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Original Article

Modeling long-term trends of diurnal and semidiurnal tides in Thailand from 2004-2017

Nitinun Pongsiri[1, 2], Rhysa McNeil[1, 2*], and Somporn Chuai-Aree[1, 2]

[1] *Department of Mathematics and Computer Science, Faculty of Science and Technology, Prince of Songkla University, Pattani Campus, Mueang, Pattani, 94000 Thailand*

[2] *Centre of Excellence in Mathematics, Commission Higher Education (CHE), Ratchathewi, Bangkok, 10400 Thailand*

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Abstract

The southern part of Thailand is heavily affected by tidal changes in the Gulf of Thailand and the Andaman Sea. This study investigates the long-term trends of diurnal and semidiurnal tides along the coasts of the Andaman Sea and the Gulf of Thailand. Daily observations of diurnal and semidiurnal tides along the coasts of the Andaman Sea and the Gulf of Thailand from 2004-2017 were obtained from the Marine Department of Thailand. Astronomical effects in the data were accounted for using a periodic regression model, while a linear regression model was applied to determine the long-term trends in highest high water (HHW), lower high water (LHW), lowest low water (LLW) and higher low water (HLW) levels for semidiurnal tides and diurnal tides. Results showed that diurnal tides at Tha Chaleap had positive trends for HHW and LLW. The results for semidiurnal tide at the Kantang and Krabi stations were positive for all water levels while trends at the Tammalang station were positive for LHW. The study revealed significantly increasing trends in water levels for diurnal and semidiurnal tides. The long-term effects could be catastrophic if proper management plans are not implemented to reduce these trends.

Keywords: long-term trends; diurnal tide; semidiurnal tide; linear regression; Thailand

1. Introduction

Tidal levels and water heights are very important as fisheries, marine resource management and coastal engineering depend on tidal dynamics. Astronomers are also interested in tides because of the effects astronomical factors have on their dynamics (Kantha & Clayson, 2000).

Over the past few years, increasing attention has been given to sea level rise and its impact on coastal ecosystems (Church, White, Coleman, Lambeck, & Motrovica, 2004; Nicholls & Cazenave, 2010). There is evidence that changes in sea level are mostly determined by astronomical and terrestrial factors (Pugh & Woodworth, 2014). Among the studies on global sea level rise, Pickering *et al*. (2017) revealed that changes in sea level mostly affect tides along coastlines.

*Corresponding author
Email address: rhysa.m@psu.ac.th

The southern part of Thailand rests on the Malay Peninsula, which separates the Gulf of Thailand from the Andaman Sea. Sea level changes continually affect the lives of people living along the coasts on both sides of the peninsula as well as the marine organisms. Along the coast on both sides of Thailand, studies have found that diurnal tides, semidiurnal tides and mixed tides exist (Brown, 2007; Saramul, 2013). Due to the numerous effects of tidal variations on coastal life in Thailand, it is important to investigate the trends in sea levels. Some studies have attempted to characterize and explain sea-level variations in Thailand (Saramul & Ezer, 2014; Sojisuporn, Sangmanee, & Wattayakorn, 2013; Trisirisatayawong, Naeije, Simons, & Fenogio-Marc, 2011). However, the focus of these studies was mainly on the mean sea levels and findings were provided on a global perspective. There has been little attempt to describe the trends in tidal levels despite the availability of tidal data. The objective of this study is to predict the long-term trends of diurnal and semidiurnal tides in Thailand. Four main water levels were investigated. For diurnal tides, highest high water (HHW) and lowest low water (LLW) were studied while lower high water (LHW) and higher low water (HLW) were studied for semidiurnal tides. The findings from this study would be important to coastal resource managers and inhabitants along the coast to understand the current trends of sea levels.

