2019

STORM SURGE ANALYSIS DUE TO HIGH WATER EVENTS AND SEA LEVEL RISE IMPACT

(Kelantan - Negeri Sembilan - Malacca)

COASTAL AND OCEANOGRAPHY RESEARCH CENTRE,
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PREFACE

A challenging topic in coastal inundation research is the accurate prediction of sea surface elevation and wave heights. This is highly relevant over the shallow continental shelf especially for the coasts facing the South China Sea and Straits of Malacca. Sea level rise and storm surge raise various degrees of implications socially and economically to coastal community resides in Kelantan, Negeri Sembilan and Malacca. The implication mostly associated with coastal erosion and coastal flooding due to breached of coastal protection structures or an erosion of a natural beach dunes, apart from anthropogenic inclined causes.

The information gathered is significant especially for coastal development planning, risk evaluation on flooding and evacuation inclusive of the structural integrity and vulnerability. Thus, we look at the possibilities of flood intrusion along the coast of study via hydrodynamic model results in each projection years, followed by the beach dune sustainability and coastal structures integrity under design aspects to face the change in climate impact. From there on, a storm surge risk levels are assigned into different categories where the risk assessment integrates the inundation hazard and the coastal structure vulnerability as the main indicator, in the zone of study.

A statistically correct approach to the inclusion of storm tide inputs to hydraulic design is not yet available or if pioneered is still not matured to an applicable stage. Thus this report provides relevant information on the incorporation of sea level rise, storm surge, and waves into the planning and design of bund, infrastructures, defence structures in coastal regions of Kelantan, Negeri Sembilan and Malacca coast. Also, it is prepared as a guide to give some practical‖ advice that will allow a reasonable and consistent assessment approach.

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EXECUTIVE SUMMARY

Being a country with almost all of it coastline is subjected to extreme marine climate conditions especially during monsoon periods, Malaysia is vulnerable to high waves and storm surges. There are two terms that need to be understood clearly when discussing storm surge which are storm surge and storm tide. Storm surge is the abnormal rise in level above normal water surface level generated by a storm, that is the difference between astronomical tidal level and the level recorded. It is therefore not an absolute water level, but a difference between expected water level and the level that actually occurs. Meanwhile, storm tide is the water level produced by the combined action of storm surge and astronomical tides. It is therefore an absolute water level as recorded.

This report describes the development of storm surge risk evaluation with particular recurrence intervals along Kelantan, Negeri Sembilan and Malacca coasts. The analysis is based on sea level rise projection by year 2020, 2040, 2060, 2080 and 2100 using the statistical combination of storm surge and tidal information. Some aspects of the storm surge responses on the northern and southern coast of study sites are also considered since they are important for an overall assessment on neighbouring spatial impact. These evaluations provide a basis for the investigation of the possible repercussions of future climate change due to sea level rise and changes in weather conditions.

In general, the analysis of more than 25 year's sea-level data in East Coast and West Coast of Peninsular Malaysia indicates that storm surges occur year round, but in various magnitudes. In west coast, the variation of surges is much smaller and normally acknowledged as tide residual. In east coast, the surge magnitudes can reach up to a metre, and is more common in Northeast monsoon. About 75% of the surge belonged to above 0.5 m height category and the trends of higher surge is increasing parallel with the change in marine climate conditions globally.

The peak surge throughout the 32-years tide level data in Geting, Kelantan recorded a surge height in a range from as low as 0.35 m up to almost 1.0 m in height. The surge height shown a decreasing trend in the first 17 years and later starts to increase steadily from year 2002 onwards. Meanwhile, the trend in Tg. Keling tide station residuals (for Negeri Sembilan and Malacca coast) shown an increasing pattern of surge height with residual heights recorded a level of above 0.37 m.

In Kelantan, five locations along the study area are selected for sea bed profile extraction via the model bathymetry to investigate the SLR impact while six profile in Negeri Sembilan and Malacca are selected. The calculated Design Water Level (DWL) for year 2100 SLR and 25yr RP storm surge is plotted for each profile to identify whether the selected coastal area is prone to inundation. Calculation on the PVI at each profile indicated a variety of risk level, from Moderate to Very Low risk of inundation.

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CHAPTER 1.0 GENERAL CONSIDERATIONS

1.1 Introduction

When people hear about typhoons, most will immediately think of an extraordinary strong wind, although the incident was nowhere near our coasts. Even if it is, most will correlate the events as typical monsoon winds rather than caused by other extreme climate effects, far less from storm surge. Whilst in other coastal regions such as in Europe, US, Philippines or even Vietnam, the so called 'a wall of water' or *storm surge* brought by strong winds are responsible for nearly 90% of fatalities. Hence, being in the neighbourhood with Thailand and Vietnam, the possibility is present, though the severity is debateable plus the answer is uncertain, still, how serious is serious.

Well, we are surrounded by waters, open sea is more like it and always subjected to northeaster winds blowing from the South China Sea for the east coast of Peninsular Malaysia and the southwester winds for the west coast facing the Strait of Malacca. However, typically, most citizen of Malaysia is not familiar with the climate term of 'storm surge', which the word surge itself is a typical, and more, lesser has experience it if you are a city dweller, even highly unlikely if you are among the coastal populace, perchance, to disintegrate or recognize it when facing the real events. Often than not, waves are always mistaken as the culprit in all extreme events that accompanied a destruction when the monsoon winds lash out the coast. Rarer still for a normal citizen to acknowledge it as a combination of two climate forces instead of one, between waves and storm surge or coupled, that brought a whole new level of catastrophe to the destruction of a coastal protection structures or washed away beaches.

Alas, with or without monsoon winds, storm surge is what we face today and will definitely redefine our future generation course of life unless we take measures to acknowledge its' impact, understand the origins, formations and evolution to better plan for flood risk management and mitigation. In fact, the phase of research on storm surge progressing today may need to be quickened in order to catch up with the effect of sea level rise on storm surge where destruction will likely to be doubled up quicker than we think possible. Many of the global researchers agreed with the assumptions and a lot more has proven the statement above. Still, there is a considerable uncertainty in predicting trends in extreme storms that caused the surge conditions 100 years into the future.

This report describes the development of storm surge risk evaluation with particular recurrence intervals along the study sites; Kelantan, Negeri Sembilan and Malacca coasts respectively, under sea level rise projection year 2020, 2040, 2060, 2080 and 2100 using the statistical combination of storm surge and tidal information. Some aspects of the storm surge responses on the northern and southern coast of both study sites are also considered since they are important for an overall assessment on neighbouring spatial impact. These evaluations provide a basis for the investigation of the possible repercussions of future climate change due to sea level rise and changes in weather conditions and will provide information for subsequent coastal protection structure design referral along the coast of interest.

The remainder of this report is structured as follows. The following Chapter 2 describes the nature of storm surges, impacts and the weather conditions most commonly responsible for the surge elevations. Chapter 3 describes the analysis and statistical approach used in this study and discuss future storm surge scenarios and level of risks resulted from the combined effect of surge and various sea level rise projections. Conclusions are summarised in Chapter 4.

Approach

This report pulls from and links together existing standards and documents and incorporates additional appropriate documents and reference material. The document provides a series of technical references with summary level synthesis to link them together and facilitate their use. The references include elements of bathymetry, topography, tide level and storm surge measurements, mapping, assessment, and the impacts of storm surge trends and change.

Key Questions

The discussion is structured around the key questions to address the required technical considerations:

- What is storm surge and how is it measured.
- What causes storm surge.
- What are the contributing factors.
- How can we protect against storm surges.
- How can users understand and apply storm surge data and information to support sea level rise mapping and assessment and aid in coastal decision making.
- What are the limitations and gaps with respect to storm surge measurement, and what are the implications of those gaps.

CHAPTER 2.0 BACKGROUND

The purpose of this chapter is to provide fundamental background in understanding storm surge catastrophic events, appropriate terminology for describing storm surge variations, causes and effects, and the climates that spawned the surge height itself. Some considerations of accuracy are also included to lay the foundation for subsequent chapters.

Design water levels vary with geo-location due to variance in cross-shore topographical and physical forcing. Astronomical tides cause sea level variations on a daily basis (high and low tides) within spring and neap tide periods. Whilst low pressure and strong winds associated with severe weather events that cause abnormal water level fluctuations, known as storm surge. Though wind waves can also contribute to extra elevation in design water level through wave setup and wave runup, these processes are considered as a generic input based on previous simulation works near the area of interest. This chapter discusses the meteorological contributions to storm surges, which are identified as the cause from extreme wind forcing and low atmospheric pressure on the surface of the ocean.

2.1 Definition of Storm Surge

A storm surge is often defined as the difference between the observed water level and that which would have occurred at the same place and time in the absence of a storm. It should be noted that this skew surge can be negative as well as positive, though of course only the positive that creates a flooding problem. It is rarely a "wall of water" as often claimed, but rather a rise of water that can be as rapid as several centimetres in just a few minutes.

Storm surge is a potentially devastating rise in the coastal water levels caused by tropical cyclones such as typhoons. Low-lying coastal area and the populace that resides along its' coast and beyond a 100 km from the ocean are susceptible to the consequences of the storm surge. With the global sea level rise between 26 and 63 cm and still counting, IPCC AR5 estimated the rise will threaten to extend the zone of storm surge impact farther inland and abound their associated damage even more (IPCC, 2019).

In very general terms, a storm surge is induced by low pressure weather system. This allows the sea-level to rise through barometric surface, known as 'wind set-up'. The water level rises where the winds are strongest. In addition, water is pushed in the direction the winds are blowing. Once the typhoons reached shallower waters near the coast, the vertical circulation in the ocean becomes disrupted by the ocean bottom, the water can no longer go down, so it has nowhere else to go but up and inland. Locally important factors such as Coriolis current, coastal geometry in plan and in section, and resonance must also be noted.

