Quasi-Continuous Tidal Datum for Peninsular Malaysia using Tide Gauge, Satellite Altimetry, and Tide Model Driver (TMD) Data

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ABSTRACT

Conventionally, information from the tide gauge stations was used to establish the localized tidal datum. However, limitations in coverage, due to the sparse station distribution along the coast, have caused insufficient tidal datum information in some areas. Therefore, this study aims to develop the Peninsular Malaysia Quasi-Continuous Tidal Datum (PMQCTD) by integrating tide gauges, satellite altimetry, and Tide Model Driver (TMD) data. The research methodology includes data acquisition from 12 Departments of Survey and Mapping Malaysia (DSMMs) tide gauge stations along the coast of Peninsular Malaysia, satellite altimetry data of TOPEX, Jason-1, Jason-2, and GEOSAT Follow-On (GFO) from Radar Altimeter Database System (RADS), and the global hydrodynamic model from TMD. The tide gauge, satellite altimetry, and TMD data encompass 23 years of tidal observation data from 1993 to 2015. For the derivation of the tidal datum, tide gauge, and satellite altimetry data were analyzed following a harmonic analysis approach in the Unified Tidal Analysis and Prediction (UTide) software. Meanwhile, for the TMD data, the tidal datum was determined based on the tidal prediction from the 11 extracted major tidal constituents. For compatibility in data integration, the derived Lowest and Highest Astronomical Tide (LAT and HAT) from tide gauge, satellite altimetry, and TMD data were referenced to the Mean Sea Level (MSL), denoted as LAT_{MSL} and HAT_{MSL}, respectively. Next, the LAT_{MSL} and HAT_{MSL} were interpolated employing Inverse Distance Weighting (IDW) to develop the PMQCTD (LAT_{MSL} and HAT_{MSL}) with the ArcGIS software. The statistical assessment indicated that the established PMQCTD (LAT_{MSL} and HAT_{MSL}) has a better agreement with the DSMM tide gauges with a Root Mean Square Error (RMSE) of ± 0.228 m for LAT_{MSL} and ± 0.159 m for HAT_{MSL} In conclusion, the establishment of PMQCTD (LAT_{MSL} and HAT_{MSL}) has led to the availability of the tidal datum at any location along the coast of Peninsular Malaysia.

Keywords-tide gauge station; satellite altimeter; tide model driver; tidal datum; IDW integration

I. INTRODUCTION

Traditionally, data from the tide gauge stations have been exploited to establish a localised tidal datum, such as the Lowest Astronomical Tide (LAT), Mean Sea Level (MSL), and Highest Astronomical Tide (HAT) along the coast [1, 2]. Currently, there are 19 continuously operating tide gauges in Malaysia by the Department of Survey and Mapping Malaysia (DSMM) [3, 4]. Accordingly, Malaysia has a maritime area of 55,629 km^2 and 329,960 km^{2}of land area [5]. Hence, relying solely on 19 tide gauge stations to monitor the variation of sea level along the 55,629 km^2 of Malaysia's coast is insufficient as there are areas without any tidal datum information [4, 6].

The satellite altimeter has been evolving since 1975. Currently, there are a total of 13 satellite missions that have been operating from 1985 to 2022, such as TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, GEOSAT Follow On (GFO), ERS-1, ERS-2, ENVISAT-1, Cryosat-2, SARAL, and Sentinel-3A and Sentinel-6 [7, 8]. Accordingly, a satellite altimeter has three long-term scientific objectives, which are observing the circulation of the oceans, monitoring the volume of the polar ice plate, and observing the variation in the sea level. Hence, due to their vast coverage for data acquisition, satellite altimeters have been considered as an additional approach to monitoring the regional sea levels [9, 10].

Nowadays, with the advancement of the Global Navigation Satellite System (GNSS) for real-time positioning and satellite altimeter for bathymetry derivation, there is a significant improvement in the hydrographic surveying technique [3, 7]. Such an advancement leads to the development of a continuous tidal datum along the coast by integrating the tide gauge and satellite altimetry data for bathymetry determination, as well as GNSS for positioning, in which all the derivation of the tidal datum will refer to a similar local reference surface, such as the MSL, or the global reference surface, for example, the World Geodetic System 1984 (WGS84) ellipsoid [1, 10, 11].

In relation to the development of a continuous tidal datum using geodetic-based approaches, many countries have begun to develop their continuous tidal datum for their respective region, e.g. France in 2005 [12, 13], UK and Ireland in 2009 [14], Canada in 2010 [15, 16], Netherlands and Belgium in 2018 [17], the Kingdom of Saudi Arabia in 2019 [18], and Malaysia [7].

