Channel Sinuosity Effects on Inland Transport in the Riverine Region of Ilaje, Nigeria

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Abstract: Transportation is an essential tool for regional social and economic growth, as well as national development. Transport has a vital social and environmental impact that cannot be overlooked. The character of naturally functioning rivers varies greatly and does not remain constant since it is mainly determined by several of physical factors and processes, among which is river sinuosity. Understanding how the inland waterways change with time and the effect or consequences of these changes on the lifestyle and economic activities of the inhabitants becomes very important. This study focused on revealing the changes that had occurred in the planforms of Igbokoda-Idiogba/Ayetoro waterways in Ilaje, Ondo state; its effects on inland transport taking cognisance of sinuosity index. It assessed morphological changes of navigable rivers in the study area from 1972-2022; the effects of river sinuosity on inland transport in the study area were considered. The study deployed geospatial techniques to assess the decadal changes of changing patterns of the channel's sinuosity taking cognizance of the sinuosity index and formula. However, the study shows the capabilities of geospatial techniques in monitoring river morphology. The study revealed significant changes in the channel's sinuosity and consequential effects of the changes. Sustainable transport measures for safety and efficiency were recommended.

Key-Words: - Inland, Waterway, Sinuosity, River, Curvature, Transport, Channel

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1 Introduction

Rivers that function naturally have a highly variable character that changes over time due to a multitude of physical factors and processes, including substrate caliber, bank line shifting, valley gradient, sinuosity, and depth variability caused by sedimentation and silting. Nonetheless, effective transportation systems offer social and economic advantages and opportunities that have a beneficial knock-on effect, improving market accessibility, creating jobs, and drawing in more capital. However, there can be social and/or economic consequences as well as a significant likelihood of a decline in quality of life when transportation networks are deficient in terms of capacity or reliability [1]. One of the challenges that Nigerians face when using waterways is health and safety. Mistakes at river curvatures (bends), vessel overcrowding and/or listing resulting in capsize at bends, poor watercraft, and sunken wrecks above and below the surface are among the causes of many waterway accidents, riverbed silting, and the disappearance of navigable channels in littoral states. Aside from natural causes, river sinuosity can be altered by human activity. However, the intricate structure of rivers, as well as increased interest in quantitative analysis of this complex structure, has prompted this study, and it is an essential area in river science that this study focuses on.

River plan change is seen as the resultant effect of change in depth, width, discharge, and the pattern of sinuosity of a river (river curvature) among which are Oluwa River, its tributaries, and distributaries threaten safe navigation for rural communities of the Ilaje area. Inland navigation becomes threatened when there is frequent shifting in river bank lines and changes in river depth due to accretion or sedimentation of material in riverbeds [2]. River channel changes such as bank erosion, downcutting, and bank accretion are natural processes for an alluvial river [3], all these natural processes have effects on inland waterways especially their navigability, environment and socio-economic benefits to locals in their catchment areas. The existence of the waterways has been an important factor in the development of several riverine communities in Nigeria; for instance, River Niger had been an important artery connecting transport activities from the north to western geopolitical regions to south and eastern geopolitical regions; and waterways have served first as paths of exploration and new settlement and later as avenues of commerce and trade in Nigeria [4]. It becomes crucial to comprehend how inland rivers change over time and the effects these changes have on the way of life and economic activity of the locals. This study emphasizes the effects of channel sinuosity on inland transit as one of the behavioral patterns of navigable rivers in the riverine region of the Ilaje local government area, Ondo state.

Water transport projects must be planned, designed, and carried out with an understanding of how river morphology changes over time. In order to advance understanding and create policies that will promote sustainable economic growth in the catchment areas, the study explored the effects of river sinuosity on inland transportation and socioeconomic activities in the riverine area of Ondo state. The results of this research will provide new information that might be used as a platform for planning and appropriate management of the Oluwa River and other rivers in the study area, as well as guidance to decision makers on inland waterways planning projects. In developing countries, rural transportation is frequently neglected and not integrated into transportation planning [5].

2 Study Area

The study area is located within the riverine area of Ilaje Local government area of Ondo State, Nigeria. Ondo State lies specifically on Latitude 7010'N and Longitude 5005'E. It is located in the South western geopolitical zone of Nigeria and bounded in the North by Ekiti and Kogi States, in the East by Edo State, in the west by Osun and Ogun states and in the south by the Atlantic Ocean (see Fig. 1). Ondo State is located entirely within the tropics. It has a population of about 3,441,024 [6].

