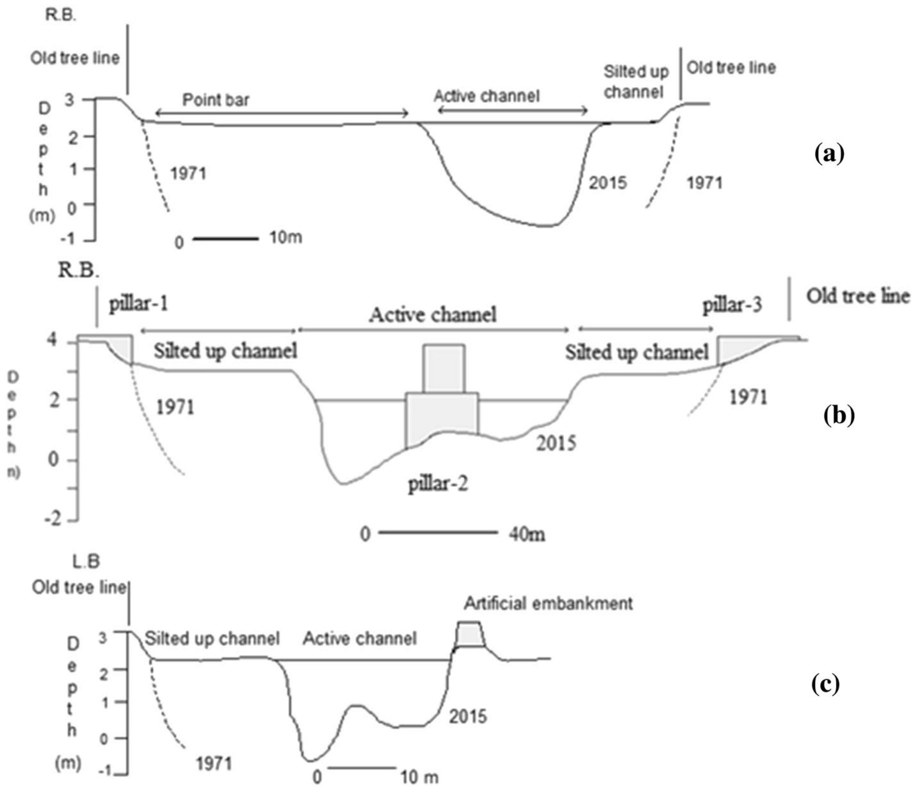


Fig. 12 Impact of Tentulia bridges on the Ichamati River: **a** cross section at 190 m upstream direction, **b** cross section at Tentulia bridge, and **c** cross section at 468 m downstream direction. R.B.: right bank, L.B.: left bank: Upstream downward (North to south): Impact of the bridge at Tentulia on the Ichamati River

4 Discussion on findings

4.1 Impact of brick kilns, agricultural land and bridges on Ichamati River

The brick kilns directly collect sand from the river in the lower course of the river. Deprived of enough sand and silt, which play an important role in distributing the internal energy, the river erodes its banks and bed, but loses the sediments to the brickfields. The man-made embankment has been constructed to protect the brick kilns and also the agricultural land from the saline water and bank protection or embankment along a meandering channel affects channel morphology (Xu 1997). These embankments force the river to contain water into its channel. As a result, sedimentation occurs during the two slack periods. Theses constructions not only lead the river to deposit sediments within the channel, but uplift the riverbed.

An interesting result has come out by a detailed survey in the study area that the height of the embankments is increasing more and more. The thalweg of the river is rising gradually due to siltation within the river channel which is followed by gradual rising of the high tidal level (HTL). So, in every year it has become a routine work to maintain the embankments by heaping up more and more earth materials along both sides of the tidal channels to protect the adjacent brick kilns and agricultural lands from ingression of tidal saline water.

