



Meander Evolution And Oxbow Lake Geometry Along The Bhagirathi River Before And After The Farakka Barrage Construction

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Abstract

Oxbow lakes are common landforms in alluvial plains formed by meandering rivers. This study aimed to examine the evolutionary history of the Bhagirathi River course along its basin before and after the construction of the Farakka Barrage, mapping from historical maps dating back to 1767, 1841, 1917, 1955, 1977, 1991, 2010, and 2024, along with satellite images from 1987, 1996, 2007, 2015, and 2024. Reduced navigability and bank degradation clearly illustrate a trajectory of change. To examine the nature of the cut-offs, lake geometry was calculated. Seven parameters—length, width, length/width ratio, curvature, distance from the river, cut-off ratio, and diversion angle—were obtained from Google Earth Pro. From 1996 to 2024, the diversion angle increased as the oxbow lakes aged and progressively separated from the main river. However, this trend differs for two oxbow lakes: one is elongated, and the other is round. In summary, the study's findings reveal the intricate relationship between river dynamics and lake water use, thus showcasing the difficulties faced by local communities.

Keywords: Meandering rivers. Farakka Barrage Project. Lake Morphometry. Bhagirathi River. Cut-off Ratio.

Introduction

Cutoffs and oxbow lakes are some of the classic features of meandering rivers, and experts recognised them as fundamental components of the floodplain of mobile rivers (Hooke, 1995). Meandering rivers, especially in older sections, are responsible for the prominent features seen in alluvial floodplains. Meandering channels show irregular changes in sinuosity, with repeated curving patterns more pronounced in floodplain areas. Such distinctive curves are called meanders, after a winding stream in Turkey known in ancient Greek times as the Maiandros and today as the Menderes (Leopold & Langbein, 1966). Increased sinuosity in natural channels leads to local straightening via chute or neck cut-offs. When a river's bends become very sharp, adjacent loops might intersect. The river then abandons the loop, forming an oxbow lake after sedimentation (Howard & Knutson, 1984). Cutoffs along the riverine area play a key role in the complex dynamics of meandering river evolution by geometrically constraining the complexity of meander planform through episodic reduction of river sinuosity and dynamically interrupting meandering river evolution by generating intermittent sediment

pulses that affect river migration and dynamics both locally and at the reach scale (Howard and Knutson 1984).

Meandering rivers create oxbow lakes by cutting off bends, leaving behind isolated, short sections of river. Oxbow lakes usually form in the later stages of a river basin's development. The Bhagirathi-Hooghly River, a Ganga tributary, is characterized by its winding course and oxbow lakes. Since the Farakka Barrage was installed in 1975, the river's erosion rate has increased. Furthermore, oxbow lake formation is most prominent in Bhagirathi's middle and lower stretches due to increased water volume from the Ajay-Mayurakshi Branch during monsoon floods. The study's objective is to map the Bhagirathi River's historical route through its floodplain, analysing how meander cutoffs have evolved by measuring lake morphometry.

Scenarios of Farakka Barrage Construction

The Farakka Barrage Project (FBP), a massive engineering project constructed by Govt. of India in 1975 on the river Ganga, was designed to revive Kolkata Port by inducing 40,000 cusecs of water through 38.8 km long feeder canal from Ganga into Bhagirathi-Hooghly river system and to provide saline free environment and fresh water to the inhabitants of Kolkata (Rudra, 2010). The hydraulics control through this barrage has induced a profound impact on the upstream and downstream areas of FBP both in India and Bangladesh.(Islam et al., 2010; Parua,2009)In the post, Farakka hydraulics regime problems of siltation and sand bar formation(Banerjee et al., 1999), riverbank erosion and channel oscillation (Rudra, 2010) Came into being. In addition, the Bhagirathi-Hooghly River faces comparable problems with channel instability and its meandering geometry. Biswas and Bandyopadhyay's 1972 work examined how meander characteristics relate to transport capacity, categorizing Bhagirathi meanders into primary (high capacity from steep slopes) and secondary (low capacity from flat slopes) types. Similarly, Ray and Dutta (1972) have shown a correlation of meander geometry (length, breadth, discharge level) for the Bhagirathi River.

1. Pre-Farakka Barrage (Before 1975)

Before the construction of the Barrage, the Bhagirathi River faced problems of siltation, reduced navigability, and riverbank erosion, particularly in the middle reach. The pre-eminent position of Kolkata Port declined due to the deterioration in the headwater supply of Bhagirathi-Hooghly, which was being cut off from the Ganga for 9 months and was gradually drying up, and each year around 9 crore cubic feet of silt accumulated in the Hooghly river. (Rahman & Rahaman, 2018). Much of this change took place during the seventeenth and eighteenth centuries.

