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Long-Term Monitoring and Forecasting of Teesta Riverbank Dynamics Using Remote Sensing and GIS

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Abstract

The primary geomorphological processes that influence the riverine environments in Bangladesh are riverbank erosion and channel migration, which in most cases result in land loss and socio-economic consequences. The Teesta River is a large transboundary river located in northern Bangladesh which is characterized by a very dynamic channel behavior based on the hydrological variability, sediment transport, and human activities. The purpose of this study is to examine long-term riverbank migration of the Teesta river and project potential future locations of the bankline using remote sensing and GIS-based tools. Google Earth Engine was used to retrieve a series of multi-temporal Landsat satellite images between 1989 and 2024 to extract the positions of historical banklines. Digital Shoreline Analysis System (DSAS) was used to measure shoreline changes in terms of statistical variables such as Net Shoreline Movement (NSM), End Point Rate (EPR) and Linear Regression Rate (LRR). Findings show that the left bank is largely erosional where erosion is present in about 69% of the transects examined and erosion rate is the highest at -74.32 m/year. Conversely, the right bank exhibits predominating accretion patterns, where deposition is present in almost 59% of the transects and the highest rate of accretion is 154.3 m/year. A trend-based forecasting method based on a Kalman filter was used to project potential riverbank locations in 2034 and 2044. These forecasts indicate that erosion may persist along the left bank and local accretion along the right bank if historical migration trends continue. The findings can be useful in river management, land-use planning, and disaster mitigation in Teesta River basin.

1 Introduction

The functioning of Bangladesh's society, economy, and environment is significantly influenced by its rivers. With over 600 rivers flowing through the country, these river systems readily respond to both natural and human-induced changes [1, 2]. Among these, the Teesta River stands out as a dynamic and geomorphologically active boundary river. It forms the fourth largest river system in Bangladesh and has a profound impact on the nature of the floodplains in the north [3].

Bangladesh faces concerns about riverbank erosion which is much more damaging than even floods or cyclones due to the lost land that can never be restored [4, 5, 6]. The lower reach of the Teesta River near Dharala is often affected by channel migration, disrupting how river habitats support people [7, 8]. Previous studies have linked sudden upstream releases from structures such as Gajoldoba Barrage to increased flooding and bank erosion in Bangladesh [9, 10, 11].

As time has passed, the Teesta River has shifted from a braided path to a meandering or even straightened one [3, 11]. The various hydrodynamic changes are a result of sediment accumulation, changing discharge rates and human interventions. Along the outer banks, erosion concentrates where the geological formations and the materials in the banks are major factors [12, 13, 14, 15, 6].

Studying these dynamic systems is simplified by using remote sensing and GIS technologies. These data support long-lasting monitoring and spatial review of river changes with high precision [6, 16, 2]. Researchers have successfully used multi-temporal satellite imagery and geospatial analysis techniques to monitor riverbank dynamics, identify paleo-channels and analyze erosion–deposition patterns across different river systems worldwide. [17, 3].

The recent Digital Shoreline Analysis System (DSAS) has made it possible to carry out detailed statistical studies and forecast the positions of banks using the Kalman filter [18]. For rivers like the Teesta, where banks face instability and settlements, farmland and infrastructure are threatened, this technique is most valuable. This study integrates left- and right-bank DSAS statistics with Kalman-filter-based trend forecasting to evaluate both historical migration and potential future bankline positions.

In this context, the present study aims to assess the long-term bankline migration of the Teesta River using remote sensing and GIS from 1989 to 2024, and to forecast future riverbank positions for 2034 and 2044 using DSAS. The findings are expected to contribute valuable insights for sustainable river management and disaster preparedness in northern Bangladesh.

2 Study Area

The study focuses on the Teesta River segment located in northern Bangladesh, where the river enters the country from India and flows southward through the Rangpur Division shown in Fig. 1. This river reach is characterized by highly dynamic channel morphology, frequent bank erosion and significant sediment transport processes that influence the surrounding floodplain landscape and local communities.