2. Materials and Methods

2.1 Data management and study areas

Data for this study were obtained from the Marine Department of Thailand, which has been collecting tidal gauge measurement of sea levels every day since 2004 at 21 stations. However, in 2013 they stopped measuring sea levels at three stations. These three stations were excluded from the study. The data for every station that had less than 25% missing data were included in the analysis. If more than 25% of the observations are missing, the seasonal cycles could be affected (Mawdsley, 2015). From the remaining 18 stations, complete data were available for only 15 stations, out of which nine measure mixed tides, and three each measured diurnal and semidiurnal tides. For this study water levels for diurnal and semidiurnal tides at the six tidal gauge stations were considered. These stations are Krabi, Kantang, Tammalung for semidiurnal tides along the Andaman Sea and Laem Ngop, Tha Chaleap and Rayong stations for diurnal tides in the Gulf of Thailand as shown in Figure 1.

Diurnal tides record two water levels daily, the HHW and the LLW at approximately 12-hour intervals. However, for semidiurnal tides, four water levels HHW, LHW, LLW and HLW, are measured daily at approximately 6-hour intervals. The data for this study spanned the period from 1st January 2004 to 31st December 2017. There was a total of 5,114 tidal gauge records for each water level. From these observations, Rayong tidal gauge station had the highest number of missing values; 611 observations were missing for HHW (11.95%), and 706 observations (13.8%) were missing for LLW.

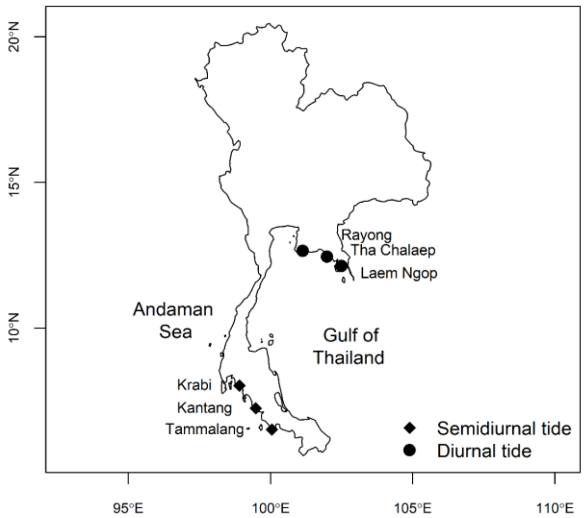

Figure 1. Tidal gauge locations

2.2 Method

In the estimation of trends in tides, methods such as linear regression, percentile analysis, cubic spline, harmonic analysis and the sea level model have been applied (Egbert, Ray, & Bills, 2004; Rasheed & Chua, 2014; Santamaria-Aguilar, Schuerch, Vafeidis, & Carretero, 2017). In Thailand, most studies have used the harmonic analysis, empirical mode decomposition and Hilbert-Huang Transform (EMD/HHT) and in some instances, regression analysis to describe the changes in mean sea level.

According to Santamaria-Aguilar *et al*. (2017), periodic time series can depict long-term linear trends. Hence, a linear regression model was fit to the data from each station. Tidal dynamics are affected by constant astronomical factors (Pugh & Woodworth, 2014) and any model for tides must account for these factors. In order to account for the effects of gravity from the sun and the moon on the tides, a periodic regression model (Derryberry, 2014) as shown in equation (1) was used. This model removes the gravitational effects of the moon and sun to reveal the actual linear trend in water levels.

The periodic regression model is given by:

$$w(t) = \mu + b\cos(2\pi t / p) + c\sin(2\pi t / p) \quad (1)$$

where w is the predicted water level after removing solar and lunar effects, t is time (in days), p is the lunar or solar period of the tide, μ is the intercept, and b and c are coefficients estimated by the model. The periodic regression model depends on the period (number of days before a repeated cycle) of each tide. First, the lunar period was used to fit the periodic regression model. Second, the solar period was used to fit the residuals from the first model. Once the astronomical effects were removed using the periodic regression model, a simple linear regression model was used to estimate the long-term trend in tidal heights for each tide at each station. The regression model is given by

$$y(t) = a + bt \quad (2)$$

where y is the predicted water level at time t (in days), a is the intercept, and b is the estimated trend. The goodness-of-fit of the linear model was assessed with a quantile plot of residuals.