Timescale	Changing scenarios of the Bhagirathi River
12th to 16th centuries	The Ganga no longer remained the mainstream in India. The River Padma carried the bulk of the Ganga water. However, the Bhagirathi River was connected with the Ganga and flows as its western distributary.
Van den Barouche's map of the 17th century	The island formation in the Bhagirathi River near its outflow from the Ganga. The Bhagirathi, Jalangi and Chandna were the only distributaries of the River Ganga.
Jean Baptiste Tavernier's map of the 17th century	At Suti, the main source of the Ganga was filled up with sand and sediment.
1768-1777	The Bhagirathi almost remained dry in the winter months.
James Rennell's map of the 18th century	Reduction of the Cossimbazar river (i.e., Bhagirathi) in connection with the Ganga and functioned only during the monsoon months.
Colebrook (1801)	The Bhagirathi and the Jalangi could not be relied upon for navigation.
Prestige Franklin(1861)	Most of the year, the Bhagirathi and the Jalangi mouths are cut off from the parent river, the Ganga.
Committee, appointed by the Port Commissioners (1902)	The Bhagirathi-Hooghly has gradually deteriorated from its confluence with the river Padma to Kolkata.
S.C. Majumder, Chief Engineer, Central Water and Power Commission in ' Ganga Barrage and Bhagirathi-Hooghly river problems' (1953)	The Bhagirathi now remains cut off from the Ganga except during the flood.

Source: (Mukherjee J, 2011) and (Parua, 2009)

2. Post-Farakka Barrage (After 1975)

The plan for the construction of a barrage on the Ganges near Rajmahal and the creation of a feeder canal to bring the surplus water from the Ganges to the Bhagirathi River first surfaced in the recommendation of Sir Arthur Cotton in 1853, and it continued. (Mukherjee J, 2011). Installation of the Farakka Barrage was completed in 1975, which revived the water flow in the lean months (January to May) for maintaining year-round navigability and providing a saline-free environment for the Kolkata urban complex. The hydrological changes due to the construction of the FBP modified the channel pattern of the Ganga from meandering to braiding in both the upstream (Rajmahal to Farakka) and downstream (Farakka to Dhulian) of the barrage. (Parua, 2009). The Ganga water is diverted through the Feeder Canal towards Kolkata. But during the lean season, the water flow drastically decreased, leading to higher sediment deposition and formation of sandbars (chars), which resulted in frequent riverbank erosion along the Murshidabad, Nadia and Purba Burdwan districts of West Bengal. Similarly, modified that the rate of channel cut-off is occurring at a faster pace in the post-barrage situation (one in 9-10 years).

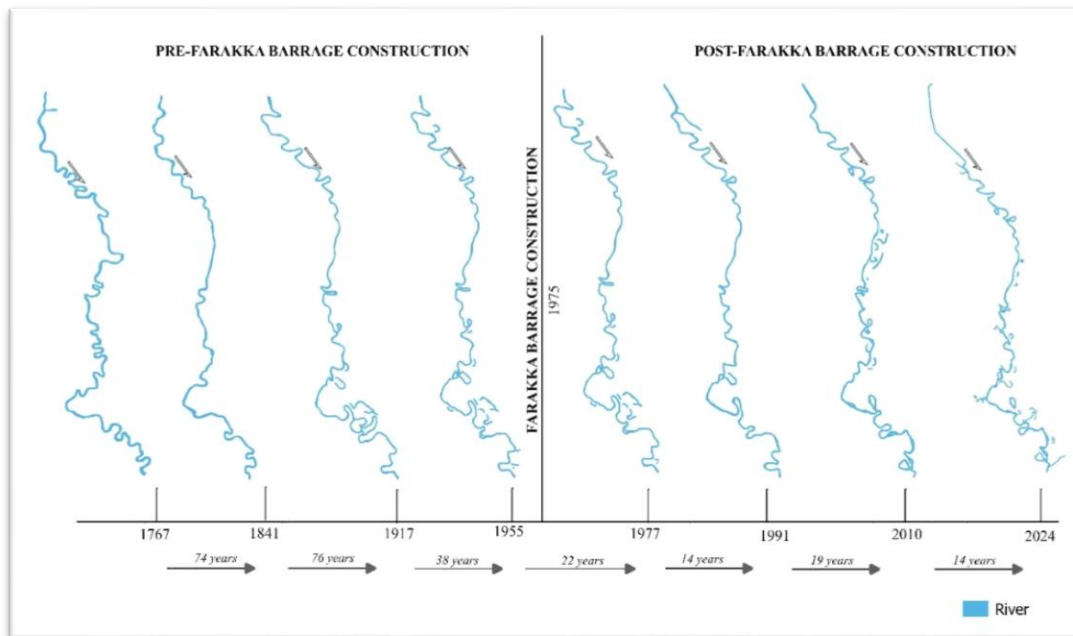


Fig 1. Changing Course of the Bhagirathi River before and after the Construction of Farakka Barrage over 257 years (Source: Atlas of Changing River course in West Bengal 1767-2010)