Knowing that tropical cyclone or typhoon is the major driver for storm surge formation, the resultant surge height is mostly significant to typhoon-prone areas such that in Philippines, Vietnam, Taiwan, East China and Japan. Where the long fetch length of the ocean surrounding or fronting their coastal areas are a wide plane of warm water surface that could easily generate a storm. Alas, west and east coast of Peninsular Malaysia with a fetch length of less than 100 km to 500 km in the Strait of Malacca and offshore east coast, respectively, is often misconstrued as not sufficiently wide and suitable to inject acceptable climate and marine characteristics to initiate any form of typhoon, unless the marine weather characteristics meet the criteria to spawn a typhoon, i.e. Typhoon Gay being so close to Kelantan shore at a distance less than 160 km in 1989 has resulted in 0.52 m surge height in Geting, Kelantan, and more than 0.4 m in height along Terengganu and Pahang coasts inclusive Tioman Island. Further offshore in other case in year 2006, Super Typhoon Durian generated almost 700 km offshore from east coast of PM resulted in more than 0.45 m surge in Geting, Kelantan, 0.54 m, 0.58 m and 0.52 m in Chendering, Terengganu, Tg. Gelang and Tioman Island in Pahang, respectively. Otherwise, the major collective of the highest storm surge may likely a result from an impinged effect of strong Northeast Monsoon (NE) winds, but yet to be proven.

2.2 Tropical Cyclones

Tropical cyclone, also called typhoon or hurricane, is an intense circular storm that originates over warm tropical oceans and is characterized by low atmospheric pressure, high winds, and heavy rain. Tropical Cyclones (TC) with lower air-pressure zones allow the ocean water level directly under the storm to rise higher than water levels would rise under normal air-pressure conditions. Drawing energy from the sea surface and maintaining its strength as long as it remains over warm water, a tropical cyclone generates winds that exceed 119 km (74 miles) per hour. In extreme cases winds may exceed 240 km (150 miles) per hour, and gusts may surpass 320 km (200 miles) per hour. Accompanying these strong winds are torrential rains and a devastating phenomenon known as the storm surge, an elevation of the sea surface that can reach 6 metres (20 feet) above normal levels. Such a combination of high winds and water makes cyclones a serious hazard for coastal areas in tropical and subtropical areas of the world.

Tropical cyclones are compact, circular storms, generally some 320 km (200 miles) in diameter, whose winds swirl around a central region of low atmospheric pressure. The winds are driven by this low-pressure core and by the rotation of Earth, which deflects the path of the wind through a phenomenon known as the Coriolis force. As a result, tropical cyclones rotate in a counter clockwise (or cyclonic) direction in the Northern Hemisphere and in a clockwise (or anti-cyclonic) direction in the Southern Hemisphere.

There are six conditions favourable for TC process to take place. The conditions are listed below:

i. The temperature of the surface layer of ocean water must be 26.5 °C (80 °F) or warmer, and this warm layer must be at least 50 metres (150 feet) deep.
ii. A pre-existing atmospheric circulation must be located near the surface warm layer.
iii. The atmosphere must cool quickly enough with height to support the formation of deep convective clouds.
iv. The middle atmosphere must be relatively humid at a height of about 5,000 metres (16,000 feet) above the surface.

v. The developing system must be at least 500 km (300 miles) away from the Equator.
vi. The wind speed must change slowly with height through the troposphere - no more than 10 metres (33 feet) per second between the surface and an altitude of about 10,000 metres (33,000 feet).

The Table 2.1 below details the stages of TC formation.

Table 2.1: Tropical cyclone stages of formation

Stage	Definition
Tropical disturbance	A discrete system of clouds, showers, and thunderstorms that originates in the tropics and remains intact for 24 hours or more
Tropical depression	When a tropical disturbance develops a closed circulation. It contains maximum sustained one-minute winds of 17 m/s or less, at an elevation of 10 meters.
Tropical Storm	Maximum sustained one-minute winds of 17.4 – 32.6 m/s, at an elevation of 10 meters.
Tropical Cyclone	Have sustained one-minute winds of at least 33.08 m/s, at an elevation of 10 meters.

The TCs are typically categorised according to the Saffir-Simpson Cyclone Wind Scale (Table 2.2), which gratefully has not been experienced anywhere near Malaysia's coast. Alas, the tail effect of the storms has had severely breaching almost every coastal protection barred along the shore and offshore repeatedly, accompanied with variance remedial and mitigation mode of protective structures utilized after each succession failure over the course of many years. Unfortunately, the reprise exercise has yet to deem fit to withhold future increment in strength in marine weather severity and frequency unless all climate parameters are met and understood literally and figuratively. In fact, the shortcomings have unintentionally imparted an unwelcome revelation of skewed judgement on the so-called optimized shore protection design thus far. However, the incline made towards the study is one encouragement towards productive improvement works for better understanding on the sustainability of our coasts in facing the challenges in climate change outcome.

Table 2.2: Saffir-Simpson cyclone wind scale

Category	Sustained Wind Speed	Extent of Damage at
1	33.08 – 42.5	Minimal
2	42.9 – 49.2	Moderate
3	49.6 – 58.1	Extensive
4	58.6 – 69.3	Extreme
5	Above 69.3	Catastrophic

2.3 Historical Incidence of Catastrophic Storm Surges

Historically, storm surges have brought disastrous inundations and have been responsible for the majority of deaths in coastal areas affected by storms. Recalling the event in 1970, more than 500,000 lives were lost in Bangladesh as a result of more than ten meters high surge. A bit earlier, in 1959, surges from Typhoon Vera were responsible for nearly 5,000 deaths in Japan. The two events are some of the destructive events that made headlines until now as well as others as shown in Table 2.3.

Table 2.3: Historical events related to storm surge height and total fatalities

Rank	Year	Storm	Max. Storm Surge Level (m)	Total Fatalities	Location
1	1876	The Great Backerganj	13.60	>200,000	Bangladesh
2	1767	Cyclone Barisal	13.03	>30,000	Bangladesh
3	1839	Coringa	12.00	>300,000	India
4	1970	Bhola	11.00	> 500,000	Bangladesh
5	1968	Didang	9.14	141	Narvacan, Philippines
6	1999	Orissa	9.10	9,885	India
7	2013	Haiyan	8.00	6,340	Anibong, Philippines
8	1780	Antilles	7.60	>25,000	Lesser Antilles Islands
9	1897	Samar/Leyte	7.30	1,500	Samap and Leyte, Phi.
10	1912	Leyte/Cebu	7.00	15,000	Leyte and Cebu, Phi.
11	1991	Bangladesh	6.00	>130,000	Bangladesh
12	1980	Joe	5.94	2	Nandu, Guangdong
13	1974	Unnamed	5.20	200	Near Cox's Bazar and Chittagong
14	1956	Wanda	5.02	4,935	Hangzhou, China
15	1984	Ike/Nitang	4.60	1,492	Sarangani Island, Phi.
16	1983	Vera	4.50	127	Near Infanta, Phi.
17	1981	Rosita	4.50	27	South of Tinambac, Phi.
18	2005	Damrey	4.00	57	Near Vinh, Vietnam
19	1959	Vera	3.90	>5,000	Japan
20	2008	Nargis	>3.00	>130,000	Myanmar

As in Malaysia, damages caused by or inundation due to storm surge is uncalled for and none is reported. But, previously may have construed by misconception as waves due to lack of segregation of the two. Furthermore, it may not be a surprise if a tropical storm was accidentally mistaken as an extreme Northeast monsoon winds normally acknowledge in the month of November until March. The fact that most peak storm surges occurred during the period of NE monsoon is most disconcerting to recognize the difference, unless closer look on the observed tide levels are scrutinized for the outliers. By the by, storm surge height should not be considered as high-water marks when interpreting the probable inundation levels. It is important to identify to what extent the public understands this in order to advise the precaution and safety measure one should be taken to evict before an upcoming flood is to occur, and with that associated with storm surge impact for risk and evacuation management plan and execution.

Nonetheless, storm floods are a common scenario in Malaysia which usually correlate to heavy rainfall brought by strong winds. But, severe storm floods due to storm surges triggered by strong tropical cyclones is rare but present. Thus, to acquire a collective report associated with storm surge significant impact worth mentioning as a catastrophic incidence that struck Malaysia, is totally scarce. Thus, a framework in assigning better observation and recording of post events and the alleged impacts should be designed to preserve it as a historical record for better understanding, future advance research and generations. However, storm surge events that has likely to occur either during strong impinge from NE monsoon or typhoon (including depression or tropical storms), could be perceived as significant in terms of engineering design, and thus covered in detail in the next chapter.

CHAPTER 3.0 DATA AND METHODOLOGY

3.1 Introduction

Producing a clear picture of either past changes or future projections of storm surges for the entire Malaysian coastline is a challenging task because of the impact of local topographical features on the surge events. But the major challenge is the undisclosed report, data or information which may or may not be existed, presented or thoroughly deciphered for what it is worth in understanding the marine climate of Malaysian waters. Not to discredit, whilst there are numerous published reports and papers produced of other coastline in Southeast Asian countries, fewer are available on Malaysia, although this situation is yet to improve.

The most popular subject of study by local researchers are the trends in the sea level from hourly tide gauge records at least for the period since 1980's (Luu et al., 2015, Md. Ali et al., 2015, Mohd Din et al., 2017, NAHRIM, 2017), and at most, one that covered storm surge pattern has been studied by Mohd Anuar et al. (2018) based on over 25 years (1984-2012) of observational tide gauge data using four standard tide station in east coast of Peninsular Malaysia, and later, correlation between the storm surge events and the typhoon records (Mohd Anuar et al., 2019).

This chapter is to report various storm surge events that have been recorded in the tide gauge data. The methodology for the computation of storm surge and interpretation of this data, has subsequently been subjected to a detailed review process by global researchers and has been adopted for storm surge assessment in this report. These contributions are referred to in this report as non-tidal residuals (for Negeri Sembilan and Malacca coasts) and in more extreme cases, storm surge (for Kelantan coast). In the subsequent section we describe the statistical approach in analysing the trends and return levels of storm surges, after which implications of the results are discussed.

