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Original Article

Tidal Trend Evaluation for Imo River between 2013 and 2021

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Abstract *- Reliable tidal prediction and estimation of water levels require accurate tidal prediction constants. To ascertain if the tide in Imo River was evolving, the investigation was carried out on the trend of tidal constituents and associated tidal constants. Trends for tidal harmonic constants, tidal datum, and tide ranges were analyzed based on sets of 35 tidal constituents derived in 2013 and 2021. Study results revealed an increase in amplitudes of diurnal constituents and a decrease for semi-diurnalsemi-diurnal components except for M2, the principal lunar semi-diurnalsemi-diurnal constituent. The trend of amplitude for the principal tidal constituents was within ±4cm. At the same time, the phase angles varied between -13.17° and 8.29° but for M2, which remained relatively stable. Tidal datum and tidal ranges for spring and neap tides had a mixed trend. Mean sea level between 2013 and 2021varied by 0.007m inferring that the relative sea-level increased by 0.88mm per year while the tidal range decreased by 53mm. Although the trend was relatively low, the study revealed that the tide in the Imo River is evolving over geological time scales due to relative sea-level rise. Care should be taken to account for the variability when predictions and investigations on tidal dynamics of the river are carried out.*

Keywords *- Amplitude, Harmonic Constants, Phase Angles, Sea Level Rise, Tidal Constituents, Tidal Trend.*

I. INTRODUCTION

Accurate tidal data are necessary for water level predictions, planning, design, and construction of marine-based engineering structures, and installation of navigational aids and platforms [3], [4], [11], [19]. This is also vital for safe navigation and disaster mitigation and prevention [1]. Information on tides is valuable for recreational boating, beach surfers, tourists [16], maintenance and recovery of structures, dredging, and hydrographic surveying operations [17].

Changes in environmental factors and the seasonal effects of astronomic tide forces cause the tide to vary across the globe [2]. As noted [13], tidal harmonic constants are not stable over time, and the largest changes in amplitude usually occur inland [27]. This raises concern for determining the tidal trend and water level variability for effective tidal analysis, prediction, and application. Determination of tidal datum consistency and water level fluctuation trend will aid in predicting sea-level rise, managing navigational challenges, and monitoring and maintaining channel depths [6].

Of recent, the water level in Imo River has risen higher than the known flood water point. This raises the need to extensively study tidal phenomena within the river basin and ascertain if tides in the river were evolving. The investigation was carried out to study the trend of the river tide, including published tidal constituents and associated harmonic constants. The study had the objectives of comparing tidal characteristics of the river based on astronomical constituents and form factors derived from tidal analyses at two different time series.

II. BACKGROUND

Tides are produced due to astronomical forcing and the collective nonlinear interactions from environmental, meteorological, and climatic factors such as river flow, water depth, channel geometry, seafloor topography, bottom friction, wind, and geographic location [14], [1]. Tides are harmonic and easily predictable for different locations based on astronomical motions. However, the interplay of natural events, anthropogenic developments, and different astronomic configurations over time induce tidal variability [7]. Although tides are not expected to change over time since they are based on predictable astronomical motions, reports on tidal characteristics variation are well documented [3]. Across the globe and in many world regions, tides vary over different time scales due to several factors [3], [9]. It is noted that tides worldwide are changing at rates not explicable by dynamics of astronomical forcing [27]. Local and regional sea-level rise induces long-term tidal changes, while geologic alteration of river basin morphology and changes in water depths causes short-period changes in tides [26]. Modification in tidal factors could be ascribed to the impact of atmospheric dynamics, ocean circulation, tidal potential, thermocline depths, stratification conditions, and changes in radiational forcing [7]. Alteration of adjacent water bodies by natural or anthropogenic factors also changes tidal characteristics at close tidal stations [11]. The shoaling effect induced by tide propagation from the ocean into coastal rivers usually results in shallow water distortion of tidal signal and changes in characteristics of river tides [20]. Response of inland waters to nonlinear interactions of oceanic, meteorological, hydrologic, or climatic forcing on channel geometry and river flow. This inherently amounts to uneven ebb and flood duration and irregularities in height and timing [14].

