The Channel Migration of Inland Waterway Channels in Ilaje, Ondo State, Nigeria

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Abstract:- The channel migration or shifting of navigable river channels have been an issue of major concern, as their effects on the transport environment, channel corridors, the manoeuvrability of vessels transiting these channels and vessels navigation amongst other factors result to inefficiency in inland transport in the riverine region of Ilaje, Nigeria. Most navigational and operational challenges have been attributable to alterations in the waterway channel due to aggradation and degradation processes in the river regime. The study's goal is to explore channel migration along the Igbokoda-Ayetoro waterway with a view to provide mitigation methods to address potential difficulties along the waterway channel and in the adjoining environment. The objectives of the study include gathering satellite imagery of the study area between 1972 and 2022; assessing the morphological planforms of the study river channel, and assessing the river channel's effective width using the segment-transect method. The study considered channel width, depth and alignment as indicators to be carefully evaluated to ensure safe, sustainable and efficient inland navigation measures. To ascertain the shapes and forms of the channel during the study period, geospatial and computer-aided techniques were used. Channel widths were extracted using the Segment-Transect method at 100-meter intervals. 50 year and 100-year estimate of the extent of channel/banklines shifting were determined. According to the study, there are changes in the channel's width, depth and planform (alignment) that make the waterway indeterminate and unsuitable for vessels transiting on two-way manoeuvrability lanes. Hence, the study recommended the sustainable mitigation strategies to tackle the potential challenges pose by channel migration and reduce its impact on the vessel manoeuvrability, navigation and the adjoining environment.

Key-Words: - channel, migration, waterway, river, manoeuvrability, transport, environment, navigation

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1 Introduction

The changing patterns of inland waterways remain one of the consequential effects of river migration. River migration is a process of river movement in which the water flow to erode the river outer bank and the sediments are deposited on the opposite site of inner bank causing a gradual shift in the river's course overtime [1]. However, a geo morphological phenomenon is the lateral migration of an alluvial river channel across its catchment areas or floodplain. The progressive point bar deposition and bank erosion are the primary driving force behind this process. Occasionally, cases are reported in which properties, agricultural land, transportation infrastructure are damaged, banks of rivers collapse, riverways become impassable or difficult to navigate. Some degrees of tangible loss are inevitably and result in damages, losses to the economy, and fatalities. As reiterated by [1], rivers naturally migrate through their floodplains, and occasionally banklines erode. This causes problems that eventually affect inland waterway transportation, nearby properties, residents of flood plains, and organizations that plan or maintain waterway infrastructure. [1]. Igbokoda-Ayetoro inland waterway is a distributary of Oluwa River that flows down south of the riverine area of Ilaje, Ondo state, Nigeria and empties its volume of water in the Atlantic Ocean. In a river network, channels move through two main processes which include: channel migration, and channel avulsion [2]. Meanwhile, channel migration and avulsion contribute to the channel's network shifting; but in the events of partial or failed channel avulsion, overbank flow can also alter river network. The consequences of channel migration on river channels and inland navigation are the main focus of this investigation. River depth, widths, and alignments are thought to experience some degree of variability and uncertainty due to channel migration. This tends to make the channels shallower or narrower, making it more probable that vessels will run aground while in transit and jeopardizing infrastructure and navigational aids. The purpose of the study is to assess the rate of channel migration in the Igbokoda-Ayetoro inland waterway between 1972 and 20 22 with a view to m onitoring and suggesting sustainable measures to lessen its effects on the river channel's permissible manoeuvring lanes and inland transportation. Furtherance to this, the study assessed the planforms of the study river channel between 1972 and 2022 using Geographic Information System (GIS) techniques; compute and quantify the effective width of the river channel using the Segment-transe ct method; determine the forms, distance and directions of the channel migration in the river reach (segment). Hence, extent of channel narrowness and widening and its co nsequential effects on the permissible manoeuvring lanes in the waterway is determined.

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 i n 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 withi n the tropics. It has a population of about 3,441,024 [3].

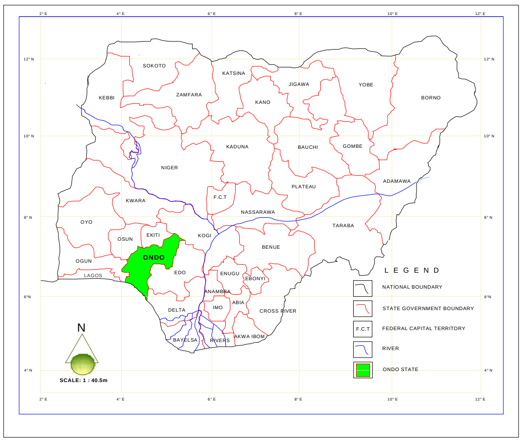


Fig. 1: Ondo State Map its National Setting
Source:[4]

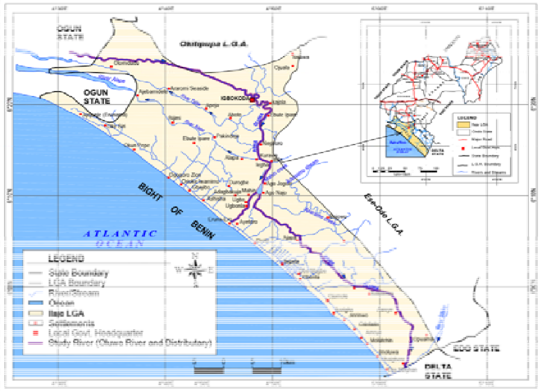


Fig. 2: The study area showing a study section of Oluwa River Network and other water bodies in Ilaje Local Government Area
Source: Adapted by the Author from [5]

The water body flows th rough inner communities from the west border to the eastern border of Ilaje LGA dissecting the local governm ent 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. This river corridor serves a s a major means of transportation for bot h freight and passengers, providing access some isolated locations within the study area. As stated by Parikesit in his studies between 2003 an d 2005, the role of river or inland water transport has become very prevalent and important, particularly when it is the onl y means of accessibility by passengers and freight movement to remote areas [6].