3.2 Operational Tide Data

It is important to understand how typhoons and storms affect coastal areas that are also subject to tidal flows. The only way to do this is to deploy many monitoring sites in the path of these storms, and collect data before, during, and after the storm passes. Sea level monitoring and measurements are performed by three main agencies in Malaysia, namely the Malaysian Meteorological Department (MMD), the Department of Survey and Mapping Malaysia (DSMM) and the Royal Malaysian Navy (RMN). Though the Malaysian tide-gauge network was not set up to monitor storm surges, it is possible to use the tide-gauge data to determine, through analysis, the contribution of sea level due to surges on coastal inundation and coastal structure disintegration.

To encourage such applications of tide level data, the Department of Survey and Mapping Malaysia has made available to the Coastal and Oceanography Research Centre via National Hydraulic Research Institute of Malaysia (NAHRIM) the hourly tide-gauge data collected during 1984-2017 at selected stations along the coast. For the purpose of the study, the selected stations are located along the east and west coast of Peninsular Malaysia: Geting in Kelantan and Tg. Keling in Malacca, respectively. The locations of existing tidal gauges in Malaysia is marked in Figures 3.1. Geting station, covered almost 32 years of observed water level and recorded as early as 1986, but Tg. Keling station is even earlier, from year 1984, with a total of almost 34 years of measured water level data.

Figure 3.1: Location of existing tidal gauges in Malaysia

To determine the storm surge height, the measured water level is subtracted with a predicted water level. In order to determine the predicted water level for the overall span of the measured data, tidal constituents for each tide station need to be obtained using a harmonic analysis. The use of this technique for tides appears to have originated with Lord Kelvin (1824–1907) around 1867.

The water level variation due to tides at any location can be generated using the following written equation:

$$h = z_0 + \sum_{n=1}^{N} H_n f_n cos[\sigma_n t - \theta_n + (\alpha_n + \beta_n)] \qquad [1]$$

where z_0 is the mean sea level at location; t is the time; n refers to a tidal constituent, and σ_n, H_n, and θ_n are, respectively, the frequency, amplitude and phase associated with that constituent. f_n, α_n and β_n are all constants that are related to the meteorological and astronomic system (Dronkers, 1975).

Using Eqn. [1] to each yearly observed tide level data for both stations have resulted in 69 constituents, i.e. n = 69 (see Tables 3.1 and 3.2), with the Mean Sea Level (MSL) was found to be 2.32 m and 2.87 m, for Geting and Tg. Keling, respectively. The annual MSL for both stations shown a rising trends over the collective periods which concur with the sea level rise assessment (NAHRIM, 2017) and illustrated in Figure 3.2. The observed and resultant predicted water level however, are as shown in Figures 3.3 and 3.4 for station Geting and Tg. Keling, respectively.

Table 3.1: Tidal constituents for Geting station

Nos.	Name	Amp.	Phase	Nos.	Name	Amp.	Phase
1	Z0	2.3174	0	36	H1	0.0081	313.27
2	SA	0.2289	356.81	37	M2	0.1673	252.99
3	SSA	0.0475	143.16	38	H2	0.0024	154.49
4	MSM	0.0038	11.49	39	MKS2	0.0043	240.57
5	MM	0.0079	358.94	40	LDA2	0.0014	217.83
6	MSF	0.0063	134.58	41	L2	0.0037	205.14
7	MF	0.005	76.08	42	T2	0.0025	251.27
8	ALP1	0.0006	320.18	43	S2	0.0783	294.15
9	2Q1	0.002	286.19	44	R2	0.0011	110.22
10	SIG1	0.0025	328.61	45	K2	0.0174	265.28
11	Q1	0.0187	296.86	46	MSN2	0.0018	76.68
12	RHO1	0.0039	290.76	47	ETA2	0.0007	291.21
13	O1	0.1152	311.79	48	MO3	0.0095	206.05
14	TAU1	0.0116	36.61	49	M3	0.0016	44.07
15	BET1	0.0019	290.89	50	SO3	0.0085	253.65
16	NO1	0.009	296.33	51	MK3	0.0114	247.26
17	CHI1	0.0025	310.38	52	SK3	0.0046	300.77
18	PI1	0.0028	314.6	53	MN4	0.0039	138.5
19	P1	0.0704	354.59	54	M4	0.0087	168.14
20	S1	0.0135	246.7	55	SN4	0.0012	167.41
21	K1	0.2283	345.34	56	MS4	0.0054	198.48
22	PSI1	0.0062	119.93	57	MK4	0.0009	65.95
23	PHI1	0.0101	322.96	58	S4	0.0014	239.88
24	THE1	0.0028	29.44	59	SK4	0.0004	81.01
25	J1	0.0114	28.4	60	2MK5	0.0063	174.49
26	SO1	0.0118	172.32	61	2SK5	0.0003	336.86
27	OO1	0.0105	338.92	62	2MN6	0.0016	7.92
28	UPS1	0.0017	29.6	63	M6	0.0033	42.21
29	OQ2	0.0006	173.3	64	2MS6	0.0039	105.06
30	EPS2	0.002	166.29	65	2MK6	0.0012	56.95
31	2N2	0.0051	212.16	66	2SM6	0.0011	160.26
32	MU2	0.0104	197.89	67	MSK6	0.0008	101.33
33	N2	0.0372	234.48	68	3MK7	0.0001	69.41
34	NU2	0.0054	241.31	69	M8	0.0006	335.49
35	GAM2	0.0008	273.53				

Table 3.2: Tidal constituents for Tg. Keling station

Nos.	Name	Amp.	Phase	Nos.	Name	Amp.	Phase
1	Z0	2.8707	0	36	H1	0.0046	148.01
2	SA	0.0439	270.54	37	M2	0.6284	225.96
3	SSA	0.0512	126.21	38	H2	0.0046	5.97
4	MSM	0.0049	331.28	39	MKS2	0.0034	41.48
5	MM	0.0205	22.99	40	LDA2	0.0146	226.83
6	MSF	0.0284	50.99	41	L2	0.0268	217.15
7	MF	0.013	330.64	42	T2	0.0175	275.08
8	ALP1	0.0063	223.59	43	S2	0.2963	275.66
9	2Q1	0.0028	166.83	44	R2	0.0037	248.16
10	SIG1	0.0292	262.14	45	K2	0.0675	255.07
11	Q1	0.0239	130.67	46	MSN2	0.0095	83.86
12	RHO1	0.0119	118.27	47	ETA2	0.0018	310.52
13	O1	0.1881	154.01	48	MO3	0.0247	226.05
14	TAU1	0.02	335.51	49	M3	0.0018	122.79
15	BET1	0.005	184.23	50	SO3	0.0206	276.57
16	NO1	0.0027	45.72	51	MK3	0.0228	252.6
17	CHI1	0.0036	180.07	52	SK3	0.0087	303.85
18	PI1	0.0091	161.04	53	MN4	0.0117	20.79
19	P1	0.0306	127.34	54	M4	0.0305	36.1
20	S1	0.0547	85.35	55	SN4	0.0044	71.21
21	K1	0.0847	145.43	56	MS4	0.0297	85.64
22	PSI1	0.0056	158.86	57	MK4	0.0086	52.78
23	PHI1	0.0012	138.45	58	S4	0.0058	129.18
24	THE1	0.0015	70.92	59	SK4	0.0035	95.89
25	J1	0.0114	79.64	60	2MK5	0.0113	328.05
26	SO1	0.0037	115.04	61	2SK5	0.001	138.02
27	OO1	0.0075	95.08	62	2MN6	0.0075	141.61
28	UPS1	0.0024	136.7	63	M6	0.0125	155.35
29	OQ2	0.0016	169.33	64	2MS6	0.016	200.66
30	EPS2	0.0048	292.89	65	2MK6	0.0045	193.98
31	2N2	0.0154	191.23	66	2SM6	0.0062	251.16
32	MU2	0.0156	303.7	67	MSK6	0.0034	243.14
33	N2	0.113	212.14	68	3MK7	0.0005	248.74
34	NU2	0.0247	210.91	69	M8	0.0019	195.47
35	GAM2	0.0021	231.88				

Year	Geting	Tg. Keling
1984	-	2.907
1985	-	2.868
1986	-	2.868
1987	2.252	2.811
1988	2.305	2.872
1989	2.284	2.858
1990	2.266	2.834
1991	2.289	2.811
1992	2.254	2.842
1993	2.287	2.848
1994	2.288	2.809
1995	2.305	2.872
1996	2.322	2.870
1997	2.297	2.766
1998	2.284	2.863
1999	2.326	2.898
2000	2.297	2.900
2001	2.329	2.898
2002	2.287	2.830
2003	2.307	2.859
2004	2.297	2.844
2005	2.250	2.827
2006	2.306	2.828
2007	2.306	2.856
2008	2.348	2.906
2009	2.343	2.891
2010	2.356	2.928
2011	2.406	2.911
2012	2.364	2.935
2013	2.386	2.953
2014	2.354	2.893
2015	2.324	2.867
2016	2.340	2.927
2017	-	2.903

