Assessing Riverbank Erosion and its Vulnerability Management of Livelihood: A Case Study of River Bhagirathi-Hugli Near Purbasthali and Agradwip Block

Chaitali Pal[1], Dr. Tuhin Roy[2]

[1]Visiting Faculty, Department of Geography, Sarojini Naidu College for Women, Kolkata, West Bengal, India.
[2]Associate Professor, Department of Geography, Sarojini Naidu College for Women, Kolkata, West Bengal, India.

Abstract
River erosion is one of the most dangerous and unpredictable natural hazards to riparian communities worldwide. The Bhagirathi-Hugli River, which is an affluent of the Ganga, has undergone massive geomorphological modifications over the last few decades, especially after the Farakka Barrage in 1975. The proposed research explores the spatiotemporal change of the bank erosion and channel shifting of a 45-kilometre section of the Bhagirathi-Hugli River between the Katwa and Purbasthali blocks in West Bengal, India, over 30 years (1990-2020). The patterns of erosion and accretion, the rate of meandering, and the process of formation of the oxbow lakes were measured, which have undergone significant geomorphological changes over the last few decades, especially after the construction of temporal satellite images combined with Geographic Information System (GIS) and verified with the help of large field surveys. The findings indicate that the channel is largely unstable, with the maximum left bank deposition at Agradwip and the right bank deposition in the same location. During the study period, three oxbow lakes formed, and two additional meander cutoffs are predicted to occur in the next 10-15 years. The study also investigates the trickle-down effects of bank erosion on agricultural livelihood, settlement patterns, and socio-economic susceptibility of the affected communities. Results show that the hydrological changes achieved by the Farakka Barrage have significantly altered the river's natural balance, affecting discharge, competence, and sediment load, leading to faster meander migration and bank erosion. The research has been significant to the literature on fluvial geomorphology by offering quantitative data on channel changes after the barrage and also gives practical advice on integrated river basin management and livelihood adaptation measures in the erosive-prone riparian areas.

Keywords: River Bank Erosion, Channel Migration, Livelihood Vulnerability, Remote Sensing, Oxbow Lake.