Notably, trends and magnitudes of tidal variations are often dependent on the relative interaction of amplitudes and phases of tide generating forces [18]. As harmonic constants are time-varying [13], changing seasonally between winter and summer [31] and at different scales [9], [10] recommended investigation into constant tidal stability through observation of tides whenever there are major anthropogenic and natural events. Morakinyo and Sunmonu [15] suggested periodic monitoring of tidal datum to ascertain the cause and magnitude of the changes. The tidal regime's variation or stability can be described by tidal range, stages or types of tides depending on geographical location, and mean water level value through multi-temporal tidal records of location [15]. Over the years, trends, magnitudes, and effects of tidal changes have been studied ([5], [8], [26], [15], [27]) by analyzing phase angles and amplitudes of tidal constituents which uniquely define tides at any location including chart datum.

Feng *et al*. [7] reported several investigations on linear trends recorded in tidal constituents' amplitudes and phase values in the Bohai Sea, British Isles, Caribbean Sea, East China Sea, and North Atlantic Ocean. Wang and Myers [30] studied the effects of 40 to 80 years of morphological changes around tidal inlets using 40 to 80 years of time-series data. The study carried out over five inlets revealed that a 10% change in depth of tidal inlet could cause over 30% alteration of tidal level value. It was also shown that changes in depth influenced the amplitudes of tidal harmonic constituents. Talke and Jay [27] reported changes in the amplitude of inland waters, strongly damped and particularly shallow rivers. Changes were also significant for systems with high wave resonance due to convergence and changes in water depth. Faizuddin and Razali [8] studied variations in chart datum values for tide gauge stations in Malaysia. They found out that the chart datum based on tide gauge observations varied between 48 to 288 millimeters per year on the East Coast and between 36 to 96 millimeters per year up on the West Coast of Malaysia Peninsular. Morakinyo and Sunmonu [15] investigated the consistency of tidal datum at Nwaniba River – Nigeria using two sets of tidal data of 30 days intervals each. The study revealed that LWL tidal datum adopted in 2007 was still consistent with the datum in 2017 within a reasonable difference of 0.001cm while the water level increased by 1.247cm. Variation of tidal range in German Bight within 3% to 11% at tide gauge stations and water level varying between −2.3 mm/yr and 7 mm/yr was reported by [12].

III. MATERIALS AND METHODS

The methodology flowchart of procedures adopted in the study and explained in different subsections is depicted in Fig. 1.

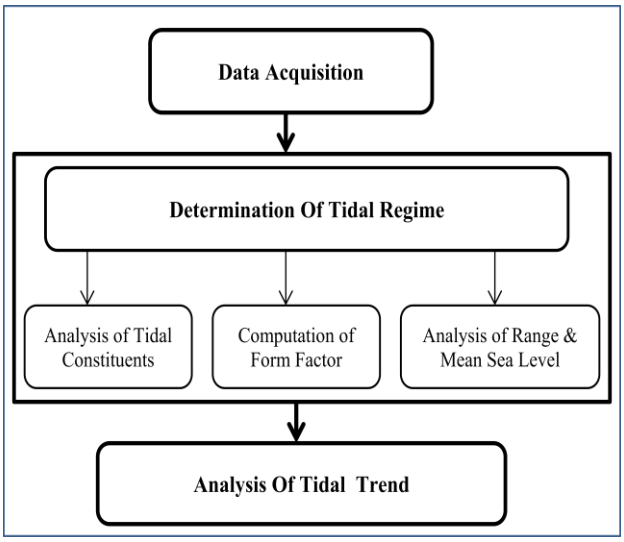


Fig. 1 Methodology flowchart

A. Study Area

The study area is the Imo River, located in the Niger Delta Region of Nigeria (Fig. 2). Imo River has an extensive river network of about 240kilometres (150mi) which flows from the hinterland into the Atlantic Ocean. Its estuary spans approximately 40 kilometers of surface area with 26,000 hectares of wetland. The river has an annual discharge of 4 cubic kilometers [6]. The shorelines are dominated by mangrove vegetation. The tidal regime in the river is strongly influenced mainly by semi-diurnalsemi-diurnal astronomical tidal forcing and by inflow from the Atlantic Ocean. It has a meso-tidal pattern with a tidal range of 2.20m to 2.50m. River depth ranges between -0.66 and 12.96m above datum [28]. The river lies between latitudes 4° 28'N and 5° 00'N and longitudes 7° 10'E and 7° 40'E while the tide gauge location was at latitude 4° 34' 21.06″ N and longitude 7° 32' 48.00″E (Fig. 2).

