FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 8 No. 6, December, (Special Issue) 2024, pp 503 - 513
DOI: https://doi.org/10.33003/fjs-2024-0806-3043

ANALYSIS FROM 1980 TO 2018 OF TIDAL OBSERVATION DATA FOR ASSESSING THE STABILITY OF TIDAL CONSTANTS FOR PRIMARY PORT

Barnabas O. Morakinyo

Department of Surveying & Geoinformatics, Faculty of Environmental Sciences, Baze University, Abuja, Nigeria

*Corresponding authors' email: barnabas.ojo@bazeuniversity.edu.ng

ABSTRACT

Tidal analysis involves the computation of tidal constants (phase lag (g) and amplitude (H)) of tidal constituents at a location. This study focuses on the assessment of the stability of g and H for the Bonny port which is the only standard tidal port in Nigeria. Monthly analysis of tidal observations was carried out with 1980, 1994 and 2018 year's data using Least Squares Method (LSM) of Harmonic Analysis with MATLAB programming codes. The observation equation technique of LSM is adopted; the dimension of the Normal (N) matrix equations obtained for the monthly analysis is 72×56 i.e. 72 rows, and 56 columns. The N matrix is inverted and gave results for mean sea level (MSL) and g and H of 28 primary constituents of tide. Four major constituents of tide (M_2, S_2, K_1 and O_1) remain stable throughout the analysis. The mean of g and H obtained for each year was observed to be almost equal to the mean obtained from the three-year data. The maximum residuals and spreads of the computed g and H over the period of study show that g and H at Bonny are stable and that results from accurately analyze one-month data observation can be employed for tidal prediction for several years. Therefore, it can be concluded that the g and H for M_2, S_2, K_1 and O_1 are stable and that the type of tide (F) at Bonny port is semidiurnal since the computed F is 0.16 which is < 0.25.

Keywords: Bonny port, Time series, Tidal constants, Least Squares Method (LSM), Standard port, Niger Delta

INTRODUCTION

Hydrography is the investigation and charting of oceans, rivers and other bodies of water, these include the charting of shoals, channels, coastlines, aid to navigations, landmarks, tides, currents and topographic features of the ocean floors and river beds (Ojinnaka, 2007). The applications of hydrography also include disciplines such as navigation and drainage, flood control, watershed managements, channel and river maintenance, hydro-electricity, oil industry, erosion studies, sediment control, domestic and industrial water supply (Morakinyo, 2003), underground seismic studies (Ezisi et al., 2023) . The surface of the water bodies are subjected to periodic fluctuations due to the influence of the tide raising forces especially those of Moon and Sun (Parker, 2007). The horizontal movement of water is called tidal stream while the vertical movement is called tide (Rusdin et al., 2024). Locations of tidal measurements and analysis are referred to as tidal ports (Morakinyo, 2003). Two types of ports known as primary port and secondary port are employed in tidal operations (Ojinnaka, 2007). Primary ports are locations where tidal analysis have been carried out from at least one-year tidal observations (Li et al, 2019; Okwuashi and Olayinka, 2017) while secondary ports are locations where observations and analysis have been made for not more than fifteen days (Ahmed et al., 2024; Pan et al., 2023; Setiyawan et al., 2022). The primary port serves as a reference point for all secondary ports and all other locations of any hydrographic projects.

Tide is a periodical vertical movement in the level of the surface of the seas or oceans due to periodical forces (Rusdin et al., 2024; Ojinnaka, 2007; Shu, 2003; Haigh, 2017) which are referred to as tide raising or generating forces. Tide is of astronomical origin and oscillatory in nature (Li et al, 2019; Ojinnaka, 2007; Morakinyo, 2003; Cartwright and Edden, 1973). The most important tide generating forces are Moon and Sun. The tide generating forces which originate from the Moon and the Sun consist of two parts: the centrifugal forces acting on the Earth due to the motion of the Earth around the resultant centre of gravity of the Moon and the Earth; and the attractive forces due to the Moon and the Sun (Parker, 2007). Tides can be reduced into various components called species according to the mode of its occurrence (Sabhan et al., 2021). These species are long term tide, diurnal tide, semi-diurnal tide, third diurnal tide, forth diurnal tide and the sixth diurnal tide (Setiyawan et al., 2022; Shu, 2003; Susanto et al., 2000). These species consist of tidal constituents which can be solar, lunar or shallow water (Cai et al., 2018; Okwuashi and Olayinka, 2017). These constituents are of great importance in that they help in grouping of tides, determination of the characteristics of tides, analysis and prediction of tidal movements (Setiyawan et al., 2022). Also, it is important to know that all tides are composed of both diurnal and semi-diurnal components and constituents, (Sabhan et al., 2021; Pugh 1987). However, the intricate nature of both the orbital motion of the Moon around the Earth and the Earth around the Sun creates several tidal generating potentials with different frequencies and strengths (Parker, 2007). Tidal generating potential at each frequency is generally represented by tidal harmonic constituents (Rusdin et al., 2024). Meanwhile, the pairs of amplitudes (H) and phase lags (g) of the constituents are defined as harmonic or tidal constants (Sabhan et al., 2021). This shows that tides can be explained as the combination of the harmonic constants of the constituents (Rusdin et al., 2024).

Tidal analysis is the breaking down of complex sinusoidal wave into the smallest ones (Cai et al., 2018; Shu, 2003). This process of breaking down a complex curve which repeats itself into a number of pure sine or cosine curves whose wavelength are all related by integral numbers or fractions constitutes harmonic analysis in one of its simpler form (Shu, 2003; Morakinyo, 2003; Hydrographer of the Navy, 1964). Tidal analysis involves the determination of the unknown amplitude (H), and the phase lag (g) for as many constituents of tide as possible, and the height of mean sea level (MSL) (h_0) above the chart datum (Rusdin et al, 2024; Ojinnaka, 2007). In tidal analysis, the aim is to produce significant time-stable values which can be used for tidal predictions; and which may be related physically to the processes of tide generation (Byun et al., 2023), and have some regional coherence (John, 1983). Also the purpose of the analysis is based on observations but the precise determination of the tidal constants aiming at the preparation of astronomical almanacs or tables to be used for practical navigation problems as well as the construction of co tidal charts in the ocean concerned, (Ojinnaka, 2007; Pugh, 1978).

Some of methods employ in tidal analysis are the response method (Cartwright, 1980), continental shelf model method (Joan, 1989) and harmonic method (Rusdin et al., 2024; Okwuashi and Olayinka, 2017; Shu, 2003). In any of the method, the requirement is that a continuous records of tidal observation for at least one month be used for any analysis if a reasonable accurate result is expected (Cai et al., 2018; Ojinnaka, 2007). Advantages of response analysis are it has the facility to input other forcing functions in addition to the gravitational potential; extensively applied to elevation data from oceanic and continental shelf stations; allows for a smoothness of ocean response and so is able to fit the observed data with satisfyingly fewer parameters (Cartwright, 1980). However, there are few detailed reports of its application to the analysis of shelf current (Cartwright, 1980). Also, much remains to be done in the physical interpretation of these response functions in terms of ocean characteristics (Ojinnaka, 2017). Tidal charts of response parameters are not being constructed, even where elaborate response analysis are made, the final presentation is in the form of charts of the major harmonic constituents (Cartwright et al, 1980).