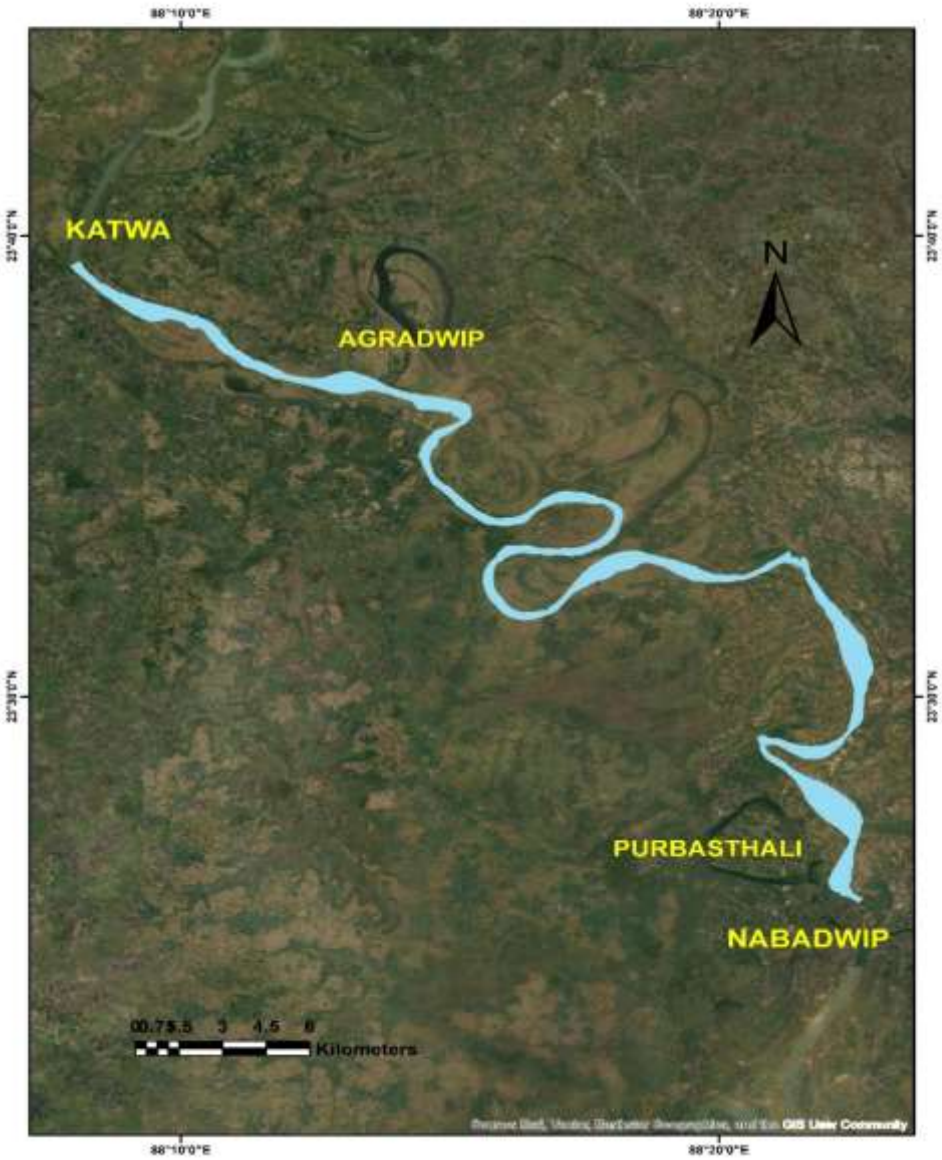
1. Introduction

Historically, rivers have served as the lifeblood of human civilisation, supplying water, fertile alluvial soils, transport routes and food to millions of human communities all around the world. Such a complex interaction of river regimes and human communities has defined the history of cultures, economies and landscapes over millennia (Macklin et al., 2015). Nonetheless, the symbiotic relationship is becoming more and more threatened due to the active and, frequently, devastating nature of riverbank erosion- a geomorphological phenomenon, which, on the one hand, forms riparian habitat, and, on the other, annihilates it. Riverbank erosion is one of the most erratic and catastrophic natural hazards, which affects communities in riverine areas, especially in the monsoon regions of South Asia (Das et al., 2014). Contrary to other disasters like earthquakes or cyclones, which are noticeable immediately and are met with immediate response, riverbank erosion is a slow-onset disaster, gradually eating up agricultural land, homesteads, infrastructure and cultural heritage sites and displacing populations to perpetuate poverty and vulnerability cycles (Hutton et al., 2004). An example of these challenges is in the Bhagirathi -Hugli River, which is one of the distributaries of the Ganga. This river system has an enormous cultural, economic and ecological importance that flows nearly 456 km through West Bengal and empties into the Bay of Bengal. The stretch of non-tidal river past Nabadwip is known as the Bhagirathi, and the tidal stretch between Nabadwip and the Bay of Bengal is the Hugli (Rudra, 2010). One of the most significant developments in the country's hydrological history took place with the completion of the Farakka barrage in 1975. This barrage was built about 100 km above Katwa at Jangipur and was intended to divert Ganga water to the Bhagirathi -Hugli channel to ensure that there was navigability at Kolkata Port (Rudra, 2010). In the course of reaching its navigational goals, the barrage essentially transformed the hydrological regime of the river with the introduction of surplus discharge, the alteration of the dynamics of sediment transport, and the emergence of numerous geomorphological changes that are still evident even decades later (Islam et al., 2020).

This research has been conducted on the fluvial dynamics of the Bhagirathi -Hugli system with substantial research. Bag et al. (2019) provided comprehensive evaluations of channel-geometry oscillation and meander-migration cardinality in response to systematic changes in the river's planform geometry over the past decades. Through their work, they showed how meander migration rates showed spatial and temporal variation, with the highest rates of displacement in the reaches that were characterised by erodible bank materials and high discharge variability. In the article by Islam et al. (2020), the post-Farakka conditions of the lower Bhagirathi were described as cross-sectional morphology and channel inefficiency, and the arguments in the article show that the changes in hydrology due to the barrage have established strong channel changes. Their study made emphasis on the fact that the competence and capacity of the river have improved due to higher discharge, which improves the transportation of higher sediment loads and facilitates the growth of meanders. Rudra (2010) also presented a detailed discussion of the hydrological impacts of the barrage, that is, water diversion of the Ganga, which doubled dry-season flows in the Bhagirathi-Hugli, radically changing the transport regime of the river in terms of sediment and morphologies. Misra et al. (2019) explored the implications of land use/land cover of the current dynamics of the floodplain and reported the impact of the change in channel patterns on agricultural activities, settlement patterns, and ecosystem services. The paper by Mukherjee (2018) specifically focuses on morpho-dynamic processes within the Purbasthali block, in which the authors record the development of oxbow lakes and their ecological value.

