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Prediction of Morphological Change of a Meandering River using Time-Series Data from Satellite Remote Sensing Imageries

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ABSTRACT

In this paper, a new stochastic method has been presented for prediction of morphological change, and bankline system using time-series data from satellite remote sensing imageries in the meandering river. Multi-temporal satellite remote sensing data i.e. Landsat series imageries from 2006 to 2020 has been used for time-series analysis through stochastic method. We have identified 105 morphological active vulnerable sites through multi-criteria analysis (MCA), and we have developed the morphological change, and bankline shifting prediction model for these 105 vulnerable sites. We have analysed the erosion / deposition pattern, river migration, sinuosity ratio, soil characterise, soil texture, bank material, and water discharge data for these vulnerable sites. We have also developed an equation for generation of predicted points (x, y) in GIS. Statistical analysis of river bankline shifting rate at each vulnerable site has been carried out and that was compared with riverbank soil type, and sinuosity ratio. Sandy soil has the highest river bankline shifting rate and sinuosity ratio, while clay / clay loam soil has the lowest river bankline shifting rate and sinuosity ratio. As we have developed that model based on banklines from Landsat imageries, we are recommending to be used high-resolution satellite images i.e. QuickBird, GeoEye, WorldView for digitization of banklines, subsequent this model will give more accurate result.

Keywords: Erosion deposition pattern, morphological change, prediction model, Landsat satellite imagery, meandering river

INTRODUCTION

Rapti River originated in Nepal and flowing through Nepal and India is a meandering river. This is a highly dynamic river system that involves complex processes of morphological changes. Developing a simulation model to predict the meander migration and morphological changes has been a major research goal for the last decades. The river morphology is changing under varying environmental conditions at both spatial and temporal scales due to river erosion and drift through natural and anthropogenic inputs (Nanson et al., 1996; Mount et al., 2013; Midha et al., 2014). Processes governing river morphology include bankfull discharge, channel dynamics, runoff events, vegetation cover, and sediment supply. Channel migration and its response to altering conservational situations are extremely dependent on local aspects such as channel type, hydrological and vegetative conditions, and that are affected by anthropogenic disturbances (Buffington, 2012; Khan et al., 2015). Understanding the characterization of processes to move the channel and assess the morphological changes of the river have long been of interest to geomorphologists, geologists, and engineers (Sarma, 2005; Dewan et al., 2017). Currently, there is increased interest on this topic among geomorphologists for the study of river valleys and watershed hydrology (Islam, 2016). Substantial progress has been made in understanding the channel morphology and river migration. The study of channel morphology is necessary to evaluate natural and human effects on morphological parameters and channel dynamics (Friend et al., 1993; Graf, 2000).

The rivers always change their morphological processes over time due to changes in shapes and conditions. Riverbank erosion-deposition and channel dynamics are geomorphological phenomena investigated by various researchers (Das et al., 2007; Mount et al., 2013). Several studies from Gorai River, Bangladesh (Sarkar et al., 1999); Santiago Rivers, United States (Clark et al., 2000); Mississippi River, United States (Hudson et al., 2000); Ganga and Yamuna Rivers, India (Sinha et al., 2005); Yellow River, China (Wang et al., 2006); Sacramento River, United States (Larsen, 2007); Mekong River, Vietnam (Kummu et al., 2008); Ebro River, Spain (Ollero, 2010); Dane River, UK (Hooke et al., 2010); Sacramento River, United States (Michalkova et al., 2011); Somesul Mic River, Romania (Persoiu et al., 2011); Tagliamento River, Italy (Surian et al., 2012); Brahmaputra River, India (Sarkar et al., 2012); Ganges River, India (Hossain et al., 2013); Jamuna River, Bangladesh (Thian, 2013); Pearl River, China (Zhang et al., 2015); Yangtze River, China (Xia et al., 2016); Padma River, Bangladesh (Abu et al., 2016); Pestan River, Serbia (Djekovic et al., 2016); Hugli River, India (Mallick, 2016); Tammaro River, Italy (Magliulo et al., 2016); Padma River, Bangladesh (Rehman et al., 2017); Wabash River, United States (Lant et al., 2018); Pravara River, India (Das, 2018); Vaitarna and Ulhas Rivers, India (Das et al., 2018); Teesta River, Bangladesh (Akhter et al., 2019); Alaknanda, Bhagirathi, Mandakini and Kali Rivers, India (Pareta et al., 2019); Ganga River, India (Pal et al., 2019); Amazon River, Brazil (Sylvester et al., 2019) reported broadly the morphological changes of major river basins using satellite remote sensing imageries with GIS techniques. These studies showed that remote sensing and GIS techniques are useful in analyzing river migration and morpho-dynamics at spatial and temporal scales.

The ultimate goal of this research study was to understand and explain how the river morphology changes (bankline shifts) for Rapti river system for prediction of river migration based on multi-temporal Landsat satellite imageries (2006-2020). This work was an attempt to predict the morphological change (bankline shift) for 2021 in a very large scale (1:1000) that had not been often measured in earlier river morphological change modeling. This study is very useful for river management planning. The main objectives of this study were: (a) understanding the spatial and temporal change in river morphology of Rapti river system using 15 years Landsat satellite imageries; (b) identification of highly vulnerable sites based on frequency and magnitude of river bankline shifting, channel migration over the years, erosion / deposition pattern over the years; and (c) prediction of river bankline on highly vulnerable sites using multi-temporal Landsat satellite imageries.

