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Research Article

Prediction of Channel curvatures in Inland Waterways channels using Sinuosity index, Centroid best-fit circles Technique

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Abstract— The study demonstrated the effectiveness of GIS datalogger centroids and computer-aided approaches in monitoring and predicting inland waterway channel movements, especially at their bends. In order to predict the possible future consequences of the channel migration on inland transport in a riverine region, Ilaje riverine area was chosen as the case study. Study's objectives include assessing the spatiotemporal planform changes of a meandering section of the river reach from 1972 to 2022, determining the river curvature pattern (channel sinuosity), assessing the rate and extent of bankline shifting, and predict the location and extent of banklines in 2122 and 2152 (predicted in 100 and 130 years). GIS technique was used to analyze and classify satellite imagery obtained from the USGS in a spatiotemporal manner. Using a datalogger process, computer-aided techniques were utilized to digitize and generate an array of yearly centroids for each bend in the channel curvatures. Results showed that during the course of 50 years (1972–2022), there were notable changes to the river planform and sinuous parts from Igbokoda to Legha; as a result, the channel extended by 448.96 meters. The investigation revealed a continuous channel extension between the years 2022, 2072, 2122, and 2152. The study observed a natural cut-off at the intersection of Bends 4 and 7, which has an impact on Bends 5 and 6 being abandoned in the anticipated year 2152. This implies that communities and settlements in the southern part of the region would not have direct access to inland waterways, and that the northern settlements in Igbokoda will be cut off from inland waterway networks. The methods provided accurate information regarding the channel reach's morphological characteristics in the past, present, and future, which can be used as a reference by professional and stakeholders involved in inland waterway planning and river engineering.

Keywords— inland, waterway, sinuosity, centroid, river, curvature, transport, channel

1. Introduction

Channel patterns exhibit in a variety of shapes, from meandering to straight through braiding. The ratio of the length of channel to the length of channel's valley, or the ratio of the channel's gradient as measured over the same length of valley, best characterizes channel configurations [1]. Nonetheless, because of the various degrees of alluvial and fluvial processes in a river channel, this phenomenon has been linked to modifications in the river plan forms. Changes in a river's depth, width, discharge, and river curvature—which can have either positive or negative effects on inland navigation—are considered to be the cause of river plan changes. The regular shifting of river bank lines and variations in river depth brought on by the accretion or sedimentation of material in riverbeds can pose a threat to inland transportation. [2]. Alluvial rivers naturally undergo channel modifications due to bank erosion, downcutting, and bank accretion [3]. It is of note that rivers are dynamic assemblies of sediment, water, and aquatic life that engage in a complex dance from their headwaters, where the journey begins, to the ocean or basin at its conclusion. The transitions that take place during the process have been explained using a continuum [4] through quantitative factors like depth, slope, and curve as well as through ideas of landscape change (Burbank & Anderson, 2020) [5] with notable consequences on inland waterways, particularly their navigability, environment, and socioeconomic advantages to communities in their catchment areas.

This study emphasized using sinuosity index and centroids of best fit method to quantify, measure and predict changes occurring in channel curvatures and its potential future effects on inland transit and the connecting settlements in a riverine region of Ondo state Nigeria. The study displays the capabilities of GIS and centroid best-fit techniques in monitoring inland waterway channel shifting in the riverine communities of Ilaje with a view to predict the potential future effects of the channel migration on the inland transport. However, the study assessed the morphological changes of

Igbokoda -Legha waterway channel in the study area from 1972-2022, determine the pattern of the river curvature (channel sinuosity), assess the rate and extent of banklines shifting and predict the extent and position of the banklines in 2122 and 2152 (100- and 130-years prediction).

The research area is in Ondo State, Nigeria's Ilaje Local Government Area, which is a riverine environment. Specifically, Ondo State is located in latitude 7010'N and longitude 5005'E. It is located in Nigeria's south-western geo-political zone and is bounded on the south by the Atlantic Ocean, to the east by Edo State, to the west by the states of Osun and Ogun, and to the north by Ekiti and Kogi States (see Figure 1). The whole area of Ondo State is covered in tropical regions. Its populace is approximately 3,441,024 [6].

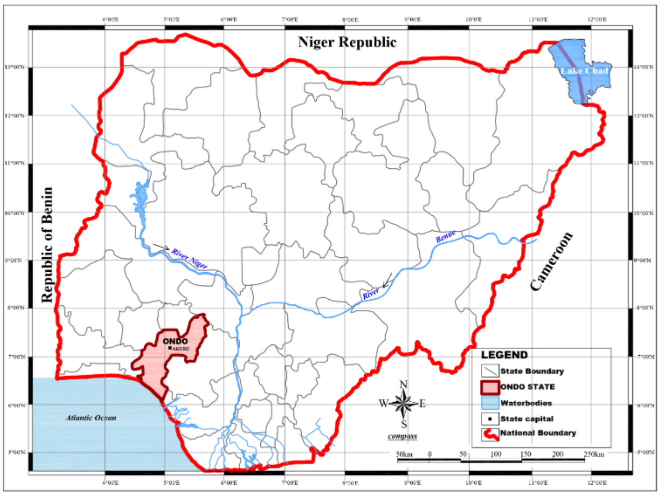


Figure 1. Ondo State Map its National Setting
Source: [7]

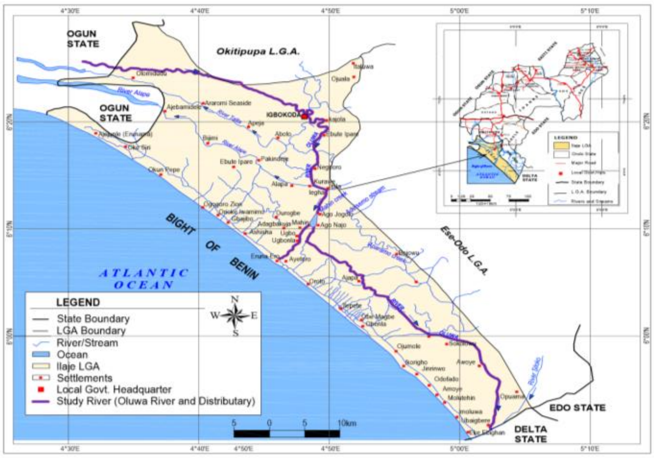


Figure 2. Oluwa River Network and other water bodies in Ilaje Local Government Area
Source: Adapted by the Author from [8]

In this study, emphasis is given to a section of river reaches of the waterway channel of River Oluwa in Ilaje Local Government Area (LGA) being part of the creeks that crisscrossed the main mangrove vegetation of the landscape in the riverine area. The water body flows through inner communities from the west border to the eastern border of Ilaje LGA dissecting the local government area into two geographical parts as shown in Figure 2. River Oluwa was selected for the study due to its significant geographical location, network and its connections to several communities. Igbokoda-Legha-Ugbonla-Idiogba/Ayetoro waterway is found to be the busiest inland waterway corridor in the area hence, its selection as the study area. This river corridor serves as a major means of transportation for both freight and passengers, providing access some isolated locations within the study area. As stated by Parikesit in his studies between 2003 and 2005, the role of inland water transport has become very prevalent and imperative, particularly when it is the only means of accessibility by passengers and freight movement to remote areas [9].