Though this is a considerable amount of work, there are still critical gaps. First, most of the studies have had temporal discontinuity, which has involved studying the channel changes at discrete moments, and not multi-decadal, continuous analysis of the erosion-accretion processes. Second, there is a gap in knowledge of human environment interactions due to the insufficient combinatorial integration between geomorphological processes and the socio-economic vulnerability assessments. Third, the overall impacts of the Farakka Barrage are largely recognised, but there are still limited quantitative evaluations of its long-term geomorphological impacts. Lastly, not many studies have tried to forecast future channels of migration and meander cutoff tendencies depending on the past trends, which restricts predictive power, which is vital in management planning. This research fills these gaps in with an in-depth exploration of the Katwa-Purbasthali reach, a 45 km stretch of the Bhagirathi-Hugli River that cuts through areas of Purba Bardhaman and Nadia district, 23°23'22.55"N to 23°40'30.92"N latitude and 88°6'34.03"E to 88°25'20.33"E longitude (Figure 1). The region, which comprises around 1000.44 km ^{2}, is a portion of the Bengal Basin, a fluvial topography that is a combination of active and old floodplains of the Bhagirathi-Hugli and the Jalangi rivers. It is located in a humid subtropical climate (Köppen: Cwa) with the southwest monsoon (June 1st September) bringing around 80% of the yearly precipitation (1400-1600 mm), causing floods and mobilising the erosion process. The Ajay River is a significant right-bank tributary that passes into the Bhagirathi-Hugli at Katwa town, creating large loads of sediment that affect the behaviour of downstream channels.

Figure 1: Selective stretch of the river Bhagirathi-Hugli



The particular objectives of the present research are as follows: (a) to evaluate the spatiotemporal dynamics of the riverbank erosion and channel shifting along the stretch of the Bhagirathi-Hugli River (Katwa to Purbasthali) between 1990 and 2020 using remote sensing and GIS methods; (b) to quantify both the rate of erosion and accretion at the key points (Katwa, Agradwip, and Purbasthali) and discuss the meander migration paths. This research is novel because of its detailed temporal study based on 30 years of satellite data with systematic decadal interval study; its unified methodology based on remote sensing, GIS analysis, field validation and socio-economic survey; its quantitative erosion-accretion maps of three key sites, and its chronological erosion-accretion chronology of oxbow lake formation and future events of these phenomena. By covering these objectives, the study is able to add value to the literature on fluvial geomorphology to have quantitative evidence of post-barrage channel adjustment, and provide practical recommendations on how to address the study on integrated river basin management and livelihood adaptation strategies in erosion-prone riparian zones.

2. Data Sources and Methodology

2.1 Data Sources

This present research is founded mainly on multi-temporal satellite images with the support of topographic maps and some on-field observations. As per the evaluation of the channel shifting and bank erosion of the Bhagirathi-Hugli River between Katwa and Purbasthali, three decades (1990 2020) satellite data were obtained in the open-access repositories. The download of Landsat series imagery was done on the portal of the United States Geological Survey (USGS) Earth Explorer, Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+), and Landsat-8 Operational Land Imager (OLI). There was also access to Indian Remote Sensing (IRS) LISS-III imagery of individual years, which was made available by the BHUVAN portal of the Indian Space Research Organisation. Images have been chosen wisely as seen on cloud-free days (<10% cloud cover) and at the post-monsoon period (October-December) to maintain the same level of water and insignificant vegetation interference over all periods. The reference data used to prepare base maps and to do georeferencing were the Survey of India toposheets (1:50,000 scale). Qualitative assessment was undertaken by visiting the field to have a qualitative idea of the erosion scenario and communicate with the local people concerning the historical development processes of the bank erosion and its effects on their livelihood. Although these interactions were not a formal survey, they presented useful contextual information that was used along with the remote sensing analysis.

2.2 Methodology

The approach of the study in relation to the methodology is to process and analyse the multi-temporal satellite data in a Geographic Information System (GIS) using a systematic processing and analysis system. To be spatially aligned with the satellite images at other times, all the satellite images were initially georeferenced with common ground control points located on toposheets of the Survey of India. Georeferencing was done in the QGIS and ArcGIS software platforms, where root mean square error (RMSE) was kept at acceptable levels to guarantee good overlay analysis. After georeferencing, on-screen digitisation of the main channel of the Bhagirathi-Hugli River was done in each of the time periods (1990, 2000, 2010 and 2020). Both the left and right bank lines were digitised as a separate vector layer at a similar scale of 1:10,000 to ensure similarity in all the time series datasets. The GIS environment was then used to overlay the digitised bank lines of the various years in order to determine the character and magnitude of channel shifting within the study period. The lateral migration distances within each time interval were determined by using the difference between the position of the bank lines in the previous time period and the current period at various locations across the study reach. Areas of erosion and deposition were also estimated by creating polygons that modelled the lost (eroded) areas and the gained (accreted) areas between time periods, the area of which was calculated using common GIS area computation tools. The channel migration distances were measured in kilometres of right and left banks at the key locations such as Katwa, Agradwip and Purbasthali. The computerised maps were also examined to determine the meander cutoffs and events of formation of the ox-bow lakes. Field visits were also done to confirm the remote sensing results by looking at the erosion sites with their eyes and having an informal interview with the locals, who gave their historical view on the channel changes and their socio-economic effects on the riparian populations.