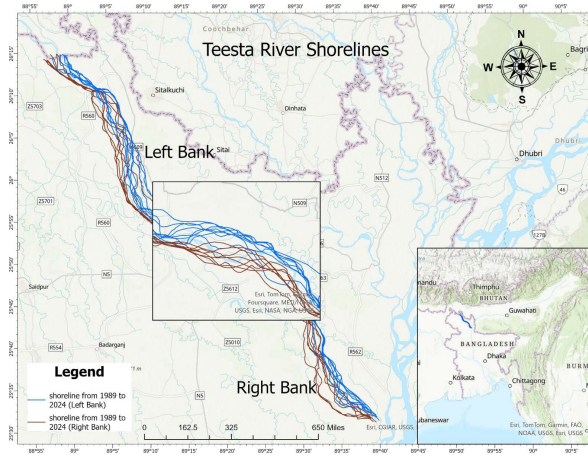


Figure 1: Teesta River Segment in Northern Bangladesh

3 Methodology

The methodology of this research is a combination of multi-temporal satellite remote sensing, geographic information system (GIS) analysis and statistical shoreline change modeling to measure riverbank movement and forecast future channel location of The Teesta River. The general process includes four key steps; (1) satellite data collection and preprocessing, (2) bankline detection, (3) statistical analysis of the movement of banklines with the Digital Shoreline Analysis System (DSAS), and (4) prediction of future riverbank locations by applying a Kalman filter-based model shown in Fig. 2.

Eight sets of Landsat images from 1989, 1994, 1999, 2004, 2009, 2014, 2019, and 2024 were used to derive past positions of riverbanks. These banklines were later examined with the help of

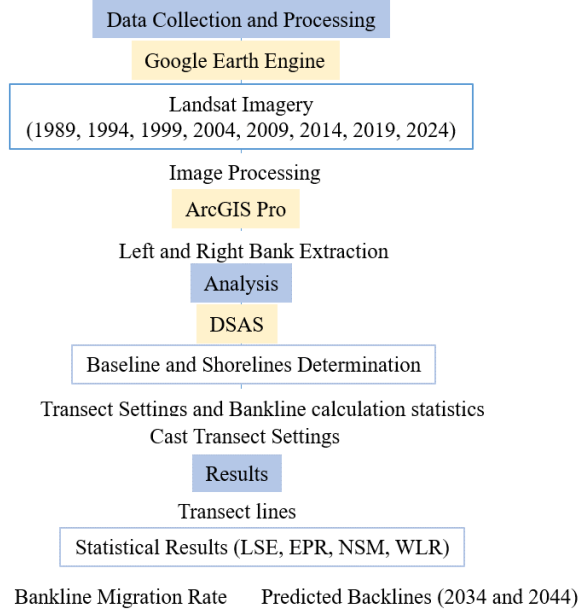


Figure 2: Workflow of Methodology: Data Collection to Prediction

DSAS to measure erosion and accretion mode of the riverbanks. Statistical measurements such as Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR) were calculated at the transects that were regularly spaced. Lastly, the historical migration patterns were predicted to make future bankline locations in 2034 and 2044, which allowed analyzing the possible geomorphic development of the river system.

3.1 Satellite Data Acquisition and Preprocessing

Landsat archive on Google Earth Engine (GEE) was used to get multi-temporal satellite imagery. Landsat data is a long-term earth observation archive which has consistent spatial resolution, therefore it is useful in analyzing how rivers used to be and the start and end of banklines.

This study used two Landsat sensors:

1. Landsat 5 Thematic mapper (TM) 1989-2009.
2. Landsat 8 Operational Land Imager / Thermal infrared Sensor (OLI/TIRS) (2014-2024).

