The Determination of Tidal Constituents using Wavelet Base Harmonic at The Strait of Malacca

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Abstract. Activity at the coastal areas required accurate tidal analysis and prediction. Tides are a result of the response of the water body to the attracting forces exerted by the moon and sun. In this paper, a new novel wavelet base harmonic model (WBH) for tidal analysis and prediction is presented. Discrete wavelet transformation is being employed to present the relationship between multiresolution analysis and wavelet to show the harmonic amplitude and phase angle as a sum of shifting and scaling functions. The coefficients of the shifting and dilating function are resolved to obtain the harmonic constituent (amplitude and phase angle) of a seawater level. It is found that the predicted tide result obtained at four tide gauge stations using the wavelet-based harmonic model agreed with the observed water tide. To test the efficiency of the model root mean square error the correlation coefficient was used.

1. Introduction

Accurate tidal analysis has become a deterministic factor for future tidal forecasting at the coastal areas, moreover, the need for accurate tidal analysis and prediction has become very paramount at the coastal areas especially the need for safe navigation, coastal engineering construction as well as in the field of science and technology such as geodesy, astronomy, oceanography, marine safety, and navigation, etc. however, fluctuation of the tide is an intricate process due to the dynamic nature of the coastal areas, weather and environmental factors which present challenges for tidal prediction.

Tides come into existence as a result of the reaction of the ocean body to the periodic fluctuation of the gravitational attraction of the moon and sun. Notwithstanding the impacting factors introduced earlier, the tide is additionally affected by the non-periodic factors, such as water temperature, wind, and air pressure (Elsobeiey, 2017; Li et al., 2018). Newton's theory of gravitation has made it a base for today's understanding of tide, great researchers such as Thomson, Ferrel, Doodson, and others improved the work of newton which gives rise to the classical harmonic analysis model for tidal prediction. Harmonic analysis is based on the fact that tides are as a result of periodic phenomena that is express as the sum of several finite numbers of sinusoidal function with known frequency to determine amplitude and phase of each sinusoid (Elsobeiey, 2017). Tidal frequencies have been developed by different researchers based on the tidal theory (Cartwright D E & Edden, 1973; Amiri-Simkooei *et al.*, 2018). The accuracy of the predicted tide depends on the mathematical model and analysis employed to estimate the tidal constituent that is tidal amplitude and phase angle which depends on the length or period of the tidal observation obtained from tide gauge or other means of data acquisition, ideally, 18.6 years is required to make an accurate tidal level prediction which is not always achieved.

Many researchers have developed a different tidal model to improve the accuracy of tidal prediction (Recupero & Zavarella, 2013; Abubakar *et al*., 2019). Classical harmonic analysis remains the most popular technique used by many scholars (Murray, 1964; Amin, 1984; Hanxing, 1984; Foreman & Henry, 1989; Pawlowicz *et al*., 2002; Daher *et al*., 2015; Egbert & Ray, 2017; Stephenson, 2017; Guo *et al*., 2018); Other scholars combine the classical harmonic analysis with another method (Yin et al., 2015; Zhang *et al*., 2017; Li *et al*., 2019). Flinchem & Jay (2000) introduces the use of wavelet transformation into tidal analysis and prediction, Erol (2011) compares harmonic analysis and wavelet analysis for tide gauge sensor at the coast of Turkey. Cai *et al.* (2018) presented an inaction method to extract the tidal constituent based on the observation method using normal time-frequency transformation. Cai applies normal morlet wavelet transformation as the transform kernel.

In this paper, wavelet transformation is engaged to develop a new novel wavelet base based harmonic (WBH) for tidal analysis and prediction. Wavelet transformation has become an important tool for tidal analysis and prediction since its introduction in 2002 by Flinchem, but wavelet-based harmonic has never been used for tidal analysis and prediction except for this study. This paper is organized into various sections as follows. The section above already introduces tide analysis and prediction based on previous literature, section 2 presents general principles of classical harmonic analysis and general principles wavelet transformation. Development of wavelet-based harmonic (WBH) for tidal analysis is presented in section 3, results and discussion are presented in section 4, and conclusions are made in section 5.