In the upper reach of the river, the character of agricultural lands also affects the river. Tillage for cropping along the banks of the river generates loose topsoil that gets transported into the river channel during the monsoon. As the river discharge is not sufficient to flush out the load, the height of the riverbed gradually increases. The pillars of bridges act as the foreign body in a river. The impacts of these foreign bodies apparently seem abstract, but must come into being after a long run. The outcome of the impacts may be emaciating the river width due to horizontal oscillation, vigorous bank erosion due to the local turbulent, created by side pillar of the bridge—the cause of channel shifting—horizontal oscillation, and uplifting of the local base level through vertical oscillation.

4.2 Changing character of longitudinal profile

Temporal basis longitudinal profiles of rivers are the interesting subject matter to many authors, especially with regard to understanding their evolution and finding the most pertinent ways to predict their development. The characteristics of long profiles constitute the third adjustable dimension of alluvial channel morphology, which is also strongly scaling dependant (Richards 1982). This section is devoted to examine the best-fit curve to the longitudinal profile along a 55-km stretch of the Ichamati River. The best-fit curve of the longitudinal profiles of two different years has been presented. After that, we have compared them with each other and also with the computed graded profile to analyse its best-fit profile condition. Three simple functions (linear, logarithmic and polynomial) have been fitted to the present data. The best fit is defined by the function, which minimizes the sum of squares of residuals and gives the minimum standard deviation of residuals. The closer a correlation or a determination coefficient is to 1.0, the lower the dimensionless value of estimated standard error (Rädoane et al. 2003). To find out the best-fitted curve, first, we have applied the three curves on the unit profile (0–55 km). Then, we have applied the curves separately, for the first window (0–26 km) and for the second window (26–55 km). The windows have been selected based on their geometric character.

From the statistical point of view, in the first window, all three functions show that the degree of fit is generally high as the coefficient of correlation (r) is >0.5. This proves the right choice of these three functions to describe the form of the longitudinal profile of the river Ichamati, and the logarithmic curve is the best fit for this reach. In the second window, there are so many variations in the profile that it is impossible to fit a single curve satisfactorily. For this reason, in the second window, different curves show the very poor value of correlation of determination (linear, $r^2=0.031$; logarithmic, $r^2=0.104$; polynomial, $r^2=0.034$). To overcome this problem, we have divided the second window into three segments (26–36 km, 36–45 km and 45–55 km) and have applied three curves separately on an individual segment. We have found the value of correlation of determination being more than 0.5, [26–36 km: (linear, $r^2=0.792$; logarithmic, $r^2=0.892$; polynomial, $r^2=0.868$), 36-45 km: (linear, $r^2=0.881$; logarithmic, $r^2=0.738$; polynomial, $r2=0.906$) and 45–55 km: (linear, $r^2=0.814$; logarithmic, $r^2=0.557$; polynomial, $r^2=0.935$)].

The overall best-fit curve for long profile follows the logarithmic model, but for the second and third segments of the second window, the polynomial curve is the best fit. Because the form of the projected curve and the observed profile is symmetrical and denotes the value of very high correlation of determination (second segment: r^2

2012 = 0.905, r^2 2004 = 0.959; third segment: r^2 2012 = 0.938, r^2 2004 = 0.995), but in decreasing mood (Fig. 13) (Mondal and Satpati 2015).

The profile of the logarithmic model in the single profile of 2012 clearly declines with distance downstream, and thus, the shape of the profile is generally concave. A logarithmic function explains a moderate proportion of the total variance of the series ($r^2 = 0.574$) having a smaller value than the total variance of the series of 2004 ($r^2 = 0.625$).