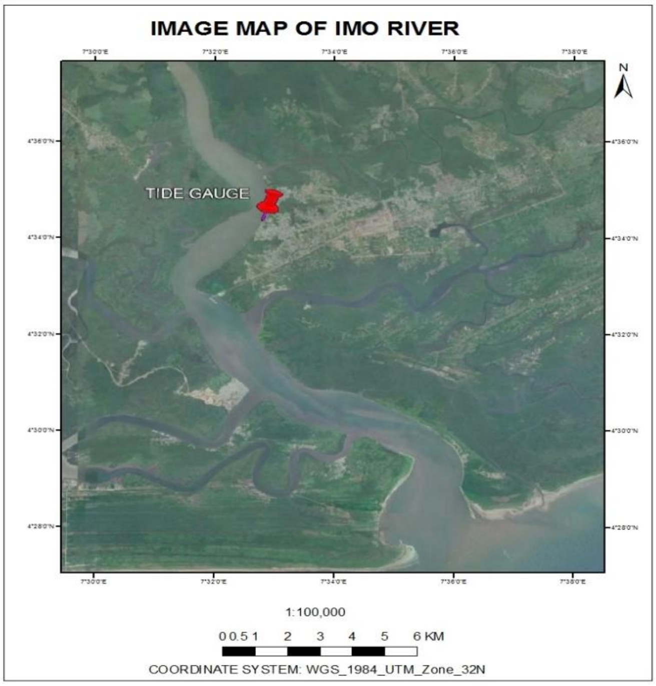


Fig. 2 Map of study location

B. Data

Data used were results of tidal analyses and predictions obtained from previous studies ([6], [28]). Independent analysis of each dataset based on least-squares harmonic analyses and prediction was conducted with the t_tide program of [22]. Tables I and II, respectively, contain the overview of time series data and tidal constituents adopted for this study.

Table 1. Overview of time series data

Observation Period	Duration of Observation (in days)	Number Of Observation (in hours)	Highest Tide Value (m)	Lowest Tide Value (m)	Range (m)
27/07/ 2013 -30/08/2013	35	840	2.670	0.250	2.420
7/01/2021- 12/02/2021	37	865	2.658	0.270	2.388

Table 2. List of tidal constituents

2013					2021		
Tide Constituent	Frequency (Hz)	Amplitude (m)	Phase (Deg)	Tide Constituent	Frequency (Hz)	Amplitude (m)	Phase (Deg)
MM	0.0015122	0.0022	286.67	MM	0.001512	0.0276	46.23
*MSF	0.0028219	0.0601	78.35	*MSF	0.002822	0.0415	141.05
ALP1	0.0343966	0.0096	98	ALP1	0.034397	0.0065	131.07
2Q1	0.0357064	0.0096	341.32	2Q1	0.035706	0.0079	268.93
Q1	0.0372185	0.0102	129.77	*Q1	0.037219	0.0126	154.16
O1	0.0387307	0.0155	3.47	*O1	0.038731	0.0234	11.76
NO1	0.0402686	0.003	89.65	NO1	0.040269	0.0028	86.48
*K1	0.0417807	0.1273	42.4	*K1	0.041781	0.1746	29.23
J1	0.0432929	0.0049	338.33	J1	0.043293	0.0076	98.72
OO1	0.0448308	0.0183	224.19	*OO1	0.044831	0.0115	71.86
UPS1	0.046343	0.0065	245.83	UPS1	0.046343	0.0051	105.32
EPS2	0.0761773	0.0304	233.55	*EPS2	0.076177	0.0174	230.94
*MU2	0.0776895	0.0774	208.07	*MU2	0.07769	0.0391	222.5
*N2	0.0789992	0.1302	148.57	*N2	0.078999	0.1228	151.29
*M2	0.0805114	0.7192	152.16	*M2	0.080511	0.7375	152.32
*L2	0.0820236	0.041	146.6	L2	0.082024	0.0171	133.42
*S2	0.0833333	0.2638	200.54	*S2	0.083333	0.2167	206.8
ETA2	0.0850736	0.0176	273.33	*ETA2	0.085074	0.0203	182.03
*MO3	0.1192421	0.0235	15	*MO3	0.119242	0.0139	73.61
M3	0.1207671	0.0085	178.11	M3	0.120767	0.0105	249.37
MK3	0.1222921	0.0114	321.86	*MK3	0.122292	0.015	320.68
SK3	0.1251141	0.0153	42.99	*SK3	0.125114	0.0146	72.96
MN4	0.1595106	0.0272	78.08	*MN4	0.159511	0.0338	87.85
*M4	0.1610228	0.0833	113.02	*M4	0.161023	0.1079	105.77
SN4	0.1623326	0.0192	175.06	SN4	0.162333	0.0104	155.9
*MS4	0.1638447	0.0513	175.69	*MS4	0.163845	0.0545	187.22
S4	0.1666667	0.0136	254.08	S4	0.166667	0.0121	301.14
2MK5	0.2028035	0.0125	218.88	2MK5	0.202804	0.0039	153.07
2SK5	0.2084474	0.0026	9.23	2SK5	0.208447	0.0007	142.04
2MN6	0.2400221	0.0071	71.23	2MN6	0.240022	0.0098	117.2
M6	0.2415342	0.0149	114.22	*M6	0.241534	0.0176	99.44

