Statistical Modeling for Sea Level Change in Thailand

Nitinun Pongsiri

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Research Methodology
Prince of Songkla University
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Major Program	Research Methodology

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This is to certify that the work here submitted is the result of the candidate’s own investigations. Due acknowledgement has been made of any assistance received.

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I hereby certify that this work has not been accepted in substance for any other degree, and is not being currently submitted in candidature for any degree.

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Candidate

ชื่อวิทยานิพนธ์ แบบจำลองทางสถิติสำหรับการเปลี่ยนแปลงระดับน้ำทะเลในประเทศไทย
ผู้เขียน นางสาวนิธินันท์ พงษ์ศิริ
สาขาวิชา วิธีวิทยาการวิจัย
ปีการศึกษา 2564

บทคัดย่อ

ระดับน้ำทะเลที่เพิ่มขึ้นสามารถเปลี่ยนรูปร่างของแนวชายฝั่ง นำไปสู่การกัดเซาะชายฝั่ง น้ำท่วม และการบุกรุกของน้ำเค็มใต้ดินมากขึ้น ระดับน้ำในพื้นที่ชายฝั่งทะเลมีความสำคัญ เนื่องจากผลกระทบของการเปลี่ยนแปลงของระดับน้ำทะเลสามารถทำลายพื้นที่ชายฝั่งทะเล และชายฝั่งทะเลที่เปราะบาง รวมไปถึงการทำลายโครงสร้างของระบบนิเวศ การศึกษานี้มีวัตถุประสงค์เพื่อศึกษาความผันแปร และการเปลี่ยนแปลงในระยะยาวของระดับน้ำทะเลตามแนวชายฝั่งอ่าวไทยและอันดามัน และเพื่อตรวจสอบแนวโน้มของระดับน้ำขึ้นน้ำลง ช่วงของน้ำขึ้นน้ำลง และระดับน้ำทะเลปานกลาง ตลอดจนองค์ประกอบหลักสี่ประการของน้ำขึ้นน้ำลง (lunisolar declination diurnal tide (K1), principal lunar declination diurnal tide (O1), principal lunar semi-diurnal tide (M2) and principal solar diurnal tide (S2)) โดยใช้ข้อมูลรายชั่วโมงจากกรมเจ้าท่าจำนวน 14 สถานี ได้แก่ สถานีแหลมงอบ ท่าแฉลบ ระยอง บางปะกง สมุทรสาคร สมุทรสงคราม บ้านแหลม หลังสวน สิชล ปากพนัง นราธิวาส กระบี่ กันตัง และตำมะลัง ซึ่งข้อมูลแต่ละสถานีมีการเริ่มเก็บข้อมูลต่างช่วงเวลากัน โดยแบ่งเป็นสองการศึกษา

การศึกษาแรก ศึกษาหกสถานีได้แก่ สถานีแหลมงอบ ท่าแฉลบ ระยอง กระบี่ กันตัง และตำมะลัง ซึ่งมีลักษณะน้ำขึ้นน้ำลงหนึ่งครั้งต่อวัน และน้ำขึ้นลงแบบสองครั้งต่อวันตามแนวชายฝั่งของประเทศไทย วิเคราะห์แนวโน้มของระดับน้ำขึ้นน้ำลงในช่วงเวลา 14 ปี ด้วยการวิเคราะห์การถดถอยแบบคาบ และวิเคราะห์ถดถอยเชิงเส้น ผลการศึกษาพบว่าระดับน้ำทะเลที่สถานีท่าแฉลบ กันตัง และกระบี่ระดับน้ำมีแนวโน้มสูงขึ้น ซึ่งตรงกันข้ามกับระดับน้ำทะเลในสถานีแหลมงอบ และระยอง ที่มีแนวโน้มลดลง

การศึกษาที่สอง ใช้ข้อมูลรายชั่วโมงจากสถานีวัดน้ำขึ้นน้ำลงจาก 14 สถานี ซึ่งมีน้ำขึ้นน้ำลง 3 ประเภท น้ำขึ้นน้ำลงหนึ่งครั้งต่อวัน น้ำขึ้นลงแบบสองครั้งต่อวัน และน้ำขึ้นน้ำลงแบบผสมตามแนวชายฝั่งของประเทศไทยในช่วงเวลาต่าง ๆ วิเคราะห์การเปลี่ยนแปลงระดับน้ำในระยะยาวและแนวโน้มของระดับน้ำขึ้นน้ำลง ช่วงความแตกต่างของน้ำขึ้นน้ำลง ระดับน้ำทะเลปานกลาง และ

องค์ประกอบหลักสี่ประการ (K1, O1, M2 และ S2) ของน้ำขึ้นน้ำลง ด้วยการวิเคราะห์เปอร์เซ็นไทล์ การวิเคราะห์ถดถอยเชิงเส้น และการวิเคราะห์ฮาร์มอนิก

ผลจากการวิเคราะห์เปอร์เซ็นไทล์ พบว่าความสูงของระดับน้ำทะเลในอ่าวไทยตอนบนสูงและแปรผันมากกว่าในอ่าวไทยตอนล่าง ในทางตรงกันข้ามทะเลอันดามันมีระดับน้ำทะเลคงที่มากกว่าในอ่าวไทย ระดับน้ำทะเลในอ่าวไทยตอนบนส่วนใหญ่แสดงให้เห็นการเปลี่ยนแปลงของแนวโน้มในระยะยาวอย่างมีนัยสำคัญ ซึ่งเกิดขึ้นจากการเพิ่มขึ้นของระดับน้ำทะเลปานกลาง แนวโน้มในระยะยาวของน้ำขึ้นน้ำลง และปัจจัยภายนอกที่ไม่ใช่น้ำขึ้นน้ำลง

ผลจากการวิเคราะห์ฮาร์โมนิกยืนยันการเปลี่ยนแปลงในองค์ประกอบของน้ำทะเลและแนวโน้มของโลกในทุกระดับน้ำขึ้นน้ำลง แนวโน้มเหล่านี้เกิดจากการเปลี่ยนแปลงขององค์ประกอบน้ำขึ้นน้ำลงหลักทั้งสี่ (M2, S2, O1 และ K1) ยกเว้นสถานีสิชล ตำมะลัง และกระบี่ ซึ่งไม่มีแนวโน้มที่มีนัยสำคัญทั้งในแอมพลิจูด และเฟส ผลการวิจัยโดยรวมบ่งชี้ว่าระดับน้ำที่เปลี่ยนแปลงตามแนวชายฝั่งของประเทศไทยเกิดขึ้นจากระดับน้ำทะเลปานกลาง กระแสน้ำทางดาราศาสตร์ และปัจจัยภายนอก การเปลี่ยนแปลงมีความชัดเจนในอ่าวไทยตอนบนเมื่อเทียบกับอ่าวไทยตอนล่างและทะเลอันดามัน

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Abstract

Increasing sea levels can change the shape of coastlines, contribute to coastal erosion, and lead to flooding and increased underground salt-water intrusion. The water levels of coastal areas are important because the effects of sea level change can be devastating to vulnerable coastal and marine areas and can impact the function and structure of their ecosystems. This study aimed to investigate variations and long-term changes in the frequency of distribution of water levels along the Gulf of Thailand and the Andaman Sea, and to examine the secular trends in tidal levels, tidal ranges, mean sea level (MSL) and four main tidal constituents.

The water level data were obtained from the Marine Department and include 14 stations, namely LaemNgop, ThaChalaep, Rayong, BangPakong, SamutSakhon, SamutSongkram, BanLaem, LangSuan, Sichon, PakPanang, Narathiwat, Krabi, Kantang and Tammalang. The data span for each station, as well as the length of available water level records, was different. This research was divided into two studies. In the first study, six stations were included in the analysis, namely LaemNgop, ThaChalaep, Rayong, Krabi, Kantang and Tammalang, which had tidal characteristics, diurnal and semi-diurnal tides along the coast of Thailand. The distinct water levels for these six stations spaned 14 years. The secular trends in tidal levels were analysed using periodic and linear regression. The results showed that all water levels at ThaChalaep, Kantrang and Krabi stations had increasing trends, contrasting to water levels in LaemNgop and Rayong stations, which had decreasing trends.

In the second study, hourly data from 14 tidal gauge stations included three types of tides, namely diurnal, semi-diurnal and mixed-diurnal tides along the coast of Thailand over different periods were analysed. The variations, long-term changes in the frequency of distribution of water levels, secular trends in tidal level, tidal range and MSL, as well as the four main tidal constituents (lunisolar declination diurnal tide (K1), principal lunar declination diurnal tide (O1), principal lunar semi-diurnal tide (M2) and principal solar diurnal tide (S2)), were analysed using percentile, harmonic and linear regression methods.

The result from percentile analysis revealed that the height of water levels in the upper Gulf of Thailand was higher and varied more than in the lower Gulf of Thailand. In contrast, the Andaman Sea had a more stable water level than in the Gulf of Thailand. Most water levels in the upper Gulf of Thailand showed significant long-term changes, which occurred due to MSL rise and long-term trends in the tidal component and non-tidal residuals.

The findings from the harmonic analysis confirmed the change in tidal components and secular trends in all tidal levels. These trends were caused by changes in the four main tidal constituents (M2, S2, O1, and K1), with the exception of Sichon, Tammalang, and Kabi stations, which showed no significant trend in both amplitude and phase. The overall finding indicated that water level change along the coast of Thailand occurred due to MSL, astronomical tides and non-tide residual. The changes were more prominent in the upper Gulf of Thailand compared to the lower Gulf and the Andaman Sea.

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I would like to express my sincere appreciation to my advisors, Asst. Prof. Dr. Rhysa McNeil and Asst. Prof. Dr. Somporn Chuai-Aree for giving me the opportunity to do research and providing invaluable guidance throughout this research and in life. Their vision, sincerity and motivation have deeply inspired me. It has been a great privilege and honour to work and study under their guidance. I am extremely grateful for what they have offered me. I am also thankful to Assoc. Prof. Dr. Phattrawan Tongkumchum, Assoc. Prof. Dr. Apiradee Lim, Asst. Prof. Dr. Mayuening Eso for their academic advice. Most especially Emeritus Prof. Donald McNeil for assisting me with his vast knowledge of research methods and new experience. Also, I would like to thank external committee Asst. Prof. Dr. Wandee Wanishsakpong for letting my defence be an enjoyable moment and for your brilliant comments and suggestions.

Special thanks go to the lecturers and staff of the Department of Mathematics and Computer Science for granting me the opportunity to broaden my knowledge in this program. I would like to acknowledge the Faculty of Science and Technology, Prince of Songkla University, and Centre of Excellence in Mathematics for their financial support and providing an enabling environment for the successful completion of this thesis.

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Nitinun Pongsiri

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Chapter 1

Introduction

This research presents a statistical model to study long-term change in water levels. In this chapter, the overview of changing in water level, problem and objective of the research as well as the expected advantages and scope of the study are discussed.

1.1 Background and Rationale

Global climate dynamics and consistent rise in atmospheric temperature continue to affect sea and tidal levels. This phenomenon also has effects on human lives (Nicholls and Cazenave, 2010; Jin et al., 2013). There has been a consistent rise in global sea level over the past century and has become a major scientific research interest in diverse academic fields (Church et al., 2007). Over the past two centuries, the average global sea-level change has been between 1.7±0.3mm/yr and 1.8±0.3mm/yr (Church et al., 2004; Church et al., 2006). Changes in the global mean sea level (MSL) affect tides and tidal elements along coastlines (Pickering et al., 2017). Tides are the temporary rise and fall of sea levels caused by the combined effects of the gravitational forces created by the Moon, the Sun and the rotation of the Earth. Tides are able to control coastal dynamics in different ways. The water levels of coastal areas are very important as their dynamics have a large impact on fisheries, marine resource management, and coastal engineering projects (Kantha and Clayson 2000). Navigation of water vessels, coastal communities, shoreline and shallow water ecosystems and sediment distribution are affected by the seasonal rise and fall in tidal levels (Allen et al., 1980; Haigh et al., 2011; Pugh and Woodworth, 2014). Such implications basically indicate that tidal changes have a wide range of scientific implications and important practical consequences. However, tides are thought to have changed very insignificantly over the same period. This perception is based on the fact that the tidal generating astronomical forces are always constant (Cartwright and Driver, 1971). Water level analyses have become very important, however, remain complicated due to the complex composition of water levels. The water level at any point depends on MSL, astronomical tides and storm surges (non-tidal residuals) and any changes in these components affect the variability of the water level (Rhein et al., 2013).

Thailand is a southeast Asian country, with two coastal zones. These coastal zones are the Gulf of Thailand coast and the Andaman Sea coast. These coasts are economically important areas with 23 provinces connected to the sea and approximately 12 million residents in these areas (Department of Mineral Resources, 2016). Along this coastline, water level variations have a great impact on marine and estuary life and people who inhabit coastlines (Dearden, 2002). The coastline of Thailand can be divided into three sections according to tidal characteristics. The upper Gulf of Thailand stretches from the coasts of Samut Songkhram province in the west to Trat province in the East (covering the shores of Samut Sakhorn, Bangkok, Samut Prakan, Chachoengsao, Chonburi, Rayong and Chanthaburi provinces). The Gulf of Thailand section covers the coasts of Petchaburi province in the north to Narathiwat in the south, along the Eastern border with Malaysia. The other section is the Andaman coastline. This coastline begins from Ranong province down to Satun province, along the western border with Malaysia (Saramul and Ezer, 2014a; Saramul and Ezer, 2014b).

The change in water level in a continuous at Thailand can causes problems for people who live near the coast and the marine organisms living along the coast. Also, can have effects on plant and animal habitats, because island and coastal areas are submerged. Therefore, changes in relative MSL and water levels could have varying effects. Although there have been local studies to characterise and explain the water level trends along the Andaman Sea, and the Gulf of Thailand, these studies focused on the MSL, which represents just one component of the water level (Angsakul et al., 2007; Saramul and Ezer, 2014b; Sojisuporn et al., 2013; Trisirisatayawong et al., 2011). Also, any water level analyses that seek to address predictive uncertainties must account for the correlation between climate indices and water level variability (Wahl and Chambers, 2015). This study aimed to investigate the water level changes along the coast of Thailand.

1.2 Objectives of Research

1. To investigate variations and long-term change of water levels along the Gulf of Thailand and the Andaman Sea
2. To examine the secular trends in tidal levels, tidal ranges and MSL, as well as the four main tidal constituents

1.3 Expected Advantages

Coastal lines in Thailand exhibit different tidal characteristics at different locations. Three different tides exist along the Gulf of Thailand and the Andaman Sea. At the end of this study, it is expected that statistical models will be used to understand how these water levels are changing. The long-term effects of the changes on coastal ecosystems and livelihood will also be explained. Information about the trends of water levels and the impacts on coastal ecosystems will enable policy makers make useful decisions to help people living along the coast in Thailand.

1.4 Scope of the Study

Increasing sea levels can change the shape of coastlines, contribute to coastal erosion, lead to flooding and more underground salt-water intrusion. Therefore, this study aims to investigate the variability of water levels, long-term trends, tidal levels, and main tidal constituents along the Gulf of Thailand and the Andaman Sea. Furthermore, the causes of sea level changes also examined. Changes in relative MSL and water levels could have varying effects caused by MSL, Tide, or non-tidal residual effects. The scope of the study is limited to specific causes of water level change from non-astronomical changes such as regional climate index, river discharge, vertical land movement, storm, physical environment or human activity.

This thesis is divided into five chapters according to the following structure. Chapter 2 presents the literature review that is relevant related to this study. The study area, data source and statistical method used are described in chapter 3. The results from percentile analysis and tidal harmonic analysis are presented in chapter 4, and the conclusion of this thesis are discussed 5.

Chapter 2

Literature Review

Water level refer to the height of water relative to a specific land elevation and are measured at tidal gauge stations. Several studies have reported high water levels at different locations. Tides form part of the most controlling forces on the earth and have more significant effects on water levels compared to other processes. Water level changes have been documented across many coastlines around the world. These changes have been attributed to location-specific factors, oceanographic processes, and astronomical effects. Therefore, this chapter presents the characteristics of water level, the impact of sea-level rise on global tidal and water levels and statistical models for studying water level changes.

2.1 Water Levels and Water Level Measurement

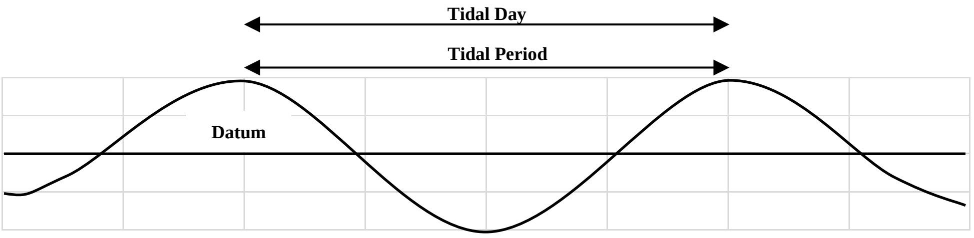
There are two types of instruments to measure water levels the tide staff and the automatic tide gauge. The tide staff is used to monitor short-term water levels. This tool measures water levels at hourly or half-an-hour intervals, except for periods close to high and low tides, where water levels are recorded every fifteen minutes. The automatic tide gauge tool records water heights associated with time, and the recordings are displayed as water curves, which can be converted to numeric values. There are three types of automatic tide gauge measuring tools. These are float, pneumatic and pressure probe. The float is a popular tool because it has mechanisms that make recordings easy and reliable. Presenting data as curves makes it easy to detect discontinuity and missingness and identify the type of water levels (Boonmhor, 1992).

Water levels (local sea level) refer to the height of water relative to a specific land-elevation and are measured by tidal stations. The MSL is also used to describe tidal datum, or a vertical reference given by a specific tidal phase. Tidal datums generated locally based on measure water levels and a compute over a period of 19 years, known as the National Tidal Datum Epoch (NTDE) (Center for Operational Oceanographic Products and Services, 2021). Tidal datums serve as the foundation for ocean boundaries and are used vertical reference planes for nautical charts. They also provide essential information for sea level change observation. The MSL is a tidal datum, calculated as the mean of hourly water heights over a 19 years period. The Sun and Moon's gravitational pull on the Earth’s rotation and the oceans cause tides. The exact tidal pattern at any given location along the coast is strongly influenced by the shoreline and the contour of the neighboring seafloor. Also, co-oscillating tides and resonance are significant factors of tidal shape in shallow oceans, bays, and estuaries. Even though the tidal-generating gravitational forces are known, theoretically, it is very difficult to compute the tides at any specific location. The fundamental frequencies of gravitational tides are related to the astronomical time constants that uniquely specify the position of the sun and moon defined as follows:

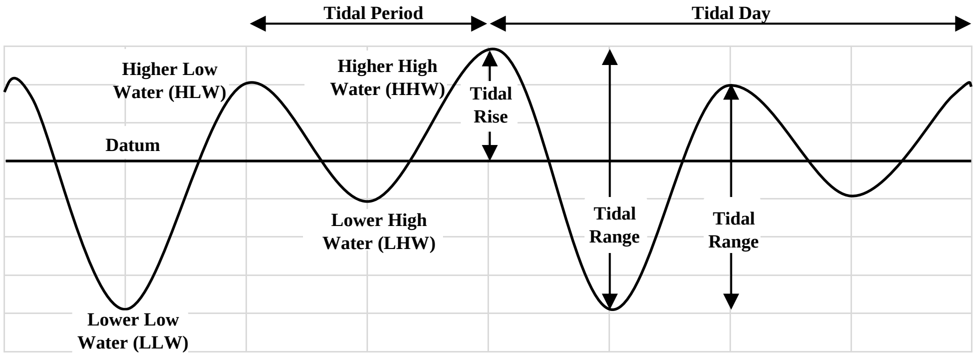
τ, the mean lunar day
s, the mean longitude of the moon
h, the mean longitude of the sun
p, the mean longitude of the lunar perigee
n', the negative of the longitude of the moon's ascending node
p', the mean longitude of the solar perigee.

These six variables have approximate periods of 24.84 hours, 27 days, 1 year, 8.8 years, 18.6 years, and 21,000 years, respectively (Foreman and Henry, 1989).

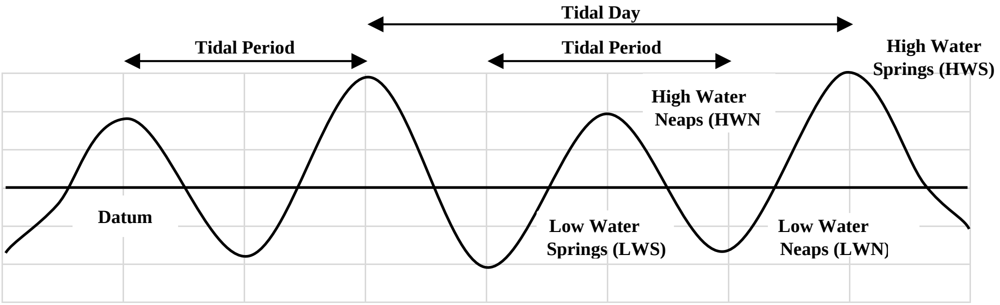
Automatic tide gauge tools measure three types of tides-: diurnal, semi-diurnal, and mixed tides. A diurnal tide has the regular pattern of one high tide and one low tide each day. The semi-diurnal tide has two high and two low tides of almost equal amplitude per day. The mixed tides are similar to the semi-diurnal tide; however, they can have two high and low tides of unequal range, as shown in Figure 2.1.



Diurnal Tide



Mixed Tide



Semi-Diurnal Tide

Figure 2.1 Three types of tide

The tidal range determines the width of the wave-affected coastline strip. The vertical difference between consecutive high and low water heights across a tidal cycle is known as tidal range (Figure 2.1). The tidal range is location and time specific. The location and time differences of tidal range are important due to their relation to the variation of coastal morphology. The size of the tidal range is an indication of the size of land strip subjected to forces of the waves.

Astronomy has detected hundreds of periodic motions of the Earth, Sun, and Moon. The tide-generating motions, known as tidal components, tidal constituents, or harmonic constituents, are represented by cosine curves as seen in Figure 2.2.

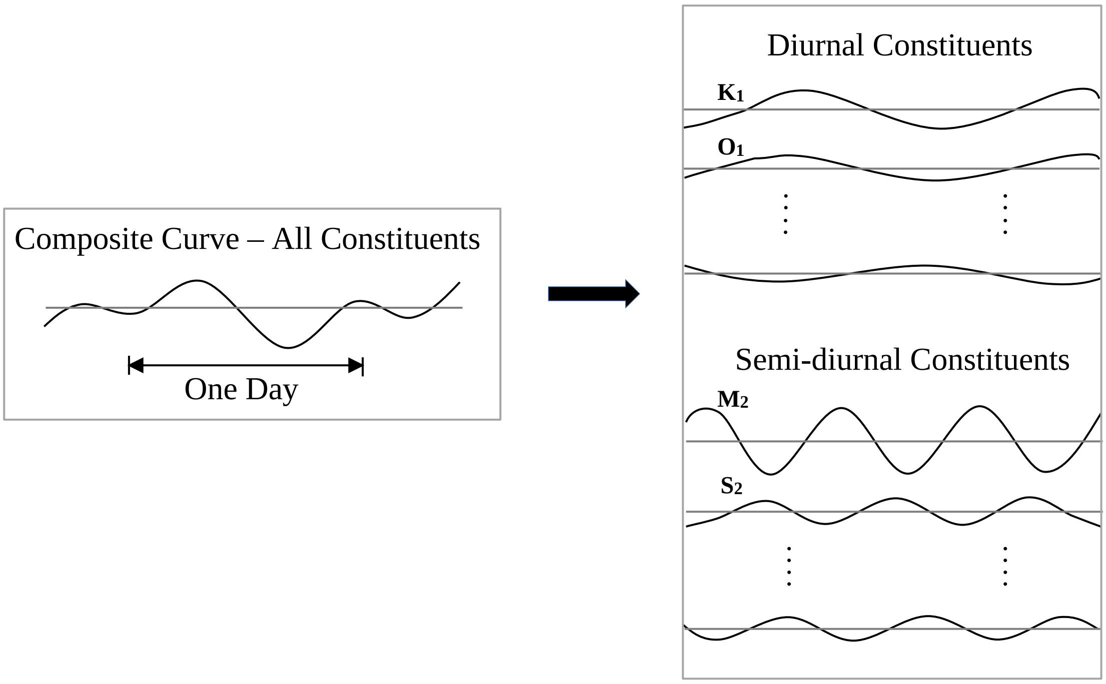


Figure 2.2 Tidal constituents

Tides are made up of 600 different harmonic constituents (Goring, 2001). However, only four main constituents, lunisolar declination diurnal tide (K1), principal lunar declination diurnal tide (O1), principal lunar semi-diurnal tide (M2) and principal solar diurnal tide (S2) are important in generating shallow water tides (Aungsakul et al., 2007). Shallow water constituents associated with bottom frictional effects and non-linear terms in the equations of motion, as well as radiation constituents resulting from atmospheric influences, make up the remaining constituents (Emery and Thomson, 1997). The summary of water level components displays as a relationship connection between them are shown in Figure 2.3

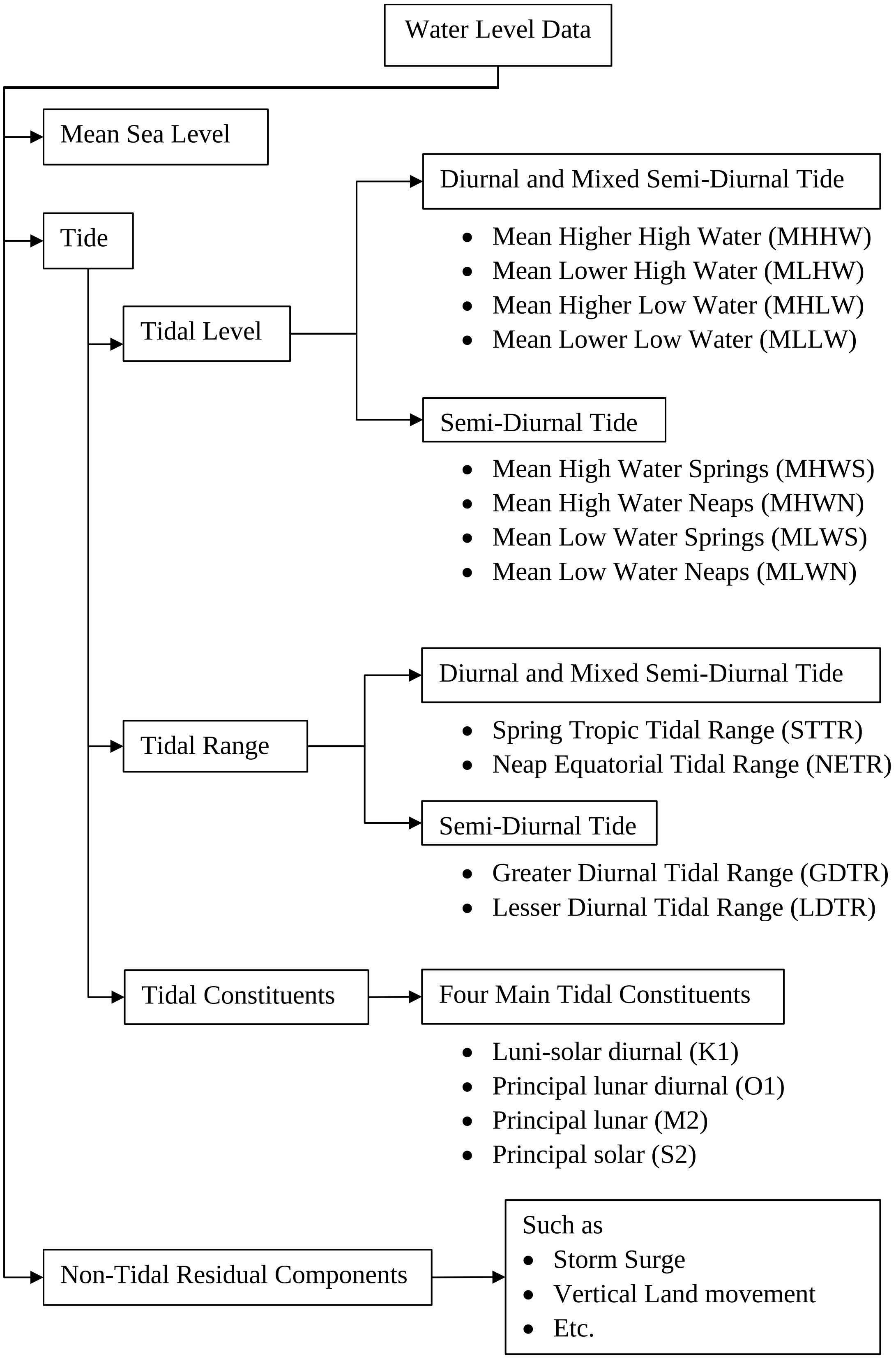


Figure 2.3 Water level components

2.2 Trends and Variations of Water Levels

At any point, the water level is composed of MSL, astronomical tides and non-tidal residuals. These non-tidal residuals include the effects of vertical land motion, topography, surface water run-off, and other ocean processes (Rhein et al., 2013). Changes in these components have significant effects on water levels. Water level changes instantaneously impact coastal zones and marine ecosystems (Menedez and Woodworth, 2010).