Table 1. Tidal gauge station information used for the analysis source Permanent Service for Mean Sea Level (PSMSL) (2020)

Station Name	Station ID	Coastline code	Latitude:	Longitude:	Timespan of data
Tanjung Keling	1593	550	2.215	102.153333	01/01/2015 to 31/12/2015
Pulau Pinang	1595	550	5.421667	100.34667	1/01/2014 to 31/12/2014
Pulau Langkawi	1676	550	6.430833	99.764167	01/01/2015 to 31/12/2015
Kukup	1677	550	1.325278	103.442778	1/01/2014 to 31/12/2014

Table 2. Statistical performance at different stations

Station Name	RMSE(m)	r
Tanjung Keling	0.08	0.99
Pulau Pinang	0.16	0.99
Pulau Langkawi	0.22	0.99
Kukup	0.16	0.99

2. Materials and Methods

2.1 Lease square harmonic analysis (LSHA)

Sea level observation time series is traditionally executed using the mathematical model (Pawlowicz *et al.*, 2002 & Foreman *et al.*, 2009) express as.

$$Y(t)_i = H_0 + \sum_{j=1}^{n} A_i \cos(\omega_i(t) + \varphi_i) \quad (1)$$

Where $Y(t)_i$ is the observed height of the tide at a time t, H_0 is the mean water level, t is the time, n is the number of a harmonic constituent, A is the amplitude and ω_i is the frequency and φ_i is the phase angle. Equation (1) can be further be expanded using a normal trigonometrical identity as

$$Y(t)_i = H_0 + \sum_{j=1}^{n} a_i \cos(\omega_i t) + b_i \cos(\omega_i t) \tag{2}$$

Where a_i and b_i are the coefficient of constituent associated through the resulting expression

$$A_i = \left(a_i^2 + b_i^2\right)^{1/2}$$

and

$$\varphi_i = \tan^{-1}\frac{b_i}{a_i} \tag{3}$$

The matrix notation of equation 2 can be express as. [1].

$$\mathrm{v}\; Y = AX \tag{4}$$

Where $Y = \left[y(t_1), y(t_2), \ldots.., y(t_n)\right]^T$ is the input vector; and $X = \left[a_0, a_1, b_2, \ldots., a_m, b_m\right]^T$ is the vector the unknown parameters, and A is the design matrix which can be express as

$$A = \begin{bmatrix} 1 & \cos(\omega_1 t_1) & \ldots & \sin(\omega_n t_1) \\ 1 & \cos(\omega_1 t_2) & \ldots & \sin(\omega_m t_1) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \cos(\omega_1 t_n) & \ldots & \sin(\omega_m t_n) \end{bmatrix}$$

The unknown parameters can be computed using the classical lease method.

2.2 Wavelet Transform

An oscillatory waveform with a short period with amplitude decomposing quickly to zero at equal ends is referred to as wavelet, it is associated to the sine wave in Fourier transform (Gomes & Velho, 2013). The simple way to represent a signal in the wavelet domain is the mother wavelet ψ(t), unlike Fourier transform which main function is to fixed Sine or Cosine function (Gomes & Velho, 2013). The wavelet transform has delighted in a huge and moment prevalence and extraordinary advancement in the most recent decade because of the way wavelet transform solved some long time known weaknesses of Fourier transformation, for instance, Fourier transform, change signal or function that is only available in the time domain into frequency domain representation for temporal processing, despite the fact that information on the frequency that must be extricated in a total length of the signal is given through Fourier transform, in any case, its gives no thought regarding the local disparity in time and required the sign to be fixed. However, wavelet transform performs local time-frequency decomposition of a non-stationary signal (Walnut, 2004).

There is an existence of similarity between continuous wavelet transformation (CWT) and Fourier transform but, continuous wavelet transform is based on single function ψ and that this function is scaled and also shift, thus generating a two parameters family of function $\psi_{(a,b)}$ that is scaling and shifting unlike Fourier transform. Therefore, a continuous wavelet transform is a device that provides a complete representation of a signal by letting the translation and scale parameter of the wavelet differ continuously. For any function to be a continuous wavelet transform the mother wavelet function $\psi(t) \in L^2(\mathrm{R})$, which is limited in the time domain that is $\psi(t)$ has a value in a certain range and zero elsewhere. Mathematically its represented as