Continental Shelf Model (CSM) method is required where extra information on the behaviour of the tide at the locations of the project is needed (Joan, 1989). CSM calculates the water level and the depth integrated flow taking into account, depth variations, acceleration of gravity, earth rotation, sea water density, air pressure, bottom stress, wind drag, wind speed and tidal forcing at the ocean boundaries of the area (Joan, 1989). Harmonic Method (HM) (Cauwenberghe, 1992) of tidal analysis starts with the assumption that the astronomical forcing terms can be adequately represented by a finite number of harmonic terms, each having different angular speed (Rusdin et al., 2024). The basis of the harmonic analysis method is the development of tidal potential in harmonic terms, and in this method, the propagation of the periodical tidal motion is split up in the computation of a series of sinusoidal waves (Cai et al., 2018; Shu, 2003). The greater the number of harmonics used for the analysis, the more nearly would their sum represent the original curve exactly (Barber, 1987).

For harmonic tidal analysis, the number of unknown is given as $N \geq 2m + 1$ (Rusdin et al., 2024; Shu, 2003)

Where m is the number of constituents

N =number of equations to solve the problem + redundancy.

Harmonic analysis method can also be applied to any scalar quantity and its application to elevations (or bottom pressures) is straight forward (Cai et al., 2018).

The two primary harmonic methods (Rusddin et al., 2024; Okwuashi and Olayinka, 2017) generally used for tidal analysis are Fourier Transform Method (FTM) (Schureman, 1994) and Least Squares Method (LSM) (Rusddin et al., 2024; Shu, 2003; Zetler, 1982; Foreman, 1977). The actual tide during a certain time interval, e.g. one day or a number of successive days can be represented by means of the Fourier series, of which the basic frequency is that of the Moon tide M_2 or of the Sun tide S_2 (Rusddin et al., 2024; Foreman, 1977). The number of terms with frequencies depends on the required accuracy of the representation (Schureman, 1994). The Fourier representation is very useful in practical applications such as the computation of the propagation of the tide for a certain time interval (Schureman, 1994). Also, irregularities in the Earth's motion can be developed into Fourier series, and the tidal wave may be deformed during the propagation into shallow water due to the non-linearity of the tidal equation and this distortion observed at a certain location can also be represented by the terms of a Fourier series ((Schureman, 1994). FTM is also good for monthly analysis of tide (Rusddin et al., 2024; Foreman, 1977).

Least Squares Method (LSM) is a well-known method for carrying out objective quality control of surveying measurements by processing sets of redundant observations according to mathematically well-defined rules (Mikhail, 1981). The term 'redundant observations' implies that more observations are available than necessary to determine a set of unknowns (Hirvonen, 1979). In the treatment of adjustment by the LSM, it is assumed that all measurements are independently made and that no correlation exists between them, that is one measurement does not influence another measurement (Hirvonen, 1979). Under this assumption, one of the two conditions would exist: (1) All of the measurements have equal reliability; and (2) Each measurement can have a different reliability (Mikhail, 1981). The reliability of a measurement is given in terms of its weight (Shu, 2003). The LSM criterion states that the sum of the squares of the residuals or weighted residuals is minimum (Mikhail, 1981). The applications of the LSM criterion to the fitting of tidal parameters are only possible using computers (Shu, 2003). That is, the LSM uses Least Squares principle to solve for tidal constants and height of MSL above chart datum with the help of computer (Rusdin et al., 2024). The basic expression for harmonic analysis will be used to generate equations (observation equations, condition equations, or mixed model) (Hirvonen, 1979). The design matrices of these equations are generated and are solved with the help of computer program which based on the LSM principle (Shu, 2003). This method is good for long period observations because large values of data can be handled with high speed due to the involvement of a computer (Zhang et al., 2017; Boon and Kiley, 1978). The LSM requirement has the advantage that it determines quite objectively, a unique solution of a given adjustment problem (Mikhail, 1981). Also, the LSM algorithm is simple to program and requires a small computer memory (Rusdin et al., 2024).

Researchers has employed LSM for analysis and prediction of tidal measurements (Rusdin et al., 2024; Madah, 2020), harmonic analysis and prediction of tides (Zhang et al., 2017; Schureman, 1994; Zetler, 1982); and analysis of tides and tidal currents (Shu, 2003).

Two types of datasets employed for harmonic method of analysis are short period datasets (Ahmed et al., 2024; Pan et al., 2023; Setiyawan et al., 2022; Sabhan et al., 2021; Abubakar et al., 2019; Li et al, 2019; Meena and Agrawal, 2015; Yen et al., 1996) from between seven (7) and fifteen (15) days which can only give a value for the main (M_2, S_2, K_1, O_1)constituents of tide generating forces; and long period datasets (Rusdin et al., 2024; Li et al, 2019; Okwuashi and Olayinka, 2017) that ranges from a minimum of one month to a year, three years etc. One month observations solve for twenty eight (28) primary constituents while up to sixty eight (68) constituents can be obtained from a year observations (Madah, 2020; Morakinyo, 2003). Some previous studies such as Sabhan et al. (2021) employed 5 days datasets with 1-hour interval for analysis; Setiyawan et al. (2022) used 15 days data with a 1-hour interval for tidal analysis, 1 month data (Jiao et al., 2019; Cai et al., 2018; Yen et al., 1996), 2 months data (Choi et al., 2000), 6 months data (Slobbe et al., 2018), and 1 year data (Okwuashi and Olayinka, 2017). However, it was found that the accuracy of harmonic analysis improved significantly when the time interval is reduced (Madah, 2020; Hall and Davies, 2005). Furthermore, Madah, (2020) obtained amplitudes and phases of tidal constituents using Harmonic Analysis method with data from two stations in the Gulf of Aden.

Furthermore, the harmonic tidal constants of water bodies vary with respect to locations and time due to the following reasons: The depths and locations of the oceans and seas are different; each water body possesses different tidal characteristics and movements; the influence of meteorological effects such as wave action, surges, barometric pressure on water bodies are not equal and the response of the water bodies to the tide raising forces are not the same (Rusdin et al., 2024; Madah, 2020; Jiao et al., 2019; Ojinnaka, 2007).

Therefore, because of the significance of primary ports in hydrographic projects, it is essential to determine the reliability of data published on them since the accuracy of such information will be reflected on the derived data of secondary ports referred to these primary ports. Errors accrue in the data from primary ports are automatically transmitted to any secondary port whose analysis is made by reference to the primary port. By carrying out tidal analysis for sets of observations separated over a long period of time, it is possible to determine any changes that have taken place in the derived tidal constants and the rate of such changes. It is therefore subsequently possible to assess the stability of such tidal constants and the length of time for which such data can be used for predictions without introducing significant errors. For Bonny primary port only height of Mean Sea level (MSL) and tidal constants for four major constituents of tide are published in the Admiralty Tide Table yearly and hydrographers make use of them for different projects. Also, Hydrographer of the Navy (1988) stated that tidal levels for standard port such as Bonny should be subjected to periodic evaluation and that due to changes in the MSL they do not necessarily remain constant. In addition, oil companies such as Shell Nigeria, Liquefied natural gas (LNG), AGIP many companies etc. have also at various times carried out tidal analysis for Bonny tidal station from observations stretching over different time spans. However, most of the results of these analyses have never been published for public use. The gap before this research is that limited research on this study has been published. Hence, the basis for carried out this study. Therefore, the 3 basic research questions for this study are: (1) How many tidal constituents can be analyzed at Bonny Port? (2) Does the tidal constants for these constituents stable over a long period? (3) Can a month observation give reliable results as a year data? (4) What is the type of tide available at Bonny port? The overall aim of this research is to carry out assessment of the stability of the tidal constants obtained for the Bonny port. The following are the objectives set: (1) Monthly tidal analysis using Least Square Adjustment Method i.e. to compute tidal constants for all primary constituents using 1980, 1994 and 2018 years of tidal observations taken from the Bonny Port; (2) Comparison of monthly results of tidal constants; (3) Statistical analysis for tidal constant in order to explore the results.