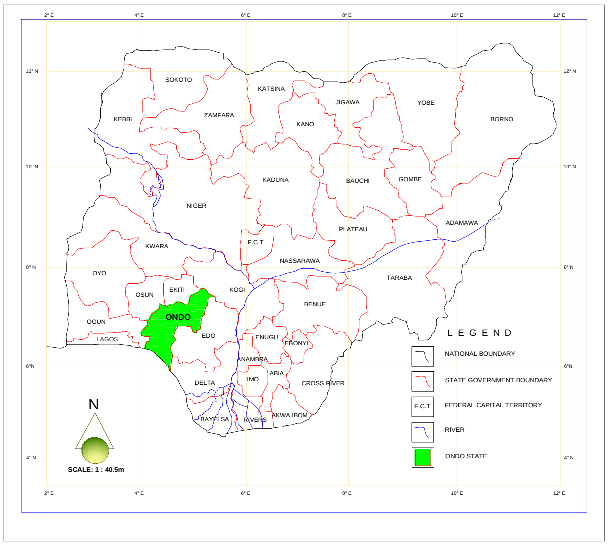


Fig. 1: Ondo State Map its National Setting
Source: [7]

Fig. 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 Fig. 2. River Oluwa was selected for the study due to its significant geographical location, network and its connections to several communities. At its middle course, a distributary 'Igbokoda-Idiogba/Ayetoro waterway channel' connects its network down to Ayetoro where it empties its water into the Atlantic Ocean. Igbokoda-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 river or inland water transport has become very prevalent and important, particularly when it is the only means of accessibility by passengers and freight movement to remote areas [9].

3 Related Reviews

Determining the effects of river shape on human socioeconomic status, quality of life, and environmental quality is crucial, as evidenced by the growing interest in sustainable inland waterway transport systems and growth [10]. In its January plenary meeting in 2022, the European Economic and Social Committee (EESC) endorsed smart shipping and multimodal transportation, emphasizing the need for inland waterway transportation to be maintained and developed [11]. Furthermore, as compared to other modes, inland waterway transport (IWT) is acknowledged as being energy-efficient, having a big freight capacity, and a lower level of greenhouse gas emissions. Consequently, IWT supports the 2030 Agenda's Sustainable Development Goals (SDGs) for Sustainable Transport to be achieved. Szymanski opined that nonetheless, transportation sustainability assessments must consider environmental, social, and economic factors [12].

It is clear that scholars researched literature and investigated facts about river morphology, socioeconomic roles, cultural effects, and environmental implications. In addition, various studies on river morphology have been conducted, including sinuosity, planform change, river shifting, banklines shifting, the use of geographic information systems and methodologies, spatiotemporal studies of river plan change using time series analysis, and so on. Among these literatures are: a review and outlook of river morphology expression by [13]. The study asserted that river is a crucial component of the global water and energy cycle [14] which morphology has been changing frequently over the last few decades due to human activities (anthropogenic factors) and weather conditions (climate change) [15]. The study focused on summarizing existing data and methods of river morphological expression in various disciplines; analyzing the main challenges and limitations faced by various river morphological expression models and methods. Thereafter, the study proposed future directions of the river for a detailed understanding of river morphology in the study area.

Ahmad conducted research on the Rapti River basin in India utilizing remote sensing and GIS techniques. His findings revealed that rivers with considerable seasonal variations in discharge and sediment loads underwent major morphological alterations [16]. The investigation also revealed significant losses as a result of the river's channel shifting as cultivated and expensive agricultural land eroded. Sediment deposition and erosion in and along the river channel had a significant impact on the river's cross-section, gradient, sediment transport rate, and discharge; however, understanding changes in river morphology is critical for engineering project planning, design, and execution. His research found that the river's behavior generated major changes in the river's bank lines, sinuosity, and depth fluctuation.