*2MS6	0.2443561	0.0158	207.73	*2MS6	0.244356	0.0218	204.96
2SM6	0.2471781	0.0093	256.4	2SM6	0.247178	0.006	279.2
3MK7	0.2833149	0.0051	281.99	3MK7	0.283315	0.0065	349.11
M8	0.3220456	0.0041	132.38	M8	0.322046	0.0058	112.91

C. Analyses of Tidal Characteristics

According to [18], the magnitude and nature of sea level or tidal variations for a particular water body are determined based on the relative interaction of amplitudes and phases of the tidal constituents of the tide generating forces. Table III contains tidal constants of the four main tidal constituents (M2, S2, K1, and O1), while Fig. 3 and Fig. 4a are graphical representations of magnitudes of the tidal constant for the two years under consideration.

Analyses of constituent amplitudes and phase values revealed M2, the principal lunar semi-diurnalsemi-diurnal constituent, as the most dominant constituent of the river. This was slightly followed by the principal solar semi-diurnalsemi-diurnal constituent, S2. In terms of tidal timing usually determined by phases of tidal constituents [18], S2 had the largest phase lag among the four principal tidal constituents
(see Fig. 4b).

Table 3. Tidal Constants Of Principal Tidal Constituents For 2013 And 2021

Constituents	M2		S2		K1		O1	
	H (cm)	α (Deg)	H (cm)	α (Deg)	H (cm)	α (Deg)	H (cm)	α (Deg)
2013	71.92	152.16	26.38	200.54	12.73	42.4	1.55	3.47
2021	73.75	152.32	21.67	206.8	17.46	29.23	2.34	11.76