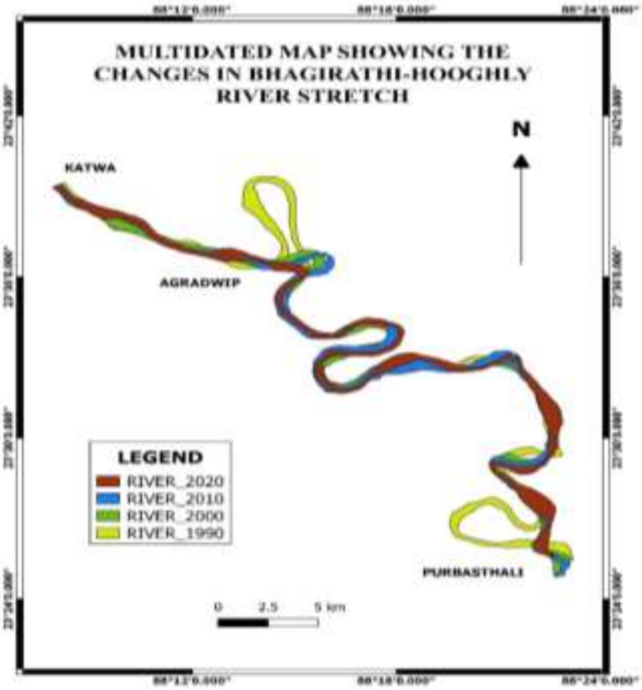
3. Results and Discussion

Riverbank erosion occurs dually, facts Physical and human factors. Rivers and streams are dynamic systems as they are constantly changing. Some stable rivers have a healthy amount of erosion; however, unstable rivers and the erosion taking place on those banks are a cause for concern. In this region, the right bank tributary of the river Bhagirathi-Hugli, the Ajay River, carries a tremendous amount of sediment, which it deposits at the mouth of the Ajay River where it meets with the Bhagirathi-Hugli River System.

3.1 Channel Migration (1990-2020) Spatiotemporal Patterns

A multi-temporal satellite image analysis shows a great and systematic channel shift along the Bhagirathi-Hugli River between Katwa and Purbasthali during the 3-decadal period of study. The multi-date overlay map (Figure 2) represents how the river channel moved in the course of four periods (1990, 2000, 2010, and 2020), which, in addition to showing the dynamic nature of the fluvial system, shows the spatial scope of the instability of the sides.

Figure 2: Superimposition of digitised river channels of 1990, 2000, 2010, and 2020 of the lateral migration and meander evolution of the Katwa Agradwip Purbasthali reach.

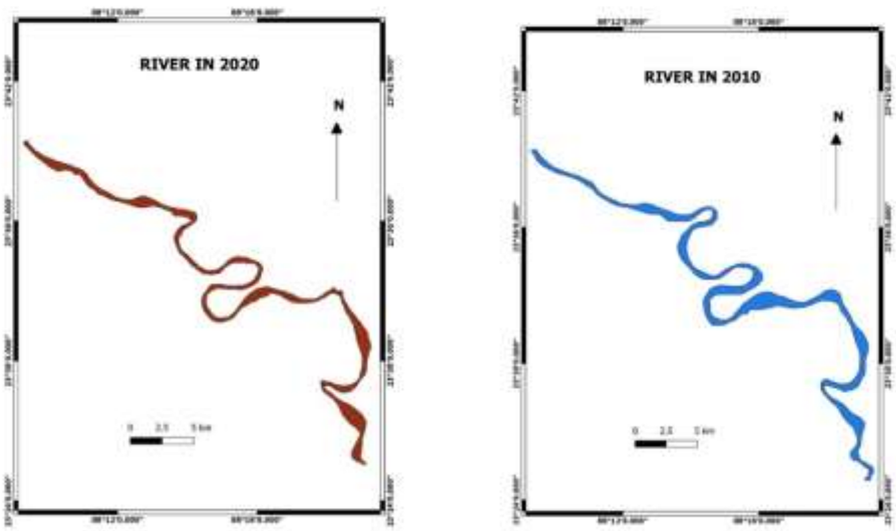


The spatial distribution that can be observed in Figure 1 shows that there is not a uniform channel migration throughout the study reach, but rather a severe spatial variation of the channel migration. It is possible to single out three different areas of increased channel activity, namely, the Katwa confluence zone, the Agradwip meander complex, and the Purbasthali meander bend. The most radical channel changes in the Agradwip and Purbasthali sectors are where the meander loop has gradually increased over time and has ultimately resulted in cutoffs and the formation of oxbow lakes. However, the Katwa region exhibits relatively moderate rates of migration, probably due to the sediment inflow of the Katwa river confluence that could create a stabilising influence. The time series illustrated by the multi-date overlay indicates that the channel migration process was also the most prolific up to the first twenty years of the study period (1990-2020), but the latter rate of migration has been relatively lower in the last decade (2010-2020). The trend here has been that the river is likely to be adapting to the hydrological changes that have been caused by the Farakka Barrage, though the mechanism is yet to stabilise.

