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Sea Level Analysis for Tidal Datum Realization at Port Tawfik, Suez, Egypt

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ABSTRACT

Nautical charts play a crucial role in ensuring safe and efficient navigation on the world's waterways. The accuracy of these charts, particularly in terms of nautical chart datums, is of the utmost importance to protect maritime vessels and enable precise navigation. Furthermore, the continuous process of updating and validating nautical chart data is of considerable importance to authorities and decision-makers since it enables them to make informed and accurate judgments in maritime operations. Due to sea level fluctuations caused by climate change and land subsidence, regular updates are essential. The objective of this research was to determine the tide levels at the southern entrance to the Suez Canal at Port Tawfik using hourly sea level data collected in the port area over four years (from June 2010 to July 2014). Harmonic analysis was implemented to separate tidal and non-tidal components of sea level using Geo-tide software. The algorithm showed that the dominant tidal constituents were M2, S2, K1, and O1 with amplitudes equal to 0.551, 0.143, 0.036, and 0.011m, respectively. The phase angles of these constituents are 330.57, 0.45, 183.05, and 199.35°, respectively. These components are fundamental in tidal datum calculations. Furthermore, results showed the calculated values of highest high-water level, lowest low-water level, mean high water springs, mean low water springs, mean high water neaps, mean low water neaps, highest astronomical tide, and finally lowest astronomical tide to be as follows: 19.11, 17.63, 19.06, 17.67, 18.78, 17.96, 19.37, and 17.37m, respectively. Furthermore, a safety margin of (± 0.10m) was added to all estimated values, as the Naval Recruiting and Training Agency recommended. Finally, the values of tidal datums calculated were compared with the predefined values in the Admiralty tidal publication, revealing a difference of (+ 0.20m) between the two years of 1906 and 2014.

INTRODUCTION

The Suez Canal is one of the world’s most important waterways, connecting the Mediterranean Sea to the Red Sea. The canal is a vital shipping route for goods traveling between Europe and Asia, and it is also an important source of revenue for Egypt. The

Port Tawfik is a key component of the canal, serving as a major hub for shipping and logistics. To ensure the safe and efficient operation of the port, it is essential to have an accurate and up-to-date information about the water levels in the surrounding area.

The chart datum is the reference level used to measure the depth of water in a particular area. It is typically based on the lowest astronomical tide, which is the lowest level that the tide can reach under normal meteorological conditions. The chart datum is used to create nautical charts, which are essential for safe navigation in the area. The chart datum was last updated in 1906 in the Suez region, and it is important to update it to ensure that the nautical charts are accurate and up-to-date.

A study conducted by **Alam El-din (1993)** focused on the examination of sea level changes along the Suez Canal. One of the findings of this investigation pertains to the determination of tidal constituents in Port Tawfik (PT). The amplitude for the main four tidal components (M2, S2, K1, and O1) were 0.551, 0.146, 0.044, and 0.015m, respectively, and they were calculated utilizing the modified equation of **Doodson (1921)**.

In 1997, data were gathered at 11 stations from 1980 to 1986. The investigation revealed significant discrepancies in the magnitude of daily average sea level fluctuations, with Port Said (PS) experiencing a range of 60cm compared to PT, which has a range of 120cm **(Eid *et al*., 1997)**.

In 2023, A recent study investigated temporal and spatial changes in sea level along the Suez Canal covering the period from June 2010 to July 2015. Hourly sea-level data were collected from three sites representing the northern Port Fouad (PF), central part of Ismailia, and southern PT areas of the canal. PT displayed seasonal variation, with the lowest MSL in September and the highest in February. Notably, the maximum tidal ranges in the canal increased from 32 to 44cm at PF and from 115 to 149cm at PT **(Ibrahim *et al*., 2023)**.

Climate change has emerged as a prominent global concern, particularly due to global warming **(Williams *et al*., 2023)**. In 2023, a recent study conducted by **Yang *et al*. (2023)** showed that the average worldwide sea level has increased by approximately 1.77± 0.38mm/ yr during the 20th century. Notably, PS has experienced an increase in sea level, with a relative sea-level rise ranging from 2.74 to 3.57mm/ yr. Conversely, at PT, the SLR has increased at a rate of 0.90 to 1.94mm/ yr during the 20th century **(Khedr *et al*., 2022)**.