2. Related Work

Several studies have been done on the dynamics of river configurations and predictive tools in measuring the rates and extent of river bank line shifting amongst which are: the studies on the Meander Planforms, river sinuosity, river migration, channel depth, width and surface area expansion. These studies emphasised on the tools and methods suitable for measuring river curvatures (river bends) as well as the movement of the curvatures at the Meandering sections of a waterway channel in the riverine area of Ilaje, Ondo state.

2.1. Meander Planform

The greatest way to understand and characterize meanders is from above, according to [10], and a lot of research has gone into characterizing and examining meander planforms. A meander bend is characterized in terms of the shape and proportions of the planform. The bend geometry's most often utilized parameters are shown in Figure 3. Using a range of mathematical functions, planform studies have sought to describe the geometry of a single bend or a pair of bends when viewed from above [10]. The sine, parabolic, and circular curves were studied by the early researchers.

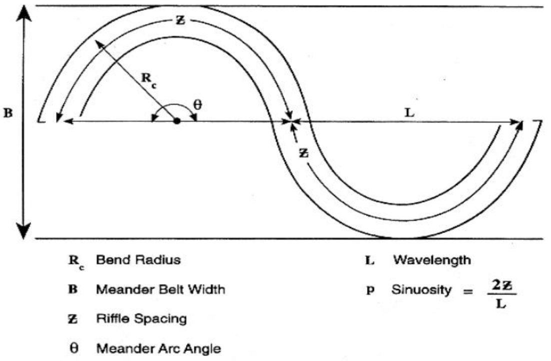


Figure 3: Parameters of bend geometry
Source: Adapted from [10].

2.2 Planform studies using maps and aerial photographs

Numerous empirical correlations for reach-scale meander shape and scale have been found through planform investigations employing maps and aerial images. Leopold and Wolman [11], for instance, found power law correlations between bend radius (Rc), meander wavelength (λ), and channel width (W). The width-wavelength equation's exponent, according to Harmar [12], does not change appreciably from unity. Based in part on his own and other researchers' findings, Stanislawski [13] proposed a set of basic meander geometry equations that, for instance, could be utilized for predicting meander reaction to discharge variations.

$$\frac{\lambda}{\mathrm{Rc}} \cong 4 \qquad (1)$$

$$\frac{\mathrm{Rc}}{W} \cong 2 \qquad (2)$$

$$\lambda \cong 10Q^{0.5} \qquad (3)$$

where: λ = meander wavelength; W = bankfull width
Rc = radius of curvature; Q = bankfull discharge

2.3 Brice Assertion

A fervent supporter of the use of aerial photos for meander planform research, Brice amassed an enormous archive of old aerial photos covering more than 350 rivers in the United States [10]. Brice utilized his data to create a categorization of meander shapes [15] and a method for assessing channel integrity using aerial images. Sinuous and braided behavior are not mutually incompatible, as Brice's classification correctly notes, and rivers close to the meandering-braiding threshold can display characteristics of both patterns. Examining Australia's Ovens and King Rivers is helpful in this sense (16]. These rivers have anastomosing planforms with several channels, and individual anabranches that have meandering patterns. Meanders behave differently from single-thread rivers, though, in that avulsion rather than migration is caused by increased sinuosity. Through their observation of the Tanana River in Alaska, Similar to meanders in single-thread rivers, Neill and Collins [17] demonstrated how meanders in a multi-channel system travel downstream, but with unpredictable internal changes and switching of sub-channels and bars influencing their rates and patterns. The most recent finding was made by Jones and Harper [18], who found that sudden decreases in sinuosity in the Rio Grande in Colorado were caused by avulsions rather than cut-offs. Tiwari [19] disclosed that sinuosity index is suitable in identifying the state of river planforms in the braided, curved and straight portions. That is, the sinuosity index can be utilised in specifying the various forms of river channels, including those that are straight, curved, meandering, and severely meandering. This assertion is illustrated in Figure 4. Sinuosity Index formula is hereby stated as follows:

$$\mathrm{SI} = \frac{\text{Thalweg length}}{\text{Valley length}} * 100 \qquad (4)$$

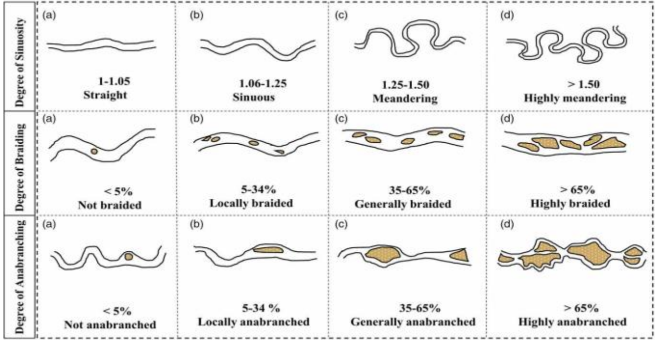


Figure 4: Definition of channel morphology based on feature parameters; Source:[21]

2.4 Historical and Monitoring Studies of Meandering Rivers

Some schorlars' understanding of meandering has greatly benefited from other initiatives, based on long-term observation and measurement, to link meander morphology to meander growth and shift. One excellent example is the work of Parrinello [22], who tracked the history of the Po River in Italy over a relatively long time period, from 1230 to 1980, utilizing historical maps. Figure 5 shows the planform features and geomorphic surfaces associated with river morphology and movement that were found by field geomorphic measurement and observation.

Relevant research on bend form and evolution was carried out by Kasvi [23] using historical data from the Beatton River in Canada. Originally, scroll bars found on the floodplain were used to infer the progression of meanders. Scroll bars are crescent-shaped ridges found inside migratory bends that are thought to indicate the inner bank's radius at the time the ridge's sediments were formed.

2.5 Predictive tools for channel migration

Before It is more realistic to measure and characterize the process rather than trying to construct forecasting tools for channel migration [10]. An orientation with regard to a baseline (e.g., down valley direction), an ending point (downstream end), a starting point (upstream end), and the location of the bend centroid (center of bend radius) and the outside bank radius (RC) should all be used to depict the initial or existing meander bend. Four different kinds of movement can also be used to fairly depict bend migration. The bend centroid is a convenient location to measure extension, which is migration over valleys. In a similar vein, translation is measured at the curve centroid and is defined as migration down-valley. Bend radius increases or decreases with expansion or contraction. Rotation is the shift in the meander bend's orientation with regard to the valley alignment [24], [10].