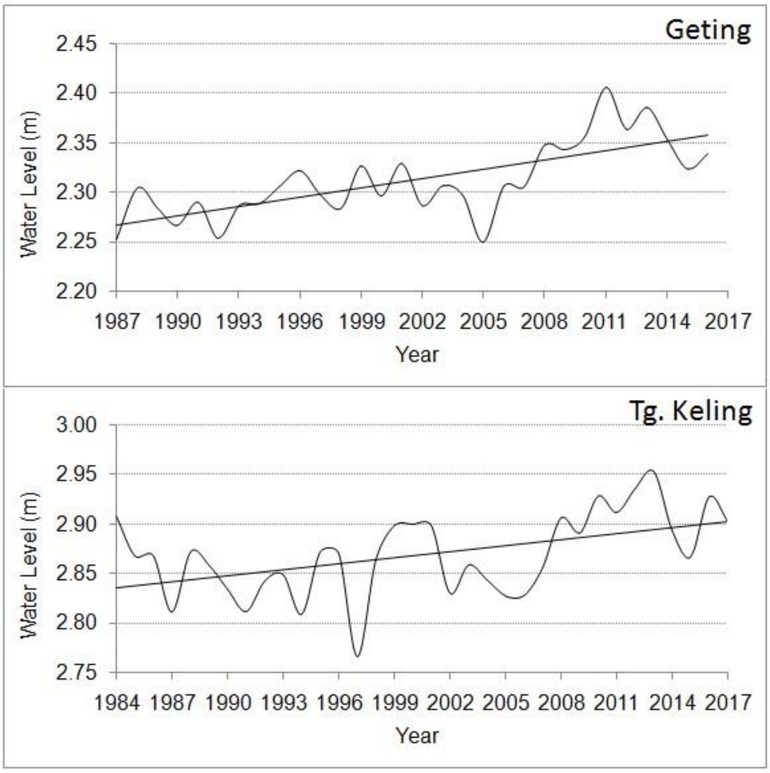

Figure 3.2: Annual MSL (m) at zero tide gauge for Geting and Tg. Keling

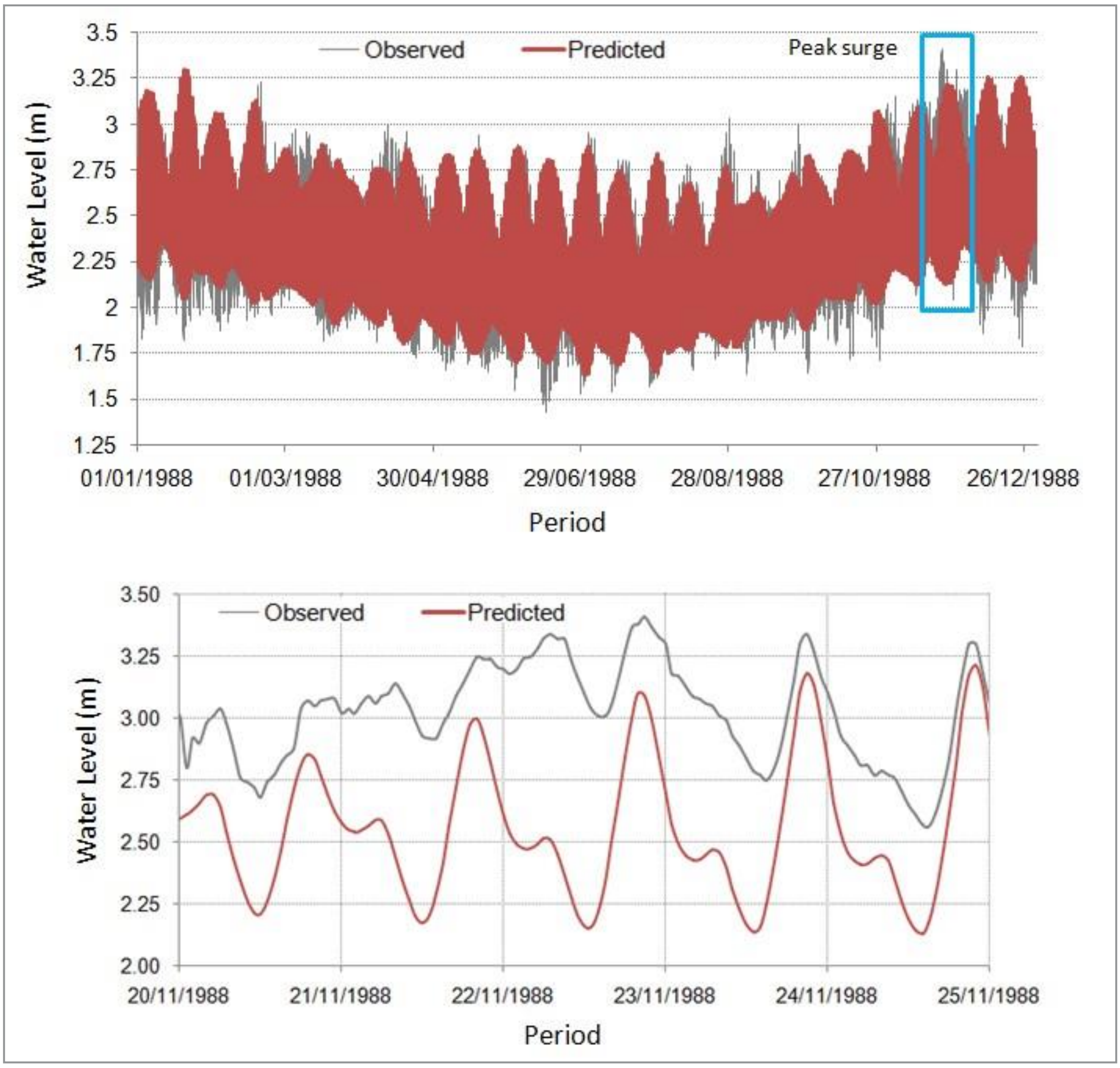

Figure 3.3: Observed and predicted water level for Geting - year 1988

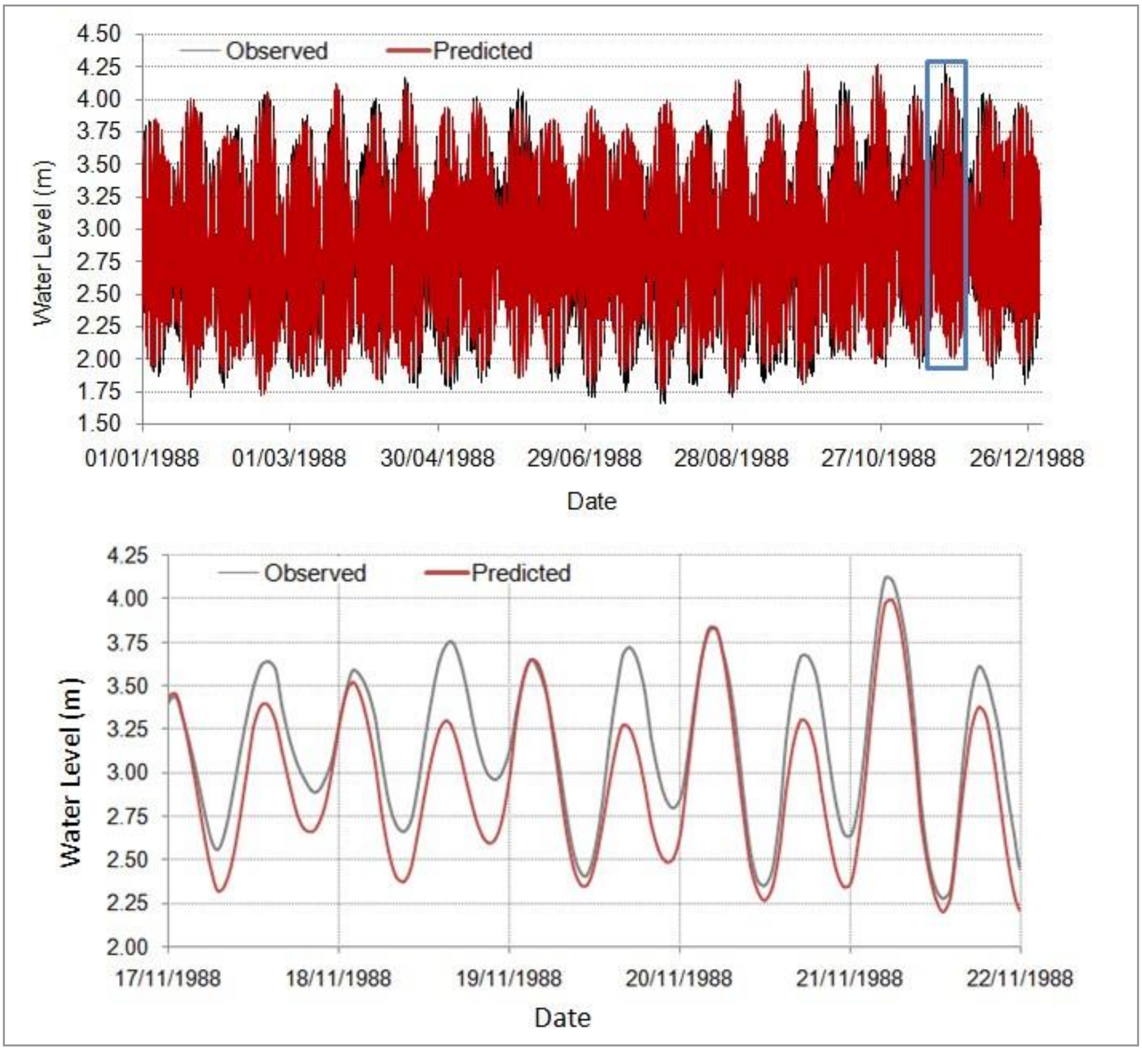

Figure 3.4: Observed and predicted water level for Tg. Keling - year 1988

3.3 Storm Surge Frequency of Occurrence

Storm surges are superimposed on the normal astronomical tides generated by variations in the gravitational attraction of the moon and sun. The storm surge component can be derived from a time-series of sea levels recorded by a tide gauge using:

Surge residual = Observed sea level – Predicted sea level [2]

producing a time-series of surge elevations. A year-long time-series of tide level was examined for storm surge record for both Geting and Tg. Keling stations. Monthly and annual peak surge were calculated for later statistical analysis. Detail assessment on the storm surge data is describe separately for Getting and Tg. Keling station in the following sections.