The admiralty tide tables are annually published by the United Kingdom Hydrographic Office (UKHO). The tidal levels mean high water spring (MHWS), mean low water spring (MLWS), mean high water neap (MHWN), mean low water neap (MLWN), lowest astronomical tide (LAT), and the highest astronomical tide (HAT) were established in Egypt at EL-Suez as a standardized reference point in the region. Following the reopening of the Suez Canal in 2015, the Egyptian hydrographic agency produced navigational charts covering all the Egyptian waters. Additionally, this agency assigned a unique international chart number (INT) for each chart. The Egyptian Navy Hydrographic Department (ENHD) developed two international (INT) charts, namely INT7156 and INT7159, as a replacement for the old admiralty nautical chart (233) **(Khedr *et al*., 2022)**.

The tidal elevation data, including MHWS, MHWN, MLWN, and MLWS with values of 1.9, 1.6, 0.7, and 0.4m, respectively, originated from a collaborative effort in 1906. The UKHO and the Indian Geodetic Survey Branch joined forces to produce these estimations in the Suez Canal region, later integrated into nautical chart 233 and INT7159. The data compilation spanned seven years, from 1897 to 1904. The primary objective of this study was to examine the fluctuations in the sea level to determine the appropriate tidal datum levels for chart computations in PT.

DATA AND METHODS OF ANALYSIS

1. Study area description

Port Tawfik (PT), also known as the Port of Suez, is an Egyptian port that falls under the dominion of the General Authority for Red Sea Ports **(Soffer, 2023)**. Positioned along the Northern Region of the Suez Gulf on the Red Sea, it serves as the southern gateway to the Suez Canal, as depicted in Fig. (1). The geographic coordinates of PT are Latitude 29° 56' N and Longitude 032° 33' E. The port area is bounded by Ibrahim Dock and Petroleum Dock, collectively encompassing a substantial water expanse measuring 158km2. The available waterway extends for a length of 1000m, with an average depth of 12m **(Nour *et al*., 2022; Egyptian Maritime Consultant Office, 2024)**.

2. Data

This study utilized an hourly sea level dataset collected from the tide gauge (TG) pressure sensor situated on the pier within PT, which is geographically positioned at the coordinates 29° 56' N and 032° 33' E, as illustrated in Fig. (2). The Suez Canal datum (SCD), serving as the universal reference point for the entire canal, was utilized as the reference geodetic datum. The mean tidal level across the canal was determined to be 18.20m above the SCD **(Ibrahim *et al*., 2023)**. The dataset encompassed a total of 35,643 records, covering 1485 days (from 22/6/2010 to 16/7/2014).

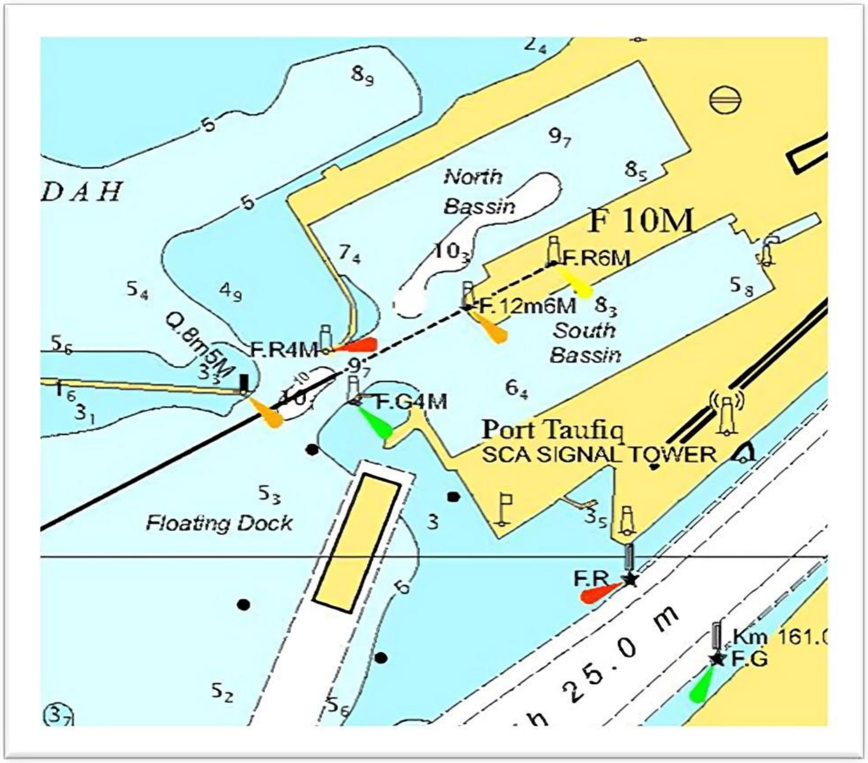

Fig. 1. The nautical chart showed PT and the southern entrance to the Suez Canal **(Egyptian Navy Hydrographic Department, 2024)**