Study Area Description

Rapti river is the largest tributary of Ghaghra river which is a major constituent of the Ganga. It extends from 26°18'00" N to

28°33'06" N and 81°33'00 E to 83°45'06" E and covers an area of 25,793 km² out of which 41% (10,642 km²) lies in Nepal and 59% (15,151 km²) in India. It rises at an elevation of 3048 m in Dregaunra Range of Nepal Siwalik and covers a total distance of 782 km (of which 565 km lies in India) before joining Ghaghra at Barhaj in Deoria district of Eastern Uttar Pradesh. The Rapti river flows through the districts of Bahraich, Shravasti, Balrampur, Siddharth Nagar, Sant Kabir Nagar, Gorakhpur and Deoria of Eastern Uttar Pradesh (Figure 1).

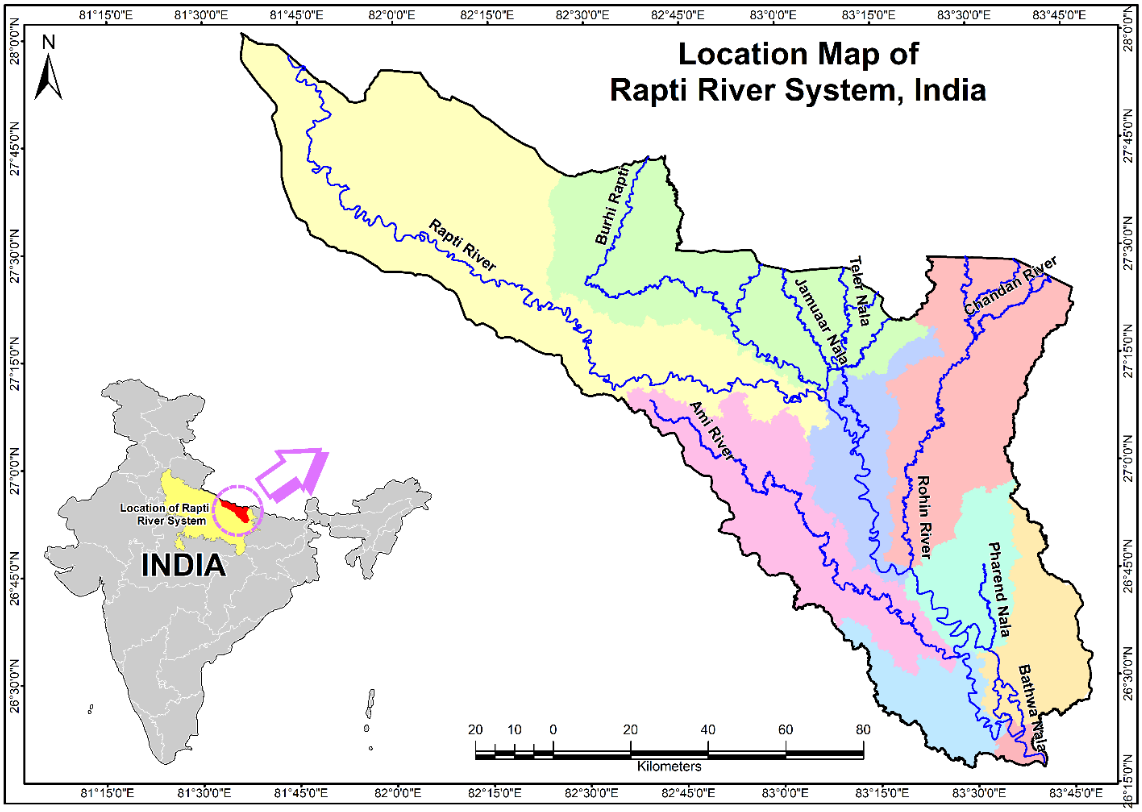

Figure 1. Location Map of Rapti River System, India

The basin consists geologically of two distinct portions - structurally it is a segment of the great Indo-Gangetic trough and it has also some portion of the Himalaya's foothills region of the Siwalik. Recent findings of the chrono-association of the Gandak mega-fans areas revealed that the alluvia of the Old Rapti Plain (Burhi Rapti) is that of 5000 years before present, and that of Rapti is more than 500 years before present (Mohindra et al. 1992).

METHODOLOGY AND DATA USED

Data Used and Sources

Pre-monsoon and moderate resolution Landsat satellite imageries i.e. Landsat-5 TM images, Landsat-7 ETM+ images and Landsat-8 OLI images from 2006 to 2020 were downloaded from Earth Explore, USGS (https://earthexplorer.usgs.gov). These multi-temporal satellite imageries were used to obtain information on river shifting and morphological trends of Rapti River and its 16 tributaries. The details of satellite remote sensing data, other data used for this study is shown in Table 1.

Table 1. Other Data Sources

S. No.	Data Type	Data Sources and methodology
1	Satellite Remote Sensing Data	Landsat-5 TM satellite image with 30 m spatial resolution for years 2006, 2007, 2008, 2009, 2010, 2011. Landsat-7 ETM+ satellite image with 30 m spatial resolution for year 2012. Landsat-8 OLI satellite image with 30 m spatial resolution for years 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020. Source: https://earthexplorer.usgs.gov

2	SoI Toposhe et at 1:50,000 scale	Survey of India Toposheets, 2005 Toposheet No.: 63E/10, 14; 63I/02, 03, 07, 08, 11, 12, 16; 63J/09, 13, 14; 63M/08, 12; 63N/01, 02, 03, 05, 06, 07, 09, 10, 11, 14 & 15 Source: http://www.soinakshe.uk.gov.in
3	Elevation Data	ALOS PALSAR (DEM) Data: Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (DEM) Data with 12.5m spatial resolution. Source: Alaska Satellite Facility, Fairbanks. U.S. state of Alaska. 2004-2015. Source: https://vertex.daac.asf.alaska.edu/

RESULT

Priority Vulnerable Sites

One hundred and five priority vulnerable sites were identified for analysis, morphology modelling for predicting changes, and conducting field assessments. The multi-temporal remote sensing data from 2006 to 2020 have been digitized in shapefiles using Esri ArcGIS-10.7 software. The river course and silt deposit areas in India side were delineated.