However, despite the previous model for continuous tidal datum yielding an acceptable result in terms of vertical and horizontal accuracy, there are still several limitations that can be further improved in the future. In this study, two significant issues were addressed. The first issue regards the utilization of an insufficient number of tide gauge stations that are sparsely distributed along the coast. Since the characteristic of the tide is site-specific, approximately within a 10 km radius around the coast, the determination of the tidal datum for the area situated further from the tide gauge is inaccurate. Moreover, only depending on the extrapolation of the tidal datum using a limited number of tide gauges is still insufficient to produce an accurate tidal datum, due to the propagation of errors during the extrapolation process from a limited and sparsely distributed known point, which will continue to increase according to the travelling distances for datum transfer. The second issue concerns the most suitable approach of integrating the derived tidal datum from multiple sources, which is achieved either by employing a hydrodynamic model, an empirical model, an assimilation model, or spatial interpolation. The derived tidal datum from the tide gauge refers to the zero-tide gauge. On the other hand, the derived tidal datum from satellite altimetry refers to the TOPEX ellipsoid for the TOPEX class satellite mission or the WGS84 ellipsoid for the ERS-class satellite mission. Hence, to develop a consistent and near-seamless tidal datum, the derived tidal datum for all tidal data sources must be referenced to a similar reference surface. This can be accomplished by either referring the derived tidal datum (LAT and HAT) to a global reference surface, such as the WGS84 or GRS80 ellipsoid, or a local reference surface, like the MSL. Thus, based on all the previous and current issues involving the approach in establishing a continuous tidal datum based on the tide gauge and satellite altimetry, this study aims to develop the Peninsular Malaysia Quasi-Continuous Tidal Datum (PMQCTD) using tide gauge, satellite altimetry, and TMD data. Its integration aims to establish a quasi-continuous tidal datum surface along the coast of Peninsular Malaysia, especially at locations without any tidal datum information, because they are located far from the DSMM tide gauge stations, and satellite altimeter track. In addition, the establishment of the PMQCTD improves the most current continuous tidal datum (MyVSEP), which only utilizes tide gauge and satellite altimetry data.

II. RESEARCH METHODOLOGY

This study is divided into 3 phases. Phase 1 highlights the literature review, the identification of the study area, and the data acquisition stages. Phase 2 focuses on the derivation of the tidal datum from the tide gauge, satellite altimetry, and TMD data. Phase 3 focuses on the integration of the tide gauge, satellite altimetry, and TMD data to develop the PMQCTD (LAT_{MSL} and HAT_{MSL}) using Inverse Distance Weighting (IDW) interpolation [19]. Conclusions were drawn based on the results of the findings.

A. Study Area

The study area is the east and west coast of Peninsular Malaysia, ranging between (1° N < Latitude < 7° N) and (99° E < Longitude < 105° E). The proposed locations for data acquisition applying the ArcGIS software are illustrated in Figure 1.

B. Data Acquisition

The data acquired for this study came from three source types, i.e. tide gauge data from DSMM, satellite altimetry data from TOPEX, Jason-1, Jason-2, and GFO from RADS, and tidal datum prediction using TMD.

1) Tide Gauge Data from 12 Tide Gauge Stations of DSMM

The DSMM tide gauge station data implemented in this study were obtained from the University of Hawaii Sea Level Centre (UHSLC) [20]. The tide gauge data of 12 stations in Peninsular Malaysia were considered over a duration of 23 years, from 1993 to 2015. According to [8, 21-22], the minimum period of tidal observation for a stable tidal datum determination is 18.6 years, which represents the time spent by the moon to make a complete revolution around the Earth. Therefore, since this study uses 23 years of tidal observation data for tide gauge, satellite altimetry, and TMD, it complies with the aforementioned requirement. The details are portrayed in Figure 2.

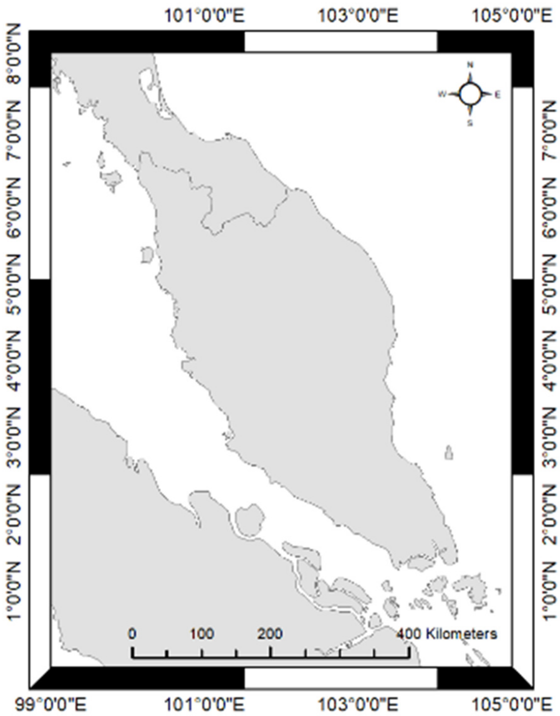

Fig. 1. Study area.