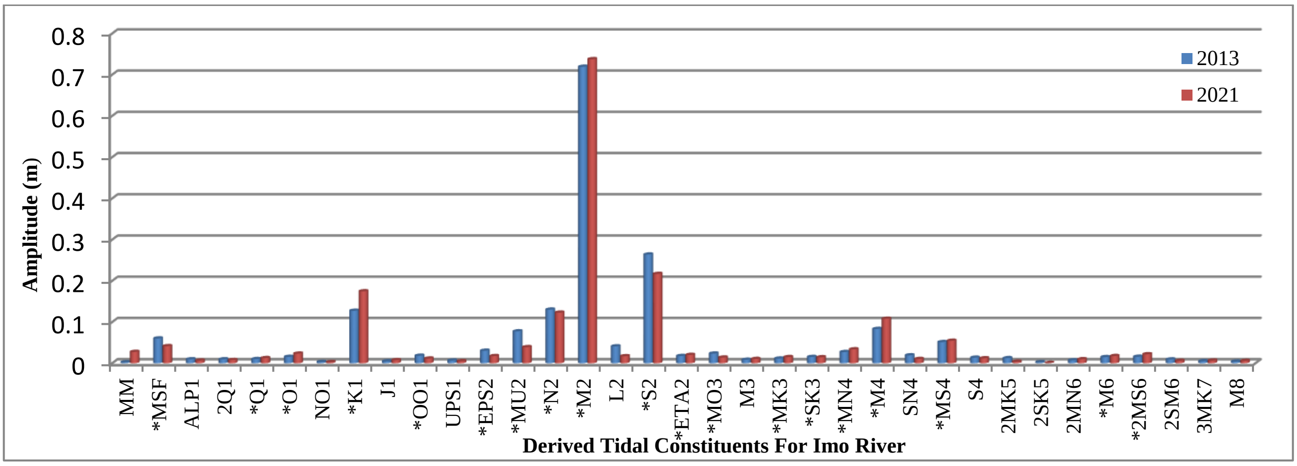
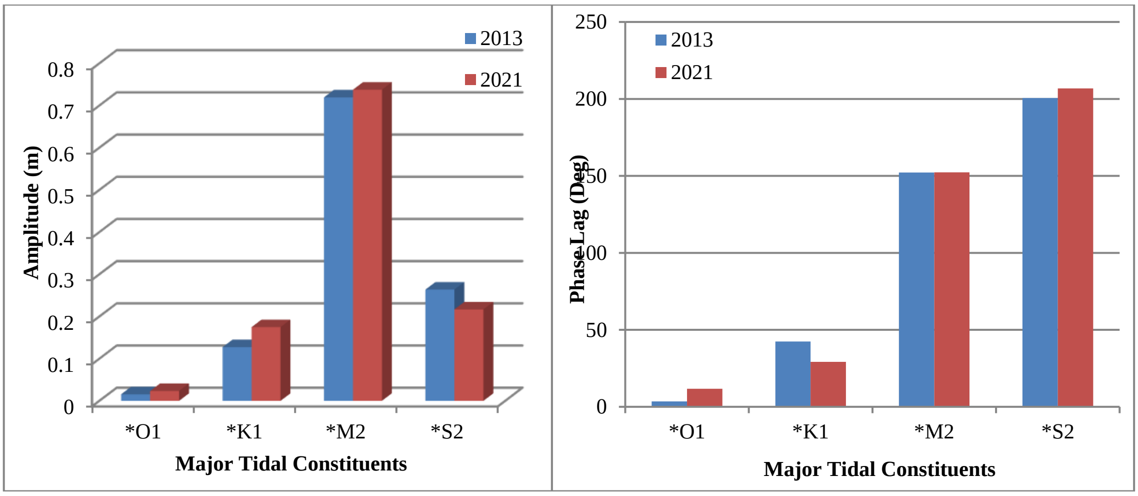


Fig. 3 Amplitude of tidal constituents for Imo River



(a) ***(b)***

Fig. 4 Amplitude and phase lag of the principal tidal constituents for 2013 and 2021

The tidal regime of the river for the two years was determined based on the form factor (F). The tidal form factor quantifies the diurnality of the tide at a location [24]. Values of F were calculated using tidal amplitudes of K_1, O_1, M_2, and S_2 (from table 2) for the two data epochs.

$$\text{The ratio, } F = \frac{(K_1+O_1)}{(M_2+S_2)} \quad \ldots \quad (1)$$

gave a value of 0.1453 and 0.2076 for 2013 [6] and 2021 [28], respectively. The form factor showed that Imo River has a semi-diurnal tidal characteristic (0 > F < 0.5) [28]. These results corresponded to the semi-diurnalsemi-diurnal pattern of two high and two low glasses of water per day but revealed a positive trend of 0.0623. The increased form factor value corroborates the variations in amplitudes of the major tidal constituents as presented in table IV and Fig. 3, 4a, and 4b.

