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Monitoring of Tidal Datum Consistency for Nwaniba River in the Niger Delta

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Abstract This research examines the consistency of the value of tidal datum obtained for Nwaniba River in Akwa Ibom State of the Niger Delta (Nigeria). Two sets of tidal data from 10/05/2007-10/06/2007 and 10/05/2017-10/06/2017 observed three times a day (Morning: 7: 30-9: 30; afternoon: 12: 00-14: 00 and evening: 16: 00-18: 00) at every 2 minutes interval were considered in order to evaluate a trend. Mean Highest Water Level (MHWL), Mean Lowest Water Level (MLWL) and Mean Water Level (MWL) for the three times per day were computed. The weekly MHWL and MLWL for each of the 5 week; average MHWL and MLWL for the 5 weeks were also computed. The water level measured within (10/05/2017-10/06/2017) is higher than that of (10/05/2007-10/06/2007) except in few cases. The highest (149.000 cm) and lowest (1.80 cm) water levels for 2007 observation were recorded on 08/06/2007 at (08: 40) and on 10/05/2007 at (7: 46) and 23/05/2007 at (8: 28) respectively; while the highest (152.300 cm) and lowest (1.801 cm) water levels for 2017 observation were recorded on 15/05/2017 at (07: 53) and on 27/05/2017 at (9: 08) and on 08/06/2017 at (08: 32) respectively. The observed Lowest Water Level (LWL) of 1.800 cm was adopted as the tidal datum for Nwaniba River in 2007. The observed LWL for 2017 is 1.801 cm; and the difference between the 2017 LWL and 2007 LWL which is (δ_{LWL}) is 0.001 cm. The value of (δ_{LWL}) = 0.001 cm shows that the value of LWL of 1.800 cm adopted in 2007 as the tidal datum still remains consistent when compared to the observed LWL of 1.801 cm for 2017 observations. Based on the LWL obtained for 2007 and 2017, it can be concluded that the tidal datum for Nwaniba River is consistent from 2007 to 2017. Also, based on the difference between average MWL for 2007 and 2017 = (δ_{MWL}) = 1.247 cm, it can be concluded that the water level at Nwaniba River has increased with 1.247 cm for the period of observation. In addition, the range of values of R^2 obtained is 0.000-0.046 i.e. 5 %, which shows that only 5 % of the variation in MHWL and MLWL can only be attributed to the variation in time.

Keywords: *tidal datum, Mean Highest Water Level (MHWL), Mean Lowest Water Level (MLWL), Mean Water Level (MWL), Nwaniba river, Niger delta*

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1. Introduction

Tide is a periodical vertical movement in the level of the surface of the seas or oceans caused by the gravitational attraction between the rotating Earth, Moon, and Sun [1,2]. Tide is essentially of astronomical origin and oscillatory in nature [3,4,5]; and the most tide generating forces are Moon and Sun [1,3]. 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 [6,7]. As tides rise, the tidal current flowing from the oceans into bays and estuaries is called a flood tide while as tides fall, the ebb tide flows back toward the oceans [8,9]. For short periods, as tides reverse, a slack tide occurs with little or no current [1]. Because the Earth is closer to the Moon than the Sun, the Moon’s gravitational pull has a larger influence (more than twice of the tide generating force due to the Sun) on tides [1,6,8]. Therefore, tidal cycles follow the lunar orbit, which takes 24 hours and 50 minutes (one lunar day). High tides occur approximately every 12 hours and 25 minutes, or one-half of a lunar day [4,7,9].

Three types of astronomical tides (Semi-diurnal, diurnal and mixed) occur globally, depending on the bathymetry, or the shape of the seafloor, and the shape and size of the coastlines at a given location [1,5]; and the tide that results at any location is unique [3]. Semidiurnal tides has two high tides and two low tides occur each day, with both highs reaching similar elevations and both lows reaching similar elevations; diurnal tides has one high and one low tide occur each day; and mixed semidiurnal tides has two high tides and two low tides occur each day, with each of the four tides reaching different elevations [2,8]. During full and new moons, spring tides (a larger than average tidal range) occur because the Sun and the Moon are aligned with respect to the Earth. During quarter Moons, when the gravity of the Sun and the Moon are opposed a smaller than average tidal range occurs known as neap tides [1,5].