3. Results

3.1 Data from tidal gauge station

The time series of the data for each type of water level and each station is shown in Figure 2.

Figure 2a, both the HHW and LLW recorded at Laem Ngop follow the same annual patterns. There were no observable changes in the trends over the study period. The data showed spikes at intermittent periods. The average levels of HHW and LLW were 3.0 and 1.8 meters, respectively. Data from Tha Chalaep and Rayong tidal gauge stations had similar features with Laem Ngop. On average, the HHW level at Tha Chalaep was 3.1 meters, while the average for LLW was 1.9 meters. Two gaps were identified in the data from Rayong station. Water level data from April to July 2008 and the whole of 2015 were not available. From the available data, HHW and LLW averaged 3.2 and 1.9 meters, respectively.

Observing Figure 2b, water levels from the Kantang tidal gauge station showed an increase between 2009 and 2013. Over the study period, the average levels for HHW, LHW, LLW and HLW were 3.6, 3.3, 1.5 and 1.6 meters, respectively. However, no observable trends were seen at the Tammalang and Krabi tidal gauge stations. The average level for the water levels at Tammalang were 3.4, 3.2, 1.3 and 1.5 meters for HHW, LHW, LLW and HLW, respectively. At the Krabi station, the average water levels were 3.6 meters for HHW, 3.3 meters for LHW, 1.4 meters for LLW and 1.5 meters for HLW.

A periodic regression model was fit to the data from each station. A lunar period of 13.66 days was used for diurnal tides, and 14.76 days was used to fit the model for semidiurnal tides (Stephenson, 2016). Figure 3 shows the results from the model, displaying only the first year for clarity.

The observed data are presented as black curves, while the fitted data are shown as red dots. The periodic regression model has provided a good fit for the water levels for semidiurnal tides (Figure3b). Each model has an r-square (R^2) value greater than 50%. However, the R^2 for the models from diurnal tides were lower. Most of the models had an R^2 value less than 30% (Figure 3a). Although these R^2 values were low, the residual time series data are stationarized by removing solar and lunar effects (Nau, 2020), and the quantile-quantile plots (Figure 6) confirms that the models are a reasonable fit for the data.