IV. RESULTS AND DISCUSSIONS

A. Analysis of Tidal Constituents

Tidal constituents resolved from the analyses of 35 and 37 days of observation covered the major tidal constituents - diurnal, semidiurnal, compound and over tides ([6], [28]). Analysis of the major five astronomical constituents (K1, O1, M2, S2, and N2) examined revealed that in 2013, the amplitude for M2 was 0.7192 but increased to 0.7375 in 2021. While the amplitudes of other semi-diurnalsemi-diurnal constituents (N2 and S2) reduced considerably, amplitudes of diurnal constituents (O1 and K1) increased by 0.79cm and 4.73cm, respectively. A comparison of phase lag revealed the relative stability of M2. Phase lag of S2 and N2 increased by 6.26° and 2.72°, respectively, while K1 reduced remarkably by -13.17°. The analysis result is presented in tables IV and V.

Table 4. Residual series in amplitude of principal tidal constituents

Tidal Constituents	2013 Amplitude (m)	2021 Amplitude (m)	Residual (m)
*O1	0.0155	0.0234	0.0079
*K1	0.1273	0.1746	0.0473
*M2	0.7192	0.7375	0.0183
*S2	0.2638	0.2167	-0.0471
*N2	0.1302	0.1228	-0.0074

Table 5. Residual series in phase of principal tidal constituents

Tidal Constituents	2013 Phase Lag (Deg)	2021 Phase Lag (Deg)	Residual (Deg)
*O1	3.47	11.76	8.29
*K1	42.4	29.23	-13.17
*M2	152.16	152.32	0.16
*S2	200.54	206.8	6.26
*N2	148.57	151.29	2.72

A look at the tidal constants of the semi-diurnalsemi-diurnal species (table VI) that accounts for the tidal characteristics of Imo River shows significant differences in magnitude except for the phase lag of M2. This principal lunar semi-diurnalsemi-diurnal constituent remains considerably stable. EPS2, MU2, and N2, L2, and S2 constituents reduced magnitudes between 1.3cm and 4.71cm, while M2 and ETA2 increased by 1.83cm and 0.27cm, respectively.

Table 6. Semi-diurnalsemi-diurnal species

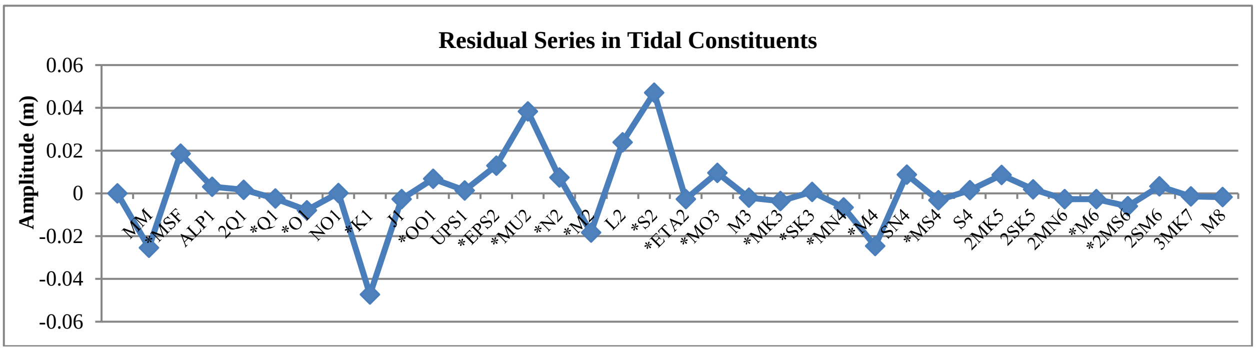
Tidal Constituents	2013		2021	
	Amplitude (m)	Phase (Deg)	Amplitude (m)	Phase (Deg)
*EPS2	0.0304	233.55	0.0174	230.94
*MU2	0.0774	208.07	0.0391	222.5
*N2	0.1302	148.57	0.1228	151.29
*M2	0.7192	152.16	0.7375	152.32
L2	0.041	146.6	0.0171	133.42
*S2	0.2638	200.54	0.2167	206.8
*ETA2	0.0176	273.33	0.0203	182.03

Overrides and compound tides which are shallow-water tidal constituents caused by nonlinear processes of parent waves, are presented in Table VII. Amplitudes of the shallow-water tide for the year 2013 were between 0.26cm and 8.33cm, whereas for 2021, the amplitudes covered 0.07cm - 10.79cm range. M4 – the first overtime of the M2 constituent had the largest amplitude (8.33cm and 10.79cm) and largest residual of 2.46cm for the two years. This was followed by MS4, the compound tide of M2 and S2 with amplitudes of 5.13cm and 5.45m for 2013 and 2021, respectively.