The tide is usually expressed in terms of tidal constituents [4]; and the relative amplitudes of each constituent of tide depend on location [3,6]. The most important constituents of semi-diurnal tides are M_2, S_2, K_2 and N_2 [9,11]. M_2 is the basic carrier wave produced by the semi-diurnal part of the attractive force of a fictitious Moon which proceeds round the celestial equator at a fixed distance in aperiod 24.84hrs. It has a period of 12.42 hrs and a speed of 28.984°/hr, and amplitude which is assumed to be 1 [11]. S_2 is the basic carrier wave produced by the semi-diurnal part of the attaractive force of the Sun which proceeds round the celestial equator at a fixed distance in a period of 24 hrs [11]. It has a period of 12 hrs and a speed of 30˚ /hr and amplitude of 0.46 of M_2 [9,11]. K_2 depends on the variation in the declination of the Moon and the Sun [9,11]; therefore K_2 is called the lunar-solar declinational semi-diurnal constituent [8,9]. The effect of the variation of the distance from the Moon determines the N_2 constituents and is called the lunar-elliptic semi-diurnal constituent [2,10]. Also, the most important constituents of diurnal tides are K_1, O_1, and P_1. K_1 is the lunar-solar declination diurnal constituent, O1 is called lunar declinational diurnal constituent and P1 is the declinational diurnal constituent [2,5,9,11]. The lunar constituents K_1 and O_1 combine to express the diurnal tide raising force of a fictitious Moon which moves in a circular orbit, but changed its declination bewteen the mean limits of declination reached by the real Moon. The lunar K_1 has a speed of 15.04107°/hr and amplitude 0.40 of M_2 while O_1 has a speed of 13.94304°/hr and amplitude 0.41 of M_2. The solar K_1 has a speed of 15.04107°/hr and amplitude 0.18 of M_2; and it has exactly the same speed as the lunar and cannot in practice be distinguished from it. The two are combined to form a luni-solar K_1. P_1 has a speed of 14.95893˚/hr and amplitude 0.19 of M_2. The difference between the amplitudes of the solar K_1 and P_1 is 0.007. When the Sun has a maximum North or South, they will be in phase and their amplitudes will be added, causing the Sun's diurnal tide to be greatest. When the Sun is on the celestial equator they will have opposite phases (180° apart), their amplitudes will be subtracted causing Sun's diurnal tide to be very small [11].

A tidal datum is a plane of reference for elevations, determined from the rise and fall of the tides [12,13]. The tidal datum is that level of water surface adopted which the tide rarely falls [14]. Many disciplines require accurate estimates of tidal datums [15,16,17]. Some examples are tsunami and storm surge modelling, coastal zone management, nautical charting and elevations on map, and environmental studies [18]; navigation and shipping, shoreline construction [15,19]; measurement of local water levels [12,20]; designing of engineering structures in coastal regions [21]; delineation of shore line, engineering and scientific investigations [22] and maritime boundary [12]; restoration of marshes [23]; measurements of height and depth [14,24]; and determination of marine boundaries [14,25,26].

There are numerous tidal datum planes adopted by different countries and each is used for a specific purpose or helps describe some tidal phenomena [13]. For example, the planes of Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Sea Level (MSL), Mean Tide Level (MTL), Mean Low Water (MLW), and Mean Lower Low Water (MLLW) are commonly used in the United States [22,27,28,29,45]. Malaysia adopted Lowest Astronomical Tide (LAT) as a reference datum for marine cadastre because of its consistency [12] while New Zealand is using Mean High Water Spring (MHWS) [38].

Global Positioning Systems (GPS) is a technology for quickly and cost saving determination, delineation and measurement of tidal datums [30]. However, the accuracy of the tidal datums depends strongly on both the duration of the water level observations and the type of tide [22,31]. The distribution of tidal datums in a region can be refined to high spatial resolution through the use of numerical tide models [32]. Several methods are employed for the computation of tidal datums; such methods include harmonic constant datum (HCD) method [18,33]. The method results in high resolution grids of tidal datums that are consistent with observed datums and tidal dynamics. HCD method leads to datum estimates that are comparable in accuracy with those derived from short-term tertiary stations. While it is possible to generate 19 years predictions from numerical tide models and then average various high and low waters to generate datums, it is far more computationally efficient for large model grids to use the HCD method [18]. The HCD method is employed to estimate tidal datums relative to MSL, without the need to compute long time series. However, datum discontinuities can occur between mixed and diurnal tidal regimes using this method [18]. Solutions to this problem are investigated, with hypothetical straits that contain a semidiurnal node, using three different procedures: algorithms specifically designed for diurnal tides (DTA), mixed tidal algorithms (MTA) throughout, and cubic polynomial interpolation (CPI) across the diurnal region. The method that works best depends on the size of the diurnal region and the application [18].