Dewan used geospatial tools to quantify channel parameters in two key reaches of Bangladesh's Ganges system during a 38-year period [17]. They also considered the Ganges and Padma rivers' bank line shifts, their nature and extent, and assessed the amount and location of erosion and deposition in the river channel. The analysis found that the river contracted and expanded, as well as changed its plan form. Furthermore, an examination of left and right bank movement revealed that each bank has distinct stretches with high and low movement [17]. Schwenk studied changes in the plan form of a river with vivid meandering features at high spatiotemporal resolution [18]. The study used Landsat imagery, and the findings provided a foundation for determining controlling factors influencing local planform changes and contextualizing them within a broader context. The study used the RivMAP toolkit, which provides easy, easily customisable, and parallelizable Matlab scripts for evaluating meandering river masks produced from satellite images and aerial photography. Estimates of uncertainty associated with categorizing and compositing Landsat data were used to generate useful annual morphodynamic information on big rivers [18]. Yu et.al established in their study a weighted usable area curve to identify inflection points and maximum values in determining the ecological flow under different sinuosities in Nansha River, Beijing. The study clarified the relationship between sinuosity and ecological flow [19]. This study reviews the related studies to unveil fundamental understanding about the dynamic of sinuosity and its associated morphological influence on riverways.

4 Methods

Morphological investigation was carried out on a section of the river reaches of River Oluwa from Igbokoda town through Legha, Mahin/Ugbonla to Idiogba/Ayetoro and Eruna-Ero waterways. This river segment was selected being the busiest inland waterway route serving as a major means of connectivity and accessibility by passengers and freight movement for many remote communities to Igbokoda (the commercial hub) in the local government area. The river segment was demarcated into reaches and sub-reaches for detailed morphological analysis.

The study adopted geospatial techniques to conduct spatiotemporal analysis of the river plan changes. Temporal scope of the study spanned between 1972 and 2022. The study explored satellite data and GIS Techniques for this purpose. Map data for river planforms between year 1972 and 2022 were collated, assessed and analysed using ArcGIS and Automated Computer Aided Techniques. Satellite data captured and used for the study include Landsat MSS TM 1972, Landsat ETM+ 1984, 2002, 2012, and 2022 Imageries. The satellite data were compared in the 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 waterbodies and river bank line class are primarily emphasised in the study. The meandering sections of the waterway were taken into consideration. This approach was considered suitable and appropriate to identify directions of meander movement and erosion using the average meander length and meandering centroids.

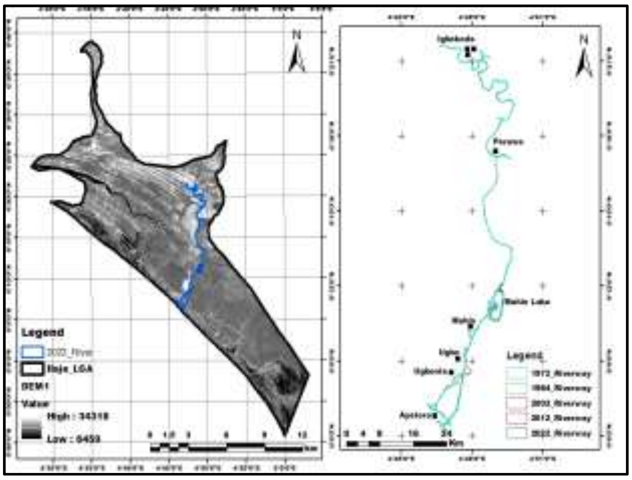


Fig. 3: River plan form of the study area
Source: Author, 2023

The sinuosity index was deployed for the study to identify the extent of curvatures and determine the sinuous state of the reaches under study. This is in agreement with [20], the sinuosity index can be utilised in defining the detailed types of the river channel such as the straight, sinuous, meandering, and extremely meandering channels [20] Sinuosity Index formula is depicted in Fig. 4 as described by Leopold, Wolman, & Miller (1964) and as follows:

$$SI = \frac{\text{Thalweg length}}{\text{Valley length}} \ldots\ldots\ldots\ldots\ldots (1)$$

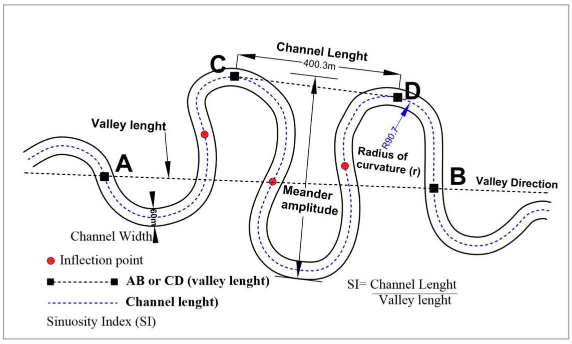
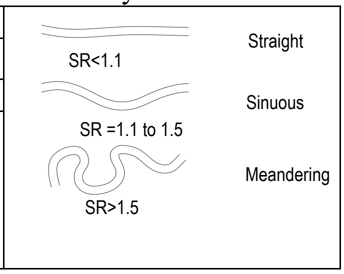


Fig. 4: Typical Shape of Channel Sinuosity between the end points of the curve.
Source: [21]

Sinuosity is a measure of how much a river (or other linear feature) deviates from being straight. It describes the curvature state of a river channel. As shown in table 1, a truly straight river has a sinuosity of 1; as the number of meanders increases, sinuosity approaches [22]. The Ratio of the sinuosity index indicates how the curvature of the river channel can be by measuring the length of the reach (a section) of river channel and dividing by the straight-line distance along the valley [23]. See Table 1.