Many studies have reported high water level increases at different locations. For instance, Woodworth and Blackman (2004) analysed global tidal datasets from 141 stations. Their analyses indicated significant interannual variability in the water levels at many stations, and these variations were consistent with the variations of MSL. Menendez and Woodworth (2010) analysed water levels using over four decades of quasi-global datasets. The study reported increments in extreme high waters, dating back to the 1970s, and these increments were mainly caused by the MSL. Wahl et al. (2013) analysed water level data covering over two century data points from 30 stations along the coastline of the North Sea. Findings from the study indicated inter-annual and decadal variations of water levels over the whole North Sea region. An overall increasing relative MSL was also reported. Therefore, the above-mentioned studies indicate that increasing trends of MSL and water level at varying magnitudes along different coastal areas. Also, the underlying causes of these trends and variability were time and location specific. Investigations along the Gulf of Thailand revealed significant increasing trends of MSL, ranging from 3.0 mm/yr to 5.8 mm/yr across various stations since the 20th century. Most of these trends were higher than global average (Trisirisatayawon et al., 2011).

2.3 Tidal Levels

Tides form part of the most controlling forces on the earth. Tides have a more significant effect on water levels, compared to other process (Devlin et al., 2018). Studies from many locations have documented changes in tidal levels consistent with changes in relative MSL. Mawdsley et al. (2015) investigated the secular trends in tidal level at over 200 sites globally. The study used water level data from 220 tidal gauge stations across different parts of the world and studies 10 tidal levels and 5 ranges. The findings indicated that more than half of the stations had tidal levels significantly different from zero, and the changes were between 2 to 5 mm per year. Thetidal changes were coherent with changes in main tidal constituents at each location. However, the correlation between the significant tidal level trends and MSL varied by station locations. A study by Santamaria-Aguilar et al. (2017) analyzed the changes in tidal levels and tidal constituents at two stations in Argentina. Based on hourly water levels and tidal harmonic analysis, the study found that changes in tidal levels and main tidal constituents at the coast of Argentina. Similarly, Rasheed and Chua (2014) assessed the secular trends of local tidal datums, ranges and constituents using data from 13 stations along the coast of Japan. The study reported positive trends for high water levels and tidal ranges, and negative trends for low water levels.

Along the coasts of Thailand, evidence is literature indicate varying tidal level trends across various time scales. The upper Gulf of Thailand has higher water levels than the lower Gulf of Thailand, and water levels in the Gulf of Thailand had more variability than the Andaman Sea (Angsakul et al., 2007).

2.4 Factors Associated with Water Level Changes

Changes in water levels have been documented across many coastlines around the world. These changes have been attributed to location-specific factors, oceanographic processes, and astronomical effects. According to the study by Mawdsley et al. (2015), changes in water levels on a global scale are significantly affected by changes in MSL. Also, the study reported no evidence consistent global patterns of water level changes, but rather regionally coherent pattens were observed along many regional coastlines. These findings indicate that regional-specific factors could affect variability of water levels in Open Ocean. Long-term variations in tidal potential can also affect water levels, however, these changes are negligible over century timescales (Woodworth, 2010). Tidal datums and tidal ranges are also significant determining factors of MSL and local water levels (Hill, 2016).

Location-specific factors associated with changes in water levels are more significant on local scale water levels. Generally, water level changes on a local scale are caused by water dissipation and turbulent mixing, water depth, surface area, width, river flow and other local morphological elements, as well as other human acts of engineering (Haigh et al., 2019; Witze, 2020).

2.5 Methods for Analysing Water Levels

Several methods have been applied to analyse water levels or the components of water levels. Analysis of water level data is not very straightforward due to the complex composition of the generating factors. Typically, different methods are employed to analyse the various composition of water levels. From the literature available, the methods for analysing trends and variability of water levels are not the same as the methods for tidal analysis. Studies from Santamari-Aguilar et al. (2017), Mudersbach et al. (2013) and Woodworth and Blackman (2004), have applied percentile analysis and linear regression to analyse water level variability in Argentina, along the German Sea and at 141 locations, respectively. Findings from these studies show that the percentile analysis can extract water level variations, and determine which factors have significant association with observed water level changes. The classical harmonic analysis is the primary method for analyzing tidal levels. The method is applied to estimate the underlying tidal harmonic constituents and the constitutents are used to reconstruct tidal datums and tidal range (Mawdsley et al., 2015; Rasheed and Chua 2014; Santamaria-Aguilar et al., 2017).

Chapter 3

Research Methodology

The Marine Department of Thailand collected hourly water level data from tidal gauge stations along the coast of Thailand. However, the hourly data used in this study have not been extensively analysed beyond the MSL and harmonic constituents. Therefore, this chapter presents the data source, study area and the methods used in the study.

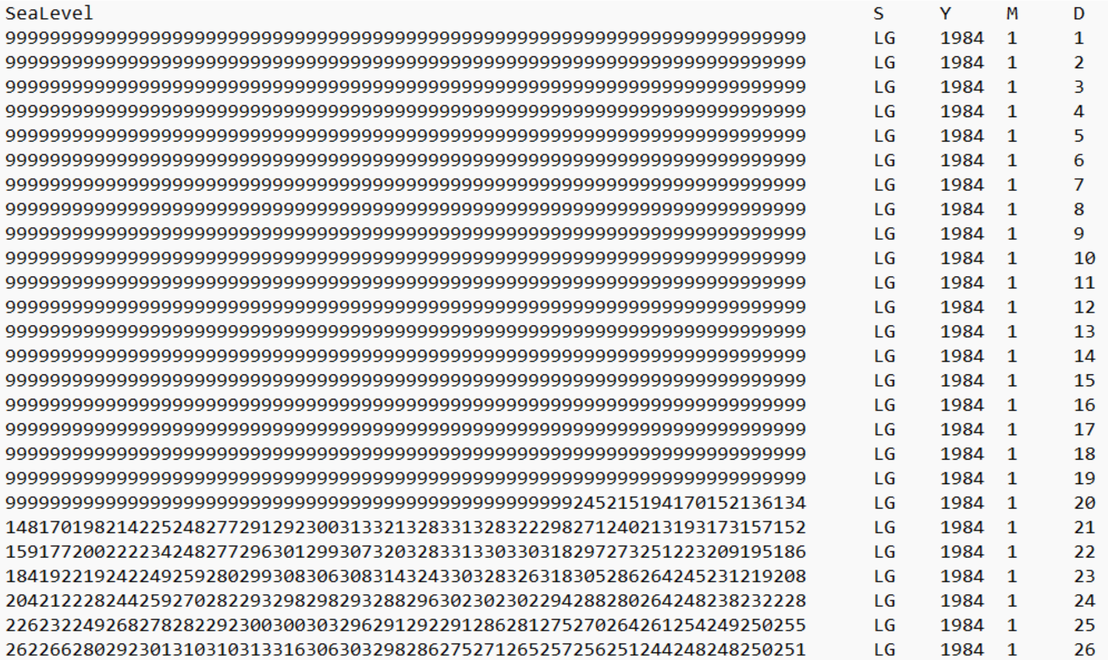
3.1 Data and Study Area

3.1.1 Data Source

The tidal information for this study was obtained from the Marine Department of Thailand. In this region, there are tidal measurement stations that record water heights every hour of the day. For a normal year and a leap year, the maximum number of water level observations were 8,760 and 8,784, respectively.

3.1.2 Data Management

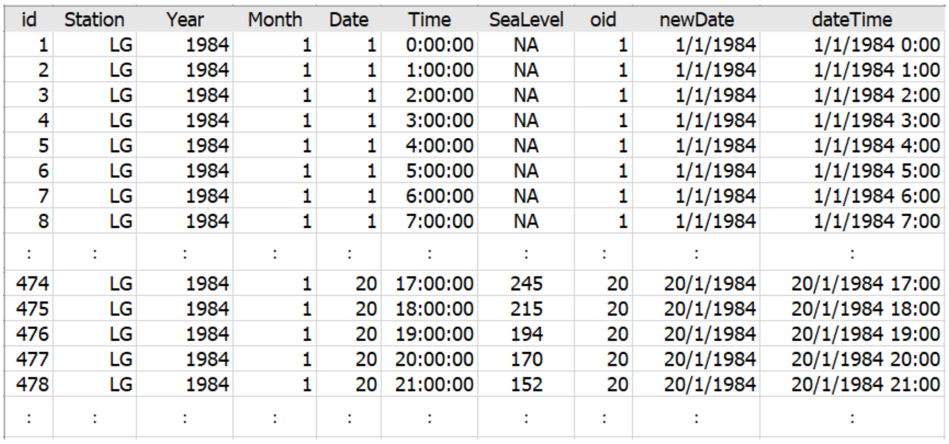
The marine department provided original hourly data are shown in Figure 3.1



```
SeaLevel                                                                    S     Y     M    D
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    1
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    2
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    3
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    4
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    5
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    6
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    7
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    8
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    9
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    10
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    11
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    12
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    13
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    14
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    15
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    16
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    17
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    18
999999999999999999999999999999999999999999999999999999999999999999999999    LG    1984  1    19
999999999999999999999999999999999999999999999999999245215194170152136134    LG    1984  1    20
148170198214225248277291292300313321328331328322298271240213193173157152    LG    1984  1    21
159177200222234248277296301299307320328331330330318297273251223209195186    LG    1984  1    22
184192219242249259280299308306308314324330328326318305286264245231219208    LG    1984  1    23
204212228244259270282293298298293288296302302302294288280264248238232228    LG    1984  1    24
226232249268278282292300300303296291292291286281275270264261254249250255    LG    1984  1    25
262266280292301310310313316306303298286275271265257256251244248248250251    LG    1984  1    26
```

Figure 3.1 Raw data obtained from the marine department of Thailand

Based on the data obtained from the Marine department (Figure 3.1), the numeric characters (digits) in the column ‘SeaLevel’ represent the hourly water level. Each row contained 72 digits (24 hour × 3 digits = 72 digits). Therefore, every three digits represented the water level for each hour, measured in centimeters. The column ‘S’ represents the station code. For instance, ‘LG’ is the station code for LaemNgop tidal gauge station. The column ‘Y’ represents the year. The last two columns are the month and dates, respectively. The data was transformed into tabular format, as shown in Figure 3.2



id	Station	Year	Month	Date	Time	SeaLevel	oid	newDate	dateTime
1	LG	1984	1	1	0:00:00	NA	1	1/1/1984	1/1/1984 0:00
2	LG	1984	1	1	1:00:00	NA	1	1/1/1984	1/1/1984 1:00
3	LG	1984	1	1	2:00:00	NA	1	1/1/1984	1/1/1984 2:00
4	LG	1984	1	1	3:00:00	NA	1	1/1/1984	1/1/1984 3:00
5	LG	1984	1	1	4:00:00	NA	1	1/1/1984	1/1/1984 4:00
6	LG	1984	1	1	5:00:00	NA	1	1/1/1984	1/1/1984 5:00
7	LG	1984	1	1	6:00:00	NA	1	1/1/1984	1/1/1984 6:00
8	LG	1984	1	1	7:00:00	NA	1	1/1/1984	1/1/1984 7:00
:	:	:	:	:	:	:	:	:	:
474	LG	1984	1	20	17:00:00	245	20	20/1/1984	20/1/1984 17:00
475	LG	1984	1	20	18:00:00	215	20	20/1/1984	20/1/1984 18:00
476	LG	1984	1	20	19:00:00	194	20	20/1/1984	20/1/1984 19:00
477	LG	1984	1	20	20:00:00	170	20	20/1/1984	20/1/1984 20:00
478	LG	1984	1	20	21:00:00	152	20	20/1/1984	20/1/1984 21:00
:	:	:	:	:	:	:	:	:	:

Figure 3.2 Water level data in tabular format

Hourly data from the marine department was divided into two studies.

First study, each station's record was chosen in the analysis as follows: First, diurnal and semi-diurnal tides along the coasts of the Andaman Sea and the Gulf of Thailand were considered. Then, only higher high water (HHW), lower high water (LHW), higher low water (HLW) and lower low water (LLW) data of each day was chosen for the diurnal tide. For stations with semi-diurnal tide, only high water springs (HWS), high water neaps (HWN), low water neaps (LWN) and low water springs (LWS) water levels were selected. Next, the percentage of missing data for each calendar year was less than 25%. Seasonal cycles are affected if the percentage of missing for each calendar year is more than 25 (Mawdsley et al., 2015). After that, each station had data records covering same period. Finally, six of the 21 stations were included in the study based on these inclusion criteria.

Second study, standard criteria were used to select the records for each station. Firstly, to ensure sufficient length and data quality, a calendar year of water level records was included if at least 75% of hourly values were present. Next, to account for the lunar-nodal cycle (18.61 years), the available data from each station was required to span at least 19 years. A 19-year span ensures that at least one lunar-nodal cycle is covered, and the phase and amplitude of nodal modulations are appropriately approximated (Mawdsley et al., 2015; Woodworth et al., 1991). Lastly, using these inclusion criteria, 14 out of the 21 stations were included in the study.

3.1.3 Study Area

Marine Department provided tidal data for 21 stations. The locations of 21 tidal gauge stations and tidal types along the coast of Thailand are shown in Figure 3.3.

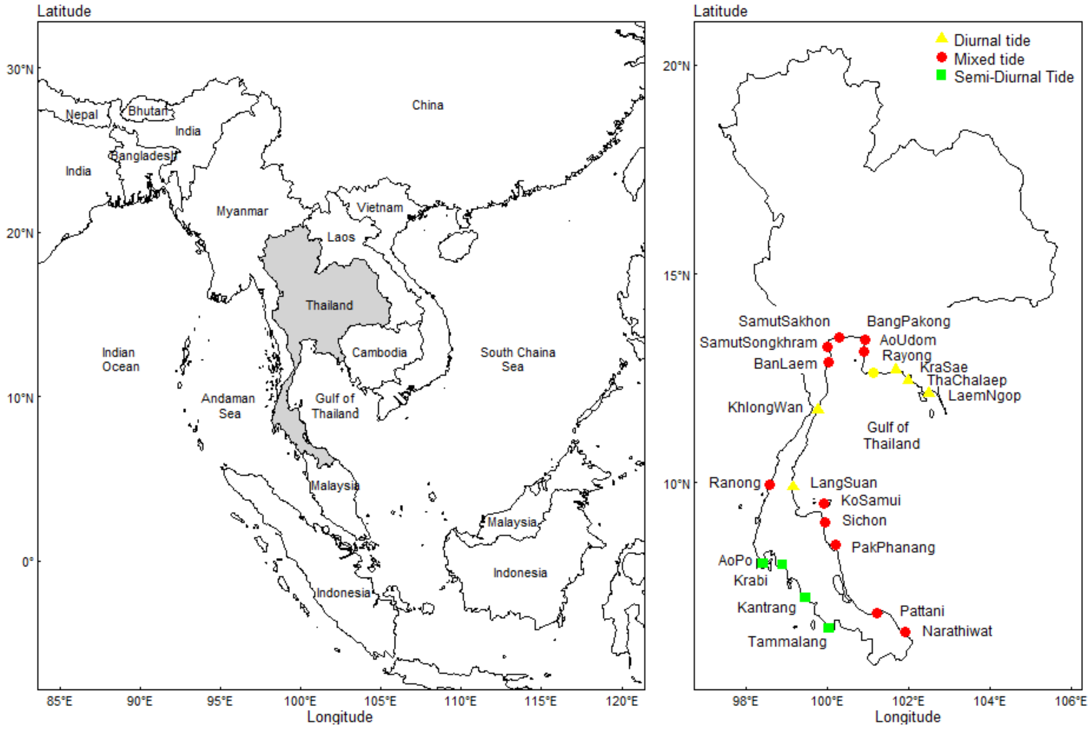


Figure 3.3 All tidal gauge locations from the Marine Department

The standard criteria mentioned above were used to select the records. Only six stations for the first study and 14 stations for the second study satisfied these criteria and were included in the analysis.

First study, the stations used in the first study are LaemNgop, ThaChalaep, Rayong, Tammalang, Kantrang and Krabi. The locations of these stations are shown in Figure 3.4.

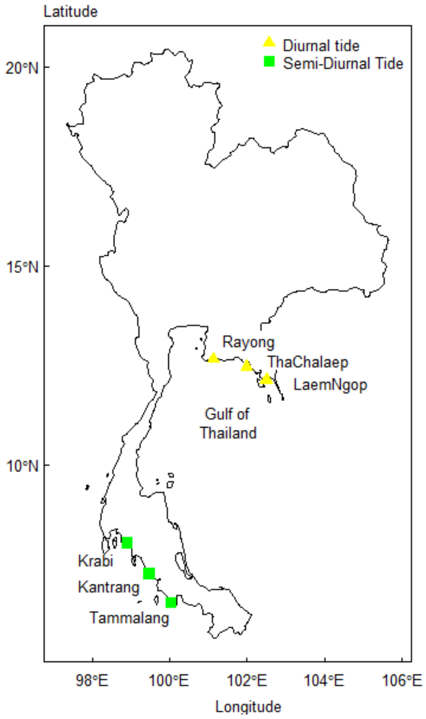


Figure 3.4 Tidal gauge locations of the first study along the coast of Thailand

The locations of six tidal gauge stations and tidal types are presented in Figure 3.4. The diurnal tide (yellow) is recorded at three stations in the upper Gulf of Thailand. Three stations in the Andaman Sea measure water levels for semi-diurnal tide (green). Hourly data were collected before 2004 with different period for each station. However, the data used for the first study spanned from 2004 - 2017 because the data were mostly completed. The distinct water levels for six stations are started in the year 2004 with the data span from January 1, 2004 to December 31, 2017 (14 years).

Second study, the 14 tidal gauges stations measure tidal levels of three different tidal types. These stations include Krabi, Kantang, Tammalang, Narathiwat, PakPanang, Sichon, LangSuan, BanLaem, SamutSongkram, SamutSakhon, BangPakong, Rayong, ThaChalaep and LaemNgop. The locations of the various stations are shown in Figure 3.5.

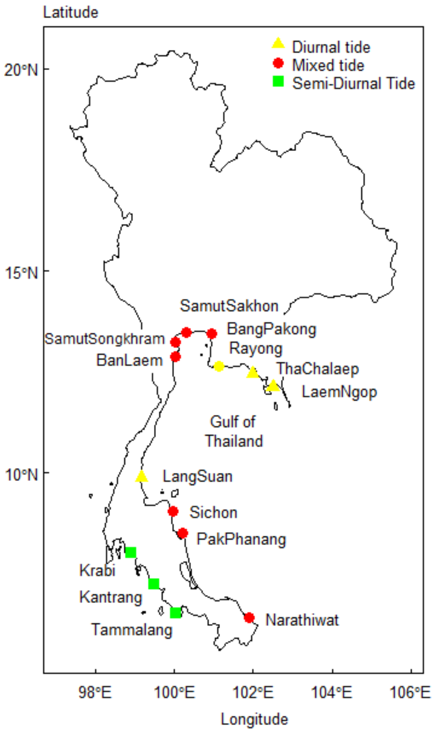


Figure 3.5 Tidal gauge locations of the second study along the coast of Thailand

Figure 3.5 shows the locations of fourteen tidal gauge stations and the type of water levels measured. Two types of tides were identified along stations in the Gulf of Thailand. There are four stations with diurnal tide and seven stations with mixed-diurnal tide. Three stations along the Andaman Sea had predominantly semi-diurnal tides. The data span for each station, as well as the length of available water level records, was different. The length of water levels for each station is shown in Figure 3.6. The number and percentage of missing data for each calendar year with station along the Gulf of Thailand and Andaman Sea are shown in Table 3.1 and Table 3.2, respectively.

In the Gulf of Thailand, SamutSakon station recorded the longest period of data between 1977 and 2017. In contrast, the shortest data span was found at BanLaem station from 1997 to 2017. For Andaman Sea, the data for all stations started in the year 1973, 1982 and 1990 for Kantrang, Krabi and Tammalang stations, respectively; and ended in the year 2017.

Table 3.1 Number of missing data along the coast in the Gulf of Thailand

Year	Obs.	Number of Missing Data																					
		Diurnal Tide								**Mixed Tide**													
		LaemNgop		**Thachalaep**		**Rayong**		**LangSuan**		**Bangpakong**		**SamutSakon**		**Samut Songkram**		**BanLaem**		**Sichon**		**Pakpanang**		**Narathiwat**	
		n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
1977	8760											4,444	50.73										
1978	8760											664	7.58										
1979	8760											1,074	12.26							1,478	16.87		
1980	8784											645	7.34	276	3.14					267	3.04		
1981	8760											4,454	50.84	433	4.94					4,003	45.70		
1982	8760			1,914	21.85					51	0.58	574	6.55	677	7.73					571	6.52		
1983	8760			2,885	32.93					93	1.06	143	1.63	1,260	14.38					666	7.60		
1984	8784	641	7.30	1,122	12.77					14	0.16	95	1.08	4,541	51.70					338	3.85		
1985	8760	116	1.32	471	5.38	8,057	91.97			475	5.42	129	1.47	98	1.12					1,612	18.40		
1986	8760	74	0.84	334	3.81	141	1.61			61	0.70	649	7.41	411	4.69					814	9.29	67	0.76
1987	8760	3,832	43.74	1,159	13.23	62	0.71			0	0.00	3,517	40.15	295	3.37					0	0.00	0	0.00
1988	8784	1,675	19.07	1,296	14.75	8,784	100.00			0	0.00	362	4.12	2,787	31.73					177	2.02	144	1.64
1989	8760	121	1.38	4,307	49.17	5,783	66.02			182	2.08	40	0.46	5,794	66.14					128	1.46	865	9.87
1990	8760	226	2.58	8,760	100.00	5,113	58.37			6	0.07	30	0.34	864	9.86					749	8.55	8,760	100.00
1991	8760	0	0.00	8,760	100.00	573	6.54			4	0.05	63	0.72	1,237	14.12					1,257	14.35	0	0.00
1992	8784	105	1.20	8,784	100.00	569	6.48			0	0.00	673	7.66	613	6.98					5,158	58.72	75	0.85
1993	8760	120	1.37	8,760	100.00	7,920	90.41	1,210	13.81	2,238	25.55	681	7.77	1,331	15.19			2,928	33.42	8,760	100.00	197	2.25
1994	8760	89	1.02	8,760	100.00	8,760	100.00	460	5.25	47	0.54	20	0.23	255	2.91			793	9.05	8,760	100.00	567	6.47
1995	8760	411	4.69	472	5.39	4,080	46.58	854	9.75	75	0.86	209	2.39	232	2.65			248	2.83	8,760	100.00	6	0.07
1996	8784	18	0.20	2,304	26.23	8,784	100.00	8,784	100.00	124	1.41	100	1.14	616	7.01			8	0.09	8,784	100.00	0	0.00
1997	8760	0	0.00	1,689	19.28	4,306	49.16	5,434	62.03	13	0.15	820	9.36	397	4.53	3,225	36.82	2	0.02	3,481	39.74	122	1.39
1998	8760	49	0.56	8,760	100.00	2,237	25.54	399	4.55	32	0.37	2,417	27.59	691	7.89	214	2.44	0	0.00	854	9.75	0	0.00
1999	8760	408	4.66	530	6.05	2,577	29.42	618	7.05	20	0.23	337	3.85	811	9.26	484	5.53	0	0.00	193	2.20	1,593	18.18
2000	8784	125	1.42	250	2.85	2,117	24.10	55	0.63	34	0.39	0	0.00	558	6.35	624	7.10	2	0.02	1,993	22.69	4	0.05

Year	Obs.	Number of Missing Data																					
		Diurnal Tide								**Mixed Tide**													
		LaemNgop		**Thachalaep**		**Rayong**		**LangSuan**		**Bangpakong**		**SamutSakon**		**Samut Songkram**		**BanLaem**		**Sichon**		**Pakpanang**		**Narathiwat**	
		n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
2001	8760	577	6.59	380	4.34	1,135	12.96	161	1.84	822	9.38	8,760	100.00	240	2.74	771	8.80	0	0.00	286	3.26	0	0.00
2002	8760	100	1.14	55	0.63	1,481	16.91	224	2.56	3,692	42.15	1,267	14.46	432	4.93	1,791	20.45	0	0.00	570	6.51	12	0.14
2003	8760	0	0.00	206	2.35	2,028	23.15	11	0.13	408	4.66	2,253	25.72	839	9.58	473	5.40	0	0.00	418	4.77	11	0.13
2004	8784	49	0.56	146	1.66	378	4.30	104	1.18	714	8.13	473	5.38	120	1.37	410	4.67	0	0.00	10	0.11	0	0.00
2005	8760	44	0.50	120	1.37	301	3.44	32	0.37	70	0.80	529	6.04	131	1.50	679	7.75	0	0.00	272	3.11	0	0.00
2006	8760	19	0.22	51	0.58	23	0.26	17	0.19	71	0.81	42	0.48	88	1.00	587	6.70	0	0.00	0	0.00	0	0.00
2007	8760	5	0.06	35	0.40	108	1.23	19	0.22	18	0.21	16	0.18	57	0.65	145	1.66	0	0.00	644	7.35	0	0.00
2008	8784	23	0.26	24	0.27	3,011	34.28	55	0.63	17	0.19	0	0.00	28	0.32	9	0.10	1,543	17.57	74	0.84	0	0.00
2009	8760	0	0.00	0	0.00	30	0.34	0	0.00	0	0.00	5	0.06	0	0.00	0	0.00	0	0.00	12	0.14	0	0.00
2010	8760	0	0.00	0	0.00	20	0.23	9	0.10	525	5.99	57	0.65	20	0.23	0	0.00	0	0.00	37	0.42	0	0.00
2011	8760	5	0.06	0	0.00	11	0.13	5,172	59.04	66	0.75	83	0.95	58	0.66	8	0.09	0	0.00	421	4.81	0	0.00
2012	8784	0	0.00	0	0.00	19	0.22	8,784	100.00	219	2.49	56	0.64	29	0.33	18	0.20	0	0.00	757	8.62	0	0.00
2013	8760	0	0.00	85	0.97	0	0.00	2,270	25.91	524	5.98	328	3.74	9	0.10	0	0.00	0	0.00	8	0.09	226	2.58
2014	8760	295	3.37	0	0.00	6	0.07	24	0.27	66	0.75	19	0.22	910	10.39	0	0.00	34	0.39	2	0.02	0	0.00
2015	8760	12	0.14	9	0.10	0	0.00	0	0.00	60	0.68	0	0.00	31	0.35	12	0.14	0	0.00	14	0.16	1	0.01
2016	8784	0	0.00	12	0.14	0	0.00	0	0.00	5	0.06	0	0.00	112	1.28	6	0.07	0	0.00	0	0.00	0	0.00
2017	8760	1,309	14.94	8	0.09	0	0.00	0	0.00	29	0.33	0	0.00	100	1.14	57	0.65	0	0.00	240	2.74	0	0.00