Also, the United States of America (USA) National Ocean Service Algorithms applied to tidal readings obtained from the fixed gauges is another method for the computation of tidal datum [32]. However, the physical gauges are expensive to install and maintain, and they suffer certain practical limitations such as requiring a storm-resistant platform and convenient access [32]; but they explored a modelling approach as a supplement to physical gauges whereby physical gauges at boundaries drive a calibrated numerical model from which the calculated time series of water level at any internal grid point was considered as a numerical gauge. The favourable comparison indicates the viability of the numerical gauge concept [32].

Other methods adopted for the computation of tidal datums are the statistical interpolation, deterministic [14,25], benchmark to project site, standard method, and amplitude ratio [34,35]. The statistical interpolation method was derived from the variational principle by blending the modelled and the observed tidal datums [36,37]. Advantages of the method include (1) Its capability to integrate data from different sources and with different accuracies without concern for their relative spatial locations. (2) It provides a spatially varying uncertainty for the entire domain in which data is being integrated. (3) It reduces the bias, maximum absolute error, mean absolute error, and root mean square error in comparison to the deterministic approach [25]. Deterministic interpolation method is helpful for (1) Decision making process for where new instruments would be most effectively placed [25]. (2) It can be used to generate a spatially continuous tidal datum distribution over the water. If a hydrodynamic tidal model exists in that region, tidal datums derived from the tidal model can be used as the first estimate field tidal datum as the reference plane is a challenge. Overall, the statistical interpolation method is a better data processing and management tool, and it produces a better tidal datum product with lower uncertainty when compared with deterministic method [25].

The transfer of tidal datums using high rate GPS buoys [38] offers advantages such as ability to determine heights relative to an absolute reference frame; and for long-term datum determination [39], over traditional techniques, which are limited by their practicality, efficiency, accuracy and cost [40]. Two general methods for transferring tidal datums as levelling (either spirit or GPS levelling) and tidal datum transfer techniques were discussed by [41]. They stated that levelling method is time consuming, expensive and typically requires extensive logistics, such as traffic management planning; and that it ignores local sea surface effects. In addition, they explained that tidal datum transfer methods can be used, where a temporary tide gauge is set up at a remote site and the datum transferred by comparing tidal observations at both the temporary and a nearby permanent gauge. They concluded that GPS buoys are a viable means of tidal datum transfer. Furthermore, [38] stated that the use of GPS buoys has the following advantages for tidal datums transfer: Efficient datum connections between the GPS buoy and benchmark; expedient and relatively easy data collection; existing GPS equipment can be used. GPS buoys can be deployed in close proximity to the shore and do not have to be attached to an existing tide gauge instrument.

Tidal stations are grouped into three namely, primary tide stations that are generally operated for 19 or more years and are expected to continuously operate in the future. They are used to obtain a continuous record of water levels in a locality [6,12]. Secondary tide stations are those that are operated for less than 19 years but at least 1 year to have a planned finite life time [6]. Tertiary tide stations are those that are operated from 7 days and above but less than 1 year [25]. Short term water level measurement station may have their data reduced to equivalent 19 years through mathematical simultaneous comparison with a nearby control station [22]. Tidal datum is frequently computed using 30 days tide observations at the project site [6,14,25].

Tidal datum elevations vary significantly with geographic distance especially in shallow water; and should not be extended into areas having differing oceanographic characteristics without substantiating measurements. In order to recover tidal datums when needed, such datums should be referenced to bench marks [12,20]; and correction to such datum is always necessary [42]. Correcting for differences in tidal datums can be difficult in locations where there is a lack of long term tide stations or where the tidal characteristics change rapidly over short distances [18]. The amount of error that occurs in tidal datum determination affects the true location; causing determination of a shoreline to be varies considerably from the true location [22]. In addition, the lateral extent of an error in tidal datum is a function of the cotangent of the angle of the beach slope. Thus, a small error in the vertical determination can lead to a considerable error in the location of the boundary, particularly on beaches with small slopes [22]. Lastly, tidal datum needs to be monitored periodically because of the geologic changes to the surface of the Earth due to the subsidence and uplift or gradual changes in sea level [43].

The aim of this research was to monitor the consistency in the computed value of tidal datum obtained for Nwaniba River in Akwa Ibom State of the Niger Delta (Nigeria).