Table 1: Classification of Sinuosity Index

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



Source: [23]

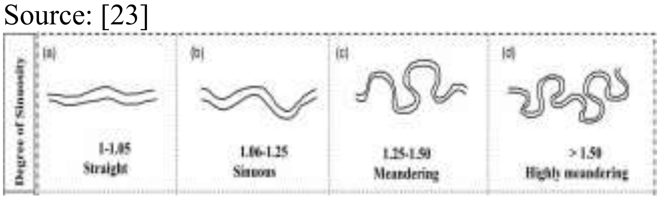


Fig. 5: Definition of channel morphology based on feature parameters
Source: [24], [13]

Besides, sinuosity is a measure of how much a river (or other linear feature) deviates from being straight. According to [24], the sinuosity index is measured as channel length along the thalweg (a line drawn through the deepest points of successive cross-sections along the length of the channel, divided by valley length. It describes the curvature state of a river channel regarding its navigability. It is expected that this study will give information on the areas that are safe for navigation or susceptible to accidents such as collision, grounding and ramming into submerged objects by watercraft or vessel.

5 Results and Discussion

A morphological survey was conducted on selected reaches (sections) of the Oluwa River, which is the distributary of River Oluwa (Ugbonla-Ayetoro/Idiogba river channel). The results obtained from the investigation represent a fractional condition of the river and its influence on inland transportation in Ilaje Local government area. The study addressed change analysis of river plan form (channel patterns), and river banklines (shorelines) with emphasis on river sinuosity; its effects on inland transport were addressed in the study area.

5.1 Changing Pattern of Sinuosity Index (SI)

The section of the river channel from Igbokoda-Ayetoro/Idiogba was divided into four (4) Reaches A, B, C and D, for detailed analysis; while subdivisions into sub-reaches were done given a total number of forty-six (46) sub-reaches. Findings revealed that the channel patterns exhibit configurations such as straight, sinuous, meandering and braiding. These configurations are best described by sinuosity which is the ratio of channel length to valley length or the ratio of valley slope or channel gradient as measured over the same length of valley.

Table 2 shows that there were significant changes in the sinuous of the river sections from Igbokoda to Ayetoro/Idiogba over the period of 50 years. The waterway channel exhibited some erosion and deposition processes causing such significant changes in its shapes and curves. The intensity of these curves was determined using the channel sinuosity index. Channel sinuosity is calculated by dividing the length of the stream channel by the valley length (straight line distance) between the endpoints of the selected channel reach. See Fig.4.

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

River Channel		1972		2022		1972	2022	Index variations	Channel length variation	Valley length variation
	SINUOSITY	Channel Length	Valley Length	Channel Length	Valley Length	INDEX S = Lc/Lv	INDEX S = Lc/Lv			
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
REACH B	SRH 1-4	4418.62	2714.4	4397.32	2714.4	1.6278	1.6200	-0.0078	-21.3	0
	SRH 5-8	4103.18	3838.2	4110.95	3838.2	1.0690	1.0711	0.0020	7.77	0
REACH C	SRH 1-3	3100.14	2816.2	3082.47	2816.2	1.1008	1.0945	-0.0063	-17.67	0
	SRH 4-8	5108.12	4818.1	5072.33	4818.1	1.0602	1.0528	-0.0074	-35.79	0
REACH D	SRH 1-4	4476.78	4018.5	4524.72	4018.5	1.1140	1.1260	0.0120	47.94	0
	SRH 5-9	4363.7	4037.7	4345.41	4071.96	1.0807	1.0672	-0.0136	-18.29	34.26
	SRH 10-11	2035.41	2166.1	2048.1	2199.88	0.9397	0.9310	-0.0087	12.69	33.78
	SRH 12-14	3152.84	3004.7	3104.64	3004.7	1.0493	1.0333	-0.0160	-48.2	0
Average Channel length		Total Channel Length								
REACH A= 448.96m		1972 Channel Length= 48,577.79m (48.58km)								
REACH B= -13.53m		2022 Channel Length = 48,953.9m (48.95km)								
REACH C=-53.46m		Channel Extension = 376.11m (0.376km)								
REACH D= -5.86m		S = Sinuosity Index; Lc= Length of channel; Lv = Valley Length								