1. GIS-Centroid Measurement Tool

Meander Bend Data Logger is a menu-driven, GIS-based circle-template procedure designed to help in predicting channel migration by streamlining bend migration data measurement and analysis [25]. River planform data can be gathered and archived quickly and easily with the help of the Data Logger. One or more ArcView themes are depicted as the physical banklines. A theme in a vista is a collection of geographical features. An interactive map called a view in ArcView lets users explore, query, display, and analyze geographic data. To give users a visual record of how each bend is interpreted, the bend delineation points for each bend and each historical record are saved in separate themes.

The Data Logger logs different river properties (bend radius, bend center, river widths, bend wavelength, etc.) for each bend in the river and for each historical record. The data is arranged in a table named after the reach name and categorized by river reach. A few of the measures taken with Data Logger are displayed in Figure 6.

The following steps must be taken at every curve for every historical record in Data Logger:

- On a river bend, locate registration locations along the outer bank.
- Using the registration points, inscribe an arc around a circle to indicate its orientation and bend radius (Rc).
- Calculate the channel widths (W) at the upstream and downstream crossings (the bend ends) as well as at the apex of the curve.
- Determine the wavelength of the meander (λ) and bend amplitude (A).

2. Centroid Circles of best-fits

This involves the combination of some components which include radius of curvature, meander bend orientation, meander wavelength and amplitude, channel length amongst others.

Radius of Curvature: By placing five or six registration sites along the bankline from the start of a bend to its conclusion, one may determine the radius of curvature (RC) of the outside bankline (Figure 5). After the points are determined, the bend is best described by a circle that matches the registration points the best. The radius of the circle indicates the radius of curvature of the outer bank, while the centroid of the circle denotes the centroid of the bend.

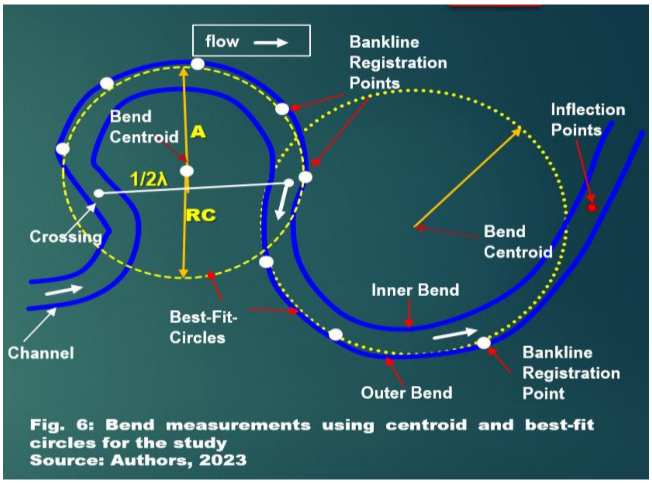


Figure 5: Bend measurements made using data logger
Source: Adapted from [10]

Meander Bend Orientation: The bend orientation is determined by a line that connects the bend centroid to a point on the outer bank arc midway between the upstream and downstream ends. The bend orientation angle is measured counter-clockwise from a zero-angle that is specified as due east, just as the valley orientation angle.

Meander Wavelength and Amplitude: Determining the upstream and downstream crossings, establishing a point at the river's centerline at the crossings, and then drawing a line between the points defines the meander wavelength (λ). This line's wavelength is twice its length. A line drawn between the wavelength line and the outer bank at the bend apex, perpendicular to the wavelength line, defines the bend amplitude (A). The outer bank's furthest extension in relation to the bend centroid is known as the bend apex.

Channel Width: At the crossings and the bend's broadest point, the channel widths are taken from top to bottom. The average of the channel widths at both crossings is the channel width of the crossing in the data set. The bend's apex is often where the channel widens the most. The GIS measuring tool is used to take and record all of the width measurements.

3. Method

3.1. Historical and monitoring of channel curvature shifting

Morphological investigation was carried out on a section of the river reaches of River Oluwa from Igbokoda town to Legha. The study adopted geospatial techniques to conduct spatiotemporal analysis of the river plan changes. This was complemented with sinuosity index and centroid best fit of circle method to predict the rates and extent of channel curvature shifting at the meandering section. Temporal scope of the study spanned between 1972 and 2022.

The study involved an overlay comparison of historic banklines on the satellite data using GIS and computer aided techniques. The study took the following step too achieve the study objectives:

STEP 1 – Satellite images of the study location were obtained from the United State Geological Survey (USGS). Map data for river planforms between year 1972 and 2022 were collated, assessed and analysed using ArcGIS and Automated Computer Aided Techniques. Satellite data used for the study include Landsat MSS TM 1972, Landsat ETM+ 1984, 2002, 2012, and 2022 Imageries. The images went through post-classification comparison for change detection. Unsupervised Image classification was deployed which involved ISO cluster unsupervised classification with optional minimum class size after which a reclassify was done to identify variations in the channel line over the years. Changes in river bank line class were primarily emphasised and digitized to create digitized maps for quantitative measurement and analysis. This approach is considered suitable and appropriate to measure migration distance, identify directions of meander movement and erosion using the average meander length and meandering centroids. Figure 6 indicates the location of meandering section in the study river planform.

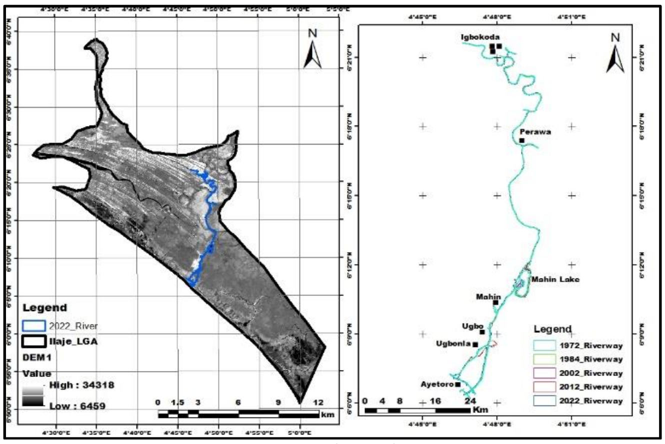


Figure 6. River plan form of the study area
Source: Author, 2023

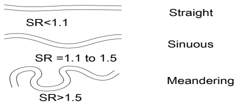
3.2. Determination of the channel sinuosity/curvatures

The degree of curvatures and the sinuous condition of the studied reaches were ascertained using the sinuosity index. This is consistent with [19], which states that the sinuosity index can be used to define the specific characteristics and types of river channels, including meandering, straight, sinuous, and severely meandering channels. Typical Shape of Channel Sinuosity between the end points of the curve.is depicted in Figure 7

Figure 7. Typical Shape of Channel Sinuosity between the end points of the curve. Source: [19]

The degree to which a river (or other linear feature) wanders away from being straight is measured by its sinuosity. It explains how a river channel is curved. A genuinely straight river has a sinuosity of 1, as indicated in table 1; sinuosity approaches 1 as the number of meanders rises [19]. By calculating the length of a reach, or a segment of the river channel, and dividing the result by the straight-line distance down the valley, The river channel's potential curvilinearity is usually represented by the Ratio of Sinuosity Index [26]. See Table 1.