2. Materials and Methods

2.1. Study Area

Nwaniba River is situated in Uruan Local Government Area of Akwa Ibom State, South-South region of Nigeria between the Latitudes of 5° 51^1 to 5° 52^1 North and Longitudes of 8° 41^1 to 8° 42^1 East (Figure 1). The area has an annual rainfall of about 2500mm with a mean annual temperature of 32 °C and a relative humidity of 75 %. The main source of Nwaniba River is Calabar - Itu River which runs from the Atlantic Ocean. During high tides it flows to Oron River and returns during low tides [44]. The River has a beach called Nwaniba beach which serves as harbour for logging activities, peasant fishing and other domestic activities like bathing and laundry. The bank of the river is mostly covered with grass such as Elephant grass and watercress. Also, mangrove swamp vegetation including shrubs and trees such as white mangrove, screw pine, mangrove palm, and other pneumatophorous plant with prop roots are present. Nwaniba River is the Le Meridian Hotel and Tourist Resort (Ibom Five Star Hotel) which attracts foreigners to the locality [44].

2.2. Characteristics of the Tide

The tide does not move at a uniform rate in its rise and fall. The rise and fall of the tide at any place is characterized by numerous features which differ at different places. The most three principal features are time of tide, range of tide, and type of the tide [8,13]. The time of tide has reference to the times of occurrence of high and low water with respect to the moon's meridian passage. That is, as a characteristic feature of the tide at a given place, the time of tide is specified by the high water and low water lunitidal intervals. These intervals are not constant, but vary periodically within relatively narrow limits as a whole. However, the time of tide is only of minor importance in connection with the determination of tidal datum planes [8,9,13]. The range of tide has reference to the magnitude of rise and fall of the tide. Moreover, the range of tide at any given place is not constant, but varies from day to day, the average rise and fall being called the mean range. In some localities the variation from the mean range is relatively small, but in others the variation may be considerable. The type of tide has reference to the characteristic form of the rise and fall of the tide as revealed by the tide curve. The type of tide is an important matter in connection with tidal datum planes [31].

2.3. Tidal Observation

The measurement of tide is called tide observation. Short period observation from between 7 and 15 days and long period observation that ranges from a minimum of 1 month to 19 years are two types of observation for tidal datum [6]. Ideally, it would be advantageous to have tidal records with close geographical spacing over 19 years period for use in determining the tidal datums in question. This is challenging as well as prohibitively expensive [6,22].

Tide gauge is the device used for the measurement of changes in water level; and there is Automatic and Manual tide gauge. The Manual tide gauge adopted for this research is a vertical staff of about 3.5 m long with painted graduations. The graduation and figures of the staff was made bold enough to be able to read from a distance. Data from daily observation with 3 sessions (Morning: 7.30-9.30; afternoon: 12.00-14.00; and evening: 16.00-18.00) of 1 month at an interval of 2 minutes for 10/05/2007-10/06/2007 and 10/05/2017-10/06/2017 was employed for the research. Changes in the direction of water flow from Oron to Itu at low tide and vice versa at high tide at every 6 hours were observed.

3. Results

MHWL and MLWL observed for the three times per day for the period of observation are plotted and are shown in Figure 2 and Figure 3**.** The weekly MHWL and MLWL for each of the 5 week, average MHWL and MLWL for the 5 weeks are presented in Figure 4. The MWL observed for 7: 30-9: 30, 12:00-14: 00 and 16:00-18:00 for (10 / 05 / 2007-10 / 06 / 2007) are 79.242 cm; 77.818 cm and 91.877 cm and for (10 / 05 / 2017-10 / 06 / 2017) are 80.031 cm; 79.135 cm and 93.513 cm respectively are presented in Figure 5. In addition, the average MWL for the period (10 / 05 / 2007-10 / 06 / 2007) is 82.979 cm while for the period (10 / 05 / 2017-10 / 06 / 2017) is 84.226 cm.

