Channel morphology and prediction of mid-line channel migration in the reach of Ganga River using GIS and ARIMA modeling during 1975–2020

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ABSTRACT

The dynamic nature of meandering poses several challenges in a river. The river Ganga shows severe bank erosion in many of its stretches which creates insecurity to the habitats. In the present study, channel morphology and lateral mid-line migration for 1975 to 2020 in 5 years intervals have been studied. The prediction of lateral mid-line migration from 2020 to 2050 by using multi-temporal Landsat satellite images was made by using the ARIMA model. The river reach was divided into 8 bends and 48 cross-sections were identified. The channel length was observed as 224.35 km in 1975 which reduces to 199.96 km in 2020. A decreasing trend was observed for the mean of channel length and meander ratio, and an increasing trend was noted in the mean of sinuosity ratio and tortuosity ratio. A total of 11 cross-sections showed the rightward shifting and 36 cross-sections showed the leftward shifting. Observed and predicted values showed a good $R^2$ value of 0.90 and 0.89 at CS-24 and CS-25, respectively. The results may be used for planning and management of various river training work and understanding the river system dynamics.

Key words: ARIMA model, channel morphology, Ganga River, GIS and remote sensing, lateral mid-line channel shifting

HIGHLIGHTS

- To investigate the variations in river morphometric parameters of the river Ganga.
- Prediction of centerline channel shifting in the middle part of river Ganga from 1975 to 2050.
- Outcome of the proposed research will definitely help the government in decision making, management and implementation of future projects.

ABBREVIATIONS

GIS Geographical Information System
ERDAS Earth Resources Data Analysis System
MSS Multispectral System
TM Thematic Mapper
ETM + Enhanced Thematic Mapper Plus
OLI Operational Land Images
USGS United States Geological Survey
UTM Universal Transverse Mercator
GCP Ground Control Points
RS Remote Sensing
ARIMA Autoregressive Integrated Moving Average
LULC Land Use Land Cover
SI Sinuosity Index
ACF Autocorrelation Function
PACF Partial Autocorrelation Function
ADF Augmented Dickey–Fuller Test
KPSS Kwiatkowski Phillips Schmidt Shin Test
AIC Akaike Information Criterion
RMSE Root Mean Square Error

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INTRODUCTION

When a river’s bank erosion occurs, the river’s drainage ability and navigation are hampered, and a huge amount of people are affected, either directly or indirectly. For the time being, erosion can be mitigated by local protective measures, but to prevent land loss, well-built river management and training systems are needed. A detailed analysis of the geomorphology of a river can help in effectively controlling the rivers. The river Ganga is not only a flowing water body but also a significant contributor to human development and a sustainable way of life in India.

The Ganga River is one of India’s 14 largest water systems and an important source of sustainable development. The Ganga River Basin is India’s largest catchment area basin with a landmass of 26% (861,404 m²) and around 43% of its population (Tare et al. 2013). The basin extends between East Longitudes of 73°2” to 89°5” and North Latitudes of 21°6” to 31°21” and covers 1,086,000 km² which comprises parts of India, Nepal, and Bangladesh. The Ganga Basin, the largest in India, covers 26% (861,404 m²) of land and 43% of the population (Tare et al. 2013). The area of the Ganga Basin is about 79% in India. In the northern part of the Basin, there are the Himalayas, in the west Aravals, and in the southern part Vindhya Plateau and Chhotanagpur. The Ganga River has a total length of 2,525 km, measured by the Bhagirathi and Hooghly rivers. The basin covers 11 States, namely, Uttarakhand, Uttar Pradesh, Madhya Pradesh, Rajasthan, Haryana, Himachal Pradesh, Chhattisgarh, Jharkhand, Bihar, and West Bengal. The tributaries of the river Ganga are shown in Figure 1.

Erosion, sediment transportation, and siltation are very dynamic processes that are exhibited as geomorphic diversity in the Ganga River stretch from Haridwar to Farraka (Tare et al. 2013). As the river flows downstream, it deposits sand and silt along its course downstream of Haridwar. The large proportion of this chosen range is in the Ganga River region of the alluvial plain. The formations are uncompacted and frequently eroded by the river’s high current. This allows the river mostly to erode and migrate to a wide flood plain laterally. The river pattern is described as the look of an area in a view of the map. Given plans on most major rivers, they can be broadly classified as three main patterns: (a) straight, (b) twisting, and (c) twisting (Leopold & Wolman 1957). There is no sinuous direction on a straight channel. A winding canal is made of alternating curves, which create an S-form for the top view of the river. One twisted river has wide, unstable banks that are generally not well defined and is portrayed by a steep, shallow route that divides the rivers by several channels. Sinuosity index varies from 1 to infinite and braiding index varies from 0 to 1.