Table 1. Classification of Sinuosity Index

Type	Sinuosity	
Straight	< 1.1	
Sinuous	1.1 – 1.5	
Meandering	> 1.5	

Source: (Kusratmoko, Wibowo, & Ahmad, 2019).

According to Brice [20], the calculation of the sinuosity index involves dividing the valley length by the channel length along the thalweg, which is a line that passes through the lowest points of successive cross-sections along the channel's length. In terms of navigability, it characterizes the curvature state of a river channel. This study is anticipated to provide insight into safe channel draft detection techniques as well as information on regions that are safe for navigation or susceptible to mishaps including watercraft collisions, groundings, and vessel ramming into submerged objects.

3.3. Meander migration analysis using an overlay technique

STEP 1: In this step, remarkable landmarks are identified as common registration points for all the images under comparison. Since comparisons can be made in pairs, the registration points only need to be common to the next image that is being compared, not to all the georeferenced maps created from the images.

The registration locations on the two sides of the channel and at both ends of the reach that bordered the site are the most advantageous because they reduce the amount of potential error within the enclosed area. To accurately register the middle regions of the reach, it is useful to have intermediate points between the end locations. Because it might be challenging to align every registration point, registration can become challenging if there are more than five or six.

STEP 2: To create vectorized maps, or digital maps that are easy to analyze quantitatively, banklines and registration points for each year were drawn from the georeferenced and processed imagery onto a new layer after the registration points were identified. The use of Automated Computer Aided Design was thought to be appropriate for digitization and simple curvature measurement. For simple data processing, every map property was digitalized on a separate layer.

In order to facilitate comparison, registration points are digitalized on the new layer attributes and can be plotted on other selected year's images with ease.

STEP 3 – Centroid technique

The channel's directions and the bends' potential future locations were predicted using the centroid technique, which was based on the features of previous channel migration. Following the digitization or vectorization of the banklines for each historical image, the average bankline arc, the bend's radius of curvature (RC), and the bend centroid position were determined by creating circles that are best-fit to the outer bank of each bend (Figure 7). A bend's defining number of circles is determined by the loop categorization as shown in Figure 8. The bend readings from before and subsequent years were compared using the bend's radius of curvature and centroid position of the circle. These measurements were done in AutoCAD drawing environment where migration rates and direction were determined, while estimate of the future bend migration were premeditated.

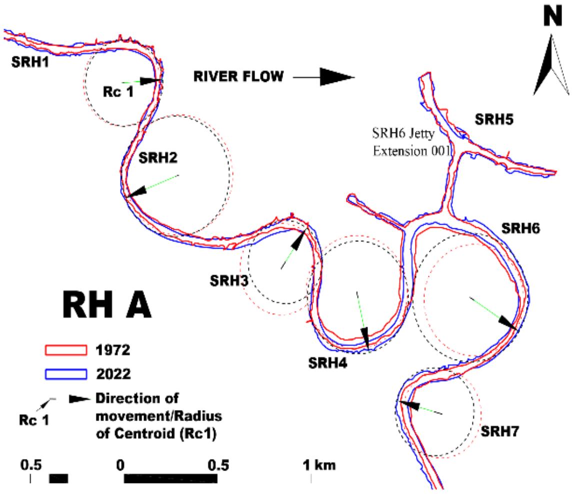


Figure 8: A typical circles that are best-fit to the outer bank of each curvature (bend); Source: Author, 2024

Since each bend movement mode has a magnitude and direction, they are all vectors. The forms of meander movement are presented in Figure 8 (positive rates are provided for each mode). Translation is done downstream in a direction perpendicular to the bend orientation, while extension is done in the direction of the curve. There is no particular direction for the bend radius. On the other hand, the rate of bend radius "expansion" is negative if the bend radius is contracting. To determine how much bank movement there was, the two migration vectors are blended into a resulting magnitude called "apex movement." The vector sum of the three components of movement at the apex position is used to calculate apex movement, which is the movement of the outer bank apex [20].

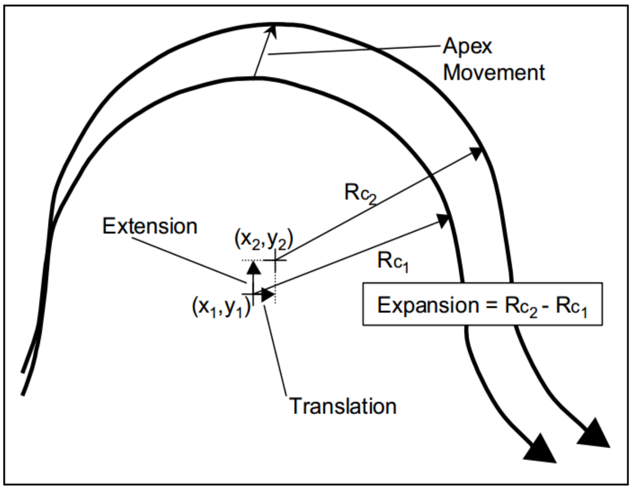


Figure 9: bend centroids and the shifting towards the right and northeast directions.

For every bend in georeferenced images between two years (initial and absolute years), Figure 9 displays the typical best-fit circles and bend centroids and the shifting towards the right and northeast directions. Each bend's vector arrow indicates the bend centroid's direction and orientation of movement between the initial and absolute year. The rates of meander migration for each bend can be found by dissecting this vector into cross- and down-valley components. Each bend's variation in radius of curvature is determined by the difference between the vector magnitudes for the initial and absolute years.

STEP 4 – Prediction
If it is expected that the bend would continue to travel at the same rate and distance measured in approximately the same direction as it had in the past, then the position of the bend at a certain date in the forthcoming years can be predicted by simple extrapolation.

The distance the centroid is expected to move in the periods between the absolute year and the predicted year is calculated by multiplying the annual rate of movement for the first year to the absolute year period by the number of years for the prediction. This allows one to estimate the position of a bend centroid in the projected year. Following that, a line was drawn to represent this distance, beginning at the Absolute year centroid point and extending in the direction indicated by the Initial year to Absolute migration vector.

By calculating the rate at which the bend radius changes from the initial year to the absolute year in relation to the absolute radius and multiplying this value by the number of years from the absolute year to the projected year/date, the radius of curvature of the bend in the projected year was established. To determine the expected location and radius of the bend in absolute year, a circle with that radius was created on a new layer using digitizing and tracing tool. The circle was centered on the centroid's estimated location. In the study river, these methods were applied to predict future channel/bend migration rates and extent. Figure 10 shows a sample of centroids' movement between initial year and predicted year.