3.3.1 Geting Station

Once an extreme event occurred, the likelihood of another extreme events occurs will be high though vary in severity or heights. In Malaysian waters, most of the peak surge with surge height of more than 0.5 m incurred during the NE monsoon period (November-March) which is found from the collected data to be a repetitive event, as shown in Figure 3.5. The surge height during SWM and IM seems to be bordered between 0.1 m to 0.4 m with an occasional record reached more than 0.4 m but seldom overboard the threshold of 0.4 m.

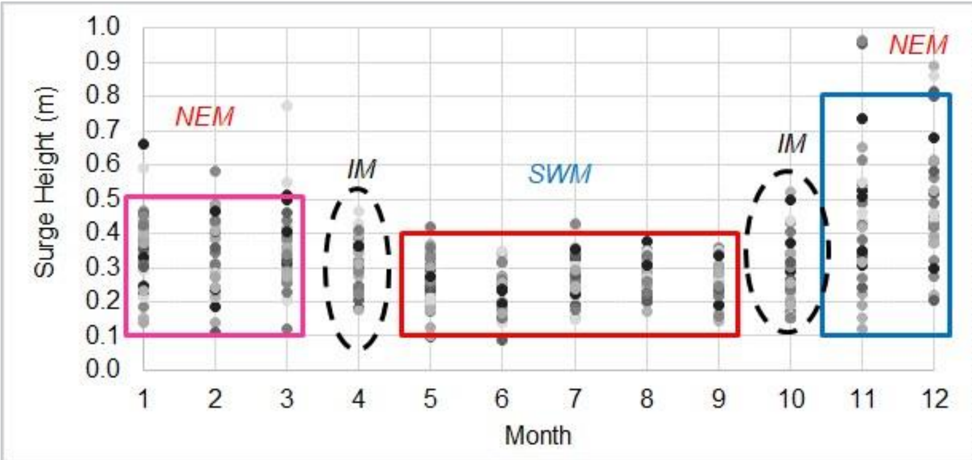

Figure 3.5: Monthly storm surge height records in accord to range of heights - Getting (1986 - 2017)

Moreover, the frequency of occurrence annually between the monsoon periods shown 49.7% of annual surge episodes occur during the Northeast monsoon (NEM), whilst 41.4% and 16.9% occur during Southwest monsoon (SWM) and Intermonsoon (IM) periods, respectively. The percentage of occurrence vary with surge height, as not all incidents were severe (storm surge height 0.3 m or less) as illustrated in Figure 3.6.

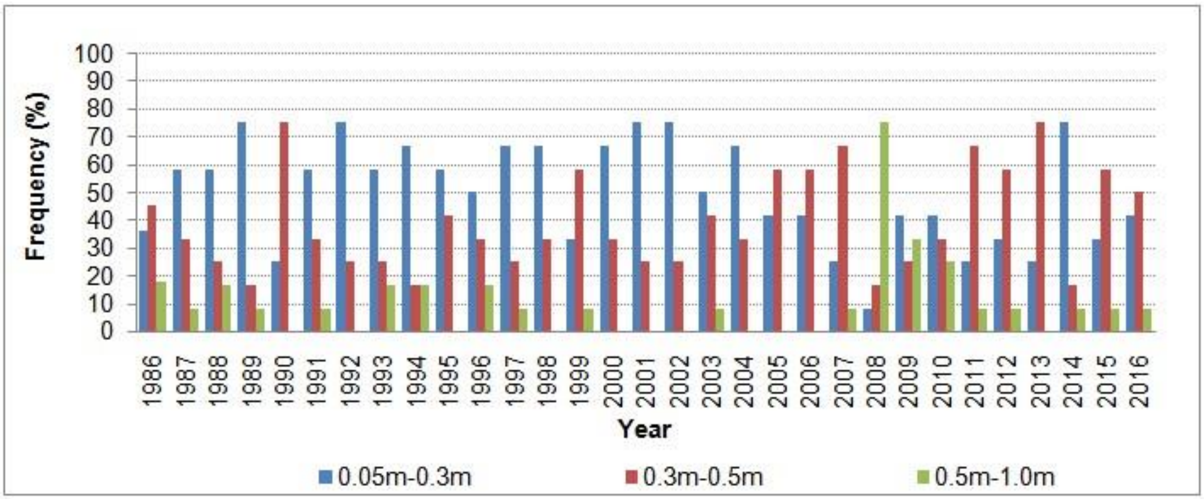

Figure 3.6: Annual peak surges from year 1986 to 2017- Geting station

From Figure 3.6, the peak surges, s_{max} were categorized into 3 distinctive heights range between 0.05m< s_{max} <0.3m, 0.3m< s_{max}<0.5m and 0.5m< s_{max}<1.0m, with almost 50% occurrence reached less than 0.3 m, 40.1% and 10.2% surged more than 0.3 m and 0.5 m in height, respectively. The peak surge of more than 0.3 m tends to rise in frequency in later years after 2007. Assessment made on the observed surges gave out year 2008 with the highest percentage of surge event with height more than 0.5 m, that is a total of 75% for surge between 0.5 m to 1.0 m, followed by surge height between 0.3 m to 0.5 m at 17% and the remaining

8% for surge level less than 0.3 m, respectively. Out of the 75% of occurrence, the maximum surge height recorded in the month of November year 2008 at 0.62 m. Initial assumption of the maximum surge record would be due to extra tropical storm incident offshore in South China Sea. However, examination on the Hong Kong Observatory tropical cyclone archive data indicated there was no significant storm or tropical cyclone found within the month of the maximum surge. Thus, lead to the likely cause which most probably due to the strong impinged of the Northeasterly winds during NEM period.

However, in November the following year of 2009, Typhoon Mirinae started in the afternoon of 26 October and lasted in late afternoon on the 2nd of November managed to result a storm surge of more than 0.6 m three days later on the 5th of November 2009 at Geting shoreline which has given a 32% of occurrence in total for surge height above 0.5 m in that year. As climate change declared by IPCC 2019 is in part the driver on storminess and subsequent severity in global marine climates, it is of no surprise that storm surge as a resultant of storm effect, continue to increase from year to the following year with a repetitive occurrence of surge height of more than 0.5 m.

Segregation by monthly events as illustrated in Figure 3.7 shown that the overall frequency of occurrence between NEM and SWM period is almost equal, that is 41.7% and 41.2%, respectively. Though, higher surges with height above 0.3 m tends to happen more frequent with 30% occurrence during NEM periods, and only 12.4% in SWM. Hence, indicates strong surges will likely to occur during extreme North-eastern storms than mild South-western storms in east coast of Peninsular Malaysia, as expected.

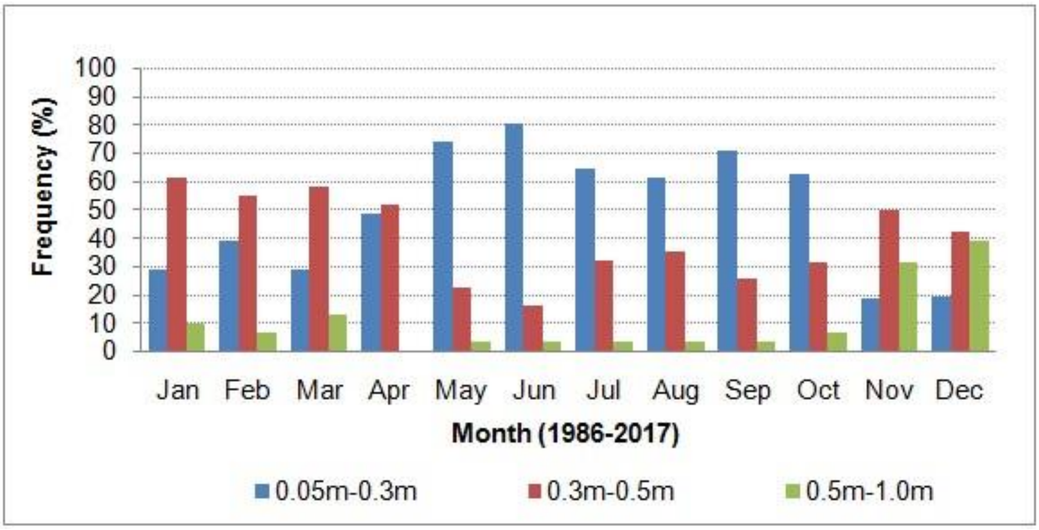

Figure 3.7: Monthly peak surges from year 1986-2017 – Geting station

Following the examination of 374 monthly the surge data, the peak surges show an evolution of winds over the South China Sea. Chosen year 1988 for the highest peak storm surge throughout the collective period for Geting, the most intense phase of the storm was therefore a couple of days before the spring tide albeit for peak surge in year 1988, it occurs on the falling tides (see Figure 3.8). A detail checking on peak surges in other consecutive years, shown an occurrence in the mix of towards a falling tides or a rising tides. Meaning, the peak surges occur irrespective of the tidal phase and periods, though the impact will be more severe if the peak surge did occur at the rising tide or high tide.