MATERIALS AND METHODS

Study Site

Bonny town, a coastal town in Rivers State is one of the stations where tidal observations and analysis have been carried out in Nigeria. Bonny is an important town to Nigeria because (i) It is the home of Nigeria's largest liquefied gas project; (ii) It is located at the mouth of Bonny River estuary which is the major gateway to Nigeria's second largest port in Port Harcourt; (iii) It is one of the early ports of settlement for the colonial masters who were engaged in oil exploration.

The Bonny tidal station is the only internationally published primary port in Nigeria till date. The geographical coordinate for the tide gauge station at Bonny is located at Latitude 4° 27' N and Longitude 7° 10' E in Rivers State, Nigeria. Figure 1 show the location of Bonny town tidal station marked with red arrow and other secondary tidal ports in Nigeria. A tide gauge was established at Bonny in 1956 for the purpose of safe navigation for oil exploration (Ojinnaka, 2007). Water level data obtained from this station for a period of one year was employed for tidal analysis (Ojinnaka, 2007). The tidal constants derived from this analysis have since then been published in the yearly volume of the Admiralty Tidal Tables (ATT) and have been employed for tidal prediction through the ensuing years (Ojinnaka, 2007).

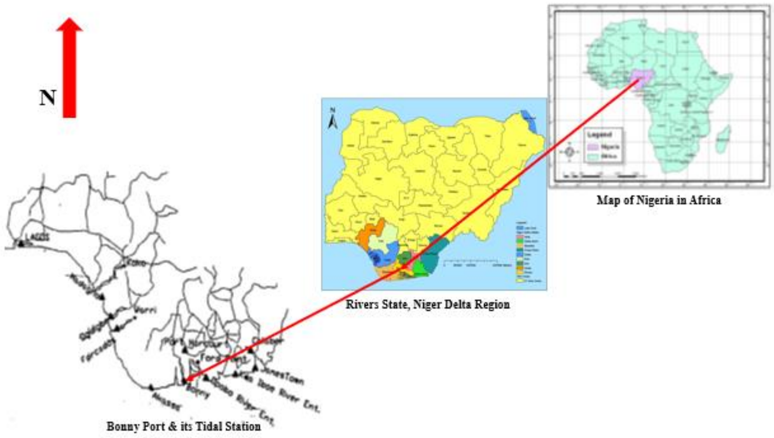

Figure 1: Locations of Bonny Port in the Rivers State, Niger Delta Region, Nigeria

Study Data

For the purpose of this study, three (3) sets of one-year data each obtained from observations made in 1980, 1994, and 2018 were used for the analysis. The data were recorded every minute of each day on monthly basis.

Methods

Least Squares Method (LSM)

In order to obtain tidal constants (the phase lag (g) and amplitude (H) of the constituents), tidal analysis (Madah, 2020; Cauwenberghe, 1992; Schureman, 1994; Stephenson, 2016) must be carried out first because two of the results obtained for tidal analysis are tidal constant. The Least Squares method (Abubakar et al., 2019; Li et al., 2019); Zetler, 1982; Rusdin et al., 2024) was employed fortidal analysis of monthly data of each year because of its accuracy advantages and computational efficiency (Abubakar et al., 2019; Li et al., 2019; Badejo and Akintoye, 2017).

MATLAB Programming codes

The MATLAB programming codes (Rusdin et al., 2024; Okwuashi and Olayinka, 2017) were used for data processing starting with the computation of equilibrium arguments and analysis of monthly tides. Each month datasets were processed independently. The yearly mean values of tidal constants were computed from the monthly values. The basic equation for tide can be expressed by the general formula in equation 1 (Rusdin et al., 2024; John, 1989; Thomson and Emery, 2014; Annunziato et al., 2016; Moore, 2020; Abubakar et al., 2021).

$$h_t = h_0 + \sum_{i=1}^{m} f_i H_i Cos(E_i + u_i + u_i t - g_i) \quad (1)$$

Where,

h_o is the height of Mean Sea Level above the chart datum;
f is the Nodal factor;
H is the Amplitude constant;
E is the phase of theoretical tide raising force at Greenwich. It increases at a rate n°/hr;
u is the Nodal correction to phase lag;
n is the speed of constituents in °/hr;
t is the time of observations;
g is the Phase lag constant at the place of observation;
h_t is the height of tide above chart datum;
m is the number of constituents.

From equation 1, the astronomical arguments (E) and the Nodal corrections (u and f) for each harmonic constituent are computed as functions of the five orbital elements s, h, P, N and P1 (Merriman, 1985).

Where,

s = Mean longitude of the moon, increasing by 0.0549017° per mean solar hour;
h = Mean longitude of the sun, increasing by 0. 041068° per mean solar hour;
P = Mean longitude of lunar perigee, increasing by 0.0 004642° per mean solar hour;
N = Mean longitude of the moon's ascending node, increasing by 0. 002206°;
P1 = Mean longitude of the solar perigee, increasing by 0.000002° per mean solar hour.

These orbital elements are calculated from the following equations:

$$s = 277.02° + 129.3848° (Y - 1900) + 13.1764° (D + i) \quad (2)$$

$$h = 280.19° - 0.2387°(Y - 1900) + 0.9857° (D + i) \quad (3)$$

$$P = 334.39° + 40.6625° (Y - 1900) + 0.1114° (D + i) \quad (4)$$

$$N = 259.16° - 19.3282° (Y - 1900) - 0.0530° (D + i) \quad (5)$$

P1= 282.8° assumed for the century 1900 to 2,000 (6)

Where,

Y = Year of observations;
D =Number of days elapsed since January first in the year;
i = The integral part of 0.25 (Y − 1901) which is the number of leap years between 1900 and the year Y, excluding Y as the leap day in this year is counted in D (Merriman, 1985).

The final formulae for the computation of the astronomic arguments E, u and f are discussed in Merriman (1984).

The observation equation technique of LSM is adopted; and the dimension of the Normal (N) matrix equations obtained for the monthly analysis is 72 × 56 i.e. 72 rows, and 56 columns. The N matrix is inverted and gave results for MSL and tidal constants (g and H) of 28 constituents of tide. The interval of 14 years between the first two sets of data, and the interval of 24 years between the second and the third is more than half of the nodal period and therefore adjudged to reflect any differences in obtained values of g and H. Figure 2 show the stages of methodology for data processing.