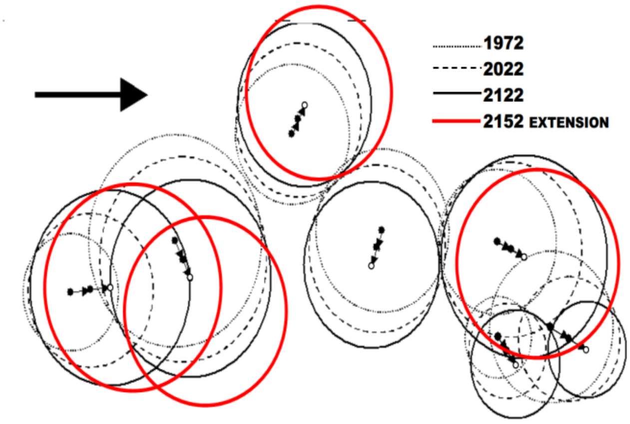


Figure 10. An array of centroids' movement in the periods between the initial year, the absolute year, middle year and the predicted years used for the study

4. Results and Discussion

The morphological survey's findings provide insight into the study river's morphological condition and how it influences inland transportation in the Ilaje Local Government Area. The study focused on river sinuosity, curvature shifting, and the possible future consequences on the inland transportation network by assessing the alteration of the meandering part of the river taking cognisance of the river banklines and their curvatures.

4.1 River Plan Form/Channel Pattern

The findings showed that the river plan form of the river way exhibited patterns of curves, channel migration, and bank line movements in different directions. This can therefore be attributed to interactions and interrelationships between different river alluvial processes and activities, including deposition, transportation, and erosion, river capacity, river competence, volume of water during peak season, soil, and geological structure, as well as anthropogenic activities (human interference) with the river way. The planform of the study river channel's meandering segment (reach A) from 1972 to 2022 is displayed in Figure 11.

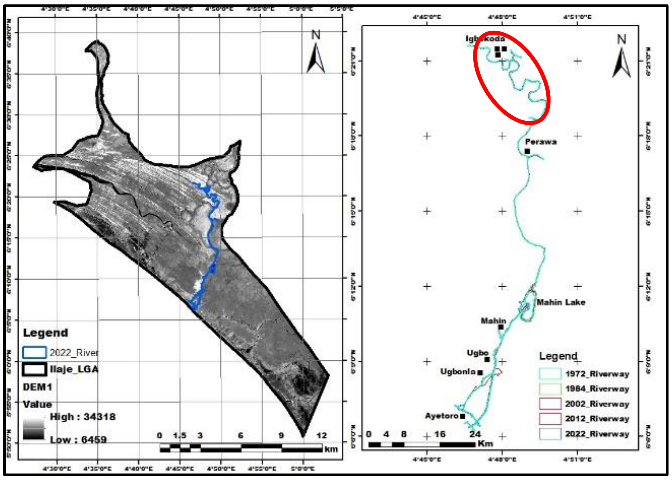


Figure 11. River planform of Igbokoda-Ayetoro Inland waterway channel showing the study reach (Reach A) from 1972 to 2022.
Source: Author, 2023

Reach A of the waterway is a meandering portion that traverses between Igbokoda and Legha, as illustrated in figure 12. The reach was subdivided into 15 sub-reaches for more in-depth examination. According to the study, each sub-reach's morphological progressions show that the river channel is defined by flowing water that constantly erodes the outer bank, widens valleys, deposits transported sediments, and eventually narrows its channels, causing to significant changes over time. For example, over the study period (1972–2022), Sub-reach 1 (SRH1) of reach A remained significantly straight with a sinuosity of less than 1.1. hence, it is verified that the river channel is highly meandering if the sinuosity index is greater than 1.5. The study revealed that the planform of the reach A is a well-defined meander. It shows the propensity to exhibit an unstable and continuous bankline shifting.

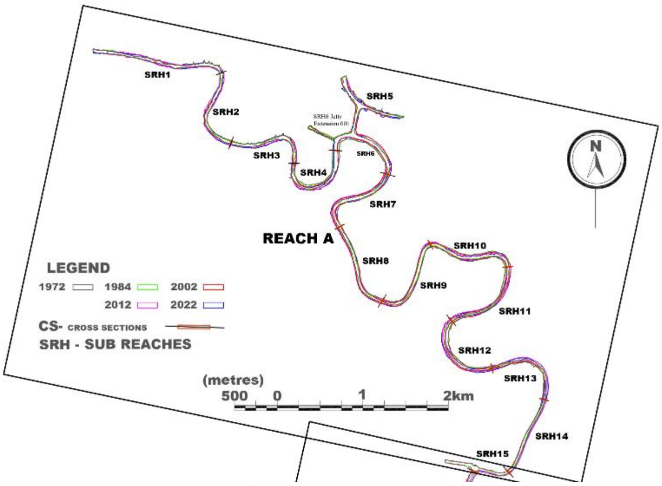


Figure 12. Demarcation of the river reach A into fifteen (15) Sub-reaches (SRH) Source: Author, 2023

4.2 Changing Pattern of Sinuosity Index (SI)

Findings revealed that the channel patterns exhibit sinuous and meandering configurations. The ratio of channel length to valley length, also known as the ratio of valley slope or channel gradient, as measured across the same length of valley, best describes these configurations.

Table 2 shows that there were significant changes in the sinuous of the river sections from Igbokoda to Legha over the period of 50 years (1972-2022). The waterway channel exhibited erosion and deposition processes causing such significant changes in its shapes and curves. It is noteworthy that identifying recurrent changes in the morphology of a river is necessary in the production of nautical charts for save ferry/vessel draft and navigation. The need for constant update of bathymetric data and production of nautical charts becomes more prominent by contemporary maritime navigation with the increasing sizes of watercrafts that operate in tighter or narrower spaces or waterway channels [27]. However, the intensity of these curves was determined using the channel sinuosity index. The valley length, or straight-line distance, between the endpoints of the chosen channel reach is divided by the length of the stream channel to get the channel sinuosity. Refer to Fig. 4.

Table 2. Sinuosity values of different Reaches of the waterway from Igbokoda to Ayetoro between 1972 and 2022

River Channel	Sinuosity	1972 Channel Length	Valley Length	2022 Channel Length	Valley Length	1972 INDEX S = Lc/Lv	2022 INDEX S = Lc/Lv	Index variations	Channel length variation	Valley length variation
REACH A	SRH 1-4	4569.78	2921	4627.58	2921	1.5645	1.5842	0.0198	57.8	0
	SRH 6-10	5007.63	2425.3	5100.88	2438	2.0647	2.0922	0.0275	93.25	12.7
	SRH 9-12	3936.9	1498.3	4088.84	1498.3	2.6276	2.7290	0.1014	151.94	0
	SRH 11-13	2943.51	1622.4	3087.67	1622.4	1.8143	1.9031	0.0889	144.16	0
	SRH 14-15	1361.18	1166.6	1362.99	1166.6	1.1668	1.1683	0.0016	1.81	0
Average Channel length REACH A= 448.96m			Total Channel Length 1972 Channel Length= 48,577.79m (48.58km) 2022 Channel Length = 48,953.9m (48.95km) Channel Extension = 376.11m (0.376km) S = Sinuosity Index; Lc= Length of channel; Lv = Valley Length							

Source: Author, 2024

As observed in the study, the variations in the values of sinuosity indicate erodibility and deposition of sediments occurring in the river bed with resultant effects on depth changeability and channel length extension. This event of action usually results in uncertainties in the river depth and unpredictability in inland navigations. The propensity for vessels or watercraft in transit to run aground is high with rapidly changing river depth, width, shapes, structures and other uncertainties. Sinuosity values recorded in 1972 and 2022 revealed a significant change in the shape and patterns of the Igbokoda-Legha waterway. Table 2 and Figure 6 indicated that the sinuosity values for sub-reaches 1-4, Sub-reaches 6-10, Sub-reaches 9-12 and Sub-reaches 11-13 between 1972 and 2022 had sinuosity index values greater than 1.5.