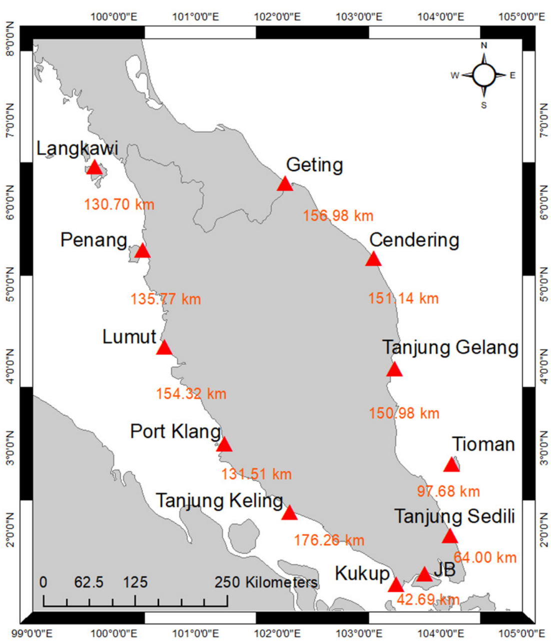

Fig. 2. The 12 DSMM tide gauge stations used in this study.

However, the distance between each DSMM tide gauge station as depicted in Figure 3 ranges from 42.690 km to 176.26 km. Such distances do not fulfil the requirement of a 10 km radius [23] for the establishment of an acceptable and reliable tidal datum (LAT, MSL, and HAT).

2) Satellite Altimetry Data from RADS

The satellite altimeter deployed in this study consists of non-sun synchronous satellite missions, which are the TOPEX class (TOPEX, Jason-1, Jason-2) and the GFO mission. The satellite altimetry data in this study were extracted from the Radar Altimeter Database System (RADS) [24]. The non-sun synchronous satellite mission was chosen in this study due to its compatibility with harmonic analysis. For this study, since it shares a similar orbit, the TOPEX class satellite mission (TOPEX, Jason-1, and Jason-2) was combined to create a single time series data encompassing 23 years of tidal observation from 1993 to 2015 [8, 9]. Equivalently to the tide gauge data, the combination of the TOPEX class mission also complies with the requirement of 18.6 years of tidal observation for a stable tidal datum determination. On the other hand, due to its different orbit from the TOPEX class satellite mission, the GFO satellite mission cannot be combined with the TOPEX class mission [7-9]. However, owing to its compatibility with harmonic analysis, the GFO mission was also utilized as an additional satellite altimetry data to ensure denser data coverage for the tidal datum determination. The satellite altimeter track for the TOPEX class and GFO satellite mission illustrated using ArcGIS is shown in Figure 3.

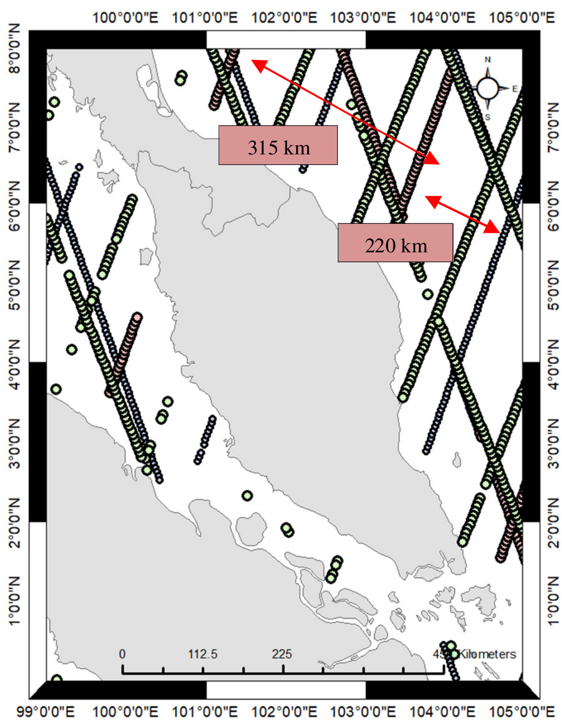

Fig. 3. Satellite altimetry points (492 points) for TOPEX class (315 km satellite altimeter track) and GFO (220 km satellite altimeter track) for the Peninsular Malaysia region considered in this study.

Unfortunately, the width of the satellite altimeter track for the TOPEX class mission is 315 km, whereas for the GFO mission, it is 220 km. Such a distance does not comply with the requirement of a 10 km radius for the establishment of an acceptable and reliable tidal datum (LAT, MSL, and HAT) [23].

3) Tide Model Driver (TMD) Data

TMD is a MATLAB package developed by Earth and Space Research (ESR) and Oregon State University (OSU) to access the tidal constituents for high-latitude tidal analysis and prediction [25]. The tidal constituent was deployed in making predictions of tidal height and currents based on the hydrodynamic model [26]. It consists of two significant functions. The first one is a Graphical User Interface (GUI) for browsing tide fields, selecting study areas, and determining a specific coordinate and duration of time for tidal predictions of a specific variable. Secondly, it comprises a set of programming codes for accessing tide fields [25, 26]. It has been generally used to model the tides engaging the resolution medium (1/40 × 1/40) [25, 26]. Accordingly, TMD has been utilized to derive the tidal datum (LAT, MSL, and HAT) within the same period of observation data with tide gauge and satellite altimetry data, which is from 1993 to 2015 (23 years). Figure 4 displays the coordinates of the 377 points and their locations, respectively, imported into the ArcGIS working layer to be integrated with the tide gauge and satellite altimetry data. For this study, TMD was introduced as a complementary tidal data source, rather than just relying on the tide gauge and satellite altimetry data. TMD is capable of predicting the specific point within 0 to 100 km from the coastline, by a set distance of 10 km radius for each point, allowing it to comply with the 10 km radius as stated in [23].