The analysis of meandering channels began in the 1930s, but Friedkin’s experimental work on the Mississippi River in 1945 was the true breakthrough (Dhari et al. 2014). Over the last century, river researchers and engineers

Figure 1 | The river Ganga with its tributaries (Source: Wikipedia).
have been drawing more attention to freely meandering rivers. Previous work has shown mender planning, bend flow, dynamics of migration, and sedimentology in lateral accretions (Leopold & Wolman 1957; Ikeda et al. 1981; Knighton 1998). There is a special time-shifting of the channels of a variety of rivers in India, such as Brahmaputra (Kotoky et al. 2005), Kosi (Wells & Dorr 1987), Ganga (Singh 1996), and several other rivers. Many works have been carried out to determine the morphometric parameters for different reaches in the whole course of river Ganga and other rivers (Yeasmin & Islam 2011; Pan 2013; Dhar et al. 2014; Kumar et al. 2016; Alber & Piegay 2017; Debnath et al. 2017; Das & Pardeshi 2018; Singh et al. 2019; Ashwini et al. 2020). The ARIMA model has also been used in some of the studies for the prediction of centerline channel migration (Akhter et al. 2019; Annavat & Sil 2020a, 2020b; Paret & Goswami 2021).

Natural streams’ gradual shifts and resilience to changing environmental conditions, which are influenced by anthropogenic influences, are largely dependent on the regional characteristics (e.g., channel type, hydrologic, and ecological variables). Identifying the processes that cause stream shifts and assessing river morphological change has constantly stimulated the interest of engineers, geomorphologists, and geologists (Sarma 2005; Sarker et al. 2014; Wang et al. 2016; Dewan et al. 2017). The surface of the earth is dynamic, with forces such as heat, isostasy, orogeny, and gravity constantly changing the materials and forms of the planet. These changes alter the streams and rivers water flowing through the earth’s surface (Bag et al. 2019).

Many researchers have used remote sensing data and GIS technology to analyses multi-temporal changes in LULC in several studies (Murthy & Rao 1997; Ahmad 2012; Kotoky et al. 2012; Rawat et al. 2013; Debnath et al. 2017). Streambank erosion is a naturally occurring phenomenon, and the river’s dynamic character alters the LULC of its surrounding basin, which has recently become a natural phenomenon. The phenomenon of lateral migration happens in turbulent flow conditions and can result in severe local or regional alterations (Nanson & Hickin 1983). The interest of geomorphologists in the study of the river basin and water shifts has increased in recent decades accordingly (Islam 2016). Over this period, important progress has been made in understanding morphological channels and clarifying the change of channels on the platform of the river basin. Channel morphology research is important to the assessment of the effects of natural and human mechanics on channel dynamics and morphometric parameters (Friend & Sinha 1993; Graf 2000).

Predicting the effects of channels is a difficult task. These events adapt to changes in the river basin as they differ effectively. Often this research has been carried out in river morphology mostly on the deterministic model. On the other hand, the river system is stormy and dynamic. In the field of the fluvial river system, several numerical models like Support Vector, ARIMA, and Artificial Neural Network are applied (Deb & Ferreira 2015; Pourbakhshian & Pouraminian 2015). These models are linked to insecurity and fluvial system difficulties, especially on the meandering river, which is the principal reason for consideration. The ability to predict the migration of channels has a certain impact as a helpful tool for guiding future methods of river management. The result is influenced by some insecurity and complications which show themselves to be decisive, self-organized, but which have certain limitations. Because of their unknown size and orientation, quantitative data for the evolution of canal morphology in a certain river basin are needed to forecast (Ziliani & Surian 2012). The change in the middle lines of the stream is a good indicator that the conduct and processes of the stream change (Montgomery & Buffington 1997). Consequently, for future river education stages to better understand flux behaviors and dangers, the interim rate of change must be predicted.