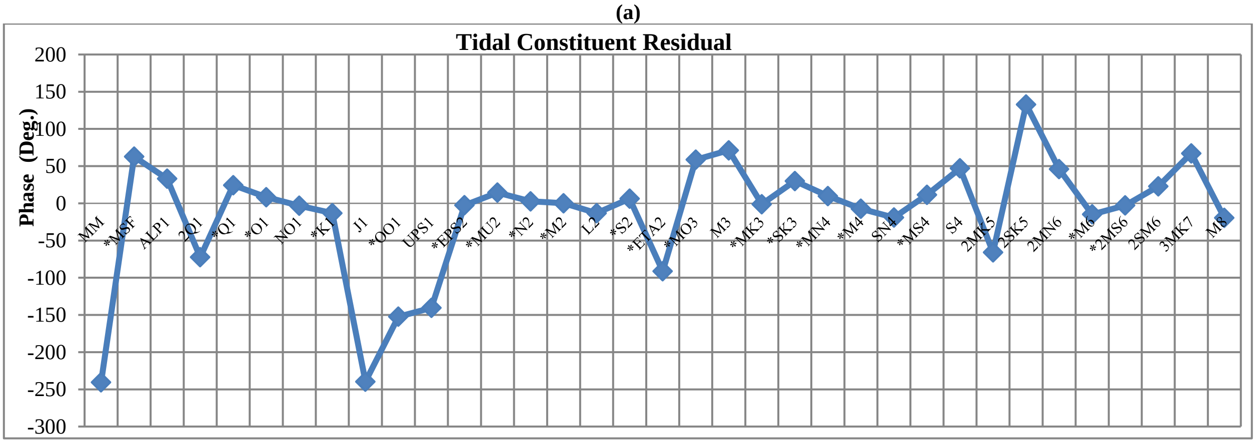
Although residuals for shallow-water constituents were between -0.96cm and 2.46cm, the trend revealed impacts of meteorological and environmental factors on the river and changes in bathymetry [18]. On the whole, residuals of tidal amplitudes varied from -0.0471m to 0.0473m, while the phase varied between -132.81° and 240.44°. Fig. 5a and 5b are residual curves of the amplitudes and phase angles of analyzed tidal constituents.

Table 7. Tidal constants for compound and overtides constituents

Tidal Constituents	Amplitude (m)			Phase (Deg)		
	2013	2021	Residual	2013	2021	Residual
*MO3	0.0235	0.0139	-0.0096	15	73.61	58.61
M3	0.0085	0.0105	0.002	178.11	249.37	71.26
*MK3	0.0114	0.015	0.0036	321.86	320.68	-1.18
*SK3	0.0153	0.0146	-0.0007	42.99	72.96	29.97
*MN4	0.0272	0.0338	0.0066	78.08	87.85	9.77
*M4	0.0833	0.1079	0.0246	113.02	105.77	-7.25
SN4	0.0192	0.0104	-0.0088	175.06	155.9	-19.16
*MS4	0.0513	0.0545	0.0032	175.69	187.22	11.53
S4	0.0136	0.0121	-0.0015	254.08	301.14	47.06
2MK5	0.0125	0.0039	-0.0086	218.88	153.07	-65.81
2SK5	0.0026	0.0007	-0.0019	9.23	142.04	132.81
2MN6	0.0071	0.0098	0.0027	71.23	117.2	45.97
*M6	0.0149	0.0176	0.0027	114.22	99.44	-14.78
*2MS6	0.0158	0.0218	0.006	207.73	204.96	-2.77
2SM6	0.0093	0.006	-0.0033	256.4	279.2	22.8
3MK7	0.0051	0.0065	0.0014	281.99	349.11	67.12
M8	0.0041	0.0058	0.0017	132.38	112.91	-19.47



(a)



(b)

Fig. 5 Residual series in tidal constituents

B. Tidal Range and Mean Sea Level

The tidal range, the 'vertical difference in height between consecutive high and low waters over a tidal cycle' [29], usually indicates the effects of tidal energy propagation due to morphological changes [30]. Evaluation of tidal range carried out was to determine the magnitude of energy induced between the periods under investigation. Predicted tidal values for the two years (i.e., 2013 and 2021) were used to determine the tide range at the study location.