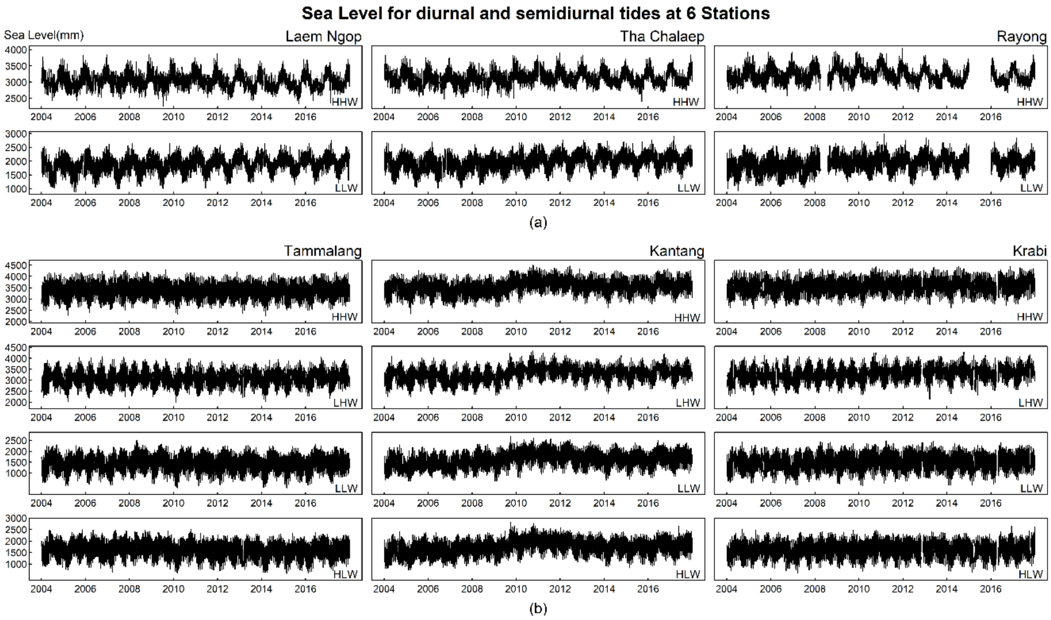

Figure 2. Data from diurnal (top) and semidiurnal (bottom) stations

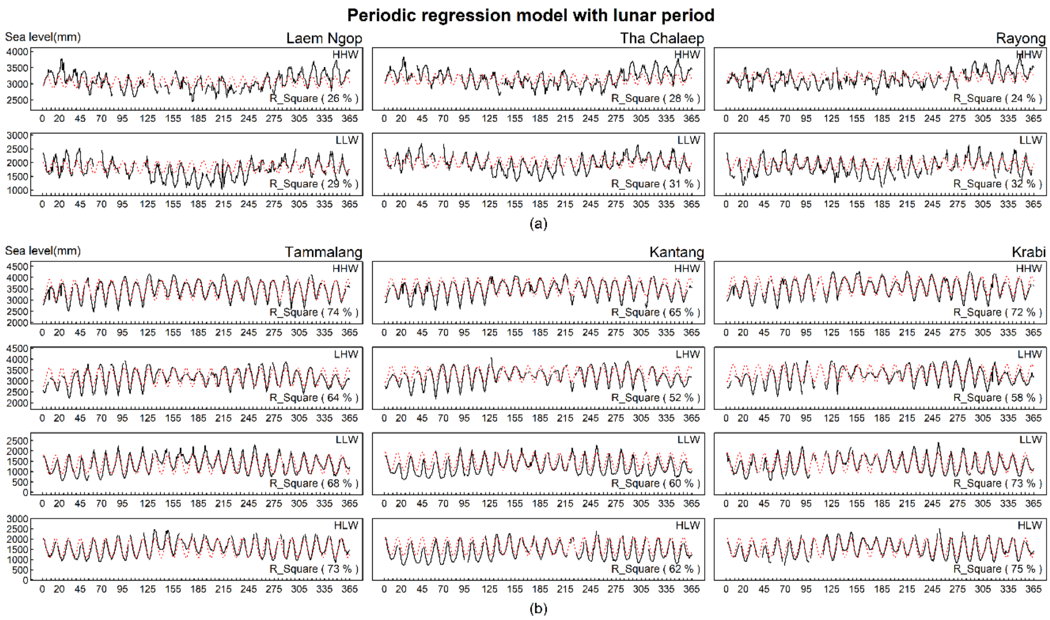

Figure 3. Results from the periodic model with lunar period

Using the residuals from this model, the periodic regression model was fit with the solar period of 365.25 days for both diurnal and semidiurnal tides. The solar period for each tide was found to be the same as one solar year. Results from fitting the solar period indicate that water levels for diurnal and semidiurnal tides at each station depended on the lunar period more than the solar period. The R^2 from the model for each water level was less than 20%. The results from the periodic regression model with solar period are shown in Figure 4.

After fitting the periodic regression model with lunar and solar periods, the astronomical effects have been removed. Results from the linear regression model, equation (2), are presented in Figure 5.