In the present study, efforts have been made to determine the various morphometric parameters like sinuosity, tortuosity, and meander ratio by using the multi-date satellite data (1975–2020) from Mokama to Jarlahi in the state of Bihar. Furthermore, a centerline channel shifting and river migration prediction were made by using the ERDAS Imagine, ArcGIS, multi-temporal Landsat data, and ARIMA model.

**MATERIALS AND METHODS**

**Study area and data processing**

The main part of the study area is extracted from Mokama to Jarlahi in the state of Bihar. The study area is located between geographical areas North latitudes 25°24′9.53″: 25°26′32.97″ and East longitudes 85°57′25.49″: 87°17′12.12″ as shown in Figure 2. Landsat images that are used in this research work is because of free availability and ease to access of the satellite data. In this study, ten satellite images were used for the investigation of morphological changes, shifting rate of the river, and mid-line shifting prediction to determine the pattern of morphological change over the past 45 years by analyzing satellite images of the years 1975, 1980, 1985,
1990, 1995, 2000, 2005, 2010, 2015, and 2020 years in Arc Map (v 10.6, a GIS application). Different tools (ArcGIS v.10.6 and AutoCAD v.10) were used for the measurement. Table 1 summarizes full details on Landsat images for the present research. Landsat images were acquired from USGS (spatial resolution 30 m). The Survey of India Toposheet and maps comprising the river stretch were imported into the ERDAS and georeferenced and later on, the mosaic was prepared. All the Landsat images of the different resolutions were resampled with the nearest neighbor method to a common resolution of 30 m. The river path was digitized and the centerline was drawn in the ArcMap for the different years from 1975 to 2020 at an interval of 5 years (Figure 3). Then, the path is divided into 8 bends within a distance of 135 km (valley length) for analyzing morphometric parameters, from upstream to downstream. Each digitized river path is divided into 48 cross-sections to observe the changes in river width. And each centerline is also divided into 48 cross-sections to detect the centerline shifting rate. The numbering is done from upstream to downstream for the cross-sections and bends. Bend 1 lies in the location of Mokama to Jafarpur consists CS-1 to CS-6, Bend 2 lies in the location of Jafarpur to Shahbegpur consists CS-7 to CS-11, Bend 3 lies in the location of Shahbegpur to Munger consists CS-12 to CS-17, Bend 4 lies in the location of Munger to Tarapur Diara consists CS-18 to 24, Bend 5 lies in the location of Tarapur Diara to Gopalpur kali patti consists CS-25 to CS-32, Bend 6 lies in the location of Gopalpur kali patti to Jalalpur consists CS-33 to CS-36,
Bend 7 lies in the location of Jalalpur to Dimha consists CS-37 to CS-42, and Bend 8 lies in the location of Dimha to Jarlahi consists CS-43 to CS-48.

Morphometric parameters

The identification of meander length, meander width, meander ratio, sinuosity ratio, tortuosity ratio, and changes of width at every cross-section were observed. The various parameters of the meander are shown in Figure 4(a). Meander length (ML) is the axial length of a meander, i.e., the tangential distance between the corresponding points of a meander and meander belt (MB) is a distance between the outer edge of the clockwise and anti-clockwise loops of the meander. Meander ratio (MR) is the ratio of the meander belt to the meander length.

\[
\text{Meander Ratio (MR)} = \frac{MB}{ML} \tag{1}
\]

In the existing literature, there are several methods for the calculation of the sinuos index (Leopold & Wolman 1957). The sinuosity ratio is the ratio of distance measured along the channel length to the distance measured along the valley length. Channel is considered as meandering when the sinuosity is greater than or equal to 1.5. Figure 4(b) shows the difference between the channel length and the valley length.

\[
\text{Sinuosity} = \frac{\text{Channel Length}}{\text{Valley Length}} \tag{2}
\]

For river, the conventional classes of the sinuosity index are:

- SI \leq 1.05, then the channel is almost straight
- 1.05 \leq SI < 1.25, then the channel is winding
- 1.25 \leq SI < 1.50, then the channel is twisty
- 1.50 \leq SI, then the channel is meandering

Tortuosity is the property of curve to be twisted, the formula for tortuosity is taken from the existing literature of Ashwini et al. (2021)

\[
\text{Tortuosity} = \left(\frac{\text{Thalweg Length} - \text{Valley Length}}{\text{Thalweg Length}}\right) \tag{3}
\]

The rate of migration is a result of the number of years between the images used dividing the migration distance. The existing literature provides the methodology for calculating the rate of shift of various years (Annayat & Sil 2020a, 2020b), the formula is given below.

\[
r = \frac{y - z}{t} \tag{4}
\]
Figure 3 | Digitized path of the river Ganga (1975–2020).

