**Discharge-driven rapid bank-erosion and its impact on sediment budgeting in lower Ganga valley: Evidences from Malda district, West Bengal, India**

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# Discharge-driven rapid bank-erosion and its impact on sediment budgeting in lower Ganga valley: Evidences from Malda district, West Bengal, India

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## Abstract

Riverbank erosion coupled with recurrent flooding has been a persistent problem in large parts of the Eastern India. Published data on bank erosion of the Ganga River in West Bengal suggests an annual average of 8 sq. km. land-loss during 1969-1999 and that potentially affected lives of nearly a million people and destroyed various human establishments. In this study, we aim to constrain the spatiotemporal change in the path of the Ganga River and its impact of on sediment reworking in the plains area. For this, we used LANDSAT imagery from the year 1987 to 2019. Our analysis is based on a MATLAB-based toolbox called RivMAP. We show that the mean reach-averaged migration rates of the Ganga River vary from 200-600m/yr. Over the last three decades, the Malda district suffered a land-loss of ~140 $km^2$, yielding an average annual loss of 4.5 $km^2$. First order mass estimate suggests ~30 Mt/yr sediment yield from the Ganga riverbank in Malda, which is ~8−15% of the total annual sediment load of the large Ganga River expected in Farakka Barrage. In the end, this study highlights the role of climate on river migration and bank erosion.

## Keywords

Ganga; Riverbank erosion; river migration; sediment flux; discharge.

## 1. Introduction

The Ganga River is one of the most important river of the Indian subcontinent as for not only the human dependency on it, but also for its' geopolitical aspects (Nearly forty million people depend directly or indirectly on the Ganga River and the Ganga River basin is one of the fertile sectors for agriculture). The Ganga River is one of the largest sediment dispersal systems characterized by high sediment load. Extensive siltation in the main Ganga River channel and its tributaries is responsible for reduction in channel capacity and frequent flooding, especially in the eastern Ganga plains (Jain and Sinha, 2003, Sinha et al., 2005). Further, downstream reaches of the Ganga River channel, especially the lower Ganga valley (Fig. 1a) has also been dominated by bank erosion process leading to channel migration. Frequent changes in the Ganga River-path have made headlines in international media over the last few decades. Unfortunately, though some notable studies have been done on Ganga migration by Philip et al., (1989), Jain and Ahmed (1993), Shukla et al., (2012), Thakur et al., (2012) and Mukherjee and Pal (2018) – there exists very limited knowledge on the quantitative aspects of bank erosion, river migration at annual time scale and its implication on reach-scale sediment budgeting.

Remote sensing-based analysis provides an excellent tool to study the spatio-temporal variability in bank erosion processes (e.g., Thakur et al., 2012; Hassan, 2015; Payne et al., 2018). Nanson and Hickin (2012) measured later-migration rate and volume of eroded sediment in various meandering rivers of western Canada. Their studies highlighted significant relationship between bank erosion and sediment transport characteristics. Further, time-series remote sensing data have been used with probabilistic approach to assess channel instability and to predict bank-erosion prone area in near future (Graf, 1984; 2000). Recent advancements in remote sensing studies provides an important tool to achieve improved understanding of spatio-temporal variability in bank erosion processes of the Ganga River.

Extensive bank erosion along alluvial reaches may also govern the sediment load in the channel. A conceptual model provided by Hooke (2003) highlights that contribution from bar and bed erosion may act as an important sediment source for coarse sediment in a river channel. A recent study from a suburban Chesapeake Bay watershed, USA having $1.5x10^5$ $km^2$ watershed shows dominance (>90%) of bank-derived material in river sediment (Cashman et al., 2018). However, this important process has mostly been ignored in sediment budgeting of the Ganga River and its tributaries. A regional scale suspended-load based sediment budgeting of the Ganga-Brahmaputra River basin suggested almost 100% sediment from the Himalayan region, and insignificant sediment contribution from the plains (<10%) and peninsular India (<10%) (Wasson, 2003). Though, significant sediment contribution through bank erosion has been observed in smaller Himalayan rivers namely Burhi Gandak and Kamla Balan River (Sinha and Friend, 1994; Sinha and Jain, 1998), such understanding and quantitative data on sediment fluxes form bank erosion are lacking from the main Ganga River channel. Limitation of sediment flux data to understand the connectivity structure of the Ganga Plains has been highlighted in a conceptual study on geomorphic connectivity (Jain and Tandon, 2010).