To make the images uniform in relation to seasonal variation and provide consistency in the discharge conditions of the river, images were chosen during winter season (January-February) for each selected observation year shown in Table 1. By choosing images within the same seasonal period, we reduce effects of monsoonal flooding, cloud cover, and seasonal changes in water levels.

Table 1: Summary of Landsat Datasets Used for Analysis

Landsat Type	Year	Date From	Date To
Landsat 5 TM	1989	January 1, 1989	February 28, 1989
Landsat 5 TM	1994	January 1, 1994	February 28, 1994
Landsat 5 TM	1999	January 1, 1999	February 28, 1999
Landsat 5 TM	2004	January 1, 2004	February 28, 2004
Landsat 5 TM	2009	January 1, 2009	February 28, 2009
Landsat 8 OLI/TIRS	2014	January 1, 2014	February 28, 2014
Landsat 8 OLI/TIRS	2019	January 1, 2019	February 28, 2019
Landsat 8 OLI/TIRS	2024	January 1, 2024	February 28, 2024

All the data used in this paper are Level-2 surface reflectance products that have been atmospherically corrected. This was done through radiometric scaling factors that standardize reflectance values regardless of sensor used and date of acquisition. The issue of cloud contamination was reduced by using filtering processes in the Google Earth Engine platform.

3.2 Riverbank Extraction

Satellite images were interpreted in GIS to extract riverbank positions. Water boundaries were identified visually from the spectral contrast between land and water surfaces. The resulting water-boundaries were then translated into vector banklines representing the left and right banks of the river-channel of each year of observation.

The bankline extraction procedure consisted of a number of steps:

1. Importing Landsat images into GIS.
2. Detecting water boundaries based on spectral contrast between water and land.
3. Digitizing riverbank edges for each selected year.
4. Transforming extracted boundaries into polyline features (vectors).
5. Separating left and right banklines for analysis.

The resulting bankline data is the spatial location of the river channel at eight time periods between 1989 and 2024.

3.3 Shoreline Change Analysis Using DSAS

Riverbank migration rates were measured using the Digital Shoreline Analysis System (DSAS) extension of the U.S. Geological Survey. DSAS is frequently applied to the study of coastal and fluvial geomorphology to assess the change in shoreline or bankline with time.

The workflow of the DSAS included the following steps:

Baseline Creation

A parallel landward generated baseline parallel with the overall orientation of the river channel was created. This baseline can be used to cast transects in the direction of the riverbanks.

Transect Generation

One created perpendicular transects at 300-meter spacing along the river reach based on the baseline. All these transects cross every historical bankline and the system can therefore compute the changes in position over the different time periods.

Statistical Calculation

DSAS calculates a number of statistical measures that indicate bankline movement over time, per transect.

3.4 Shoreline Change Indicators

Three statistical indicators were used to quantify riverbank migration patterns.

Net Shoreline Movement (NSM)

NSM represents the total displacement distance between the earliest and most recent bankline positions along each transect. It provides a direct measurement of cumulative bankline change over the study period.

Positive NSM values indicate accretion (bank advance), whereas negative values represent erosion (bank retreat).

End Point Rate (EPR)

The End Point Rate calculates the average annual rate of shoreline change between the earliest and most recent banklines.

$$EPR = \frac{Distance_{latest} - Distance_{earliest}}{Time\ Interval} \quad (1)$$

EPR is widely used because it provides a simple estimate of long-term bank migration rate.

Linear Regression Rate (LRR)

The Linear Regression Rate is calculated by fitting a least-squares regression line through all bankline positions along each transect.

This method considers all historical shoreline observations rather than only the first and last points. As a result, LRR provides a more robust estimate of long-term shoreline trends and reduces the influence of short-term fluctuations.

3.5 Forecasting Future Riverbank Positions

The forecasting module, which includes a Kalman filter-based prediction algorithm, was used to predict future riverbank positions with the help of the DSAS v5 beta forecasting module.