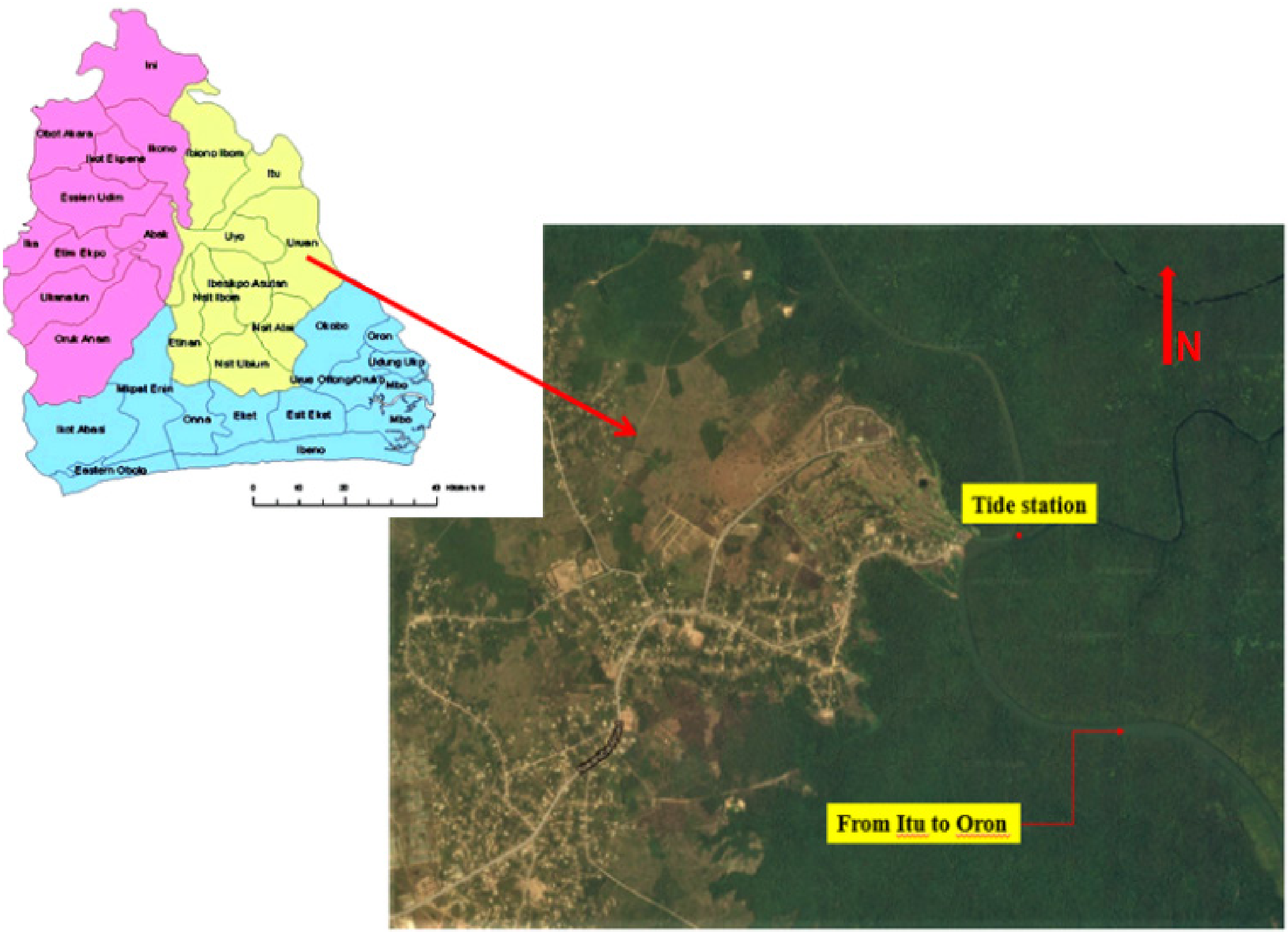

Figure 1. The location of Tide Station at Nwaniba River in Nwaniba village, Uruan LGA, Akwa Ibom State (Google Earth, 2018)