Table 3.2 Number of missing data along the coast of Andaman Sea

		Number of Missing Data					
		Semi-Diurnal Tide					
Year	**Obs.**	**Tammalang**		**Kantrang**		**Krabi**	
		n	**%**	**n**	**%**	**n**	**%**
1973	8760			0	0.00		
1974	8760			351	4.01		
1975	8760			0	0.00		
1976	8784			7	0.08		
1977	8760			30	0.34		
1978	8760			24	0.27		
1979	8760			49	0.56		
1980	8784			551	6.27		
1981	8760			154	1.76		
1982	8760			0	0.00	1,949	22.25
1983	8760			105	1.20	8,760	100.00
1984	8784			213	2.42	8,784	100.00
1985	8760			298	3.40	8,760	100.00
1986	8760			1,470	16.78	567	6.47
1987	8760			888	10.14	8,695	99.26
1988	8784			2,090	23.79	8,784	100.00
1989	8760			139	1.59	3,157	36.04
1990	8760	107	1.22	579	6.61	132	1.51
1991	8760	160	1.83	497	5.67	818	9.34
1992	8784	8,784	100.00	5,304	60.38	954	10.86
1993	8760	45	0.51	8,760	100.00	1,173	13.39
1994	8760	176	2.01	8,760	100.00	153	1.75
1995	8760	401	4.58	8,760	100.00	4,053	46.27
1996	8784	40	0.46	8,784	100.00	0	0.00
1997	8760	168	1.92	8,760	100.00	958	10.94
1998	8760	22	0.25	5,384	61.46	290	3.31
1999	8760	28	0.32	8,760	100.00	156	1.78
2000	8784	55	0.63	1,017	11.58	126	1.43
2001	8760	64	0.73	505	5.76	34	0.39
2002	8760	1	0.01	704	8.04	393	4.49
2003	8760	61	0.70	1,015	11.59	8,760	100.00
2004	8784	40	0.46	181	2.06	416	4.74
2005	8760	84	0.96	54	0.62	616	7.03
2006	8760	140	1.60	62	0.71	298	3.40
2007	8760	4	0.05	91	1.04	6	0.07
2008	8784	10	0.11	0	0.00	11	0.13
2009	8760	0	0.00	20	0.23	18	0.21
2010	8760	9	0.10	0	0.00	13	0.15
2011	8760	0	0.00	0	0.00	10	0.11
2012	8784	18	0.20	21	0.24	60	0.68
2013	8760	99	1.13	9	0.10	22	0.25
2014	8760	24	0.27	0	0.00	0	0.00
2015	8760	59	0.67	0	0.00	243	2.77
2016	8784	18	0.20	0	0.00	29	0.33
2017	8760	29	0.33	0	0.00	167	1.91

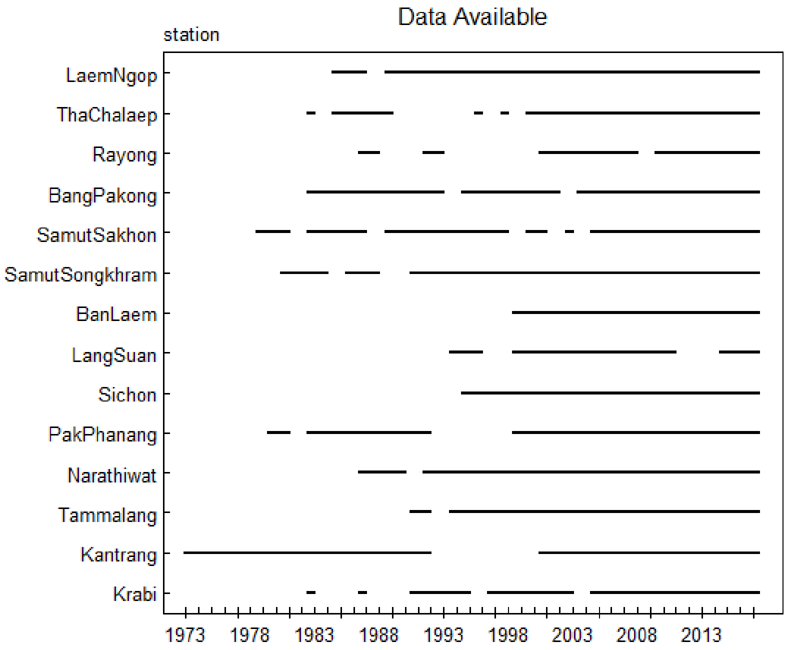


Figure 3.6 Data available

3.2 Statistical Methods

The data were analysed with four methods (periodic regression, percentile analysis, harmonic analysis and linear regression). In the first study, the periodic regression model was used to account for the effects of the moon's phases and the sun's gravitational pull. Once the astronomical effects were removed, a simple linear regression model was used to estimate the long-term trend in tidal levels. The second study was analysed using two approaches. Firstly, percentile analysis was used to determine the variation and changes in water levels relative to the MSL. Secondly, tidal harmonic analysis was applied to determine the secular trends in tidal levels, tidal range and main tidal constituents. After these two approaches, long-term trends were assessed using the simple linear regression model.

3.2.1 Periodic Regression Model

There are constant astronomical effects such as gravity from the moon and sun on tides. Therefore, any models of tidal water heights needs to account for these effects (Pugh and Woodworth, 2014; Cartwright, 1985). A periodic regression model (Derryberry, 2014) was used to account for the effects of the moon's phases and the sun's gravitational pull.

The regression model for periodic data is given by

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

where w is the predicted water level after removing solar and lunar effects, t is the integers indexing time, p is the lunar or solar period of the tide, μ is the intercept, b and c are coefficients.

The periodic regression model depends on the period of each tide. Diurnal, semi-diurnal and mixed tides water levels show different periodic patterns. Hence, the model was fitted with different period estimates for each tide. Since tide formation depends on both solar and lunar periods (Pugh and Woodworth, 2014), the periodic regression model for each tide was fitted using two different period values (solar period and lunar period). The periodogram function in Time Series Analysis (TSA) package in R was used to identify the period of each tide. This function used Fourier transformation to provide a list of possible periods (Abugaber, 2017). The period that provides a best fit was selected. Thus, a periodic regression model was fitted using a lunar period from the periodogram. Residuals from this model were used to fit a second model (with the same function) using the solar period. The processes of calculating long term trend used periodic regression model are shown in Figure 3.6 (Section 3.3.1)

3.2.2 Linear Regression Model

The regression model is given by

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

The simple linear regression (2) was used to estimate the long-term trends in water heights and tidal levels at each station. In the first study, $y(t)$ is the residual water level, a is the intercept, b is the trend, and t is time (days). In the second study, $y(t)$ is the water level percentile, tide percentile, reduce mean, residual percentile, tidal level, tidal range or tidal constituents b is the trend and t is time (hour).

3.2.3 Percentile Analysis

Percentile time series analysis was used to study the annual variability in extreme water levels. Furthermore, percentile analysis can be used to examine if changes in extreme water levels are similar to changes in MSL, or if other factors influence the distribution of extreme water levels. For a normal year and a leap year, the maximum number of water level observations were 8,760 and 8,784, respectively. Each calendar year, observed water level records were ordered, and 13 percentile levels were calculated for each year. These percentiles were 0.05th, 0.5th, 2th, 5th, 10th, 20th, 50th, 80th, 90th, 95th, 98th, 99.5th, and 99.95th percentiles, presented as annual water level percentiles (WL).

The 50th percentile or median was subtracted from each percentile in the same calendar year to remove MSL signals. The 50th percentile is less affected by outliers than the annual mean and presents a better approximation of the MSL than the annual mean (Santamaria-Aguilar et al., 2017). Subtracting the 50th percentile also eliminates the signal of vertical land movement (Woodworth and Blackman, 2004). A new percentile series, reduced to the mean (RedM), is obtained by deleting the 50th percentile. When the MSL effect is removed, what remains is a combination of astronomical tides and residuals due to surge and storms (Woodworth and Blackman, 2004). The water level records for each calendar year were analysed with tidal harmonic analysis, using 60 tidal constituents to obtain the tidal percentile series (Tide). The tidal harmonic method is available in the ***ftide*** function from the TideHarmonic package in R (Stephenson, 2017). The ***ftide*** function was also used to account for the effects of the 18.6-year nodal modulation (Stephenson, 2017). From the tidal constituents, astronomical water levels (Tide) were predicted, and a percentile series (0.05th, 0.5th, 2nd, 5th, 10th, 20th, 50th, 80th, 90th, 95th, 98th, 99.5th, and 99.95th) was constructed from the predicted water levels for each calendar year. To generate the annual residual percentile series (Res), the annual Tide series was subtracted from the annual RedM series. The astronomical tide and MSL have no effect on these annual residual percentile series. By removing the MSL and astronomical tides, any variations and trends in the Res series were due to non-linear effects of the MSL and tides (Woodworth and Blackman, 2004). The process of calculating percentile analysis is shown in Figure 3.7 (Section 3.3.2).

3.2.4 Tidal Analysis

The only water level data were detrended using a 30-day centre moving average (Carlberg, 2015). The 30-day centre moving average is preferred over the annual mean as it removes seasonal variations, time-scale signals, and seasonal cycles mainly due to oceanographic factors (Mawdsley et al., 2015). The solar monthly (MSm), and lunar monthly (Mm) constituents are affected by the 30-day signals, however, these constituents reflect more meteorological than tidal energy and therefore have minimal effect on the reconstructed tidal levels (Crawford, 1982).

After the detrending at times, the harmonic analysis method was applied to each calendar year of the data to separate astronomical tides and non-tidal residuals. A harmonic analysis requires calculating the amplitude and phase for a finite number of sinusoidal functions with known frequencies. Calculation of the amplitude and phase for the sinusoids representing each constituent cluster. This is done by solving a system of linear equation (Foreman and Henry, 1989). Amplitude and phase can be estimated by using equation (3).

$$\hat{y}(t) = Z + \sum_{n=1}^{N} A_n \cos\left(\frac{\pi}{180}(\omega_n t - \psi_n)\right), \tag{3}$$

where t is time in hours, N is number of harmonic constituents, ω_n is the know angular frequency of the n component in degree of hour, with in the tidal analysis is referred to speed of the tidal component, A_n is the amplitude, ψ_n is the phase lag, Z is the mean sea level.

Hamonic analysis without nodal adjustment from equation (3), the amplitude of M2 (principal lunar semi-diurnal tide) will increase or decrease by 37 %. The Hamonic analysis with nodal adjustment can be computed by equation (4).

$$\hat{y}(t) = Z + \sum_{n=1}^{N} H_n f_n(t) cos\left(\frac{\pi}{180}(\omega_n t - g_n + u_n t + v_n)\right), \tag{4}$$

where $A_n = H_n f_n(t)$ is the amplitude, $\psi_n = g_n + u_n t + v_n$ is the phase lags, v_n is known value can be calculated for any given date. Equation (4) can write as a numerical form by using trigonometric identity $cos(A-B) = cos(A)cos(B) - sin(A)sin(B)$ as shown in equation (5)

$$\hat{y}(t) = Z + \sum_{n=1}^{N} C_n f_n(t) cos\left(\frac{\pi}{180}(\omega_n t+u_n t+v_n)\right) + S_n f_n(t) cos\left(\frac{\pi}{180}(\omega_n t+u_n t+v_n)\right), \tag{5}$$

where $C_n = H_n \cos(g_n)$, $S_n = H_n \sin(g_n)$, $H_n = (C_n + S_n)^{1/2}$ and $g_n = arctan(S_n/C_n)$.

The ***ftide*** function in R solves equation (5) to estimate tidal harmonic constituents from observed water level records. The function is incorporated with selectable harmonics and other options which account for the 18.6-year lunar-nodal cycle. The function also allows for missing values in the water level observations only; and not for date/time. A standard set of 60 constituents were used in the tidal harmonic analysis. However, this study considered only four main tidal constituents K1, O1, M2 and S2, because these four main tidal constituents are important in generating shallow water tides. Amplitudes and phase lag obtained from the harmonic analysis were used to re-construct tidal contributions to the water levels for each calendar year.

The tidal levels and tidal ranges calculated for each station depended on the station classification, thus, diurnal, semi-diurnal or mixed tide. Out of the 14 stations, three stations along the Gulf of Thailand, had predominantly diurnal tides, with one high and one low tide per day (LaemNgop, ThaChalaep, and LangSuan). Also, eight stations (Rayong, BangPakong, SamutSakhon, SamutSongkram, BanLaem, Sichon, PakPanang and Narathiwat) had mixed tides, with two unequal high and two unequal low tides per day. All the stations along the Andaman Sea had semi-diurnal tides (Krabi, Kantang, Tammalang). The amplitudes of tidal constituents were used to reconstruct tidal levels. For stations with diurnal and mixed tides, the standard tidal levels were calculated (Stephenson, 2016)

Mean Higher High Water (MHHW) = Z + (M2 + K1 + O1)
Mean Lower High Water (MLHW) = Z + |M2 - (K1 + O1)|
Mean Sea Level (MSL) = Z
Mean Higher Low Water (MHLW) = Z - |M2 - (K1+ O1)|
Mean Lower Low Water (MLLW) = Z - (M2 + K1 + O1).

For semi-diurnal sites, the following tidal levels were calculated

Mean High Water Springs (MHWS) = Z + (M2 + S2)
Mean High Water Neaps (MHWN) = Z + |M2 - S2|
Mean Low Water Neaps (MLWN) = Z - |M2 - S2|
Mean Low Water Springs (MLWS) = Z - (M2 + S2)

The Z was estimated as the normal mean based on the number of observations available per calendar year. Tidal ranges were calculated as below.

Greater Diurnal Tidal Range (GDTR) = MHHW – MLLW
Lesser Diurnal Tidal Range (LDTR) = MLHW – MHLW
Spring Tropic Tidal Range (STTR) = MHWN - MLWN
Neap Equatorial Tidal Range (NETR) = MHWS - MLWS

These tidal water levels and tidal ranges were calculated for each year, and a linear regression model (equation 2) was used to assess the trends over the study period. Also, the changes in the main tidal constituents: K1, O1, M2 and S2 are examined. The process of calculating long term trend of tidal level and tidal range is shown in Figure 3.8 (Section 3.3.3).

3.3 Flow Diagram of Calculations

Figures 3.7, 3.8 and 3.9 show the flow diagrams for data analysis using three approaches. Figure 3.7 shows the calculation step to assess long term trends of water levels after accounting for the effects of the moon’s phases and the sun’s gravitational pull using periodic regression model. Steps to calculate and describe the the annual variability in water levels using percentile analysis are displayed in Figure 3.8, while Figure 3.9 describes the processes for investigating the long-term trends of tidal level, tidal range and main tidal constituents by harmonic analysis.

3.3.1 Periodic Regression Model

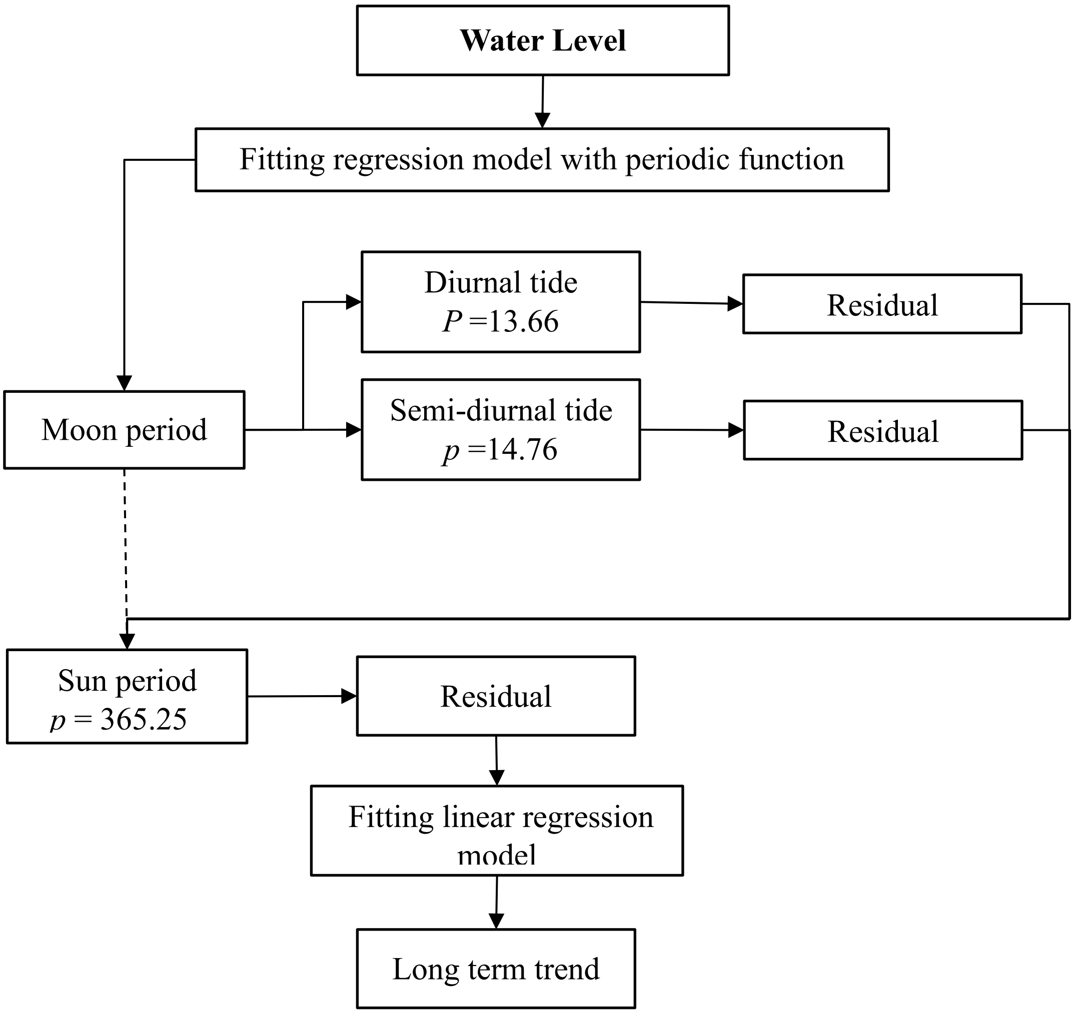


Figure 3.7 Diagram for calculating periodic regression

3.3.2 Percentile Analysis

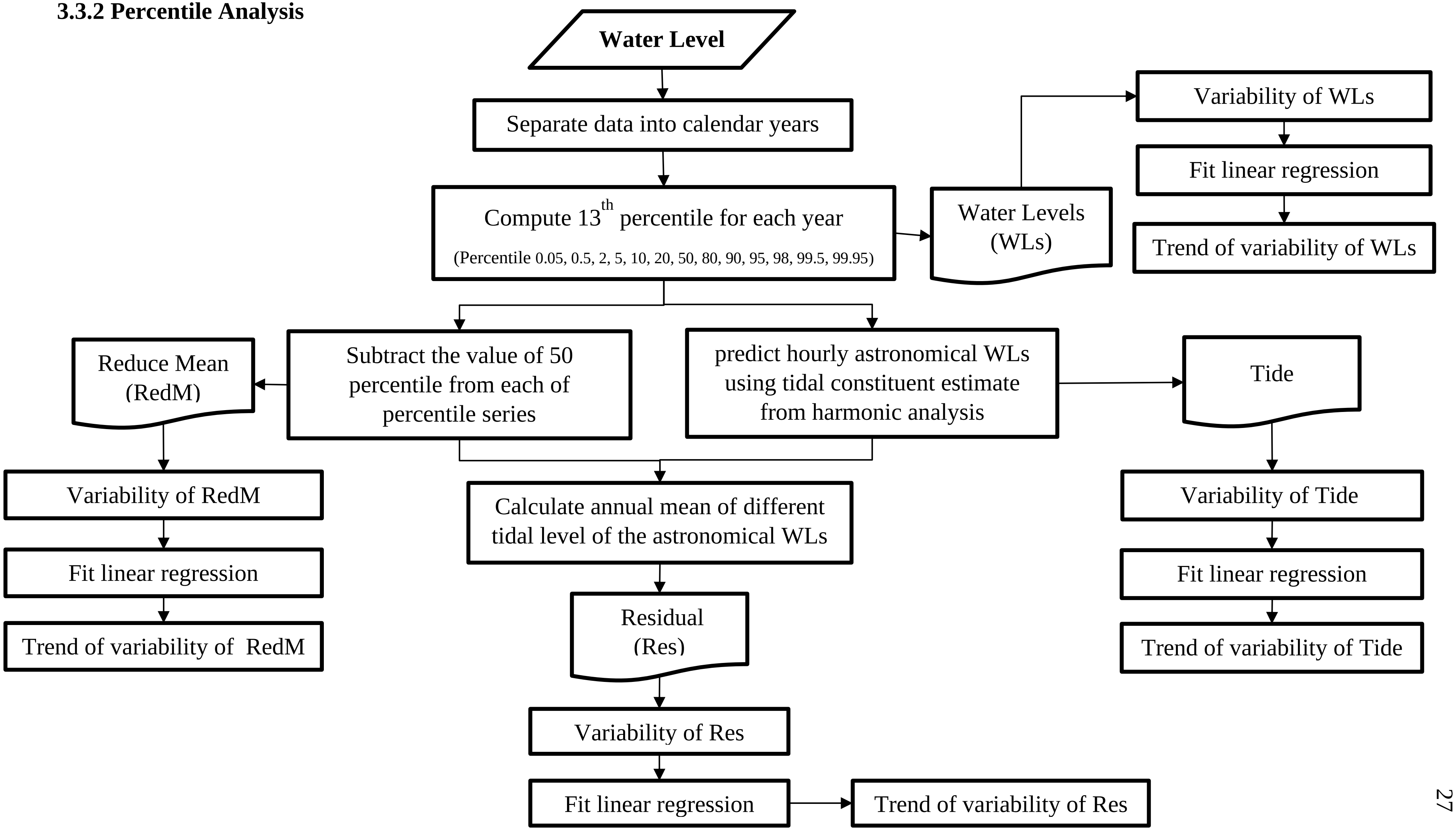


Figure 3.8 Diagram for calculating percentile analysis

3.3.3 Harmonic Analysis

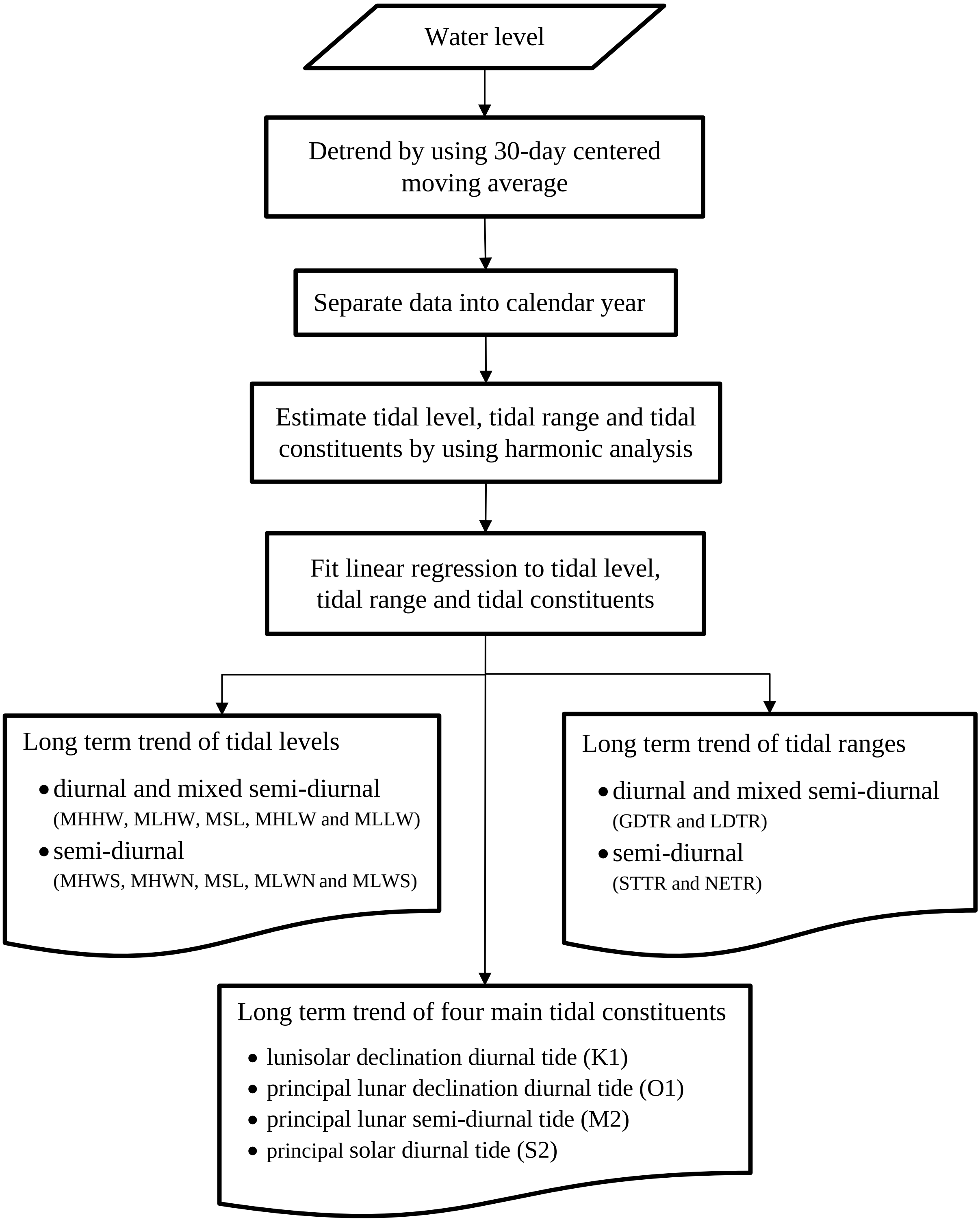


Figure 3.9 The diagram of tidal level, tidal range and tidal constituents calculation

Chapter 4

Results

This chapter presents the results from the analysis, which was divided into two studies. The first study illustrates the result of water level data from six tidal gauge stations, which were analysed using a periodic regression and linear regression model. The second study reports the result of water level data from 14 tidal gauges analysed with percentile analysis, harmonic analysis and linear regression model.