In this study, we explored the upper part of the lower Ganga valley. We selected ~100 km traverse upstream from the geopolitically important Farakka barrage. Geographically it falls in the district of Malda, West Bengal (cf. Fig.1 for location and geographic extent). We quantified the planform changes in the river-path by analyzing multispectral remote sensing imagery of the last three decades, to be specific from 1987 to 2019. With this study, we highlight the annual-to-decadal scale changes in channel migration rate and compute areas of land accretion/ land loss due to river migration. Our work underlines the significance of bank erosion in alluvial plains in the total sediment budget of a large river. This work on the 100 km long stretch of the Ganga River indicates the total sediment contribution from alluvial plains may be significant in the total sediment budgeting of a river system.

## 2. Description of the study area

The Ganga River originates from the Gangotri glacier in the western Himalaya and flows ~2900 km till it meets the Bay of Bengal (Fig. 1a). The Ganga River and its tributaries originating from the western and the central Nepal Himalaya are major source of water in the Indo-Gangetic Plains. More importantly, the Ganga drainage basin delivers a massive amount of sediment each year to the submarine depo-centers (e.g., Lupker et al., 2011; Wasson, 2003). Over centennial to millennial scales, the sediment budget can be as high as 610±230 Mt/yr (Lupker et al., 2012). Over annual-decadal scale, several studies have come up with a range of estimates. There exist a few older studies from Bangladesh which portray a range of 200–550 Mt/yr (Coleman, 1969; BWDB). Average sediment budget measured for Ganga River in Bangladesh is ~ 390 Mt/yr (Lupker et al., 2011 and references therein). In Farakka, India (our study area), Abbas and Subramanian (1984) estimated the annual sediment load to be ~ 728 Mt. Recently, a study by Khan et al., (2018) report average annual sediment load at Farakka to be ~200 Mt (data from CWC, Govt. of India). On the other hand, the discharge measured far from the Himalaya, is dependent mostly on monsoonal rainfall. Monthly discharge at the Indo-Gangetic plain is highly biased towards the monsoonal month (Khan et al., 2018; Singh et al., 2007; Rao, 1975). Monthly hydrographs show that nearly 80% of the annual discharge is related to the monsoonal months (July-October) (Rao, 1975). Measured 15-year average annual discharge at Farakka is 3807 x $10^3$ $m^3/s$ (Khan et al., 2018; CWC data from 1994-2008) (http://www.cwc.gov.in).

Our study area is situated in the upstream part of the lower Ganga valley (Fig. 1a). The lower Ganga valley starts from the eastern end of Bihar, easterly to the confluence of

Kosi with Ganga River (cf. Fig.1a). The Ganga River takes a southerly turn near the town of Sahibganj and it enters the state of West Bengal and flows southwards till the Farakka barrage (Fig. 1b). The western flank of the Ganga River in this 100-110 km stretch is covered mostly by the Rajmahal hills and its' characteristic basalts. Riverbank erosion is the biggest problem in the districts of Malda on either side of the Farakka barrage. Riverbank migration and flooding in this area is a recurring headline during monsoon months in national and international news media. Sinha and Ghosh (2011) favor that the oscillation and geomorphological changes in the Ganga River in this stretch is due to the existence of the Farakka barrage. According to reports by several official surveys, ~8 $km^2$ area is wiped out annually by erosion of the Ganga Riverbank in West Bengal (Das et al., 2014). During 1979-1999, approx. 3850 Hectares (~40 $km^2$) of land was lost due to bank erosion in Malda (Rudra, 2000). The land loss data show a rise during 1995-1999. Therefore, estimation of the following decades is crucial. It is estimated that nearly half a million people were affected by recurrent flood in the Ganga River in this stretch over the past couple of decades.

## 3. Materials and methods

Our work is based on remotely-sensed satellite images from LANDSAT data repository spanning from 1987 to 2019 (https://www.usgs.gov/core-science-systems/nli/landsat). We used the data from the month of December of every year as it contains the least cloud-cover. Clear images of the years 1998, 2002, 2007 and 2012 were not found and therefore ignored for the analysis. From 1987 to 2011, LANDSAT-5 has been used whereas; from 2013 LANDSAT-8 images are available. Then for images of all the 29 years, the Near Infrared (NIR), Short-wave infrared-1 (SWIR-1) and red bands were used for producing false color composite. The composite image was classified into 6 classes using the "Iso Cluster Unsupervised Classification" tool in ArcGIS. With this classification the water pixels became distinctly identifiable. The classified image was again reclassified by giving the water pixels a value of 1 and all the other pixels a value of 0. This reclassified raster was converted into a polygon by and the polygon was edited to separate out the 'hydrologically-connected' segment of the river by setting the values of all the other features as 0. Similarly, the single threaded component was also separated out. Finally, these hydrologically connected and single threaded components were again converted back into raster files. In this manner, the binary channel masks (both hydrologically connected and single threaded component) were prepared for all the 29 years. For the analysis, we have used the 'single-threaded component' in this study. We acknowledge that this involves ignoring several narrow channels associated with the main channel during computation. But the cumulative area for those narrow channels is < 5 – 8% of the main channel. So, that can be counted as a methodological uncertainty. These binary Channel Masks were then converted into '.mat' format and the .mat file was run in MATLAB R2019a environment. We primarily followed the codes provided by the RivMap toolbox (Schwenk et al., 2016). The modified code used in this study is given in Appendix A. Figure 3 illustrates the key methodology adopted for this study.