3 Related Reviews

River channel m igrations have been th e subject of both theoretical and experim ental investigations. Numerous insights into the dynamics of channel migration and its im pact on water transportation, ecosystems (environments), and infrastructure inside and along w ater corridors have been gained from these studies. Ielpi, for instance, highlighted that the displacement-based approach—which measures migration rates pri marily in ter ms of the displacement of channels between satellite phot os taken at various times—is a typical way to estimate migration rates. He pointed out that although the displacement's direction can be manually determined, doing so is a labor-i ntensive and subjective procedure, therefore it needs to be backed by on-site validation [7]. Other studies too k cognisance of bankline sh ifting and channel forms, shape and networks and also high lighted the difficulty of making efficient, precise measurements of migration [8]. In order to identif y the migration patterns of the Padma and Jamuna rivers, Md. Tariqul Islam conducted research on river channel migration utilizing remote sensing and GIS analysis. Migration patterns to the north, northeast, south, and southwest were observed. The river showed depositions at several points along the banklines and erosion of the riverbanks. It was also established what the Padma and Jamuna rivers' net migration was between 1977 and 2004 [9]. Besides, Yan investigated the features of migration in the Okavango Delta's several river zones. The Goole Earth and Alaska Satellite Facility were used in the study to gather satellite photos at 10-year intervals. Four factors were taken into account: curvature, deflection angles, expansion coefficient, and sinuosity index (SI), while different migration models were developed in different zones [10]. None of these studies have linked their inferences to river navigability or inland waterway navigation, effects on lives, the adjoining environment and infrastructure in and around the watersheds. It is of note that as the channel migrates, it can become narrower, making it more difficult for vessels to navigate safely due to series of sedimentation processes. In modern fluvial sedimentology, a variety of elements, including flow, bank type, intensity of flow, slope, soil texture, climate, and so on, influence how rivers evolve and take on their shapes and planforms. Nonetheless, pertinent queries about what, how, and in which directions patterns evolve are raised. It's important to consider what the migratory pattern says about the surroundings (the catchment areas), inland navigation and transportation as well as the users.

4 Methods

Geospatial and computer-aided approaches were used to examine river planforms. This was done to assess channel migration from the plan view, as illustrated in Fig. 3. The river channel was divided into reaches and subreaches to facilitate precise segment-transaction computations and morphological investigation. The study addressed the spatial and temporal breadth of a 38-year river plan adjustment. As a result, the study investigated satellite data and GIS techniques to accomplish this goal. Map data for river planforms from 1972 to 2022 were collected and evaluated using ArcGIS and Automated Computer Aided Techniques as illustrated in Fig. 7. The study used satellite data from Landsat MSS TM 1972, Landsat ETM+ 1984, 2002, 2012, and 2022.

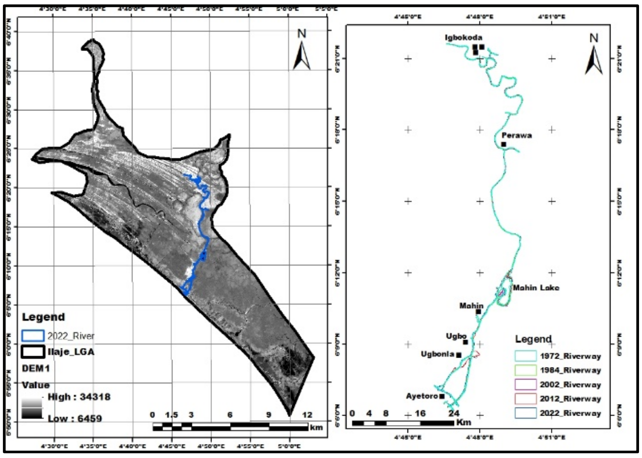


Fig. 3: River plan form of the study area
Source: Author, 2023

The satellite data were compared after classification to discover changes. Unsupervised image classification was used, which included ISO cluster unsupervised classification with an adjustable minimum class size, followed by a reclassification to identify changes in the channel line over time. Changes in river bankline class throughout time are emphasized, overlayed, and digitized (traced) for comparison analysis. The segment-transact approach was used to determine the channel widths. The width of the channel segments was calculated by the area between transects, which were spaced 100 metres apart (see Fig. 4). The segment-transact approach was thought to be ideal for calculating the effective widths of the river channel as well as variations in channel width over time.

Fig. 4 showed the segment-transect method used to calculate the average river width according to selected reaches and sub reaches. The segment extent was determined as the area between transects at interval of 100metres spacing. The sum total of width measured was generated across the study river channels using computer aided techniques.

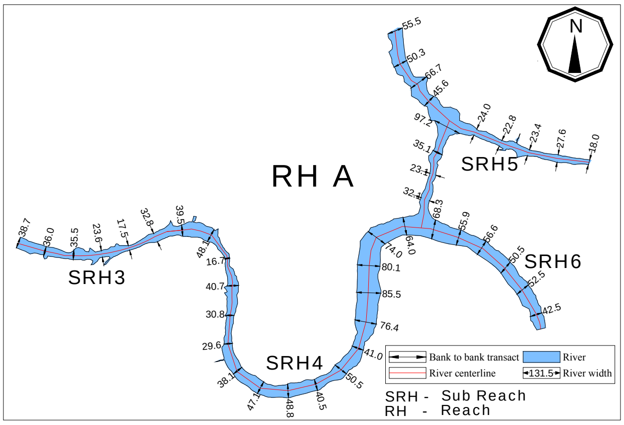


Fig. 4: Illustration of the Segment -transect method used to calc ulate the eff ective width of the river channel.
Source: Author, 2023
Note: the segment extent i s determined as the area between transects and it is shown a t spacing of 100metres

The centroid technique was used to d etermine the directions of the channel movement or shifting erosion, especially in meandering sections. The centroid of an object or region can be used to determine channel movements. The centroid is the object's weighted average location, which can be followed over time to detect channel movement and predict the rate and extent of channel migration, especially in meandering sections. To determine the channel shifts and directions of t he bankline shifts, the banklines of each histo ric planform were traced, and successive circles were best-fit to the outer bank of each bend to define the average bankline arcs, the bend's radius of curvature (RC), and the bend centroid positions. (See Fig. 5). The number of circles required to define the bend is based on the loop classification such as co mpound symmetrical, compound asymmetrical, simple symmetrical, and simple asymmetrical as propounded by Brice [11]

The radius of curvature and centroid p osition of the circle were used to describe the bend and compare it to bend measurements from previous y ears under study. These observations were utilized to estimate migration rates and predict future channel/bend migration features, which is consist ent with t he NCHRP study in [12]. As a result, th e distance it traveled between 1972 and 2022 and the bend centroid's position in 2072 (50 years) were calculated by multiplying the yearly rate of centroid movement for the period 197 2-2022 by 50 and calculating the distance between the centroids. Thus, the 50-y ear distance was plotted along a line beginning at t he 2022 centroid point and extending in the direction given by the 1972 to 2022 migration vector drafted using computer aided tech nique. By calculating the rate of change of the bend radius from 1972 to 2022 as a percenta ge with respect to the 2022 radius and multiplying the result by 50 y ears (from 2022 to 2072), the radius of curvature of the bend in 2072 was determined. The expected location and radius of the bend in 2072 were p lotted by centering the 2072 circle with the calculated radius figure on the centroid's forecast location.