The Kalman filter is a recursive statistical algorithm that integrates past data and predictions to determine future behaviour of a system. When applied to riverbank migration, the filter uses the past positions of the shoreline and the rates of migration to forecast the future bankline positions.

The three important steps in the forecasting process include:

1. Initialization

The input observations were historical shoreline positions between 1989 and 2024.

2. Trend estimation

The migration trend was estimated using Linear Regression Rate (LRR) values at each transect.

3. Prediction and updating

The Kalman filter calculates future shoreline locations and perpetually redefines the prediction error using the observed variability.

This framework was used to project bankline positions for 2034 and 2044. The forecasting model also generates uncertainty bands which reflect the confidence boundaries of the predicted shoreline positions. These projections are trend-based estimates rather than deterministic predictions of future river morphology.

3.6 Limitations of the Forecasting Approach

Even though the forecasting model is useful in getting insight on the possible riverbank evolution, it is mostly based on past migration trends. Thus, the forecasts presuppose the continuation of the past geomorphic processes in the future. In addition, uncertainties may arise

from the spatial resolution of Landsat imagery (30 m) which may introduce positional errors in the extracted banklines. Minor inaccuracies may also occur during manual digitization of river boundaries and the generation of transects in the DSAS framework. Therefore, the predicted bankline positions should be interpreted with consideration of these uncertainties.

Nonetheless, there are various factors that affect river systems, which include:

1. extreme flood events
2. variations in sediment transport.
3. human interventions (e.g., barrages or embankments)
4. channel avulsion processes

These are factors that can bring nonlinear shifts in the behavior of rivers that cannot be completely reflected by trend-based prediction models. Discharge, sediment transport, barrage operation, and future extreme-event scenarios were not explicitly incorporated in the forecasting model. This means that the forecasted bankline positions are to be taken as indicative positions and not deterministic positions.

4 Results

4.1 Left Bank Analysis

The left bank of the Teesta River exhibits shoreline retreat as the dominant process because most transect points indicate this phenomenon. Figure 3 shows positive NSM values around Transects 80–130, where EPR and LRR values are also generally positive. In contrast, strongly negative LRR values occur after approximately Transect 350.

The Linear Regression Rate (LRR) analysis demonstrated erosional behavior in 265 out of 384 transects with 300-meter intervals placed along the left bank which amounts to 69.01% shown in Table 2. Erosion establishes itself as the dominating geomorphological process affecting this area of the river bank.

Erosion hotspots take priority over uniform patterns in its spatial distribution across specific zones. Transect 360 displays the highest erosion rate, with a retreat rate of -74.32 meters per year.

Most of the action happens through erosion yet some parts of the bank demonstrate accretion dynamics. Irregularities due to accretion processes can be observed across 119 transect areas (30.99%) along the left river bank. The statistical analysis shows that only 1.3% of the accretional transects exhibit statistically significant trends. Transect 113 shows the highest accretion rate at 52.68 meters per year, indicating localized deposition.

Table 2 shows that the average erosion rate across the erosional left-bank transects is -31.96 meters per year. The results indicate substantial bank retreat and lateral channel shifting during the study period.