With time, the cut-offs along the Bhagirathi river have developed into an Oxbow lake. It remains connected with the parent river, either by an occasional flood or a channel. Oxbow lakes are frequently described as ‘nurseries of the floodplain’ due to their calm and nutrient-rich environments. (Ekka.A.et al.,2024). However, the ecological health of oxbow lakes worldwide is under threat because of encroachment, habitat destruction, and pollution.

This study uses the following objectives to understand the occurrence of the meander cut-offs along the Bhagirathi River:

1. Analyze the evolutionary stages and formation of the meander cut-offs.
2. Identifying the key changes in the lake morphometry by measuring variables from Google Earth Pro

Study Area

For the present research, the lower reach of the Bhagirathi- Hooghly River ($23^{\circ}40'$ twenty-one"N to $23^{\circ}24'42''$ N and $88^{\circ}08'01''$ E to $88^{\circ}22'45''$ E) located within Nadia and Purba Burdwan district of West Bengal has been considered. As per Kolkata Port Trust (KoPT), presently renamed as Syama Prasad Mookerjee Port Trust, the river Bhagirathi is divided into three reaches- head reach (Bhagirathi off-take to Nasipur), Middle reach (Nasipur to Sihati) and Tail reach(Sitahati to Nabadwip). The dynamic river course produces numerous lakes, cut-offs, ox-bow lakes and floodplain wetlands (Rudra, 2014). The Paleo-meander belt along the Bhagirathi-Hooghly river system is a relatively older geomorphic surface of the area and is characterised by different abundant channels, meander scars, ox-bow lakes (neck cut-offs) and back swamps (Chatterjee et al., 2022). In a meandering stage, the river has created a river cut-off along the left and right banks, two cut-offs, i.e., Char- Chakundi (left bank)and Purbasthali (right bank). The Oxbow Lake is selected from the tail reach (Nasipur to Nabadwip). The principal source of water comes from its parent river, the Bhagirathi.