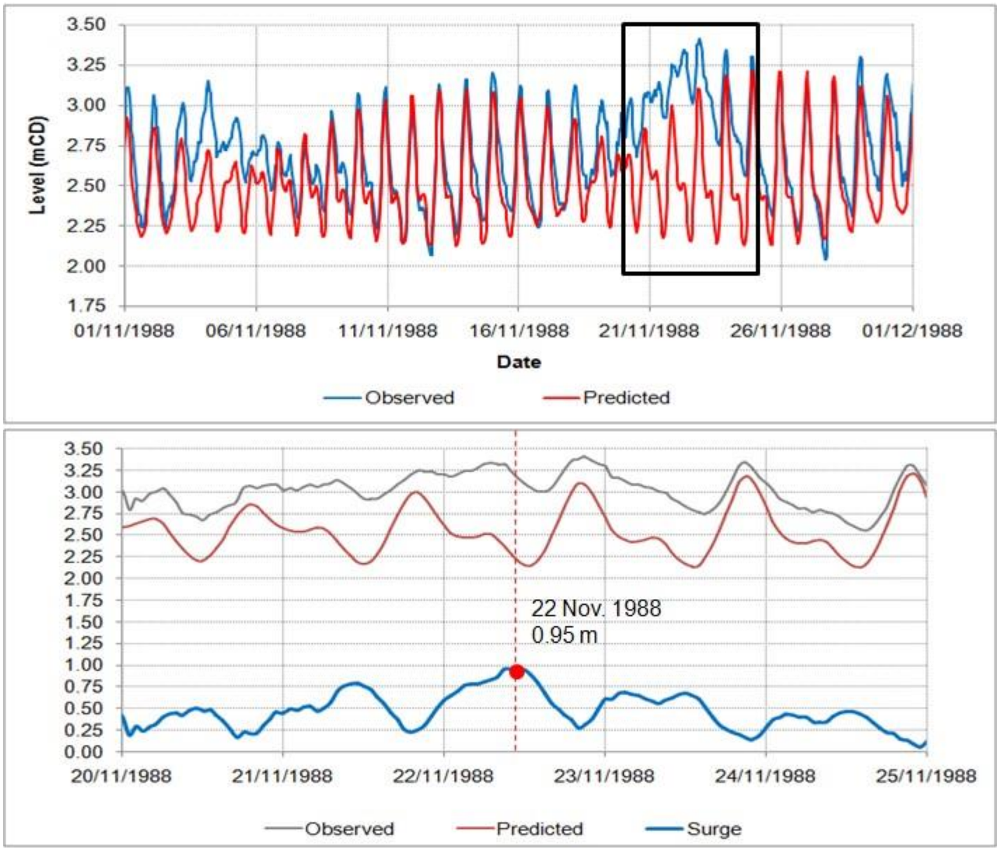

Figure 3.8: 5-days peak surge hydrograph during November month in year 1988 - Geting station

Furthermore, cross examination on peak surge data indicated that the peak events occurred within an extreme water level period, though may or may not happen during the rising tide or high tide. The incident of peak surge with respect to the time and occurrence of tidal phase is not covered in this report. Moreover, the incident of peak surge may not altogether occur concurrently at or within the period of maximum water level or abnormal water level. The assumption made is based on an analysis on annual peak surges with respect to their rank of severity and compared with the highest recorded water level during the time of peak surge which is shown in Table 3.3.

Table 3.3: Annual peak surges and maximum water level with their ranking for Geting

Year	No.	Peak Surge (m)	Rank	Observed Water Level (mCD)
1988	1	0.96	20	3.41
1986	2	0.95	9	3.47
2009	3	0.89	1	3.76
1987	4	0.89	23	3.39
2017	5	0.86	2	3.76
1997	6	0.86	5	3.62
2014	7	0.81	26	3.36
2011	8	0.77	22	3.41
1994	9	0.74	15	3.43
2010	10	0.73	19	3.42
1996	11	0.68	28	3.35
1991	12	0.65	6	3.58
2012	13	0.61	8	3.48
1999	14	0.61	4	3.62
1993	15	0.58	24	3.38
2016	16	0.58	14	3.44
2004	17	0.55	7	3.48
2008	18	0.53	11	3.46
1989	19	0.53	13	3.44
2007	20	0.52	18	3.42
2006	21	0.49	3	3.63
1992	22	0.49	29	3.34
2005	23	0.48	32	3.30
2001	24	0.48	25	3.37
1995	25	0.46	21	3.41
2003	26	0.44	17	3.42
1990	27	0.44	27	3.35
2013	28	0.44	10	3.47
2000	29	0.42	30	3.34
1998	30	0.39	16	3.42
2015	31	0.37	12	3.45
2002	32	0.35	31	3.33

From the table, the first ranking of highest surge occurs in year 1988, whilst the maximum water level suggested a ranking of 20 in the same year, though the first rank of maximum water level is in year 2009 accompanied with the surge height in the third rank. The event of peak surge seems not to occur in parallel or almost parallel to the maximum water level, or in other words, the peak surge is not dependent on the maximum water level. Close examination on both variables (peak surge and maximum water level) indicated that the maximum water levels mostly occurred less than 12 hours after the peak surges.

Looking back at the worst flood event in year 2014, which considered by many researchers as the most severe flood event in modern history in east coast of PM, at the end of December

2014, either tide gauge or river gauging recorded a very unusual high water level overtopped the danger level set by DID along the Kelantan River and Golok River bordering Thailand. the storm surge height recorded during the flood was less than a few centimetres to 1.0 m. The extreme surge height which almost repeat the year 1988 event may likely spurred by the tail effect from Super Typhoon Hagupit crossed the Philippines and traversed into the South China Sea, less than 500 km offshore from ECPM. The severity in inland flooding was caused not only by heavy precipitation brought by the monsoon NE-tern winds but also the high tide coupled with surge that occur concurrently which upset the ability of the river to flush out the flood discharge, thus contributed to prolonged inundation, hence increase the already severe flooding conditions upstream. Overall, the correlation of these two events point out the unusual correspondence between the peak surge and maximum water level incidence within the extreme period of the respective surge events. Nonetheless, with the trends of surges overlooking an increase pattern, the probability that future surge over the years will likely to exceed the presumption values herein with the aid of severe marine climate storminess is plausible. Figure 3.9 illustrates the comparison of ranking between peak surge and maximum water level for the total of 32-year collective records.

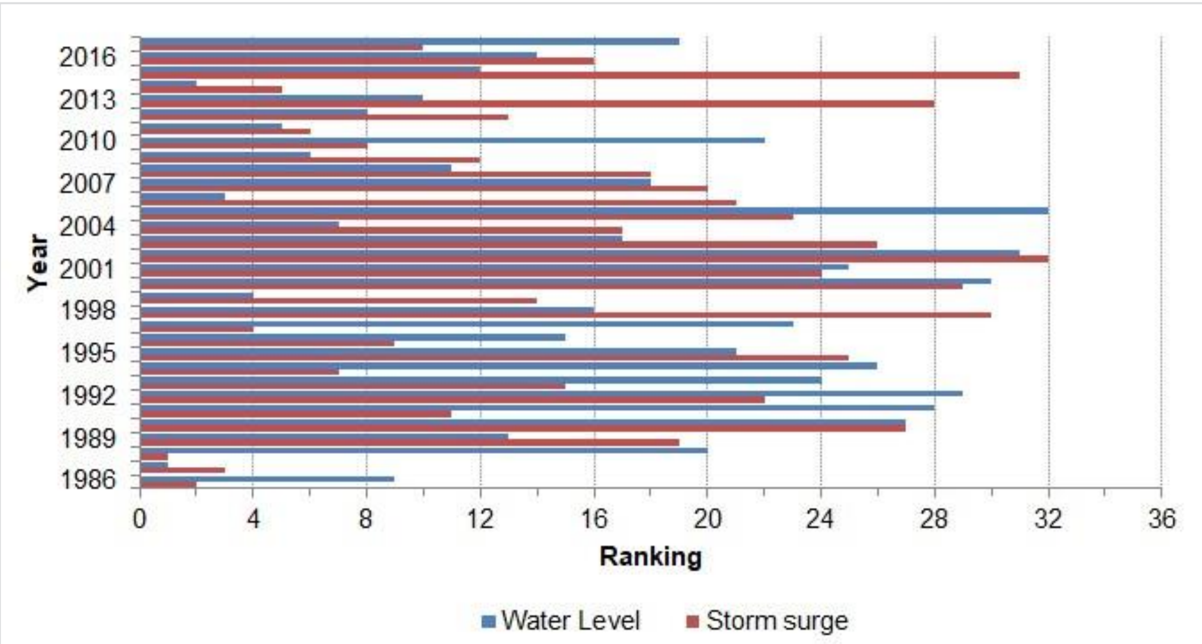

Figure 3.9: Rank of events between peak surge and maximum water level - Geting

3.3.2 Tg. Keling Station

Tg. Keling station located close to the State of Negeri Sembilan border and boasted of 34 years of tide level data from year 1984 to 2017. The location of the station is almost at one third in distance from north to south of the west coast region of PM. It is also one out of five (5) tide gauge mobilised at standard ports that belonged and monitored by the Malaysia Meteorological Department (MMD). Subtraction of the observed and predicted tide level data indicated an almost uniform surge height throughout the year with very small percentage of occurrence of surge height exceed 0.35 m during all three monsoon seasons and an occasional peak surge exceed more than 0.45 m during IM and NEM, respectively (see Figure 3.10).

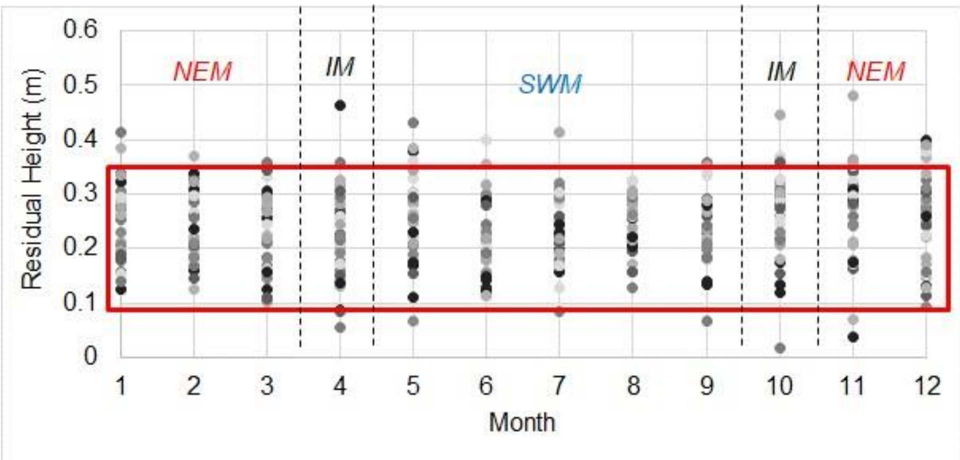

Figure 3.10: Monthly residual height at Tg. Keling – recorded from year 1984-2017

The occasional spike in the records is detected only during NEM and considered as a normal. As a matter of fact, the overall observation in the observed tides are a typical pattern of tides under mild storm effect with random occasional of extreme events. Throughout this report, the differences between the observed and predicted tide level data for Tg. Keling station is most appropriate to be known as 'residual' rather than storm surge, due to the absence of extreme storm such like in the east coast of PM. The location of the tide gauge though not close to experience direct hit from north-easterly strong winds during NEM period, is still considered possible to be subjected to the tail effect of the winds diverted during its' propagations towards the Java islands. However, the aftereffect may not be so severe as compared to the coastal areas in the eastern coast of PM.