Figure 4 | Meandering parameters.
where $r$ is the shifting rate (m/year); $y$ is node points between the cross-section of the first river and mid-line channel; $z$ is node points between the cross-section of the river which is compared with the first one and mid-line channel; and $t$ is the time variance between the analytical images.

**ARIMA model**

The ARIMA model is constructed using R-Studio in this study, version 1.4.1106 (a statistical computing and graphics programming language). After the calculation of the above meandering parameters, the prediction of the shifting of the centerline channel was carried out by using the ARIMA model. ARIMA is the Autoregressive Integrated Moving Average, a statistical method that provides an approach to time-series prediction. This model is first presented by Box & Jenkins (1970). Before moving on to ARIMA models, it is important to cover the concepts of stationarity and time-series differencing. A stationary time series is independent of seasonality or trends. If a series is non-stationary, then there should be a difference between two consecutive observations. The ARIMA model is based on three parameters, i.e., $p$, $d$, and $q$. The dependent relationship between a current observation and a previous observation is used in an AR ($p$) auto-regression model. It shows the recent values used for forecasting the next value. The AR term is defined by parameter ‘$p$’ in ARIMA. The value of ‘$p$’ is calculated by the Partial Autocorrelation Function (PACF) plot. The flowchart of time-series forecasting (ARIMA Model) is shown in Figure 5. To make time-series steady, the integration uses differencing of data (subtracting an observation from the preceding time step). ADF and KPSS tests can be performed to see if the series is stationary and to figure out what the ‘$d$’ value is. Furthermore, the moving average model makes use of the relation between an observation and a residual error from a lag observation using a moving average model. A moving average component represents the model’s error as a sum of prior error terms. The parameter ‘$q$’ in ARIMA represents the MA term. ACF (Autocorrelation Function) plot is used to identify the correct ‘$q$’ values. The order of differencing is normally applied to make the series stationary.

![Flowchart](http://iwaponline.com/h2open/article-pdf/4/1/321/955422/h2oj0040321.pdf)

**Figure 5** | Flowchart of entire methodology followed.
In this study, we identify the stationarity of the series, by plotting the autocorrelation function graph which decays rapidly to zero. When the series still exhibit the trends, we increased the order of differencing. We found that, in some cases, model has no order of differencing, which means the original series is stationary. we had checked the stationarity of the series, by making ADF (Augmented Dickey–Fuller) test, some series is already stationary and in most of the series we have to increase the order of differencing to make the series stationary, it rejects the null hypothesis and the \( p \)-value is less than the significance level (say 0.05). After making the series stationary, the parameters are checked for the AR and MA term. Finally, the model is built with the minimum AIC (Akaike Information Criterion) value and set the number of forecasting periods.

**Mathematical approach for the ARIMA model**

The equation for a \( p \)th order autoregressive (AR) model, that is AR \((p)\) model:

\[
y_t = C + \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_p y_{t-p} + \epsilon_t
\]

(5)

where \((y_t)\) is the data to be used with the ARMA model. That signifies, in that order, the series has already been power converted and differed. AR coefficients are represented by the parameters \(\phi_1, \phi_2\) and so on.

The equation for a \( q \)th order moving average (MA) model, that is MA \((q)\) model:

\[
y_t = C + \epsilon_t - \theta_1 \epsilon_{t-1} - \theta_2 \epsilon_{t-2} - \cdots - \theta_q \epsilon_{t-q}
\]

(6)

where \((y_t)\) is the data to be used with the ARMA model. And \(\theta_1, \theta_2\) and so on are MA coefficients.

The equation for an ARMA \((p, q)\) model:

\[
y_t = C + \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_p y_{t-p} + \epsilon_t - \theta_1 \epsilon_{t-1} - \theta_2 \epsilon_{t-2} - \cdots - \theta_q \epsilon_{t-q}
\]

(7)

**RESULT AND DISCUSSION**

**Changes in channel geometry**

Channel width is the cross-sectional distance measured at every point. The width of the Ganga River was measured at 48 cross-sections from Mokama to Jarlahi at a distance of 3 km (Valley length) (Figure 6). During the assessment, it is observed that the maximum width is 3,342 m at cross-section 45 in the year 2005 and the minimum channel width is 475 m at cross-section 19 in the year 2010. The mean of every cross-section for each year shows a slightly increasing trend. Variations of each cross-section are shown in Figure 7.