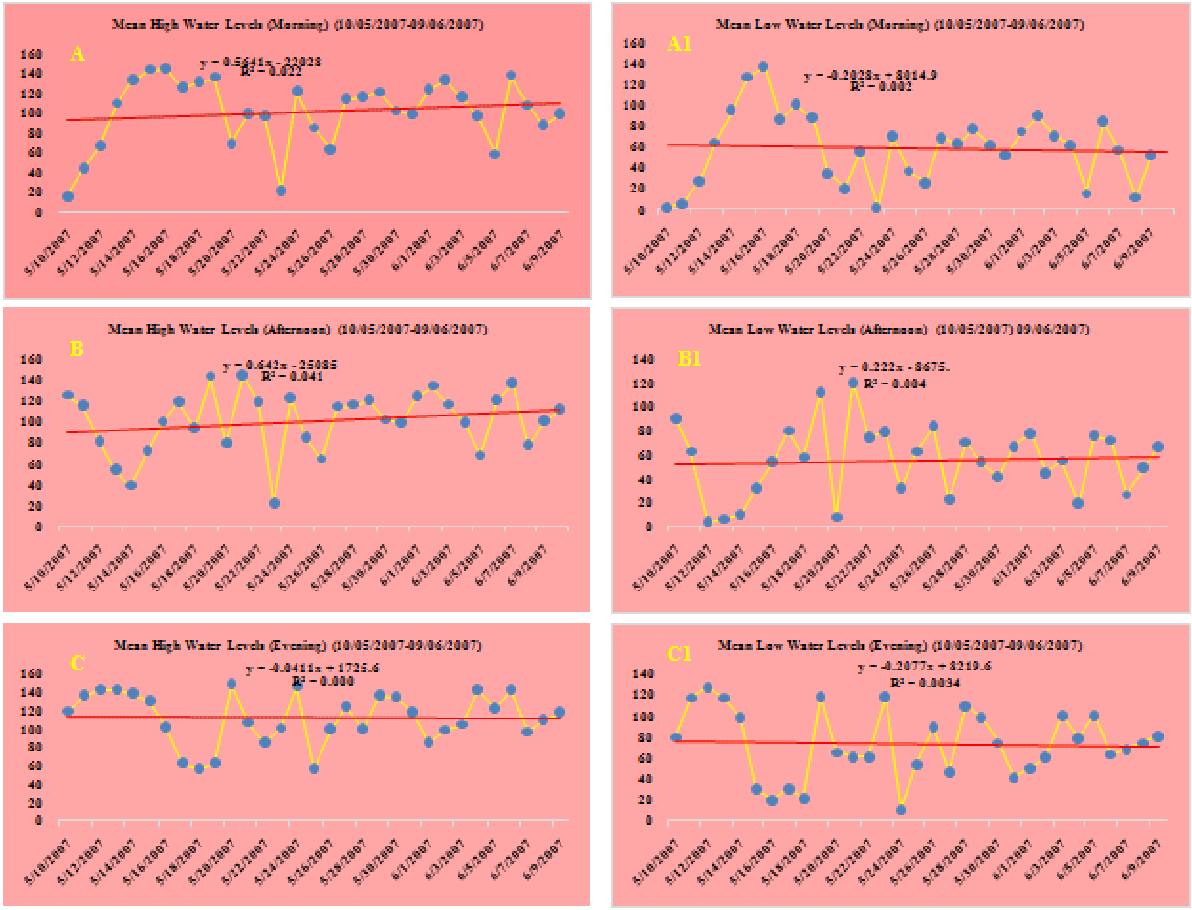

Figure 2. MHWL (A, B, & C) & MLWL (A1, B1, & C1) (10/05/2007-10/06/2007)