Let $\psi(t) \in L^2(\mathbb{R})$ and let a, b $\in\mathbb{R}$, a $\neq 0$
Then

$$\int_{-\infty}^{\infty} \psi(t)dt = 0$$

$$\|\psi(t)\|^2 = \int_{-\infty}^{\infty} \psi(t)\psi^*(t)dt = 1 \tag{5}$$

Where

$$\psi_{a,b}(t) = \psi\, a^{-(t-b)} \frac{1}{\sqrt{a}}$$

Which is the dilation and shifting of the main wavelet $\psi(t)$ finally the continuous wavelet transform becomes

$$\Psi_{(a,b)}(t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi * \left(\frac{t-b}{a}\right) dt \tag{6}$$

Where $\psi *$ denote complex conjugate of $\psi(t)$. The value (a) corresponds to the scale and value (b) corresponds to the time shift of the $\psi(t)$, while $\frac{1}{\sqrt{a}}$ is the normalization value of $\Psi_{(a,b)}(t)$. More detail and mathematical proof can be found in Davis (1973).

Wavelet transforms are of different types subject to the method and application needed for or desired. In this work we shall be using discrete wavelet transform (DWT), In discrete wavelet transform any continuous function f(t) can be estimated as a sum of wavelet and scaling function given by

$$f(t) = f_0(t) + \sum_{j=0}^{N} \Delta f_j(t) \tag{7}$$

$$= \sum_{k\in z} c_{0,k}\varphi_{0,k}(t) + \sum_{j=0}^{N}\sum_{k\in z} d_{j,k}\psi_{j,k}(t) \tag{8}$$

Where $\varphi_{0,k}(t)$ and $\psi_{j,k}(t)$ are the scaling function and wavelet function correspondingly with $c_{0,k}$ and $d_{j,k}$ as their corresponding coefficients.

2.3 Data collection and study area

Height of water level at four different tide gauge stations along the strait of Malacca was obtained namely Tanjung Keling, Pulau Pinang, Pulau Langkawi, and Kukup. Figure 1 shows the google earth image of the tide gauge stations. Table 1 presents information's on the tide gauge stations. Data used for this study were downloaded from UHSLC website (University of Hawaii sea level center: *http://uhslc.soest.hawaii.edu/data/*). Root mean square error and correlation coefficient was used to test the performance of the methodology applied for this study These can be written as follows.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}} \tag{9}$$

$$R = \frac{\sum_{i=1}^{N}(x_i \quad x)(y_i - y)}{\sqrt{\sum_{i=1}^{N}(x_i - x)^2 \sum_{i=1}^{N}(y_i - y)^2}} \tag{10}$$

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Figure 1. Tide gauge stations

3. Wavelet Base Harmonic Model

The sum of a finite number of cosine waves that have a specified amplitude, frequency, and phase normally describes the changes in elevation of the sea at a point by harmonic analysis is given in equation 1 which can be simplified using trigonometrical Identity as.

$$\sum_{i=1}^{n} A_i(t)\,\mathrm{Cos}\,\theta(t)\times\mathrm{Cos}\,i\omega t - A_i(t)\mathrm{Sin}\,\theta(t)\times\mathrm{Sin}\,i\omega t_i) \tag{11}$$

Using $x_{1i}(t)$ and $x_{2i}(t)$ to denote $A_i(t)\ \mathrm{Cos}\,\theta(t)$ and $A_i(t)\ \mathrm{Sin}\,\theta(t)$ respectively then equation (11) becomes

$$Y_i(t) = \sum_{i=1}^{n} x_{1i}\,\mathrm{Cos}\ i\omega t - x_{2i}\,\mathrm{Sin}\ i\omega t_i) \tag{12}$$

In each harmonic, these two components $x_{1i}(t)$ and $x_{2i}(t)$ can be decomposed using equation (8).

Therefore, the orthogonal decomposition of $x_{1i}(t)$ and $x_{2i}(t)$ will be,

$$x_{1i}(t) = \left[\left(c_{0,1}^{1,i}\ Cos\ i\omega t\right) - \left(c_{0,1}^{2,i}\ Sin\ i\omega t\right) + \left(\sum_{j=0}^{J}\left(d_{0,1}^{1,i}\ Cos\ i\omega t\right) - \left(d_{0,1}^{2,i}\ Sin\ i\omega t\right)\right)\right] \tag{13}$$

$$x_{2i}(t) = \left[\left(c_{0,1}^{1,i}\ Cos\ i\omega t\right) - \left(c_{0,1}^{2,i}\ Sin\ i\omega t\right) + \left(\sum_{j=0}^{J}\left(d_{0,1}^{1,i}\ Cos\ i\omega t\right) - \left(d_{0,1}^{2,i}\ Sin\ i\omega t\right)\right)\right] \tag{14}$$

The above equation two equation (13) and (14) is a wavelet decomposition representation, this is done to create the orthogonal relation in equation (7).