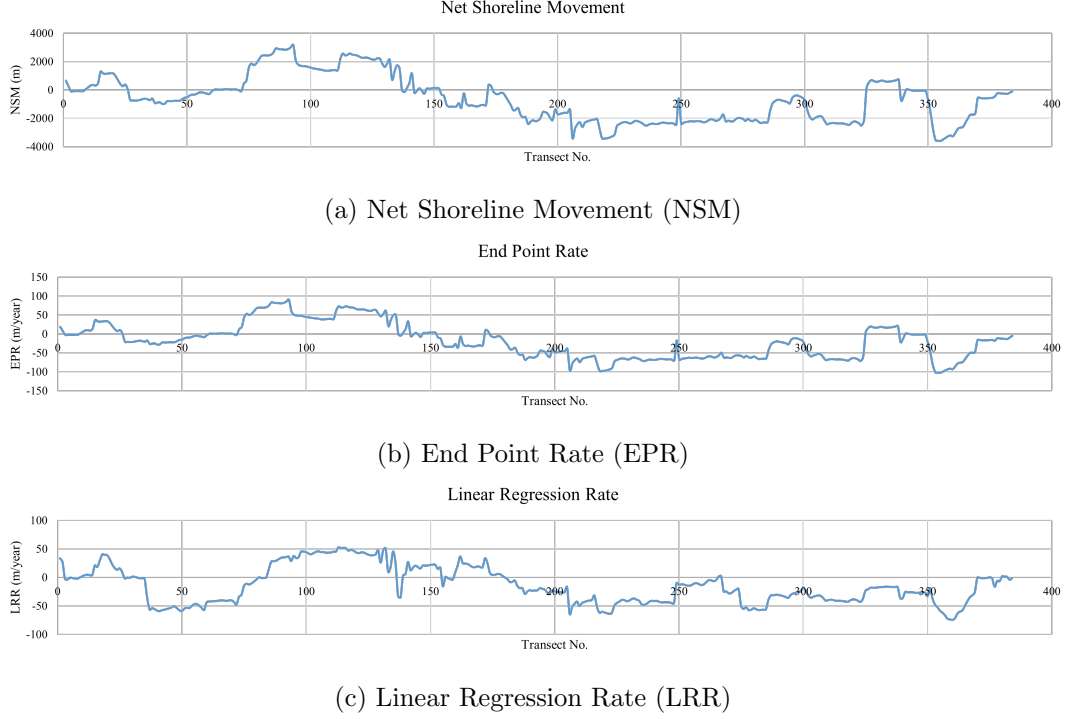


Figure 3: Shoreline Change Metrics for Left Bank Transects: (a) NSM, (b) EPR, and (c) LRR

4.2 Right Bank Analysis

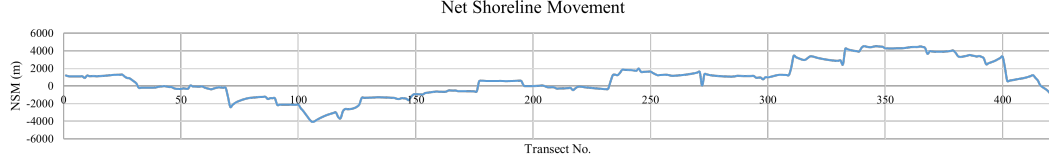
The right bank shoreline of the Teesta River shows accretion as the prevalent process based on affected transects while maintaining its position as the most common shoreline change. The analysis of 421 transects showed that accretional behavior was observed in 250 transects which made up 59.38% of the surveyed area in Table 2. An examination of 171 transect sites (40.62%) leads to erosion findings thus indicating deposition dominates spatially though both processes remain active.

Figure 4 shows how NSM values demonstrate continuous erosion across most transects until they reach number 260. Around transect number 300 significant changes occur because NSM values show positive tendencies. The End Point Rate (EPR) and Linear Regression Rate (LRR) graphs parallel each other in this region through steadily rising values to indicate major shoreline expansion in right bank downstream areas.

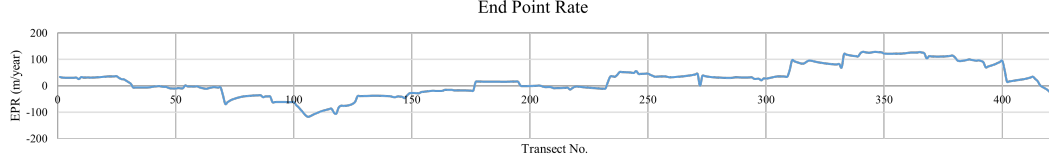
The maximum shoreline loss occurs at Transect 106, with an annual erosion rate of -80.33 meters. The studied right-bank erosional transects demonstrate an average annual erosion rate of -20.48 meters per year.