Sinuosity condition: According to [30], sinuosity greater than 1.5 is highly meandering. This is the situation of the river reach that traverse Igbokoda through Kajola to Legha. Sub-reaches 1-4 had a sinuosity index value of 1.5842, SRH 6–10 recorded 2.0922 indices, SRH 9–12 had an estimated value of 2.7290, and SRH 11–13 had a value of 1.9031. These sub-reaches, which are all located in Reach A, are collectively referred to as extremely meandering channels. This is consistent with [28], which states (see Figure 13) that extremely meandering channels have a sinuosity index value greater than 1.50. Reach A's final segment is made up of SRH14 and SRH15, which link Igbokoda and Ebute-Ipare/Legha. With index values of 1.166 and 1.168, these routes are comparatively sinuous. However, the consequential effects of this change included channel extension and channel stretching.

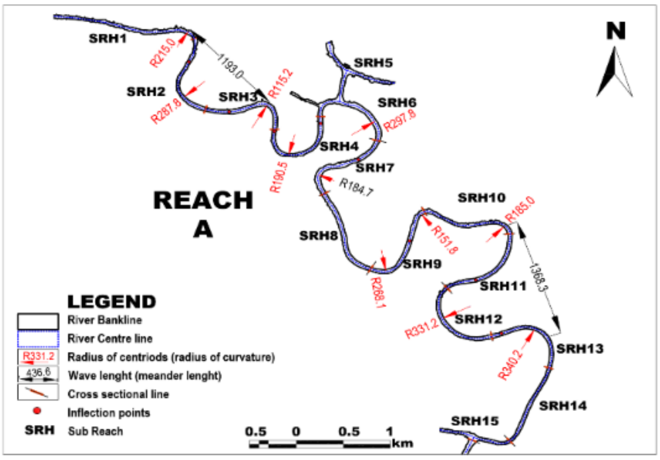


Figure 13. Planform view of Meandering section of the river reach A; Source: Author, 2024

Channel extension: Findings revealed that the river channel extended in length on the curvatures. As shown in Table 2, in 1972, the river channel length was 48,577.79m (48.58km) long; but in the year 2022, the channel had increased in length to 48,953.9m (48.95km). The Reach A, extended (stretched) by 448.96 metres over a 50-year period (1972-2022); however, this is because erosion and water flow have altered the river channel's route. The Igbokoda-Ayetoro Canal's meandering section is characterized by its shifting positions. Its valley is filled with meandering rivers that run sideways and slightly downstream, giving the waterway the appearance of a snake curve. Table 2 shows the changes in valley and channel lengths based on the selected reaches.

The study of river velocity at bends revealed that the river flow migrated sideways as a result of the stream's greatest velocity shifting beyond the bend and eroding the outer bank. At the same time, silt is deposited by the lower stream on the meander's inner bend. Therefore, the river flows sideways without changing the width of its channel since it erodes its outer bank and deposits material along its inner bank. however, the channel length (distance) varies as the stream flows faster around these curves due to its protrusion force, which lengthens the channel, Refer to figure 14. This was supported by Writer [29] stating that the channel length increases as meanders grows by extension.

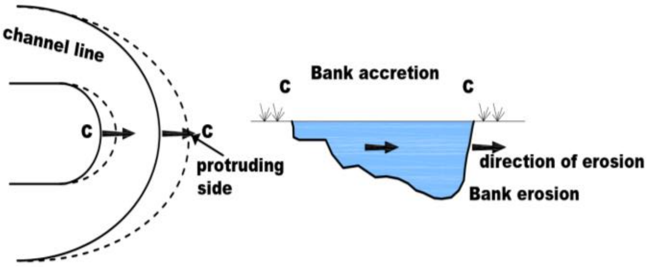


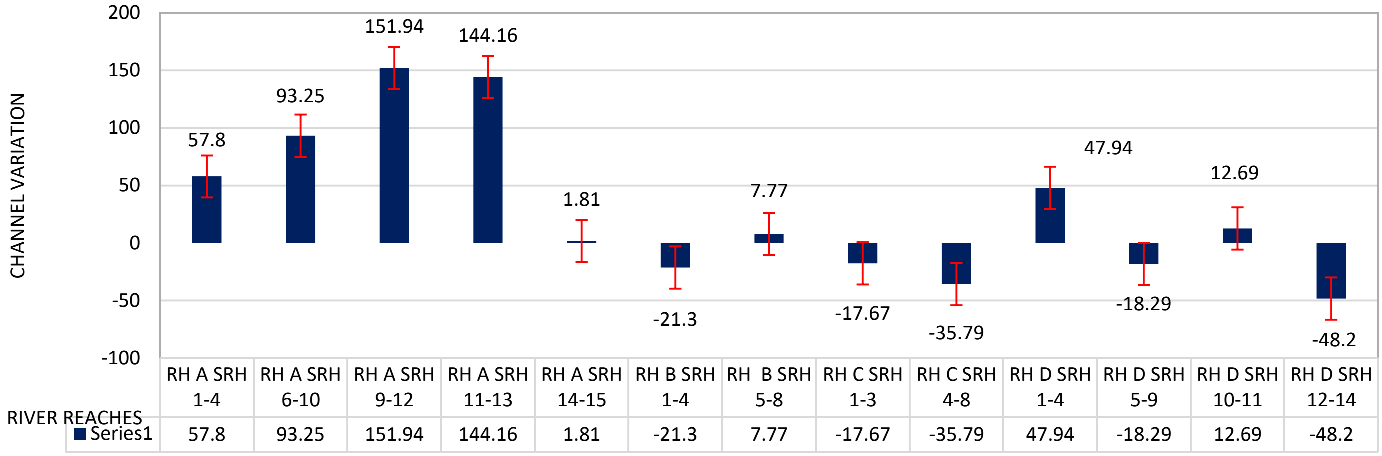
Figure 14. Action of river flow at river's inner and outer bends
Source: Author, 2024

Generally speaking, the current of a river accelerates in areas with the deepest channels and the fewest obstacles. In a riverbed of a meandering river, the water moves in what is known as helicoidal flow. In a helicoidal flow, the main current corkscrews from the opposite side of the river to the other bank side, causing further erosion and carving out a deeper channel on the outside of the meander. It traverses Negboro, Kurawe to Ibila on meandering lanes with a sinuosity index value of 1.62. Conclusively, it is noteworthy that between 1972 and 2022, the Igbokoda-Legha river channel exhibited meander-sinuous configurations within sinuosity parameters of 1.1 and greater than 1.5 index values. From 1972 to 2022, the sinuosity of the riverway had a significant change and extension in channel length with a tendency to continue as the year progressed teething troubles to inland navigation and transport see Fig.6. At Reach A, sinuosity parameter is relatively high.