To identify the priority vulnerable locations from the temporal analysis of the satellite imageries, certain criteria were used. They are - (i) frequency and magnitude of river bankline shifting, (ii) channel migration over the years, (iii) erosion / deposition pattern over the years and (iv) presence of critical flood management assets like barrages, bridges, launching aprons, rain cuts, regulator inlets outlets, spur structures, and embankment structures. By using these criteria, 105 vulnerable sites in the Rapti river system were identified. The locations of priority vulnerable sites are shown in Figure 2.

Riverbank Erosion and Deposition Areas Analysis

Erosion plays a significant role in the changing environment of a river. It affects water flow, water quality, channel width and depth and safe use of a river as a transportation corridor. Generally, riverbank erosion or deposition is a mechanism of sediment (bank material) transportation by a river that affects the river channel courses (Biswajit et al., 2013). Fluvial geomorphic processes are very active in most of the rivers in north India. As a result, river erosion is common in the study area, Rapti River and its 16 tributaries.

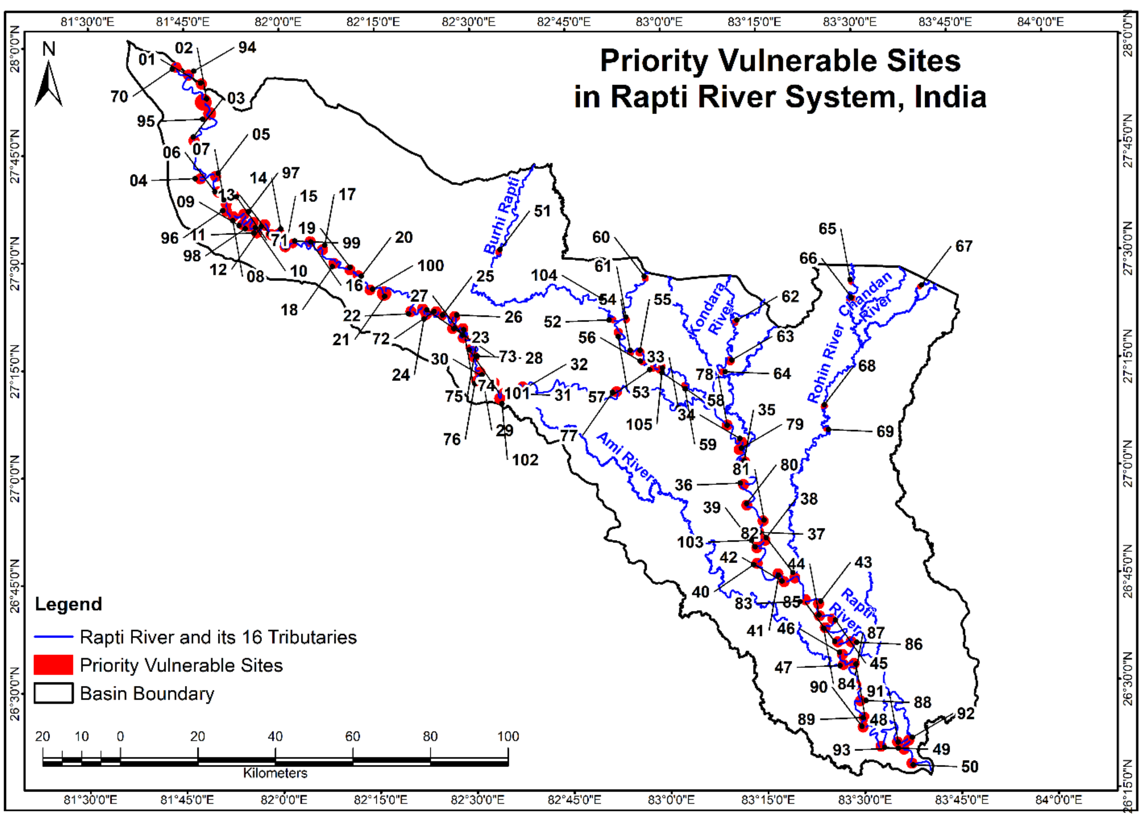

Figure 2. Priority Vulnerable Sites in Rapti River System in India

Multi-temporal Landsat satellite remote sensing data from 2006 to 2020 have been used for this analysis. The two resultant shapefiles were superimposed in-order-to demarcate union wise erosion and deposition areas. The high erosion and higher bar deposition areas were also identified, which have been verified in field. The total area of erosion and deposition from all the unions were calculate by using ArcGIS 10.7 software. The erosion and deposition area of Rapti river system has been extracted of years 2006 to 2020 and shown in **Error! Not a valid bookmark self-reference.**.

Table 2. Erosion and Deposition Area (2006 - 2020) in Rapti River System

S. No.	Years	Deposition (Km^2)	Erosion (Km^2)
1	2006-2007	33.27	24.91
2	2007-2008	31.6	42.95
3	2008-2009	43.43	30.95
4	2009-2010	21.29	45.26
5	2010-2011	41.02	21.71
6	2011-2012	35.92	31.08
7	2012-2013	24.29	25.57
8	2013-2014	22.28	41.98
9	2014-2015	41.25	22.61
10	2015-2016	29.06	24.19
11	2016-2017	16.09	52.29
12	2017-2018	34.12	46.79
13	2018-2019	31.13	34.19
14	2019-2020	33.13	43.19

The morphology and behavior of Rapti River undergo drastic changes in response to various flow regime. The erosion and flood are a common phenomenon in Rapti River, but it becomes a matter of serious concern when it takes the form of disaster. The study area is also prone to devastating floods. But due to severe erosion of bankline with floods, the situation in the area is critical. During the monsoon season, the rivers coming from the hills bring huge amount of water and sediment and fill the entire channel area. Due to this it affects the stability of channels and banklines.