Further assessment on the frequency of annual peak residual with variance in heights as illustrated in Figure 3.11 shown only one (1) year has experienced peak residual greater than 0.5 m in height, that is in the year of 1988. Which seems to concur with extreme events happen in Geting, where the time and phase at peak residual almost similar (see Figure 3.12).

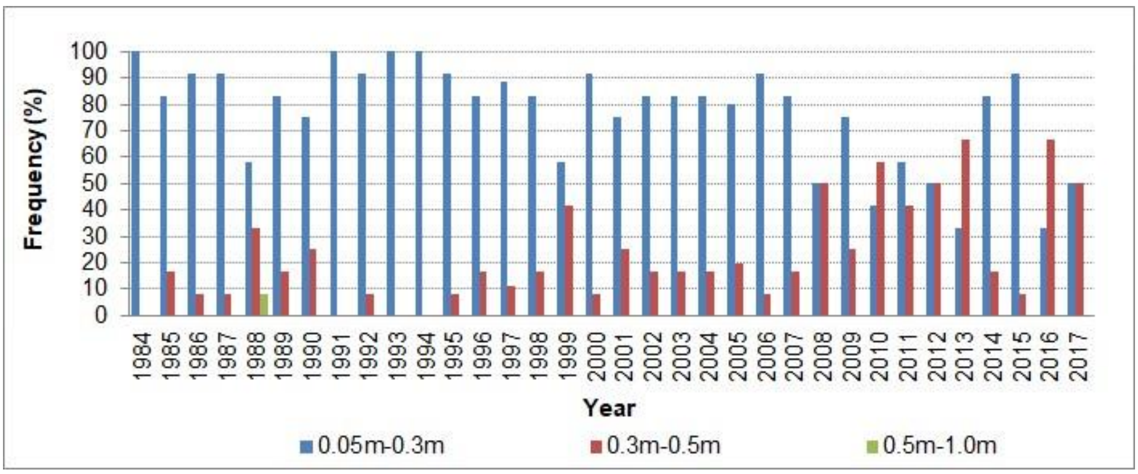

Figure 3.11: Annual peak residual from year 1984 to 2017 - Tg. Keling station

The rest of the records shown a residual with range in height between 0.15 to 0.3 m dominates from year 1984 until 2007, with occasional residual range between 0.3 to 0.5 m. The frequency of residual greater than 0.3 m starts to increase again after year 2007 onwards.

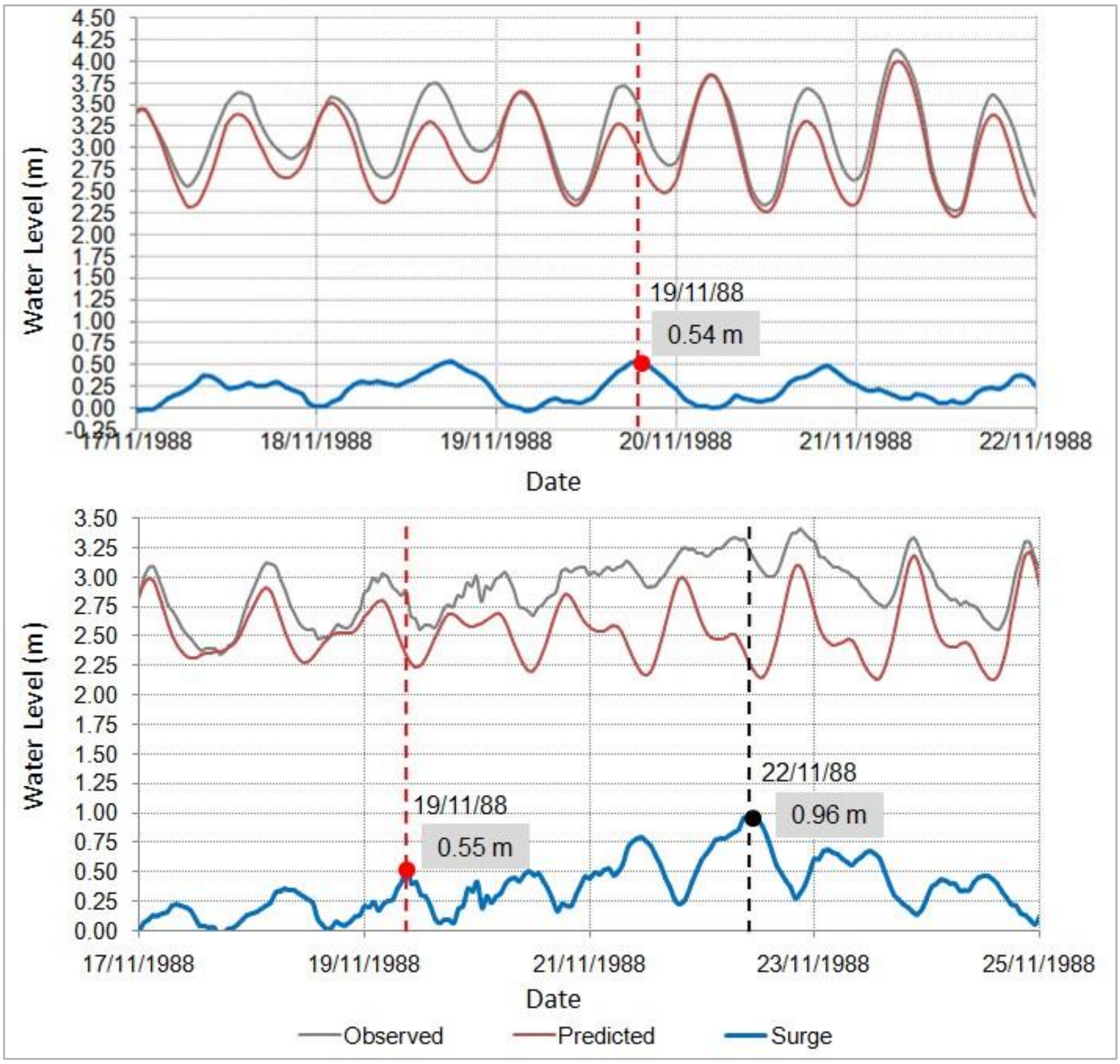

Figure 3.12: Peak residual in year 1988 at Tg. Keling (top) and Getting (bottom) stations

Monthly residual in various height range shows that residual with height below 0.3 m dominates from January until December with a total of 76.4% occurrence annually (see Figure 3.13). The rest of the percentage is taken up by residuals between 0.3 to 0.5 about 23.3% and residual greater than 0.5 m in height about 0.3% which occur only in November month, respectively. Whilst according to monsoon seasons, residual with heights below 0.3 m occurs about 30.3% during NEM periods, 34.6% and 11.5% during SWM and IM periods, respectively. The overall percentage of frequency of occurrence with respect to various range of residual heights is given in Table 3.4. From the table, it can be concluded that the difference in observed and predicted tides mostly lies within the range of less than 0.3 m. Hence, in general, the negative impacts observed along the coast of Melaka was likely not cause by high wave coupled with high residual, but chances are the possibility of higher waves propagated and frequented the channel of Straits of Malacca during SWM periods.

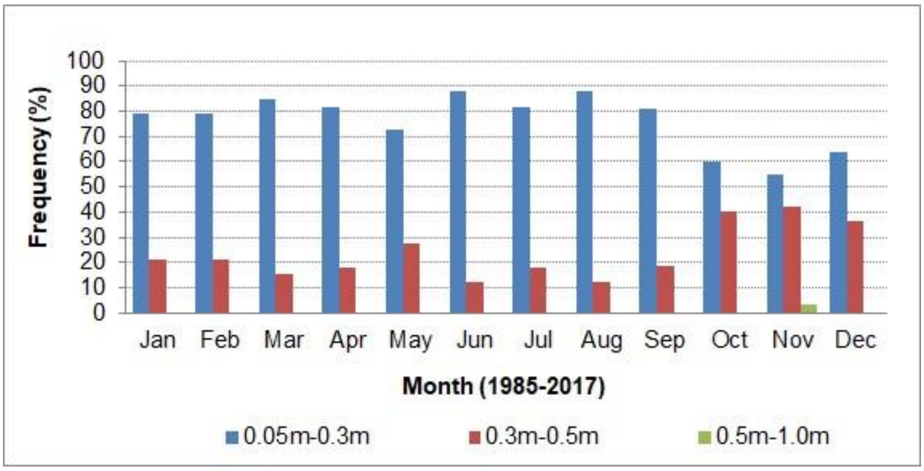

Figure 3.13: Monthly residuals from year 1984-2017 – Tg. Keling station

Table 3.4: Frequency of occurrence of residual NEM, SWM and IM seasons

Season	Month	Residual Range (m)			Total (%)
		0.05 – 0.3	0.3 – 0.5	0.5 – 1.0	
Northeast	Nov - Mar	30.3	11.3	0.3	41.8
Southwest	May - Sep	34.6	7.4	0.0	42.1
Inter	Apr & Oct	11.5	4.6	0.0	16.2

Residual range within the collective years are relatively mild with peak residual events and maximum water level befall within a lap of 48 to 72 hours after the peak event, but in an occasion the maximum water level befalls later than 72 hours. Thus, indicates that the peak residual is independent of maximum water level. The incident of peak residual is less likely accompany or coincides with maximum water level or vice versa. The analysis on ranking levels between the two maximum variables (residual and water level) indicate as much and support earlier conclusion on dependency between variables. Table 3.5 shows the ranking level from year 1984 to 2017 events and illustrated for comparison in Figure 3.14.