3.2 Bank Line Migration and Deposition Rates.

A quantitative study of bank-line displacement from 1990 to 2020 indicates that there is significant lateral migration with significant asymmetry between left and right banks, depending on their location. Figure 3 shows the river structure in the initial (1990) and final (2020) years of the study period, giving a visual account of the overall change in the net change over 30 years.

Figure 3: Comparison of visualisation of the river channel at the beginning (1990) and the end (2020) of the study period as a demonstration of the net change in the morphology of the river channel over 30 years



The comparison of 1990 and 2020 channels indicates that the meander bends are greatly enlarged, especially in the sectors of Agradwip and Purbasthali. The river has literally stretched its lacey band, and the most apparent alterations with it have taken place at the point where the channel borders upon its external banks. New channel courses have been cut off by meander cutoffs, with detached oxbow lakes remaining in testimony to the migratory history of the river.

The changes are expressed quantitatively by the accretion/deposition rates computed using the digitised bank lines (Table 1). These values reflect the total lateral movement of each of the banks over the 30 years of study. The rates of deposition shown in Table 1 indicate some very important trends:

Table 1: Deposition rate of a stretch of the Bhagirathi-Hugli River from Katwa to Purbasthali in the years 1990-2020

Location	**Accretion/Deposition (M)**	
	Left Bank	**Right Bank**
Near Katwa	260.44	88.02
Near Agradwip	6172.41	6050.47
Near Purbasthali	4626.55	4218.47

- Katwa Sector: Katwa is a left bank that has moved by around 260.44 metres in 30 years, which translates into a yearly flow of 8.68 metres per year. The right bank, conversely, has migrated 88.02 metres (2.93 metres/year) only. This asymmetry indicates that the river is eroding its left bank disproportionately in this area and this could be as a result of the shape of the Ajay River confluence that might, in turn, divert the river to the left bank.
- Agradwip: The most radical bank migration is found at Agradwip, where there has been a migration of the left bank of the average 6172.41 metres (or over 6 kilometres) over the duration of the study, which amounts to a bank migration rate of 205.75 metres per annum. There has also been a significant migration of the right bank (201.68 feet/year). These extremely high values show that there have been meander cutoffs in the Agradwip region; the river has not been following its ancient path but has cut off and has taken up a new path, which is shorter. These huge values of displacement cannot be attributed to the progressive erosion of the banks but indicate the presence of avulsive channels

displacement related to the formation of the oxbow lakes. Their almost identical left and right bank migration (6 172 m vs 6050 m) indicates what may have happened to the channel; it has completely migrated over its meander belt in this spot.

- Near Purbasthali: Near Purbasthali, there is 4.626.55 metres (154.22 metres/year) of left bank deposition and 4.218.47 metres (140.62 metres/year) of right bank deposition, which also suggests processes of meander cutoff. The marginally increased movement of the right bank indicates that there is a favourable erosion on the left bank, which is in line with the asymmetric cross-sectional profile that is recorded at this site.

3.3 Meander Evolution and Oxbow Lake Formation

The above trends of channel migration are closely associated with the processes of meandering and cutoff. On analysis of the temporal progression of the channel positions (Figure 2), we are able to see a gradual increase in the meander bends that eventually leads to cutoff events. The study reach has experienced three different oxbow lakes that have developed between 1990 and 2020. The chronology of the formation by the reconstruction of the satellite imagery series is the following:

- 1991 Oxbow Lake (Purbasthali): The first cutoff happened around 1991 at a very developed meander loop that was cut off the main channel, forming an oxbow lake that is still visible in the 2020 images. It is a characteristic of the first phase of the river adjustment after Farakka in this area.
- 2000 Oxbow Lake (Agradwip): The second cutoff occurred around 2000 during a meander bend around Agradwip, which had been increasing in strength during the 1990s. The channel section that is abandoned can be well recognised in the later images as a crescent-shaped water body that has been separated by the active river.