## 4. Results

The processed LANDSAT images from different years point out drastic changes in the channel pattern, channel width and most importantly the spatial shift in drainage (Fig. 4). To avoid complexity in calculation, we used the mainstem river for our analysis of total bank erosion, annual reach-averaged river migration and erosional/ accretional areas. The mainstem river selection is mentioned as 'St' method in RivMAP (Schwenk et al., 2017).

### 4.1. Migration mapping and channel migration rate

Fig. 5 illustrates how the channel has migrated within the time period of 1987-2019. It illustrates that the lateral migration or meandering of the mainstem river is most prominent in the upper part of the study area (up to the town of Rajmahal) where two distinct loops of meanders are visible. Fig. 5 tells us that the meanders grew over the last three decades. The extent of migration is ~8−10 km in the meandering zone. Channel migration in the lower part of the study area is low and shows more or less channelized flow of the mainstem river, the width or the migration is also minimal. However, during 2006-2012, channel widening is seen in the southern part. The total erosion/ accretion area is plotted in Supplementary Fig. S1.

Computed average migration rates vary from 200 to 600 m/yr (Fig. 6). This is the riverbank migration rate. Centerline migration rates are provided in Supplementary Fig. S2. Migration rates are high (>400 m/yr) during 1998-2002 (except 2001), 2009-2013 (except 2010) and 2016.

### 4.2. Riverbank erosion/ accretion rate and cumulative area analysis

Annual bank erosion rates vary from 5 to 22 km during 1987−2019. This represents the average length of riverbank eroded per year. The accretion rate eventually lower and in the range of 2−7 km/yr. Therefore, in this time window, erosion dominates over accretion and we face land loss. Surface area calculation for eroded and accreted area was done using the difference between two consecutive years. Pixel values are multiplied by each pixel area (900 $m^2$). Fig. 7b illustrates land erosion/ accretion through time. In 32 years, the total erosion was ~255 $km^2$ while accretion was only ~105 $km^2$. Erosion was faster during 1995−1998, 2000−2002 and 2009-2013. The slope of the cumulative accretion hints nearly uniform accretion through time. The net land loss is ~140 $km^2$ (Fig. 7c)

### 4.3. Land loss

During 1987-2001, the net land loss was increasing steadily and the average channel width was also increasing (Fig. 7c). This was the major phase of channel widening. Looking at the migration map (Fig. 6), we see that channel widening as well as meandering has happened in the northern part of the study area up to the town of Rajmahal. The meandering loop increased with time, increasing the channel sinuosity. During 2001-2005, the channel width was steady and so was the net land loss. During this time, accretion was at par with erosion, so net land loss was minimal. Then, during 2006-2012, the channel width was reduced although the rate of land loss picked up (Fig. 7b). This can be explained by change in the river pattern. Prior to 2006, the mainstem river was wide. But somewhere in between 2003 and 2008, possibly around 2006, the channel pattern changed to anabranching, as number of anabranches across floodplains have been observed (cf. Fig. 4). Therefore, the width of the mainstem river declined, but its' numerous branches started to erode. Since 2012, the rate of land loss as well as the mainstem channel width declined. The anabranching of the river reduced while the mainstem river got wider and since then, the mainstem river is contributing to the bank erosion.

## 5. Discussion

LANDSAT image analysis using RivMAP toolbox in MATLAB (Schwenk et al., 2016) has enabled us to detect and quantify planform changes in river pattern of a part of the Lower Ganga valley. In the following text, we discuss how we used the outputs to quantify erosion over annual-decadal scale. We also discuss the reason behind rapid erosion of the riverbank and implications of our study.