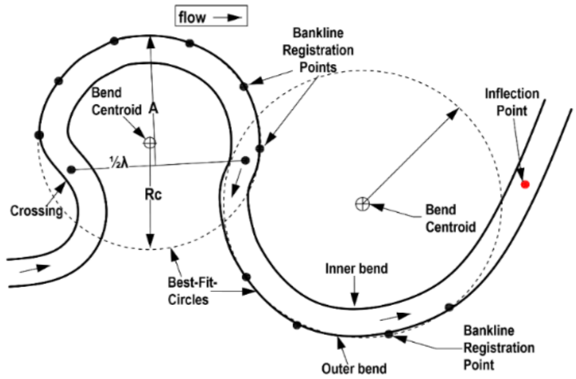


Fig. 5: Bend measurements using centroid and best-fit circles for the study
Source: Authors, 2023

5 Results and Discussions

As illustrated in Fig. 6, Reach A of the riverway is a meandering portion that runs between Igbokoda and Legha. It could be described as the cur ving shape of a meander. However, for more extensive study, reach A is sub-divided into 15 sub-reaches. This section discusses the morphological progressions that happened in each sub-reach. The river channel is characterized by moving water that continuously erodes the o uter bank an d widens val leys, deposits carried sediments, and narrows its channels at various locations, resulting in significant modifications over time.

The analysis found that R each A's gen eral river channel planform is a well-defined meander. Reach B is relatively sinuous in shapes. The middle part of the river channel (reach B) between Perawe and Mahin is configured as straight. Also, River Reach C is relatively straight; while River reach Dplanform is also a straight-shaped riverway with braided channel at Oropo Lagoon (Mahin Lake). Other parts of Reach D at Ay etoro downstream to the Atlantic Ocean where it empties its volume of water into the ocean are straight channel.

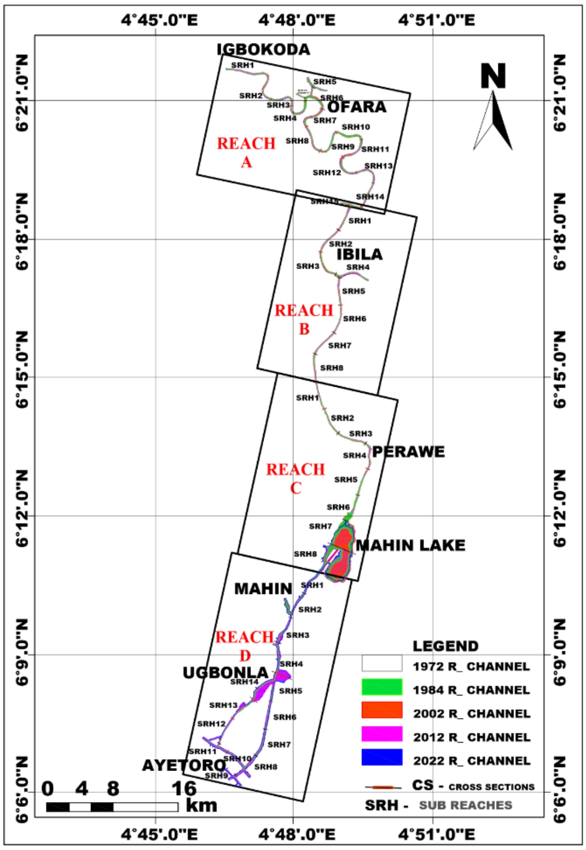


Fig. 6: Igbokoda-Ayotoro waterway channel into reaches and subreaches.
Source: Authors, 2023

The results revealed that the mean average width of the river channel at Reach A reduced from 35.39m in 1972 to 33.19m in 1984. The river channel increased in 2002 to 36.29m; it became wider in 2012 as 43.51m. In the year 2022, results revealed that there was a decrease in the river width to 42.72m as shown in Table 1. The rate of narrowness between 1972 and 1984 was principally as low as -2.2m. The river width increased by width average of 3.11m between 1984-2002; that is, between the period of 18years, 3.11m river widening distance was observed. These statistics showed that the river exhibited significant changes in its channel width (either narrower or wider). Comparing the initial year and the absolute year (1972 and 2022) data, study disclosed that, the river reach A became widened by 7.33m; that is, from 35.3m in 1972 to 42.72m in 2022.

In Reach B, results showed that there was a continuous river widening from 1972 to 2022. In 1972, the mean average of the river channel width was estimated as 23.88m; in 1984, the river channel width increased to 24.58m; the widening continued in 2002 and 2012 to 34.56m and 43.33m wider. Hence, in 2022, there was a narrowness in the river channel width as the mean average reduced by 3.31m wide to 39.98m. Findings revealed that Reach C exhibits two classes of common alluvial rivers such as braiding, and straight. The result indicated high rate of erosion and deposition of sediments from the upper stream zone particularly into Oropo Lagoon (Mahin Lake). The river channel width in this section is relatively wide and deep. As shown in Tables 1 and 2, In 1972, the mean average width of SRH8 was 104.4m wide, but increased by 4.08 m to 108.48m in 1984.