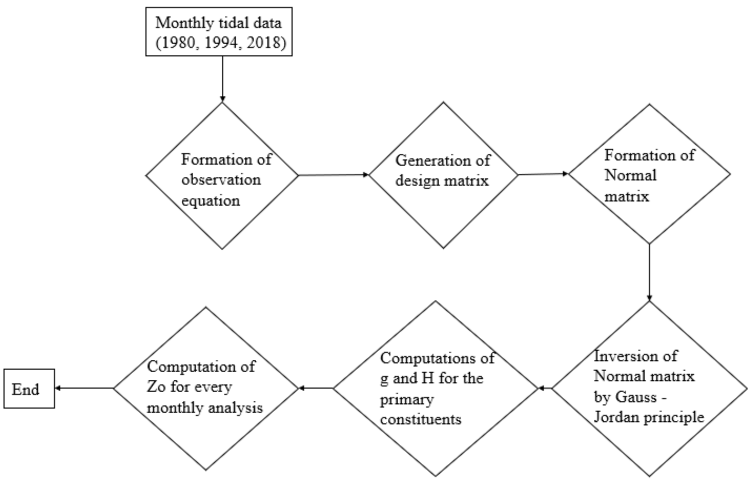

Figure 2: Methodological diagram for processing g, H and Z_o.

The results of monthly observations were subjected to statistical analysis using as mean and standard deviation (SD). The reliability of the results was evaluated by comparing the results of the monthly analysis using the following items, computed yearly mean of g and H, computed three-year mean of g and H, and computation of residuals. Even though analysis was carried out to derive the g and H of 28 primary constituents, however, only the four (4) major principal constituents were considered for the assessment because they are more frequently employed for both short and long period analysis.

Type of Tide

The type of tidal can be classified based on tidal form factors (F) calculated using amplitudes of four dominant constituents, including lunisolar diurnal K1, principal lunar diurnal O1, principal lunar semidiurnal M2, and principal solar semidiurnal S2 (Byun, and Hart, 2020; Byun et al., 2023). Among researchers that have used this method for different studies at different locations and got reliable accuracy are Parker. (1977); Amin. (1986); Daher et al. (2015); Godin and Taylor. (1973); and Lee and Chang. (2019). Tidal classification was carried out based on the ratio between amplitudes of diurnal and semidiurnal as shown in equation 7:

$$F = (HK_1 + HO_1) \div (HM_2 + HS_2). \quad (7)$$

Where,

HK_1 is the Amplitude of K_1;
HO_1 is the Amplitude of O_1;
HM_2 is the Amplitude of M_2; and
HS_2 is the Amplitude of S_2.

Tidal types are divided into four categories including $F < 0.25$ for semidiurnal; $0.25 \leq F < 1.50$ for mixed mainly semidiurnal; $1.50 \leq F < 3.00$ for mixed mainly diurnal; and $F \leq 3.00$ for diurnal.

RESULTS AND DISCUSSION

Results of Monthly Tidal Analysis

Tidal analysis of monthly data was carried out. The results for January to December for 1980, 1994 and 2018 were obtained. However, only results for January, June and December for each year are presented in Tables 1-9 in order to reduce the space. The amplitude (H) and phase lag (g) of each of the 28 primary constituents are presented. The 28 constituents are made up of five (5) diurnal tide, five (5) semi-diurnal tide, five 3-diurnal tide, five 4-diurnal tide, five 6-diurnal tide and three long period tides. Table 10 shows the 28 primary constituents and their speed.

Table 1: H and g for 28 Primary Constituents of Tide for January 1980

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.03	0.00	0.01	0.01	0.00	0.10	0.01	0.00	0.10
Phase (g)	0.00	276.93	319.49	280.26	345.47	113.33	20.36	270.09	250.79	125.24

	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.68	0.00	0.18	0.04	0.02	0.02	0.03	0.01	0.03	0.05
Phase (g)	148.90	358.14	182.42	204.99	101.62	72.32	186.76	37.88	96.61	76.24

	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.04	0.01	0.01	0.03	0.02	0.01	0.02	0.03
Phase (g)	110.43	155.19	194.18	52.30	4.38	286.31	319.92	314.32

Table 2: H and g for 28 Primary Constituents of Tide for June 1980

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.07	0.11	0.01	0.00	0.00	0.10	0.00	0.01	0.35
Phase (g)	0.00	86.71	202.57	273.38	337.18	152.30	14.36	239.04	285.69	151.81

	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.64	0.02	0.24	0.02	0.03	0.01	0.01	0.01	0.01	0.02
Phase (g)	147.18	233.17	187.13	57.50	76.74	96.16	306.91	125.45	290.79	95.86

	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.04	0.01	0.03	0.01	0.01	0.01	0.01	0.00
Phase (g)	94.85	71.47	145.11	78.95	311.02	297.95	39.12	194.72

Table 3: H and g for 28 Primary Constituents of Tide for December 1980

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.04	0.02	0.00	0.02	0.01	0.10	0.00	0.01	0.31
Phase (g)	0.00	260.32	282.71	63.20	341.92	181.12	17.76	213.36	87.05	152.99

	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.72	0.00	0.26	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Phase (g)	146.31	165.90	180.93	114.07	271.26	103.56	276.03	115.55	241.95	86.44

	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.06	0.02	0.02	0.00	0.01	0.01	0.01	0.01
Phase (g)	98.74	227.97	145.35	239.53	324.00	277.27	222.47	288.91

Table 4: H and g for 28 Primary Constituents of Tide for January 1994

	1	2	3	4	5	6	7	8	9	10
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.00	0.04	0.00	0.03	0.00	0.14	0.00	0.01	0.10
Phase (g)	0.00	343.02	74.81	185.43	345.35	298.90	16.54	183.91	293.09	115.74

	11	12	13	14	15	16	17	18	19	20
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.69	0.01	0.21	0.01	0.03	0.00	0.03	0.02	0.01	0.02
Phase (g)	148.57	19.04	187.92	181.71	142.04	332.88	345.79	76.06	20.04	110.82

	21	22	23	24	25	26	27	28
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.05	0.01	0.02	0.02	0.02	0.02	0.01	0.02
Phase (g)	108.98	223.87	229.68	189.23	352.61	22.91	329.71	143.20

Table 5: H and g for 28 Primary Constituents of Tide for June 1994

	1	2	3	4	5	6	7	8	9	10
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.03	0.03	0.01	0.03	0.01	0.06	0.01	0.01	0.23
Phase (g)	0.00	206.45	1.91	57.70	340.45	81.44	17.19	298.65	64.05	175.17

	11	12	13	14	15	16	17	18	19	20
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.67	0.01	0.21	0.03	0.02	0.01	0.01	0.01	0.01	0.02
Phase (g)	147.42	152.20	187.39	61.46	85.53	341.65	259.93	68.76	19.15	17.58

	21	22	23	24	25	26	27	28
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.03	0.02	0.01	0.01	0.01	0.00	0.01	0.00
Phase (g)	109.95	50.74	81.77	185.35	11.36	340.61	93.42	59.75