The fact that three oxbow lakes have been formed in 30 years on a reach 45 kilometres long is a higher rate of meander cutoff than would occur during the pre-barrage periods. History and domestic history indicate that, in the state of nature, the meander cutoffs in this reach were periodical, at an interval of 40-50 years or more. The fact that the cutoff frequency tripled after Farakka is a strong testament to the effects of the barrage on the river action.

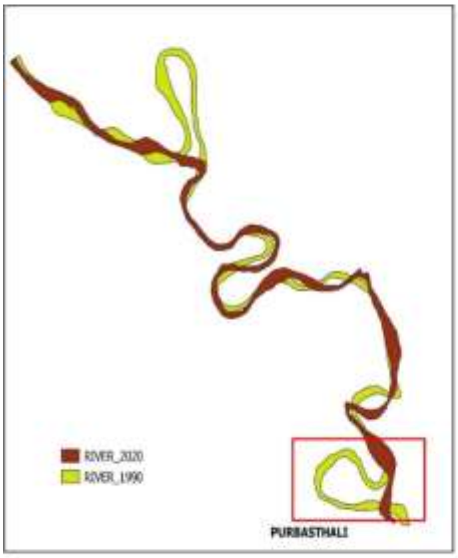
3.4 Cross-Sectional Morphology

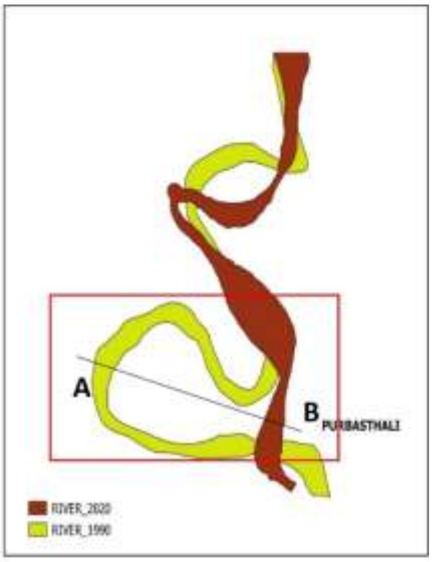
The lateral profiles of the Bhagirathi-Hugli River at some key points provide important information on the asymmetric erosion and deposition processes involved at meander bends. A channel geometry study of Purbasthali and Agradwip shows that the morphology is of a characteristic meander, so that the cut-bank and point-bar morphology are distinct.

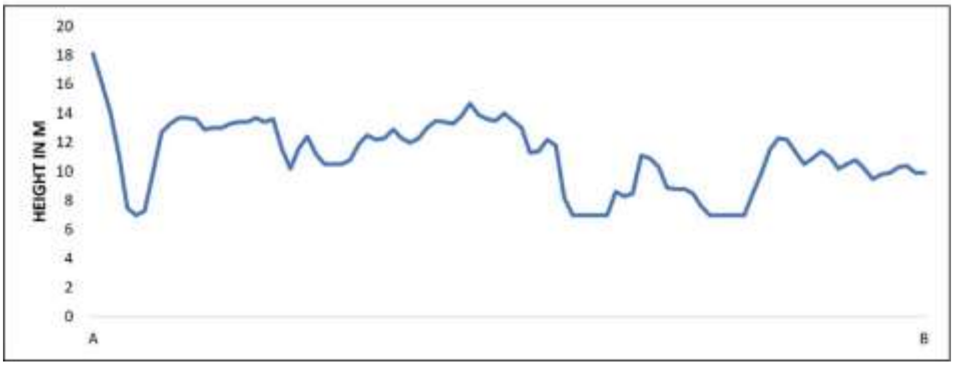
3.4.1 Cross-Sectional Profile close to Purbasthali

The projection of a cross-section of the river Bhagirathi-Hugli River just before Purbasthali (Figure 4) demonstrates the archetypal asymmetric zeal of a migratory meander bend.