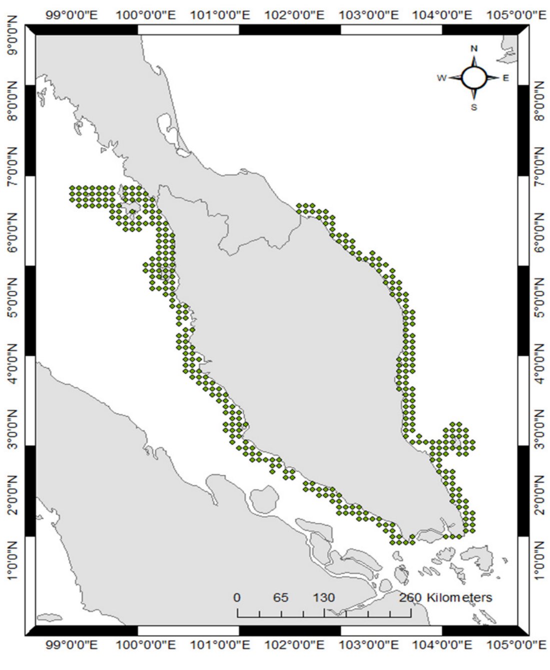

Fig. 4. 377 points within 0 to 20 km from the coastal line to be predicted using TMD.

Hence, with the addition of TMD, along with its integration with the tide gauge and satellite altimetry data, a reliable tidal datum along the coast of Peninsular Malaysia can be established in comparison with [3].

III. DATA PROCESSING AND ANALYSIS

A. Derivation of Tidal Datum for Tide Gauge Data

The tide gauge data (1993 to 2015) from 12 DSMM tide gauge stations were processed deploying harmonic analysis, which uses Unified Tidal Analysis and Prediction Software (UTide) in MATLAB based on 11 major tidal constituents (K_1,O_1,P_1, Q_1, M_2, S_2, N_2, K_2, M_4, MS_4, and MN_4) [8-9, 27]. The 11 tidal constituents are tabulated in Table I. The derived tidal datum (LAT, MSL, and HAT) was then integrated with the satellite altimetry and TMD data.

TABLE I. 11 MAJOR TIDAL CONSTITUENTS

Tide Category	Tidal constituents	Phenomenon
Semi-Diurnal	M_2	Lunar principle
	S_2	Solar principle
	N_2	Large lunar ecliptic
	K_2	Lunar solar semi-diurnal
Diurnal	K_1	Luni solar diurnal
	O_1	Principle lunar diurnal
	P_1	Principle solar diurnal
	Q_1	Large lunar ecliptic
Shallow Water	M_4	Twice the angular velocity M_2 due to the influence of the moon in shallow water
	MS_4	M_2 and S_2 interactions in shallow water
	MN_4	Shallow water quarter diurnal constituent

B. Derivation of Tidal Datum from Satellite Altimetry Data

The TOPEX class mission is truncated to create a time series of 23 years of tidal data for a stable determination of the tidal datum. Similarly, the satellite altimetry data for TOPEX class and GFO satellite missions, were processed using UTide. The amplitude and phase of 11 tidal constituents, K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2, M_4, MS_4, and MN_4 were estimated based on the SSH time series from the TOPEX class and GFO satellite missions using harmonic analysis. The derived tidal datum (LAT, MSL, and HAT) with a total of 492 points for satellite altimetry data as illustrated in Figure 4 was interpolated following the IDW interpolation technique.

C. Derivation of Tidal Datum from Tidal Prediction using TMD

The TMD was used to derive the tidal datum for 377 locations within 0 to 20 km from the coast of Peninsular Malaysia. The derivation of the tidal datum through TMD was also based on 11 tidal constituents utilizing the Indian Ocean 1/12° hydrodynamic model [28]. The derived tidal datum (LAT, MSL, and HAT) with a total of 377 points for TMD data as observed in Figure 5 was then interpolated adopting the IDW interpolation technique.