The simple linear regression model shows that the water levels at each station have different trends (*b*) for each type of tide. A value of *b* greater than zero indicates an increasing trend while a value less than zero indicates a decreasing trend. The HHW and LLW for diurnal tide at Laem Ngop have opposite trends. For the 14 years, HHW has decreased at an average of 0.012mm/day (p-value < 0.05) while LLW increased at an average of 0.047 mm/day (p-value < 0.05). However, the water levels at Tha Chalaep station had an increasing trend. Both HHW and LLW at this station had increases of 0.007 mm/day and 0.062 mm/day, respectively. Results from the Rayong station were similar to Laem Ngop. The regression model revealed opposing trends for HHW (-0.012 mm/day) and LLW (0.054 mm/day).

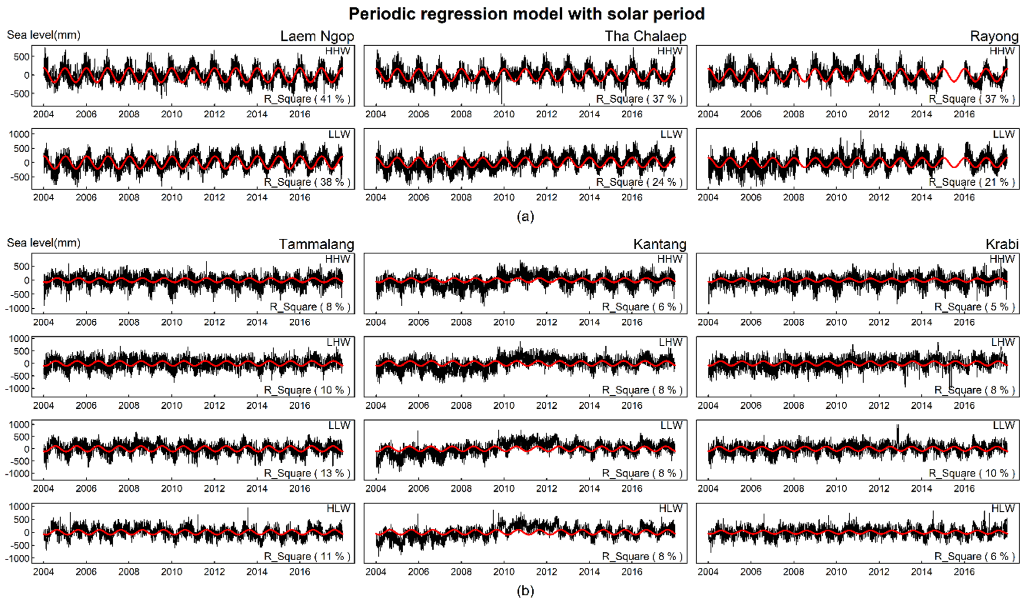

Figure 4. Results from the periodic model with solar period

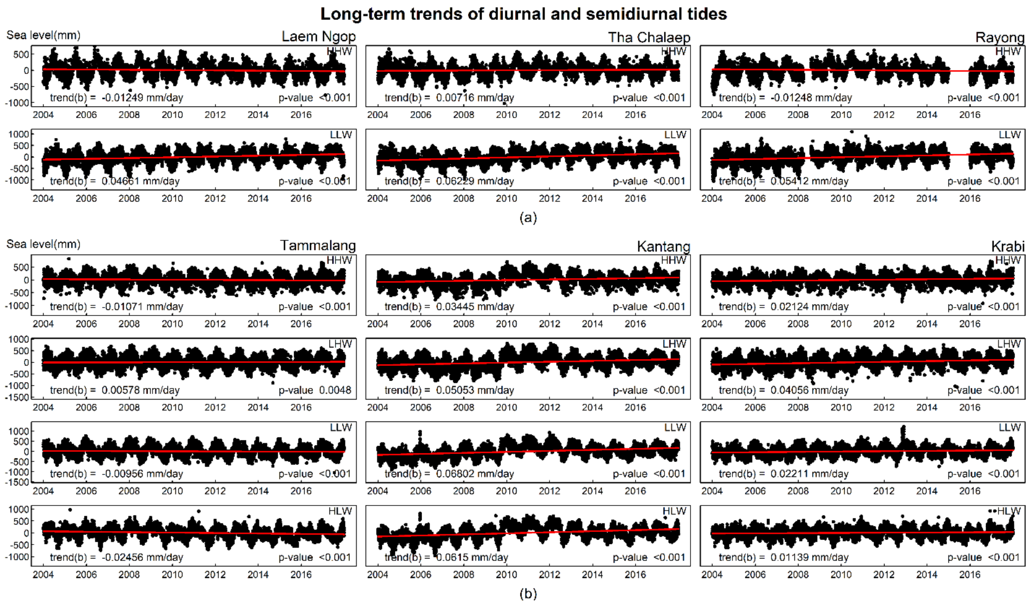

Figure 5. Long-term trends in water levels

For semidiurnal tides, the linear regression model showed that water levels at Kantang and Krabi stations had increased during the study period (14-year). At the Kantang station, the trends for LHW, LLW and HLW were found to be higher than 0.05 mm/day (all p-values < 0.05). An average increase of 0.034 mm/day was found for HHW at the same station. Results from the model also revealed an increasing trend for Krabi, although the trend was lower compared to Kantang station. The highest trend was found to be 0.041 mm/day (p-value < 0.05) for LHW and the lowest was 0.011 mm/day (p-value < 0.05) for HLW. Despite the increasing trends identified at Kantang and Krabi stations, the model found mixed trends for semidiurnal tide at Tammalang station. HHW, LLW and HLW at this station had decreased at an average of 0.011 mm/day, 0.009 mm/day and 0.025 mm/day, respectively. Residuals from the linear regression model for each water level were presented as quantile-quantile (Q-Q) plots to assess the goodness-of-fit and are shown in Figure 6.