### 5.1. Channel migration and river dynamics

Over the last three decades or even over the last half a century, the trajectory of the Ganga River in Malda district has changed (Thakur et al., 2012). But the change is not uniform or steady throughout its' course. Moreover, different parts of the traverse have different planform geometry. Interestingly, in the years when migration rates are high (1998-2002, 2009-2013 and 2016) (Fig. 6), the annual discharge is also high (CWC data; Pal and Pani, 2016) and the flood hazard is also high (DFO Flood observatory) (http://floodobservatory.colorado.edu/ SiteDisplays/ 51.htm (Accessed 10 June 2021)).

Migration map in Fig. 5 suggest that the upper part of the study area is affected strongly by meandering. We see two large meander loops which grow opposite to each other with time (cf. Fig. 5 where white arrows mark the spatiotemporal shift). Loop 1, near Sahibganj, has grown ~8 km towards SSW; whereas, loop 2, in between Sahibganj and Rajmahal has grown ~4.5 km towards NNE. With this trend, the town of Sahibganj in Bihar, will be under threat in few years' time. The town of Rajmahal is fairly safe. The southern part of the trajectory has very small evidences of meandering and rather follow a direct N-S path till Farakka. The migration map of this area does not show big lateral shifts. But we must mention that this part of the trajectory is characterized by anabranching of the river channel (cf. Fig. 4, time slice 2008, 2011). The reason for changing the channel pattern may be linked to change in slope. But with existing field/ DEM data, it is very hard to verify.

### 5.2. Control of discharge on erosion

As the monsoon arrives in Bengal, recurrent events of bank erosion get the attention of the media. Thus, we favor to test the role of rainfall on bank erosion. Monsoon brings more water in the channel; therefore, river discharge data and surface runoff data are important. River discharge data and runoff data of the station Rajmahal (station id: 51) for the duration of 1999–2019 were downloaded from the DFO Flood Observatory (https://floodobservatory.colorado.edu/). The data is based on microwave radiometry (Brakenridge et al., 2021). The rainfall distribution in Indian Sub-continent is heavily nonuniform and positively biased for the monsoon months (June-September) (Rao, 1975). In Rajmahal station, the discharge and runoff are high in end-monsoon to post-monsoon months of August to November (Supplementary Fig. S3). Thus, we used the peak discharge data for correlation (possibly September- October). To test the correlation of peak discharge and runoff with our new erosion rates, we fit linear regression using 95% confidence interval (Fig. 8). Regression fit for the discharge (Fig. 8a) is much better ($R^2$ = 0.83) than the same for runoff (Fig. 8b) ($R^2$ = 0.26). This clearly hint that peak discharge is the key driving factor for river-bank erosion. That underlines the fact that the stronger monsoon in the upstream or even sudden influx of flooding in the channel would warrant destruction of the river-bank. The local rainfall is probably not that significant, else, we would have seen a better correlation with surface runoff (Fig. 8b). Similar high correlation is seen when we compare migration rate with peak discharge ($R^2$ = 0.80) (Fig. 8c) than with runoff ($R^2$ = 0.23) (Fig. 8d). Therefore, we may conclude that migration rate and erosion rate co-vary with each other and both are controlled by discharge (a proxy of climate).

**5.3. Implication of bank erosion on sediment budgeting**

Fig. 7a shows annual variations in erosion and accretion in the study area. More often, erosion is higher than accretion. The scenario is further elaborated in Fig. 7b which portray annual change in cumulative erosion and accretion within the study area. As erosion is much stronger than accretion within the reach, therefore, the study area records a net land loss in the stipulated time-period (Fig. 7c). Especially, during 1996-2002 and 2009-2012, the erosion was high. In Fig. 7c, we portray the net land loss (area) with time. ~140 $km^2$ land has been eroded along reach of ≈ 100 km in last 30–32 years, which results in an annual average of 4.4 $km^2/yr$. Considering the average bank height to be ~ 3m (Fig. 2 – field photos) and bulk density of cohesive soil to be 2000–2200 $kg/m^3$, a rough estimate of annual eroded mass will be ~26 - 29 Mt from ≈ 100 km length of the study reach. Or in other words, the sediment yield is 0.26 – 0.29 Mt per km length of the channel per year. Considering the annual average sediment load at downstream station at Farakka or at Harding Bridge, Bangladesh as 200−390 Mt (Lupker et al., 2011; Khan et al., 2018), we claim that 8−15% of the sediment load is derived from erosion of the river-bank from 100 km stretch within the Malda district, West Bengal. Considering the total length of the river in the alluvial plains as ~1800 km, the contribution from the plains area could be much higher. This finding highlights the role of significance of alluvial area as a sediment source at modern time scale within the Gangetic foreland basin.