D. Integrating Tide Gauge, Satellite Altimetry, and Tide Model Driver (TMD) Data using IDW Interpolation

There are two approaches for integrating the tidal datum from the tide gauge, satellite altimetry and TMD data, either by using the reference ellipsoid or the offset of MSL. For this study, the integration of three datasets was performed on the basis of the offset, using the MSL as a reference surface, denoted as LAT_{MSL} and HAT_{MSL}. The determination of LAT_{MSL} and HAT_{MSL} for the tide gauge, satellite altimetry, and TMD-derived tidal datum were based on (1) and (2),

$$LAT_{MSL} = LAT - MSL \quad (1)$$

$$HAT_{MSL} = HAT - MSL \quad (2)$$

Accordingly, the location of 12 DSMM tide gauge stations is portrayed in Figure 2. On the other hand, the satellite altimetry data for TOPEX, Jason-1, and Jason-2 for Phase (A and B), as well as GFO (Phase A), are illustrated in Figure 3. The 377 points of tidal prediction using TMD are depicted in Figure 4. The integration of all datasets (with a total of 881 points) is illustrated in Figure 5. The integration of the derived tidal datum from the tide gauge, satellite altimetry data, and TMD was conducted in ArcGIS. The tide-gauge, satellite altimetry, and TMD-derived tidal datum (LAT_{MSL} and HAT_{MSL}) in point-based were further interpolated using IDW to establish the PMQCTD (LAT_{MSL} and HAT_{MSL}) along the coast of Peninsular Malaysia.

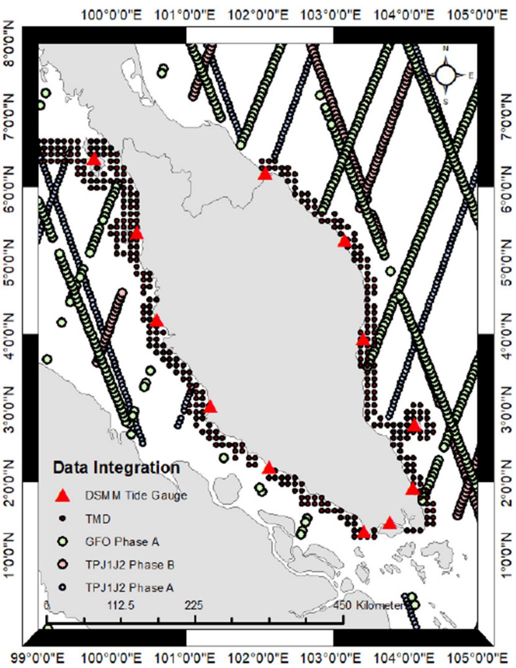

Fig. 5. Integration of 12 DSMM tide gauges, 492 satellite altimetry points, and 377 TMD data in ArcGIS.

Consequently, the reliability of the PMQCTD (LAT_{MSL} and HAT_{MSL}) still needs to be assessed. Therefore, in this study, the PMQCTD (LAT_{MSL} and HAT_{MSL}) was statistically evaluated in terms of their standard deviation (STD) and Root Mean Square Error (RMSE) by comparing the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from the combination of the tide gauge and satellite altimetry data with the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from the combination of tide gauge, satellite altimetry, and TMD data. The statistical assessment was based on the offset of PMQCTD (LAT_{MSL} and HAT_{MSL}) with the offset from the DSMM tide gauge (LAT_{MSL} and HAT_{MSL}). In addition, the comparison of the two combinations was conducted to identify the rate of improvement of the PMQCTD (LAT_{MSL} and HAT_{MSL}) with the addition of TMD data.

IV. RESULTS AND DISCUSSION

A. Derivation of Tidal Datum for Tide Gauge Stations

The derived tidal datum of LAT, MSL, and HAT with respect to zero tide gauge for the 12 DSMM tide gauge stations along the coast of Peninsular Malaysia is tabulated in Table II. The result is based on the duration of tide gauge data from 1993 to 2015 (23 years). Accordingly, the tidal datum has been determined using harmonic analysis focusing on 11 tidal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2, M_4, MS_4, and MN_4) employing UTide. The derived tidal datum, LAT, and HAT were referenced to MSL, denoted as (LAT_{MSL} and HAT_{MSL}) according to (1) and (2).

TABLE II. TIDE-GAUGE-DERIVED TIDAL DATUM

Tide gauge stations	LAT (m)	MSL (m)	HAT (m)	LAT_{msl} (m)	HAT_{msl} (m)
Cendering	0.819	2.137	3.500	-1.318	1.363
Geting	1.644	2.310	3.246	-0.666	0.936
Tanjung Gelang	1.042	2.835	4.661	-1.793	1.826
Tioman	0.988	2.781	4.399	-1.793	1.618
Sedili	1.108	2.392	3.691	-1.284	1.299
Langkawi	0.440	2.240	3.957	-1.800	1.717
Penang	1.037	2.679	4.106	-1.642	1.427
Lumut	0.724	2.204	3.563	-1.480	1.359
Port Klang	0.640	3.509	6.457	-2.869	2.948
Tanjung Keling	1.645	2.845	4.186	-1.200	1.341
Kukup	2.401	4.024	5.991	-1.623	1.967
Johor Bahru	0.794	2.879	4.508	-2.085	1.629

B. The IDW Interpolation of Tidal Datum (LAT_{msl} and HAT_{msl}) for Satellite Altimetry Data

The derived tidal datum (LAT_{MSL} and HAT_{MSL}) from the satellite altimetry data (TOPEX class and GFO) with a total of 492 points was interpolated following the IDW interpolation technique using ArcGIS. The result of the interpolation is illustrated in Figure 6.