Source: Author, 2024

The sinuosity index is mathematically expressed as:

$$SI = \frac{Lc}{Lv}$$

that is: $SI = \frac{\text{Channel length}}{\text{Valley length}}$ where, SI is Sinuosity Index; Lc is channel length and Lv is the Valley length

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-Ayetoro/Idiogba waterway. Table 2 and Fig.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.

According to [13], sinuosity greater than 1.5 is highly meandering. This is the section of river reaches that traverse Igbokoda through Kajola to Ebute Ipare. Sub-reaches 1-4 had a sinuosity index of 1.5842, SRH 6-10 recorded 2.0922 indices, 2.7290 was estimated for SRH 9-12 and SRH 11-13 had a 1.9031 sinuosity index value. All of these sub-reaches are found in Reach A and can be referred to as highly meandering channel. This is in agreement with [25] asserting that highly meandering channels have a sinuosity index value exceeding 1.50 (see Fig.5). The ending section of Reach A is constituted by SRH14 and SRH15 which connects Ebute-Ipare remained relatively sinuous with 1.166 and 1.168 index values. However, the consequential effects of this change included channel extension and channel stretching.

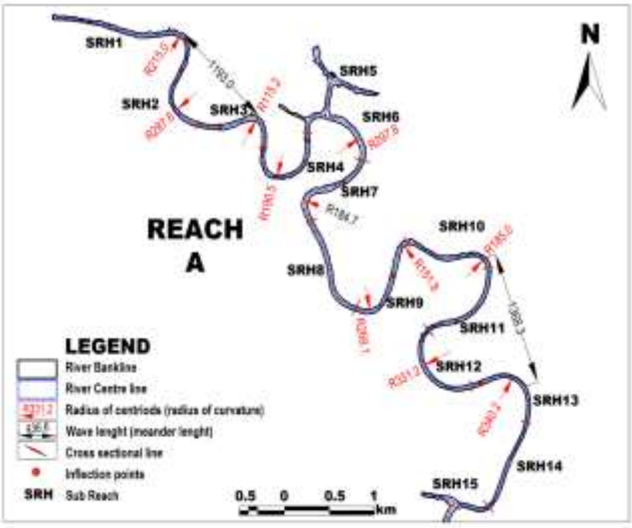


Fig. 6: Planform view of Meandering section of the river reach A
Source: Author, 2024

Findings revealed that the river channel extended in length. 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 river sections, which include Reach A, B, C, and D, extended (stretched) by 448.96 metres over a 50-year period (1972-2022); however, this is owing to changes in the course of the river channel caused by river flow and erosion. The meandering part of the Igbokoda-Ayetoro/Idiogba canal is distinguished by shifting positions, as it exhibits a snakelike shape with meandering rivers flowing through its valley, eroding sideways and slightly downstream. Table 2 shows the changes in valley and channel lengths based on the selected reaches.

Investigation of river velocity at river bends indicated that the river flow moved sideways because the maximum velocity of the stream shifted to the outside of the bend, causing erosion of the outer bank. Simultaneously, the lower stream on the inner bend of the meander causes silt deposition. Thus, by eroding its outer bank and depositing material along its inner bank, the river moves sideways without affecting its channel size. However, the channel length (distance) varies as the stream flows faster through its protrusion force around these curves and causes the channel to increase in length. (see Fig.7). This was supported by [26] Writer (2020) that as meanders grow by extension, the channel length increases.

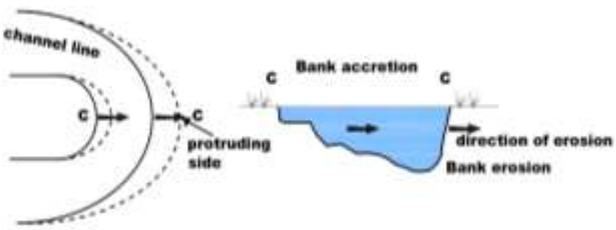


Fig. 7: Action of river flow at river's inner and outer bends
Source: Author, 2024