River Bankline Shift Analysis

The Rapti river and its tributaries are constantly changing due to the geomorphic (e.g. water velocity), climate agents (e.g. flooding) and human activities (e.g. sand excavation, removal of vegetation cover and fertile soil excavation). The gradient (or slope), the amount of water, the velocity of water and the nature of a river or tributary are the parameters due to changes in the shape and size of a river / tributary (Pareta, 2013). The GIS technique (spatio-temporal analysis of satellite imagery) using advanced remote sensing data over the last 15 years has been used to identify changes in river course (both river and tributaries) and further calculations have had analysed river shifting and bank erosion. The bankline of Rapti River and 16 tributaries have been manually digitized from 2006 to 2020 by using multi-temporal Landsat satellite imageries i.e. Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI. By overlaying this database locations of bank channel shifting of Rapti river and tributaries have been identified. The shifted parts of the river have been mapped by vectorisations in GIS.

We have fixed 31 cross-section lines at every vulnerable site, and riverbank line shift has been measured for 105 vulnerable sites. The bank line shift has been measured in both bank lines i.e. right bank line and left bank line (where the vulnerable site is situated) with reference to length (in metres) and direction from 2006 to 2020. A positive value (+) indicates that the riverbank line has shifted in the right direction from previous year, while a negative value (-) indicates that the riverbank line has shifted in the left direction from previous year. After a detailed study of river bank line shift data of Rapti river system, we have observed a relationship between erosion / deposition and bankline shifting, which is shown in Table 3.

Table 3. Relationship between Erosion, Deposition and Bankline Shift

S. No.	From previous year to next year	Remarks
1	Right bankline shift to left direction	Deposition
2	Right bankline shift to right direction	Erosion
3	Left bankline shift to left direction	Erosion
4	Left bankline shift to right direction	Deposition

A river cross section can be defined as the change of river depth (elevation) in relation to the horizontal distance from one river to another bank. Total 31 cross-sections for each vulnerable site have been demarcated perpendicular to the river (year 2020), and separation of cross-sections is 100 meters.We have measured riverbank line shift at 3255 locations (105 vulnerable sites x 31 cross-sections = 3255 locations) in Rapti river system. Here, we have demonstrated only two vulnerable sites data (Site No. 05, and Site

No. 33), which we have future analysed and used for prediction of bankline change.

Time Series Modeling and Forecasting

Bank erosion (accretion) and / or river movement modeling based on exceeding a critical threshold becomes unstable for simulations, giving rise to local problems of widening or narrowing at unrealistic values. Furthermore, the results struggle to handle the system's response to cutoffs (Esther, 2013; Esther et al., 2014a, b). To solve these problems, a statistical approach has been applied. Time-series generated for various river morphometric attributes from multi-temporal satellite image analysis (pre-monsoon only) has been used. Other data from satellite imagery i.e. erosion / deposition, sinuosity ratio; discharge data, and soil data have been used for correlation of model output data.

The time-series of these morphometrics are divided into two sets, (i) Set-1: 80% of the time-series has been used for the calibration of model, (ii) Set-2: 20% of the time-series has been used for validation of the forecast model. A stochastic method has been used to predict the morphological change in Rapti river system. Validation assessment approach measures the fit between model predictions and satellite data of that predicted year. We have compared the riverbank line data from satellite imagery and model output for 2019 and 2020 with the error of $\pm$ 15 m (half size of a pixel in Landsat-8 OLI satellite imagery).

We have validated of model output with satellite data, for graphical representation of validation of model output vs satellite data for site no. 05, and site no. 33 is shown in Figure 3 and Figure 4 respectively.

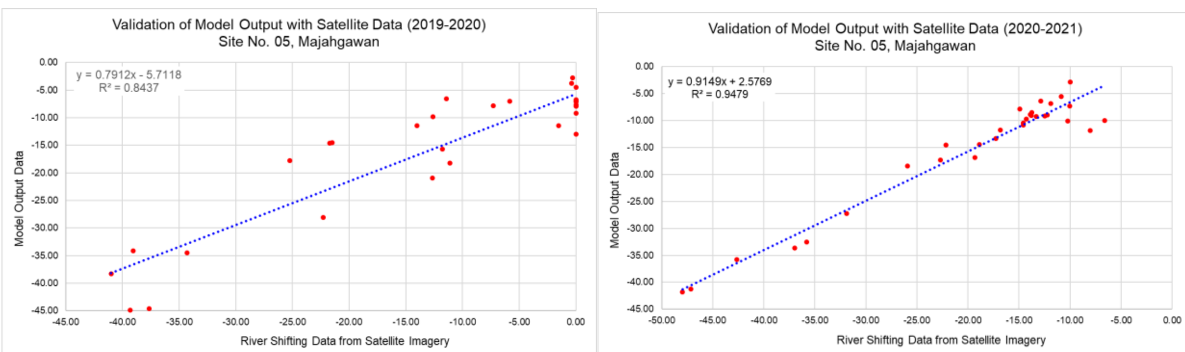

Figure 3. Validation of Model Output with Satellite Data for Site No. 05, Majahgawan

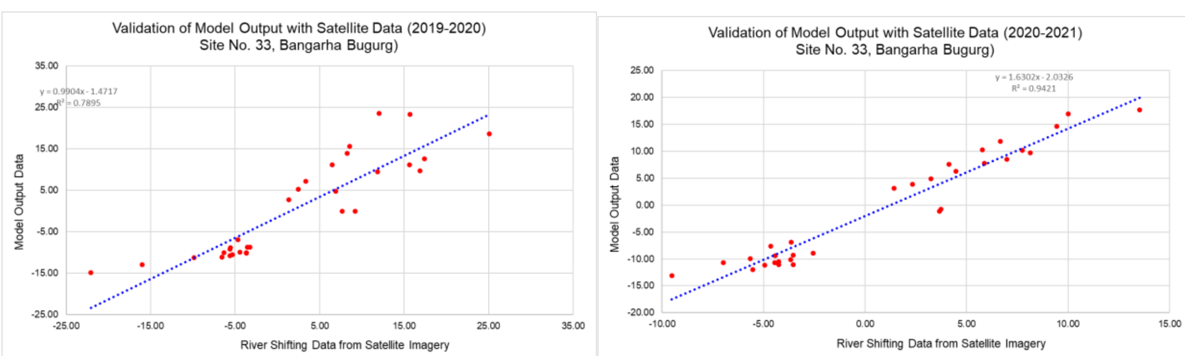

Figure 4. Validation of Model Output with Satellite Data for Site No. 33, Bangarha Bugurg