4.3. Effect on inland transport

Increased Travel Distance and Operating cost- The results showed that the river channel stretched 448.98 meters in length. The river from Igbokoda to Legha traveled 48,577.79 meters (48.58 kilometers) as of 1972; in 2022, the predicted transit distance is 48,953.9 meters (48.95 kilometers). The channel length changes for the river planforms in 1972 and 2022 are shown in figure 15 in both positive and negative fluctuations. While negative values indicate a reduction in channel length, positive values indicate an extension of the channel length. Reach A exhibits the positive variations (SRH 1-4, SRH 6-10, SRH 9-12, and SRH 11-13). According to the data, over a 50-year period, the river channel's length increased by 448.96 meters (0.449 kilometers).

However, this may have a direct negative effect on travel distance and operating cost of transport, particularly fuel consumption. The longer the travel distance, the fuel consumption and the higher the operating cost to travel' [30]. The standard error reflected that the values are of a high percentage of accuracy with no-skewed error bar. It is note taking that the determinants of vessel fuel consumption can be directly related to the type of vehicle engine, vehicle travel distance, and vehicle load on reductions of energy used. The effects of potential future changes in vessel travel distance while other factors remain constant are significant in operating cost on fuel. This is in agreement with Sivak who asserted that the amount of fuel consumed is directly proportional to vehicle distance travelled (holding everything else constant) [30]. Thus, any proportional increase in the vessel's travel distance (e.g., by an increase in the length of the channel) would translate into same proportional increase in fuel used for transportation (operating cost).



	RH A SRH 1-4	RH A SRH 6-10	RH A SRH 9-12	RH A SRH 11-13	RH A SRH 14-15	RH B SRH 1-4	RH B SRH 5-8	RH C SRH 1-3	RH C SRH 4-8	RH D SRH 1-4	RH D SRH 5-9	RH D SRH 10-11	RH D SRH 12-14
■ Series1	57.8	93.25	151.94	144.16	1.81	-21.3	7.77	-17.67	-35.79	47.94	-18.29	12.69	-48.2

Figure 15. Standard Error of the Channel Length variations of 1972 and 2022 river planforms; Source: Authors, 2024

4.4. Prediction of the rate and direction of erosion from the average meander length.

Table 3, Figures 16 and 17 reveal spatio-temporal predictions of the rate and direction of erosion from the average meander length of the waterway channel planforms between 1972-2022, 2072 and 2152; that is 130 years prediction. Attributes of the map analysis include inscribed circles that define the average outer bank lines of 1972 and 2022 planforms, arc of centroids of 2072 and 2152, the bends of centroids and the radius of curvature (Rc) for the bends shown in different colors lines and the direction of channel movements in green arrows.

As indicated in Table 3, the highest yearly migration rates are observed in subreaches SRH4, SRH5, SRH10, SRH11 and SRH13 with estimates of 0.851m, 0.901m, 0.883m, 0.809m and 0.800m respectively. Meanwhile, the average mean of the migration rate in the meandering section between 1972 and 2022 is estimated as 0.694metres/year. However, this is attributable to gradual force of erosion on the outer bank lines causing the channel shifting to protruding directions. The Table indicates the predictions and the extent of channel migration in 50 years (2072) and 130years (2152).

Table 3. Prediction of the rate and extent of channel migration/shifting at meandering section of Igbokoda-Ayetoro waterway channel and predicted positions of the outer bank of the bends in 2072 and 2122

RIVER REACH A	Migration rate between 1972-1984	Migration rate between 1984-2002	Migration rate between 2002-2012	Migration rate between 2012-2022	Dir	Rate aggregate (m)	1972-2022 Average Rate metre/year (m)	Migration Distance in 2072 (50years) in metres	Migration Distance in 2152 (130years) in metr
SRH1	0.215	0.303	1.271	0.48	S	2.269	0.567	28.5	73.71
SRH2	0.468	0.553	1.202	0.416	SW	2.639	0.660	33.0	85.8
SRH3	0.776	0.375	1.236	0.624	SW	3.011	0.753	37.6	97.89
SRH4	1.042	0.731	0.947	0.684	S	3.403	0.851	42.5	110.63
SRH5	0.396	0.811	1.18	1.217	S	3.604	0.901	45.1	117.13
SRH6	0.436	0.525	0.43	1.213	S	2.604	0.651	32.6	84.63
SRH6 Ext	0.627	1.013	0.65	0.61	E	2.900	0.725	36.3	94.25
SRH7	0.613	0.974	0.553	0.797	W	2.936	0.734	36.7	95.42
SRH8	0.378	0.584	0.662	0.425	W	2.048	0.512	25.6	66.56
SRH9	0.227	0.611	0.776	0.395	NW	2.010	0.503	25.1	65.39
SRH10	1.671	0.655	0.616	0.588	SW	3.531	0.883	44.1	114.79
SRH11	1.120	0.773	0.948	0.394	NW	3.237	0.809	40.5	105.17
SRH12	0.933	0.785	0.721	0.528	W	2.967	0.742	37.1	96.46
SRH13	0.586	0.409	1.661	0.542	NE	3.198	0.800	40.0	104
SRH14	0.622	0.326	1.034	0.359	E	2.340	0.585	29.3	76.05
SRH15	0.545	0.287	0.627	0.265	SE	1.725	0.431	21.6	56.03
Mean Avg	0.665938	0.607188	0.907125	0.596063		2.776375	0.694188	34.725	90.24

Source: Authors, 2023

Figure 16 and figure 17 showed the expected outer bank circles for each of the bends of the Igbokoda –Legha waterway channel between 2022 and 2152. This estimation was based on extrapolation of the rates and directions of change during 1972-2022. To design banklines for the 2072 and 2152 channels, the outer bank circles are interpolated onto a new layer by tracing with reference to the 1972 and 2022 banklines which represent the channel's reach-scale configuration.

Assessment of the estimated banklines reveals that SRH4 will encroach into SRH7 by 2152 and would likely cut-off SRH 5 and SRH6. See figure 16.