In 2002, the river widening processes continued to 212.5m along its downstream channel. This expansion can be attributable to abrasion, hydraulic action and solution having a substantial effect on the river bed and banks, deepening and widening the river. When forces of water flows against the river banks, either the saturated river bank soils or weak river bank constituents are eroded and transported as sediment along the flow of river water. This is in agreement with Annayat et.al. 2022 asserting that sedimentation process in rivers is the main source of erosion in alluvial rivers [13]. This phenomenon in a river system is called hydraulic action which is an important factor contributing to what happened in Reach C. Softer sections of the river bank may sometimes become over saturated and slumps into the river causing width expansion. According to [14], River widening is a lateral expansion of the channel. It is characterised by critical process that maintains fluvial ecosystems and is part of the regular functioning of rivers.

Results revealed that the river width at Reach A reduced; as mean average value estimated for 2012 indicated a negative difference as 196.69m lower than the previous year (2002). Also, between 2012 and 2022, the mean average value of the river width estimated for 2022 was 198.84m wide indicating a decrease. Reach D is the downstream zone of the Oluwa river channel.

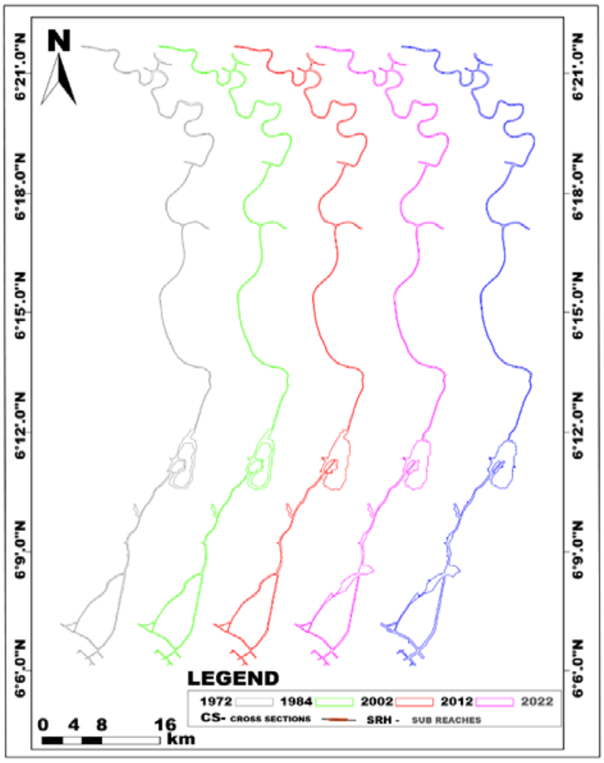


Fig. 7: Channel planforms between 1972 and 2022
Source: Authors, 2023

The reach D is characterised by high rate of sediment accumulation transported from upstream and middle stream zones as well as the mud sediments being transported from the ocean. However, this section of the river channel (reach D) is expected to experience wide river width and flattened riverbed; why? as the riverbed gradient flattens, the water's velocity decreases, this would lead to the deposition of sediments and an increase in the river's width.

However, due to constant dredging and channelization projects in the zone, the river channel width as well as the river bed and depth have been under control and management.

Table 1: River Channel Width and Surface water area of the river channel under study (Igbokoda-Ayetoro waterway)

	1972		1984		2002		2012		2022	
REACH A	AV_WIDTH (m)	SURF_A 00'(m^2)	AV_WIDTH (m)	SURF_A 00'(m^2)	AV_WIDTH (m)	SURF_A 00'(m^2)	AV_WIDTH (m)	SURF_A 00'(m^2)	AV_WIDTH (m)	SURF_A 00'(m^2)
SRH1	45	450	46.5	465	49.3	493	65.8	658	61.2	612
SRH2	29.2	292	26.5	265	33.5	335	47.4	474	38.6	386
SRH3	32.8	328	26.4	264	29.7	297	39.9	399	45.7	457
SRH4	48	480	41.4	414	37.9	379	47.8	478	42.2	422
SRH5	47.4	474	36.6	366	38.4	384	36.7	367	43.1	431
SRH6	53.9	539	64.4	644	69.9	699	69.3	693	69.7	697
SRH6 Extension	6.6	66	8.7	87	8.9	89	8.1	81	7.3	73
SRH7	31.7	317	37.3	373	48	480	54.4	544	51.8	518
SRH8	33.2	332	30.9	309	41.3	413	51.6	516	51	510
SRH9	38.2	382	35.6	356	33.6	336	45.6	456	46.4	464
SRH10	62.2	622	45.5	455	46.2	462	41.7	417	40.4	404
SRH11	29.2	292	27.7	277	31.3	313	42.8	428	41.9	419
SRH12	34.4	344	33.6	336	39.4	394	39.4	394	40.5	405
SRH13	29.7	297	27.2	272	21.7	217	40.7	407	39.3	393
SRH14	24.7	247	19.7	197	25.5	255	36.5	365	34.6	346
SRH15	20.1	201	23	230	26.1	261	28.5	285	29.8	298
Mean Average	35.39	350.23	33.19	331.88	36.29	362.94	43.51	435.13	42.72	427.19
REACH B										
SRH1	21.9	219	21	210	34.3	343	39.9	399	41.8	418
SRH2	25.4	254	19.3	193	34.1	341	45.6	456	38.5	385
SRH3	29.6	296	35.3	353	41.4	414	45.1	451	45.1	451
SRH4	37.3	373	38.2	382	42.3	423	57.6	576	58.8	588
SRH5	18.1	181	20.4	204	36.2	362	41.7	417	39.8	398
SRH6	17.4	174	21.3	213	27.9	279	34.7	347	29	290
SRH7	20.4	204	19.7	197	29	290	40.5	405	31.7	317
SRH8	20.9	209	21.4	214	31.3	313	41.3	413	35.2	352
Mean Average	23.88	238.75	24.58	245.75	34.568	345.63	43.3	433	39.99	399.88