The projection of Rapti river at site no. 05 is NE. The average shifting rate (2006 to 2020) in this direction is 12.03 m per year. The validation of model output versus satellite imagery has an accuracy of 90%. The projection of Rapti River at site no. 33 is SW. The average shifting rate (2006 to 2020) is 5.17 m per year. The validation of model output versus satellite imagery has an accuracy of 87%.

Equation for Generation of Predicted Points (x, y)

By using the stochastic model, we have extracted the predicted distance from 2020 (bankline from satellite imagery) to 2021 (model output), but our concern is how to draw this distance in GIS. To solve the problem, an equation has been produced, which can draw the distance in GIS from 2020 to 2021, and generate the x,y coordinate of model output at each cross-section line. The mathematical explanation is shown in Figure 5.

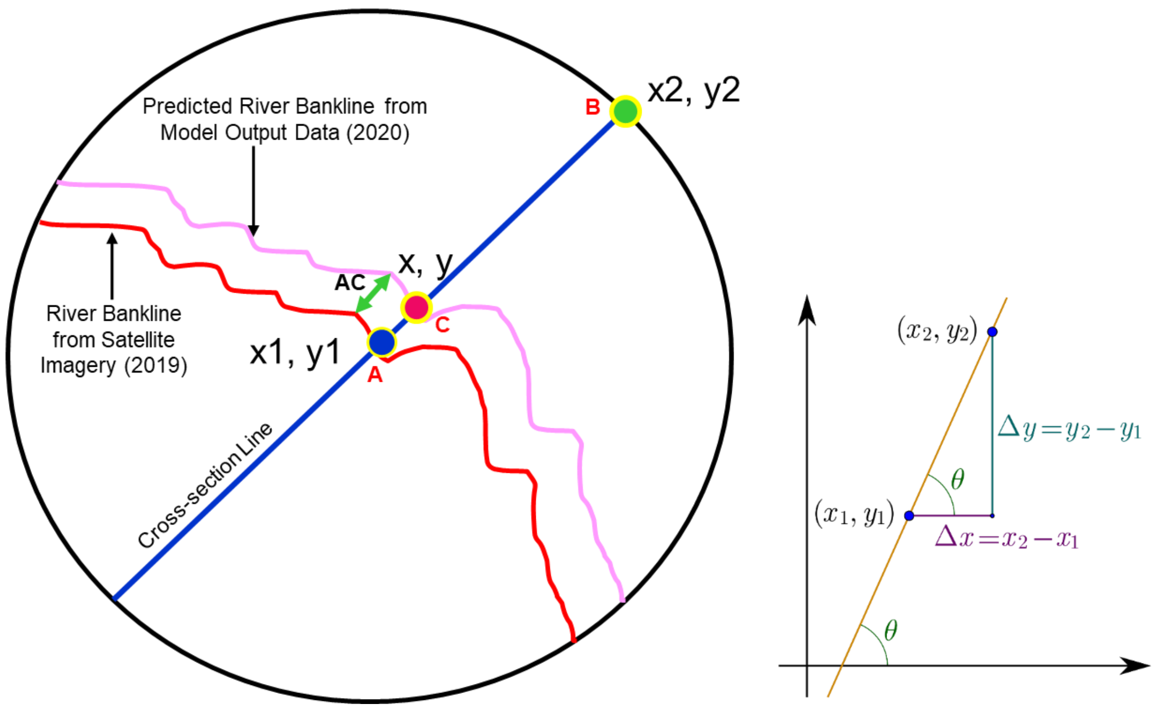

Figure 5. Conceptual Diagram for Generation of Predicted Points (x, y)

For measurement of slope between x1y1 and x2y2 or x1y1 and xy; the below stated equations have been used.

Slope (m) = y2 - y1 / x2 - x1……………………………………………………………………… (3)

In equation (3) we can generate the coordinate of x1y1 and x2y2 in GIS.

Slope (m) = y - y1 / x - x1………………………………………………………...……………… (4)

Equation (4) can be written as Equation (5)

y - y1 = Slope (m) * (x - x1) ………………………………………………………………………… (5)

For measurement of distance between point (A) and point (B), the below stated equation has been used.

Distance (AB) = $\sqrt{(x2 - x1)^2 + (y2 - y1)^2}$…………………………………………………………… (6)

The same equation can be used for measurement of distance between point (A) and point (C)

Distance (AC) = $\sqrt{(x - x1)^2 + (y - y1)^2}$……………………………………..…………………………… (7)

Equation (7) can be written as Equation (8)

$[\text{Distance (AC)}]^2$ = $(x - x1)^2 + [\text{Slope (m)} * (x - x1)]^2$…………………………………………………… (8)

Equation (8) can be written as Equation (9)

$[\text{Distance (AC)}]^2$ = $(x - x1)^2 + \text{Slope (m)}^2 * (x - x1)^2$……………………………………………………… (9)

Equation (9) can be written as Equation (10)

$[\text{Distance (AC)}]^2$ = $(x - x1)^2 * [1 + m^2]$………………………………………...……………………… (10)

Equation (10) can be written as Equation (11)

$(x - x1)^2$ = $AC^2 / (1 + m^2)$……………………………………..……...…………………… (11)

Equation (11) can be written as Equation (12)

x - x1 = $\sqrt{[AC^2 / (1 + m^2)]}$……..……..………………………...……...…………………… (12)

Equation (12) can be written as Equation (13)

$$x = \sqrt{[AC^2 / (1 + m^2)]} + x1 \quad (13)$$

Distance between A&C has been extracted from model; m is slope, which has been calculated by using x1y1 and x2y2 coordinate. If, we put these two values in equation (13), the coordinate of x can be generated.