The maximum accretion rate measured 154.3 meters per year stands at Transect 361 where significant accumulation occurs. The high deposition values suggest lateral channel expansion and localized bar formation. The statistical assessment of geomorphic change found 17.58% of accretional transects to be significant, indicating persistent morphological change in these sections. Accretion rates from accretional transects measure an average of 51.88 meters per year while showing higher values than the recorded erosion rates.

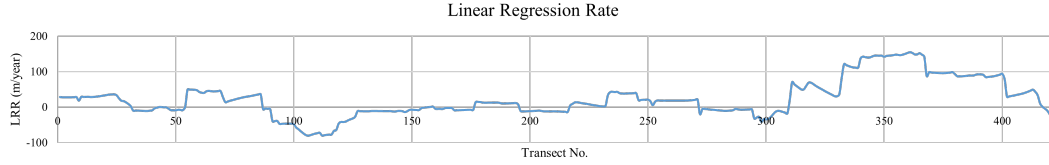
The right bank of the Teesta River shows substantial morphological variability through areas that erode alternately with sections that build up. Some sections show extensive accretion that may reflect changing channel paths and localized sediment deposition. River management strategies should recognize the area-specific nature of geomorphic activities because they shape both riverbanks.



(a) Net Shoreline Movement (NSM)



(b) End Point Rate (EPR)



(c) Linear Regression Rate (LRR)

Figure 4: Shoreline Change Metrics for Right Bank Transects: (a) NSM, (b) EPR, and (c) LRR

Table 2: Comparative Statistical Summary of Erosion and Accretion (Left vs Right Bank – LRR)

Metric	Left Bank Value	Right Bank Value
Number of erosional transects	265	171
Percent of transects that are erosional	69.01%	40.62%
Statistically significant erosional transects	24.74%	3.09%
Maximum erosion rate (m/year)	-74.32	-80.33
Transect ID of maximum erosion	360	106
Average erosion rate (m/year)	-31.96	-20.48
Number of accretional transects	119	250
Percent of transects that are accretional	30.99%	59.38%
Statistically significant accretional transects	1.3%	17.58%
Maximum accretion rate (m/year)	52.68	154.3
Transect ID of maximum accretion	113	361
Average accretion rate (m/year)	25.84	51.88

4.3 Shoreline Forecasting

The DSAS v5 beta forecasting tool processed historical bankline information to predict future riverbank positions at 2034 and 2044. The forecasting model utilizes a Kalman filter to analyze past shoreline observations together with model predictions to determine future shoreline locations. Initiation of the Kalman filter starts with using Linear Regression Rate (LRR) from previous shoreline modifications to update estimated positions that minimize errors between actual and modeled data points.

The Kalman filter forecasting mechanism tracks temporal changes in positions together with data position errors. The model presents an uncertainty band to indicate increasing prediction uncertainty as time moves away from the last known observational point.

This forecasting model depends on past trends showing linear progression into future times which might not always hold true in systems with complex fluvial system dynamics. The model fails to consider important shoreline modifiers consisting of peak monsoonal flows, channel migration, human interference and sediment availability patterns. These predictions exist for indicative planning purposes only since they require careful interpretation before official use.

4.3.1 Left Bank Prediction

The predicted left banklines from Figures 5 indicate that specific downstream areas may continue to erode, while selected sites may experience stabilization or limited sediment deposition if historical trends persist. The forecaster projections match previously confirmed erosion hotspot areas.

4.3.2 Right Bank Prediction

The right bank projections in Figure 6 indicate continued accretion in several upstream sections, whereas some downstream sections may remain susceptible to erosion (Figure 6).