REACH C										
SRH1	22.2	222	18.4	184	27.1	271	31.2	312	28.7	287
SRH2	22.9	229	24.4	244	33.8	338	35.3	353	32.6	326
SRH3	24.1	241	25.9	259	31.8	318	42.8	428	39.1	391
SRH4	22	220	14.8	148	24.5	245	41.8	418	35.2	352
SRH5	23.8	238	35.6	356	25.4	254	39.4	394	24.3	243
SRH6	71.3	713	88.3	883	83.9	839	41.5	415	30.3	303
SRH7[Oropo]	255.4	2554	266 2660		635.5	6355	546.7	5467	532.8	5328
SRH8[Oropo]	393.5	3935	394.4	3944	838	8380	794.8	7948	867.7	8677
Mean Average	104.4	1044	108.48	1084.75	212.5	2125	196.69	1966.88	198.84	1988.38
REACH D										
SRH1	40.3	403	33.2	332	52.6	526	51.6	516	59.1	591
SRH2	82.5	825	83.4	834	109.6	1096	105	1050	120.8	1208
SRH3	37.5	375	34	340	32.6	326	78.4	784	86.6	866
SRH4	52.7	527	54.9	549	63.4	634	159.2	1592	176	1760
SRH5	49.3	493	49.8	498	46.3	463	118.9	1189	157	1570
SRH6	45.1	451	48.6	486	34.7	347	44.5	445	63.7	637
SRH7	43.7	437	42.4	424	43.9	439	50.2	502	74.7	747
SRH8	33.7	337	33.3	333	29.1	291	53.5	535	87.3	873
SRH9	28.3	283	29.4	294	31.8	318	51	510	70.4	704
SRH10	38.7	387	38.9	389	40.4	404	52.7	527	85.1	851
SRH11	32.2	322	32.8	328	33.5	335	47.7	477	100.7	1007
SRH12	15.3	153	12.5	125	15.2	152	33.8	338	39.3	393
SRH13	34.9	349	34.4	344	34.9	349	77.9	779	77.5	775
SRH14	45.1	451	49.8	498	49	490	221.3	2213	236.9	2369
Mean Average	40.3	403	33.2	332	52.6	526	51.6	516	59.1	591

Source: Authors, 2023

Note: AV_WIDTH – Average width; SURF_A – Surface Area; SRH – Subreach;

Table 2: Estimate of Channel migration rates and directions of Igbokoda-Ayetoro waterway channel from 1972 to 2022

RIVER REACH	Channel Migration															
	1972-1984				1984-2002				2002-2012				2012-2022			
	SURF. AREA	Dir	Distance (m)	Migration rate m/year	SURF. AREA	Dir	Distance	Migration rate m/year	SURF. AREA	Dir	Distance (m)	Migration rate m/year	SURF. AREA	Dir	Distance (m)	Migration rate m/year
RH A																
SRH1	465	NE	2.58	0.215	493	NE	5.46	0.3033	658	S	12.71	1.271	612	NE	4.8	0.48
SRH2	265	SW	5.62	0.4683	335	SW	9.95	0.5528	474	SW	12.02	1.202	386	NE	4.16	0.416
SRH3	264	W	9.31	0.7758	297	NE	6.75	0.3750	399	SW	12.36	1.236	457	SW	6.24	0.624
SRH4	414	S	12.50	1.0417	379	S	13.15	0.7306	478	S	9.47	0.947	422	SE	6.84	0.684
SRH5	366	SW	4.76	0.3967	384	S	14.6	0.8111	367	S	11.8	1.18	431	N	12.17	1.217
SRH6	87	W	5.24	0.4367	89	N	9.45	0.5250	81	S	4.3	0.43	73	SW	12.13	1.213
Ext SRH6	644	NW	7.53	0.6275	699	NE	18.23	1.0128	693	E	6.5	0.65	697	NE	6.10	0.61
SRH7	373	SW	7.35	0.6125	480	NW	17.54	0.9744	544	W	5.53	0.553	518	SE	7.97	0.797
SRH8	309	SW	4.53	0.3775	413	S	10.52	0.5844	516	W	6.62	0.662	510	SE	4.25	0.425
SRH9	356	NW	2.73	0.2275	336	SE	11.01	0.6117	456	NW	7.76	0.776	464	SE	3.95	0.395
SRH10	455	N	20.06	1.6717	462	S	11.79	0.6550	417	SW	6.16	0.616	404	SE	5.88	0.588
SRH11	277	N	13.45	1.1208	313	SE	13.93	0.7739	428	NW	9.48	0.948	419	SE	3.94	0.394
SRH12	336	SW	11.20	0.9333	394	W	14.13	0.7850	394	W	7.21	0.721	405	SW	5.28	0.528
SRH13	272	W	7.03	0.5858	217	NE	7.37	0.4094	407	NE	16.61	1.661	393	E	5.42	0.542
SRH14	197	NW	7.46	0.6217	255	SE	5.87	0.3261	365	E	10.34	1.034	346	SE	3.59	0.359
SRH15	230	-	6.54	0.545	261	S	5.18	0.2878	285	SE	6.27	0.627	298	S	2.65	0.265
RH B																
SRH1	210	E	1.53	0.1275	343	NW	13.40	0.7444	399	W	7.69	0.769	418	SE	3.63	0.363
SRH2	193	SE	8.10	0.675	341	NW	10.29	0.5717	456	W	8.92	0.892	385	SE	4.55	0.455
SRH3	353	E	9.18	0.765	414	SW	16.28	0.9044	451	WS	7.04	0.704	451	SW	4.33	0.433
SRH4	382	SW	6.85	0.5708	423	S	7.94	0.4411	576	S	11.09	1.109	588	S	5.07	0.507
SRH5	204	SW	6.46	0.5383	362	E	9.88	0.5489	417	W	9.75	0.975	398	SE	2.17	0.217
SRH6	213	W	7.71	0.6425	279	E	6.58	0.3656	347	W	6.29	0.629	290	SE	3.03	0.303
SRH7	197	NW	4.57	0.3808	290	NW	6.90	0.3833	405	W	8.34	0.834	317	SE	3.91	0.391
SRH8	214	W	9.45	0.7875	313	W	8.45	0.4694	413	W	5.24	0.524	352	SE	4.93	0.493
RH C																
SRH1	184	NE	10.59	0.8825	271	W	7.94	0.4411	312	NE	3.56	0.356	287	SW	4.79	0.479
SRH2	244	SW	21.1	1.7583	338	SW	10.50	0.5833	353	NE	4.55	0.455	326	SW	4.03	0.403