C. The IDW Interpolation of Tidal Datum (LAT_{msl} and HAT_{msl}) for TMD Data

The derived tidal datum (LAT_{MSL} and HAT_{MSL}) from TMD with a total of 377 points was interpolated via the IDW interpolation technique using ArcGIS. The result of the interpolation is detected in Figure 7.

(a)

(b)

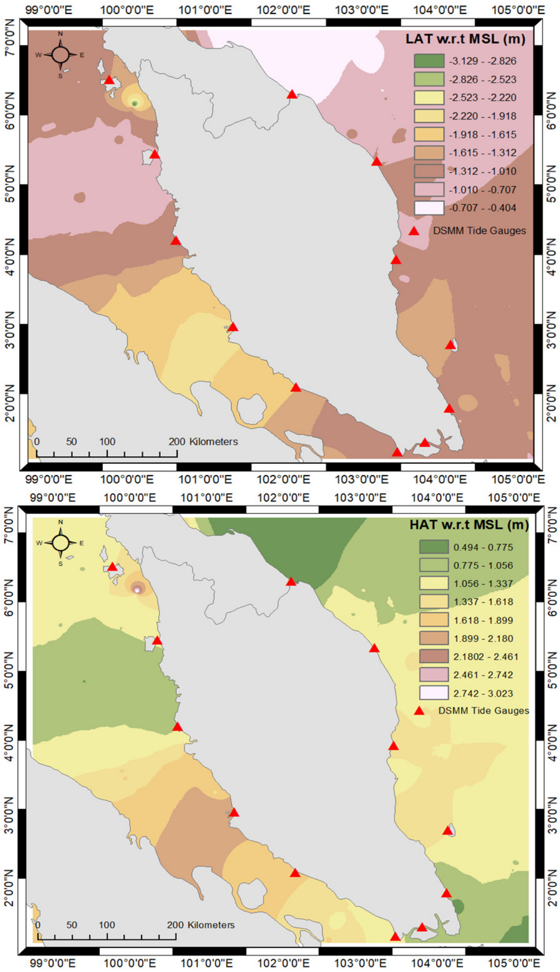

Fig. 6. (a) LAT_{MSL} and (b) HAT_{MSL} for satellite altimetry data using IDW interpolation in ArcGIS.

D. Integration of Tide Gauge, Satellite Altimetry, and TMD Data to Develop the PMQCTD (LAT_{MSL} and HAT_{MSL})

Once the tidal datum from tide gauge stations, satellite altimetry, and TMD has been determined and referenced to a similar reference surface, the tidal datum (LAT_{MSL} and HAT_{MSL}) can finally be integrated employing the IDW interpolation in ArcGIS. Hence, the quasi-continuous tidal datum, LAT_{MSL} and HAT_{MSL} , for Peninsular Malaysia was established. However, the accuracy of the PMQCTD (LAT_{MSL} and HAT_{MSL}) must be statistically assessed in terms of its STD and RMSE with the DSMM tide gauge (in-situ).

The assessment was made between the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from tide-gauge and satellite-altimetry-derived tidal datum and the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from tide-gauge, satellite-altimetry, and TMD-derived tidal datum. The reliability of both approaches was reviewed implementing 9 DSMM tide gauge stations as in-situ data. Such assessments were conducted to show the rate of improvement by deploying TMD, as additional tidal data. The PMQCTD (LAT_{MSL} and HAT_{MSL}) based on the integration of tide gauge, satellite altimetry, and TMD-derived tidal datum is exhibited in Figure 8.

(a)

(b)

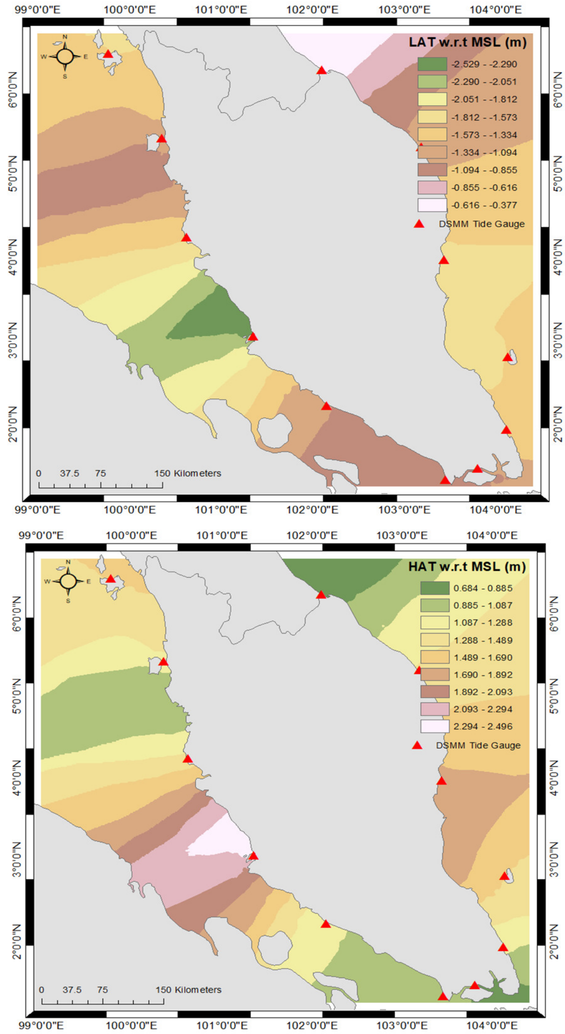

Fig. 7. (a) LAT_{MSL} and (b) HAT_{MSL} for TMD data using IDW interpolation in ArcGIS.