Temporal change in channel length is measured for the study area from Mokama to Jarlahi from the year 1975 to 2020. During the entire period of study, it is found that the maximum channel length is 237.95 km in the year
1980 and the minimum channel length is 179.26 km in the year 1985. The variation in channel length is shown in Figure 8(a). There is a drastic change in stream length from 1980 to 1985 as the sinuosity index is increasing within the entire length of the Ganga River taken under consideration for this work. It is observed that over the periods, channel length shows a decreasing trend, which means that the channel has straightened its course.

**Channel pattern**

River meandering is a natural phenomenon, in which a river gradually migrates its course and bank erosion occurs. After analyzing the data from 1975 to 2020, a total of 8 bends is taken from the whole reach from Mokama to Jarlahi, to identify the sinuosity, tortuosity, and meander ratio. A total of 48 cross-sections are obtained to examine the river’s width and centerline shifting. During the whole procedure, many changes were observed in the morphometric parameters from 1975 to 2020. The changes in the meander ratio are shown in Figure 8(b). The highest meander ratio in 2000 at bend 4 is 1.9, while the lowest meander ratio in 1990 at bend 7 is 0.19 (Figure 8(b)). The mean of the meander ratio from 1975 to 2020 shows a decreasing trend. In Figure 8(c), it can be visualized that the maximum sinuosity is 2.05 in 2000 at bend 4, and the minimum sinuosity ratio is 1.01 in 1975 at bend 2. In 1975, highly meandering bends are 4 and 5, the sinuosity value is 1.68 at bend 4 and 1.51 at bend 5. Bends 1, 3, and 6 are twisted in nature. Bend 8 is winding and the rest bends are almost straight. In 2020, only bend 8 shows a highly meandering nature, its sinuosity value is 1.51, and in bends 3, 5, and 7, it is twisted in nature, the rest are winding. The mean value of the sinuosity index shows an increasing trend from 1975 to 2020 (Figure 9(c)). It shows that in the reach of Ganga from Mokama to Jarlahi, the river is increasing its meandering nature year by year. It may depend on the flow velocity and discharge. The tortuosity index was calculated from bend 1 to 8 for different years. The changes observed in the tortuosity index are shown in Figure 8(d), it can visualize that the maximum tortuosity is 1.05 at bend 4 in the year 2000 and the minimum tortuosity is 0.01 at bend 2 in the year 1975. In Figure 10, the mean value of the tortuosity index shows an increasing trend from 1975 to 2020 (Figure 9(d)).

**Centerline shifting of the channel**

Meandering is a natural phenomenon that causes slow river channel changing in a floodplain and alluvial river system by depositing sediment in a convex bank and eroding the concave bank of a meander. Many factors are responsible for river channel shifting, like bank erosion, sediment deposition, flow velocity, natural activity, human activity, climatic factors, topography, and vegetation cover. Measurement of centerline shifting was made between two different years in which 1975 is taken as a base image. So, with a base image for the year (1975–1980, 1975–1985, 1975–1990, 1975–1995, 1975–2000, 1975–2005, 1975–2010, 1975–2015, and 1975–2020) the centerline shifting was computed (Figure 10).

The negative sign indicates leftward shifting, and the rest indicates rightward shifting. After observing the shifting of the mid-line, it is found that among 48 cross-sections, 21 cross-sections showed leftward shifting and 27 cross-sections rightward shifting in the year 1975–1980, the maximum leftward shifting is 507 m/year at cross-section 28 and the maximum rightward shifting is 1,601.6 m/year at cross-section 33. In 1975–1985, 10 cross-sections reveal the leftward shifting direction and 38 cross-sections in the rightward shifting direction, the maximum leftward shifting is 158.7 m/year at cross-section 42 and the maximum rightward shifting is 915.8 m/year at cross-section 20. In 1975–1990, 11 cross-sections reveal leftward shifting and 37 cross-sections reveal rightward shifting.
Figure 8 | Change in (a) channel length, (b) meander ratio, (c) sinuosity, and (d) tortuosity with time from 1975 to 2020.