Table 6: H and g for 28 Primary Constituents of Tide for December 1994

	1	2	3	4	5	6	7	8	9	10
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.04	0.03	0.01	0.02	0.01	0.02	0.00	0.01	0.22
Phase (g)	0.00	68.28	336.31	163.84	341.99	252.57	21.89	168.54	248.10	181.03

	11	12	13	14	15	16	17	18	19	20
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.71	0.02	0.31	0.02	0.03	0.02	0.02	0.01	0.00	0.01
Phase (g)	146.62	90.36	192.58	267.92	280.27	195.49	2299.45	316.05	90.01	91.30

	21	22	23	24	25	26	27	28
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.03	0.01	0.01	0.00	0.00	0.01	0.01	0.01
Phase (g)	87.97	119.56	116.38	47.69	257.63	31.86	93.79	30.15

Table 7: H and g for 28 Primary Constituents of Tide for January 2018

	1	2	3	4	5	6	7	8	9	10
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.01	0.03	0.00	0.03	0.00	0.14	0.00	0.01	0.11
Phase (g)	0.00	55.56	70.36	193.58	343.50	316.19	18.30	252.85	286.07	114.31

	11	12	13	14	15	16	17	18	19	20
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.66	0.01	0.22	0.00	0.02	0.01	0.03	0.02	0.01	0.02
Phase (g)	146.24	342.16	189.24	225.84	170.52	295.04	335.71	79.70	148.21	119.07

	21	22	23	24	25	26	27	28
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$
Amp. (H)	0.04	0.01	0.02	0.01	0.01	0.02	0.00	0.01
Phase (g)	135.73	215.64	230.24	250.77	31.87	75.04	324.40	146.25

Table 8: H and g for 28 Primary Constituents of Tide for June 2018

	1	2	3	4	5	6	7	8	9	10
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.11	0.12	0.01	0.03	0.01	0.06	0.00	0.00	0.16
Phase (g)	0.00	156.57	344.64	12.21	347.33	47.99	10.42	297.35	181.79	125.10
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.63	0.00	0.21	0.01	0.02	0.01	0.01	0.01	0.10	0.02
Phase (g)	147.05	269.91	184.86	49.12	91.49	108.80	282.92	123.30	6.67	346.50
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**		
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$		
Amp. (H)	0.02	0.01	0.01	0.00	0.01	0.01	0.01	0.01		
Phase (g)	71.00	352.86	79.19	349.711	7.01	312.49	107.99	8.95		

Table 9: H and g for 28 Primary Constituents of Tide for December 1980

	1	2	3	4	5	6	7	8	9	10
Const.	ZO	MM	MSF	Q_1	O_1	M_1	K_1	J_1	MU_2	N_2
Amp. (H)	0.00	0.04	0.02	0.01	0.03	0.01	0.02	0.00	0.01	0.17
Phase (g)	0.00	77.98	342.93	202.42	353.97	265.53	26.81	162.84	230.84	192.32
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Const.	M_2	L_2	S_2	MQ_3	MO_3	M_3	MK_3	$2MQ_3$	$3MS_4$	MN_4
Amp. (H)	0.68	0.02	0.31	0.02	0.03	0.02	0.01	0.01	0.00	0.01
Phase (g)	147.08	80.12	184.92	302.72	321.74	40.15	313.60	46.89	92.41	110.65
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**		
Const.	M_4	SN_4	MS_4	$4MS_6$	$2MN_6$	M_6	$4MN_6$	$2MS_6$		
Amp. (H)	0.03	0.00	0.01	0.00	0.00	0.01	0.01	0.01		
Phase (g)	120.33	140.41	120.85	85.91	254.37	82.71	153.18	31.90		

Table 10: The 28 Primary Tidal Constituents and their Speed (Merriman, 1985)

S/N	Constituents	Speed (o/hr)	S/N	Constituents	Speed (o/hr)
1	Zo	0.00000	15	MO_3	42.92714
2	Mm	0.54437	16	M_3	43.47616
3	MSf	1.01590	17	MK_3	44.02517
4	Q_1	13.39866	18	$2MQ_3$	44.56955
5	O_1	13.94304	19	$3MS_4$	56.95231
6	M_1	14.49205	20	MN_4	57.42383
7	K_1	15.04107	21	M_4	57.96821
8	J_1	15.58544	22	SN_4	58.43973
9	μ_2	27.96821	23	MS_4	58.98411
10	N_2	28.43973	24	$4MS_6$	85.93642
11	M_2	28.98410	25	$2MN_6$	86.40794
12	L_2	29.52848	26	M_6	86.95231
13	S_2	30.00000	27	$4MN_6$	87.49669
14	MQ_3	42.38277	28	$2MS_6$	87.96821

The results presented in Tables 1-9 show that the H and g for K_1, O_1, M_2, and S_2 constituents are stable throughout the period of observation. Hence, the reason for further analysis.

Major Tidal Constituents for Bonny port

The four major tidal constituents (K_1, O_1, M_2, and S_2) recorded for the Bonny port are shown in Table 11. The constituents K_1 and O_1 are diurnal tide; and M_2 and S_2 are semi-diurnal tide. Their period of occurrence, angular speed, generating potential and minimum record length are presented in the Table 11.

Table 11: Major Tidal Constituents and their Parameters for Bonny Port (Merriman, 1985)

S/N	Symbol	Type	Period (hour)	Angular speed (o/hour)	Tide generating potential, CEi	Required minimum record length, TR (hours)
1	K_1	Diurnal	23.9344721	15.04107	0.53011	24
2	O_1	Diurnal	25.8193387	13.94304	0.37694	328
3	M_2	Semidiurnal	12.4206012	28.98410	0.90809	13
4	S_2	Semidiurnal	12.0000000	30.000000	0.42248	355

Statistical Analysis

The results obtained from the analysis shows that the following constituents; M_2, S_2, K_1 and O_1 remained fairly stable with standard deviations as shown in Table 12. The values in Table 12 shows the values of the means obtained from the computations; and Table 13 is for standard deviations.

Table 12: Computed Mean Value of g and H for 1980, 1994 and 2018 for M_2, S_2, K_1 and O_1

Year	M_2		S_2		K_1		O_1		MSL
	H(m)	g (°)	H (m)	g (°)	H (m)	g (°)	H (m)	g (°)	Z° (m)
1980	0.700	148.80	0.230	186.90	0.120	019.10	0.020	341.90	1.540
1994	0.700	149.00	0.240	188.30	0.140	019.00	0.020	342.30	1.540
2018	0.700	148.90	0.238	187.50	0.138	019.10	0.020	342.28	1.540
Mean	0.700	148.90	0.240	187.60	0.130	019.00	0.020	342.10	1.540

Table 13: Standard Deviations for g and H

Constituent	1980		1994		2018	
	H (m)	g (°)	H (m)	g (°)	H (m)	g (°)
M_2	0.010	1.000	0.010	1.000	0.010	1.000
S_2	0.020	2.000	0.020	2.000	0.020	2.000
O_1	0.010	4.000	0.010	4.000	0.010	4.000
K_1	0.010	3.000	0.010	3.000	0.010	3.000

From Table 13 the equivalent total propagated errors in amplitude for the 4 constituents are 0.026m, 0.036m and 0.031m for 1980, 1994 and 2018 respectively. This error is insignificant for all practical purposes for most bathymetric survey including the special-order survey category. It is therefore concluded that for the Bonny standard port, analysis of 1-month data can give reliable tidal constants which can be employed in prediction for most practical purposes. The reliability of the results was verified by comparing the monthly results using the computed g and H, and residuals from the 3-year mean. Table 14 shows the residuals of amplitude for the monthly values from the average of the values obtained from 1980, 1994 and 2018; and Table 15present the corresponding values for the phase lags. Figure 3 shows the plot of the mean values for phase lag (g) against time for M_2, S_2, K_1 and O_1; and Figure 4 for the corresponding mean values of amplitude (H) for M_2, S_2, K_1 and O_1 respectively.