As a general rule, a river's current flows fastest where the channel is deepest and there are fewest obstructions. When a riverbed contains a meander, the water moves in what is known as a helicoidal flow. In a helicoidal flow the main current corkscrews from one side of the river to the other, creating more erosion and carving out a deeper channel on the outside of the meander. River reach B was sectionalized into 4 sub-reaches 1, 2, 3 and 4. It traverses Negboro, Kurawe to Ibila on meandering lanes with a sinuosity index value of 1.62. Other reaches studied include Reach C and Reach D which showed a clear straight index value of less than 1.1. This observation is traceable to the dredging and channelization project carried out in 2011 by OSOPADEC and NDDC on the section of the river along the Ugbonla to Ayetoro/Idiogba waterway

Conclusively, it is noteworthy that between 1972 and 2022, the Igbokoda-Ayetoro-Idiogba river channel exhibited meander-sinuous and straight configurations within sinuosity parameters of less than 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 especially at the meandering sections specifically Reach A (see Fig.6). For instance, in 1972, Reach D sub-reaches 1-4 was on the straight index value of 1.05 (below 1.1); but as at 2022, its morphological status changed to sinuous with a 1.13 increase in the sinuosity index value (above 1.1 Straight threshold index value). At Reach A, sinuosity parameter is relatively high compared to Reaches B, C and D. Besides, between 1972 and 2022, the sinuosity parameters seemed to be negative, very low and having a proportional decrease in sinuosity as shown in Table 2. This subtle drop in the sinuosity index of these reaches is an indication of the impact of inland waterway dredging and channelization projects done in the river channel in 2011.

5.2 Changing Pattern of Sinuosity and Inland Transport in the Study Area

5.2.1 Increased Travel Distance and Operating cost:

Findings revealed that the length of the river channel extended by a distance of 448.98metres. As of 1972, the travel distance on the waterway from Igbokoda to Ayetoro/Idiogba region was 48,577.79m (48.58km); in 2022, the travel distance is estimated as 48,953.9m (48.95km). Fig.8 depicts both negative and positive fluctuations in values of the channel lengths of 1972 and 2022 river planforms. The positive values connote channel length extension, while the negative values show channel length reduction. The positive variations are apparent in Reach A (SRH 1-4, SRH 6-10, SRH 9-12 and SRH 11-13), Reach D (SRH 1-4 and SRH 10-11). The analysis showed that the river channel extended in length by 448.96m (0.449km) over the period of 50 years. However, this has direct negative effects on travel distance and operating cost of transport particularly fuel energy consumed. A Theory states that 'the longer the travel distance, the fuel consumption and the higher the operating cost to travel' [27]. 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) [27] (Sivak, 2013). 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).

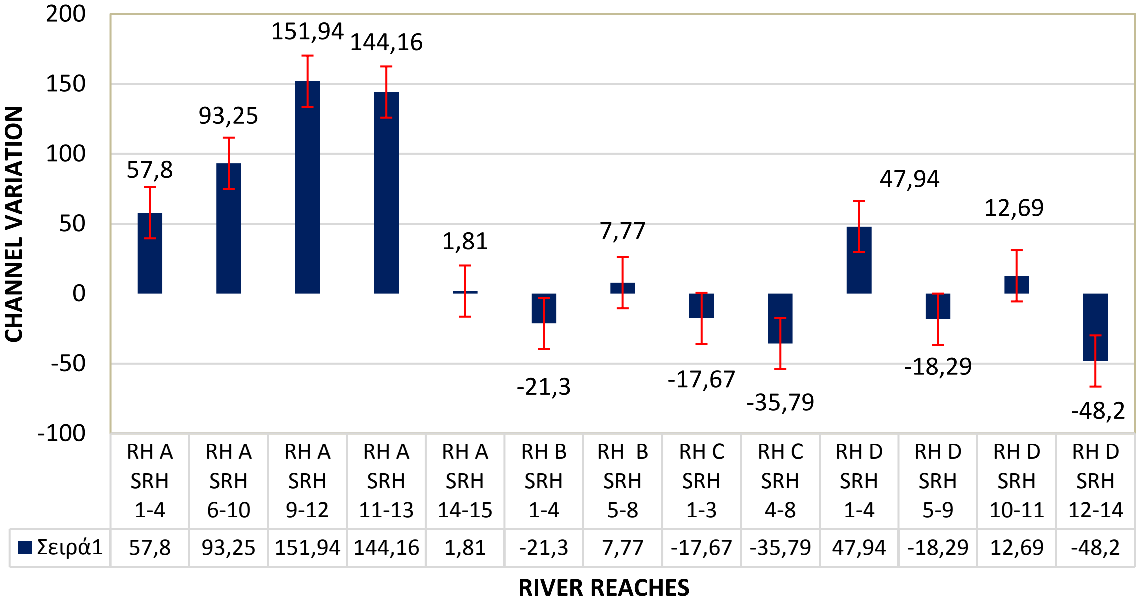


Fig. 8: Standard Error of the Channel Length variations of 1972 and 2022 river planforms
Source: Authors, 2024

