STUDY ON FORECASTING TIDAL WATER LEVELS IN THE SAI GON DONG NAI RIVER FOR ASSESSMENT OF FLOOD IMPACTS IN HO CHI MINH CITY

Nguyen Van Hong, Nguyen Phuong Dong, Pham Thanh Long, Pham Anh Binh, Ho Cong Toan
Sub-Institute of HydroMeteorology and Climate Change

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Abstract: *In recent years, due to the impact of extreme weather, the evolution of rain and tides in Ho Chi Minh City (HCMC) has many changes. Particularly, rainfall and rainfall intensity have been increasing more and more, duration of rainfall has been longer and longer, the number of some heavy rains with a volume of 50 - 100 mm has been boosted, the high tide level on the river has also multipled in rencent year. As the result, the flooding situation of the city is heavily and seriously impacted, causing inevitable damage and challenges for the socio-economic activities of city people. Therefore, research on the impact of coastal water levels on flooding in the city is very necessary. In this paper, UTide software is applied to calculate and forecast tidal water levels along the coastal areas and inland stations of the Sai Gon River, thereby assessing the impacts of flooding due to high tides on HCMC with water level forecast results for 3 stations Nha B, Phu An and Vung Tau respectively 0.82, 0.83 and 0.97.*

Keywords: *UTide, flood, high tide, forecast, Ho Chi Minh City.*

1. Preface

Sea level fluctuation is a combination of tidal components due to the gravitational pull of the moon, sun and non-tidal factors such as wind, storm, waves, etc. Tidal phenomenon has been studied very early; it is predicted quite accurately in the deep sea. However, there are some certain difficulties in tidal prediction in the coastal area (the area less affected by tides) [10].

HCMC is one of the megacities in the word thanks to its urban scale, role and size in economic development. However, in addition to the opportunity creation for development, urbanization also increases the risk due to climate change for coastal urban dwellers. HCMC is easy flooded due to urbanization, rainfall, runoff from upstream and rising sea levels. Besides, the city is also ranked in the top 10 cities in the world most affected by climate change [6].

Corresponding author: Nguyen Van Hong
E-mail: nguyenvanhong79@gmail.com

The spatial area of HCMC has been expanded from 86.2 km² in 1990 to 351.1 km² in 2010, and nearly 60% of the total area of HCMC is below the elevation of 1.50 m above sea level. As a result, the city usually faces flooding problems during the rainy season from June to November and the high tide cycle from September to December every year due to semi-diurnal influence and discharge from the upstream of the Saigon - Dong Nai River. There are several causes for flooding in Ho Chi Minh City, including the objective causes, such as climate change (CC), sea level rise (NBD), increased rainfall and tidal peaks, and increasing urbanization resulting in the sharply increase in population beyond the capacity of the drainage system. Previously, there were only studies on sea level rise to inundation patterns and there were no detailed studies on coastal tidal water affecting inland stations and flooding urban areas. Therefore, the study of the impact of coastal tide levels has a very important role in assessing and finding out the causes for flooding in HCMC [3].

In this paper, UTide software is applied by the research team to analyze fluctuations and forecast water levels at some stations in the coastal area and some stations of HCMC such as Vung Tau marine station, Phu An hydrological station (on the Saigon River) and Nha Be hydrological station (on Nha Be River) by the Least Squares Method [11]. The hourly water level data at the stations in 2018 will be used to analyze the set of harmonic constants and test the water level in April 2020, thereby forecasting the monthly water level in 2021. Research above results is the part of the purpose for the assessment of impacts on flooding situation of the city [10].

2. Study method

2.1. Study area

HCMC is located in the southwest of the Southeast region, adjacent to Binh Duong Province in the North, adjacent to Tay Ninh province in the Northwest, adjacent to Dong Nai province in the East and Northeast, adjacent to Ba Ria - Vung Tau province and the East Sea in the Southeast and adjacent to Long An and Tien Giang Province in the West and Southwest.