E. Statistical Assessment of the PMQCTD (LAT_{MSL} and HAT_{MSL}) with DSMM Tide Gauge Stations

The reliability of the PMQCTD (LAT_{MSL} and HAT_{MSL}) was statistically assessed based on the offset of LAT_{MSL} and HAT_{MSL} in terms of their STD and RMSE. The statistical assessment of both approaches (using TMD and without using TMD) of PMQCTD (LAT_{MSL} and HAT_{MSL}) was conducted to determine which combination demonstrates a better agreement with the 9 DSMM tide gauge stations (excluding Johor Bahru, Tanjung Keling, and Kukup due to poor coverage of satellite altimetry data). The PMQCTD (LAT_{MSL} and HAT_{MSL}) with the smallest RMSE and STD in comparison with the DSMM coastal tide gauges signify the best approach for establishing the PMQCTD (LAT_{MSL} and HAT_{MSL}). The statistical analysis for PMQCTD (LAT_{MSL} and HAT_{MSL}) with the 9 DSMM tide gauge stations is presented in Tables III and IV, respectively.

(a)

(b)

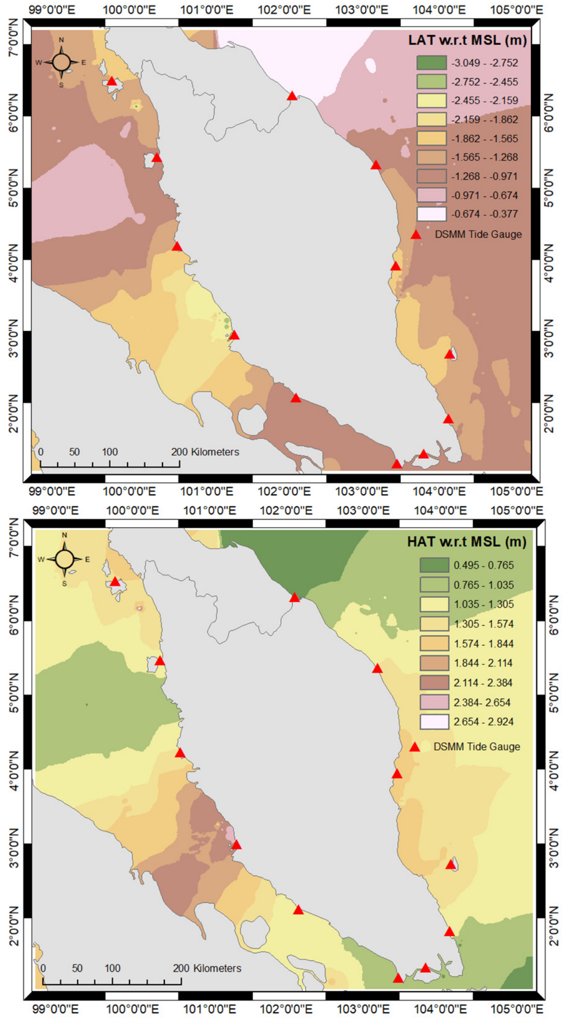

Fig. 8. PMQCTD (a) LAT_{MSL} and (b) HAT_{MSL} from the combination of tide-gauge, satellite-altimetry, and TMD-derived tidal datum in ArcGIS.

TABLE III. STATISTICAL ASSESSMENT OF PMQCTD (LAT_{MSL}) WITH DSMM TIDE GAUGE STATIONS

Tide gauge station	**In-Situ (m)**	**PMQCTD (LAT_{MSL}) from TG and SALT (m)**	**PMQCTD (LAT_{MSL}) from TG and SALT - In Situ (m)**	**PMQCTD (LAT_{MSL}) from TG, SALT, and TMD (m)**	**PMQCTD (LAT_{MSL}) from TG, SALT & TMD - In Situ (m)**
Cendering	-1.318	-0.978	0.340	-1.219	0.099
Geting	-0.666	-0.610	0.056	-0.415	0.251
Lumut	-1.480	-1.230	0.250	-1.527	-0.047
Penang	-1.642	-1.003	0.639	-1.194	0.448
Langkawi	-1.800	-1.970	-0.170	-1.526	0.274
Port Klang	-2.869	-1.821	1.048	-2.476	0.393
Tioman	-1.793	-1.337	0.456	-1.563	0.230
Tanjung Gelang	-1.793	-1.030	0.763	-1.629	0.164
Tanjung Sedili	-1.284	-1.185	0.099	-1.463	-0.179
		STD	0.334	STD	0.175
		RMSE	± 0.410	RMSE	± 0.228