## 6. Conclusion

By combining the results from LANDSAT image analysis and comparing them with remotely-sensed flow parameters from the study area, we conclude the following –

1. The Ganga River in the Malda district of West Bengal is causing land loss due to channel migration. The northern part of the district is facing problems due to increase in meandering while the southern part is facing an eastward shift of the channel.
2. High correlation between annual bank erosion rate and annual peak discharge for the duration of 1999−2018 underlines the dominant control of climate on river-bank erosion.
3. The total land loss along ≈ 100 km long reach over the last 3 decade is ~140 km$^2$, yielding an erosion rate of 4.4 km$^2$/yr. Considering an average bank height of ~3m, the annual sediment yield from this part of the Ganga River is ~26−29 Mt.

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**Figures**

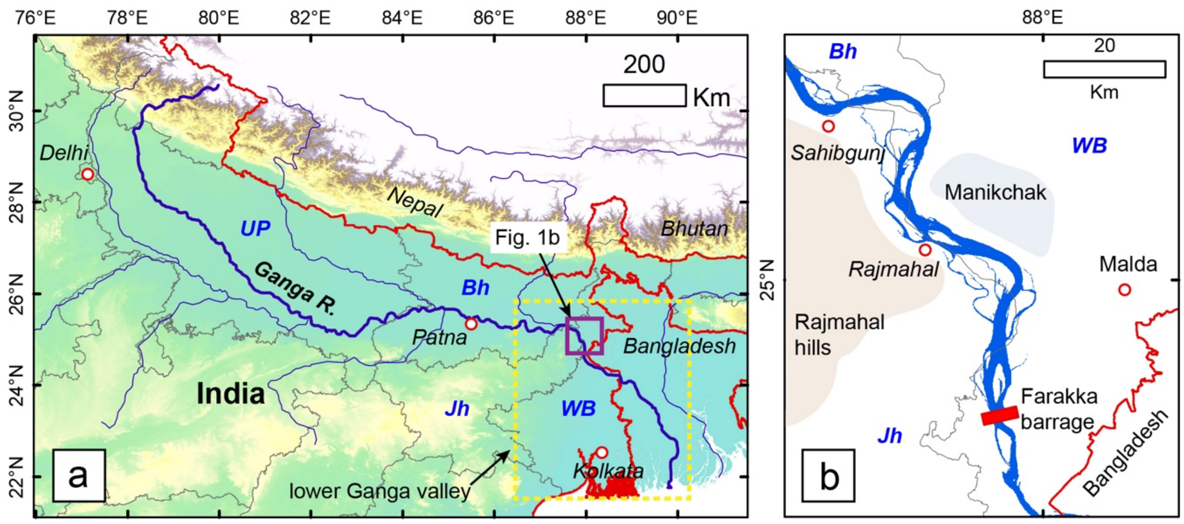


Figure 1: (a) An overview map of the Ganga basin showing the geographic boundaries (labelled in blue font) and our study area as purple rectangle. (b) Enlarged view of the study area showing the present-day track of the Ganga River (as in December, 2019) and the important towns/ places along the river. The lower bound of our study area is the Farakka barrage. [ Abbreviations: UP – Uttar Pradesh, Bh – Bihar, WB- West Bengal, Jh – Jharkhand].


Fig. 2: Field photographs. (a) human establishments at eroding bank of the Ganga River near Manikchak, Malda. (b) Eroding Ganga riverbank at Samserganj, Murshidabad (downstream from Farakka Barrage). (c) Migration of Ganga River engulfing the cultivation land in Malda. (d) Villages in Kaliachak, Malda are facing the threat of abolishment due to river migration.