Equation (5) can be written as Equation (14)

$$y = [\text{Slope } (m) * (x - x1)] + y1 \quad (14)$$

In Equation (14), Slope (m) has been calculated by using x1y1 and x2y2 coordinate, Coordinate of (x) has been obtain from Equation (13), and Coordinate of x1y1 has been generated in GIS.

By using these equations, we have generated predicted points for all 105 vulnerable sites. By using this method, we have predicted the bankline shifting for years 2019, 2020, and 2021 for all 105 sites, but here we are showing site no. 5 and site no. 33 in

Figure **6**and

Figure **7**, respectively.

Limitations of Model

Empirical equations which relate hydrologic and geomorphic channel characteristics offer a way to estimate and predict meander river dimensions, reducing the extensive data needs of planimetric assessments. However, the empirical models which have been developed appear to exhibit site-specific nature apparent in planimetric assessments. The following points are considered as limitations of the empirically based model:

- The riverbank line has an error of ± 15 m due to the size of half a pixel in Landsat satellite imageries.
- This model is based on past condition, if there are any future human intervention from present condition i.e. establishment of new embankment, stud structure, spur structure, porcupine structures, cutter and any other anti-erosion or river training work, then the model will not show the accurate result.

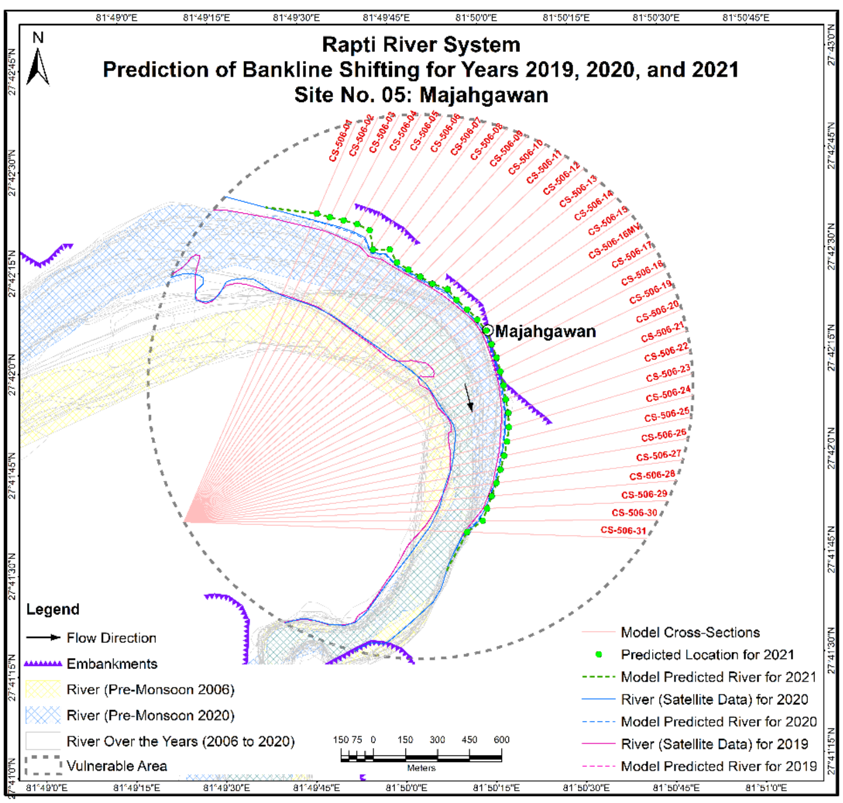

Figure 6. Prediction of Bankline Shifting for Years 2019, 2020, and 2021 of Site No. 05, Majahgawan

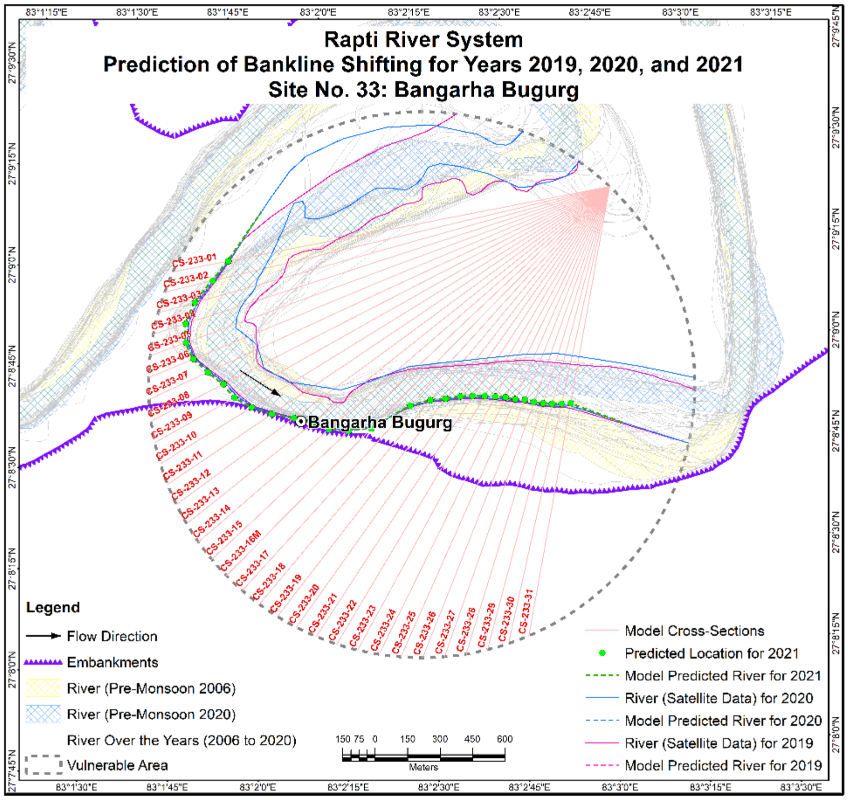

Figure 7. Prediction of Bankline Shifting for Years 2019, 2020, and 2021 of Site No. 33, Bangarha Bugurg