4.1 First Study

4.1.1 Preliminary Data Analysis

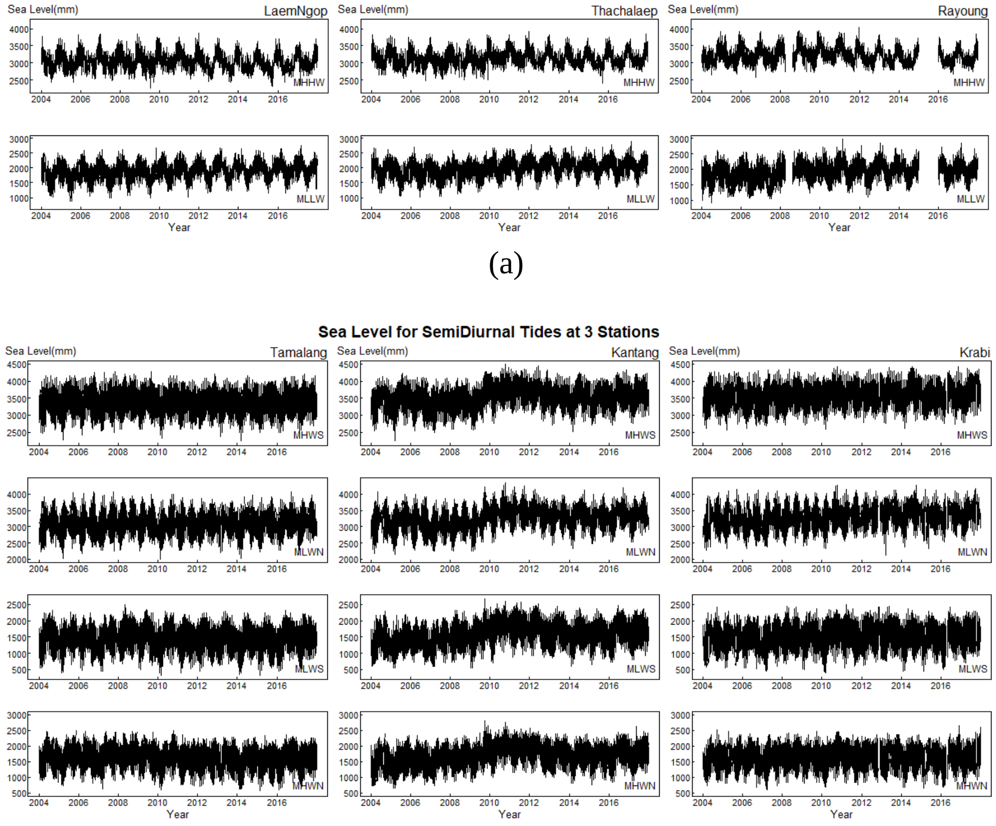
Although the data for each station had the same period (14 years) in the preliminary data analysis, however, each water level had a different length. At the Tammalang station, 5,066 observations were recorded for MHWS. The maximum observation was 4,290 mm and the minimum were 2,240 mm while the mean was 3,442.77 mm. The standard deviation was also 379.77 mm. The maximum observation for MLWS was 2,500 mm and the average water level was 1,338.62 mm. The descriptive characteristics of other water levels at different stations are shown in Table 4.1.

Table 4.1 Descriptive characteristics of water levels for each station

Tidal Type	**Water Level**	**Size**	**Mean**	**Standard Deviation**	**Median**	**Min** (mm.)	**Max** (mm.)
Diurnal tide							
LaemNgop	MHHW	4,823	3,052.24	245.16	3,040	2,260	3,880
	MLLW	4,848	1,840.28	302.13	1,850	880	2,760
	MHLW	483	2,705.22	178.88	2,690	2,100	3,320
	MLHW	434	2,267.95	238.08	2,310	1,490	3,070
ThaChalaep	MHHW	4,848	3,135.16	228.68	3,120	2,400	3,910
	MLLW	4,831	1,925.88	301.88	1,940	1,020	2,900
	MHLW	474	2,846.75	199.93	2,840	1,680	3,690
	MLHW	471	2,371.89	294.88	2,420	1,400	3,100
Rayong	MHHW	4,503	3,212.26	228.88	3,200	2,580	4,040
	MLLW	4,408	1,857.08	317.26	1,850	920	2,980
	MHLW	278	2,874.60	181.34	2,855	1,800	3,560
	MLHW	312	2,464.62	191.87	2,480	1,480	2,940

Tidal Type	Water Level	Size	Mean	Standard Deviation	Median	Min (mm.)	Max (mm.)
Semi-diurnal tide							
Tammalang	MHWS	5,066	3,442.77	379.77	3,500	2,240	4,290
	MLWS	5,077	1,338.62	395.09	1,320	320	2,500
	MHWN	4,752	3,151.95	368.74	3,180	2,000	4,080
	MLWN	4,734	1,527.99	384.41	1,500	580	2,500
Kantang	MHWS	5,066	3,565.33	364.67	3,600	2,250	4,500
	MLWS	5,068	1,487.98	400.49	1,480	540	2,670
	MHWN	4,777	3,294.15	357.67	3,320	2,150	4,340
	MLWN	4,759	1,612.35	392.97	1,600	640	2,800
Krabi	MHWS	4,974	3,616.39	366.36	3,650	2,570	4,430
	MLWS	4,975	1,415.26	405.50	1,370	410	2,490
	MHWN	4,636	3,330.72	358.88	3,350	2,130	4,280
	MLWN	4,615	1,546.08	382.50	1,510	590	2,650

The time series plots of each water level were shown in Figure 4.1



(a)

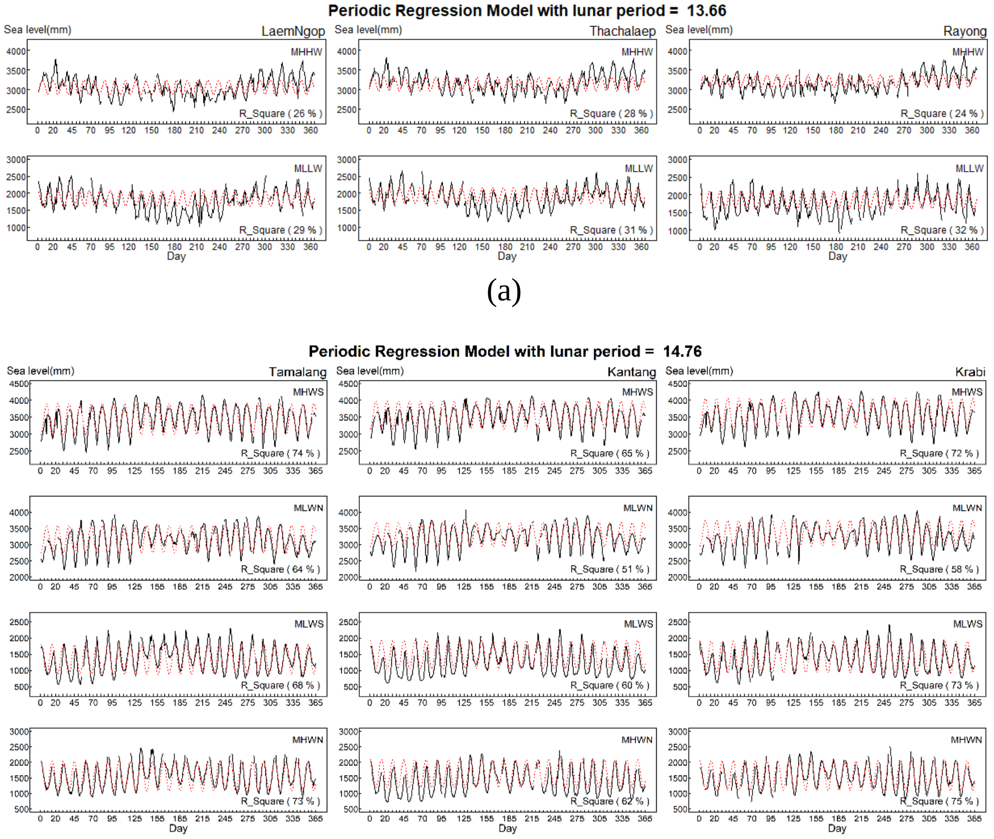
(b)

Figure 4.1 Time series plots of each water level for diurnal and semi-diurnal tides at different stations

Figure 4.1 shows the 14 years plot of the original observations of diurnal tidal data for LaemNgop, ThaChalaep and Rayong stations (Figure 4.1a) and semi-diurnal tide for Tammalang, Krabi and Kantang stations (Figure 4.1b). At Kantang station, all the four water levels experienced a spontaneous rise between 2009 and 2014. After 2014, the tidal water levels seem to have a stable pattern. For other stations, showed stable pattern.

4.1.2 Periodic Regression Model

The regression model from equation (1) was fitted to the data to account for the lunar effects on tidal heights. The lunar period for diurnal tides was found to be 13.66 days, while the lunar period for semi-diurnal tides was 14.76. Using these values, the results from the periodic regression model for the first year (2004) are shown in Figure 4.2



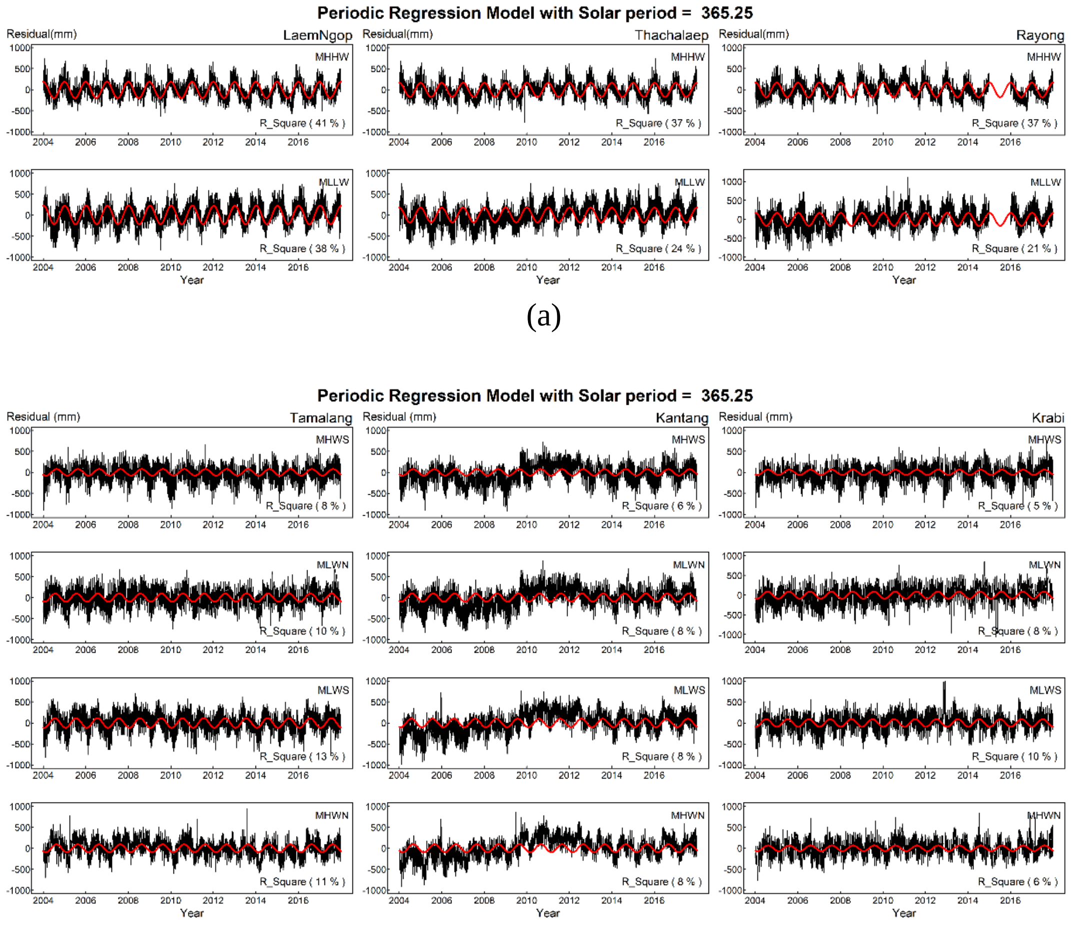
(a)

(b)

Figure 4.2 Periodic model of data with lunar periods for diurnal (a) and semi-diurnal (b) tides

From Figure 4.2(a) and Figure 4.2(b) the solid lines represent the original tidal data while the red dots show the predicted values from the model. Using the lunar periods, the periodic regression model provides a good fit for semi-diurnal water levels. The r-squares are substantially high for each model. However, the r-squares for diurnal tides are low.

The residuals from each model was used to fit a second periodic model (equation 1), by using the solar period. The solar period was found to be 365.25 days (exactly the number of days in a year). The results from the model with solar period for 14 years are shown in Figure 4.3

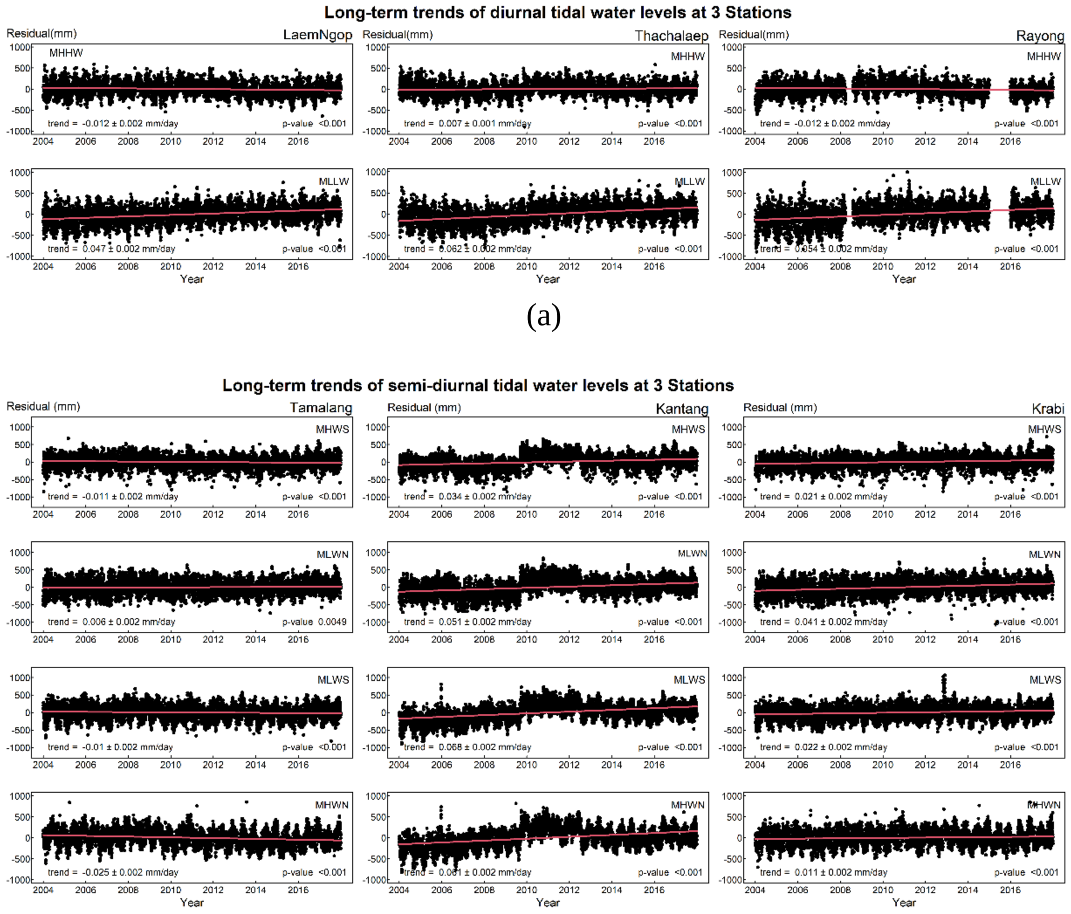


(a)

(b)

Figure 4.3 Periodic model of data with solar period for diurnal (a) and semi-diurnal (b) tides

The r-squared for each water level in diurnal tide was higher than that of semi-diurnal tide. Using the solar period, the periodic regression model fitted diurnal tides better than semi-diurnal tides. After the astronomical effects from the sun and the moon have been removed, the long-term trends were estimated by using the linear model (equation 2). Figure 4.4 shows the estimated trends in each water level for 14 years.



(a)

(b)

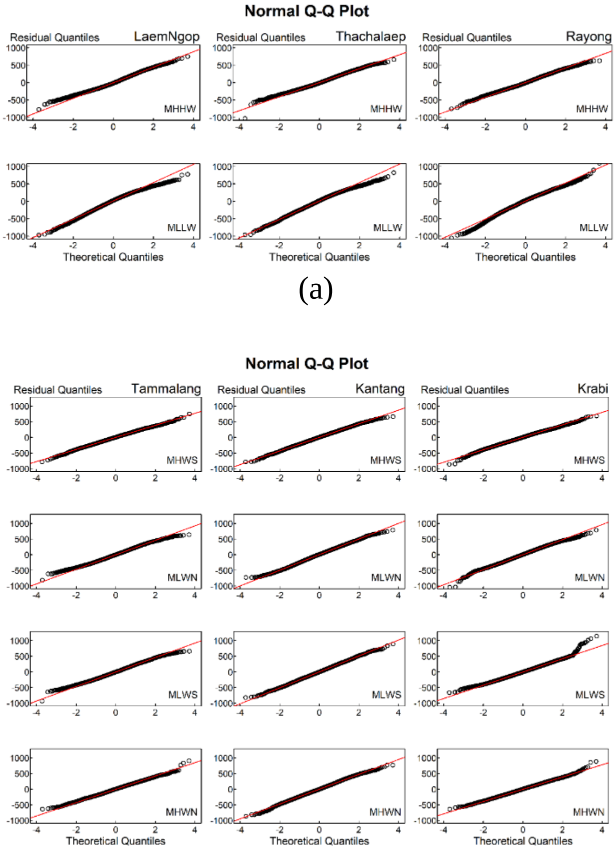
Figure 4.4 Linear trends in water levels for diurnal (a) and semi-diurnal (b) tides

Figure 4.4(a), LaemNgop and Rayong stations, MHHW and MLLW showed opposite trends. LaemNgop station, the trend in MHHW is -0.01 mm/day while MLLW has a significantly higher trend 0.046 mm/day. Rayong station, there was an average reduction of 0.012 mm/day for MHHW and an average daily increase of 0.054 mm/day for MLLW. The trend for MLLW at ThaChalaep was also positive (0.062 mm/day). However, for MHHW, the trend was positive, unlike the same water level for the other two stations.

Results from the model also showed that semi-diurnal tides measured at Kantang and Krabi stations have positive trends for all water levels (Figure 4.4b). At the Kantang station, the highest trend was found in MLWS (0.068 mm/day). The trends in MHWS, MHWN and MLWN ranged between 0.03 mm/day to 0.06 mm/day. For the Krabi water gauge station, the trend in water levels ranged from 0.01 mm/day to 0.04 mm/day. MLWN had the highest trend. An increase of 0.04056 mm/day was recorded over the 14 years period.

According to linear regression model, the Tammalang station had relatively stable water levels. The trend in MHWS was found to be 0.01 mm/day, MLWN was 0.005 mm/day. MLWS at Tammalang station is in a downward trend.

The quantile-quantile plot of residual from each model is shown in Figure 4.5.



(a)

(b)

Figure 4.5 Residual quantile-quantile (Q-Q) plot from the linear regression model

Figure 4.5 shows the Q–Q plot of residuals from each model. The plots indicate that the residuals are normally distributed. This implies that the linear model has provided a reasonable fit for water levels at each station.

4.2 Second Study

In the second study, the preliminary data analysis and results from percentile and harmonic analysis with hourly data from 14 stations are presented. The results from the analyses were displayed separately between Gulf of Thailand and Andaman Sea. These results also appeared in Pongsiri et al. (2020).

4.2.1 Preliminary Data Analysis

Gulf of Thailand

The available hourly water level data for each station along the Gulf of Thailand included in the analysis spanned at least 19 years. The mean and standard deviation of water level was high at Rayong, BangPakong, SamutSakon, SamutSongkram and BanLaem stations, with a high range between maximum and minimum water levels. In contrast, the low mean and low standard deviation of water levels were found at ThaChaLaep station, with a small range between maximum and minimum water levels. The descriptive characteristics of other water levels at different stations along the Gulf of Thailand are shown in Table 4.2.

Table 4.2 Descriptive characteristics of water levels for each station along the Gulf of Thailand

Stations	**Size**	**Mean**	**Standard Deviation**	**Median**	**Min** (mm.)	**Max** (mm.)
LaemNgop	289,296	2,463	457.55	2,500	740	3,880
ThaChalaep	236,688	2,002	491.72	2,004	1,982	2,017
Rayong	184,080	2,614	507.08	2,670	920	4,020
BangPakong	298,056	2,717	748.24	2,820	610	4,520
SamutSakon	306,840	2,757	782.78	2,840	200	4,800
SamutSongkram	306,792	2,785	755.13	2,880	400	4,720
BanLaem	175,320	2,658	782.83	2,770	230	5,080
LangSuan	175,296	2,502	490.28	2,460	1,000	4,380
Sichon	210,384	2,435	358.63	2,400	1,340	4,050
PakPhanang	280,512	2,562	373.62	2,550	630	4,300
NaraThiwat	271,752	2,660	300.87	2,630	1,740	4,170

Andaman Sea

The three stations along the Andaman Sea had a high range between maximum and minimum water levels. Also, these three stations found a high mean and high standard deviation of water levels. The maximum observation (324,336 observations) was reported at Kantrang station. Also, the highest (5,020 mm) and the lowest (320 mm) of water levels were reported. The descriptive characteristics of other water levels at different stations along the Andaman Sea are displayed in Table 4.3.

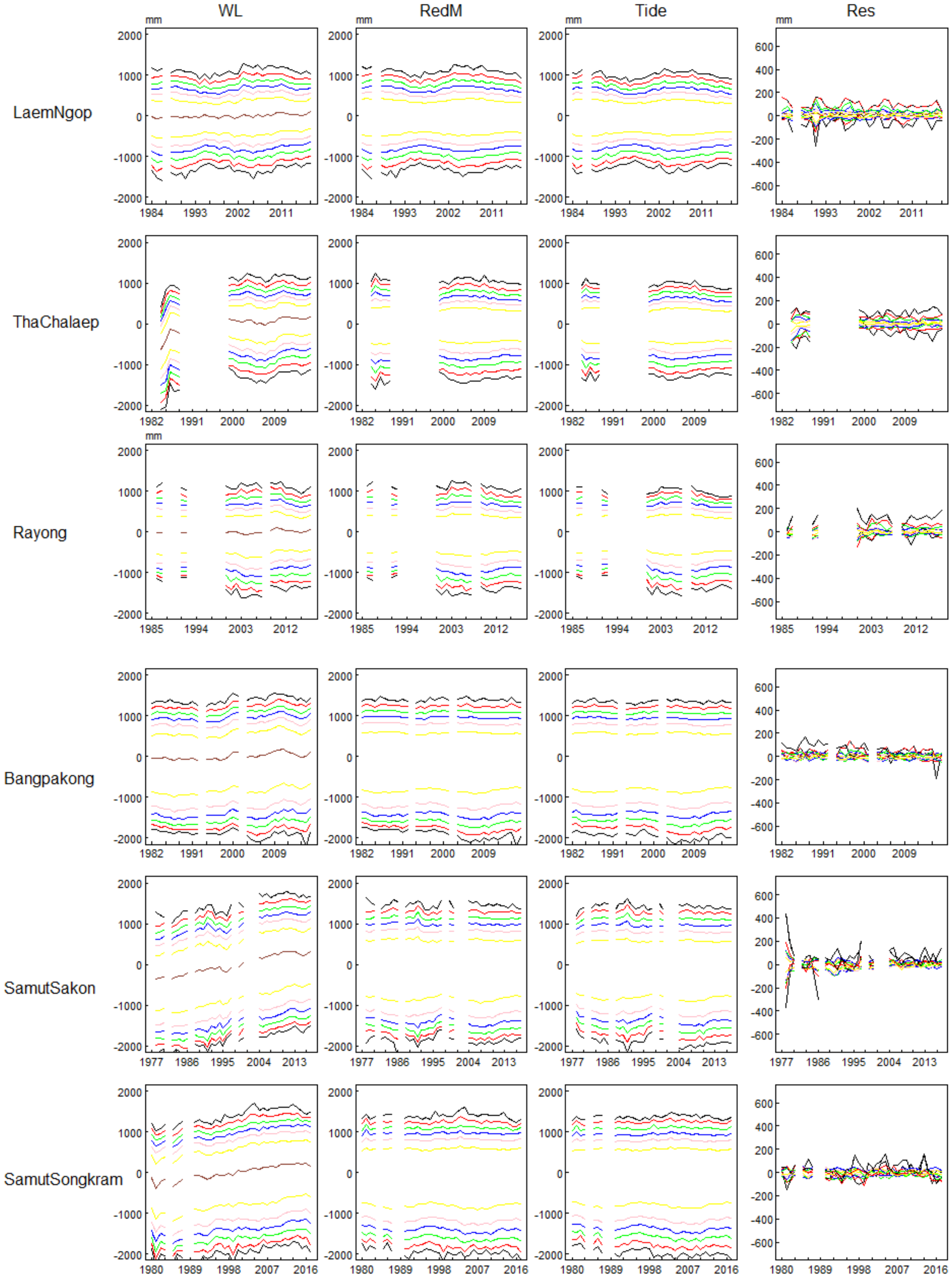
Table 4.3 Descriptive characteristics of water levels for each station along the Andaman Sea

Stations	**Size**	**Mean**	**Standard Deviation**	**Median**	**Min** (mm.)	**Max** (mm.)
Krabi	245,448	2,439	771.56	2,450	350	4,450
Kantrang	324,336	2,450	763.53	2,440	320	5,020
Tammalang	236,664	2,363	736.14	2,340	340	4,360

4.2.2 Percentile Analysis

Gulf of Thailand

The WL percentile series along the Gulf of Thailand showed that most of the frequency of distribution of extreme water level are high for all stations except at BanLaem and LangSuan stations. Most of variations between lower water levels (0.05^{th}, 0.5^{th}, 2^{nd}, 5^{th}, 10^{th}, 20^{th}) and upper water levels (80^{th}, 90^{th}, 95^{th}, 98^{th}, 99.5^{th}, 99.95^{th}) at upper Gulf of Thailand are high compared to station at lower Gulf of Thailand (Sichon, PakPhanang and Narathiwat stations). The variation of extreme water levels for water levels (WL), reduced to the mean (ResM), tide and residual (Res) along the Gulf of Thailand are shown in Figure 4.6.