$$\text{Range} = \text{Highest tidal value} - \text{Lowest tidal value} \quad \dots \quad (2)$$

For year 2013,

$$Range \quad = 2.750 - 0.250 \quad = \quad 2.500m$$

For year 2021,

$$Range \quad = 2.546 - 0.315 \ = \ 2.231m$$

The mean spring range (MSR) and mean neap range (MNR) was computed using the formula presented by [21]:

$$MSR = 2(H_{M2} \ + H_{S2})m \qquad \dots \qquad (3)$$

$$MNR = 2(H_{M2} \ + H_{S2})m \qquad \dots \qquad (4)$$

H_{M2} and H_{S2} were the amplitudes of M2 and S2 constituents. A comparison of range values obtained in 2013 and 2021 showed a -0.053m, whereas MSR and MNR differed by -0.0576m and 0.1308m, respectively. (see Table VIII). Changes in the tidal range and MSR were adjudged to be the outcome of reduced tidal strength during the summer period. The 2021 data was obtained as the water column usually experienced a more stabilized or reduced slack action. An increase in MNR indicated that low water levels were higher in recent times than in the previous year (2013). This could be attributable to the increased water level in the river.

Mean sea level (MSL), the average level of water above the adopted tidal datum, was estimated from predicted tidal values based on each time series data set. Predicted values covering each year (2013 and 2021) were extracted and used for the analysis. The mean sea level was computed using equation 5.

$$MSL = \sum_{i=1}^{n} \frac{O_i}{n} \qquad \dots \qquad (5)$$

Tidal datum, namely means low water spring (MLWS), mean low water neap (MLWN), mean high water spring (MHWS) and mean high water neap (MHWN), were calculated to check their consistency over the eight years interval. Formulae presented in [25] for semi-diurnalsemi-diurnal sites were used for the computations.

Table 8. Computed tidal datum

Tidal Datum	2013	2021	Residual	Mean
MLWS	0.6700m	0.7058m	0.0358m	0.6879m
MLWN	1.1976m	1.1392m	-0.0584m	1.1684m
MHWS	2.6360m	2.6142m	-0.0218m	2.6251m
MHWN	2.1084m	2.1808m	0.0724m	2.1446m
MSL	1.653m	1.660m	0.007 m	1.6565m
MSR	1.966m	1.9084m	-0.0576m	1.9372m
MNR	0.9108m	1.0416m	0.1308m	0.9762m

The results (table VIII) revealed that the least variation (-0.0218) was in MHWS. This implied low variation in water level during spring tide when water levels are usually high. However, computed values were markedly different for each year, and the datum was inconsistent. Tidal datum and tidal ranges for the spring and neap tide had a mixed trend. These results indicated that tidal regimes for the river are evolving over geological time scales due to relative sea-level rise.

V. CONCLUSION

Reliable tidal prediction and estimation of sea levels require accurate tidal prediction constants. Periodic assessment of tidal constants, monitoring of tidal datum, and information on stability or changes in tidal values are very necessary for the face of geologic and sea-level changes. In this study, an analysis of the tidal constant for Imo River in South-South Nigeria was carried out. The study was marked as essential based on the impact of the Atlantic Ocean on the dynamics of the river and its perceived importance in the region. From the 35 tidal constituents analyzed, the amplitude of the principal constituents was close but with a mixed trend of ±4cm. Phase angles varied between -13.17° and 8.29° except for M2, which remained relatively stable with a phase difference of 0.16°. The mean sea level trend between 2013 and 2021 varied by 0.007m, inferring that the relative sea-level for the river increased by 0.88mm per year while the tidal range decreased by 53mm. Variations of tidal datum and ranges for spring and neap tide indicated that tide in Imo River is evolving over geological time scales due to relative sea-level rise.

The study results underscore the need for periodic investigation of the tidal trend of navigable channels to determine the stability of tidal constants and adopted datum. This will enhance confidence in predicted tidal values and ensure maritime safety. Marine and coastal-based operations and installations will also be safeguarded from unforeseen tidal action.

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