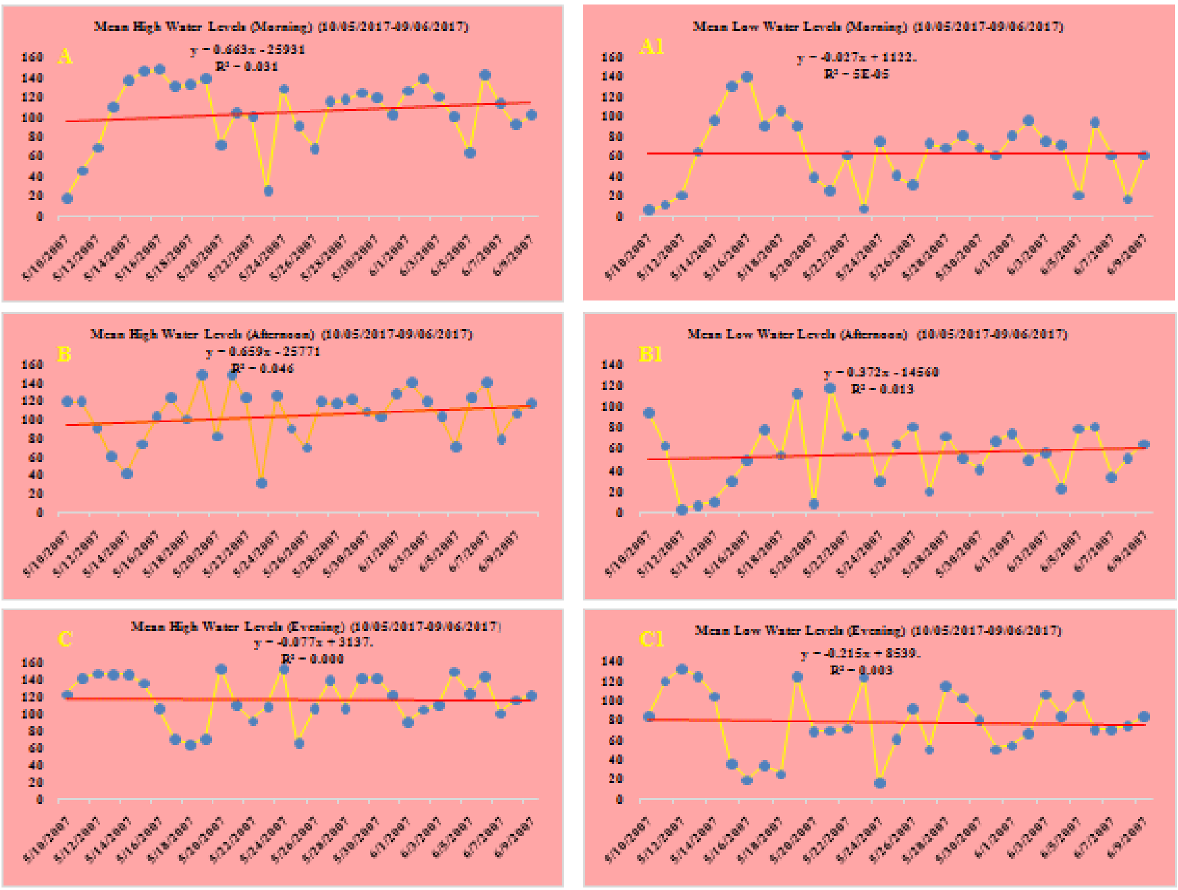

Figure 3. MHWL (A, B, & C) & MLWL (A1, B1, & C1) (10/05/2017-10/06/2017)

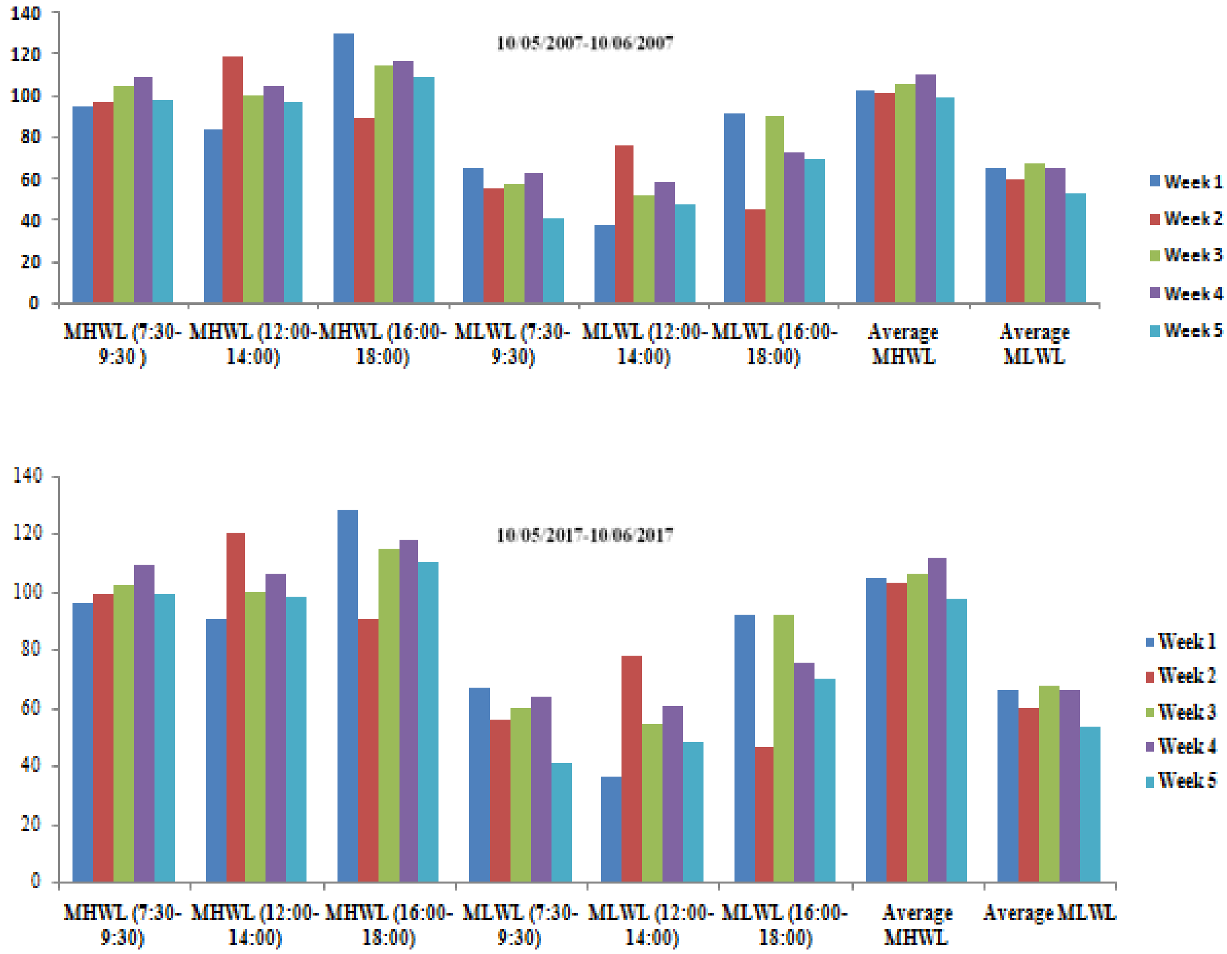

Figure 4. MHWL, MLWL, Average MHWL (Weekly), Average MLWL (Weekly) for 10/05/2007-10/06/2007 and 10/05/2017-10/06/2017