WL
RedM
Tide
Res
mm
LaemNgop
ThaChalaep
Rayong
Bangpakong
SamutSakon
SamutSongkram
2000
1000
0
-1000
-2000
600
400
200
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-200
-400
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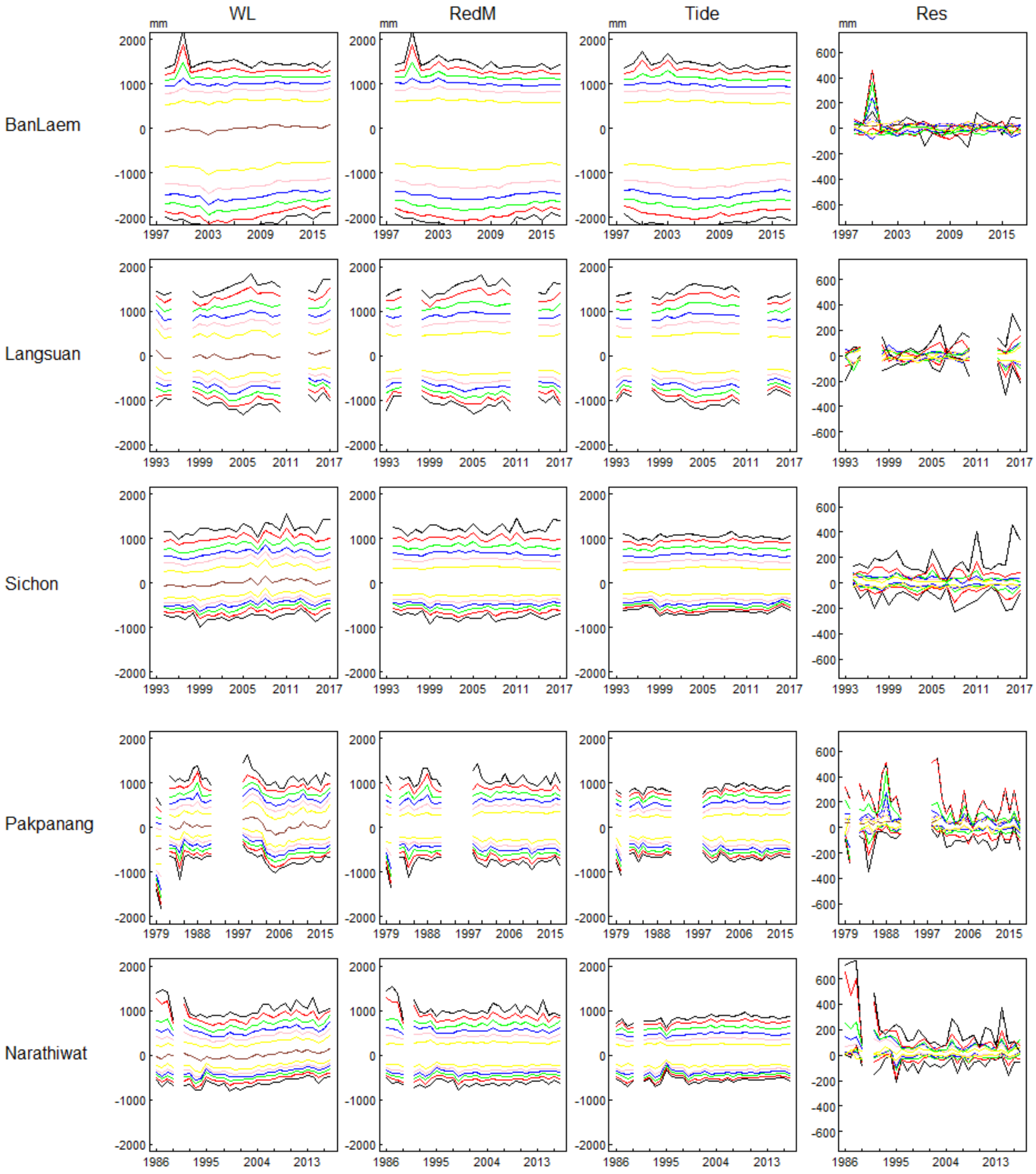

Figure 4.6 Variation of extreme water levels for water levels (WL), reduced to the mean (ResM), Tide and residual (Res) for the station along the Gulf of Thailand

To assess long-term changes in the extreme high and low water levels, the variability of WL, RedM, Tide and Res percentiles was accessed by fitting linear regression as shown in Table 4.4. For a better understanding, it is illustrated as a graph in Figure 4.7. The horizontal red line in Figure 4.7 indicates the overall mean, and the grey bars are the 95% confidence interval of the variability. If a 95% confidence interval includes the overall mean, then there is no statistically significant trend.

For stations along the Gulf of Thailand, the result showed all water level percentiles less than 95th had significantly increasing trends at LaemNgop station. These trends ranged from 6.16 mm/yr for 0.05th percentile to 1.94 mm/yr for 90th percentile. The trends were reduced with increasing percentiles. When reduced to the mean (by subtracting the 50th percentile) from water levels, ResM did not have any significant change for lower water level percentiles (0.05th to 20th percentiles) except percentile 0.05. Most of the lower RedM percentiles still shown significantly increased. In contrast, no significant trends were observed for tide and residual percentile series.

At ThaChalaep station, the WL percentiles showed increasing trends for both lower and upper percentile. For the lower percentile after removing mean, apart from the 0.05th and 10th percentiles, all ResM percentiles had no significant change, still had a significantly increasing trend in the range of 3.96 mm/yr and 1.53 mm/yr. At the same time, the tide and residual for all lower percentile showed no significant and significant increasing trend, respectively. The rising in lower water levels seems to be caused by a change in the tide as found a significant positive trend in the lower tide percentile. However, after removing mean from water levels in the upper percentile, the result showed upper RedM percentiles (80th to 99.95th percentiles) was changed from a significant positive trend to a significant negative trend in the range 1.801 mm/yr and 0.39 mm/yr. In addition, the upper tide percentiles showed significant decreasing trends only 80th and 90th percentiles and all residual percentile show significantly decreasing trends except 90th and 99.95th percentile. Therefore, the rise in upper water level percentile may be cause by MSL, Tide, and non-tidal residual effects as found a significant change of water level after removing MSL and a significant trend in Tide and residual percentile.

At the SamutSakon station, significant increasing trends were found for all water level percentiles and lower residual percentile series. After reducing to the mean, the water levels percentile changed from significantly increasing trends to no significant trend for all RedM except 0.05th, 80th, and 90th RedM percentiles, which had decreasing trends. This change in water levels seems to be caused by MSL. The Tide percentiles lower than 20th percentile and residual percentile higher than 98th percentile also showed significant decreasing trends in the range of -4.89 to -2.12 mm/yr and -0.74 to

-0.61 mm/yr, respectively. Therefore, changes in the water levels at SamutSakon station were not only caused by an increase in MSL, but also by the changes in tidal components and non-tidal residual components for the lower percentile. The water level lower than 80th percentile at BanLaem station showed a significant positive trend. These trends were reduced with increasing percentiles ranging from 4.3 mm/yr to 12.09 mm/yr. When MSL was subtracted, the upper percentile for RedM and tide showed significant decreasing trends for all. In contrast, none of the residual percentile series shows a statistically significant trend. These results suggest that much of the significant changes in upper water level could be due to changes in MSL and tide.

The water levels at Sichon station, all percentiles had a significant increasing trend except 0.05th percentile. Whereas all percentiles of RedM and tide at Sichon station had no significant trends after removing the mean, while only the 90th and 95th residual percentiles showed significantly reducing trends. Hence, the main cause of change in extreme water levels may depend on an increase in MSL. At Narathiwat station, the water level less than 95th percentile series showed significant positive trends ranging from 4.33 to 6.02 mm/year. The analysis found a pronounced 6.02 mm/yr trend for water level 0.5th percentile. When removing mean, water level less than 95th percentile series was changed to no significant trend. This change in water level cause could be due to changes in MSL. The tide percentile series higher than 90th percentile had shown a statically significant increasing trend in the range of 1.33 to 5.26 mm/yr. In contrast, the residual percentile showed significant decreasing trends ranging from -1.04 to -11.96 mm/yr for percentile higher than 80th.

Table 4.4 Variability trend of water levels for station along the Gulf of Thailand

Stations	Quan	0.05	0.50	2.00	5.00	10.00	20.00	50.00	80.00	90.00	95.00	98.00	99.50	99.95
LaemNgop	WL	*6.16 ± 1.8	*5.82 ± 1.4	*5.56 ± 1.22	*5.3 ± 1.1	*4.94 ± 1.04	*4.6 ± 0.78	*3.1 ± 0.52	*1.94 ± 0.83	*1.94 ± 0.93	1.96 ± 1.08	1.8 ± 1.2	1.55 ± 1.33	2.07 ± 1.6
	RedM	3.06 ± 1.7	*2.73 ± 1.3	*2.46 ± 1.1	*2.21 ± 0.97	*1.85 ± 0.88	*1.5 ± 0.61		-1.15 ± 0.67	-1.16 ± 0.81	-1.14 ± 1.01	-1.3 ± 1.15	-1.54 ± 1.29	-1.03 ± 1.55
	Tide	2.41 ± 1.53	2.23 ± 1.3	1.77 ± 1.16	1.61 ± 1	1.54 ± 0.88	1.1 ± 0.6		-1.15 ± 0.65	-1.13 ± 0.89	-1.12 ± 1.09	-0.92 ± 1.2	-0.54 ± 1.38	-0.2 ± 1.5
	Res	0.65 ± 1.08	0.5 ± 0.51	0.69 ± 0.37	0.6 ± 0.3	0.31 ± 0.23	0.41 ± 0.2		0 ± 0.16	-0.02 ± 0.16	-0.02 ± 0.23	-0.38 ± 0.29	*-1.01 ± 0.47	-0.83 ± 0.65
ThaChalaep	WL	*16.97 ± 3.32	*17.81 ± 2.81	*17.39 ± 2.72	*16.89 ± 2.63	*16.15 ± 2.48	*15.85 ± 2.26	*14.52 ± 2.06	*12.72 ± 1.96	*12.21 ± 1.89	*11.86 ± 1.9	*11.72 ± 2	*11.19 ± 2.12	*10.71 ± 2.26
	RedM	2.45 ± 1.67	*3.29 ± 1.12	*2.87 ± 1.12	*2.37 ± 1	1.63 ± 0.85	*1.33 ± 0.52		*-1.8 ± 0.54	*-2.31 ± 0.68	*-2.66 ± 0.83	*-2.8 ± 0.99	*-3.33 ± 1.1	*-3.81 ± 1.3
	Tide	-0.789 ± 1.748	-0.67 ± 1.56	-0.82 ± 1.31	-0.14 ± 1.1	-0.12 ± 0.99	-0.19 ± 0.64		*-1.41 ± 0.55	*-2.02 ± 0.77	-1.84 ± 0.9	-1.77 ± 0.99	-1.53 ± 1.14	-1.27 ± 1.41
	Res	*3.24 ± 1.11	*3.96 ± 0.85	*3.69 ± 0.51	*2.51 ± 0.43	*1.75 ± 0.35	*1.53 ± 0.28		*-0.39 ± 0.15	-0.29 ± 0.2	*-0.82 ± 0.21	*-1.03 ± 0.29	*-1.8 ± 0.52	-2.53 ± 1.43
Rayong	WL	*-7.17 ± 3.42	-4.63 ± 2.94	-1.7 ± 2.46	0.96 ± 2.22	2.41 ± 1.88	2.97 ± 1.45	2.13 ± 1.01	0.73 ± 1.06	-0.06 ± 1.08	-0.11 ± 1.19	-0.2 ± 1.49	-0.56 ± 1.9	-1.69 ± 1.93
	RedM	*-9.31 ± 3	*-6.77 ± 2.54	-3.84 ± 2.05	-1.18 ± 1.76	0.27 ± 1.41	0.84 ± 0.92		-1.41 ± 0.76	*-2.19 ± 0.87	*-2.25 ± 0.93	-2.33 ± 1.35	-2.69 ± 1.85	-3.82 ± 1.87
	Tide	*-9.86 ± 3.02	*-7.13 ± 2.42	*-4.37 ± 2.08	-2.49 ± 1.87	-1.2 ± 1.57	0.13 ± 1.01		*-1.87 ± 0.79	*-2.28 ± 0.97	-2.13 ± 1.02	*-2.59 ± 1.22	*-3.98 ± 1.52	*-5.3 ± 1.91
	Res	0.55 ± 0.88	0.36 ± 0.74	0.53 ± 0.38	*1.31 ± 0.31	*1.47 ± 0.28	*0.7 ± 0.28		0.47 ± 0.26	0.08 ± 0.31	-0.12 ± 0.24	0.26 ± 0.47	1.29 ± 0.68	1.48 ± 1.08
BangPakong	WL	*-3.98 ± 1.38	-1.19 ± 1.13	1.8 ± 1.07	*3.87 ± 1.08	*5.36 ± 1.02	*6.49 ± 0.96	*5.07 ± 0.93	*4.35 ± 1.03	*4.02 ± 0.97	*3.88 ± 0.97	*3.98 ± 0.97	*4.33 ± 0.96	*4.87 ± 1.19
	RedM	*-9.05 ± 1.2	*-6.26 ± 0.93	*-3.27 ± 0.92	-1.2 ± 0.98	0.29 ± 0.93	1.43 ± 0.74		-0.72 ± 0.37	*-1.05 ± 0.31	*-1.18 ± 0.34	*-1.09 ± 0.36	-0.73 ± 0.49	-0.2 ± 0.71
	Tide	*-5.09 ± 1.19	*-4.47 ± 1.06	*-3.02 ± 0.97	-1.08 ± 0.94	0.22 ± 0.88	1.1 ± 0.75		*-0.89 ± 0.36	*-1.25 ± 0.31	*-1.46 ± 0.3	*-0.98 ± 0.32	-0.39 ± 0.45	-0.09 ± 0.64
	Res	*-3.95 ± 0.79	*-1.78 ± 0.31	-0.24 ± 0.18	-0.12 ± 0.18	0.07 ± 0.2	*0.32 ± 0.16		0.17 ± 0.13	0.2 ± 0.15	0.27 ± 0.17	-0.11 ± 0.16	-0.34 ± 0.24	-0.11 ± 0.52
Samut Sakhon	WL	*18.45 ± 1.42	*16.58 ± 1.05	*16.87 ± 1	*17.21 ± 0.92	*18.18 ± 0.78	*19.33 ± 0.72	*19.05 ± 0.83	*18.14 ± 1.03	*18.14 ± 1	*18.08 ± 1.04	*18.28 ± 1.08	*18.25 ± 1.1	*17.06 ± 1.47
	RedM	-0.59 ± 1.55	*-2.47 ± 1.17	-2.18 ± 1.12	-1.84 ± 1.04	-0.87 ± 0.94	0.28 ± 0.8		*-0.91 ± 0.42	*-0.9 ± 0.41	-0.96 ± 0.49	-0.77 ± 0.53	-0.79 ± 0.63	-1.99 ± 1.08
	Tide	*-4.89 ± 1.5	*-4.15 ± 1.3	*-3.78 ± 1.18	*-3.1 ± 1.07	*-2.11 ± 0.98	-0.75 ± 0.79		-0.3 ± 0.4	-0.29 ± 0.42	-0.23 ± 0.51	-0.06 ± 0.63	-0.1 ± 0.85	-0.19 ± 1.02
	Res	*4.3 ± 1.37	*1.68 ± 0.57	*1.6 ± 0.4	*1.26 ± 0.32	*1.24 ± 0.28	*1.04 ± 0.2		*-0.61 ± 0.18	*-0.61 ± 0.21	*-0.73 ± 0.25	-0.71 ± 0.36	-0.69 ± 0.59	-1.8 ± 1.25
Samut Songkharm	WL	*10.04 ± 1.72	*9.88 ± 1.39	*11.08 ± 1.13	*11.96 ± 1.16	*12.82 ± 1.15	*14.23 ± 1.12	*14.69 ± 0.91	*15.02 ± 0.92	*14.74 ± 0.87	*14.71 ± 0.81	*14.62 ± 0.86	*14.41 ± 1.13	*15.08 ± 1.51
	RedM	*-4.65 ± 1.34	*-4.81 ± 1.02	*-3.61 ± 0.76	*-2.73 ± 0.88	-1.87 ± 0.95	-0.46 ± 0.87		0.33 ± 0.37	0.05 ± 0.4	0.02 ± 0.43	-0.07 ± 0.51	-0.28 ± 0.77	0.39 ± 1.22
	Tide	*-6.38 ± 1.18	*-5.28 ± 0.95	*-4 ± 0.86	*-3.2 ± 0.92	*-2.07 ± 0.93	-0.66 ± 0.83		0.45 ± 0.38	0.18 ± 0.36	0.07 ± 0.43	0.65 ± 0.49	0.95 ± 0.56	0.88 ± 0.79
	Res	1.74 ± 1.05	0.46 ± 0.58	0.38 ± 0.3	*0.47 ± 0.19	0.19 ± 0.15	0.2 ± 0.19		-0.12 ± 0.16	-0.13 ± 0.17	-0.04 ± 0.22	*-0.71 ± 0.23	*-1.23 ± 0.43	-0.49 ± 0.84
BanLaem	WL	*10.77 ± 4.78	*12.09 ± 3.99	*9.74 ± 3.25	*8.65 ± 3.01	*9.52 ± 2.7	*8.92 ± 2.39	*7.19 ± 1.57	*4.3 ± 1.38	2.53 ± 1.33	1.75 ± 1.58	-0.75 ± 3.1	-4.88 ± 5.31	-7.45 ± 6.8
	RedM	3.57 ± 4.8	4.9 ± 3.77	2.54 ± 2.84	1.46 ± 2.56	2.33 ± 2.33	1.73 ± 2.02		*-2.89 ± 0.93	*-4.66 ± 1.11	*-5.44 ± 1.4	*-7.94 ± 2.83	*-12.07 ± 5.14	*-14.65 ± 6.61
	Tide	3.77 ± 3.64	2.77 ± 3.26	1.59 ± 2.84	1.09 ± 2.8	1.55 ± 2.62	1.6 ± 2.13		*-2.49 ± 0.89	*-3.66 ± 0.85	*-4.86 ± 1.06	*-4.99 ± 1.85	*-6.98 ± 2.95	*-8.73 ± 3.63

Stations	Quan	0.05	0.50	2.00	5.00	10.00	20.00	50.00	80.00	90.00	95.00	98.00	99.50	99.95
	Res	-0.2 ± 3.07	2.13 ± 1.24	0.96 ± 0.52	0.37 ± 0.92	0.77 ± 0.77	0.12 ± 0.64		-0.4 ± 0.26	-0.99 ± 0.49	-0.58 ± 0.65	-2.96 ± 1.92	-5.09 ± 3.13	-5.91 ± 3.97
LangSuan	WL	2.27 ± 4.16	2.55 ± 3.82	3.73 ± 3.53	3.07 ± 3.05	2.78 ± 2.64	2.47 ± 2.43	3.14 ± 1.79	3.44 ± 1.96	*4.16 ± 1.91	3.45 ± 2.04	4.32 ± 2.23	*7.18 ± 3.23	*11.49 ± 3.9
	RedM	-0.87 ± 3.96	-0.6 ± 3.33	0.59 ± 2.76	-0.08 ± 2.18	-0.36 ± 1.68	-0.67 ± 1.14		0.29 ± 1.08	1.01 ± 1.35	0.31 ± 1.68	1.17 ± 2.28	4.04 ± 3.46	8.35 ± 4.28
	Tide	2.26 ± 4.26	1.64 ± 3.68	1.46 ± 3.11	1.14 ± 2.47	0.8 ± 1.98	-0.24 ± 1.25		-0.11 ± 1.25	0.22 ± 1.77	-0.25 ± 2.09	0.18 ± 2.49	0.9 ± 2.94	0.85 ± 3.63
	Res	-3.13 ± 2.56	-2.23 ± 1.64	-0.87 ± 1.06	-1.21 ± 0.74	-1.16 ± 0.66	-0.43 ± 0.5		0.4 ± 0.64	0.79 ± 0.66	0.56 ± 0.87	1 ± 0.72	*3.14 ± 1.43	*7.5 ± 2.29
Sichon	WL	4.21 ± 2.45	*4.72 ± 1.93	*5.55 ± 1.8	*6.23 ± 1.63	*6.15 ± 1.68	*5.71 ± 1.52	*6.2 ± 1.58	*5.98 ± 1.98	*5.48 ± 2.12	*5.32 ± 2.16	*5.48 ± 2.39	*5.8 ± 2.46	*10.25 ± 3.35
	RedM	-1.99 ± 2.21	-1.48 ± 1.77	-0.65 ± 1.52	0.03 ± 1.1	-0.05 ± 0.95	-0.49 ± 0.57		-0.22 ± 0.68	-0.72 ± 0.87	-0.88 ± 0.98	-0.72 ± 1.36	-0.4 ± 1.58	4.05 ± 3.08
	Tide	0.28 ± 1.84	0.29 ± 1.7	0.2 ± 1.48	0.14 ± 1.28	-0.24 ± 1.01	-0.85 ± 0.62		0.29 ± 0.74	0.34 ± 0.86	0.55 ± 0.95	0.4 ± 0.99	0.2 ± 1.15	-0.51 ± 1.52
	Res	-2.26 ± 1.82	-1.77 ± 1.08	-0.84 ± 0.73	-0.11 ± 0.48	0.19 ± 0.38	0.36 ± 0.36		-0.51 ± 0.34	*-1.06 ± 0.44	*-1.43 ± 0.43	-1.12 ± 0.71	-0.59 ± 1.18	4.56 ± 2.95
PakPhanang	WL	5.85 ± 3.85	4.9 ± 3.77	4.67 ± 3.58	4.14 ± 3.37	3.26 ± 2.98	2.45 ± 2.63	4.19 ± 2.32	*5.99 ± 2.21	*5.75 ± 2.24	*5.37 ± 2.34	4.63 ± 2.38	3.04 ± 2.52	2.57 ± 3.21
	RedM	1.66 ± 2.16	0.71 ± 1.94	0.48 ± 1.72	-0.05 ± 1.43	-0.93 ± 0.99	*-1.74 ± 0.59		*1.81 ± 0.36	*1.56 ± 0.53	1.18 ± 0.7	0.44 ± 0.95	-1.15 ± 1.22	-1.62 ± 1.91
	Tide	0.88 ± 1.43	0.43 ± 1.3	-0.26 ± 1.2	-1 ± 1.11	-1.28 ± 0.97	-1.33 ± 0.68		*1.43 ± 0.34	*1.75 ± 0.47	*2.21 ± 0.56	*2.65 ± 0.66	*2.69 ± 0.74	*2.85 ± 0.88
	Res	0.78 ± 1.13	0.28 ± 0.88	0.74 ± 0.71	0.95 ± 0.47	0.34 ± 0.35	-0.4 ± 0.39		0.38 ± 0.24	-0.19 ± 0.3	*-1.03 ± 0.44	*-2.2 ± 0.68	*-3.85 ± 1	*-4.47 ± 2.02
Narathiwat	WL	*5.84 ± 1.6	*6.02 ± 1.31	*5.63 ± 1.27	*5.58 ± 1.23	*5.21 ± 1.18	*4.92 ± 1.14	*5.01 ± 1.02	*5.78 ± 1.02	*4.72 ± 1.23	*4.33 ± 1.5	3.55 ± 1.76	-1.64 ± 3.08	-1.69 ± 3.66
	RedM	0.83 ± 1.25	1 ± 0.95	0.62 ± 0.91	0.57 ± 0.8	0.2 ± 0.69	-0.09 ± 0.55		0.76 ± 0.46	-0.29 ± 0.69	-0.68 ± 0.94	-1.46 ± 1.23	*-6.65 ± 2.53	*-6.7 ± 3.23
	Tide	1.55 ± 1.38	1.6 ± 1.29	1.24 ± 1.19	0.72 ± 1.09	0.36 ± 0.97	-0.26 ± 0.66		0.28 ± 0.39	0.75 ± 0.44	*1.33 ± 0.59	*2.76 ± 0.78	*4.12 ± 0.93	*5.26 ± 1.13
	Res	-0.72 ± 1.16	-0.6 ± 0.85	-0.62 ± 0.57	-0.15 ± 0.49	-0.16 ± 0.38	0.17 ± 0.3		0.49 ± 0.33	*-1.04 ± 0.48	*-2.01 ± 0.72	*-4.22 ± 1.02	*-10.77 ± 2.46	*-11.96 ± 3.19

* significant at 95% confidence interval; WL is water levels; RedM reduced to the mean; Res is residual

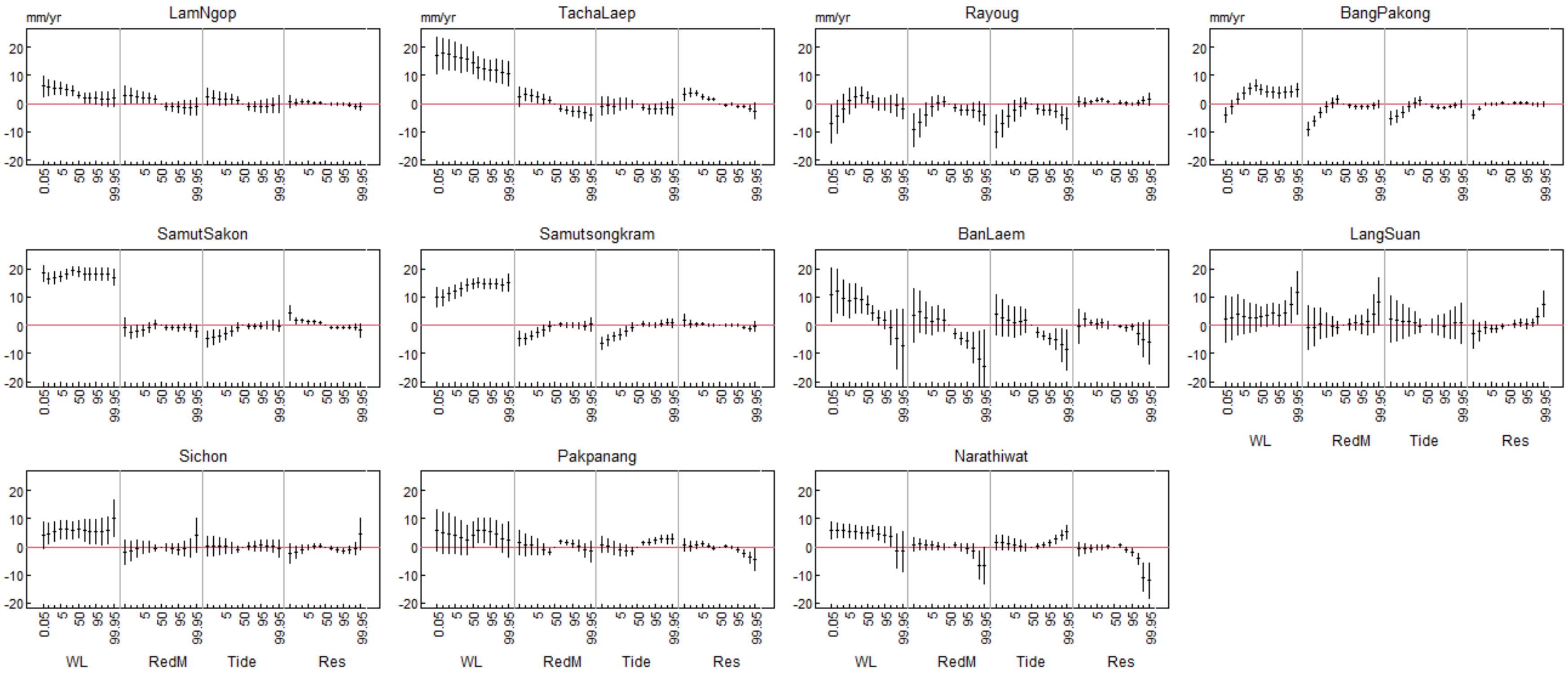

Figure 4.7 The 95% confidence interval of annual variability trend of water levels for station along the Gulf of Thailand