Table 14: Deviations of H (m) from Mean forM_2, S_2, K_1 and O_1 for 1980, 1994 and 2018Analysis

Month	1980	1994	2018	1980	1994	2018	1980	1994	2018	1980	1994	2018
	M_2	M_2	M_2	S_2	S_2	S_2	K_1	K_1	K_1	O_1	O_1	O_1
Jan.	-0.010	0	0	-0.010	-0.020	-0.010	-0.010	0.030	-0.02	-0.010	0.010	-0.010
Feb.	0	0.010	0.010	0	0.010	0	0	0.030	0.020	0.010	0.010	0.010
March	0.020	-0.020	0.020	-0.010	0.010	0.010	0.030	0.030	0.030	-0.010	-0.010	-0.010
April	0.020	0.010	0.020	0	0	0	0	-0.010	0	0	0	0
May	0.010	-0.020	0.010	0.030	0.030	0.030	0	-0.030	-0.010	0	0	0
June	0.010	-0.020	-0.020	0.010	-0.020	0.010	-0.010	-0.010	-0.010	0	0.010	0.010
July	0.030	-0.020	-0.010	-0.010	-0.020	-0.010	0.010	0.020	0.020	-0.010	0	-0.010
August	0.010	0.010	0.010	-0.030	0.010	0.010	0.020	0.020	0.020	0.010	0	0.010
Sept	0	-0.020	0	-0.020	0	0	0	0.020	0	0.010	-0.010	0
Oct	-0.010	0	0	0	0	0	-0.020	0.020	-0.020	-0.010	0	-0.010
Nov	0	-0.010	0.010	0.030	0.020	0.030	-0.010	0	0	0.010	-0.010	-0.010
Dec	0.030	0.020	0.020	0.030	0.020	0.020	-0.010	0.010	0.010	0	0	0
Mean	0.010	0		0	0	0	0	0.010	0.010	0	0	0
SD	0.010	0.020		0.020	0.020	0.020	0.010	0.020	0.020	0.010	0.010	0.010

Table 15: Deviations of g from Mean for M_2, S_2, K_1 and O_1 for 1980, 1994 and 2018 Analysis

Month	1980	1994	2018	1980	1994	2018	1980	1994	2018	1980	1994	2018
	M_2	M_2	M_2	S_2	S_2	S_2	K_1	K_1	K_1	O_1	O_1	O_1
Jan.	2.000	2. 000	2.000	-2. 000	0	-2.000	1. 000	-2. 000	1.000	7. 000	6. 000	7.000
Feb.	0	1. 000	1.000	-2. 000	3. 000	-2.000	-2. 000	1. 000	-2.000	7. 000	4. 000	6.000
March	-1. 000	2. 000	-1.000	3. 000	2. 000	3.000	7. 000	7. 000	7.000	3. 000	1. 000	3.000
April	1. 000	1. 000	1.000	2. 000	2. 000	2.000	2. 000	4. 000	4.000	-1. 000	3. 000	-1.000
May	1. 000	-1. 000	1.000	0	1. 000	0	3. 000	-2. 000	-2.000	3. 000	-5. 000	3.000
June	0	0	0	-1. 000	-1. 000	-1.000	-5. 000	-2. 000	-3.000	-2. 000	1. 000	-2.000
July	0	2. 000	2.000	-2. 000	2. 000	-2.000	-1. 000	-3. 000	-1.000	2. 000	-2. 000	2.000
August	-2. 000	-1. 000	-2.000	0	-2. 000	0	4. 000	-4. 000	4.000	-4. 000	5. 000	-4.0000
Sept	2. 000	0	0	1. 000	1. 000	1.000	-2. 000	-2. 000	-2.000	6. 000	4. 000	5.000
Oct	2. 000	0	0	2. 000	3. 000	2.000	4. 000	1. 000	1.000	-3. 000	-7. 000	-5.000
Nov	1. 000	0	1.000	-2. 000	-1. 000	-2.000	3. 000	0	0	7. 000	4. 000	6.000
Dec	-1. 000	0	-1.000	-3. 000	5. 000	-3.000	-1. 000	3. 000	-2.000	3. 000	4. 000	3.000
Mean	0	1. 000	1.000	0	1. 000	1.000	1. 000	0	1.000	2. 000	1. 000	2.000
SD	1. 000	1. 000	1.000	2. 000	2. 000	2.000	3. 000	3. 000	3.000	4. 000	4. 000	4.000

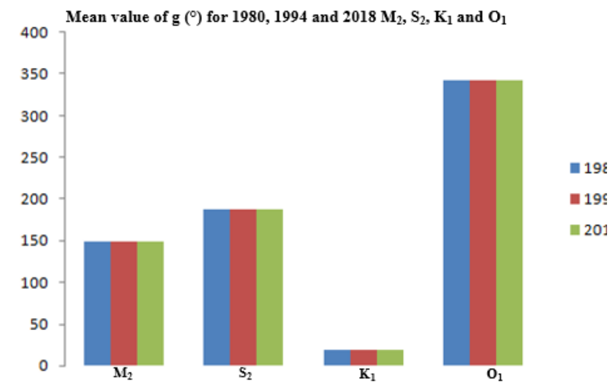

Figure 3: Mean value of g (°) for 1980, 1994 and 2018 M_2, S_2, K_1 and O_1

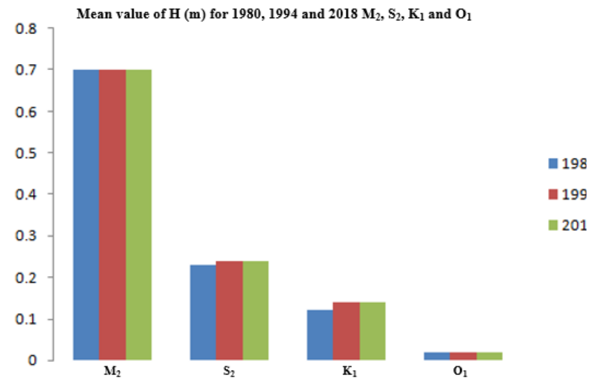

Figure 4: Mean value of H (m) for 1980, 1994 and 2018 M_2, S_2, K_1 and O_1

The maximum errors in H and g of the constituents as obtained from Tables 14 and 15 and Figures 4 and 5 are shown in Table 16. It should however be noted that maximum errors in H do not necessarily correspond to maximum errors in phase lags but the combinations in Table 15 have been chosen to allow for any possible extreme combination of errors in H and g.