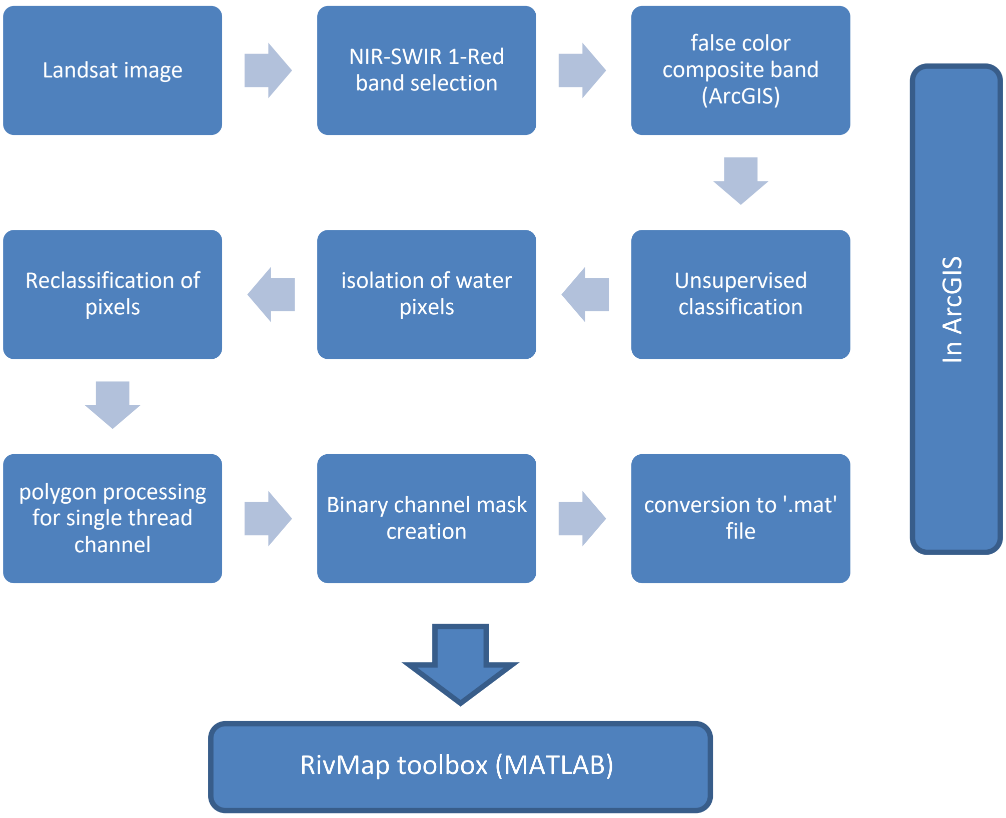

Fig. 3: A conceptual flowchart explaining the methodological steps adopted for this study. This process has been repeated for 29 datasets spanning from 1987 till 2019.

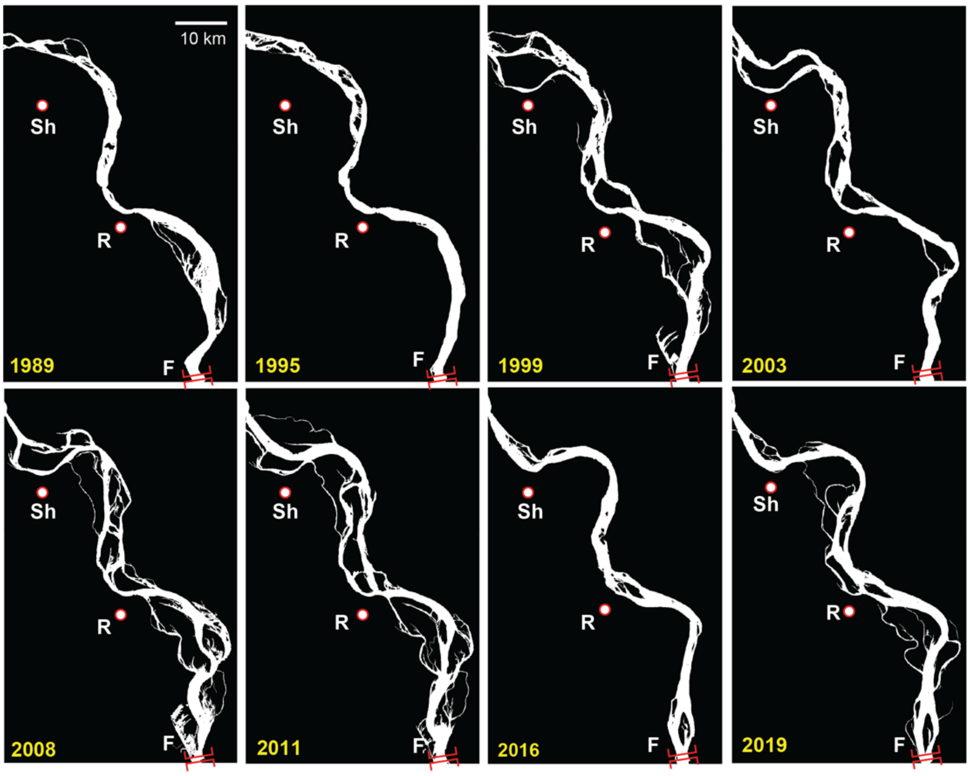


Fig. 4: Classified LANDSAT images from different years (mentioned in yellow text) show changes in drainage pattern and spatial shift in drainage over the last 3 decades. [Abbreviations: Sh- Sahibganj, R- Rajmahal, F- Farakka].