Andaman Sea

Stations along the Andaman Sea have predominantly semi-diurnal tides. Result from percentile analysis showed that the variability of water levels along the coast of Andaman Sea are high for all stations, especially at Kantrang station as shown in Figure 4.8

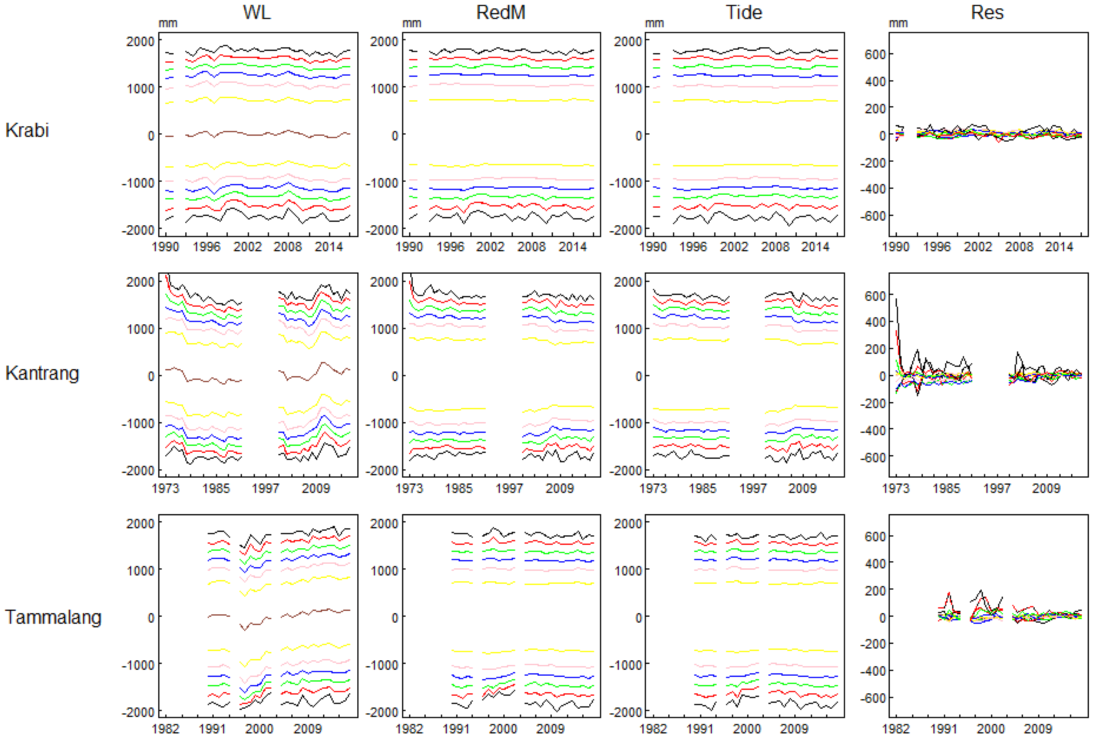

Figure 4.8 Variation of extreme water levels for water levels (WL), reduced to the mean (ResM), Tide and residual (Res) for station along AndamanSea

The variability of WL, RedM, Tide and Res percentiles was accessed by fitting linear regression are shown in Table 4.5. For a better understanding, it is illustrated as a graph in Figure 4.9. Krabi station, all of the water level percentile series show significant positive trends ranging from 4.17 to 7.72 mm/year, and MSL was 6.84 mm/year. The lower water levels percentile series showed larger trends ranging from 4.17 mm/yr to 7.72 mm/yr than upper percentiles series ranging from 6.37 m/yr to 5.79 mm/yr. The lower water level series increased with increasing percentiles, while the upper series decreased with increasing percentiles. These indicate that the lower extreme water levels have been increasing faster than upper extreme water levels. When the MSL was subtracted, only two percentiles 90th and 95th showed significant reducing trends in the RedM. Also, only the 95th and 98th tide percentiles had significant increasing trends. The upper percentiles of the residual percentile series showed no significant trends; however, the lower percentile series had mostly significant increasing trends between 0.64 mm/yr and 1 mm/yr. These results suggest that much of the significant changes in water level could be due to changes in MSL.

At Kantrang station, the water levels percentile series lower than 50th percentile showed significant positive trends, ranging from 3.41 mm/yr to 4.48 mm/year, except 0.05th percentile series. The most pronounce trend was found at 10th percentile series, which was increasing at an average of 4.48 mm/yr. When reduced to the MSL, the RedM percentiles were generally significant, although, with varying trends. Most of the lower percentiles were increasing significantly between 1.16 mm/yr and 1.74 mm/yr. Meanwhile, the upper RedM percentiles were decreasing significantly. The upper percentiles of tide also had significant decreasing trends over the study period.

All percentile series at Tammalang station show no significant trends, except residual percentile series. A significantly increasing trend was observed in the 5th residual percentile and significant decreasing trends were found in the 98th and 99.95th residual percentile series. Removing the MSL did not have any significant effects on the water levels percentiles. The trends in the tide and residual percentiles are generally consistent with the water level trends.

Table 4.5 Variability trend of water levels for the station along Andaman Sea

Stations	Quan	0.05	0.50	2.00	5.00	10.00	20.00	50.00	80.00	90.00	95.00	98.00	99.50	99.95
Krabi	WL	*4.17 ± 1.8	*5.95 ± 1.69	*6.9 ± 1.95	*7.34 ± 2.09	*7.49 ± 2.14	*7.72 ± 2.11	*6.84 ± 1.83	*6.37 ± 1.81	*6.15 ± 1.68	*5.84 ± 1.66	*6.05 ± 1.67	*6.28 ± 1.65	*5.78 ± 1.89
	RedM	-2.68 ± 2.24	-0.89 ± 1.41	0.06 ± 0.95	0.5 ± 0.73	0.65 ± 0.61	0.88 ± 0.49	0 ± 0	-0.47 ± 0.31	*-0.69 ± 0.33	*-1 ± 0.36	-0.79 ± 0.43	-0.56 ± 0.69	-1.06 ± 1.07
	Tide	-1.76 ± 1.74	-0.87 ± 1.2	-0.58 ± 0.82	-0.51 ± 0.65	-0.25 ± 0.55	0.23 ± 0.42	0 ± 0	-0.47 ± 0.33	-0.75 ± 0.39	*-1.12 ± 0.38	*-1.19 ± 0.48	-0.87 ± 0.57	0.3 ± 0.89
	Res	-0.91 ± 1.25	-0.02 ± 0.61	*0.64 ± 0.25	*1 ± 0.24	*0.9 ± 0.23	*0.65 ± 0.17	0 ± 0	0 ± 0.21	0.06 ± 0.19	0.12 ± 0.17	0.4 ± 0.22	0.32 ± 0.4	-1.36 ± 0.88
Kantrang	WL	2.18 ± 1.28	*3.41 ± 1.37	*3.89 ± 1.47	*4.35 ± 1.51	*4.48 ± 1.54	*4.46 ± 1.46	2.74 ± 1.36	0.56 ± 1.3	-0.15 ± 1.28	-0.19 ± 1.32	-0.1 ± 1.46	-0.35 ± 1.77	-1.64 ± 2.13
	RedM	-0.56 ± 0.78	0.67 ± 0.55	*1.16 ± 0.47	*1.61 ± 0.5	*1.74 ± 0.47	*1.73 ± 0.37	0 ± 0	*-2.18 ± 0.35	*-2.89 ± 0.44	*-2.92 ± 0.43	*-2.83 ± 0.57	*-3.08 ± 0.93	*-4.37 ± 1.36
	Tide	-0.69 ± 0.82	-0.42 ± 0.55	-0.37 ± 0.44	-0.05 ± 0.4	0.64 ± 0.39	*1.55 ± 0.37	0 ± 0	*-2.34 ± 0.32	*-2.77 ± 0.4	*-2.91 ± 0.43	*-2.65 ± 0.51	*-1.83 ± 0.59	*-1.65 ± 0.64
	Res	0.13 ± 0.81	*1.09 ± 0.34	*1.53 ± 0.18	*1.65 ± 0.18	*1.1 ± 0.17	0.17 ± 0.12	0 ± 0	0.17 ± 0.1	-0.12 ± 0.13	-0.01 ± 0.12	-0.19 ± 0.29	-1.26 ± 0.64	*-2.72 ± 1.11
Tammalang	WL	-0.86 ± 2.17	0.39 ± 1.72	0.11 ± 1.37	0.63 ± 1.3	0.44 ± 1.25	0.19 ± 1.05	-0.13 ± 1.03	-0.2 ± 0.97	-0.69 ± 1.12	-0.82 ± 1.1	-0.79 ± 1.1	-0.51 ± 1.15	-1.16 ± 1.45
	RedM	-0.73 ± 1.86	0.52 ± 1.32	0.24 ± 0.8	0.76 ± 0.55	0.58 ± 0.48	0.33 ± 0.36	0 ± 0	-0.07 ± 0.37	-0.56 ± 0.5	-0.69 ± 0.39	-0.66 ± 0.62	-0.37 ± 0.7	-1.02 ± 0.98
	Tide	-0.8 ± 1.89	0.38 ± 1.14	0.07 ± 0.66	0.3 ± 0.54	0.47 ± 0.45	0.42 ± 0.32	0 ± 0	0.12 ± 0.41	-0.14 ± 0.43	-0.35 ± 0.39	-0.15 ± 0.59	0.11 ± 0.74	1.1 ± 1.09
	Res	0.07 ± 0.78	0.14 ± 0.45	0.17 ± 0.27	*0.46 ± 0.21	0.11 ± 0.2	-0.1 ± 0.24	0 ± 0	-0.19 ± 0.27	-0.42 ± 0.25	-0.34 ± 0.22	*-0.5 ± 0.24	-0.48 ± 0.37	*-2.13 ± 0.8

*Significant at 95% confidence interval; WL is water levels; RedM is reduced to MSL; Res is residual

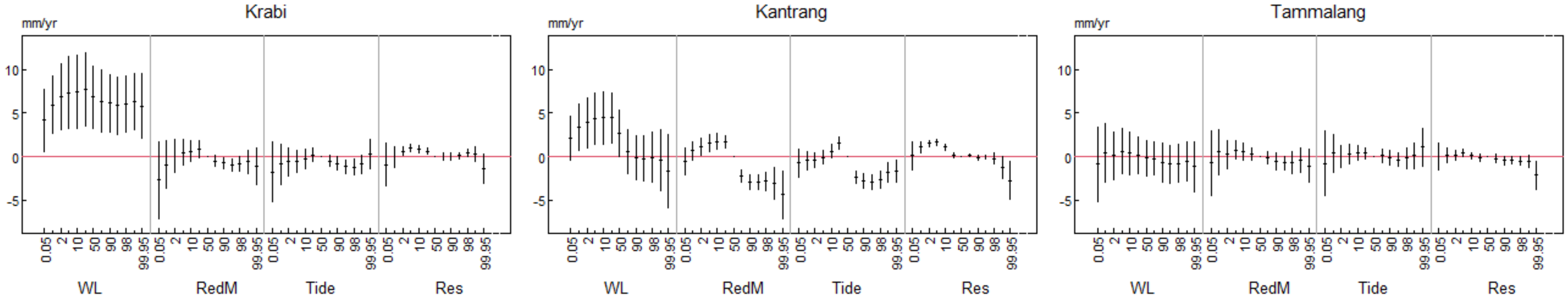

Figure 4.9 The 95% confidence interval of annual variability trend of water levels for the station along the coast of Andaman Sea

4.2.3 Tidal Analysis

Gulf of Thailand

1) Tidal Levels, Tidal Ranges and Mean Sea Level

The results of the tidal analysis show that the tidal water levels at all 11 stations have changed. While most of the reported changes in tidal levels and tidal ranges were significant, a few were not as shown in Figure 4.10 and Figure 4.11. Figure 4.10 shows 95% confidence interval of the tidal level, tidal range and MSL variability. The observed trends of MHHW were significantly increasing trend for all except LangSuan station. The observed trends of MLLW were significant for all stations except LangSuan, PakPhanang, and Narathiwat stations. MSL trends were also not-significant at the Rayong, LangSuan, and PakPhanang stations. At most stations, the annual MHHW and MLLW have increased. The GDTR trends for LaemNgop, BanLaem, and LangSuan stations were statistically not significant. The GDTR trend was more pronounced at Narathiwat (11.36 mm/yr) and Rayong (10.23 mm/yr) stations. The opposite trends of MHHW (10.74 mm/yr) and MLLW (-0.61 mm/yr) in Narathiwat cause high GDTR. Similar to Narathiwat station, Rayong station also had increasing trends of MHHW (6.63 mm/yr) and decreasing trends of MLLW (-3.56 mm/yr).

LangSuan and Sichon stations had the lowest significant and non-significant trend for GDTR, respectively. MHHW and MLLW trends at LangSuan were both increasing, although not significant, resulting in a non-significant trend of 0.68 mm/yr for GDTR. However, at Sichon, the GDTR trend (1.70 mm/yr) was significantly positive, while the changes in MHHW and MLLW (6.64 mm/yr and 4.94 mm/yr, respectively) were also significant. Although SamutSakhon station had the highest increase in MHHW, the GDTR trend was relatively low in comparison to Narathiwat station. The trends for each tidal water level, tidal range and MSL for each station in the Gulf of Thailand coast are shown in Figure 4.10. and Figure 4.11

The MSL and GDTR trends were similar for all stations, although the amplitude of the trends was different. The highest MSL increasing trend was reported at the Samut Sakhon tidal gauge station (18.67 mm/yr), while the lowest increasing trend was found at the LaemNgop station (3.24 mm/yr). While Rayong and LangSuan stations had the lowest MSL trends, they were not significant.

The trends of LDTR found were similar to the trends of GDTR, except at Samut Sakhon and PakPhanang stations, where the trends of LDTR were negative. However, unlike GDTR, the magnitude of LDTR trends was generally lower. Lang Suan was the only station where the LDTR trend was higher than the GDTR trend.

The LDTR trends for the remaining nine stations, with the exception of ThaChalaep and Rayong, were not significant. The LDTR increasing trends for ThaChalaep station were 5.55 mm/yr and 4.76 mm/yr for Rayong station. In Rayong station, the MHLW and MLHW showed opposite trends between -0.86 mm/yr and 3.90 mm/yr. A summary of the trend of tidal levels, tidal ranges and MSL for all stations along the Gulf of Thailand is shown as a map in Figure 4.11.

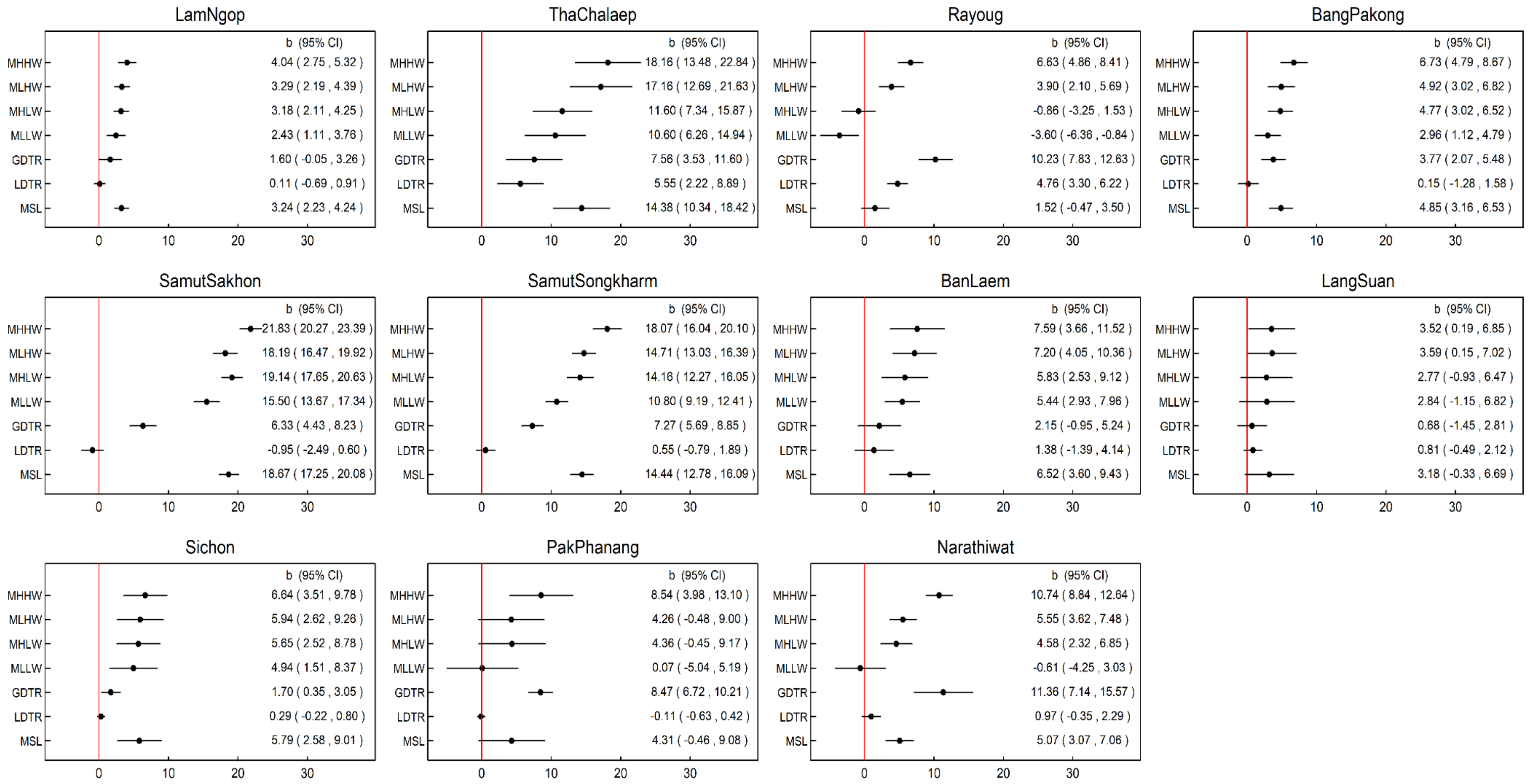

Figure 4.10 The 95% confidence interval of trend of tidal levels, tidal ranges and MSL for station along the Gulf of Thailand

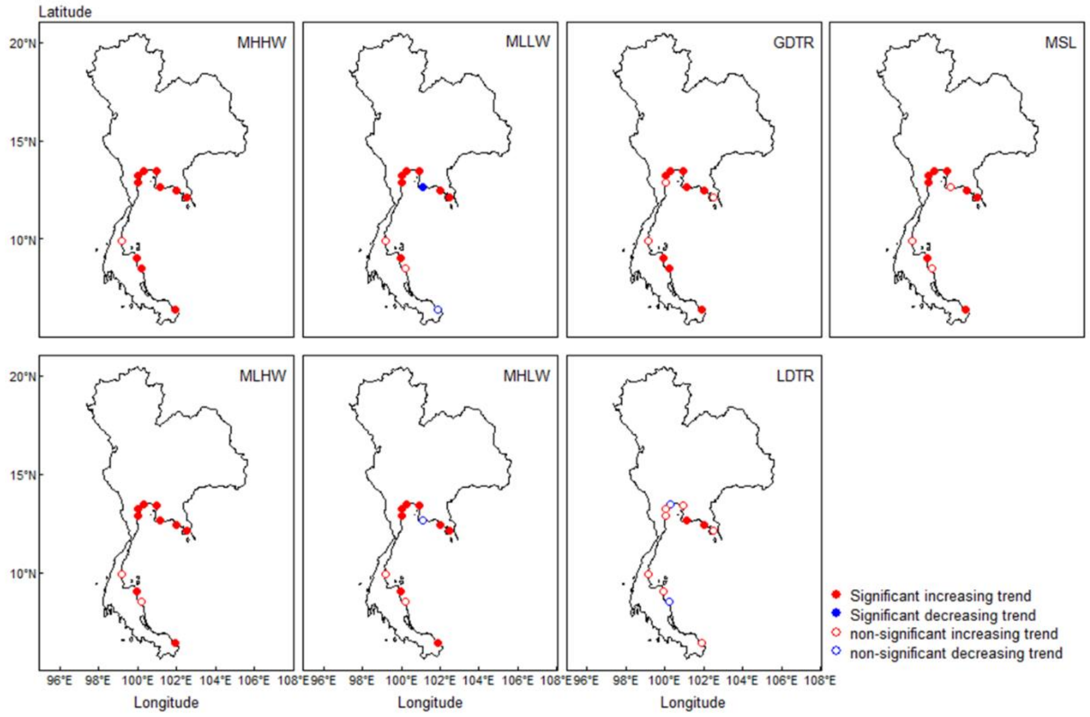

Figure 4.11 Summarizes the tidal levels, tidal ranges, and MSL trends for stations along the Gulf of Thailand.

2) Tidal Constituents

Tidal constituents are the net result of multiple influences impacting tidal changes over certain periods of time. The K1 constituent showed significant amplitude trends at seven of the eleven stations, as shown in Figure 4.12. The amplitude and phase trends of the four main tidal constituents are summarized as a graph and map in Figure 4.12 and Figure 4.13, respectively. At LaemNgop, LangSuan, Sichon and PakPhanang stations, the trends in the amplitude of the K1 constituent were not statistically significant. The amplitudes in ThaChalaep and Rayong exceeded 2 mm/yr, whereas Narathiwat's was -1.84 mm/yr. At Rayong, BangPakong, and Samut Songkhram stations, the trends of K1, O1 and M2 amplitudes revealed significant increases. The amplitudes of O1 and M2 at any of the stations did not show any significant decreases. Three stations ThaChalaep, SamutSakhon, and Samut Songkhram had significantly decreasing trends in the amplitude of the S2 constituent between -0.84 mm/yr and -0.30 mm/yr. In contrast, S2 at LangSuan station had a significantly increasing trend in the magnitude of 1.44 mm/yr.

The phase trends for diurnal constituents, O1 constituent showed a significantly increasing trend at Narathiwat station (3.52 mm/yr), while the K1 constituent showed decreasing trend at SamutSakhon station (-4.14 mm/yr). The M2 and S2 constituents for mixed tide found a significant increasing trend for M2 constituent at SamutSakhon and PakPanang stations and S2 constituent found at Rayong and SamutSakon stations. In contrast, the S2 constituent found a significantly decreasing trend at LangSuan station.

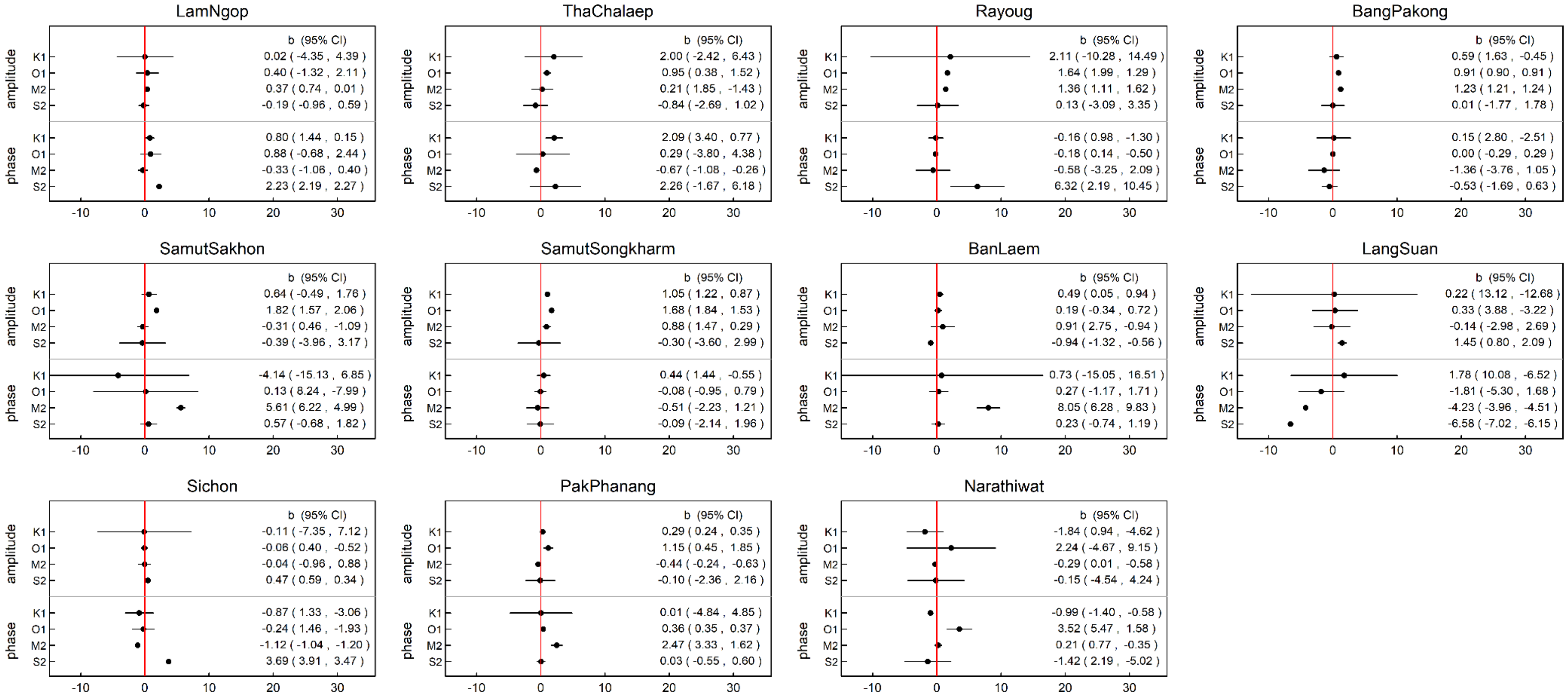

Figure 4.12 The 95% confidence interval of amplitude and phase trend of four main tidal constituents for station along the Gulf of Thailand

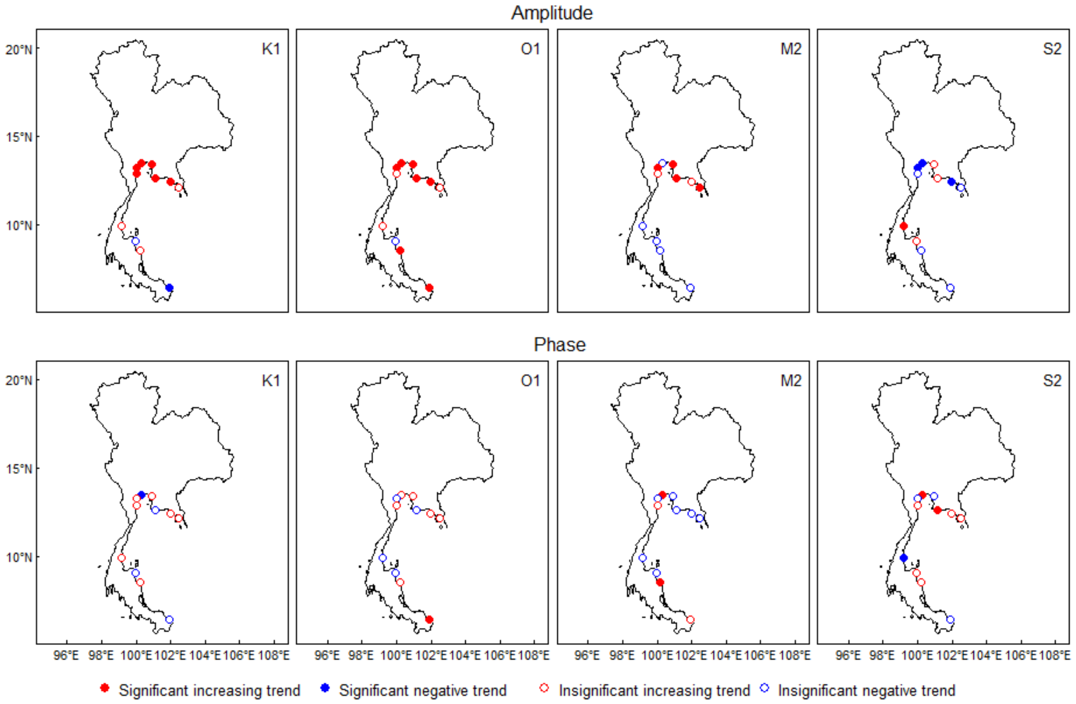

Figure 4.13 Summary of amplitude and phase of four main tidal constituents for stations along the Gulf of Thailand.