5.2.2 Increase Cases of Grounding or Ramming

The navigability of a riverway usually becomes more uncertain particularly on the meandering sections due to the degree of depositions on its convex banks and erosion corkscrewing the concave banks. Because of the structure of the riverbeds, the water continues to exaggerate the differences in depths between the inside and outside of the meander. This makes these parts of the channel unsafe for navigation; watercrafts become susceptible to accidents such as collision, grounding and ramming into submerged objects. Fig.9 shows potential accident-prone spots on the meandering lanes in the waterway. A boat accident that occurred at Osumaga, Ilaje in 2002 was attributed to collision and ramming against a larger wooden watercraft. The accident claimed the lives of 12 passengers; though, 45 adults and 35 children were rescued. According to Wilzbach and Cummins, sinuosity index is measured as channel length along the thalweg (a line drawn through the deepest points of successive cross-sections along the length of the channel, divided by valley length [25]. The safest path for vessel passage is the Thalweg line in the river channel as shown in Fig.9. Most of the boat operators in the study area rely on their pre-knowledge in identifying safer paths in red dotted line (Thalweg line positions) on riverways; this is not safe enough for vessel navigations as the channel bed levels and Thalweg line positions at river bends exhibit continuous change over time. Kastrisios and Ware asserted that the need for constant updates of bathymetric data and production of nautical charts becomes more prominent in contemporary maritime navigation with the increasing sizes of watercrafts that operate in tighter or narrower spaces or waterway channels [28].

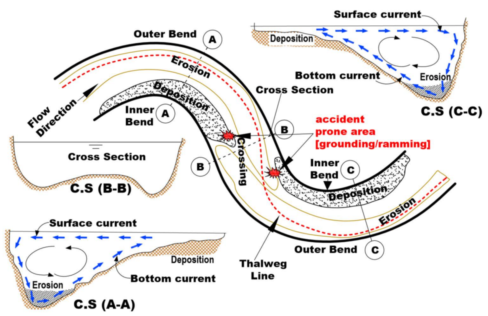


Fig. 9. Cross Section Formations at River Curvatures
Source: [29]; [30] adapted by Author, 2024

As shown in Fig.9, cross-sections A-A and C-C revealed actions of bottom and surface currents on erosion and deposition of sediments in the river reaches, while cross-section B-B shows a passage free for safe navigation. Identifying recurrent changes in morphology of river is necessary in the production of nautical charts for save ferry/vessel navigation.

5.2.3 Increased Difficulty in Manoeuvring

Findings revealed that several curvatures are found in-between reach A (Igbokoda -Perawe waterway corridor). Reach A had an increased river curvature with a sinuosity index above 1.5; this part of the river is highly meandering. The greater the degree of sinuosity index of the meandering waterway, the wider is the angle of deflection and the more vulnerable vessels are to collision against the river banks or with another vessel. Minimum speed is expected at river curvatures for vessels in transit to manoeuvre on their lanes. Boats operator are encouraged to reduce speed at bends to avoid collisions either against the river banks or other vessels on the water. The observed bends (river curvatures) as indicated in Fig. 10 require more precise manoeuvring, as there is less room for error due to the narrowness of the channel. The average channel width of the Igbokoda-Ayetoro waterway is been estimated as 50metres for two-way manoeuvring lanes. This can be challenging for larger vessels or those with limited manoeuvrability particularly when the river curvature is narrow. Fig. 10 shows the typical manoeuvrability positions of watercraft in opposite directions at the curvature of the waterway channel. It indicates that the difficult situation of narrow width is more pronounced at channel bends or curvatures as vessels tend to sway sidewards (at swept path zone) on the manoeuvring lane before adjusting back on the straight.

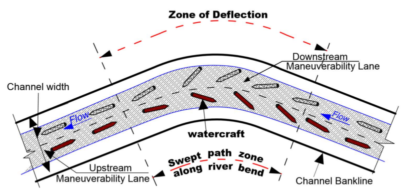


Fig. 10: Typical manoeuvrability positions of watercrafts in opposite directions at river curvature (bends) - (swept path zone); Source: Adapted from [30].