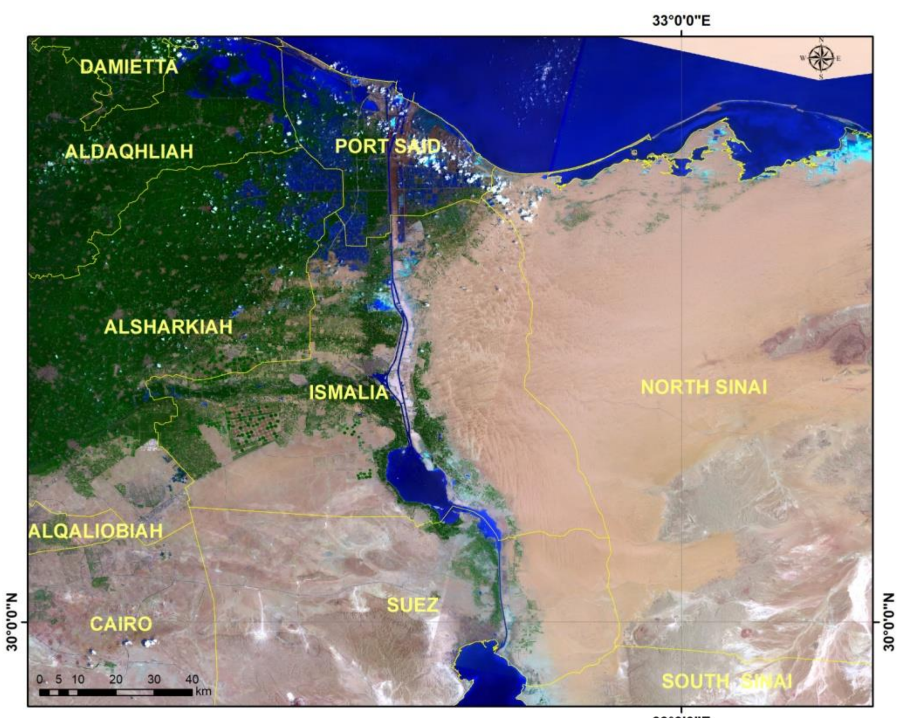

Fig. 2. The location of T.G. in PT, Suez, Egypt

3. Methods of analysis

3.1. Data arrangement

To ensure data integrity, the records were organized using Excel format and subjected to a precise double-checking for any inconsistencies. The sea level dataset of PT, spanning a period of four years and twenty-five days, showed no gaps from June 2010 to July 2014, as depicted in Fig. (3).

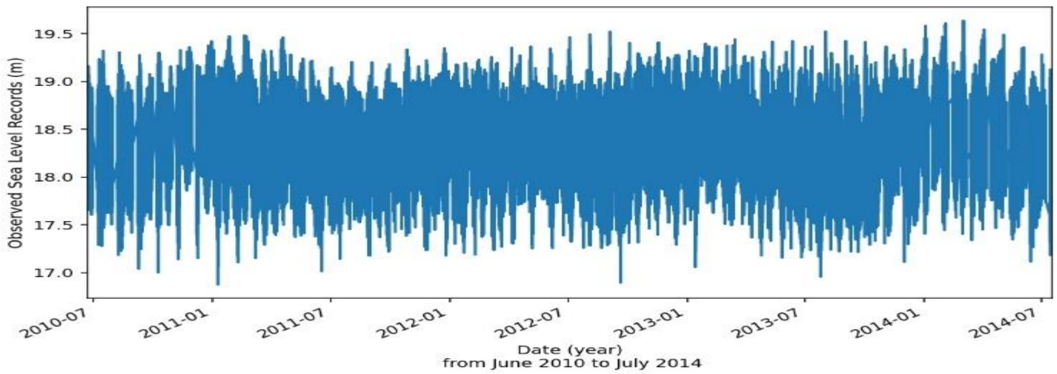

Fig. 3. Sea level measurements in meters within PT harbor during the study period

3.2. Statistical analysis

Quantitative measurements were conducted to characterize the original data signal independently. The descriptive statistics of hourly sea level data, analyzed each year individually, were computed using a statistical package for the social sciences (SPSS) software, which included the calculation of the minimum and maximum values, range, mean, and standard deviation in meters.