The Q-Q plots from the linear regression model with diurnal tides are shown in Figure 6a. From this figure, the residuals of each model were normally distributed. However, LLW at Laem Ngop and Tha Chalaep stations exhibited slight deviations at the upper tails. The plots of residuals from the models for semidiurnal tides (Figure 6b) indicate that the residuals are normally distributed. However, the residuals of LLW from Krabi station showed deviations at the upper tail. Overall, the linear models provided good fits for the water levels of diurnal and semidiurnal tides.

4. Conclusions and Discussion

This study investigated the water levels, based on daily observed data from six tidal gauge stations in Southern Thailand using a periodic regression model and a linear regression model. The models estimated the trends in water levels for diurnal and semidiurnal tides. The simple linear regression model fits the data quite well and provided significant trends of water levels along the coast of Thailand. Results showed average decreases in HHW of diurnal tides at the eastern part of the Gulf of Thailand and average increase in LLW. Along the Andaman coast, water levels for semidiurnal tides showed average daily increments at two stations while one station recorded different trends for all water levels.

Another study from Thailand applied the linear regression model to estimate the trends in mean sea level but focused only on the Gulf of Thailand. The model found an average increase of 0.0123 mm/day in the mean sea level at the eastern part of the Gulf of Thailand (Sojisuporn *et al*., 2013). Santamaria-Aguilera *et al*. (2017) also used a linear regression model to estimate the trends in semidiurnal tides at two tidal gauge stations off the coast of Argentina. Results