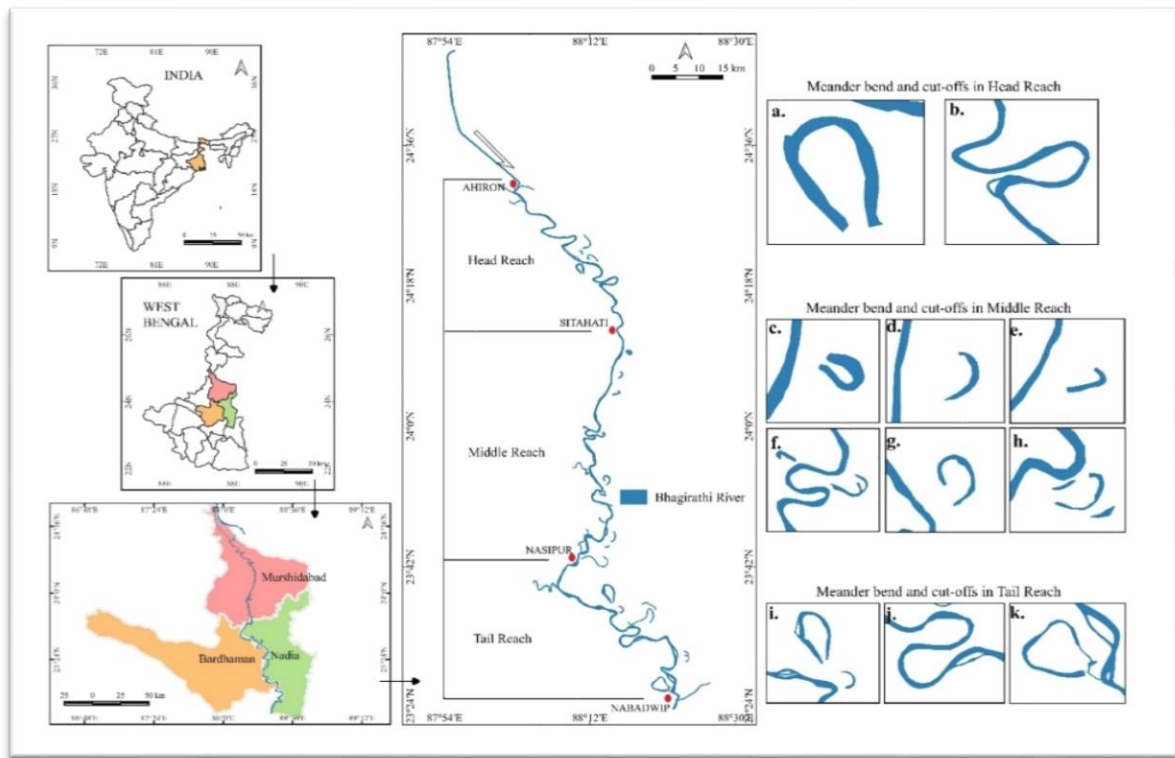


Fig 2. Location of the Study Area **a.** Balagachi Damus Lake **b.** Meander bend near Diar Balagachi **c.** Motijhil oxbow Lake **d.** Bishnupur Bill **e.** Chaltia Bill **f.** Meander bend near Chak Katalia and Hotnagar **g.** Oxbow lake at Sadatpur **h.** Oxbow lake at Chak Chandpur **i.** Chakundi Bill and Agradwip lake **j.** Meander bend at Patuli and Dampal **k.** Chupi Bill

Database and Methodology

The study relies on the combination of remote sensing data, historical maps, and field surveys to assess the dynamic change of the Bhagirathi River course spanning the period from 1987 to 2024. In this case, satellite data was collected through NASA's official portal, USGS Earth Explorer. The digitization of the maps and the Normalised Difference Water Index (NDWI) of the selected wetlands are derived from ArcMap 10.8 and QGIS 3.28.4 software.

S/N	Satellite/ Data type	Sensor	Path/Row	Scale/Resolutions	Bands
1	Landsat 5	Thematic Mapper TM	139/043	30m x 30m	1,2,3,4,5,6 and 7
2	Landsat 5	Thematic Mapper TM	139/043	30m x 30m	1,2,3,4,5,6, and 7
3	Landsat 7	ETM+	139/043	30m x 30m	1,2,3,4,5,6, and 7
4	Landsat 8	OLI TIRS	138/044	30m x 30m	1,2,3,4,5,6,7,8, and 9
5	Landsat 9	OLI TIRS	138/044	30m x 30m	1,2,3,4,5,6,7,8,9, 10 and 11

Table 1. Description of Landsat data

Methods

Lake Geometry

The lake geometry encompasses various measurable features of the oxbow lake. For the study, different morphometric variables- the length (L), Width (W), Length/width ratio (R), Distance from the active channel (D), and curvature (C). The diagrammatic part of the evolutionary stages has been presented, but some geometric attributes, like cut-off ratio and diversion angle (Giardino & Lee, 2012), are required to decipher the morphometry. The cut-off ratio is a geometric application for defining the relation between the length of abandoned wetted channel and the length of the main active channel that is characterised by the infilling and sedimentation of cut-off lakes. (Biswas & Dhara, 2019). The cut-off ratio is derived from the following equation:

$$C_R = O_L / M_L$$

Where, C_R = the cut-off ratio; O_L = the length(m) of the oxbow; M_L = the length(m) of the main channel, between the upstream and downstream oxbow channel ends. The diversion angle is measured considering the angle between the upstream portion of an abandoned channel and the main channel in the downstream direction.(Giardino & Lee, 2012). The greater the diversion angle, the farther the abandoned channel will be from the main river and Vice versa.