Figure 4: Cross-sectional Profile of River Bhagirathi-Hugli off Purbasthali







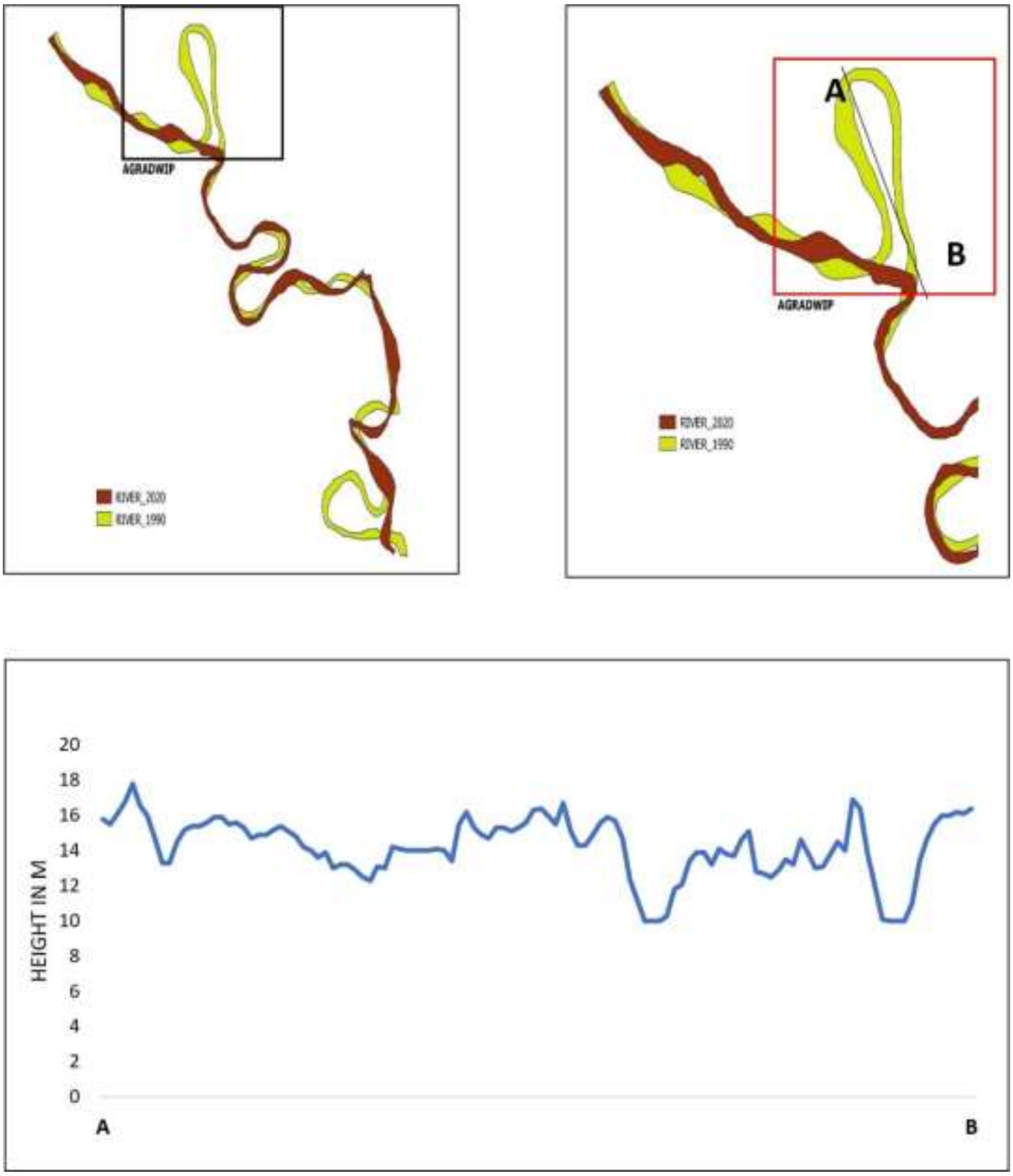
The cross-sectional profile explains some of the diagnostic characteristics that are relevant to meander dynamics, that is, the right bank of this part has a significantly stiffer slope, indicating erosion is occurring with the flow velocities being at their highest and hydraulic action undermining the bank. There is a natural vulnerability to failure in the steep outer bank through slumping and mass wasting processes, especially when in flood conditions, when the bank materials are saturated and the hydrostatic pressure is high.

The bank on the left has a less steep slope, which is a sign of point-bar deposition in which the flow velocities drop and the sediments are deposited. This asymmetric geometry will be diagnostic of dynamically active migrating meander bends and will attest to the fact that the Purbasthali sector is still adjusting dynamically. The channel (thalweg) is the deepest, and it is found along the outer bank, which focuses the energy of the flow on the bank toe and the erosion is further enhanced. This arrangement creates a self-perpetuating cycle where erosion by outer banks increases the depth of the channel close to the bank, which subsequently increases the concentration of erosive energy on the same bank. The Purbasthali cross-section, therefore, gives geometric support to the substantial left-bank deposition (4626.55 m) and right-bank deposition (4218.47 m) recorded during the study period, which indicates that lateral migration in the sector is achieved by asymmetric processes of erosion-deposition that are operating during the meander bend.

3.4.2 Cross-sectional Profile close to Agradwip

The cross-sectional morphology along Agradwip (Figure 5), with even a stronger asymmetry, can be attributed to the remarkable rates of bank migration, which have been reported at this point (6172.41m left-bank deposition; 6050.47m right-bank deposition).