Table 16: Results of Maximum Residuals for M_2, S_2, K_1 and O_1

Constituents	1980		1994		2018		Max. errors	
	e_H (m)	e_g (°)	e_H (m)	e_g (°)	e_H (m)	e_g (°)	e_H (m)	e_g (°)
M_2	0.030	2. 000	0.020	2. 000	0.020	2.000	0.030	2. 000
S_2	0.030	3. 000	0.030	2. 000	0.030	3.000	0.030	3. 000
K_1	0.030	7. 000	0.030	7. 000	0.030	7.000	0.030	7. 000
O_1	0.010	7. 000	0.010	7. 000	0.010	7.000	0.010	7. 000
Total	0.100		0.090		0.090		0.100	

Type of tide at Bonny port

The type of tide occurring at Bonny port can be calculated using equation 7.

$$F = (HK_1 + HO_1) \div (HM_2 + HS_2) \quad (7)$$

$HK_1 = 0.132$; $HO_1 = 0.020$;
$HM_2 = 0.700$; and $HM_2 = 0.237$.
Therefore, $F = (0.132 + 0.020) \div (0.700 + 0.237) = (0.152 \div 0.937) = 0.160$
Since the computed F obtained from equation 7 is 0.160 and is < 0.25.
Hence, the type of tide at the Bonny port is semidiurnal.
Furthermore, from Table 12, the spring range is given by
$R = 2(HM_2 + HS_2) = 2(0.700 + 0.240) = 1.880$ m
In the extreme case where the maximum errors in M_2 and S_2 occur simultaneously, which will also be at spring tide, the error introduced in spring range is, from Table 15:
$e = 2(eHM + eHS) = 2(0.030 + 0.030) = 0.120$m
Consequently, the error in water level introduced by the maximum error from the monthly analysis of tide is less than the allowable bathymetric uncertainty of 0.300 m in Special Order surveys (Ojinnaka, 2007). Therefore, it can be concluded that the tidal constants at Bonny Primary ports are stable and that tidal constants obtained from a properly analyzed water level from one-month data can be employed for continuous tidal prediction for fifteen years and above. Tables 14 and 15 also show that the constituents M_2, S_2, K_1 and O_1 remained fairly stable with maximum spreads of g = 4° and H = 0.050 m, g = 7° and H = 0.060 m, g = 9° and H = 0.060 m, g = 14° and H = 0.020 m respectively. It is also observed from the tables that the mean of the tidal constants for the constituents for 1980, 1994 and 2018 are in most cases equal.

CONCLUSION

Tidal analysis involves the computation of tidal constants (g and H) of the various constituents and MSL (Z_o) above the chart datum. The analysis of the results obtained show that the yearly mean of (g and H) is as good as the three-year means; and that the g and H for the four principal constituents M_2, S_2, K_1 and O_1 remained very stable over the period 38 years for which data was available for the Bonny port. This is supported by Rusdin et al. (2024) whose results of tidal analysis for Donggala port, Watusampu, and Taman Ria, Indonesia show that the most dominant and stable constituents based on g and H are the same M_2, S_2, K_1 and O_1. In addition, Okwuashi and Olayinka, (2017), and Liu et al. (2019) also supported the results. Furthermore, for M_2, S_2, K_1 and O_1, there is no significant difference in the values of g and H recorded from monthly analysis when compared with the values obtained from the mean obtained from the whole period of study. In addition, the results obtained from the computation of type of tide (F) for the Bonny port show that F at Bonny port is semidiurnal. Therefore, it can be concluded that for the Bonny primary port, the g and H are stable and that one-month tidal analysis can give reliable g and H which can be employed for predictions for several future years without introducing any significant errors. More data prior 1980 and up to date data is required for further study on this research. It is therefore recommended that the Nigerian policy makers should initiate a comprehensive policy on tidal work and sea level monitoring as aid to surge prediction and other marine activities for regular evaluation of data employed for projects in the marine environment.

REFERENCES

Abubakar, A. G., Mahmud, M. R., Tang, K. K. W., Hussaini, A., & Md Yusuf, N. H. (2019). A Review of modelling approaches on tidal analysis and prediction. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-4/W16, 23-34. https://doi.org/10.5194/isprs-archives-xlii-4-w16-23-2019 .

Abubakar, A. G., Mahmud, M. R., Tang, K. K. W., & Husaaini, A. (2021). The determination of tidal constituents using Wavelet Base Harmonic at the Strait of Malacca. IOP Conference Series: *Earth and Environmental Science*, 731, 012001. https://doi.org/10.1088/1755-1315/731/1/012001 .

Ahmed, A. A. M., Jui, S. J. J., AL-Musaylh, M. S., Raj, N., Saha, R., Deo, R. C., & Saha, S. K. (2024). Hybrid deep learning model for wave height prediction in Australia's wave energy region. *Applied Soft Computing*, 150, 111003. https://doi.org/10.1016/j.asoc.2023.111003 .

Amin, M. (1986). On the conditions for classification of tides. *The International Hydrographic Review*, 63(1), 161-174.

Annunziato, A., & Probst, P. (2016). Continuous harmonics analysis of sea level measurements: Description of a new method to determine sea level measurement tidal component. *Publications Office of the European Union*, Luxembourg, Luxembourg. https://doi.org/10.2788/4295 .

Badejo, O. T., & Akintoye, S. O. (2017). High and low water prediction at Lagos harbour, Nigeria, *Nigerian Journal of Technology*. https://doi.org/10.4314/njt.v36i3.39 .

Boon, J. D., & Kiley, K. P. (1978). Harmonic analysis and tidal prediction by the method of least squares: A user's manual. Virginia Institute of Marine Science, Virginia, United States.

Byun, D. S., Hart, D. E., Kim, S., & Ha, J. (2023). Classification of monthly tidal envelopes in mixed tide regimes. *Scientific Reports*, 13(1), 4786. https://doi.org/10.1038/s41598-023-31657-x .

Byun, D. S., & Hart, D. E. (2020). A monthly tidal envelope classification for semidiurnal regimes in terms of the relative proportions of the S_2, N_2, and M_2 constituents. *Ocean Science*, 16(4), 965-977. https://doi.org/10.5194/os-16-965-2020 .

Cai, S., Liu, L., & Wang, G. (2018). Short-term tidal level prediction using normal time-frequency transform, *Ocean Engineering*. Elsevier, 156: 489-499.

Cartwright, D. E. (1980): Report on tides and surges. *The Hydrographic journal*, 1(3): 31-33, published by the Hydrographic society, London.

Cartwright, D. E., & Edden, A. C. (1973). Corrected tables of tidal harmonics. Geophysical Journal of the Royal Astronomical Society, 33(3): 253-264. https://doi.org/10.1111/j.1365-246X.1973.tb03420.x .

Cauwenberghe, C. V. (1992): Harmonic tidal predictions along the Belgium *Coast*. The *hydrographic journal*, 63, 31-47, published by the hydrographic society, London.

Choi, I. C., Mok, K. M., & Tam, S. C. (2000). Solving harmonic sea-level model with Kalman filter: a Macau case study, *Carbonate Beaches*, 38-52. https://doi.org/10.1061/40640(305)4 .