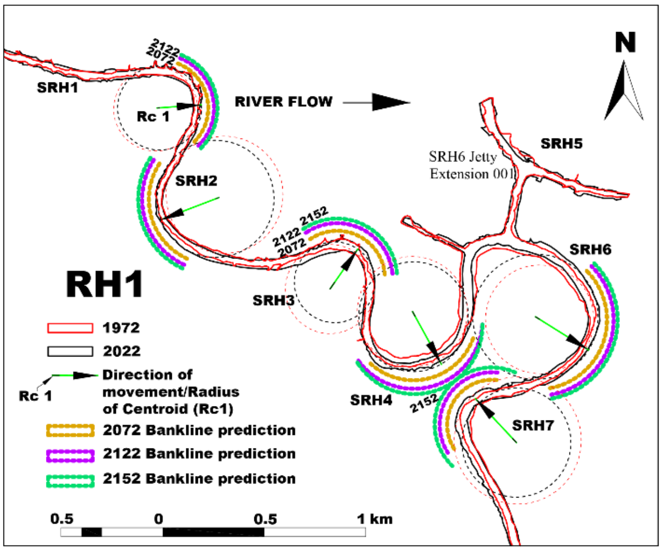


Figure 16: Spatio-temporal predictions of the curvatures of the waterway channel between 2022 and 2152 (130 years prediction)

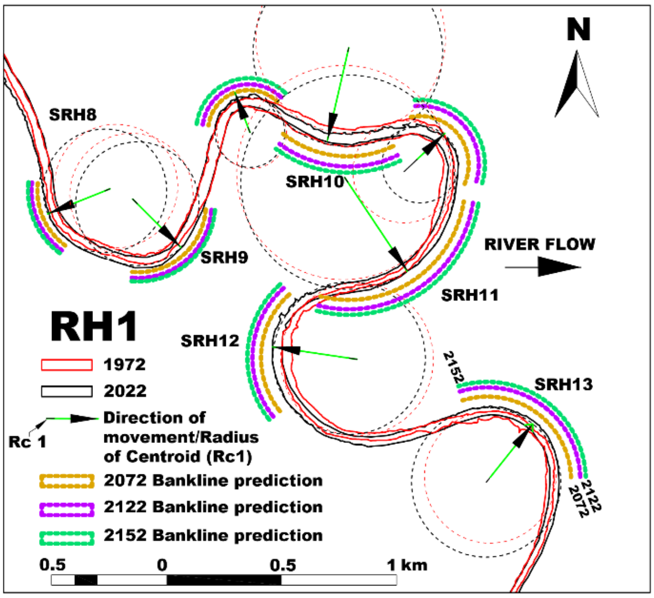


Figure 17: Spatio-temporal predictions of the curvatures of the waterway channel between 2022 and 2152 (130 years prediction)

In figure 16, the migration of Bends 4, and 7, the cut-off of Bend 5 and 6 and their abandonment are predicted with sufficient precision to meet the objectives of this study. The case study of the Igbokoda–Legha waterway used a single period (1972 to 2022) to predict the position of the banklines in 2072, 2122 and 2152. For reliability and accuracy of predictions it is desirable to use multiple pairs of satellite images to run more than one period of analysis. Meander migration analysis is able to identify time-averaged values as well as trends of change in the rate and direction of bend migration by analyzing several periods. In summary, the direct implication of this is:

(i) A continuous channel extension between periods of 2022, 2072,2122 till 2152
(ii) A natural cut-off at joining of curvature (Bend) 4 and curvature (Bend) 7 that affects to Bends 5 and 6 being abandoned in the predicted year 2152.

Concave banks are the curves' corners that are closest to one another. With time, the concave banks, or outside bends, erode. The ground on the meandering, concave banks of the rivers is worn away by the force of the flowing water. Convex banks, also known as inner bends, are the banks that face the concave banks; erosion occurs here in the opposite direction. Sediment and silt accumulate on convex banks. The accumulation is known as deposition. A new channel will eventually emerge to cut through the little strip of land at the narrow end of the meander as a result of erosion and deposition. At the concave bends of SRH4 and SRH7, the river takes a detour and takes a shorter route, cutting off 2.158 kilometers of travel distance which constitutes SRH5, SRH6 and SRH6 extension 001 at Jetty waterfront as shown in Figure 16. The waterway channel becomes shorter, causes a reduction in the travel time and distance from Igbokoda to other settlements beyond Legha.

It is note taking that settlements and locations such as Ofara, Igbokoda water front, Ugbene Omi, Ugbene Yoyo, Igbanran, Kofewa, Kurugbene and several other settlements in the northern part of Igbokoda will be cut-off from inland waterway networks and there will be no direct inland waterway access connection to the communities/settlements in the southern part of the region.

However, Figure 17 revealed movement of concave banks of SRH9 and SRH12 towards each other. In the projected year (2152), it implies an existence of channel extension of SRH9 and SRH12 moving towards joining together and cutting off SRH9, SRH10 and SRH11 which may eventually develop to an OX-bow lake. Substantial channel length will be completely cut-off thereby causing about 3024.97m (3.024km) reduction in the travel distance between Igbokoda and Legha.

5. Conclusion and Future Scope

The river planform features including the geomorphological features were discovered through field measurement, observation and analysed using computer aided and centroid best-fit techniques. Findings revealed the movements of concave banks of the meandering section of the inland waterway channel between Igbokoda and Legha community owing to the capabilities of these deployed. The techniques gave a precise information about the morphological conditions of the channel; the sinuosity index revealed the sinuous values and determined the physical configuration of the river reach being highly meander; it is noteworthy that condition has subjected the inland navigation in this transport corridor to certain levels of uncertainties and vulnerability to risks of grounding and collisions at angles of deflection. Centroid best-fit technique deployed for prediction of the channel curvature shifting disclosed the eventual joining of channel bends overtime thereby cutting-off of parts of the community from inland transport network. Investigations revealed channel extension with a significant travel distance in kilometers. It is of note that the technique is useful for assessing and monitoring geomorphological conditions of inland waterways for effective and efficient decision making as well as sustainable management of inland waterway transport in the riverine areas. The use of these techniques is recommended for river planner, river engineers and other stakeholders on inland waterway planning, pre-dredging and channelization projects. The study highlights a stepwise procedure in carrying out a geospatial study on river morphology taking cognizance of sinuosity, river depth, river width, velocity, planforms amongst others. Based on the findings, the study recommends channel modification and regular sediment control in order to maintain safe channel depth for inland navigation.

Besides, further study should be caried out on computation in waterway designs for the waterways as well as the morphology and dynamics of braided rivers using improved version of data logger tool in ArcPro and new GIS applications. There should be close monitoring of the meandering sections of the channel particularly on estimating angle of deflection and vessel's manoeuvrability at river curvatures.

Data Availability

Data used for this study was gotten from United State Geological Survey (USDS) being the satellite imageries for spatio-temporal analysis. Techniques adopted were adapted from literature reviews.
Study limitation: None

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Authors' Contributions

B. S. Olisa carried out the study at all stages, develop the procedures used in carrying out the analysis geospatial analysis using ArcGIS and Computer aided techniques. He did all typesetting and formatting of the document.

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