SRH3	259	S	17.94	1.495	318	SW	8.32	0.4622	428	NE	13.05	1.305	391	SW	4.73	0.473
SRH4	148	SW	21.21	1.7675	245	SW	10.50	0.5833	418	NE	16.7	1.67	352	SE	10.76	1.076
SRH5	356	W	16.78	1.3983	254	SW	11.30	0.6278	394	NW	9.43	0.943	243	SE	13.54	1.354
SRH6	883	W	23.16	1.93	839	NW	12.94	0.7189	415	NW	15.24	1.524	303	SE	11.46	1.146
SRH7 [OROPO	2660	-	12.20	1.0167	6355	W	15.37	0.8539	5467	W	49.99	4.999	5328	SE	15.89	1.589
SRH8 [Oropo]	3944	-	15.9	1.325	8380	SE	16.36	0.9089	7948	W	33.8	3.38	8677	SE	17.74	1.774
RH D																
SRH1	332	SW	12.89	1.0742	526	W	18.64	1.0356	516	SE	5.32	0.532	591	NW	12.45	1.245
SRH2	834	W	5.78	0.4817	1096	W	15.15	0.8417	1050	SE	4.96	0.496	1208	SW	10.24	1.024
SRH3	340	W	9.52	0.7933	326	W	5.44	0.3022	784	SW	45.73	4.573	866	SW	5.87	0.587
SRH4	549	W	9.38	0.7817	634	W	10.81	0.6006	1592	E	133.9	13.39	1760	SW	6.45	0.645
SRH5	498	E	6.03	0.5025	463	W	12.62	0.7011	1189	E	140.23	14.023	1570	SW	7.50	0.75
SRH6	486	E	6.69	0.5575	347	W	17.88	0.9933	445	W	11.45	1.145	637	SW	12.31	1.231
SRH7	424	E	4.85	0.4042	439	W	7.11	0.3950	502	NW	11.18	1.118	747	SW	12.71	1.271
SRH8	333	E	3.51	0.2925	291	W	11.03	0.6128	535	NW	15.67	1.567	873	SW	15.43	1.543
SRH9	294	SW	3.29	0.27419	318	W	4.45	0.2472	510	NW	15.64	1.564	704	SW	18.66	1.866
SRH10	389	S	4.68	0.39	404	NE	5.09	0.2828	527	NW	17.25	1.725	851	SW	11.98	1.198
SRH11	328	S	4.53	0.3775	335	E	5.55	0.3083	477	NW	14.05	1.405	1007	SW	12.43	1.243
SRH12	125	S	7.01	0.58416	152	SE	4.80	0.2667	338	NW	16.98	1.698	393	SW	5.88	0.588
SRH13	344	NW	5.23	0.43583	349	SE	6.92	0.3844	779	NW	88.37	8.837	775	SW	8.51	0.851
SRH14	498	NW	10.318	0.85983	490	NW	5.76	0.3200	2213	SE	242.31	24.231	2369	SW	9.35	0.935

Source: Authors, 2023;
Note: Dir- Direction; SURF AREA- Surface Area; E-East, SW-Southwest; NE-Northeast; S-South; W-West

The outcome of waterway planning and management by Ondo State Oil Producing Area Development Commission (OSOPADEC) and Niger Celta Development Commission (NDDC) is reflected in the morphological structure of the river channel width and its depths since 2011. In Reach D, Findings disclosed that between 1972 and 2022, there were significant variations in the mean average values of the river channel width. This indicates a river widening process in the river systems. As shown in Table 1, in 1972, the mean average of the river channel width was 40.3m, but as of 2022, the river channel width was calculated as 59.1 m revealing an increase of 18.8m. Reach D has the highest range of river widening; this can be attributed to high rate of silting processes in the zone. Mud sediments from the ocean is a major contributor to the river widening incidents in the downstream zone (Reach D). Table 1 shows the results of river width and surface water area carried out for detail discussions. It indicates average values of river width (m) in sub-reaches and their reaches surface water area in square metre (m^2).

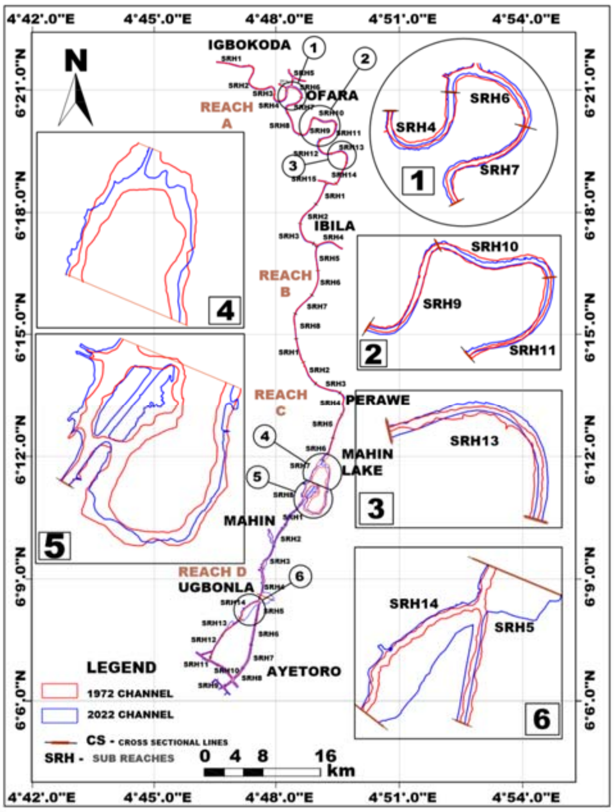
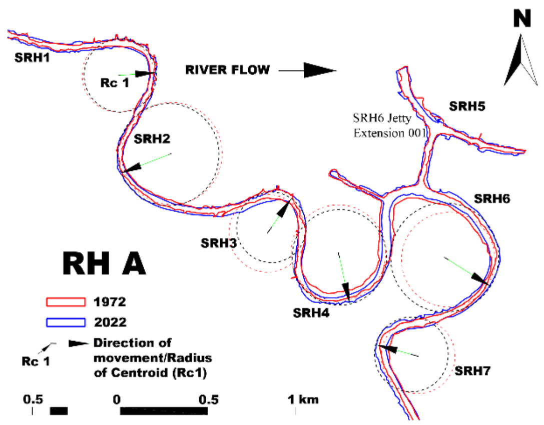


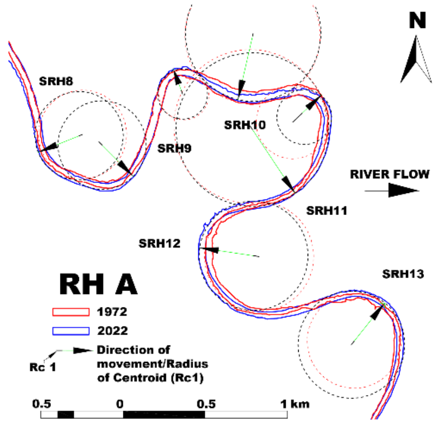
Fig. 8: Channel shifting from 1972 and 2022
Source: Authors, 2023

Fig. 8 revealed spatial variations of the channel planforms of 1972 and 2022. Meanwhile, the enlarged six different sites (locations) along the waterway channel revealed a clear indication of bankline shifting. Location 6 revealed a migration distance of 254.39metres away from 1972 channel bankline. The location 1 showed a propensity of eventual joining of SRH4 and SRH7; Location 2 is an extension of Location 1 revealing the highly meandering status of the entire Reach 1. Location 5 exhibited braided channel patterns characterised by isolated islands of deposited materials.