The equilibrium profile of a river can also be a profile of small concavity, with a high slope, described by a theoretical, linear–exponential curve, and the linear–exponential equilibrium profile is also a profile of the equilibrium between erosion and accumulation, a transport profile (Rädoane et al. 2003). The computed logarithmic profile of 2004 coincided with the observed profile of 2004 at Swarupnagar region at 24 km distance from Kalanchi (0.0 km). This coinciding point is a significant demarcating point which has divided the river profile into two segments, e.g. first: the segment, above the equilibrium line and increasing its height gradually which clearly indicates an ungraded profile; second: the segment, below the equilibrium profile but is trying to achieve the equilibrium profile through siltation. We have noticed that the coinciding point between the two profiles in 2012 (observed profile and the computed profile) has migrated about 1.5 km downstream. The ungraded reach of the river profile not only approaching downward but also increasing its bed height by about 1 m. The approaching rate of the dying portion is about 187.5 m year^{-1}, and the rate of bed uplift is 12.5 cm year^{-1} (Fig. 14). In these two observational years, the polynomial curve is the best-fit curve for the unit (whole) profile. In 2012, the polynomial second-order curve shows the highest value of correlation determination ($r^2 = 0.692$). In 2015, the polynomial curve is the best-fit curve ($r^2 = 0.655$). Significantly, the value is smaller than the year of 2012. Both for the first and the second windows, the best-fit curves are the polynomial curve. In 2015, the value of the r^2 is 0.39 and for the second window, the value of r^2 is 0.32 (Fig. 13). The

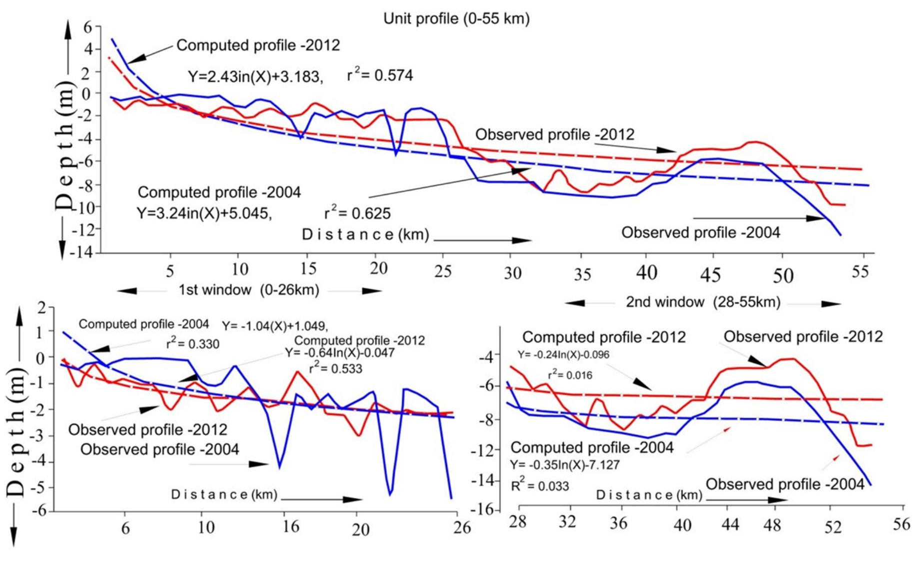


Fig. 13 The best-fit curve for long profile: Logarithmic curve for the single profile (2004 and 2012), and also both for the first window and the second window (2004 and 2012) (Mondal and Satpati 2015)