3.3. Harmonic analysis

Geo-tide software was utilized to extract the harmonic tidal constituents conducted by **Pugh (2004)**. The geo-tide software, which separates tidal and non-tidal components **(Bazli & Joanes, 2012; Radwan *et al*., 2021)**, relies heavily on the principle of representing tidal amplitudes at any given point as the combined sum of all harmonic elements. This principle was established by **Pugh** in several studies **(1987, 1996)** and further developed by **Jorda *et al.* (2012)**, as follows:

$$h_{(t)} = H_0 + \sum_{i=1 \ to \ n} f_i H_i \cos(\alpha_i t + \{V_0 + u\}_i - k_i) \qquad (1)$$

Where,

$h_{(t)}$: Height of the tide at any time t, above a reference datum.

H_0: The mean sea level above the datum.

n: Constituents number which is being used in prediction.

f_i: Tidal constituent node factor.

H_i: Tidal constituent amplitude.

α_i: Tidal constituent angular speed (degrees/hour).

t: The time from the initial epoch (hours).

$\{V_0 + u\}_i$: Tidal constituent equilibrium argument at t = 0 (degrees).

$(\alpha_i t + \{V_0 + u\}_i - k_i)$: The phase at any time t relative to the moon's transit.

k_i: Tidal constituent epoch relative to the transit of the moon over the location of the tide.

3.4. Tidal datum realization

Vertical tidal datum levels, (HHWL, LLWL, MHWS, MLWS, MHWN, MLWN, LAT, and HAT) were calculated after harmonic analysis of observed sea level data. The datum level values were determined using theoretical formulas derived from the amplitudes of the four primary tidal constituents (M2, S2, K1, and O1) obtained through a harmonic analysis **(Doodson, 1957)**.

Highest High-Water Level (HHWL) = MSL +(M2+ S2+ K1+ O1) (2)

Lowest Low Water Level (LLWL) = MSL - (M2+ S2+ K1+ O1) (3)

Mean High Water Spring (MHWS) = MSL+ (M2+ S2) (4)

Mean Low Water Spring (MLWS) = MSL- (M2 + S2) (5)

Mean High Water Neaps (MHWN) = MSL + (M2- S2) (6)

Mean low Water Neaps (MLWN) = MSL - (M2 - S2) (7)

Lowest Astronomical Tide (LAT) = P.T Tide gauge zero level (TGZL) + MSL – Absolute Minimum Tidal level – Absolute Average residuals. (8)

Highest Astronomical Tide (HAT) = P.T Tide gauge zero level (TGZL) + MSL+ Absolute Minimum Tidal level + Absolute Average residuals. (9)

Where,
MSL: Mean sea level.
M2: Lunar semidiurnal constituent.
S2: Solar semidiurnal constituent.
K1: Lunisolar diurnal constituent.
O1: Lunar diurnal constituent.

RESULTS AND DISCUSSION

1. Sea level rise rate

The sea level analysis results revealed that the average value of the hourly recorded sea level data is 18.368 meters referred to SCD. A mean removal (MR) was applied to the observed data to eliminate its influence on the data, as shown in Fig. (4).