With the solid backing of wavelets, the quantity of wavelets that have nonzero coefficient's in a specific chosen time period of a signal is limited, and henceforth equation (14) can be revamped as

$$x_{1i}(t) = \sum_{j=0}^{p} \alpha_{,}\psi_j(t)$$

Where $\psi_j(t)$ include both the shifting of the wavelet function $\psi_{j,k},(t)$ as well as the scaling function $\varphi_{0,k}(t)$, p is the quantity of wavelet and scaling functions that are nonzero inside the analysed time stretch and furthermore subject to three factors, the mother wavelet, the quantity of scales utilized and the total number of samples per time span.

Similarly, $x_{2i}(t)$ can be taken as a summation of these function, but with a dissimilar set of coefficients. Therefore $x_{2i}(t)$ in equation (14) becomes

$$x_{2i}(t) = \sum_{j=0}^{q} \beta_{,}\psi_j(t)$$

Where q is the quantity of wavelet and scaling function that are nonzero inside the time span, ordinarily the mother wavelet and scaling function are equivalent, that is p = q, in this manner the new signal can be signified as

$$Y_i(t) = Z_0 + \sum_{i=1}^{n}(\sum_{j=0}^{p}\psi_j(t)(\alpha_j \operatorname{Cos} i\omega t - \beta_j \operatorname{Sin} i\omega t_i)) \qquad (15)$$

The above equation is the new novel hybrid algorithm for the tidal analysis and prediction known as the wavelet base harmonic model (WBH). The harmonic constituent of the water level is the coefficient α_j *and* β_j which represents the amplitude $A_j(t)$ and phase angle $\phi_j(t)$ as in the popular classical harmonic model. After computing the coefficient α_j *and* $\beta_j, x_{1i}(t)$ consequently, the amplitude and phase angles of the harmonic can be resolved as follows.

$$A_i(t) = \left(x_{1i}^2(t) + x_{2i}^2(t)\right)^{1/2}$$
$$\theta_i(t) = arctng\frac{x_{2i}}{x_{1i}} \qquad (16)$$

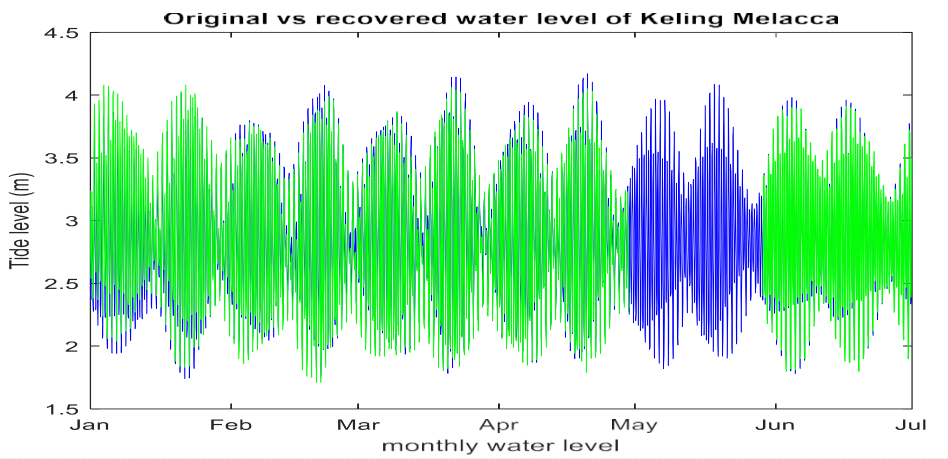

Figure 2. Comparison between observed water level and the predicted water level between May and June.