Daher, V. B., Paes, R. C. de O. V., França, G. B., Alvarenga, J. B. R., & Teixeira, G. L. G. (2015). Extraction of tide constituents by harmonic analysis using altimetry satellite data in the Brazilian coast. *Journal of Atmospheric and Oceanic Technology*, 32(3): 614-626. https://doi.org/10.1175/JTECH-D-14-00091.1 .

Ezisi, O. P., Ezugwu, N. C., & Mmonwuba, C. N. (2024). The impact of 2018 Earth tremors on groundwater quality in the Federal Capital Territory, Abuja. *FUDMA Journal of Sciences (FJS)*, 8(6): 1-4.

Foreman, M. G. G. (1977). *Manual for tidal heights analysis and prediction*. Institute of Ocean Sciences, Patricia Bay, British Columbia, Canada.

Godin, G., & Taylor, J. (1973). A simple method for the prediction of the time and height of high and low water. *The International Hydrographic Review*, 50(2): 75-81.

Haigh, I. D. (2017). Tides and water levels, *Encyclopedia of Maritime and Offshore Engineering*, pp. 1-13. https://doi.org/10.1002/9781118476406.emoe122 .

Hirvonen, R. A. (1979): *Adjustment by Least Squares in Geodesy and photogrammetry*, Fredrick Ungar Publishing Company, New York, USA.

Hydrographer of the Navy (1988): *Admiralty Tide Tables and Tidal Streams*, Vol. 2, Printed in England, U.K.

Hydrographer of the Navy (1964). *Harmonic Tidal Analysis for Short Period Observations*.

Joan, B. (1989): *Waves, Tides and Shallow - Water process*, 1st edition, Pergamon press limited, England.

Lee, S. H., & Chang, Y. S. (2019). Classification of the global tidal types based on Auto-correlation Analysis. *Ocean Science Journal*, 54(2): 279-286. https://doi.org/10.1007/s12601-019-0009-7 .

Li, S., Liu, L., Cai, S., & Wang, G. (2019). Tidal harmonic analysis and prediction with least-squares estimation and inaction method. Estuarine, *Coastal and Shelf Science*, 220: 196-208. https://doi.org/10.1016/j.ecss.2019.02.047 .

Madah, F. A. (2020). The amplitudes and phases of tidal constituents from Harmonic Analysis at two stations in the Gulf of Aden. *Earth Systems and Environment*, 4(2), 321-328. https://doi.org/10.1007/s41748-020-00152-y .

Meena, B. L., & Agrawal, J. D. (2015). Tidal level forecasting using ANN. Procedia Engineering, 116(1): 607-614. https://doi.org/10.1016/j.proeng.2015.08.332 .

Meriman, A. G. (1985). *Harmonic tidal analysis. Errors due to Poor Inferences*. *The Hydrographic Journa*l, UK

Mikhail, M. (1981): *Analysis and Adjustment of Survey Measurements*, 1st Edition, published by Van Nostrand Reinhold Company Ltd, New York

Moore, R. A. (2020). *Characterization of seasonal variability in tides*. Department of Mathematics, The University of Utah, Salt Lake City, United States.

Morakinyo, B. O. (2003). *Evaluation of Stability of Tidal Constants for Bonny Standard Port.* M.Sc. Dissertation, Department of Geoinformatics & Surveying, University of Nigeria, Enugu Campus, Enugu State, Nigeria.

Ojinnaka, O. C. (2007). *Principles of Hydrographic Surveying: From Sextant to Satellite*. El 'Demak Publishers, Enugu State, Nigeria.

Okwuashi, O., & Olayinka, D. N. (2017) Tide modelling using the Kalman filter, *Journal of Spatial Science*. Taylor & Francis, 62(2): 353-365. https://doi.org/10.1080/14498596.2016.1245162 .

Pan, H., Xu, T., & Wei, Z. (2023). A modified tidal harmonic analysis model for short-term water level observations. Ocean Modelling, 186, 102251. https://doi.org/10.1016/j.ocemod.2023.102251

Parker, B. B. (2007). *Tidal analysis and prediction*. Silver Spring, Department of Commerce, Maryland, United States.

Parker, B. B. (1977). *Tidal hydrodynamics in the Strait of Juan de Fuca--Strait of Georgia (No. 69)*. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Survey, Silver Spring, Maryland, United States.

Pugh, D. T. (1987): *Tides, surges, mean sea level*. A Handbook for Engineers and Scientists, John Wiley and Sons, Chichester England.

Rusdin, A., Oshikawa, H., Divanesia, A. M. A., & Hatta, M. P. (2024). Analysis and prediction of tidal measurement data from temporary stations using the Least Squares Method. *Civil Engineering Journal*, 10(2): 384-403, (E-ISSN: 2476-3055; ISSN: 2676-6957).

Sabhan, S., Badaruddin, Kurniawan, M., & Rusydi, M. (2021). Tidal and bathymetry characteristics after the 2018 earthquake and tsunami in Watusampu Waters, Palu Bay, Central Sulawesi. Natural Science: *Journal of Science and Technology*, 10(1): 26-30. https://doi.org/10.22487/25411969.2021.v10.i1.15505 .

Schureman, P. (1994). *Manual of harmonic analysis and prediction of tides (No. 98)*. US Department of Commerce, Coast and Geodetic Survey, Washington, United States.

Setiyawan, Rusdin, A., Amaliah, T., & Olphino. (2022). *Potential of tidal power plants on Tibo Beach with spectrum method*. IOP Conference Series: Materials Science and Engineering, 1212(1), 012039. https://doi.org/10.1088/1757-899x/1212/1/012039 .

Shu, J. (2003). Prediction and analysis of tides and tidal currents. *International Hydrography Review*, 4(2), New Series, 57-64.

Slobbe, D. C., Sumihar, J., Frederikse, T., Verlaan, M., Klees, R., Zijl, F., & Broekman, R. (2018). A Kalman filter approach to realize the lowest astronomical tide surface. *Marine Geodesy*, 41(1): 44-67.

Stephenson, A. G. (2016). Harmonic analysis of tides using tide harmonics. The Comprehensive R Archive Network (CRAN). Retrieved 26 June 2024 from: https://cran.biotools.fr/web/packages/TideHarmonics/vignettes/austides.pdf

Susanto, R. D., Gordon, A. L., Sprintall, J., & Herunadi, B. (2000). Intra-seasonal variability and tides in Makassar Strait. *Geophysical Research Letters*, 27(10): 1499-1502. https://doi.org/10.1029/2000GL011414 .

Thomson, R. E., & Emery, W. J. (2014). *Data analysis methods in physical oceanography* (3rd Ed.). Elsevier Science, Amsterdam, Netherlands. https://doi.org/10.1016/C2010-0-66362-0 .

Wang, W., & Yuan, H. (2018). A tidal level prediction approach based on BP Neural Network and Cubic B-Spline Curve with Knot Insertion Algorithm.

Yen, P.-H., Jan, C.-D., Lee, Y.-P., & Lee, H.-F. (1996). Application of Kalman Filter to short-term tide level prediction. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 122(5): 226-231. https://doi.org/10.1061/(asce)0733-950x(1996)122:5(226) .

Zetler, B. D. (1982). *Computer applications to tides in the national ocean survey (No. 98)*. National Oceanic and Atmospheric Administration, National Ocean Survey, Silver Spring, Maryland, United States.