CONCLUSION

This study aimed at understanding the morphological changes and predicting river bankline shifting in the Rapti river system, India using satellite imageries and model. Multi-temporal Landsat satellite imageries for 15 years (2006-2020) were used to measure the lateral river bankline shifting in 105 identified vulnerable sites. These empirical and forecast models have been used to predict the morphological changes of the vulnerable sites in the near future. Though indicative, these forecasts will aid in river management and training activities and early warning against erosion risk. To more accurately model river bankline shifting against measurement it is suggested to use the high-resolution satellite images i.e. QuickBird, GeoEye, WorldView with at-least 50 cm spatial resolution.

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Conflict of Interest

The authors declare that there are no conflicts of interests.

Peer-review

External peer-review was done through double-blind method.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCE

1. Abu R and Islam T. 2016. Assessment of fluvial channel dynamics of Padma River in north-western Bangladesh. Universal Journal of Geoscience. Vol. 4(2), pp. 41-49.
2. Akhter SE, Islam KU, Islam ST, Reza MA, Chu R, and Shuanghe R. 2019. Predicting spatiotemporal changes of channel morphology in the reach of Teesta river, Bangladesh using GIS and ARIMA modeling. Quaternary International. Vol. 513, pp. 80–94.
3. Biswajit N, Sultana N, and Paul A. 2013. Trends analysis of riverbank erosion at Chandpur, Bangladesh: A remote sensing and GIS approach. International Journal of Geometrics and Geosciences. Vol. 3(4), pp. 454-464.
4. Buffington JM. 2012. Changes in channel morphology over human time scales, gravel bed rivers - processes, tools, environments. In: Michael Church, Pascale M. Biron and Andre' G. Roy, first ed. John Wiley & Sons, Ltd. pp. 435-465.
5. Clark J, and Wilcock P. 2000. Effects of land-use change on channel morphology in north-eastern Puerto Rico. Geological Society of America Bulletin. Vol. 112, pp. 1763-1777.
6. Das JD, and Saraf AK. 2007. Remote sensing in the mapping of the Brahmaputra / Jamuna river channel patterns and its relation to various landforms and tectonic environment. International Journal of Remote Sensing. Vol. 28, pp. 3619–3631.
7. Das S, and Pardeshi SD. 2018. Morphometric analysis of Vaitarna and Ulhas river basins, Maharashtra, India - using geospatial techniques. Applied Water Science. Vol. 8, pp. 158.
8. Das S. 2018. Geomorphic characteristics of a bed-rock river inferred from drainage quantification, longitudinal profile, Knick zone identification and concavity analysis - a DEM-based study. Arabian Journal of Geosciences. Vol. 11, pp. 680.
9. Dewan A, Corner R, Saleem A, Rahman MM, Haider MR, and Sarker MH. 2017. Assessing channel changes of the Ganges-Padma river system in Bangladesh using Landsat and hydrological data. Geomorphology. Vol. 276, pp. 257-279.
10. Djekovic V, Milosevic N, Andjelkovic A, Djurovic N, Barovic G, Vujacic D, and Spalevic V. 2016. Channel morphology changes in the river Pestan, Serbia. Journal of Environmental Protection and Ecology. Vol. 17, pp. 1203-1213.
11. Esther CE, Matthew J, Czapiga E, Yasuyuki SJ, Sun IT, and Parker G. 2014a. Coevolution of width and sinuosity in meandering rivers. Journal of Fluid Mechanics. Vol. 760, pp. 127-174.
12. Esther CE, Matthew J, Czapiga E, Yasuyuki SJ, Sun IT, and Parker G. 2014b. Numerical modelling of erosional and depositional bank processes in migrating river bends with self-formed width - morpho dynamics of bar push and bank pull. Journal of Geophysical Research. Vol.119(7), pp. 1455-1483.
13. Esther CE. 2013. Numerical modeling of river migration incorporating erosional and depositional bank processes. PhD thesis, Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign.
14. Friend PF, and Sinha R. 1993. Braiding and meandering parameters. Geological Society of London, Special Publication. Vol. 75, pp. 105-111.
15. Graf WL. 2000. Locational probability for a dammed, urbanizing stream - salt river, Arizona, USA. Environmental Management. Vol. 25, pp. 321-335.
16. Hooke JM, and Yorke L. 2010. Rates, distributions and mechanisms of change in meander morphology over decadal timescales, river Dane, UK. Earth Surface Processes and Landforms. Vol. 35(13), pp. 1601-1614.
17. Hossain MA, Gan TY, and Baki ABM. 2013. Assessing morphological changes of the Ganges river using satellite images. Quaternary international. Vol. 304, pp. 142-155.
18. Hudson PF, and Kesel RH. 2000. Channel migration and meander-bend curvature in the lower Mississippi river Prior to major human modification. Geology. Vol. 28(6), pp. 531-534.
19. Islam ARMT. 2016. Assessment of fluvial channel dynamics of Padma river in north-western Bangladesh. Universal Journal of Geoscience. Vol. 4, pp. 41-49.
20. Khan S, and Islam A. 2015. Anthropogenic impact on morphology of Teesta River in northern Bangladesh - an exploratory study. Journal of Geosciences and Geomatics. Vol. 3, pp. 50-55.
21. Kummu M, Lu XX, Rasphone A, Sarkkula J, and Kopone, J. 2008. Riverbank changes along the Mekong river - remote sensing detection in the vientiane - Nong Khai area. Quaternary International. Vol. 186, pp. 100-112.
22. Lant JG, and Boldt JA. 2018, River meander modeling of the Wabash river near the Interstate 64 bridge near Grayville, Illinois. U.S. Geological Survey Scientific Investigations Report, 2017-5117. pp. 12.
23. Larsen EW, Girvetz EH. 2007. Landscape level planning in alluvial riparian floodplain ecosystems using geomorphic modeling to avoid conflicts between human infrastructure

and habitat conservation. Landscape and Urban Planning. Vol. 81, pp. 354-373.