HCMC is located at the downstream of major rivers, including Dong Nai River, Saigon River, Be River, on the fringe of the Mekong Delta. HCMC is located in an area with a sub-equatorial monsoon tropical climate. The amount of radiation is abundant, and the average sunshine is 6.10 hours/day. The average annual temperature is about 28.4°C. Monsoon brings a large amount of moisture from the West and Southwest. The relatively low natural topography of HCMC along with different purposes of land use results in a clear distribution of space and rainfall, even depending on the difference of the inner - city districts. Total rainfall in HCMC ranges from 1,200 to 2,100 mm/year [4 - 8].

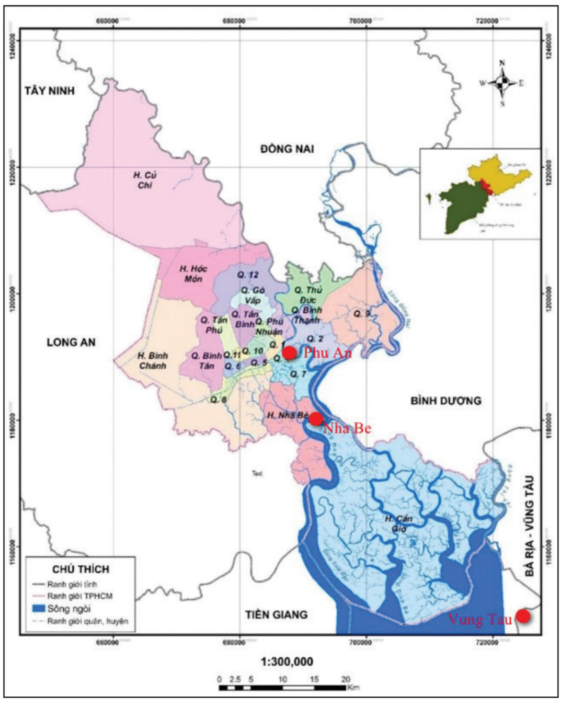

Figure 1. Map of the study area

2.2. Research Methods

2.2.1. Basic system of equations

The first step is to analyze the real tides using the Least Squares Method for the component waves in order to find their suitable harmonic constants (phase and amplitude).

The formula for tidal height (y) by harmonic tidal analysis method is rewritten as follows [2]:

$$y_i = C_0 + \sum_{j=1}^{M} A_j \cos[2\pi(\sigma_j t_i - \emptyset_j)]$$
$$= C_0 + \sum_{j=1}^{M} [C_j \cos(2\pi\sigma_j t_i) + S_j \sin(2\pi\sigma_j t_i)] \quad (2.1)$$

In there:

t_i: Time of monitoring series; M: Number of waves to be analyzed; σ_j: Angular frequency of the wave; C_0: Average water level; $A_j = (C_j^2 + S_j^2)^{1/2}$: Tidal amplitude; $\emptyset_j = (1/2\pi).(\arctan S_j / C_j)$: Wave phase.

In N number of hourly water levels, the sum of squared error of the observed water level and the analyzed water level is calculated as formula (2.2) below:

$$\varepsilon = \sum_{i=1}^{N} \left[y_i - C_0 - \sum_{j=1}^{M} \left(C_j cos 2\pi\sigma_j t_i + S_j \sin 2\pi\sigma_j t_i\right)\right]^2 \quad (2.2)$$

The formula (2.3) - (2.5) is the derivative of the above equation with respect to C_0, C_j, S_j $(j=1, M)$:

$$0 = \frac{\partial\varepsilon}{\partial C_0} = 2\sum_{i=1}^{N}\left(y_i - C_0 - \sum_{j=1}^{M} C_j cos 2\pi\sigma_j t_i + \sum_{j=1}^{M} S_j \sin 2\pi\sigma_j t_i\right)(-1) \quad (2.3)$$

$$0 = \frac{\partial\varepsilon}{\partial C_j} = 2\sum_{i=1}^{N}\left(y_i - C_0 - \sum_{j=1}^{M} C_j cos 2\pi\sigma_j t_i + \sum_{j=1}^{M} S_j \sin 2\pi\sigma_j t_i\right)(-cos 2\pi\sigma_j t_i) \quad (2.4)$$

$$0 = \frac{\partial\varepsilon}{\partial S_j} = 2\sum_{i=1}^{N}\left(y_i - C_0 - \sum_{j=1}^{M} C_j cos 2\pi\sigma_j t_i + \sum_{j=1}^{M} S_j \sin 2\pi\sigma_j t_i\right)(-\sin 2\pi\sigma_j t_i) \quad (2.5)$$