shifting, the maximum leftward shifting is 176.33 m/year at cross-section 35 and the maximum rightward shifting is 579.87 m/year at cross-section 33. In 1975–1995, 14 cross-sections show leftward shifting and 34 cross-sections show rightward, the maximum leftward shifting is 207.48 m/year at cross-section 42 and the maximum rightward shifting is 369.08 m/year at cross-section 33. In 1975–2005, 15 cross-sections reveal leftward shifting and 33 cross-sections reveal rightward shifting, the maximum leftward shifting is 2.12.17 m/year at cross-section 42.
and the maximum rightward shifting is 445.3 m/year at cross-section 20. In 1975–2010, 8 cross-sections reveal leftward shifting and 40 cross-sections reveal rightward shifting, the maximum leftward shifting is 136.23 m/year at cross-section 43 and the maximum rightward shifting is 401.66 m/year at cross-section 20. In 1975–2015, 15 cross-sections reveal leftward shifting and 33 cross-sections reveal rightward shifting, the maximum leftward shifting is 195.02 m/year at cross-section 43 and the maximum rightward shifting is 308.57 m/year at cross-section 20. In 1975–2020, 12 cross-sections reveal leftward shifting and 36 reveals rightward shifting, maximum shifting, the maximum leftward shifting is 156.05 m/year at cross-section 35 and the maximum rightward shifting is 401.1 m/year at cross-section 11. In 1975–2000, 16 cross-sections reveal leftward shifting and leftward shifting is 173.91 m/year at cross-section 43 and the maximum rightward shifting is 260.13 m/year at cross-section 20. It is found that in leftward, the most vulnerable cross-section is 43 and in rightward, the most vulnerable cross-section is 20. The spatio-temporal changes, for example, in the reach of the Ganga River width and shifting direction

**Figure 9** | Decreasing trend of (a) channel length, (b) meander ratio and increasing trend of (c) sinuosity, (d) tortuosity from 1975 to 2020.
from 1975–1980, 1980–1985, 1985–1990, and 1990–1995 is shown in Figure 11. Similar changes were observed for the remaining years up to 2020. River shifts may occur in the river system when the main river canal shifts unforeseen to a newer river canal. This river is especially susceptible to such modifications (Wang et al. 2012). Analysis was carried within alluvial lengths of the upper river with context to the shift from 1950 to 2007 and the long rhythm of channel shifts was determined by shifts up and down on the banks of the river (Bag et al. 2019). In Bhagirathi River, it was discovered that the actual channel adjustments often follow a major flood event, but due to other reasons, the system is vulnerable to a shift. The most common cause for the build-up of sediment is the change in the tangle in the river with high chaotic sinuosity. The river system can also be subject to abrupt changes in the course by human activity, such as agriculture, building homes, other temporary structures, as well of canals extension. A change in position in the river channel has important implications for the environment, for the economy and society, especially for the availability of water, which is essential for farming and transport. Streamflow is influenced mostly by rainfall, leading to annual flooding. Due to more frequent and extensive heavy rainfall in the catchment, flood regimes of devastating magnitude emerge, resulting in a shift in rivers. Limited research is now possible into the impacts of seismic shocks in the catchment of the Ganga River, so future research on the dynamics of the river canal could have an impact on the movements of the centerline canal and ultimately on river behavior.

Prediction of centerline channel shifting using the ARIMA model

After recognizing the lateral shifting of the centerline channel for the year 1975 to 2020 with the base image of 1975, now the future prediction was made by using ARIMA modeling. In this study, R-Studio-version 1.4.1106 (a programming language for statistical computing and graphics) are used to build the ARIMA model. Finally, the minimum AIC (Akaike Information Criterion) value is chosen for the best model. The AIC is an estimator of prediction error and thereby the relative quality of statistical models for a given set of data. AIC provides means for model selection. The predicted values from the year 2020 to 2050 is given for all 48 cross-sections as well as RMSE (Root Mean Square Error) and AIC value are also given in Supplementary Material, Table S6.

Figure 10 | Spatial-temporal lateral centerline channel shifting rate (m/year) for each cross-section.