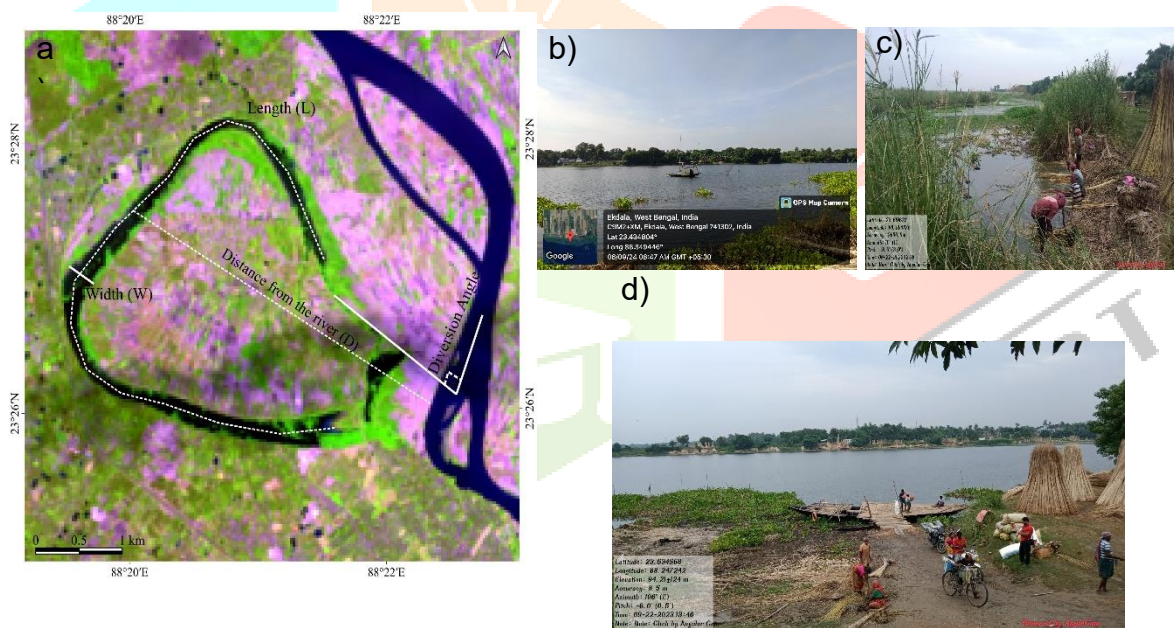


Fig 3: a) The morphometry of the selected oxbow lake (Purbasthali)in Nabadwip, b) Fishing as a daily activity of people, c) Dependency of lake water for Jute retting, d) Mode of navigation through boating.

Results and Discussion

The neck cut-off morphology along the alluvial floodplain of the Bhagirathi River depends on site specification, i.e., Characteristics of the soil, slope of the land, Elevation of the bed and water discharge by the tributaries and parent river itself. So, the point of cut-off and formation of separate oxbow lakes is a long-term process that needs to be studied individually since the meander cut-off has been formed in different timescales for alternative reasons.

Spatiotemporal evolution and channel migration

The Chakundi neck cut-off (23°39'44"N to 23°36'5' N and 88°13'27'E to 88°15'05"E) along the river Bhagirathi in the Nadia district witnessed significant morphological changes due to the oscillation of

the channel. Most of the cut-offs occurred due to sudden flood impulses after the operation of FBP. The Bhagirathi River made a complete bend till the year 1985, which got separated in 1994, decreasing the channel length by 11.85 km. Another cut-off took place in the year 2007 in the same area, reducing the channel length by 3.6km. A recurrent cut-off in the same area proves rejuvenated channel dynamics in that reach by hydro-fluvial control and subsurface geology. (Islam & Guchhait, 2017).

Phase	Time-period	River Morphometry	Features
Phase I	1987-1995	Sinuuous bend	The River Bhagirathi developed pronounced sinuous bends due to lateral erosion and deposition.
Phase II	1996-2007	Loop formation	The narrowing of the river further accelerated leading meander loop
Phase III	2007-2015	Neck cutoff	The river breached the narrow neck, creating a new channel and abandoning the old channel flow.
Phase IV	2015-2024	Oxbow lake	The abandoned channel became isolated and formed an oxbow lake. Further sediment sealed the former loop.

Table 2 : Different phases of the formation of the Chakundi Oxbow lake

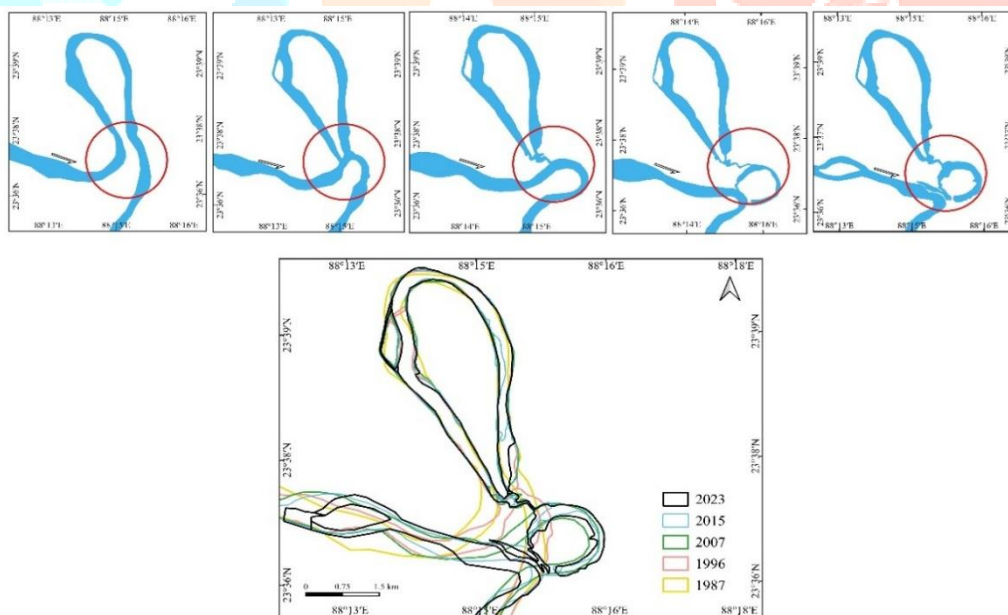


Fig 3: Distinct phases of Chakundi Oxbow Lake formation from 1987 to the Present date