From formulas (2.1) to (2.5) it is possible to set up a matrix to solve the system of equations as follows:

$$\begin{pmatrix} N & C_1 & C_2 & \cdots & C_M & S_1 & S_2 & \cdots & S_M \\ C_1 & CC_{11} & C_{12} & \cdots & CC_{1_M} & CS_{11} & CS_{12} & \cdots & CS_{1_M} \\ C_2 & CC_{21} & CC_{22} & \cdots & CC_{2_M} & CS_{21} & CS_{22} & \cdots & CS_{2_M} \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots & & \\ C_M & CC_{M_1} & CC_{M_2} & \cdots & CC_{MM} & CS_{M_1} & CS_{M_2} & \cdots & CS_{MM} \\ S_1 & SC_{11} & SC_{12} & \cdots & SC_{1_M} & SS_{11} & SS_{12} & \cdots & SS_{1_M} \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots & & \\ S_M & SC_{M_1} & SC_{M_2} & \cdots & SC_{MM} & SS_{M_1} & SS_{M_2} & \cdots & SS_{MM} \end{pmatrix} \begin{pmatrix} C_0 \\ C_1 \\ C_2 \\ \vdots \\ C_M \\ S_1 \\ \vdots \\ S_M \end{pmatrix} \begin{pmatrix} \sum_{i=1}^{N} y_i \\ \sum_{i=1}^{N} y_i \cos 2\pi\sigma_1 t_i \\ \sum_{i=1}^{N} y_i \cos 2\pi\sigma_2 t_i \\ \vdots \\ \sum_{i=1}^{N} y_i \cos 2\pi\sigma_M t_i \\ \sum_{i=1}^{N} y_i \sin 2\pi\sigma_1 t_i \\ \vdots \\ \sum_{i=1}^{N} y_i \sin 2\pi\sigma_M t_i \end{pmatrix} \quad (2.6)$$

Thanks to solving the above matrix equation, the harmonic constants (including tidal amplitude and oscillation phase) to be analyzed are determined. Once we have obtained the amplitude and oscillation phase of each component tidal wave, we can insert them into the formula (2.1) to calculate and predict the water level fluctuation in any time.

2.2.2. The Unified Tidal Analysis and Prediction (UTide) software

The development of the Unified Tidal Analysis and Prediction (UTide) software is based on the harmonic tidal analysis theory given by [1] and with the support of Fortran Software, in addition to the methods analysis from previous platforms such as T_tide, r_T_tide and "versatile" [2].

The software is built with the following criteria:

The software can be taken into account with two-way cases for flow velocity data or one-way for sea level forecasting. The software is specially designed to handle recording times that are unevenly distributed and/or blank adaptable of analyzing data at regular or irregular intervals of time, providing accurate cycle correction results for series of time up to 18.6 years [2]. It is also able to provide easy-to-use and comprehensive diagnostics to aid the component selection process.

Regarding the water level processing (amplitude and phase), for missing data series, or difference in amplitude and phase error, Utide software has processing tools such as Fourier transform (for uniformly distributed time), Lomb-Scargle (for irregular time) and residuals between unprocessed input data, appropriate harmonic constants, etc.

The Least Squares Method is incorporated strongly with the iterative adjustment of L1/L2 [1] to minimize the effect of extrinsic values and reduce confidence intervals.

With the software Matlab, it is possible to analyze groups of chronological series by calling a function *.m. The flexible and interchangeable interface of the analysis configurations can be easily used by the arguments to the *.m function.