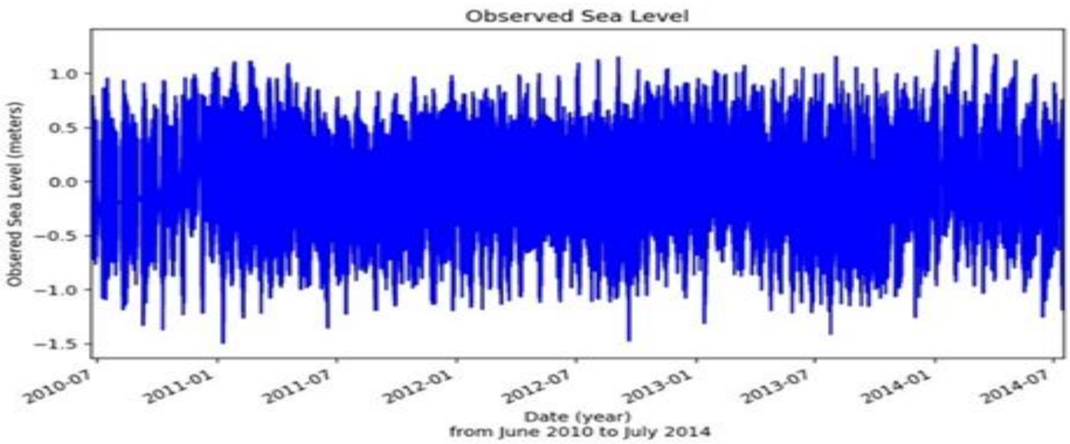

Fig. 4. Time series of sea level data from June 2010 to July 2014, after the MR

After removing the mean, the maximum range of hourly sea level fluctuations was approximately 2.763m, ranging from -1.493 to 1.270 meters. The mean monthly fluctuations in sea level during the study period are depicted in Fig. (5). To represent the linear trends in sea level variations in the PT site, the following equation was employed:

$$SL = 2*10^{-5} \text{ Mean Monthly SL} - 0.688 \qquad (10)$$

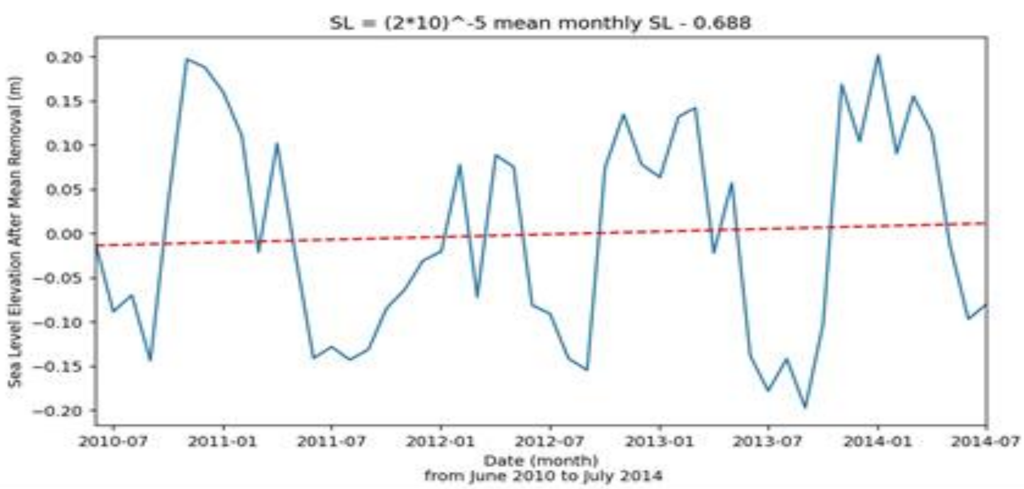

Fig. 5. Monthly fluctuations in sea level at PT for the duration of the study

Sea level rise has been observed at a significant rate of 0.24mm/ yr, as displayed in Fig. (5). This finding is further supported by the research of **Ibrahim *et al.* (2023)**, who calculated a similar rate over five years from June 2010 to July 2015.

2. Statistical analysis

The conducted descriptive statistical analysis determines the annual statistics of observed sea levels, including the minimum, maximum, range, mean, and standard deviation. The results are presented in Table (1).

Table 1. Descriptive data of the sea level records for each year individually

Year	Count	Minimum (m)	Maximum (m)	Range (m)	Mean (m)	Std. deviation
June_2010	4621	17.000	19.421	2.421	18.387	0.458
2011	8760	16.875	19.482	2.607	18.335	0.465
2012	8784	16.896	19.521	2.625	18.365	0.454
2013	8760	16.959	19.525	2.566	18.359	0.471
July_2014	4718	17.117	19.638	2.521	18.432	0.471

From the Table (1), the data analysis revealed that the highest water level was observed at 19.638m in 2014 during the study period, while the lowest water level was recorded at 16.875m in 2011. Furthermore, the highest range was documented at 2.625m in 2012, while the lowest range was observed at 2.421m in 2010.