Andaman Sea

1) Tidal Levels, Tidal Ranges and Mean Sea Level

The result from tidal analysis revealed that, except for STTR and NETR, most of the observed changes in tidal levels and tidal ranges at Krabi station were significant. While the changes for all tidal levels and tidal ranges at Tammalang were not significant. For Kantrang station, only the MLWN, MLWS, and NETR showed statistically significant changes as shown in Figure 4.14 and Figure 4.15.

Annual MHWS (5.77 mm/yr) and MLWS (8.33 mm/yr) showed significant increasing trends at Krabi station. On the other hand, no significant pattern was found for STTR. Due to increases in the annual MHWS and MLWS, the STTR at Kantrang was decreasing (though not significant). The opposite trends of the MHWS (0.09 mm/yr) and MLWS (-0.43 mm/yr) are due to increasing trend of STTR at Tammalang station. The decreasing trend in the STTR was more pronounced at the Krabi station (-2.56 mm/yr) than at the Kantrang station (-0.73 mm/yr). NETR reported decreasing trends of -4.73 and -0.25 mm/yr at the Kantrang and Tammalang stations, respectively, whereas it had an increasing trend of 0.16 mm/yr at the Krabi station. Although the NETR trend at Kantrang station was significant, it was not at Krabi or Tammalang stations.

The trend of MSL increased at the Krabi station while it decreased at Tammalang. The largest significant increasing trend of the MSL was reported at the Krabi tidal gauge station (7.05 mm/yr), while the trend at the Kantrang station was 2.51 mm/yr and not significant. The trend of MSL at Tammalang station was also not statistically decreasing significant (-0.17 mm/yr). The summary of trend of water level, water rang and MSL are shown in Figure 4.14 and Figure 4.15.

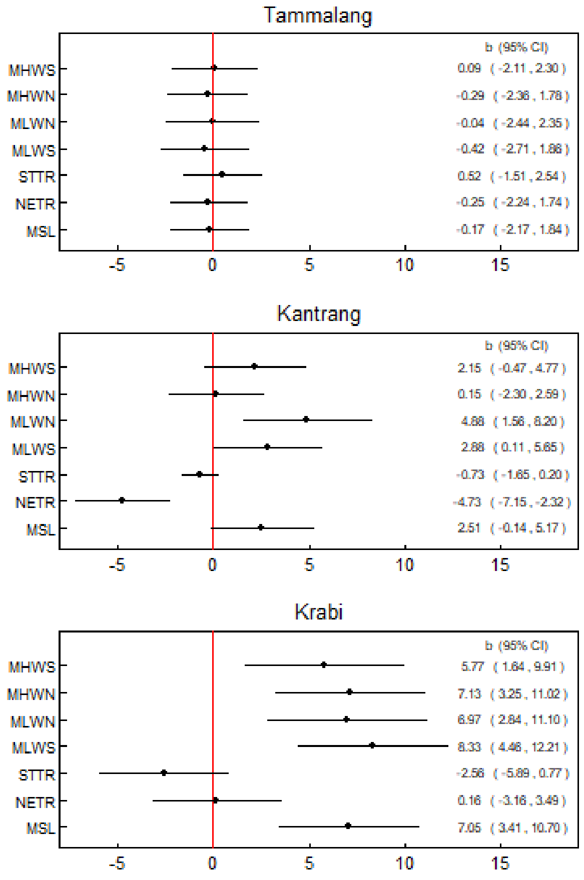

Figure 4.14 The 95% confidence interval of tidal levels, tidal ranges and MSL trend for station along Andaman Sea

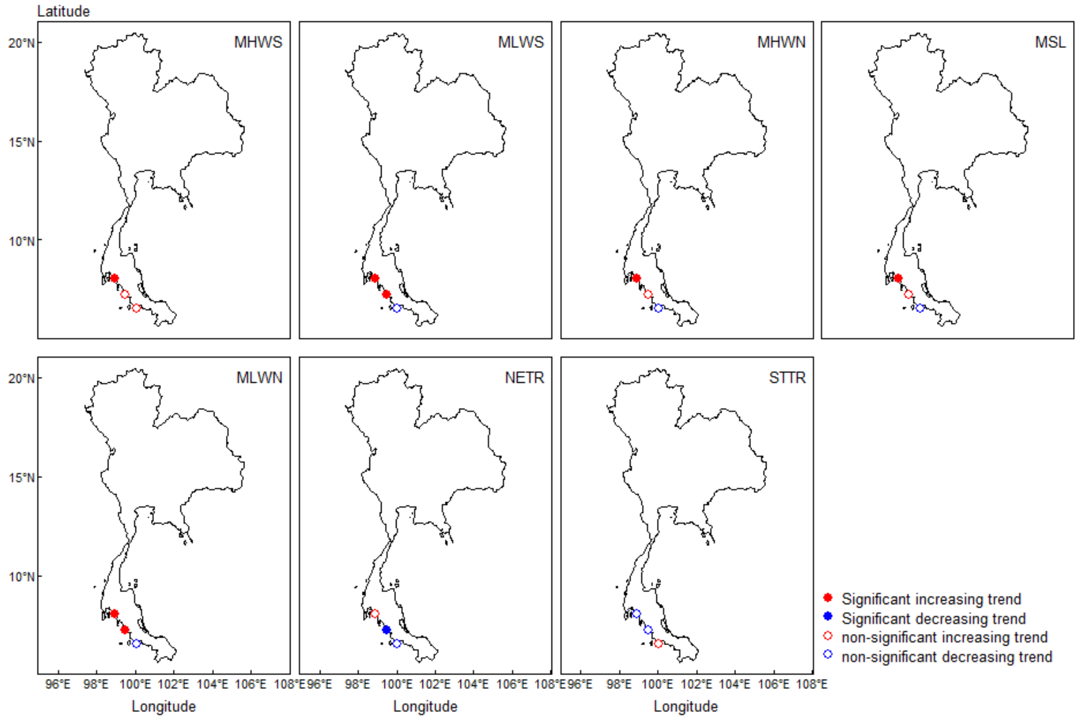

Figure 4.15 Summary of the tidal levels, tidal ranges, and MSL trends for stations along Andaman Sea.

2) Tidal Constituents

Changes in the tidal level might be due to a secular change in one or more of the main tidal constituents. A significantly reducing trend (-1.365 mm/yr) for K1 constituent was observed at Kantrang station. The K1 constituent had no trends at Krabi and Tammalang stations. The M2, S2 and O1 constituents showed no significant trends at all the stations. The trend of four main tidal constituents: M2, S2, K1 and O1 of amplitude and phase changes for station along Andaman Sea are shown in Figure 4.16 and Figure 4.17.

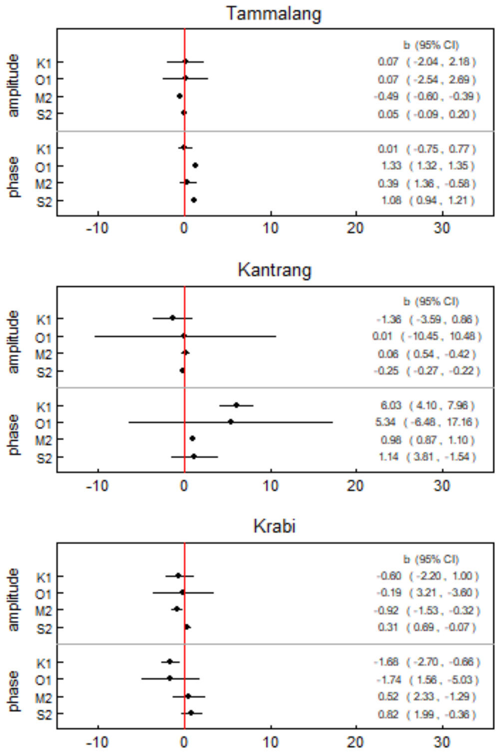

Figure 4.16 The 95% confidence interval of amplitude and phase trend of four main tidal constituents for station along Andaman Sea

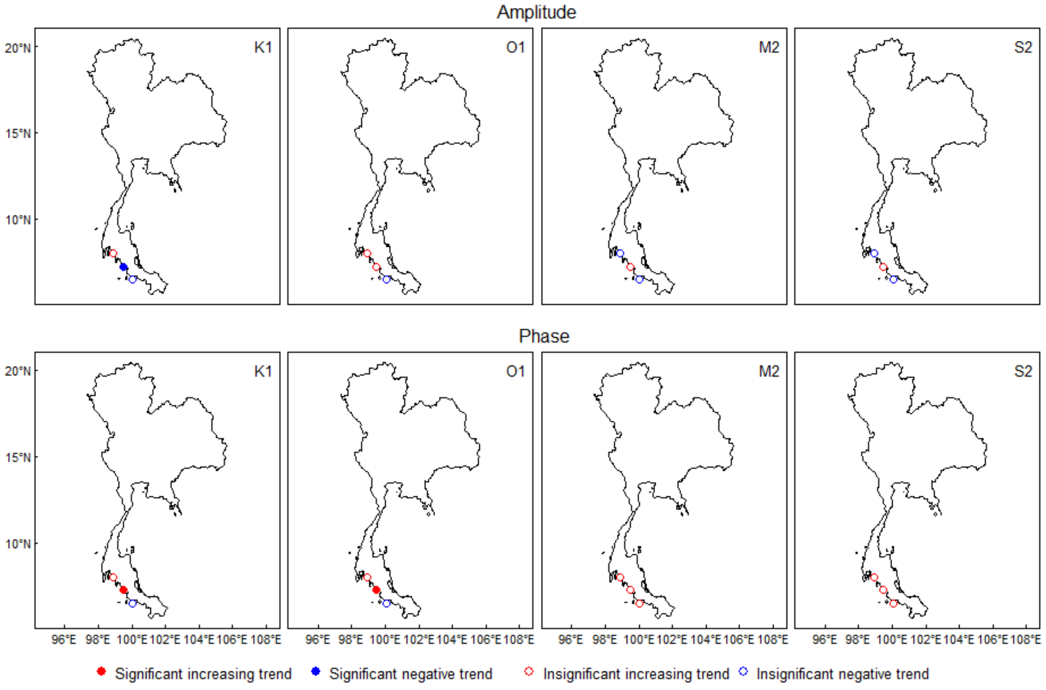

Figure 4.17 Summary of amplitude and phase of four main tidal constituents for stations along Andaman Sea.

Chapter 5

Discussions and Conclusions

5.1 Summary and Discussions

Hourly sea level data along the Gulf of Thailand and the Andaman Sea was obtained from the Marine Department of Thailand. The data were used to study extreme water level variability, long-term changes in tidal levels, tidal range and main tidal constituents. The hourly data from the Marine Department was divided into two studies.

In the first study, data from six tidal gauge stations were analyzed. Hourly records for these stations were chosen according to specific criteria. For stations with mixed-diurnal tides, HHW, LHW, HLW, and LLW were extracted for analysis, while for the stations with semi-diurnal tides the HWS, HWN, LWN, and LWS were selected for analysis. The periodic regression model was used to estimate long-term changes in the trends of each water level while accounting for the effects of lunar phases and the sun’s gravitational pull. The findings revealed that diurnal tides at ThaChaleap had positive MHHW and MLLW trends. Semi-diurnal tides at the Kantang and Krabi stations were positive for all water levels, while MLWN trends were positive at the Tammalang station. The detailed variability of extreme water levels and the causes of long-term trends were assessed using percentile and harmonic analyses.

In the second study, the stations were selected using standard criteria different from the first study. To account for the effects of 18.6-year lunar-nodal cycle, the hour water level records from each station was required to span at least 19 consecutive years. Fourteen stations were analyzed in the second study.

Percentile analysis was used to investigate the variability of extreme water levels and long-term changes in their frequency distribution. The findings revealed that the height of water levels in the upper Gulf of Thailand was higher and varied more than in the lower Gulf of Thailand. The water levels in the Andaman Sea were more stable than the Gulf of Thailand. At most of the stations, lower water level percentile series appeared to have risen faster than MSL, especially in the upper gulf of Thailand. Such findings are important on the effects of rising sea levels on coastal areas

(Woodworth et al., 2003). If changes in extreme water levels are influenced by different physicodynamics than the changes in MSL, then there could be large uncertainties in the occurrence of extreme water levels than MSL. Long-term trends in water levels can arise from changes in their different components: MSL, tides and non-tidal residuals. The tides are affected by each of these changes. Percentile analysis revealed that most water levels in the upper Gulf of Thailand showed significant long-term changes, which arise from MSL rise and long-term trends occurring in the tidal component and non-tidal residuals.

Harmonic analysis and linear regression model were applied to determine the secular trends in tidal levels, tidal range, and main tidal constituents. The results from harmonic analysis showed secular trends in all tidal levels caused by changes in the four main tidal constituents (M2, S2, O1, and K1), except the Sichon, Tammalang, and Kabi stations, which showed no significant trends in both amplitude and phase. At all stations along the coast, the MHHW, MLHW, GDTR, and MSL showed a generally increasing trend. At the same time, there were no significant trends for all tidal levels, tidal range and MSL at LangSuan and Tammalang stations. These rising patterns are in line with the trends observed throughout the Southeast Asia region (Mawsdley et al., 2015). The highest trends in all tidal levels and the MSL can be seen at three stations in upper Gulf of Thailand (ThaChalaep, Samut Sakhon, and Samut Songkhram stations). The amplitudes of K1 and O1 show trends consistent with tidal levels and MSL at the same locations (significant increasing trend). Findings from Saramul and Ezer (2014a) also showed that stations in the upper Gulf of Thailand had higher increasing trends of MSL than other locations, which was attributed to land subsidence. MSL interannual deviations were higher in the upper Gulf of Thailand, similar to findings from Sojisuporn et al. (2013). The South China continental shelf is a major source of water in the upper Gulf of Thailand. Hence, water levels and heights are likely to be higher and more varied than at other parts in the Gulf of Thailand (Aungsakul et al., 2007).

The tidal range determines extreme sea levels in addition to changes in MSL. Hence tidal range increases the flood risk when MSL rises. Three types of tidal range changes can be found along the Gulf of Thailand and Andaman Sea. These three types of change are increases in tidal range which amplify flood risk, no change in tidal range and decreases in tidal range which reduces the flood risk. Increases in tidal range were found along the Gulf of Thailand for all station and only Tammalang station in the Andaman Sea. However, LaemNgop, BanLaem, LangSuan, Sichon and Tammalang stations found very small increases in tidal range (it’s seemed to be no change in tidal range). In contrast, Kantrang and Krabi stations showed decreases in tidal range.

Many factors could have contributed to the changes in tidal levels and tidal ranges. Changes in tidal levels and tidal ranges have been observed at many locations on a global scale, and these changes are caused by underlying large-scale location-specific oceanic processes (Mawdsley et al., 2015). While variations in MSL and ocean stratification have helped to explain tidal shifts on a global scale. Tidal changes on a local scale are caused by land reclamation, dredging, river flow, surface area and other local morphological elements, as well as other human acts of engineering, have modified coastal ebbs and flows around the world (Woodworth 2010; Hill 2016; Haigh et al., 2019). In areas where tidal changes are likely large, tidal changes must be considered into future flood risk estimates. Tidal changes should not be treated as inconsequential. Consequently, future coastal management policies should account for these tidal changes and incorporate evaluations of the impact of sea-level rise.

5.2 Conclusions

According to the findings from this study, changes in both tidal levels and MSL could instigate significant changes in water levels in coastal basins within the next century. The increase/decrease in water levels could have catastrophic consequences for coastal ecosystems and people who live along the coastlines of Andaman Sea and the Gulf of Thailand. Therefore, future coastal management policies should consider these tidal changes and include impact assessments caused by sea-level change.

5.3 Limitations

Although this study has provided insights into the long-term trends and changes in water levels, tides and MSL along the Thailand coast, there are some limitations. Firstly, data from 7 tidal gauge stations contained a lot of missing values, which could have affected the statistical power and produce biased estimates. These stations were no included in the study. Secondly, weather events such as storms and surges and human activities could affect water levels at specific locations. However, data on such non-tidal events were not available to be included in this study.

5.4 Further Research

This research studied water level variability, long-term changes in water levels, tidal levels, tidal ranges, MSL and main tidal constituents along the coast of Thailand. Also, it provided some insight on how to prevent the future damage. The changes in relative MSL and water levels could have varying effects caused by MSL, tide, or non-tidal residual effects. There is a considerable amount of evidence of record extreme levels worldwide. However, it is unclear if the increasing extremes are due to interannual, long-term MSL change or due to future non-astronomical changes such as regional climate index, river discharge, vertical land movement, storm, physical environment or human activity. Therefore, it will be very interesting to explore if the relationship of the extreme water levels is linked between the residual percentiles series and effects mentioned above.

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APPENDICES

Appendix I

Manuscript I

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Trends in Tidal Levels and Mean Sea Level in the Gulf of Thailand

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Abstract – Astronomical tides have a major impact on coastal sediment distribution, seawater levels, coastal navigation, and other coastal dynamics. Any significant change to tides could have impacts on coastal ecosystems. This study explored the hourly water level from 11 tidal gauge stations along the Gulf of Thailand over different periods using harmonic analysis. Secular trends of tidal levels, tidal range, mean sea level and tidal constituents were assessed using a linear regression model. We found changes in all the tidal levels assessed. Increasing trends were observed for almost all tidal levels and the mean sea level at all locations. At most of the locations, the trends in tidal levels were similar to the mean sea level. Widespread increasing trends were observed in relation to the tidal levels, and in most cases, the trends were consistent with the mean sea level. Analysis of the tidal harmonic constituents showed significant trends for the luni-solar diurnal constituent (K_1) at most stations. However, the magnitude of the trends in the harmonic constituents was less pronounced compared to the trends in water levels. Coastal management policies should take into account these widespread changes in tides.

Keywords – Gulf of Thailand, mean sea level, tidal constituent, tidal level, trend

1. Introduction

The water levels of coastal areas are very important as their dynamics have a large impact on fisheries, marine resource management, and coastal engineering projects (Kantha and Clayson 2000). In recent years, analysis of water levels has become vital due to the huge impact climate change is having on sea-level rise. However, such an analysis is quite complex because the water levels depend on the tides, mean sea level (MSL) and non-tidal residuals. A change in any of these components affects the variability of the water level (Rhein et al. 2013). While attempting to model the future dynamics of water levels, it is important to understand their historical trends and variability (Wahl and Chambers 2015, 2016).

There is evidence in the literature to suggest that the trends in global extreme water levels over the last century are consistent with those of the MSL. For example, Woodworth and Blackman (2004), using global tidal datasets from 141 stations, found that interannual variations of extreme water levels were consistent with those of the MSL. Similarly, increments in extreme high waters, dating back to the 1970s, were detected by Menéndez and Woodworth (2010) based on quasi-global datasets. These increments in the extreme high water levels were found to have been caused by a rise in the MSL. Also, the magnitude of tidal levels and tidal ranges have been observed to be consistent with that of the MSL at many locations around the world (Mawdsley et al. 2015). In the analysis of tidal water levels, different methods have been employed. Consistent among them are the classical harmonic analysis (Rasheed and Chua 2014; Mawdsley et al. 2015; Santamaria-Aguilar et al. 2017) and tidal percentile analysis (Woodworth and Blackman 2004; Mudersbach et al. 2013; Santamaria-Aguilar et al. 2017). Apart from the global water level and a handful of regional water level analyses that target isolated locations around Asia and Africa (Marcos et al. 2015; Mawdsley et al. 2015; Haigh et al. 2019; Devlin et al. 2018), these regions lack extensive research on extreme water levels, partly due to a lack of credible observational data (Menéndez and Woodworth 2010). One such place is Thailand, where trends and variability of long-term extreme water levels have been analyzed from a global perspective (Mawdsley et al. 2015).

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In terms of geographical location, in Thailand, the eastern region borders the Gulf of Thailand and the southern parts lie between the Andaman Sea and the Gulf of Thailand. Marine inhabitants and terrestrial ecosystems along the coastline are immediately affected by extreme events such as storms due to the northeast and southwest monsoon winds. The eastern and western coastlines of southern Thailand serve as a hub for the majority of tourist activities in Thailand. Although there have been local studies to characterize and explain the water level trends, these studies focused on the MSL, which represents just one component of the water level (Saramul and Ezer 2014; Sojisuporn et al. 2013; Trisirisatayawong et al. 2011). Time-series data on observed water levels are available for the majority of the tidal gauge stations along Thailand's coast. At these stations, the Marine Department of Thailand collects hourly water level data. The hourly time-series data from the Marine Department has not been extensively analyzed in any global or regional study.

This study explores the hourly tide-gauge datasets of 11 stations over different periods using harmonic analysis and takes into account the effects of the 18.6-year lunar-nodal cycle. We investigate the secular trends in tidal levels, tidal ranges and MSL, as well as the main tidal constituents, luni-solar declination diurnal tide (K_1), principal lunar declination diurnal tide (O_1), principal lunar semi-diurnal tide (M_2) and principal solar diurnal tide (S_2), at various stations along the Gulf of Thailand using a linear regression model. The water levels include two high water levels, two low water levels, and two tidal ranges per day.

2. Data and Methods

Water level data, which are recorded hourly by the Marine Department of Thailand (https://www.md.go.th/md/), were obtained for 16 tidal gauge stations along the Gulf of Thailand. These stations cover the eastern coast of the country. The data for each station covered different periods. Standard criteria were used to select the records for each station. First, to ensure sufficient length and data quality, a calendar year of water level records was included if at least 75% of hourly

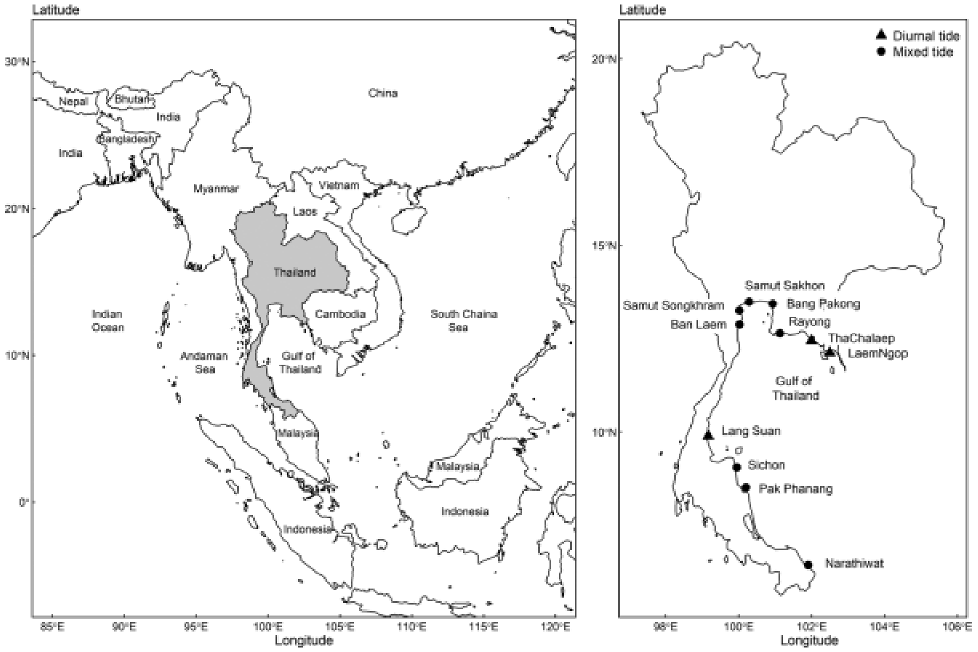

Fig. 1. Tidal gauge locations

values were present. Next, in order to account for the lunar-nodal cycle (18.61 years), the available data from each station was required to span at least 19 years. A 19-year span ensured that at least one lunar-nodal cycle is covered and the phase and amplitude of nodal modulations are appropriately approximated (Mawdsley et al. 2015; Woodworth et al. 1991). Of the 16 tidal gauge stations, 11 satisfied these inclusion criteria and were included in the analysis. The locations of these 11 stations are shown in Fig. 1. The data span for each station, as well as the length of available water level records, was different. The Samut Sakhon station had the highest data span of 40 years (1978–2017), with 35 years of the data available for analysis. The span and data availability (in years) for the 11 stations is shown in Fig. 2, with gaps representing years with less than 75% of data available. The hourly water levels for each of the 11 stations were detrended to remove the MSL effects. Instead of an annual mean, detrending was done by subtracting a 30-day centered moving average of each hourly record from the time-series (Carlberg 2015). The 30-day moving average is used to remove seasonal variations, time-scale signals related to land movement, and seasonal cycles caused mainly by oceanographic factors (Mawdsley et al. 2015). Although the 30-day signals could affect the solar monthly (MSm) and lunar monthly (Mm) constituents, these constituents reflect more meteorological aspects than tidal energy, and therefore, have minimal effects on the reconstructed tidal levels (Crawford 1982).

The detrended time series records for each station were separated into calendar years, and a harmonic analysis was done for each year of records to separate the astronomical tides and non-tidal residuals. The harmonic analysis was done using the *ftide* function from the TideHarmonics package in R (Stephenson 2016). The function estimates tidal harmonic constituents from observed water level records. Incorporated in the function are selectable tidal harmonics and other options which account for lunar-nodal cycles. The function also allows for gaps in the water level observation, but missing values in the date/time are not allowed. The harmonic analysis was performed using a standard set of 60 constituents. Amplitudes and phase lag obtained from the harmonic analysis were used to re-construct tidal contributions to the water levels for each calendar year.