Regarding calculation requirements:

Utide software may have higher computational requirements than previous software like Ttide... (More requirements about memory and longer processing time) [2], because:

Perform phase correction and amplitude calculation using validation time. Build complex value formulas of the matrix system to solve.

In the case of irregular times, the Lomb-Scargle periodigram calculations are slower than their counterparts for uniformly distributed times. Calculating the new confidence interval takes a little more time than previous versions. The selection of characteristic components requires additional calculations. In the Software, the confidence interval estimation is taken into account to consider the instability of the sin/cos model parameters.

Using software:

The functions of Signal Processing Toolbox (pwelch(), cpsd(), hanning()) and Satistic Toolbox (robustfit(), mvrnd()) functions in Matlab (Daniel, 2011; Wedsite MathWorks.com) are utilized in Utide. Therefore, if these toolsets are not available, it will cause errors in the default configuration of UTide.

UTide software includes 3 functions:

- ut_solv.m (for harmonic analysis for tidal flows and water levels);

- ut_reconstr.m (use analysis results to forecast tidal flows and water levels);

- ut_constants.mat contains calculated constants including 146 component tidal waves.

- Utide software runs on Matlab platform.

2.2.3. Software testing

The test results between the measured and calculated water level data of Vung Tau, Phu An and Nha Be stations in April 2020 are presented in Figure 2 - 4. According to the comparison results, the predicted tides are lower in comparison with actual measurements, proving that non-tidal factors such as wind, waves, etc. have an influence on the total water level fluctuation. The largest error in April 2020 was 0.20 m, the correlation between the calculated and measured results was quite good, with a correlation coefficient R^2 greater than 0.80 (Table 1)

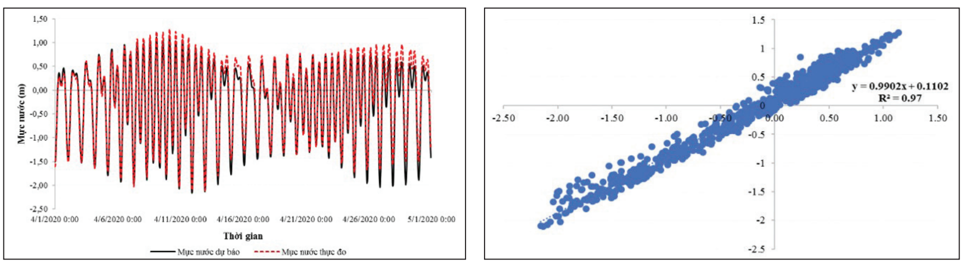

Figure 2. Test the water level (a) and the correlation graph (b) between the forecast water level and the calculated water level in April 2020 at Vung Tau station

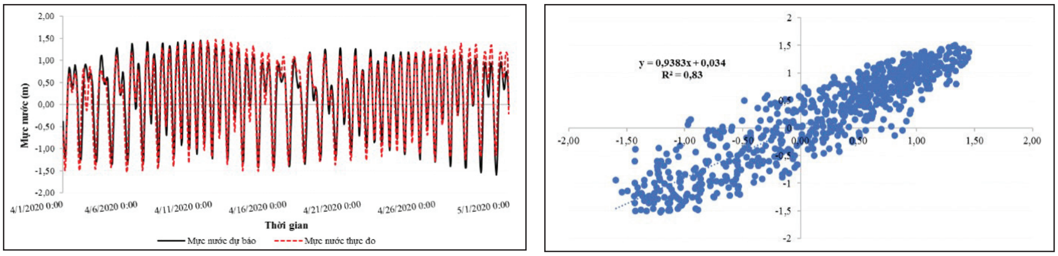

Figure 3. Test the water level (a) and the correlation graph (b) between the forecast water level and the calculated water level in April 2020 at Phu An station