3. Harmonic analysis

Out of the 23 tidal components determined by the tide program algorithm through the harmonic analysis (Table 2), only 13 relevant constituents were identified and marked with an asterisk. To compute tidal datum values, the amplitudes of the primary principal diurnal and semidiurnal components were utilized. The tidal signal obtained from Geotide's harmonic analysis, and the residual signal are depicted in Fig. (6).

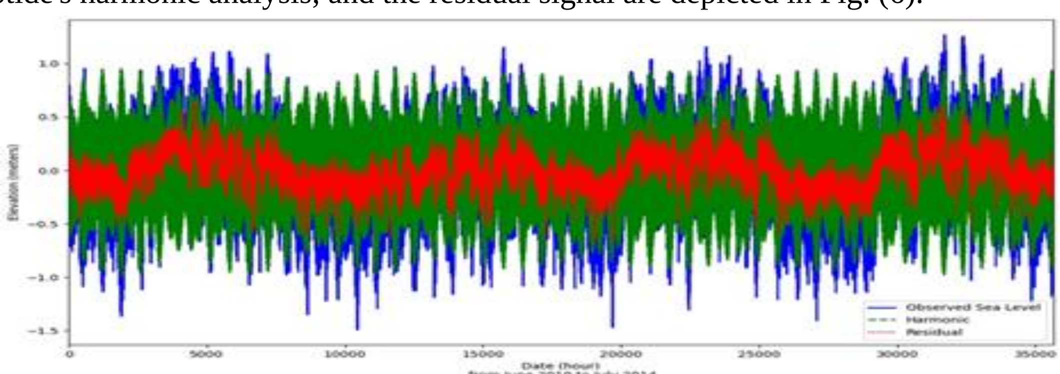

Fig. 6. Observed – harmonic - residual from harmonic analysis from June 2010 to July 2014

Table 2. The tidal constituents, amplitudes (A), and phase angles (Φ) obtained by harmonic analysis using Geo-tide

Tide constituent	A (m)	Φ (°)	Tide constituent	A (m)	Φ (°)
***M2**	0.551	330.57	***L2**	0.024	11.7
***K1**	0.036	183.05	***T2**	0.01	7.63
***S2**	0.143	0.45	***2N2**	0.035	231.49
***O1**	0.011	199.35	**OO1**	0.003	272.31
***P1(R)**	0.013	131	***MSF**	0.015	197.87
***N2**	0.183	302	**M3**	0.004	359.18
***K2**	0.043	355.24	**PI1**	0.002	225.52
MM	0.003	2.14	**PHI1**	0.001	267.06
Q1	0.004	186.36	**M1**	0.001	207.86
***NU2**	0.037	312.21	**2SM2**	0.003	229.6
J1	0.002	221.5	**PSI1**	0.005	88.24
***MU2**	0.027	210.48			

Table (2) presents a comprehensive compilation of the amplitudes and phases of tidal elements derived from the harmonic analysis performed at the tide gauge station of PT, employing equation (1) for harmonic analysis. Among the constituents, M2, N2, and S2 exhibited amplitudes that were 0.551, 0.183, and 0.143m larger than the other constituents, respectively. This observation indicates a semi-diurnal regime and highlights the predominance of seasonal fluctuations in the area.

Table 3. The five main harmonic constituents compared to previous studies

Tide constituent	Alam El-Din (1993)		Ibrahim *et al*. (2023)		Current study	
	A (m)	Φ (°)	A (m)	Φ (°)	A (m)	Φ (°)
M2	0.511	339	0.551	330.41	0.551	330.57
S2	0.146	4	0.145	359.93	0.143	0.45
N2	0.159	315	0.182	301.58	0.183	302.00
K1	0.044	175	0.039	190.18	0.036	183.05
O1	0.015	224	0.011	197.45	0.011	199.35

Table (3) reveals a good agreement between amplitudes of major tidal constituents were observed (M2, S2, and N2), with some discrepancies for K1. Phase comparisons show larger variations, particularly for S2. The current study aligns well with the findings of **Ibrahim *et al.* (2023)** for phases M2, N2, and O1. However, the findings of **Alam El-din (1993)** display the largest deviations.