Figure 5: Cross-sectional profile of the river Bhagirathi-Hugli near Agradwip



The cross-sectional profiles of Agradwip indicate a great asymmetry. The bank slope difference is bigger than at Purbasthali, which is indicative of a more advanced state of meandering development and of occasional cutoffs in this area. The outer bank has almost vertical slopes in some areas, which reveal undercutting and mass wasting taking place. The cross-sectional views, in combination with the course change diagrams, show that there are channel segments (paleochannels) abandoned along the sides of the active river. Such characteristics are abandoned previous locations of the river due to meander cutoffs, which is in line with the chronology of the oxbow lake formation reported in Section 3.3. The series of diagrams with the cross-sections shows the gradual shift of the Agradwip meander bend towards the present, which ends with the cutoffs of the years 2000 and 2014. The geometrical relations between the positions of successive channels can be taken as a visual confirmation of the rates of migration measured in Table 1. Figure 5 is very persuasive in the visual representation of the dynamic adaptation of the river in this sector. The quantitative story of the extreme bank migration rates is contained in the extreme cross-sectional asymmetry and the existence of more than one channel segment that has been abandoned.

Comparison of the cross-sectional profile at Purbasthali and Agradwip indicates a strong spatial distribution in meander morphology, which is consistent with the differences in the erosion intensity. In Purbasthali, there is a normal asymmetry where there is a steep outer bank (12-15 °), which is due to active cut-bank erosion and a long, gradual inner bank (4- 6 °), which is due to point-bar deposition. This site only had one cutoff event in 1991 and had some 4.6 km of net left-bank movement. Agradwip, on the other hand, shows more pronounced asymmetry with outer bank slopes of between 15 and 20 °, with some areas approaching near-vertical with evidence of intense undercutting and mass wasting of the material. The slopes of the inner banks are highly gentle (2-4°), which is a sign of a high bar development. It was noted to have two cutoff events in 2000 and 2014, and a net left-bank movement of nearly 6.2 km. The greater dynamism of Agradwip could also be linked to the downstream location compared to the Ajay River confluence, where a greater sediment load enhances bar development and increases meander evolution. As a result, it is established that Agradwip is the geomorphologically active sector in the study reach.

4. Conclusion

The paper was conducted to examine the spatiotemporal dynamics of river bank erosion and channel shifting in the Bhagirathi-Hooghly River section between Katwa and Purbasthali during 1990-2020 and to determine the consequences of the geomorphological changes on riparian livelihoods and the management of the environment. The significant observations indicate high instability of the channel, with top right bank deposition being 6172.41 metres above Agradwip and at 4626.55 metres above Purbasthali throughout the three decades. The study revealed three different oxbow lakes that formed in the years 1991, 2000, and 2014 and reflect an accelerated cutoff frequency relative to the situation prior to the onset of the barrage. The cross-sectional analyses test the occurrence of classical meanders asymmetry at the two sites with more extreme morphological expression at Agradwip, attributed to the higher migration and two cutoff events. Such quantitative data show that the river system has been experiencing a deep geomorphological adaptation over the period of the study. The implication of this study is not limited to the study area but to other large river systems that have been affected by human anthropogenic interventions in different parts of the world. The effects of the Farakka Barrage operations on the Bhagirathi-Hooghly can be discussed as a good example of the cascading geomorphological effects that may occur when the hydrological regime is altered on a large scale, and can provide valuable insights into how rivers can be managed in similar situations in South Asia and other regions. The knowledge of such adjustment processes is critical in forecasting channel behaviour in the future and the formulation of sustainable management strategies. The novelty of the proposed study lies in combining multi-decadal analysis of satellite imagery and quantitative measurements of erosion-deposition processes with cross-sectional morphological analysis to record the entire sequence of meandering evolution and cutoff processes. The forecast of future cutoff areas as per past migration history trends is one more contribution that adds to the predictive ability, which is very crucial in management planning. This study contributes to the growing body of literature documenting post-Farakka modifications in the Bhagirathi-Hooghly system, and it offers a replicable methodological framework for similar studies in other areas. Some shortcomings of this study cannot be denied. Landsat images have a metre spatial resolution, which might not be able to capture small-scale erosion processes, and the time resolution (decadal intervals) can fail to capture intermediary channel readjustments between acquisitions of images. Moreover, the lack of systematic flow and sediment discharge data during the study period does not allow for a direct correlation of hydrological variables and erosion rates. Future studies should focus on higher temporal resolution, the incorporation of hydraulic modelling into the study of flow-bank interaction mechanisms, and the further development of the socio-economic evaluation to systematise the measurement of livelihood effects. Real-time erosion monitoring programmes that are incorporated into long-term monitoring programmes would go a long way in improving the knowledge and management of this dynamic river system.

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