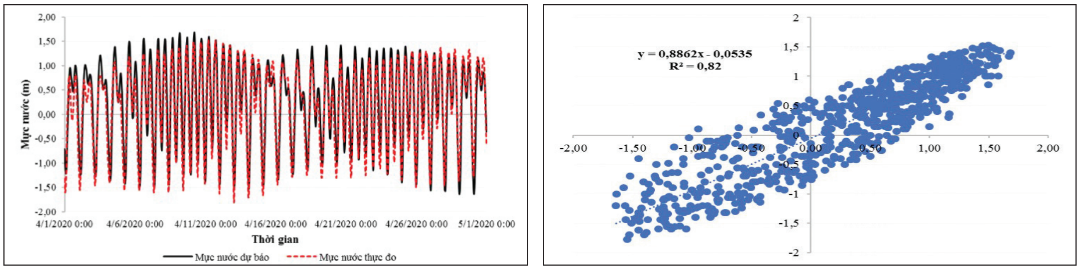

Figure 4. Test the water level (a) and the correlation graph (b) between the forecast water level and the calculated water level in April 2020 at Nha Be station

Table 1. Result of correlation coefficient between forecasted water level and actual water level measured at four stations, April 2020

Station	Correlation value
Vung Tau	0.97
Phu An	0.83
Nha Be	0.82

The result of comparing the data extracted from the tide table of Phu An station provided by the Southern Regional HydroMeteorological Center with the data calculated by Utide software for 10 days from November 1 to November 10 are presented in Table 2, showing the reliability and accuracy of Utide software in case of comparing errors in the range of 0.05 to 0.1.

Table 2. Comparison of the measured data at Phu An station of Southern Region HydroMeteorology Center and calculation data of Utide

Time	Time to appear	Actual water level measured by SRHC	Water level calculation software by UTide
1/11/2020	4:00	1.49	1.39
2/11/2020	18:00	1.48	1.38
3/11/2020	5:00	1.43	1.36
4/11/2020	5:00	1.42	1.34
5/11/2020	5:00	1.43	1.35
6/11/2020	1:00	0.32	0.3
7/11/2020	6:00	1.06	1.18
8/11/2020	15:00	-1.3	-1.16
9/11/2020	8:00	0.73	0.76
10/11/2020	10:00	0.41	0.43

3. Research results and discussion

3.1. Water level analysis and forecast results

The data in this study is a series of hourly water level monitoring data from 2010 to 2018 at Nha Be station (located in Nha Be district of HCMC), Phu An station (located in District 1 of HCMC) and Vung Tau station (located in Ward 2, Vung Tau City) and there are 77,760 real hourly-measured data at each station. Based on the analysis results, harmonic constants are used as input for forecasting. To test the water level forecasting ability of UTide software, we calculate the water levels at the three stations as above using the set of the harmonic constants in April 2020 to verify with real measured data as well as forecast the water level in January 2021.

The analysis results of the harmonic constants will have 68 wave components; Due to the structure of the article, only 20 wave components have the largest oscillation amplitude and are typical for irregular semidiurnal tides of Vung Tau station are presented. The harmonic constants at Vung Tau station are presented in Table 3. The calculated amplitudes of component waves M2, K1, O1 and S2 are 0.77 m, 0.59 m, 0.45 m and 0.30 m, respectively.

The contribution by variation of each component wave is shown in Figure 5. Accordingly, the component tidal waves are mainly concentrated at the frequency of 0.04 and 0.08 (cycle/hour). Correspondingly, diurnal and semi-diurnal tidal components have the largest contribution to the water level fluctuations. Most of the tidal waves are concentrated at an insignificant amplitude of less than 4 cm. 8 component waves with the largest amplitude above these 68 component waves calculated in Vung Tau is shown in Figure 5. Where the component wave with the highest amplitude and the largest percentage of energy is wave M2, the second component wave with amplitude and energy percentage is wave K1.