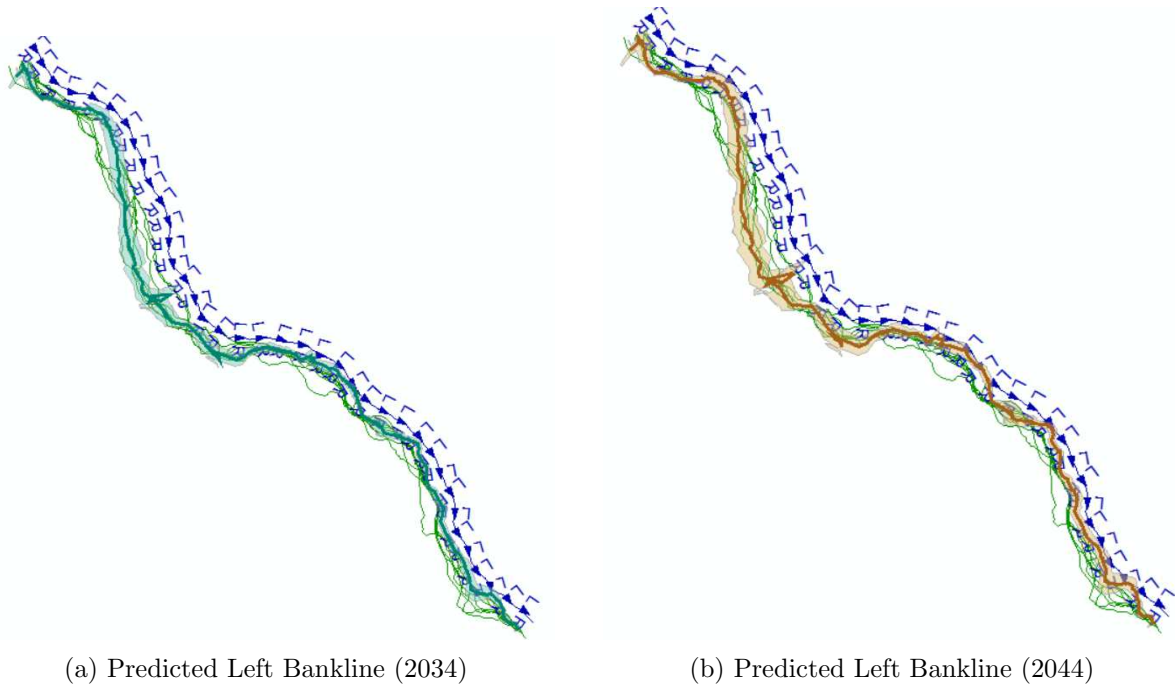


Figure 5: Predicted Left Banklines for 2034 and 2044

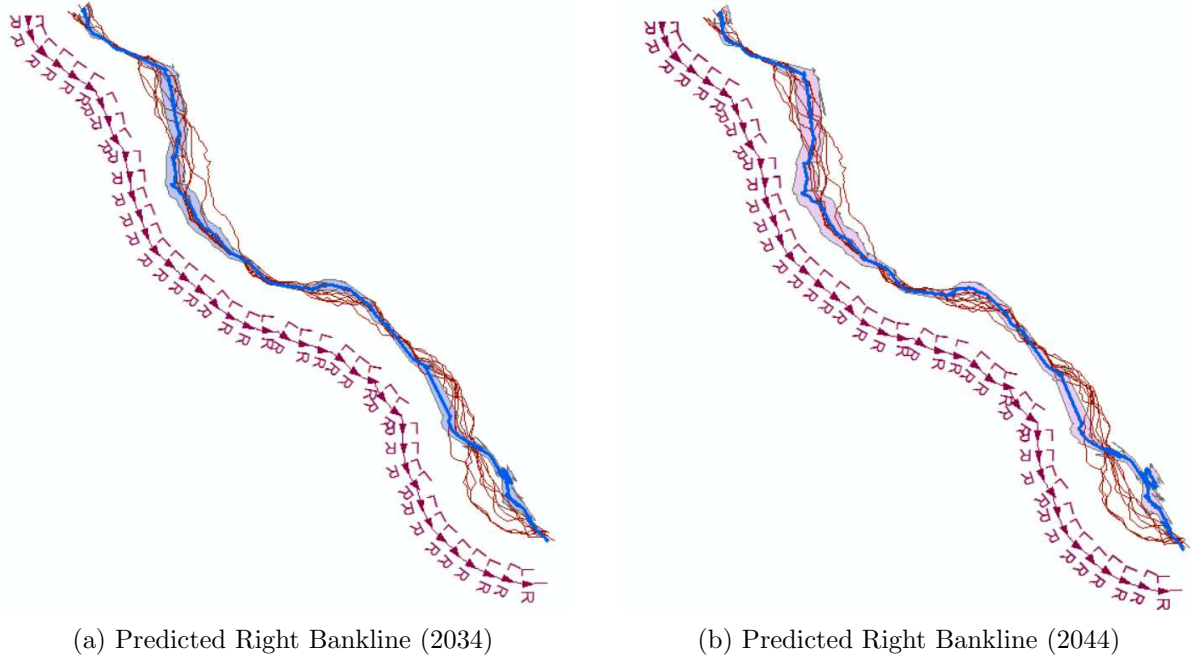


Figure 6: Predicted Right Banklines for 2034 and 2044

4.4 Discussion

Studies of Teesta River bankline movement through space and time show different geomorphic behavior develops between its left bank and right bank. Evidence shows that the left bank is predominantly erosional, with about 69% of transects exhibiting bank retreat. The maximum yearly erosion rate of -74.32 meters at Transect 360 and LRR values confirm the existence of severe erosion points throughout the study area. Sediment deposition happens infrequently on the left bank because such occurrences remain rare and statistically unimportant.

The conditions on the right bank possess distinct characteristics from those observed on the left bank. Data indicate that accretion is prevalent because 59.38% of transects experienced accretion, while 17.58% exhibited statistically significant accretion rates. Transect 361 demonstrates the maximum rate of accretion reaching 154.3 meters per year while surpassing the average right-bank erosion rate at -20.48 m/year. The observed right-bank accretion may reflect sediment redistribution, local channel geometry, flow variability, and upstream regulation; however, these mechanisms were not explicitly evaluated in this study.

Accumulated shoreline data predicts continued patterns of accretion and erosion up until 2034 and 2044. The predictions for the left bank show that the lower river section may continue to experience bank retreat if historical migration trends persist. Forecasted predictions on the right bank indicate shoreline buildup in the upper area and potential erosion patterns will develop in future years downstream. Through the Kalman filter model the linear forecasts match current river process relationships to show essential information about system evolution until 2044.

5 Conclusion

The study of Teesta River demonstrates that its left and right shoreline areas are experiencing divergent transformations. The left bank experiences substantial bank retreat over time, indicating persistent erosional behavior in many sections. The right bank demonstrates strong growth patterns specifically near the upstream areas where accumulating sediments lead to new land development. The right side of the river experiences accretion as its dominant process.

The future projections for 2034 and 2044 indicate trends broadly comparable to those observed historically. The results suggest continued left-bank erosion alongside right-bank aggradation, with some downstream sections remaining susceptible to erosion.

The study reveals that the riverbank transformations require separate management measures because the processes differ between the left and right sides. To stop additional erosion on the left bank proper measures like protective embankments along with vegetation need implementation. Monitoring the sediment deposition areas on the right bank will help avoid potential issues stemming from blocked water flow and altered river course.

The study provides essential knowledge about Teesta River changes to help us find methods which safeguard land and people in the region.

Declarations

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Ethics Approval

Not applicable.

Competing Interests

The author declares no competing interests.

Author Contributions

M.R. conceived the study, conducted the analysis, prepared the figures, and wrote the manuscript.

Data Availability

The datasets analyzed during the current study are publicly available from the Landsat archive via Google Earth Engine.

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