5.2.4 Slower Speeds and Increased Travel Time

Boat speed can be determined by various factors, including the river's width, depth, curvatures, current, and the presence of obstacles such as rocks, sandbars, or other boats. Travel time between Igbokoda and Ayetoro increased due to the channel extension and increase in the angle of deflection in some reaches of the waterway channel. Narrower and bend sections of the reaches require vessels (watercraft) in transit to slow down, as there is less sight distance (visibility) and less room for two vessels (watercraft) on the two-way manoeuvring lanes to manoeuvre; hence high risk of collisions. This usually leads to increased travel times and reduced efficiency. Taking cognizance of speed and minimum sight distance, Benetou and Tate asserted that the operating speeds are considerably lower at locations where the minimum sight distances are below 250 feet (76.2m) than at locations where the lowest sight distances are greater than 500 feet (152.4m). [30], [31]. The radius of the curve and the angle of deflection are directly related to visibility or sight distance and the speed of vehicle on curvatures. Hence, the minimum permissible boat speed on a meandering riverway needs to be ensured, considered and adhered to by boaters because a slower speed will give the boat driver enough time to sight and avoid unwanted collisions against opposite objects or obstacles. Minimum permissible boat speed refers to the lowest speed at which a boat can safely navigate a river that has bends or curves. It is set to ensure that watercraft can safely navigate the river or at its bends without causing damage to the environment or posing a risk to other boaters.

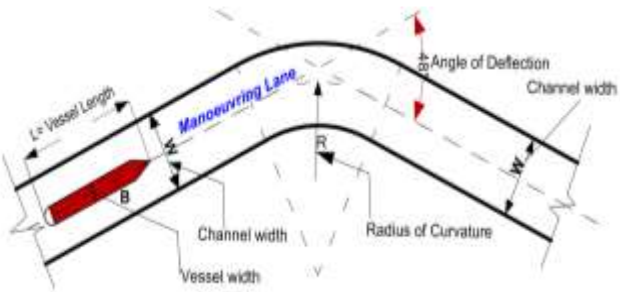


Fig. 11: Illustration of the Angle of Deflection and vessel's manoeuvrability at river curvature
Source: Author, 2024

6 Conclusion

The study revealed banklines shifting, channel elongations, an increase in deflection angles at river curvatures/bends and the potential depth variability in the river beds at bends. All of these occurrences had resultant effects on inland transportation and its users in the form of increased travel time, distance and difficulty in watercraft manoeuvres in the river reaches. The results of the sinuosity index showed the effects of aggradation at inner bends and degradation at outer bends in the reaches during different flow conditions of the river. These caused variations in the channel patterns as there are observed differences in sinuosity indexes. Reach A (SRH 1-13) reveals the more unsafe conditions of accidents/incidents such as grounding, ramming, collision and likely flood hazards as it exhibited the sinuosity index between 1.58, 2.09, 2.73 and 1.90 in 2022. Sub-reach (SRH) 6-10 with a sinuosity index of 2.09 and SRH 9-12 with a sinuosity index of 2.73 are highly vulnerable sites to flood. The study recommends frequent monitoring of the deposition of transported materials particularly along the river curvatures in order to ensure manoeuvring lanes that are safe and efficient for vessel navigation. It is believed that identifying recurrent changes in the morphology of waterways (riverways) is essential for inland waterway planning and the production of nautical charts for safe and efficient inland transport. The study gives an insight into further studies towards assessing channel resilience to floods, straight channel bankline migrations, determination of sediments transported and discharge at different locations per period of time, a medium for predicting the extent of erosion and curvatures overtime, as well as assessing uncertainties in the thalweg lines of the waterway channel using Remote sensing and high tech-bathymetric techniques.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Babatope Sunday Olisa carried out field and collaborate with Stephens and Njoku to develop the procedures used in carrying out the field study. He did all typesetting and formatting of the document.
Mobolaji Stephen, Stephens is the major supervisor of the study. He monitored and carried field records, statistics and computations of sinuosity indices as well as plotting charts.
Ikpechukwu. Njoku is the co-supervisor who coordinated the field study and operated on the instrument used.
Chiamaka Lovelyn Olisa carried out geospatial analysis using ArcGIS and Computer aided techniques.

In summary, everyone contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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