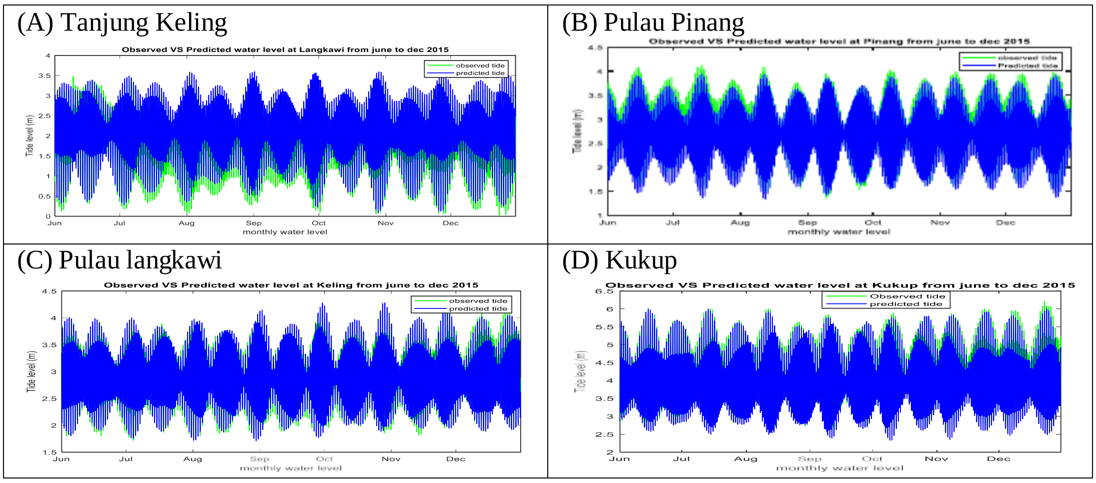

Figure 3. Comparison between the observed water level and the Predicted water level for the four tide gauge station from June to December.

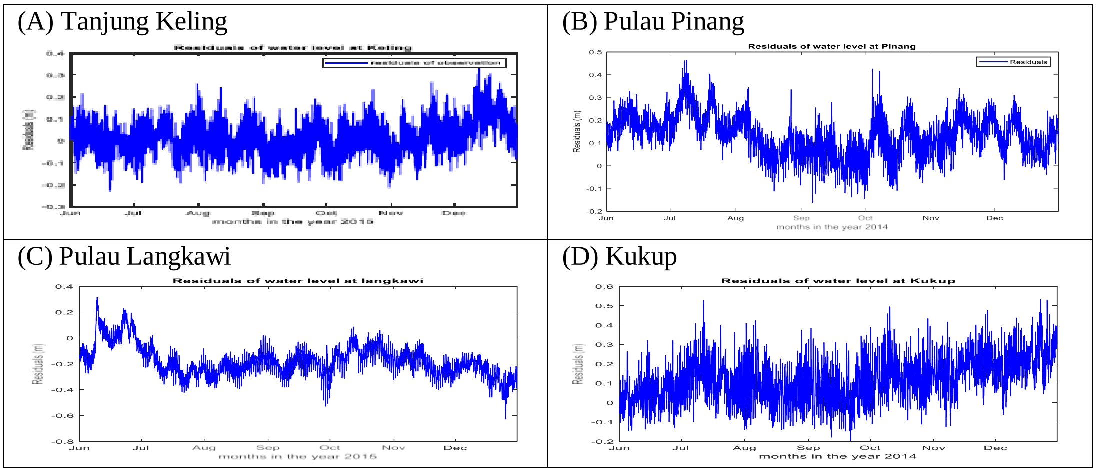

Figure 4. Residual of water level at four tide gauge stations. The difference between the original water level and predicted water level using the novel wavelet-based harmonic (WBH).

4. Results and Discussions

In this section, the tidal constituent (amplitude and phase angle) were computed from the novel wavelet-based harmonic (WBH) model. The computed amplitude and phase angle are shown in the appendix below. Moreover, the prediction was made for future water level based on the computed constituents at four different tide gauge station at the Strait of Malacca the result obtain was compare with theoriginal water level height obtained by the tide gauge instrument in Matlab environment.

Due to the coastline nature and human activity at the coast with addition to faulty instruments, missing data for a particular period can be found in the tide gauge time series. However, the new novel wavelet-based harmonic allowed for data input with a missing gap. a gap of about a month from the period of May to June was detected. However, the recovery of the data was achieved when the prediction was made Figure 2 shows the comparison between the observed water level with gap and the predicted water level with recovered missing data, the result of the prediction quite agrees with the observed water level.