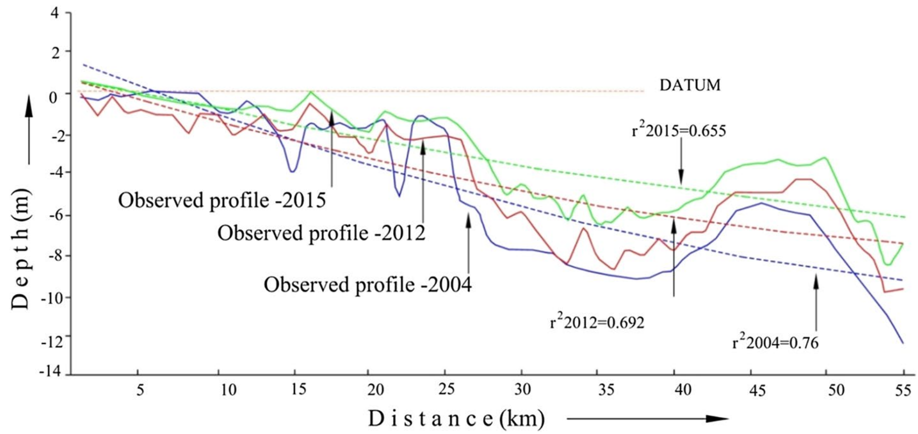


Fig. 14 The best-fit curve for the long profile: polynomial second-order curve for the single profile (2004 to 2015)

approaching rate of the dying portion is about 33.3 m year^{-1}, and the rate of bed uplift is 33.3 cm year^{-1} (Fig. 14) from 2012 to 2015.

4.3 Changing character of cross profile

Temporal basis of the data of 2012 indicates that the area of the river channel increases with distance from upstream downward ($r = 0.881$, $r^2 = 0.777$), but not in a regular event ($r = 0.038$, $r^2 = 0.001$) due to bank erosion (3–7 m/year) (Mondal 2011a, b). The repeated scenario in 2015 ($r = 0.84$, $r^2 = 0.709$) (Fig. 15) indicates the width and depth both abruptly increase from 40 km to downward but not as an allometric growth. The rate of increase in the width is 2450%, whereas the increase rate of the depth is 340% (Fig. 8; Table 1).

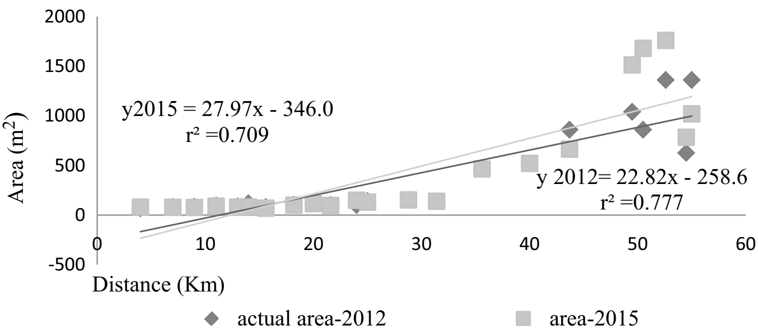


Fig. 15 Area decrease upstream downward (relation between channel area and distance in 2012 and 2015)

Table 1 Changing scenario of cross-sectional area

Stations	Year	
	Area in m^2	
	2012	2015
Profile-1 (Kalanchi)	80	80
Profile-2	80	70
Profile-3	85.2	80
Profile-4	95	90
Profile-5	87	75
Profile-6	118.4	114.4
Profile-7	80	70
Profile-8	105	100
Profile-9	115	115
Profile-10	104	96
Profile-11	180	150
Profile-12 (Tentulia)	240	130
Profile-13	152	90
Profile-14	139.2	114.4
Profile-15 (Faridkati)	515	520
Profile-16 (Faridkati)	520	465
Profile-17 (Sarfarajpur)	860	664
Profile-18 (Harispurferry)	1040	830
Profile-19	800	1560
Profile-20 (Taparcchar)	1360	1760
Profile-21 (Basirhat)	626	784
Profile-22 (Basirhat bridge)	1360	1080

4.4 Changing character of the discharge

Spatially, the Ichamati River is a tidal stream which is fully dependant on the tidal input of energy and mass. The input discharge of the river is 882,360 $m^3\ s^{-1}$. But at Tentulia, after a 33 km (upstream direction), the discharge has reduced to 13,600 $m^3\ s^{-1}$ (Mondal and Satpati 2016) and after 55 km, at Kalanchi the discharge is 86.32 $m^3\ s^{-1}$ (Mondal et al. 2016) due to the deduction by various human exploitations. As a result, the loss of the potential energy of the river is 1.38 (Fig. 16), and the head loss of the energy level is 4.2 m that is 38.2% of total energy. At present, the river has lost 25% of its tidal prism. The sediment transport varies inversely as about the 0.8 power of particle size (Yilmaz 2006), so the river is not able to carry relatively course sand towards upstream.