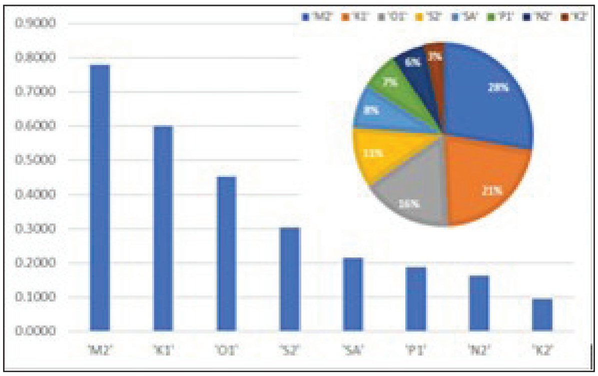

Figure 5. Component waves in Vung Tau with the largest amplitude and percentage of component waves

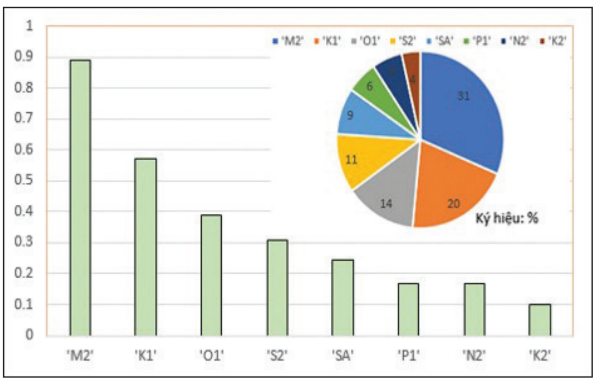

Figure 6. Component waves at Nha Be with the largest amplitude and percentage of component waves

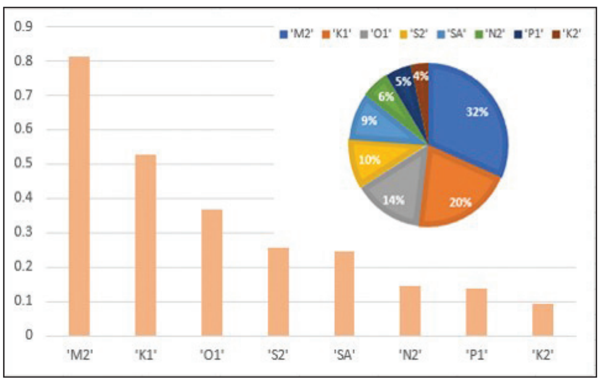

Figure 7. Component waves at Phu An with the largest amplitude and percentage of component waves

Table 3. Air conditioning constant of Vung Tau station from 2010 - 2018

Wave	Frequency	Amplitude	Amplitude error	Phase	Phase error	Signal Noise (SNR)
'M2'	0.08	0.77	0.0013	38.84	0.09	1441152.21
'K1'	0.04	0.59	0.0008	312.92	0.07	1946113.21
'O1'	0.03	0.45	0.0008	263.41	0.09	1486431.39
'S2'	0.08	0.30	0.0013	80.63	0.20	312634.18
'SA'	0.0001	0.22	0.0038	354.09	1.20	8575.71
'P1'	0.04	0.18	0.0007	308.76	0.23	204161.37
'N2'	0.07	0.16	0.0012	15.94	0.46	99561.22
'K2'	0.08	0.09	0.0011	94.26	0.69	28834.75
'Q1'	0.03	0.08	0.0008	243.03	0.42	44167.48
'SSA'	0.0002	0.05	0.0045	97.78	4.08	616.67
'NU2'	0.08	0.03	0.0012	21.44	2.16	3499.46
'MK3'	0.12	0.02	0.0007	188.56	1.42	6240.88
'NO1'	0.04	0.02	0.0008	290.76	1.67	5000.79
'2N2'	0.07	0.02	0.0012	351.55	2.74	1350.99
'H1'	0.08	0.02	0.0013	27.24	3.23	2060.63
'MU2'	0.07	0.02	0.0012	319.14	3.19	1339.12
'J1'	0.04	0.02	0.0007	351.78	1.95	2752.38
'L2'	0.08	0.02	0.0014	60.36	2.81	792.83
'H2'	0.08	0.01	0.0011	244.49	3.64	967.42
'MO3'	0.11	0.01	0.0007	130.47	2.42	3014.33