The Purbasthali cut-off ($23^{\circ}25'56''\text{N}$ to $23^{\circ}27'48''\text{N}$ and $88^{\circ}19'36''\text{E}$ to $88^{\circ}21'52''\text{E}$) lies on the right bank of the Bhagirathi River. From 1927 to 1956, the river migrated towards its right, forming a loop-like structure. The rate of bank shifting accelerated in the lower reach, which led to further migration of the channel towards the southeastern direction. The first cut-off occurred around the year 1992. Till then, the loop migrated away and finally, in 1996, it got separated from the parent river. At present, it is connected with a small channel near Mayapur.

Phase	Time-period	River Morphometry	Features
Phase I	1927-1968	Sinuious bend	Shifting of the riverbank accelerated eastward, making a sinuous bend
Phase II	1968-1978	Loop formation	Migration of the river to the southeast direction leading to meander loop formation
Phase III	1978-1996	Chute Cut-off	The river overtopped its bank and carved out a new shortcut channel across the point bar, initiating a chute channel.
Phase IV	1996-2015	Neck Cut-off	The chute began to evolve into a new permanent channel. During the heavy flood of 2000, the channel got separated through a neck cut-off.
Phase V	2015-2024	Oxbow lake	The cut-off has now grown into an oxbow lake with semi-permanent water connected with the parent river through a narrow channel.

Table 3: Distinct phases of the formation of Purbasthali oxbow lake

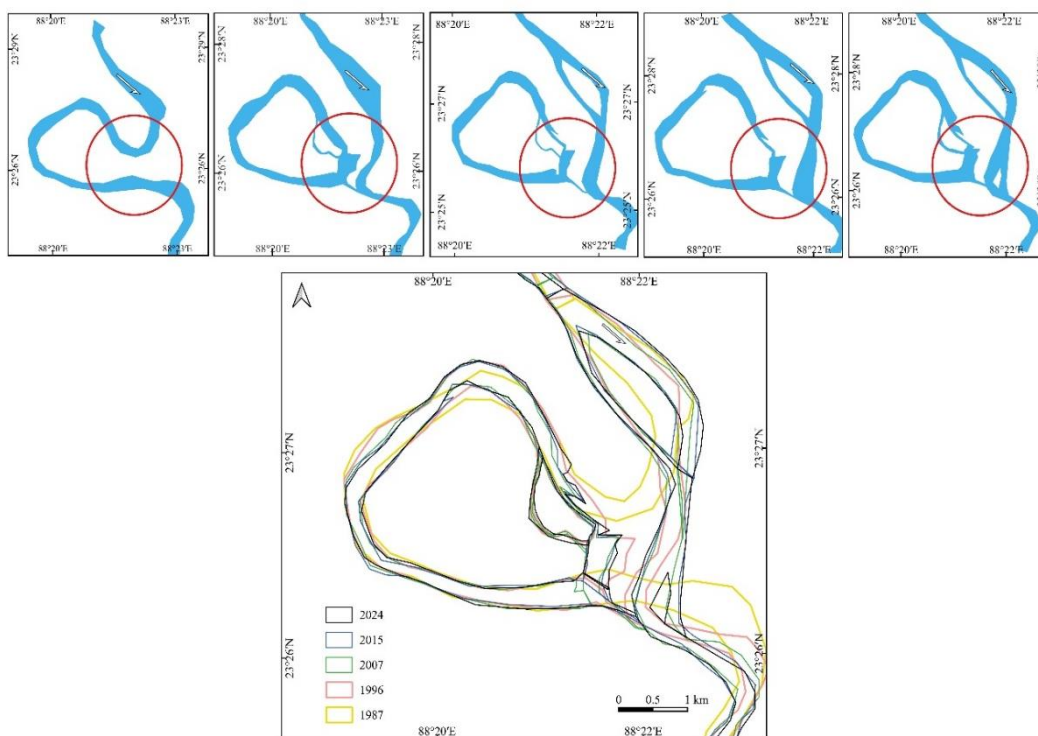


Fig 4: Distinct phases of the formation of Purbasthali oxbow lake from 1987 to 2024

Morphological Characteristics

The oxbow lake, which is naturally connected to the main river, typically results in dynamic changes in shape and size, which are pronounced during monsoon seasons. With seasonal variation in the curvature, it experiences a more regulated hydrological regime. An increasing curvature often identifies active meandering and sediment deposition, while a decreasing curvature suggests a more stabilised and less dynamic environment.