TABLE IV. STATISTICAL ASSESSMENT OF PMQCTD (HAT_{MSL}) WITH DSMM TIDE GAUGE STATIONS

Tide Gauge	**In-Situ (m)**	**PMQCTD (HAT_{MSL}) from TG and SALT (m)**	**PMQCTD (HAT_{MSL}) from TG and SALT - In Situ (m)**	**PMQCTD (HAT_{MSL}) from TG, SALT, and TMD (m)**	**PMQCTD (HAT_{MSL}) from TG, SALT, and TMD - In Situ (m)**
Cendering	1.363	1.154	-0.209	1.315	-0.048
Geting	0.963	0.534	-0.429	0.730	-0.233
Lumut	1.359	1.062	-0.297	1.360	0.001
Penang	1.427	1.073	-0.354	1.199	-0.228
Langkawi	1.717	1.309	-0.408	1.511	-0.206
Port Klang	2.948	1.958	-0.990	2.465	-0.483
Tioman	1.618	1.357	-0.261	1.513	-0.105
Tanjung Gelang	1.826	1.388	-0.438	1.742	-0.084
Tanjung Sedili	1.299	0.973	-0.326	1.133	-0.166
		STD	0.272	STD	0.079
		RMSE	± 0.368	RMSE	± 0.159

For the statistical assessment of the PMQCTD (LAT_{MSL}), the result has indicated a better STD of 0.175 m and RMSE of ± 0.228 m for the PMQCTD (LAT_{MSL}) established from the tide-gauge, satellite-altimetry, and TMD-derived tidal datum in comparison to the PMQCTD (LAT_{MSL}) established from the tide-gauge and satellite-altimetry-derived tidal datum, which demonstrates an STD of 0.334 m and RMSE of ± 0.410 m. The addition of TMD-derived tidal datum with tide gauge and satellite altimeter has showcased an increase by 44%.

A similar outcome was achieved for PMQCTD (HAT_{MSL}) established from tide-gauge, satellite-altimetry, and TMD-derived tidal datum, which exhibits an STD of 0.079 and RMSE of ± 0.159 m in comparison to the PMQCTD (HAT_{MSL}) established from tide-gauge and satellite-altimetry-derived tidal datum with an STD of 0.272 m and RMSE of ± 0.368 m, respectively. Likewise, the addition of TMD-derived tidal datum with tide gauge and satellite altimeter has manifested an increase by 57%.

According to [8, 11, 29], such a rate of improvement emerges from the lack of data coverage in the coastal region owing to the utilization of low-resolution satellite altimetry data, in which the contaminated signals due to the presence of land areas have been removed before the interpolation. However, with the utilization of the tidal prediction of 377 points within 0 to 20 km from the coastal line from TMD, this limitation was mitigated. In addition, the employment of the Indian Ocean hydrodynamic model [25] contributed to this improvement. According to [7], the period of observation for the TOPEX and TOPEX-tandem satellite altimetry mission is approximately from 1993 to 2002. Hence, this study, by including Jason-1 and Jason-2 (Phase A and B) to create a time-series of 23 years from the TOPEX class satellite altimetry mission, along with the additional GFO satellite mission (from 2000 to 2008) has contributed to the acquisition of data from a longer period of observation and with a denser network of tidal observation for a reliable tidal datum determination. The statistical assessment has indicated that the rate of improvement for the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from tide-gauge, satellite-altimetry, and TMD-derived tidal datum is 44% and 57%, respectively, in comparison to the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from tide-gauge and satellite-altimetry-derived tidal datum.

V. CONCLUSIONS

In conclusion, the establishment of the Peninsular Malaysia Quasi-Continuous Tidal Datum (PMQCTD) (LAT_{MSL} and HAT_{MSL}) from tide-gauge, satellite-altimetry, and TMD-derived tidal datum has led to the availability of a tidal datum at any location along the coast of Peninsular Malaysia. Its establishment has solved the first issues of the determination of tidal datum from limited and sparsely distributed DSMM tide gauge stations (with distances from 42.690 km to 176.26 km) and wide satellite altimeter tracks for TOPEX class (315 km) and GFO missions (220 km) along the coast of Peninsular Malaysia. In addition, the utilization of TMD along with the tide gauge and satellite altimetry data for establishing (PMQCTD) (LAT_{MSL} and HAT_{MSL}) has demonstrated a better RMSE with an increase of 44% and 57% for LAT_{MSL} and HAT_{MSL}, respectively, in comparison to the PMQCTD (LAT_{MSL} and HAT_{MSL}) established from tide gauge and satellite altimetry data only.

Furthermore, regarding the issue involving the integration of the tidal datum from multiple sources (tide gauge stations, satellite altimeter, and Tide Model Driver), utilizing the MSL as a common reference surface and the Inverse Distance Weighting (IDW) spatial interpolation approach in developing the PMQCTD (LAT_{MSL} and HAT_{MSL}), led to a uniform and consistent establishment of the tidal datum along the coast of Peninsular Malaysia for any hydrographic-related application.

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