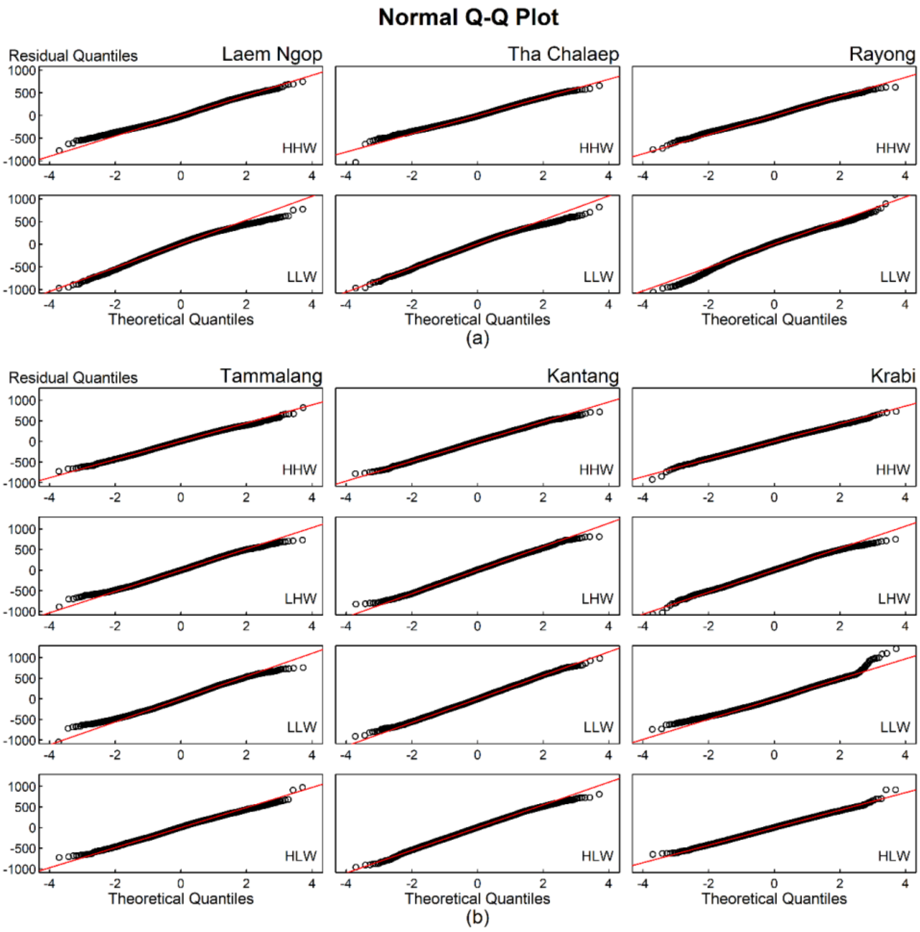

Figure 6. Residual Q-Q plot from the linear regression model.

from their study confirm our results that the linear regression model provides an adequate fit for periodic data after accounting for the astronomic effects.

For diurnal tides, the linear model showed mostly increasing trends at all stations along the eastern part of the Gulf. These increasing trends are consistent with the results from Sojisuporn *et al*. (2013), which found positive trends in the mean sea level between 1982 and 2004.

This study also found that the trends in sea levels for semidiurnal tides along the Andaman Sea were mostly positive. Only Tammalang station recorded decreasing trends in HHW, LLW and HLW. The positive trends could be attributed to the increase in the tidal constituents along the South-east Asian region (Rasheed & Chua, 2014). Such increases are not just peculiar to the tide along the Andaman coast. Semidiurnal sea levels around Calais in France have also recorded significantly increasing trends averaging 6 mm/year over the past two centuries (Mawdsley, Haigh, & Wells, 2015). Estimating the trends in water levels for diurnal and semidiurnal tides has shown that daily change in sea levels differs by station. Most sea levels are rising gradually. These increases may have significant effects on coastal areas. There is evidence of coastal erosion and inundation of low-lying areas, saltwater intrusion into groundwater, flooding and high tides, and habitat loss. The economic impact, including destruction of properties along the coast, changes in land use patterns, and water management systems, may be significant. Strategies to mitigate the impact of sea level rise such as zoning and land use management, erosion and flood control, water management, and reinforcement of existing coastal structures need to be implemented.

Although the coastline of Thailand is predominantly mixed tides, this study analyzed only diurnal and semidiurnal tides from just six stations because the period of mixed tides could not be estimated.

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