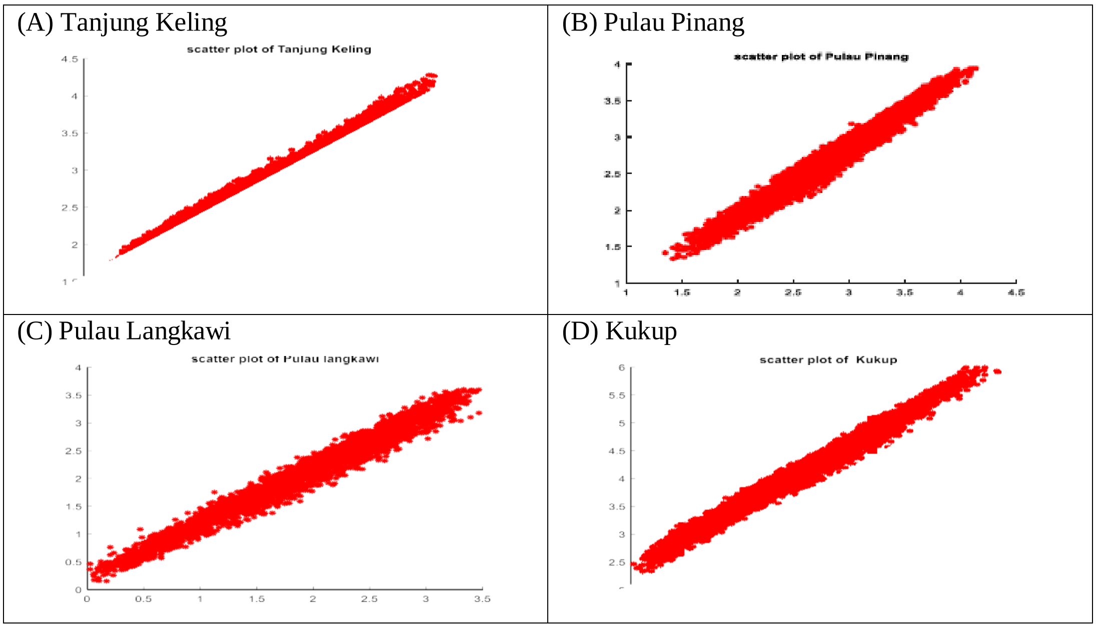

Figure 5. Scatter plot for the predicted tidal level at the four different stations showing 0.99 index

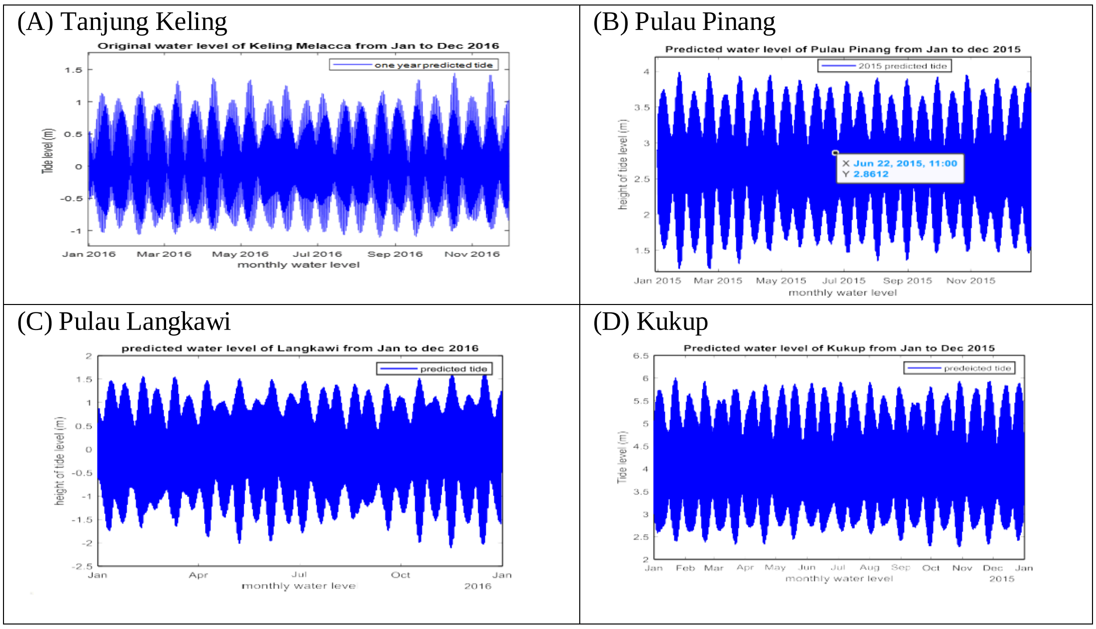

Figure 6. One year of predicted water level using the new novel wavelet-based harmonic (WBH)