Figure 11 | Rightward, leftward, and mean channel shifting rate (m/year) from 1975 to 2020.
The outcomes of the ARIMA model reveal that the shifting of the channel is abruptly changed to the leftward and rightward directions. Eleven cross-sections shift the rightward direction, 36 cross-sections shift toward the leftward direction, and CS-5 suddenly change the shifting direction. The most vulnerable cross-section in the leftward direction is CS-29, which lies in between the location of Tarapur Diara to Gopalpur kali patti and in the rightward direction is shows CS-42, which lies at the location of Dimha. The observed and predicted values show good $R^2$ values ($R^2$ observed = 0.90 and $R^2$ predicted = 0.89) for CS-24 and CS-25. The predicted value for centerline channel shifting is then generated between the time interval of 2020–2025, 2025–2030, 2030–2035, 2035–2040, 2040–2045, and 2045–2050. Outcomes of the ARIMA model reveal that a central channel shift to the left is noticed as a major concern over the entire reach of the river, between 48 CS. Engel & Rhoads (2012), Ollero (2010), and Timár (2003) proposed that riverbank erosion is controlled by riparian vegetation cover, an important aspect of the migration of rivers. The reason for the centerline shifts in a critical region of the river basin may be explained by thin-riparian vegetative cover alongside the Ganga River's alluvial plains, non-cohesive sediments fine-graded and floodplains that have been relocated. Ahmed & Fawzi (2011) have reported in the Nile study that agricultural land experiences higher bank erosion than riparian vegetation regions. Hence, it can be said that the process of centerline channel shifting relies heavily on vegetation cover. A study of Tarim River, northwestern China stated that erosion resistance is low for fine-grained non-cohesive sediments (Li et al. 2017). Therefore, they are prone to excessive erosion because of the poor resilience of the loose bed and bank materials and thus as a result, the banks are subjected to more lateral erosion. We suggest that the results help to identify future hazards in the centerline channel and that effective settlement planning and the implementation of bank protection measures prevent these effects. This modeling can be used to create a risk map for riverbank erosion and deposition. This research could, therefore, be extremely helpful for the government’s future risk prevention and mitigation activities.

Changes in river courses occurred due to multiple factors, such as the amount of flow of water, fluctuation in the intensity of water flow, rate of erosion, and sedimentation. The high current of flowing water in rivers causes desilting from the upstream and silting up as they surge down the hills and spread out on the plains. The deposits cause interruption over time that enables the river to flip to a less resistant zone. Another reason for the shifting of the river is nature’s fury such as earthquakes, landslides, and hurricanes. Human activity and climate change are also one of the reasons for the change in the river course, as climate change has triggered the melting of glaciers more quickly, thus the water volume in rivers has increased, which leads to a greater flow force. Overall, the river changes its course when it overflows during flooding by cutting bunds. The overflow of the river makes new channels and changes its course.

CONCLUSION

The Ganga River Basin is India’s largest river basin. This Ganga basin faces many problems like shifting of the river channel, flood, and bank erosion. The Ganga River’s behavior is of interest, as it raises several issues ranging from flood management to navigation to water resource development, with water scarcity occurring as a result of the abandonment of the channels. The study is done in the lower reach of the Ganga River from Mokama to Jarlahi in the state of Bihar. The main incentive of this study is to understand the various morphometric parameters like meander width, meander length, sinuosity index, meander ratio, tortuosity ratio, and changes of width at every cross-section. Multi-temporal satellite images were used to analyze the lateral centerline channel migration for the last 45 years from 1975 to 2020 at an interval of 5 years using the GIS technique and prediction of centerline channel migration from 2025 to 2050 by the ARIMA model. The study period chosen was the post-monsoon in November to January. Data for this study are available free. The whole river reach is divided into 8 bends and 48 cross-sections. The morphological analysis indicates that the mean of channel length and meander ratio shows a decreasing trend. Whereas the mean of sinuosity index and tortuosity index reveals an increasing trend. During the entire period of study, it is found that the channel length in 1975 is 224.35 km and the channel length in 2020 is 199.96 km. It is found that in leftward, the most vulnerable cross-section is 43, and in rightward, the most vulnerable cross-section is 20. The river is shifted randomly toward the left and right banks. The outcomes of the study can be used as a base for understanding future dynamics and bank migration. Adapting bank protection measures can help to prevent bank migration. This study can be helpful for the hazard preparedness program and future mitigation by the government authority. This is a time-series model based on past data. If there is
any anthropogenic factor like the establishment of any structure, vegetation, anti-erosion or any river training work done in future from present condition, then the model will not show the accurate result.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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