24. Magliulo P, Bozzi F, and Pignone M, 2016. Assessing the planform changes of the Tammaro River (southern Italy) from 1870 to 1955 using a GIS-aided historical map analysis. Environmental Earth Sciences. Vol. 75, pp. 1-19.
25. Mallick S. 2016. Identification of fluvio-geomorphological changes and bank line shifting of river Bhagirathi-Hugli using remote sensing technique in and around of Mayapur Nabadwip Area, West Bengal. International Journal of Scientific Research. Vol. 5, pp. 1130-1134.
26. Michalková M, Piegay H, Kondolf GM, and Greco SE. 2011. Lateral erosion of the Sacramento River, California (1942-1999), and responses of channel and Floodplain Lake to human influences. Earth Surface Processes and Landforms. Vol. 36(2), pp. 257-272.
27. Midha N, and Mathur PK. 2014. Channel characteristics and planform dynamics in the Indian Terai, Sharda river. Environmental Management. Vol. 53, pp. 120-134.
28. Mohindra R, Prakash B, and Prasad J. 1992. Historical geomorphology and pedology of the Gandak megafan, middle gangetic plains, India. Earth Surface Process and Landforms. Vol. 17, pp. 643-662.
29. Mount NJ, Tate NJ, Sarker MH, and Thorne CR. 2013. Evolutionary, multi-scale analysis of riverbank line retreat using continuous wavelet transforms - Jamuna river, Bangladesh. Geomorphology. Vol. 183, pp. 82-95.
30. Nanson GC, and Knighton A. 1996. Anabranching rivers - their cause, character, and classification. Earth Surface Processes and Landforms. Vol. 21, pp. 217-239.
31. Ollero A. 2010. Channel changes and floodplain management in the meandering middle Ebro River, Spain. Geomorphology. Vol. 117, pp. 247-260.
32. Pal R, and Pani P. 2019. Remote sensing and GIS-based analysis of evolving planform morphology of the middle-lower part of the Ganga river, India. The Egyptian Journal of Remote Sensing and Space Science. Vol. 22(1), pp. 1-10.
33. Pareta K, Jakobsen F, and Joshi M. 2019. Morphological Characteristics and Vulnerability Assessment of Alaknanda, Bhagirathi, Mandakini and Kali Rivers, Uttarakhand (India). American Journal of Geophysics, Geochemistry and Geosystems. Vol. 5(2), pp. 49-68.
34. Pareta K. 2013. Geomorphology and Hydrogeology: Applications and Techniques using Remote Sensing and GIS. LAP Lambert Academic Publishing, Germany. pp. 1-413.
35. Persoiu I, and Radoane M. 2011. Spatial and temporal controls on historical channel responses - study of an atypical case: Someşu Mic River, Romania. Earth Surface Processes and Landforms. Vol. 36(10), pp. 1391-1409.
36. Rahman M, and Islam M. 2017. Bank erosion pattern analysis by delineation of course migration of the Padma river at HarirampurUpazila using satellite images and GIS. Part II. Journal of Geology & Geophysics. Vol. 6, pp. 2-7.
37. Sarkar A, Garg RD, and Sharma N. 2012. RS-GIS based assessment of river dynamics of Brahmaputra River in India. Journal of Water Resource and Protection. Vol. 4, pp. 63-72.
38. Sarker M, Kamal M, and Hassan K. 1999. The morphological changes of a distributary of the Ganges in response to the declining flow using remote sensing. In: 20th Asian Conference on Remote Sensing. Vol. 1, pp. 1-10.
39. Sarma JN. 2005. Fluvial process and morphology of the Brahmaputra River in Assam, India. Geomorphology. Vol. 70, pp. 226–256.
40. Sinha R, Jain V, Babu GP, and Ghosh S. 2005. Geomorphic characterization and diversity of the fluvial systems of the Gangetic plains. Geomorphology. Vol. 70, pp. 207-225.
41. Surian N, and Ziliani L. 2012. Prediction of channel morphology in a large braided river. I.S. Rivers - International conference on integrative sciences. pp. 1-3.
42. Sylvester Z, Durkin P, and Covault JA. 2019. High curvatures drive river meandering. Geology, Vol. 47, pp. 1-4.
43. Thian YG, and Baki ABM. 2013. Assessing morphological changes of the Ganges river using satellite images. Quaternary International. Vol. 304, pp. 142-155.
44. Wang SSY, and Wu W. 2006. Formulas for sediment porosity and settling velocity. Journal Hydraulic Engineering. Vol. 132(8), pp. 858-862.
45. Xia J, Deng,S, Lu J, Xu Q, Zong Q, and Tan G. 2016. Dynamic channel adjustments in the Jingjiang reach of the middle Yangtze river. Scientific Reports. Vol. 6, pp. 1-10.
46. Zhang W, Xu Y, Hoitink AJF, Sassi MG, Zheng J, Chen X, and Zhang C. 2015. Morphological change in the Pearl river delta, China. Marine Geology. Vol. 363, pp. 202-219.