Fig. 9a and b indicated inscribed circles that define the average outer banklines from the 1972 and 2022 planforms of the river way (Igbokoda-Ayetoro waterway channel) in the riverine area of Ilaje. It shows the bends of centroids and the radius of curvature (Rc) for the bends in green arrow and the direction of channel movements.



9a.



9b.

Fig. 9 a & b.: Inscribed cirdes that define the average outer banklines from the 1972 and 2022 planforms of the riverway (Igbokoda-Ayetoro waterway channel) Source: Authors, 2023

As indicated in Table 2, the study revealed the rate, direction and extent of the channel shifting in the meandering section of Igbokoda-Ayetoro waterway channel between 1972 and 2022. Also, as shown in Fig. 9 a & b and Table 3, the extent of the channel migration/shifting in 2072 (100 years prediction) are presented. As shown in Fig 9b. Subreaches 4 and 7 are tending towards joining together which may eventually develop an OX-bow lake. 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.

Table 3: Rate and extent of Channel migration /shifting at meandering section of Igbokoda-Ayetoro waterway channel in 2072 (100 years projection)

RIVER REACH A	Migration rate between 1972-1984	Migration rate between 1984-2002	Migration rate between 2002-2012	Migration rate between 2012-2022	Rate aggregate (m)	1972-2022 Average Rate metre/year (m)	Migration Distance in 2072 (50years) in metres	Migration Distance in 2122 (100years) in metres
SRH1	0.215	0.303	1.271	0.48	2.269	0.567	28.5	56.73
SRH2	0.468	0.553	1.202	0.416	2.639	0.660	33.0	65.98
SRH3	0.776	0.375	1.236	0.624	3.011	0.753	37.6	75.27
SRH4	1.042	0.731	0.947	0.684	3.403	0.851	42.5	85.08
SRH5	0.396	0.811	1.18	1.217	3.604	0.901	45.1	90.12
SRH6	0.436	0.525	0.43	1.213	2.604	0.651	32.6	65.12
SRH6 Extension	0.627	1.013	0.65	0.61	2.900	0.725	36.3	72.51
SRH7	0.613	0.974	0.553	0.797	2.936	0.734	36.7	73.42
SRH8	0.378	0.584	0.662	0.425	2.048	0.512	25.6	51.22
SRH9	0.227	0.611	0.776	0.395	2.010	0.503	25.1	50.25
SRH10	1.671	0.655	0.616	0.588	3.531	0.883	44.1	88.27
SRH11	1.120	0.773	0.948	0.394	3.237	0.809	40.5	80.92
SRH12	0.933	0.785	0.721	0.528	2.967	0.742	37.1	74.18
SRH13	0.586	0.409	1.661	0.542	3.198	0.800	40.0	79.96
SRH14	0.622	0.326	1.034	0.359	2.340	0.585	29.3	58.52
SRH15	0.545	0.287	0.627	0.265	1.725	0.431	21.6	43.12

Source: Authors, 2023

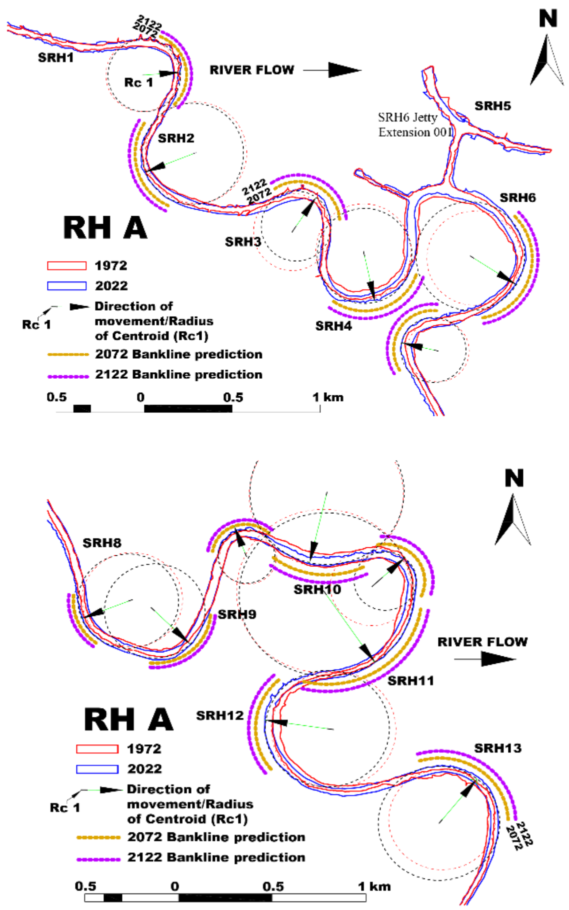


Fig. 10a & b: Channel/Bankline Shifting Prediction for 2072 and 2122
Source: Authors, 2024

5.1 Influence of the channel shifting on Inland transportation

5.1.1 Reduced permissible channel width

Study revealed that there are some narrow reaches along the waterway channel due to the changing pattern of channel migration in the study area overtime. These reaches include: Reach A SRH15 (29.8 m), Reach B SRH6 (29.0m), Reach C SRH5 (24.3m), SRH6 (30.3m), and Reach B SRH7 (31.7m). However, the channel migration led to changes in the width of the navigable channel, affecting the turning ability and passing clearance for vessels particularly lager watercrafts used in transporting goods and luggage in the riverine communities of Ilaje . For instance, the manoeuvrability of a larger watercraft as shown in Figure 11 can be much difficult at locations of narrow reaches like Reach A SRH15 (29.8 m), Reach B SRH6 (29.0m) and Reach C SRH5 (24.3m).