The above discussions reveal that the Ichamati River system river has been controlled by three types of human activities, which can be pointed as: (a) human control-1: the lower reach (Fig. 17: set-1) of the river is interrupted by brick kilns; (b) human control-2: the upper portion (Fig. 17: set-2) of the river water is being diverted by agricultural land; and (c) human control-3 (Fig. 17; set-3): there are three bridges on the Ichamati River which promote the rapid siltation within the channel. Suspended sand of the tidal water is collected only from the lower portion of the river through nearby bricks fields. Sands or silts are the important elements which play an important role for distributing the internal energy,

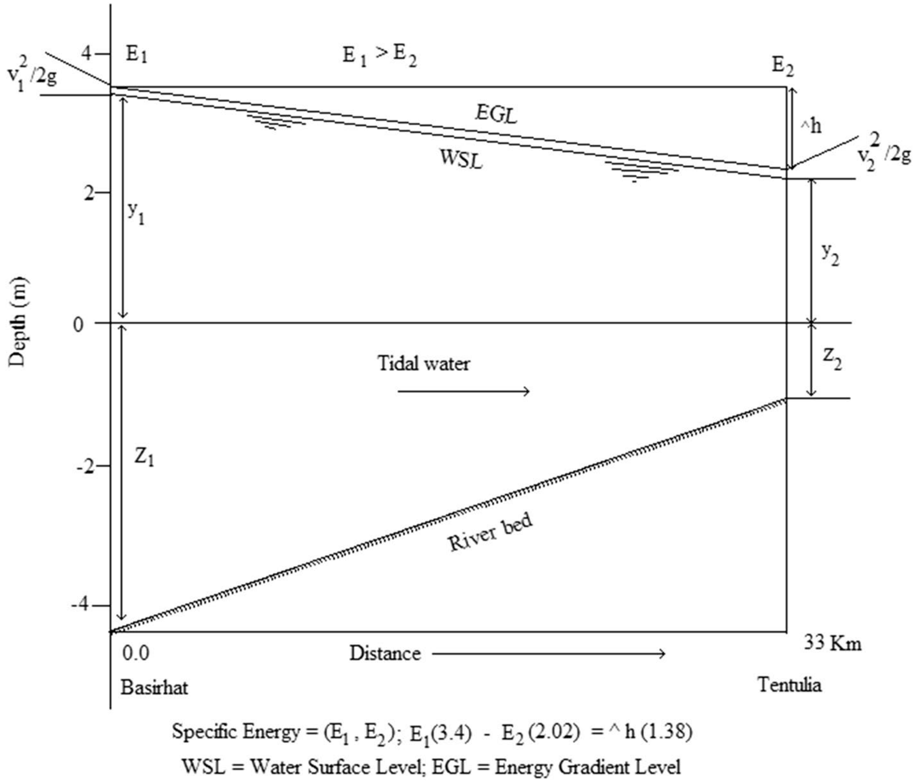


Fig. 16 Loss of potential energy from Basirhat to Tentulia (Mondal and Satpati 2016)

and therefore, some selective bank erosion is common in this zone (Mondal 2012) by the river to compensate this loss. All of the sequences indicate the negative feedback system that occurs when a change in input is magnified by the system operation such that its effect is enhanced or continued (Chorley et al. 1984a, b) and significantly there is a tendency to maintain the internal distribution of energy through negative feedback system (Fig. 17: set-1), i.e. internal energy management. With the diversion of the tidal water through brick kilns and agricultural land, the upper portion of the river gets the least amount of water. So, the river gets shrink its cross-sectional area itself with the availability of discharge (Fig. 17).