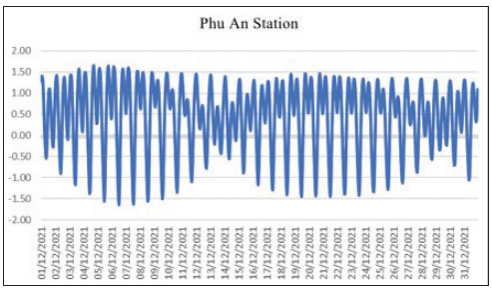

Figure 8. Water level forecast in December 2021 in Phu An

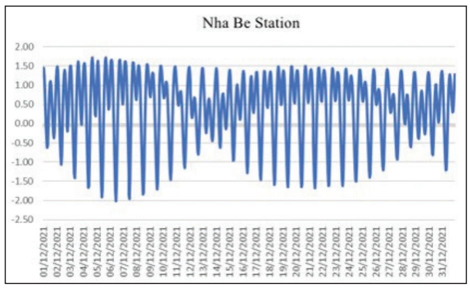

Figure 9. Water level forecast in December 2021 in Nha Be

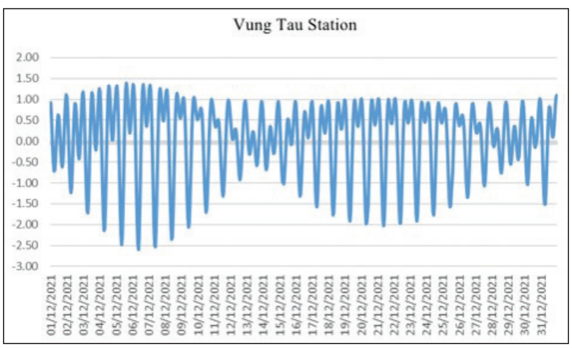

Figure 10. Water level forecast in December 2021 in Vung Tau

3.2. Assessment of the impact of tidal level on flooding in HCMC

According to the tidal level forecast results, the impact of tidal level in HCMC, especially the inner - city area, is very serious at the end of 2021. The forecasted maximum water level in 2021 at Vung Tau station is 1.41 m, while that at Phu An and Nha Be stations is 1.75 and 1.81 m, respectively, revealing that the coastal water level has a great influence on the water level in rivers and canals. The water level on the Saigon River at Phu An station is 0.34 m higher than that of Vung Tau station, and the water level on the Soai Rap river at Nha Be station is 0.40 m higher than that of Vung Tau station. The maximum water level exceeds the alarm level III of 1.60 m, which will cause flooding in HCMC. It is very necessary to have more research on the impact of tidal levels in HCMC in the future.

4. Conclusion

The results of analysis and calculation of water levels at Vung Tau, Phu An and Nha Be stations using UTide software archived good results, with a high correlation coefficient from 0.81 to 0.97. The comparison results between forecast and actual water levels in April 2020 have negligible deviations in both phase and amplitude. The results of water level analysis show that tidal waves M2, K1, O1 and S2 have the largest amplitude among tidal waves.

Based on the results of analysis and prediction of water level fluctuations at Vung Tau station, Phu An station and Nha Be station, it can be concluded that the software has the ability to analyze well the set of harmonic constants, have a reliable forecast of water level fluctuations Based on that, UTide software can be applied for coastal tidal forecasting and river water level forecasting for the southern region.

From the calculated results, it is shown that the hydrographic station, namely Vung Tau station, archives high result in the correlation coefficient of 0.97 compared to the ones of hydrological stations such as Phu An and Nha Be of approximately 0.83 and 0.82 This shows that the hydrographic stations subject to the strong influence of the tide have higher accuracy. The hydrological stations located deeply in the field are less affected by tides and subject to the influence of river flows, they have lower accuracy.

Contributions of authors: *Developing research ideas: N.V.H., C.T.H.; Selection of a research method: N.P.D., C.T.H., P.A.B.; Data processing: N.P.D.; Writing the paper: P.A.B., C.T.H., N.P.D.; Paper editing: N.V.H., P.A.B., C.T.H., N.P.D..*

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