Narrower channels make navigation more difficult for vessels to navigate safely and increasing the risk of collisions due to less manoeuvrable space to manoeuvre. This risk can be further exacerbated by the increased traffic density that is often found particularly at river bends or curvatures in narrower channels coupled with a reduced speed. For instance, Findings revealed several river curvatures at reach A (Igbokoda-Perawe waterway corridor) are highly meandering. Minimum speed is expected at these river curvatures for vessels in transits to manoeuvre on their lanes. It is worth noting that average channel width of Igbokoda-Ayetoro waterway is been estimated as 50metres for two-way manoeuvring lanes. The observed narrow reaches as indicated in the Table 1 are far below the permissible channel width for vessel manoeuvrability. Hence, shifts in channel alignment due to migration requires vessels to adjust their course, impacting manoeuvrability and potentially increasing the risk of collisions against the riverbank or other vessels in transit.

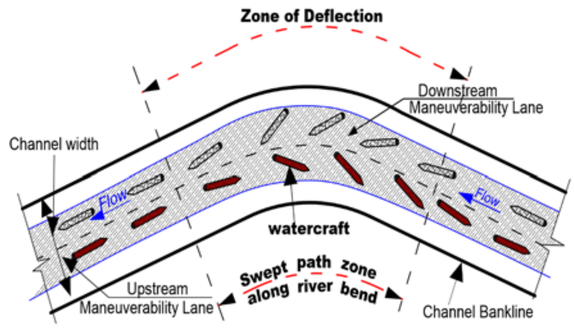


Fig. 11: Typical manoeuvrability positions of watercrafts in opposite directions at river curvature (bends) - (swept path zone);
Source: Adapted from [15].

Fig.11 show typical positions of two watercrafts in opposite directions swaying sidewards on the manoeuvring lanes along the swept path zone before adjusting back into straight channel. This indicates the difficult situation of narrow width being more pronounced at channel bends or curvatures. Fig. 12 shows a 23 metre long watercraft in transit along Igbokoda-Ayetoro waterway carrying passenger and market commodities. The length of the watercraft requires a careful manoeuvring in narrow channel bends of relatively between 30-40metres wide.

Fig. 12: Larger watercraft carrying goods and market commodities in in transit at Igbokoda
Source: Author, 2023

Besides, study revealed that the navigable depths of the Igbokoda-Idiogba/Ayetoro waterway vary significantly in different locations. In the field investigation conducted in the Au gust 2022 and January, 2023, study revealed that river channel depth between Igbokoda and Mahin kingdom is relatively stable. Changes in the depth became pronounced from Ugbonla down t o Idiogba and Eruna-Ero. In the downstream of Ayetoro, Idiogba and Eruna-Ero corridor, the river depth has greatly reduced by the accumulated mud sediments; and this is already threatening navigations in the zone . Navigable river bed in this zone is characterised by mud sediments from the Niger river discharge through the ocean. Findings revealed that the emergence of mud sediments in Ayetoro seaside has caused a continuous change in the channel depth of the downstream zone of the Ig bokoda-Ayetoro waterway. Shallower depths along the channel are apparently revealing and hindering the movement of vessels especially large watercrafts.

5.1.2 Navigation restrictions

Boat operators operating on the larger watercraft expressed their fear over the conditions of the channel depth every time they navi gate around Ajapa-Idiogba-Eruna-Ero enroute Awoy e axis and other parts of the riverine area. The river channel depths observed in reach D is gradually limiting the size and draft of vessels that can navigate the waterway. Larger vessel s require deeper water s to avoid running aground. Meanwhile, the shallow depths restrict the types and sizes of vessels that can transport goods. It is notet aking that availability of sufficient water depth in the waterw ay is the chief requirement for navigation. Figure ?? shows typical picture of th e type of wa tercraft operating i n the study area.

5.1.3 Reduced Cargo Capacity

Larger vessels operating in shallower waterway are however, affected by shallow waterway as they may need to reduce their c argo capacity to avoid grounding or damaging the vessel. This reduces the efficiency of transportation as fewer goods can only be transported in each trip, leading to increased costs per unit of goods transported.

6 Conclusion

Strategies for river m anagement and conservation must take in to account the beneficial effects and negatives of variations i n river chan nel widths. Maintaining healthy river ecosystems, promoting biodiversity, and reducing adverse effects on human activities and inland tra nsportation all depend on striking a balance betw een these ele ments. The research was able to identify river sections, such as Reach D, where sudden channel expansion m ight happen. This study found that river widening and narrowing processes have altere d vessels' manoeuvring lanes, hinder passage s of watercrafts, and reduced freight capacity. Channel migration as a factor of lateral river channel expansion and contraction, is an essential process that ensures the regular operation of rivers and one that preserves fluvial habitats. However, it has negatively impacted the inland w aterway transportation in Ilaje local government area of Ondo state. Among the effect are reduced permissible channel width, navigation restrictions and reduced c argo capacity. Also, it is worth noting that in densely populated areas, abrupt channel widening might cause flood damage. As a result, effective flood risk management requires identifying river sections where sudden channel enlargement is possible [14].

7 Recommendation

River width variability has one advantage: it serves as flood control indicators, a measure for sediment transport dynamics, habitat diversity, and provides a variety of leisure activities. River width variabili ty refers to how a river's wid th varies across ti me and space. It is a natural occurrence caused by a variety of causes including geology, hydrology, vegetation, and human activity. Understanding the benefits and drawbacks of river width fluctuation is critical for successful river management and conservation.

Yang stated that variabilit y in ri ver width is an essential ecological trait to research since it indicates the diversity of riverine ecosystems [16] and specific river morphodynamics [17]. Scherelis reiterated that river width i s one of the key variables needed to calculate river discharge, along with river depth and velocity, and is thus a key shape property for many hydrological studies [18]

The study recommends bank st abilization, sediments monitoring and manage ment as well as channel realignment. These may involve regular dredging to maintain channel dim ensions, the construction of training structures to gui de the flow of water and sedim ent, and the im plementation of navigation aids will enhance visibility and safety.

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