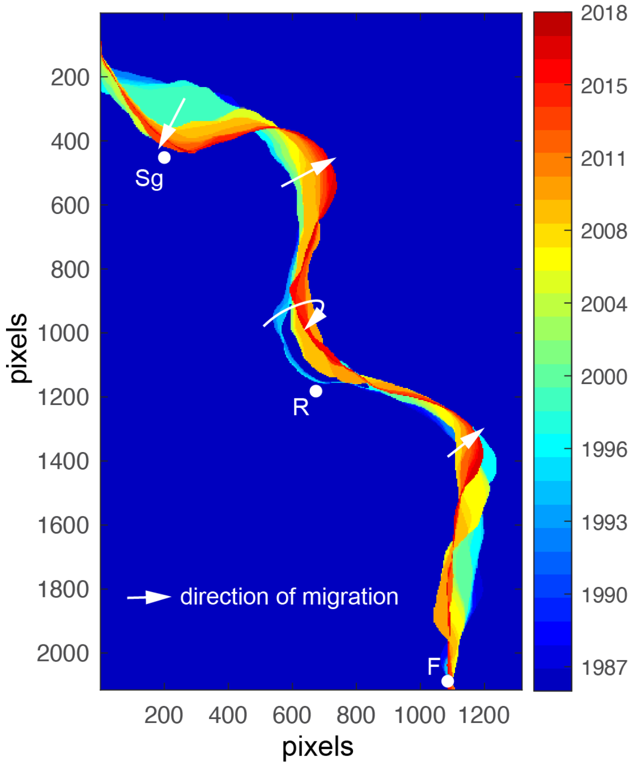


Fig. 5: Channel migration map of the study area showing annual shift in channel path and overall increase in meander in the upper part of the study area. Temporal migration of the channel is indicated by arrows.

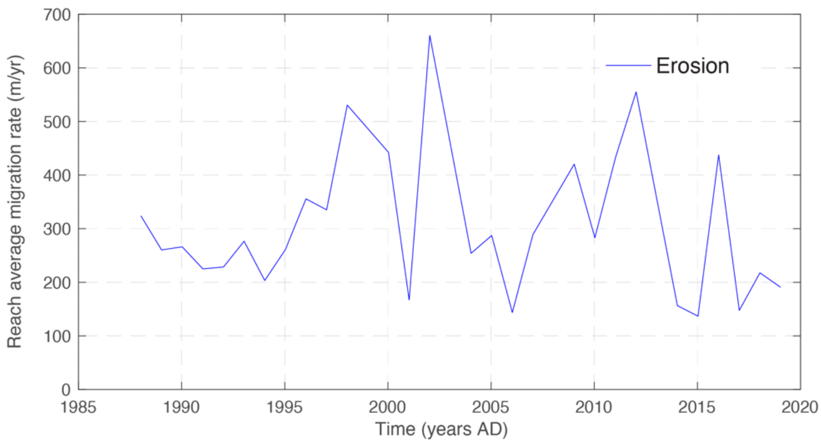


Fig. 6: Reach-averaged migration rate over the last 3 decades. CL stands for centerline migration while Erosion indicates bank migration. Both the trends are identical and major migration happened in 1997, 2000 and 2010.