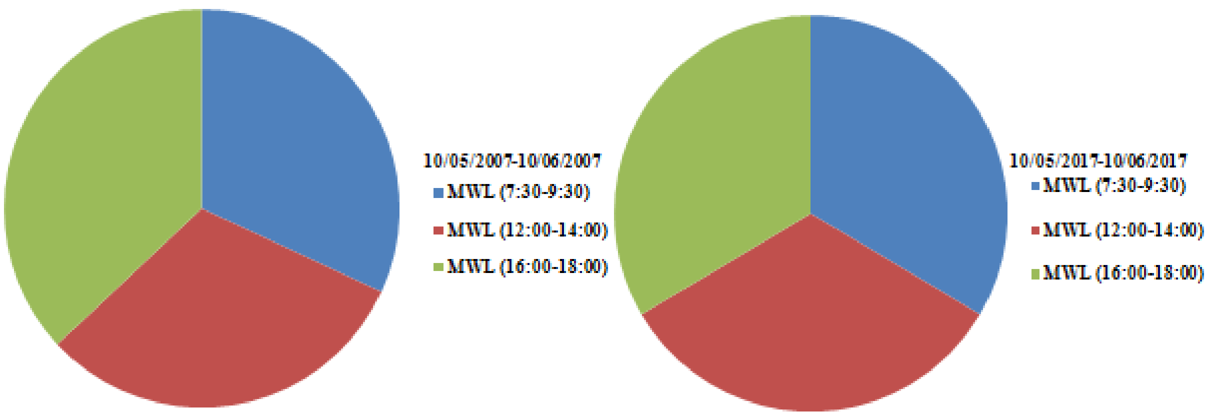

Figure 5. MWL for (7: 30-9: 30), (12: 00-14: 00) and (16: 00-18: 00) for (10/5/2007-10/6/2007) and (10/5/2017-10/6/2017)

4. Discussions

Generally, the water levels changes at each time of observation, and when compared the water level measured within (10/05/2017-10/06/2017) is higher than that of (10/05/2007-10/06/2007) except in few cases. Figure 4 also shows that the MWL for the 3 sessions of observation differs, with (10/05/2017-10/06/2017) higher than that of (10/05/2007-10/06/2007). For 2007 observations, the highest water level 149 cm was recorded on 08/06/2007 at 08: 40 and the lowest water level is 1.80 cm on 10/05/2007 at (7: 30-9: 30), 23/05/2007 at 7: 30-9: 30; while for 2017 observations, the highest water level 152.3 cm was recorded on 15/05/2017 and 27/05/2017 (7: 30-9: 30) and the lowest value of 1.801 cm was recorded on 08/06/2017 at (7: 30-9: 30). The Lowest Water Level (LWL) of 1.80 cm was adopted as the tidal datum for Nwaniba River in 2007. LWL observed in 2017 is 1.801 and the difference between 2007 LWL and 2017 LWL = (δ_{LWL}) = 0.001 cm, which shows that the value of 1.80 cm adopted as the tidal datum still remains consistent when compared to 1.801 cm obtained for 2017 observations. In addition, the difference between average MWL for 2007 and 2017) = (δ_{MWL}) = 1.247 cm. In addition, the range of values of R^2 obtained is 0.000-0.046 i.e. 5 %, which shows that only 5 % of the variation in MHWL and MLWL can only be attributed to the variation in time. This is supported by [13] who stated that the time of tide is only of minor importance in connection with the determination of tidal datum planes.

5. Conclusions

The Lowest Water Level (LWL) of 1.8 cm was adopted as the tidal datum for Nwaniba River in 2007. LWL observed in 2017 is 1.801 cm which shows that the value of 1.80 cm adopted as the tidal datum still remains consistent when compared to 1.801 cm obtained for 2017 observations. Based on the LWL obtained for 2007 and 2017, it can be concluded that the tidal datum for Nwaniba River is consistent from 2007 to 2017. Also, based on the difference between average MWL for 2007 and 2017) = (δ_{MWL}) = 1.247 cm, it can be concluded that the water level at Nwaniba River has increased with 1.247 cm for the period of observation. In addition, the range of values of R^2 obtained is 0.000-0.046 i.e. 5 %, which shows that only 5 % of the variation in MHWL and MLWL can only be attributed to the variation in time.

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