Chakundi Oxbow Lake							
Year	Length (L) in m	Width (W) in m	Distance from River (D) in m	Length/Width Ratio (R)	Curvature (C) W/D	Cutoff ratio (Cr)	Diversion Angle (in degree)
1996	11274	307	5089	36.72	0.060	1.60	14
2007	11804	318	5868	37.12	0.054	1.48	10
2015	11502	353	5984	32.58	0.058	1.82	345
2024	11672	341	6714	34.22	0.050	1.94	340

Purbasthali Oxbow lake							
Year	Length (L) in metres	Width (W) in metre	Distance from River (D) in metre	Length/Width Ratio (R)	Curvature (C) W/D	Cutoff ratio (Cr)	Diversion Angle(in degree)
1996	9866	425	3845	23.21	0.110	1.60	15
2007	9810	310	3950	31.64	0.078	2.00	25
2015	10070	240	3960	41.96	0.060	2.05	29
2024	9653	254	3912	27.27	0.064	2.41	30

Table 4: Calculation of the lake geometry

Identify the most influencing variables among the dataset, regression analysis has been done. Further predictions on the diversion angle can be done by considering the length, width, and distance of the oxbow lake from the main river through regression. The coefficient of determination (R^2) represents how well the independent variable explains the dependable variables, and the p-value in the equation measures whether the relationship is statistically significant.

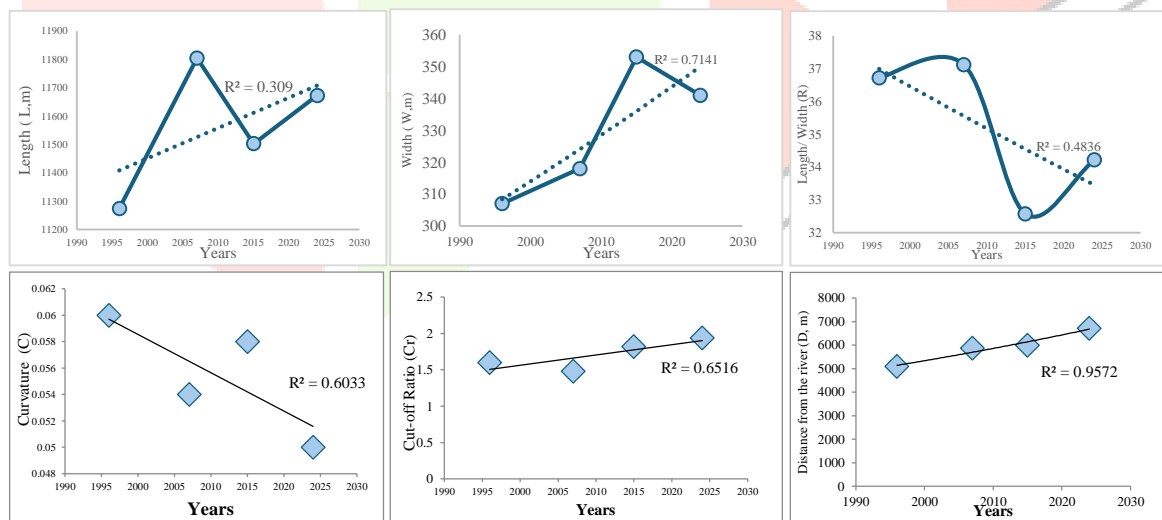


Fig5: Geometry of the studied Chakundi Oxbow lake over the years

As the years increase, the Chakundi oxbow lake has elongated because of the increased sinuosity of the river Bhagirathi towards its left. The width(W) of the lake increased after a certain time because of bank erosion and sediment movement (from 307m in 1996 to 341 m in 2024). The lake's length/width ratio did not ultimately match its length because the lake was elongated (36.72) when it was cut off. With time, it became wider from the middle and more rounded (34.22). The curvature of the lake has been decreasing over the years, gradually turning into a straightening or flattening shape. A higher cut-off ratio (1.94) indicates the lake is isolated or detached than before (1.60) over the years. The flow velocity at the lake inlet and outlet tends to be reduced, causing high sediment deposition and natural aquatic growth, which is quite obvious as the distance from the major river shows a higher value (from 5089 m in 1996 to 6714 m in 2024).