One-year data (12 months) was used, each one of the four-tide gauge water level data was divided into two data set, the first six months of the year (January to June) were used for the constituent's determination using the novel wavelet-based harmonic model, about 36 harmonic tidal constituents are found. The table in the appendix shows all the constituent that was used to predict for the remaining six months from July to December, the result of prediction with the original data was compared. Figure 3 shows the original water level as well as the predicted water level of each station. Figure 4 shows the residuals of the water level that is the difference between the observed water level and the predicted water level. Figure 5 shows the scatter plot of the prediction. Result obtained from the prediction quit agree with the original data these give us confidence for any subsequent future prediction of tide level along the strait of malacca if desired were needed, albeit data used for this study were mostly six-month data, at Tanjung Keling and Pulau Langkawi stations, observed water level from January to June of 2015 was used and prediction for January to December was made for the year 2016 while stations at Pulau Pinang and Kukup, January to June of the year 2014 data were used for the prediction of the future tide from January to December 2015 as it can be seen in Figure 6.

Table 2 statistical validation of the six-month tidal forecast starting from June to December are presented using root mean square error (RMSE) and Pearson correlation coefficient (r).

5. Conclusion

This study is the first attempt to present a new novel approached wavelet base harmonic (WBH) for tidal analysis and prediction, tidal constituents were extracted using six-month data subsequently prediction was made based on the extracted constituent using the wavelet-based harmonic model. Tide gauge water level data from four different stations along the Strait of Malacca were selected namely Pulau Pinang, Pulau Langkawi, Tanjung Keling, and Kukup. All data used in this study were downloaded from UHSLC website (University of Hawaii sea level center). The data were divided into two sets, that is, the first six months of the data January to June were used for the tidal analysis using the wavelet-based harmonic to extract tidal harmonic constituent. The prediction was made for the remaining six months based on the extracted constituent for the period of June to December. The result of the observed water level was compared with the predicted water level and the result obtained based on statistical index affirmed the applicability of the novel wavelet base harmonic (WBH) method for tidal analysis and prediction. In conclusion, a one-month water level should be used to test the capability of the wavelet-based harmonic to perform analysis and predict future tide.

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Appendix

Computed amplitude and phase angle using the known astronomical frequencies of the four tide gauge stations along the strait of Malacca using the new novel wavelet-based harmonic.