Tidal levels and tide ranges were calculated based on the site classification (semi-diurnal, diurnal, or mixed). Four of

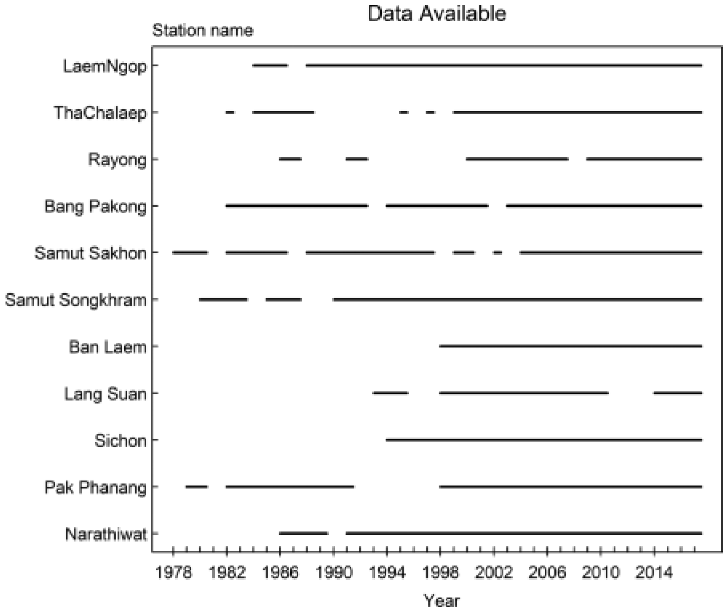

Fig. 2. Data span and data availability for each year of the 11 stations

the eleven stations (LaemNgop, ThaChalaep, Rayong, and Lang Suan) had predominantly diurnal tides, with one high and one low tide per day. The remaining stations had mixed tides, with two unequal high and two unequal low tides per day. Tidal levels were calculated based on the amplitudes of tidal constituents from the harmonic analysis (Stephenson 2016). For stations with diurnal and mixed tides, the standard tidal levels calculated include:

Mean Sea Level (MSL) $= Z$
Mean Higher High Water (MHHW) $= Z + (M_2 + K_1 + O_1)$
Mean Lower High Water (MLHW) $= Z + |M_2 - (K_1 + O_1)|$
Mean Higher Low Water (MHLW) $= Z - |M_2 - (K_1 + O_1)|$
Mean Lower Low Water (MLLW) $= Z - (M_2 + K_1 + O_1)$.

Z was estimated as the normal mean based on the number of observations available for each calendar year. Tidal ranges were estimated as shown below.

Greater Diurnal Tidal Range (GDTR) = MHHW − MLLW
Lesser Diurnal Tidal Range (LDTR) = MLHW − MHLW.

These tidal water levels were calculated for each year, and a linear regression model was used to assess the trends over the study period. Significant trends were identified based on the p-value from the linear model, assessing a null hypothesis that the slope of the fitted line was equal to zero, using a critical value (alpha) of 0.05. Trends with a p-value less than alpha were considered statistically significant. The changes in the main tidal constituents K_1, O_1, M_2 and S_2 were examined.

3. Results

Results from the tidal analysis reveal that there were changes in the tidal water levels at all 11 stations. While most of the observed changes in tidal levels and tidal ranges were significant, some of them were not. For example, the observed trends of MHHW were significant for all stations (p-value < 0.05) except at Lang Suan, and the trends of MLLW were significant for all stations except the Lang Suan, Pak Phanang and Narathiwat stations (p-value > 0.05) as shown in Table 1. The Rayong, Lang Suan, and Pak Phanang stations also had non-significant trends of MSL. The trends of six tidal levels and the MSL of selected stations are shown in Fig. 3. due to increases in annual MHHW and MLLW at most of the stations. The trends of GDTR were not significant for LaemNgop, Ban Laem, and Lang Suan stations. The increasing trend of GDTR was more pronounced at Narathiwat (11.36 mm/yr) and Rayong stations (10.23 mm/yr). In Narathiwat, high GDTR arises from the opposite trends of MHHW (10.74 mm/yr) and MLLW (-0.61 mm/yr). Similar to Narathiwat station, Rayong station also had increasing trends of MHHW (6.63 mm/yr) and decreasing trends of MLLW (-3.56 mm/yr). The stations with the lowest decreasing trends in GDTR were Lang Suan and Sichon. The trends of both MHHW and MLLW at Lang Suan were increasing, although non-significant, and these resulted in a non-significant increasing trend of 0.68 mm/yr for GDTR. However, the trend of GDTR (1.70 mm/yr) at Sichon was significantly positive, and the changes of MHHW and MLLW were also significant (6.64 mm/yr and 4.94 mm/yr, respectively). Although the highest increase of MHHW was observed at Samut Sakhon station, a corresponding trend of GDTR was relatively low compared to Narathiwat station. The trends of each tidal water level and MSL for each station are shown in Table 1. For all stations, trends in MSL and GDTR were similar, although the magnitude of the trends was different. The Samut Sakhon tidal gauge station recorded

Table 1. Trends in tidal levels and tide ranges (mm/yr) at 11 tidal gauge stations along the Gulf of Thailand

Station	MHHW	MLHW	MHLW	MLLW	GDTR	LDTR	MSL
Laem Ngop	4.037 ± 0.655*	3.289 ± 0.562*	3.182 ± 0.545*	2.434 ± 0.676*	1.604 ± 0.844	0.107 ± 0.407	3.236 ± 0.515*
Tha Chalaep	18.160 ± 2.389*	17.156 ± 2.281*	11.602 ± 2.177*	10.598 ± 2.215*	7.563 ± 2.059*	5.554 ± 1.702*	14.379 ± 2.06*
Rayong	6.632 ± 0.905*	3.897 ± 0.917*	-0.863 ± 1.22	-3.598 ± 1.409*	10.23 ± 1.227*	4.760 ± 0.746*	1.517 ± 1.013
Bang Pakong	6.732 ± 0.989*	4.921 ± 0.97*	4.770 ± 0.894*	2.958 ± 0.935*	3.774 ± 0.871*	0.151 ± 0.730	4.845 ± 0.858*
Samut Sakhon	21.832 ± 0.797*	18.194 ± 0.88*	19.140 ± 0.760*	15.502 ± 0.936*	6.330 ± 0.971*	-0.946 ± 0.790	18.667 ± 0.721*
Samut Songkhram	18.072 ± 1.036*	14.711 ± 0.856*	14.161 ± 0.963*	10.799 ± 0.823*	7.272 ± 0.807*	0.550 ± 0.685	14.436 ± 0.844*
Ban Laem	7.591 ± 2.006*	7.205 ± 1.608*	5.829 ± 1.682*	5.443 ± 1.283*	2.148 ± 1.580	1.376 ± 1.409	6.517 ± 1.487*
Lang Suan	3.520 ± 1.698	3.585 ± 1.753	2.770 ± 1.888	2.836 ± 2.031	0.684 ± 1.087	0.815 ± 0.666	3.178 ± 1.791
Sichon	6.644 ± 1.598*	5.937 ± 1.693*	5.651 ± 1.595*	4.944 ± 1.749*	1.701 ± 0.689*	0.286 ± 0.260	5.794 ± 1.640*
Pak Phanang	8.544 ± 2.327*	4.257 ± 2.418	4.362 ± 2.453	0.075 ± 2.610	8.469 ± 0.89*	-0.105 ± 0.268	4.309 ± 2.432
Narathiwat	10.744 ± 0.969*	5.550 ± 0.984*	4.582 ± 1.156*	-0.612 ± 1.857	11.356 ± 2.15*	0.968 ± 0.674	5.066 ± 1.019*

*Significance level of 0.05

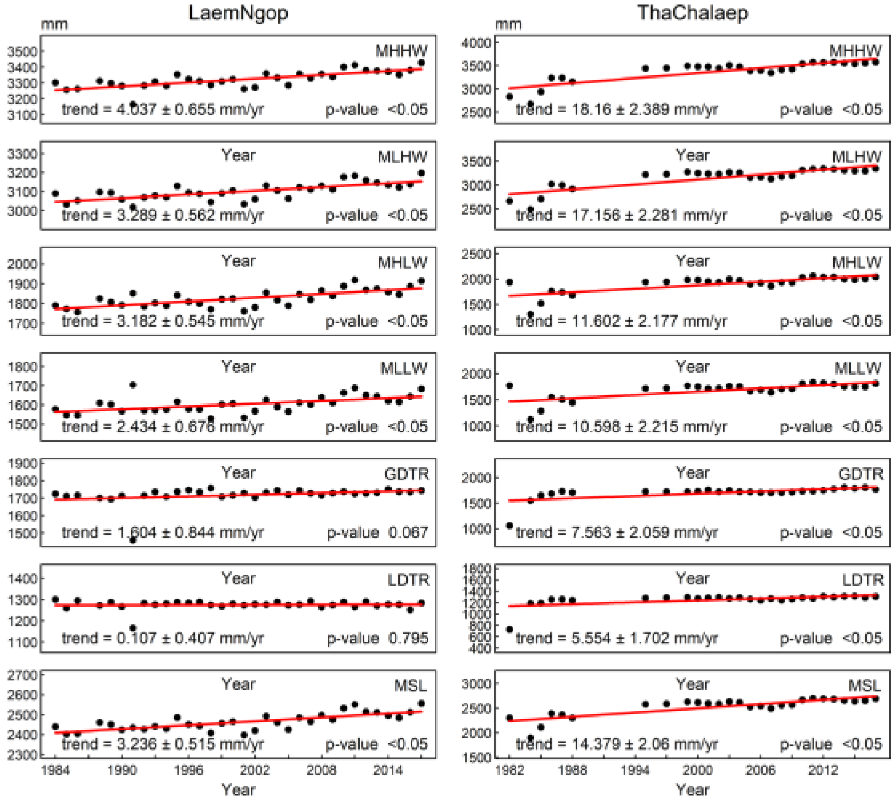

Fig. 3. Trends of six tidal levels and mean sea level for LaemNgop and ThaChalaep stations

the highest increasing trend of MSL (18.67 mm/yr), while the lowest increasing trend was observed at LaemNgop station (3.24 mm/yr). Although the trends of MSL were lowest for Rayong and Lang Suan stations, they were not significant.

The trends of LDTR found were similar to the trends of GDTR, except at Samut Sakhon and Pak Phanang stations where the trends of LDTR were negative. However, unlike GDTR, the magnitude of LDTR trends was generally lower. The only station where the LDTR trend was higher than the GDTR trend was Lang Suan. Apart from ThaChalaep and Rayong stations, the LDTR trends were not significant for the remaining nine stations. The magnitude of the increasing trends of LDTR was 5.55 mm/yr for ThaChalaep station and 4.76 mm/yr for Rayong station. The MHLW and MLHW in Rayong station revealed opposite trends, with the former decreasing (-0.86 mm/yr) and the latter increasing at a magnitude of 3.90 mm/yr. The maps shown in Fig. 4 indicate the summary of the trends of tidal levels, tidal ranges and MSL at all stations. The K_1 constituent showed significant trends in amplitude at seven of the eleven stations. The trends in the amplitude of the K_1 constituent were not statistically significant at LaemNgop, Lang Suan, Sichon and Pak Phanang stations. At ThaChaleap and Rayong the amplitudes exceeded 2 mm/yr, while that of Narathiwat was -1.84 mm/yr. The trends of O_2 and M_2 amplitudes revealed significant increases at Rayong, Bang Pakong, and Samut Songkhram stations. No significant decreases were found in the amplitudes of O_2 and M_2 at any of the stations. For the amplitude of the S_2

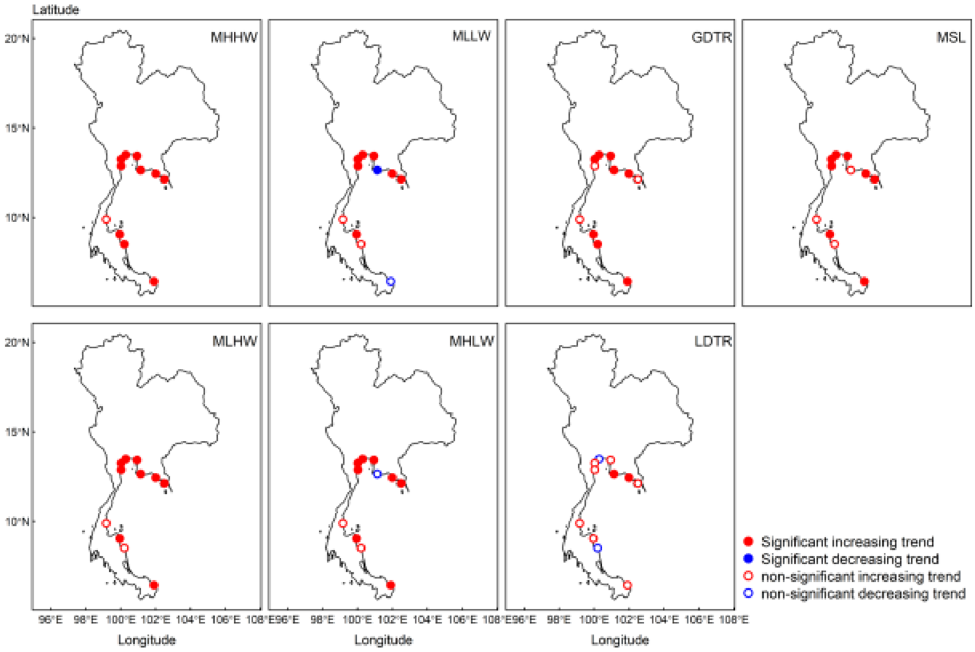

Fig. 4. Trends of tidal levels, tidal ranges and mean sea level

constituent, three stations (ThaChalaep, Samut Sakhon and Samut Songkhram) had significantly decreasing trends between 0.84 mm/yr and 0.30 mm/yr while an increasing trend in magnitude of 1.44 mm/yr was observed at the Lang Suan station. The trends in amplitudes of tidal constituents are shown in the table below. For the diurnal constituents, a significantly increasing trend was found for the O_1 constituent at Narathiwat station and an opposite trend was found for the K_1 constituent at

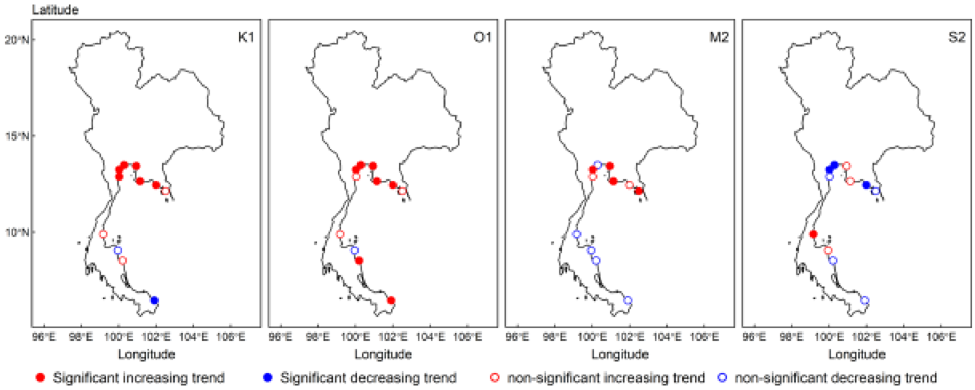

Fig. 5. Trends of amplitude

Table 2. Amplitudes of the tidal constituents

Station	Amplitude			
	K_1	O_1	M_2	S_2
LaemNgop	0.021 ± 0.073	0.395 ± 0.280	0.374 ± 0.130*	-0.188 ± 0.094
ThaChalaep	2.004 ± 0.739*	0.948 ± 0.302*	0.210 ± 0.165	-0.836 ± 0.229*
Rayong	2.106 ± 0.249*	1.641 ± 0.254*	1.364 ± 0.165*	0.132 ± 0.147
Bang Pakong	0.592 ± 0.097*	0.906 ± 0.378*	1.228 ± 0.323*	0.007 ± 0.099
Samut Sakhon	0.638 ± 0.119*	1.819 ± 0.391*	-0.314 ± 0.253	-0.394 ± 0.143*
Samut Songkhram	1.047 ± 0.097*	1.681 ± 0.340*	0.878 ± 0.256*	-0.301 ± 0.105*
Ban Laem	0.494 ± 0.222*	0.193 ± 0.676	0.905 ± 0.778	-0.940 ± 0.488
Lang Suan	0.222 ± 0.203	0.330 ± 0.613	-0.141 ± 0.158	1.447 ± 0.439*
Sichon	-0.112 ± 0.375	-0.063 ± 0.821	-0.042 ± 0.133	0.469 ± 0.498
Pak Phanang	0.295 ± 0.783	1.151 ± 0.162*	-0.436 ± 0.315	-0.099 ± 0.112
Narathiwat	-1.838 ± 0.626*	2.239 ± 0.412*	-0.287 ± 0.220	-0.151 ± 0.178

*Significance level of 0.05

Samut Sakhon station. The summary of trends of amplitudes of the four main tidal constituents are shown in Fig. 5.

4. Discussion and Conclusion

Changes in the MSL, astronomical tides, and non-tidal residuals can cause significant long-term changes in water level. This study has presented long-term trends of astronomical tides and MSL along the Gulf of Thailand, based on trends of tidal levels, tidal ranges and tidal constituents at 11 tidal gauge stations. Although local studies have been conducted on the water level trends in Thailand, most of them focused on either harmonic constituents or MSL; none of them went beyond the MSL to emphasize the changes in the mean levels of astronomical tides origin. The harmonic and linear regression analyses from this study show that long-term changes have occurred not just in the MSL but also in the tidal levels and tidal ranges, as well as the underlying harmonic constituents at each station.

Generally, long-term increasing trends were observed in the tidal levels, mainly due to increases found in the amplitudes of the main diurnal constituents K_1 and O_1. The MHHW, MLHW, GDTR and MSL present general increasing trends at all stations along the coast. These patterns are consistent with the trends observed throughout South-east Asia (Mawsdley et al. 2015). Three stations in the upper Gulf of Thailand (ThaChalaep, Samut Sakhon and Samut Songkhram) illustrate the highest trends in all tidal levels and the MSL. At the same stations, the amplitudes of K_1 and O_1 show trends consistent with the tidal levels and MSL. Another study by Saramul and Ezer (2014) also found higher increasing trends of MSL at stations in the upper Gulf of Thailand compared to other locations, which was attributed to land subsidence. An analysis from Sojisuporn et al. (2013) also showed that the inter-annual deviations of MSL were higher at the upper Gulf of Thailand. A major source of water in the upper Gulf of Thailand is the South China continental shelf. Hence, water heights and sea levels are likely to be higher and more varied than at other parts of the Gulf of Thailand (Aungsakul et al. 2007).

The MSL trends observed in this study with tidal gauge data could be different if compared the estimate with satellite altimetry data. Such differences can be explained by annual and decadal variations such as the El Nino Southern Oscillation (ENSO) and regional vertical co-seismic displacements (Trisirisatayawong et al. 2011). The changes in tidal levels and ranges could have been caused by other factors as well. For instance, on a global scale, changes in tidal levels and tidal ranges have been observed at different locations, and these changes are caused by underlying large scale location-specific oceanic processes (Mawdsley et al. 2015). While changes in MSL and ocean stratification have helped explain tidal changes on a global scale, tidal changes on a local scale are caused by land reclamation, dredging, river flow, surface area and other local morphological factors (Woodworth 2010; Hill 2016; Haigh et al. 2019).

Although this study did not attempt to establish a relationship between tidal levels and MSL, the presence of any relationship between them could be positive or negative (Haigh et al. 2019). The correlation between MSL and tidal levels are determined by several mechanisms, including the movement of constituent amphidromic points (Mawdsley et al. 2015;

Jay 2009). Coherent increases were found in the K_1 and M_2 amplitudes, which could be due to shifts in diurnal and semi-diurnal amphidromic regions (Qi-Zhou et al. 1994; Yanagi and Takao 1998; Jay 2009). The present analysis suggests that there could be a significant increase/decrease in water levels at the coastal basin within the next century as a response to changes in both tidal levels and MSL. These significant changes could be catastrophic for coastal inhabitants and coastal ecosystems along the Gulf of Thailand. Consequently, future coastal management policies should take into account these tidal changes and include impact assessments caused by sea-level change.

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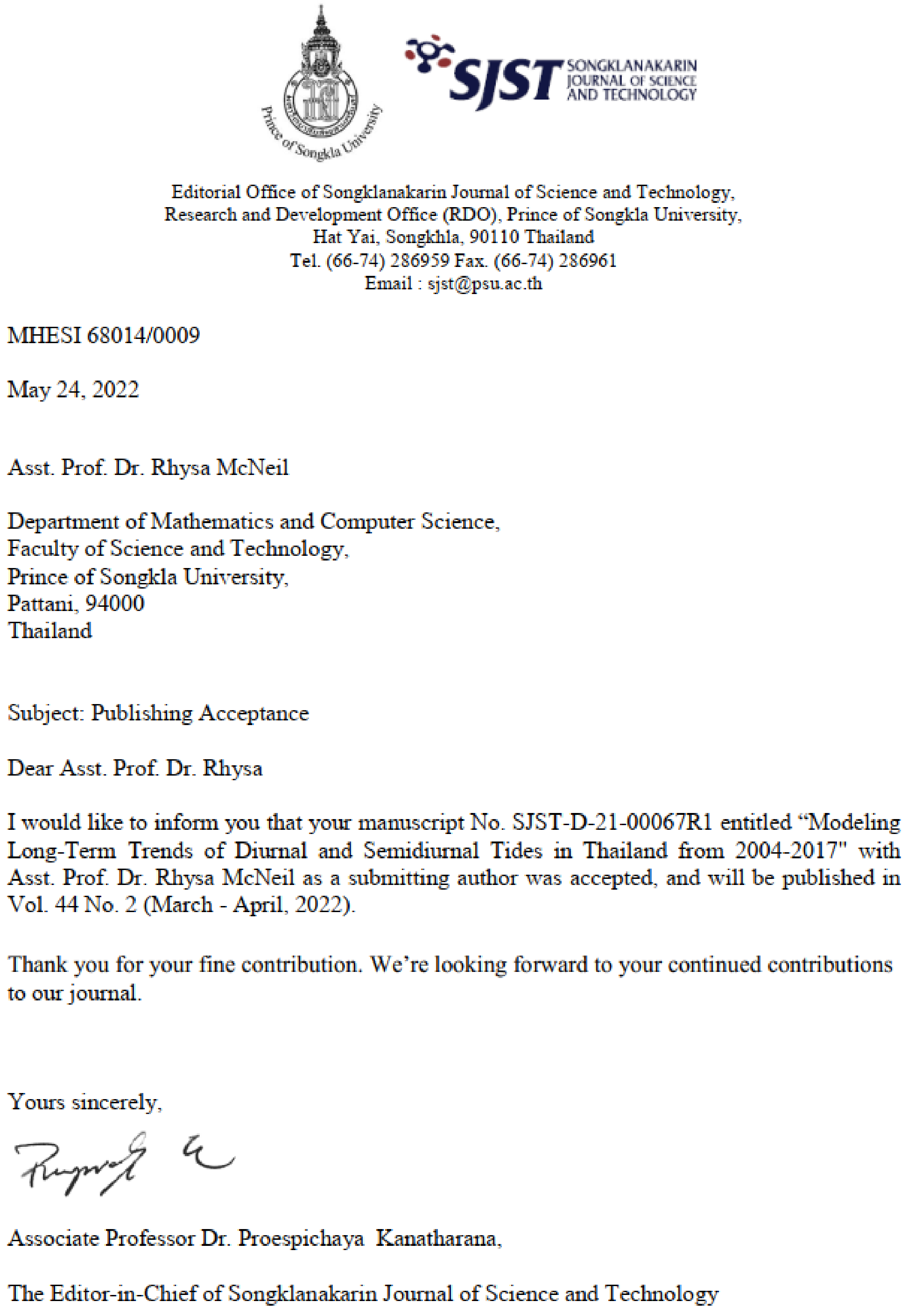
Appendix II

Manuscript II



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May 24, 2022

Asst. Prof. Dr. Rhysa McNeil

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Thailand

Subject: Publishing Acceptance

Dear Asst. Prof. Dr. Rhysa

I would like to inform you that your manuscript No. SJST-D-21-00067R1 entitled “Modeling Long-Term Trends of Diurnal and Semidiurnal Tides in Thailand from 2004-2017" with Asst. Prof. Dr. Rhysa McNeil as a submitting author was accepted, and will be published in Vol. 44 No. 2 (March - April, 2022).

Thank you for your fine contribution. We’re looking forward to your continued contributions to our journal.

Yours sincerely,

Associate Professor Dr. Proespichaya Kanatharana,

The Editor-in-Chief of Songklanakarin Journal of Science and Technology

APPENDIX III

Conference

Mean Sea Level and Variability of Water Levels and Tides in the Gulf of Thailand

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Abstract: The eastern southern part of Thailand is bordered by the Gulf of Thailand. Sea level variability has been reported to have negative effects along the coastline. The causes extreme water level changes are mean sea level, tides of astronomical origin and non-tide residuals such as storm or climate change. This study aimed to investigate historical trends and variability of extreme water levels along the Gulf of Thailand by using hourly data from 11 different tidal gauge stations at different periods, and applying percentile analysis. Results from the analysis show that at LaemNgop, ThaChalaep, BangpaKong, SamutSakhon, SamutSongkhram, BanLaem, Sichon and Naratiwat stations had an increasing trend in water level. For LaemNgop, ThaChalaep and Narathiwat stations low water levels (<50 percentile) had risen faster than mean sea level (50 percentile). However, there is no significant difference between the high-water level (> 50 percentile) at LaemNgop and ThaChalaep stations. The percentile analysis suggests that the greater trend in low water levels is mainly caused by tide components.

Keywords: Gulf of Thailand; mean sea level; variability of extreme water levels

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PRINCE OF SONGKLA UNIVERSITY

IMT-GT

International Statistical Institute

CERTIFICATE

AWARDED TO

NITINUN PONGSIRI

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ON MATHEMATICS, STATISTICS AND THEIR APPLICATIONS

HELD FROM 13 - 14 DECEMBER 2021
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1. Research Assistantship (RA) Scholarship Supported by Centre of Excellence in Mathematics (CEM), Commission on Higher Education, Thailand.
2. Faculty of Science and Technology, Pattani campus, Pattani, Thailand.

Conference and Proceeding

Publications

Pongsiri, N., McNeil, R., and Chuai-Aree, S. 2021. Modeling Long-Term Trends of Diurnal and Semidiurnal Tides in Thailand from 2004-2017. Songklanakarin Journal of Science and Technology, Manuscript ID: SJST-D-21-00067R1.

Pongsiri, N., McNeil, R., and Chuai-Aree, S. 2020. Trends in Tidal Levels and Mean Sea Level in the Gulf of Thailand. Ocean Science Journal, 55(4), 495-503.

Conference

Pongsiri, N., McNeil, R., Chuai-Aree1, R. and Owusu, B.O. 2021. Mean Sea Level and Variability of Water Levels and Tides in the Gulf of Thailand. The 17th IMT-GT International Conference on Mathematics, Statistics and Their Applications (ICMSA2021), Department of Mathematics and Computer Science, Faculty of Science and Technology, Prince of Songkla Univerisity, Pattani canpus, Pattani, Thailand, 13-14 December. (Oral Presentation)