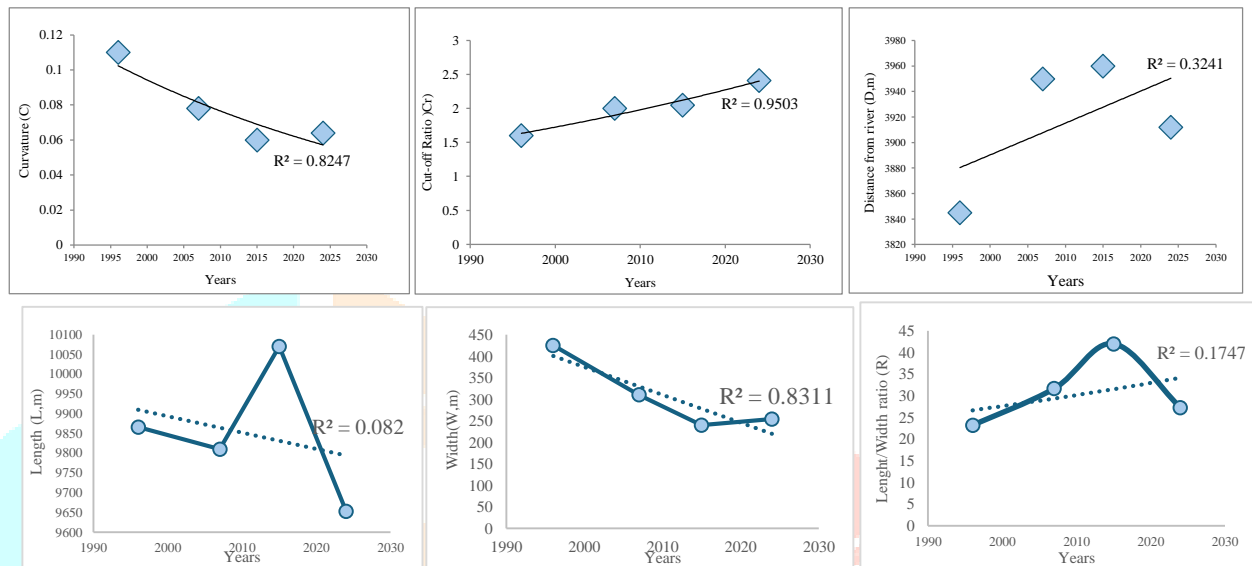


Fig. 6: Geometry of the studied Purbasthali Oxbow lake over the years

Figure 6 displays the relationship between the lake geometry of the Purbasthali oxbow lake over the years. The length of the oxbow lake showed a dynamic pattern that increased from 9866 m in 1996 to 10070m in 2015 because of seasonal flooding and a high rate of erosional activity. Long-term degradation of the channel is justified by reduced width over the years. Initially, the cut-off took a long and narrow shape (Length/width ratio was 23.21 in 1996). Due to episodic erosion and siltation, the shape gradually became increasingly circular and wider (27.27 in 2024). A strong correlation exists between the curvature of the lake over the years, which increased at first, forming a loop or circle. As it developed, it has flattened and isolated. A higher cut-off ratio of 2.41 indicates the meander has become more pronounced. The formation of the loop became severe after the heavy flood that occurred in 2000.

Temporal Phases of Lake Evolution

The morpho dynamics of the observed lakes showed a common five-phase trajectory: From sinuous bend loop formation chute cut-off → neck cut-off → abandonment → oxbow lake. The regression analysis showed that the distance from the river and the length/width ratio are key predictors of diversion angle, reflecting increasing detachment from the main river. With references to this, the abandoned oxbow lake has huge socio-ecological implications. The field visit in the villages confirmed that the abandoned oxbow lake serves as a vital resource body for their livelihood, particularly in jute retting, fishing, and navigation. However, increased sedimentation and weed infestation sometimes create huge problems regarding the utilisation of the lake.

Conclusion

The construction of the Farakka Barrage and the seasonal flood regime have influenced the transformation in the course of the Bhagirathi River. One can notice the significant implications in the meandering patterns and formation of oxbow lakes. Within the middle and tail reach, the no. of oxbow lakes is found to be higher. The evolutionary stages of the individual lake are significant and have passed through all stages of cut-off formation. Major lakes were formed during the 18th century 19th century since the initiation of the cutoff. Evaluating individual lake morphometry was helpful to understand the past, present and future scenarios of the selected oxbow lakes. Such insights are crucial to making any decisions on water resource utilization and ecological restoration. The livelihood of the local people depends on the lake water. But in reality, it is far more difficult to restore because of the growth of natural weeds. Therefore, ongoing monitoring and an adaptive management strategy with the consultation of the local people is of utmost necessary to mitigate the problem of land submergence and flood situation.

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