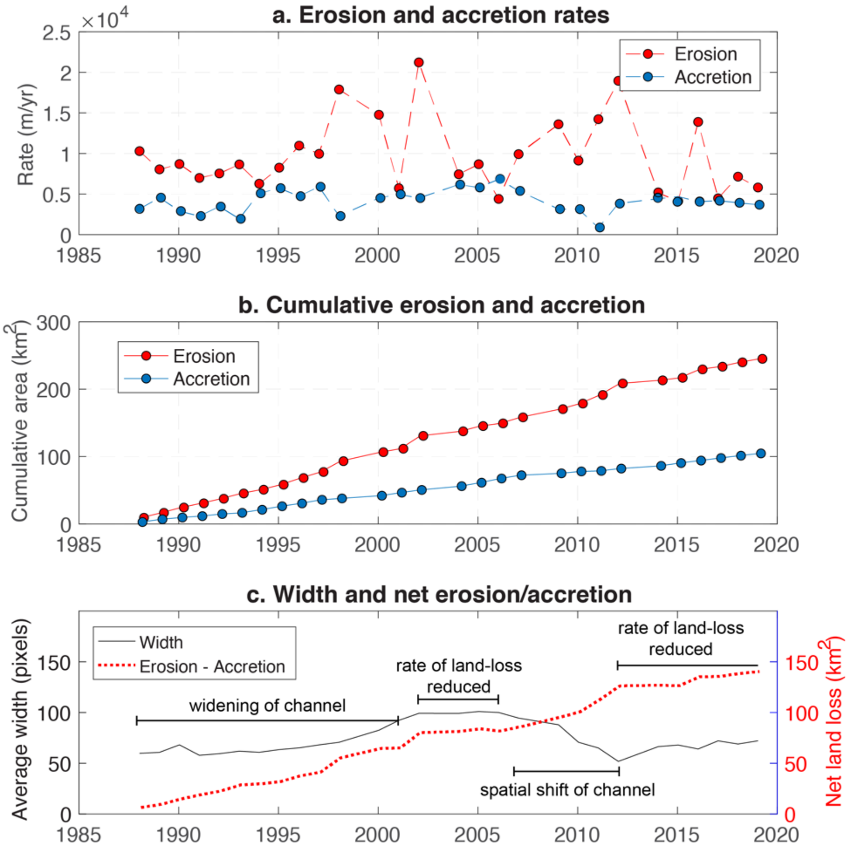


Fig. 7: (a) Annual bank erosion rate vs. accretion rate throughout the study area. This portrays how much km of riverbank has been eroded/ accreted per year. (b) Cumulative area of erosion and accretion are plotted against time. It shows that erosion is faster than accretion, therefore, the study area is facing land-loss. (c) Net loss is predicted from the difference between cumulative erosion and accretion. The slope of the blue line tells that over the last decade land-loss slowed down than 2000-2010. The average channel width also decreased since 2010.

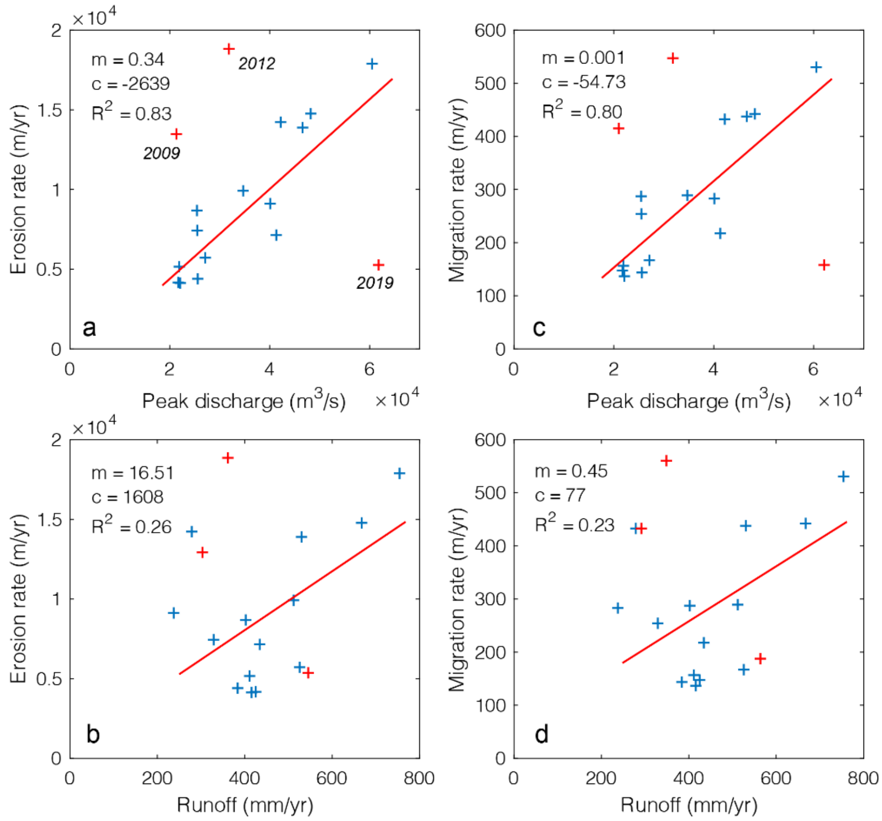


Fig. 8: Scatter-plot exploring relationship of erosion rate with (a) peak annual discharge and (b) annual runoff for the duration of 1999-2018. Microwave radiometry-based discharge and runoff data are collected from DFO flood observatory (https://floodobservatory.colorado.edu/). Linear fit parameters are obtained by using 95% confidence interval. Peak discharge shows a better fit ($R^2 = 0.83$) than runoff ($R^2 = 0.26$). We ignored data from 2003, 2009 and 2012 (marked in red) while calculating regression-fit as we consider them as outliers. Similar results are obtained using migration rate with peak discharge (Fig. 8c) and runoff (Fig. 8d).