constituent Name and Speed		Pulau Keling		Pulau Pinang	
		amp	phase	amp	phase
'M2'	28.98410422	0.628855	2.730837	0.635671	-0.84528
'S2'	30	0.295593	0.644675	0.346348	-3.02872
'N2'	28.43972952	0.113967	1.421757	0.120025	-2.01897
'K1'	15.0410686	0.088591	0.404766	0.178601	-2.39565
'M4'	57.96820844	0.034318	-1.70579	0.029749	2.70405
'O1'	13.94303558	0.177002	-2.72868	0.043541	-0.03359
'M6'	86.95231266	0.012392	-0.89065	0.004435	0.907494
'MK3'	44.0251729	0.022694	1.313488	0.006658	0.34624
'S4'	60	0.006382	0.395103	0.008806	-0.88669
'MN4'	57.4238337	0.012887	-2.90812	0.014596	1.358804
'NU2'	28.5125831	0.024264	0.162672	0.018773	3.086181
'S6'	90	0.000152	0.211758	0.000947	-2.75429
'MU2'	27.9682084	0.015409	0.523964	0.042534	1.946526
'2N2'	27.89535482	0.012867	0.41285	0.017916	2.861183
'OO1'	16.1391017	0.003278	-0.41683	0.008978	-2.59258
'LAM2'	29.4556253	0.012146	1.901103	0.011997	-2.4349
'S1'	15	0.040746	-0.86739	0.025385	-3.13893
'M1'	14.49669394	0.002367	-0.34827	0.004582	-1.24687
'J1'	15.5854433	0.017439	0.387057	0.013668	-0.78153
'MM'	0.5443747	0.022284	2.489205	0.022187	2.067871
'MSF'	1.01589578	0.031168	-1.86646	0.001418	1.305661
'MF'	1.09803306	0.010331	1.447013	0.005882	-2.03833
'RHO'	13.4715145	0.014068	0.528502	0.000272	0.416388
'Q1'	13.39866088	0.029321	2.001351	0.009093	-2.22213
'T2'	29.95893332	0.016639	1.48474	0.026628	-2.85774
'R2'	30.04106668	0.00271	1.744177	0.018946	-1.61194
'2Q1'	12.85428618	0.008353	-2.71519	0.002915	2.812422
'P1'	14.95893136	0.032051	0.841625	0.062197	-1.9536
'2SM2'	31.0158958	0.016694	1.455319	0.015159	-3.05371
'M3'	43.47615633	0.003831	1.360562	0.004079	-1.30969
'L2'	29.5284789	0.02701	0.916396	0.022539	3.080131
'2MK3'	42.9271398	0.024709	-2.63174	0.001497	-2.86572
'K2'	30.0821373	0.059741	-2.93304	0.076824	-0.50148
'M8'	115.9364169	0.001689	-1.37219	0.001354	-0.07693
'MS4'	58.9841042	0.033959	2.510425	0.029356	0.487649

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constituents Name and Speed		Langkawi		Kukup	
		amp	phase	amp	phase
'M2'	28.9841	0.842726	-0.74023	0.970627	-1.90216
'S2'	30	0.315173	-2.99436	0.419202	2.403423
'N2'	28.43973	0.197902	-2.16571	0.1753	3.058184
'K1'	15.04107	0.35752	-0.61765	0.229301	0.496747
'M4'	57.96821	0.014192	1.138901	0.065776	1.076012
'O1'	13.94304	0.16262	2.606405	0.211539	-3.08545
'M6'	86.95231	0.014369	-2.113	0.028501	-2.99595
'MK3'	44.02517	0.013621	-0.12027	0.033011	-2.57124
'S4'	60	0.003307	2.028005	0.009358	-2.88123
'MN4'	57.42383	0.010543	-0.11958	0.022391	-0.269
'NU2'	28.51258	0.040169	2.915046	0.035907	1.712092
'S6'	90	0.002066	-2.32852	0.00092	-2.53883
'MU2'	27.96821	0.02603	1.380015	0.033562	2.321128
'2N2'	27.89535	0.027285	2.49144	0.031919	1.721535
'OO1'	16.1391	0.009513	0.0931	0.010135	-0.11632
'LAM2'	29.45563	0.00528	-1.64555	0.025486	-2.51124
'S1'	15	0.036699	-0.99093	0.045734	-0.54783
'M1'	14.49669	0.029172	-1.95583	0.009574	-3.11556
'J1'	15.58544	0.021771	0.709439	0.006852	0.779975
'MM'	0.544375	0.037025	2.587751	0.011337	2.140451
'MSF'	1.015896	0.008921	1.076673	0.04374	-2.00684
'MF'	1.098033	0.020365	-0.61116	0.014686	-1.67045
'RHO'	13.47151	0.003624	0.363172	0.01172	0.692067
'Q1'	13.39866	0.031414	1.596958	0.034763	1.418859
'T2'	29.95893	0.015469	-2.1395	0.028123	2.75827
'R2'	30.04107	0.0019	-0.86528	0.010018	-2.5042
'2Q1'	12.85429	0.006922	0.114947	0.008207	-2.45092
'P1'	14.95893	0.123039	-0.18606	0.089311	0.899806
'2SM2'	31.0159	0.003426	2.902444	0.031632	-2.88939
'M3'	43.47616	0.009758	-2.8033	0.00797	-1.64377
'L2'	29.52848	0.02063	-2.87818	0.046739	2.416596
'2MK3'	42.92714	0.008564	2.715032	0.033444	0.054392
'K2'	30.08214	0.063138	-0.29323	0.103759	-1.23985
'M8'	115.9364	0.001901	-1.8772	0.00482	-0.35963
'MS4'	58.9841	0.009079	-2.03619	0.061689	-0.87621

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