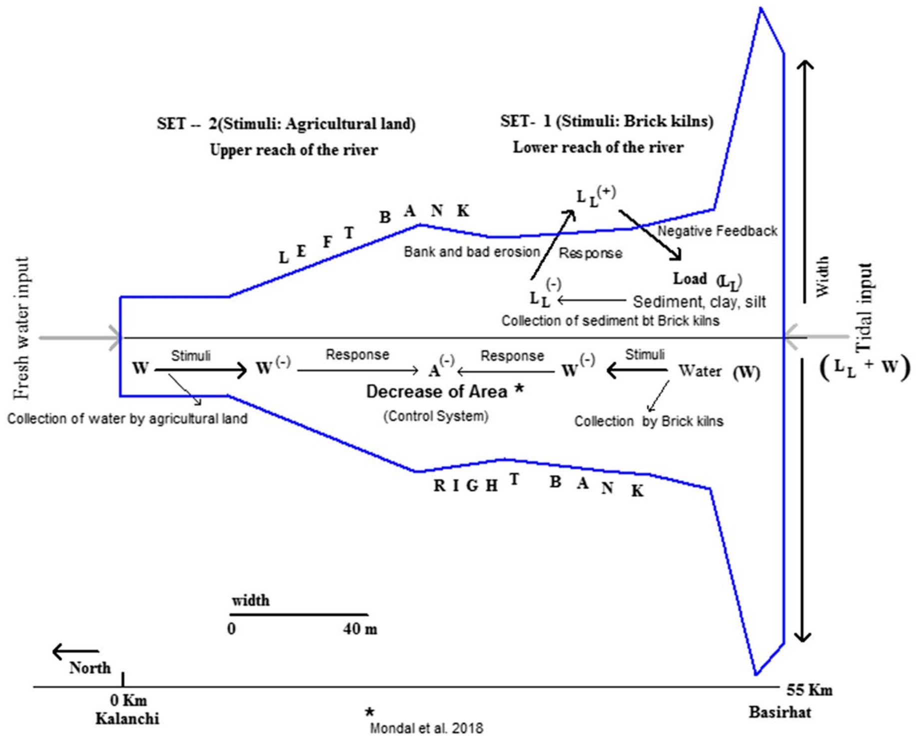


Fig. 17 Flowchart showing the response of the Ichamati River to the human behaviour. Area of the river has been decreased abruptly due to the intake of water from the river for various anthropogenic uses

5 Conclusion

The data regarding Ichamati River provide detailed summary of information on modification of channel character and change of discharge, e.g. (a) the input discharge at Basirhat is 882,360 L s^{-1}, and it is reduced to 135,600 L s^{-1} (33.2% of total volume) at Tentulia due to diversion of water for the brick kilns; (b) in the upper portion 34.3% of entire amount of water is diverted for agricultural land. All these interruptions have been reflected through negative feedback or homoeostasis process, i.e. uplift of the longitudinal profile, emaciation of the cross-sectional area and also the selective bank erosion at lower reach. Polynomial curve ($r^2 = 0.69$) reveals that the ungraded portion of the longitudinal profile is approaching upstream downwards (187.5 m $year^{-1}$) with the bed uplift (12.5 cm $year^{-1}$). The area of river channel has also been decreased abruptly ($r = 0.038$, $r^2 = 0.001$, 2012) and ($r = 0.84$, $r^2 = 0.709$, 2015). In the lower reach, the suspended load is collected by the brick kilns, and (c) brick kilns also promote the rapid siltation by obstruction the river flow. All the three sets collectively control the Ichamati River system in an irreversible chaotic way. Finally, the present study suffers from lack of data such as TS, TSS, TDS, etc., due to insufficient infrastructure available to the researchers. This gap can be taken up for subsequent work in future to understand the hydrodynamics river and sediment budget in the river system in this region.

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