4. Tidal datum levels calculations

Applying mathematical equations within the range of 2 to 9. The determination of datum levels involved a systematic process that relied on the amplitude values of four fundamental harmonic components obtained through harmonic analysis. These components are M2, S2, K1, and O1, played a crucial role in establishing the datum levels, as presented in Table (5). Additionally, this information holds a particular significance concerning the geodetic datum employed by the SCD.

Table 4. Comparison of the current study with the previous study on tidal datum levels referred to the SCD at PT

Tidal datum (m)	Current study	Ibrahim *et al*. (2023)	Difference
Highest high-water level (HHWL)	19.11m	19.14m	0.03
Lowest low water level (LLWL)	17.63m	17.65m	0.02
Highest water range	1.48m	1.49m	0.01
Mean high water spring (MHWS)	19.06m	19.10m	0.04
Mean low water spring (MLWS)	17.67m	17.70m	0.03
Mean spring range	1.39m	1.40m	0.01
Mean high water neap (MHWN)	18.78m	18.81m	0.03
Mean low water neap (MLWN)	17.96m	17.99m	0.03
Mean neap range	0.82m	0.82m	Zero
Highest astronomical tide (HAT)	19.37m	------	------
Lowest astronomical tide (LAT)	17.37m	------	------
Astronomical tide range	2m	------	------

The values reported for the highest water range, mean spring range, and mean neap range are 1.48, 1.39, and 0.82m, respectively. These results are in close agreement with the comparable values reported by **Ibrahim *et al*. (2023)**, which were 1.49, 1.40, and 0.82m, respectively (Table 4).

Table 5. The tidal datum levels have been recalculated using sea level data analysis from 2010 to 2014, with reference to LAT

Place	MHWS	MHWN	MLWN	MLWS
Old datum values (1906)	1.9	1.6	0.7	0.4
Current study	1.7	1.4	0.6	0.3

To update and correct the tidal datum levels data depicted on the recently published Suez Canal charts (INT charts, 7156, 7159), calculations were conducted to establish datum levels regarding the LAT, as presented in Table (5). The analysis shows a consistent difference of 0.2m in MHWS & MHWN, and 0.1m in MLWS & MLWN between the current tidal datum levels and the historical values.

These differences suggest a disparity between the reference level (LAT) datasets. This difference can be attributed to either the analytical and definitional approaches employed in 1906 to determine LAT or a consistent alteration of the reference level by 0.2m throughout the 108 years.

CONCLUSION

The precise determination of tidal datum and the subsequent adjustment of nautical charts play a crucial role in maritime navigation and coastal management. Tidal datum, which serves as a reference point for chart datum, directly impacts navigational safety, particularly in areas with significant tidal fluctuations. Regular updates to nautical charts, based on an accurate tidal datum, ensure the reliability of these charts in accurately representing the true characteristics of maritime environments, which are susceptible to the effects of climate change and land subsidence.

Based on the analysis of vertical datum levels, it has been established that the lowest LAT and highest HAT values for chart datum and chart heights, which are referred to as the SCD, are 17.37 and 19.37m, respectively. Tidal vertical datum levels were calculated from the observed sea level data analysis in Port Tawfik harbor. The additional tidal datum levels, or recommended MHWS, MHWN, MLWN, and MLWS, are 1.7, 1.4, 0.6, and 0.3, respectively. According to the Naval Recruiting and Training Agency **(NRTA, 2004)**, a safety margin of ±0.10m should be taken into account and applied to all final estimated vertical datum levels.

In this essence, the revised definition of LAT level by the International Hydrographic Organization (IHO) in 2011 resulted in an increase in values, leading to a consistent difference of 0.20m in LAT between 1906 and 2014. It is recommended that the astronomical level values for HAT and LAT should be revised in all relevant nautical publications to 19.47 and 17.27m, respectively. This adjustment implies that the range of astronomical tidal levels is now 2.2m, with the same SCD zero level as before.

RECOMMENDATIONS

The tidal vertical datum should be realized concerning the most recent international terrestrial reference frame (ITRF 2018), and the geodetic datum in the area should be updated to align with the latest ITRF. Further studies will be conducted to determine and realign tidal datum values for a minimum of 18.6 years to accommodate the tidal nodal cycles. A precise geodetic benchmark is needed in the area to monitor subsidence, uplift, and hence an absolute sea level. Additionally, an offshore observing sensor is required to collect off-harbor data for future calculations and modeling.

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