From Table 3.5, year 1988 top the first rank of peak residual accompanied by maximum water level in the 13th ranking, which initiates no dependency between the two variables. Whilst, the first ranking of maximum water level occurred in year 1999 but the peak residual came out on the tenth in rank. The two variables peak event mismatched in severity and the probability of one variable to reach its' peak followed by the other variable is less likely. Year 1986 and 2008 can be considered a close match to a concurrent event, parallel with the peak events occurred in Geting station where its' surge heights were above 0.5 m but the variables (peak surge and water level at Geting) did not paired well.

Table 3.5: Ranking levels between residuals and water levels for Tg. Keling records

Year	No.	Peak Residual (m)	Rank	Maximum Water Level (mCD)
1988	1	0.54	13	4.26
2010	2	0.48	8	4.30
2008	3	0.46	2	4.41
2004	4	0.43	20	4.21
2011	5	0.41	21	4.21
2016	6	0.40	10	4.30
2001	7	0.40	14	4.26
2017	8	0.39	29	4.18
2013	9	0.38	23	4.20
1999	10	0.37	1	4.42
1996	11	0.36	22	4.20
2007	12	0.36	3	4.37
1990	13	0.36	27	4.18
1992	14	0.36	30	4.16
1998	15	0.36	12	4.28
2005	16	0.35	33	4.12
2012	17	0.34	9	4.30
1985	18	0.34	25	4.19
2002	19	0.34	17	4.24
2009	20	0.33	18	4.23
1995	21	0.33	7	4.31
2015	22	0.32	31	4.16
2000	23	0.32	19	4.22
1989	24	0.32	4	4.36
1986	25	0.32	26	4.18
2003	26	0.32	5	4.33
2006	27	0.32	6	4.33
2014	28	0.31	16	4.25
1987	29	0.31	11	4.28
1997	30	0.30	34	4.05
1994	31	0.28	32	4.13
1984	32	0.28	24	4.19
1993	33	0.27	15	4.25
1991	34	0.27	28	4.18

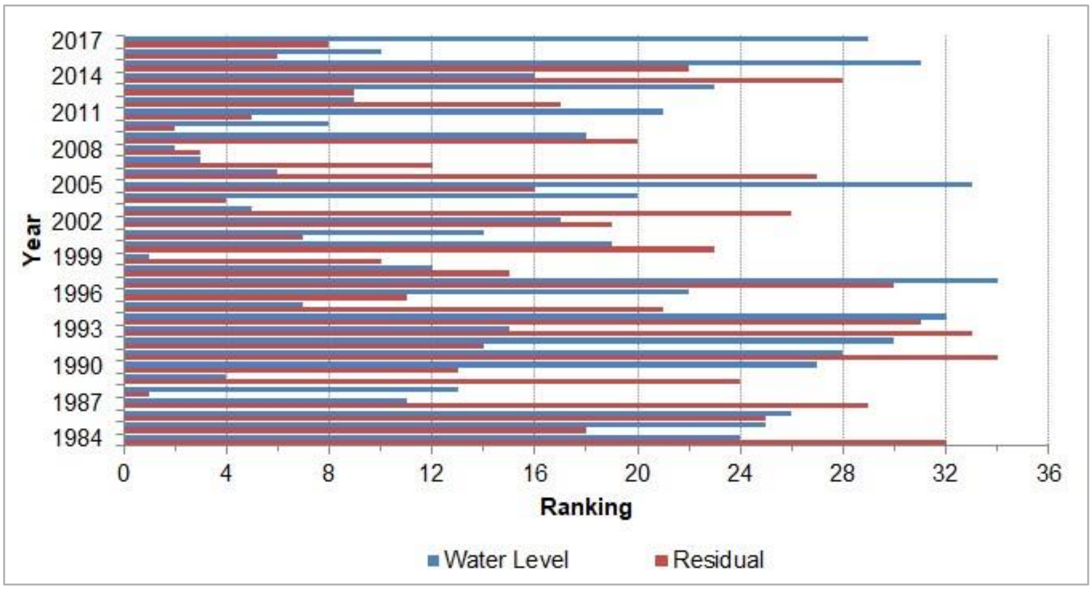

Figure 3.14: Rank of events between peak surge and maximum water level - Tg. Keling station

3.4 Storm Surge Trends

Annual peak surges and residuals are assessed for trends analysis. Correlation analysis between station was performed only between limited station as not every station content similar time frame of observation. Each station located on each side of the coastal region in the PM expose different characteristics in trends of calculated surges or residuals. Geographically, Geting station is openly encountered by strong north-easterly winds and far fetch tropical storms or typhoon albeit occasionally. Whilst Tg. Keling, being only less than 60 km distance west before encountering the landmass of Sumatera Island, accompanied by series of Java islands further south, is unlikely to experienced strong north-easterly winds that could alter the course and trends in the resultant residuals. Alas, south-westerly winds may have its' energy driven the peak residual up to several centimetre increment than usual, though not by far could cause severe impact by residual surge individually. The following section elucidates the trends and correlation in the resultant surges or residual for both tide stations and their neighbouring stations as well.

3.4.1 Geting Station

The peak surge throughout the 32-years tide level data recorded a surge height in a range from as low as 0.35 m up to almost 1.0 m in height. The rise and fall of the recorded surge do not frequent a normal increment as expected. Instead, the surge height shown a decreasing trend in the first 17 years and later starts to increase steadily from year 2002 onwards, as shown in Figure 3.15.

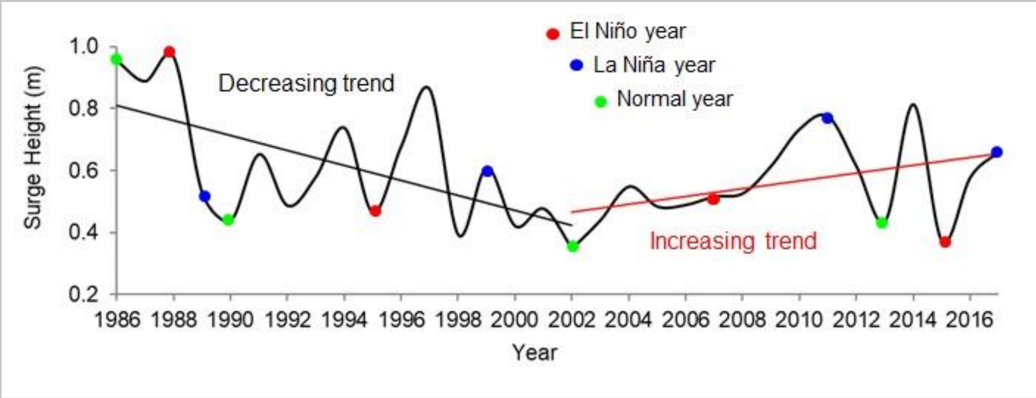

Figure 3.15: Annual peak surge heights from 1986 to 2017 – Geting station

The descending trend in surge height pattern is believed to be influenced by the strong warm El Niño effects whilst the increase trends is due to strong cold La Niña effects, where the normal easterly winds along the equator become even stronger thus encouraged stronger than usual surges, respectively. Table 3.6 list out the El Niño, La Niña and Normal year or ENSO years as referral material regarding the variance in storm surge heights.

Table 3.6: Normal, El Niño and La Niña (NOAA, 2019)

Normal Year	El Niño	La Niña
1896, 1898-1899, 1901-1902, 1905, 1907-1908, 1912-1914, 1916, 1920-1924, 1927-1930, 1932-1933, 1935-1938, 1940, 1944-1949, 1952-1954, 1957, 1959-1961, 1963-1965, 1967-1970, 1972, 1975, 1977, 1979, 1981-1982, 1984-1986, 1990-1991, 1993-1994, 1996-1997, 2001-2002, 2004-2006, 2009, 2013-2014 and 2017	1897, 1900, 1903, 1906, 1915, 1919, 1926, 1931, 1941, 1942, 1958, 1966, 1973, 1978, 1980, 1983, 1987-1988, 1992, 1995, 1998, 2003, 2007, 2010, 2015-2016 and 2019	1904, 1909, 1910, 1911, 1917, 1918, 1925, 1934, 1939, 1943, 1950-1951, 1955-1956, 1962, 1971, 1974, 1976, 1989, 1999, 2000, 2008, 2011, 2012, 2016, and 2017-2018

The projected upsurge of severe El Niño and La Niña events will cause an increase in storm events and its' associated storm surges, leading to extreme coastal flooding and erosion in populated regions especially the coastal areas independent of sea level rise (Barnard et al., 2015). Previous study by Hilmi et al. (2015), has analyzed the El Niño and La Niña or El Niño/La Niña Southern Oscillation (ENSO) impacts at local levels in Malaysia, but on tidal variations and Mean Sea Level (MSL), proved that the effect of ENSO is significant. Their research found that actual MSL values are lower than yearly MSL during El Niño, and vice versa during La Niña. Which is as expected, as climate changes, so as the ENSO effect. Their analysis on the Southern Oscillation Index (SOI) in Tg. Keling and Tg. Gelang tide station, both represents the west and east coast of PM tidal characteristics, have shown stronger La Niña from year 1998 onwards, and an increasing trend in sea level anomalies (see Figure 3.16). Hence, through this study, this is the first to pull together data to determine the possibility of ENSO effects on storm surge, though generically, and hopefully shall assist in detailing out the level of risk that accompany it.

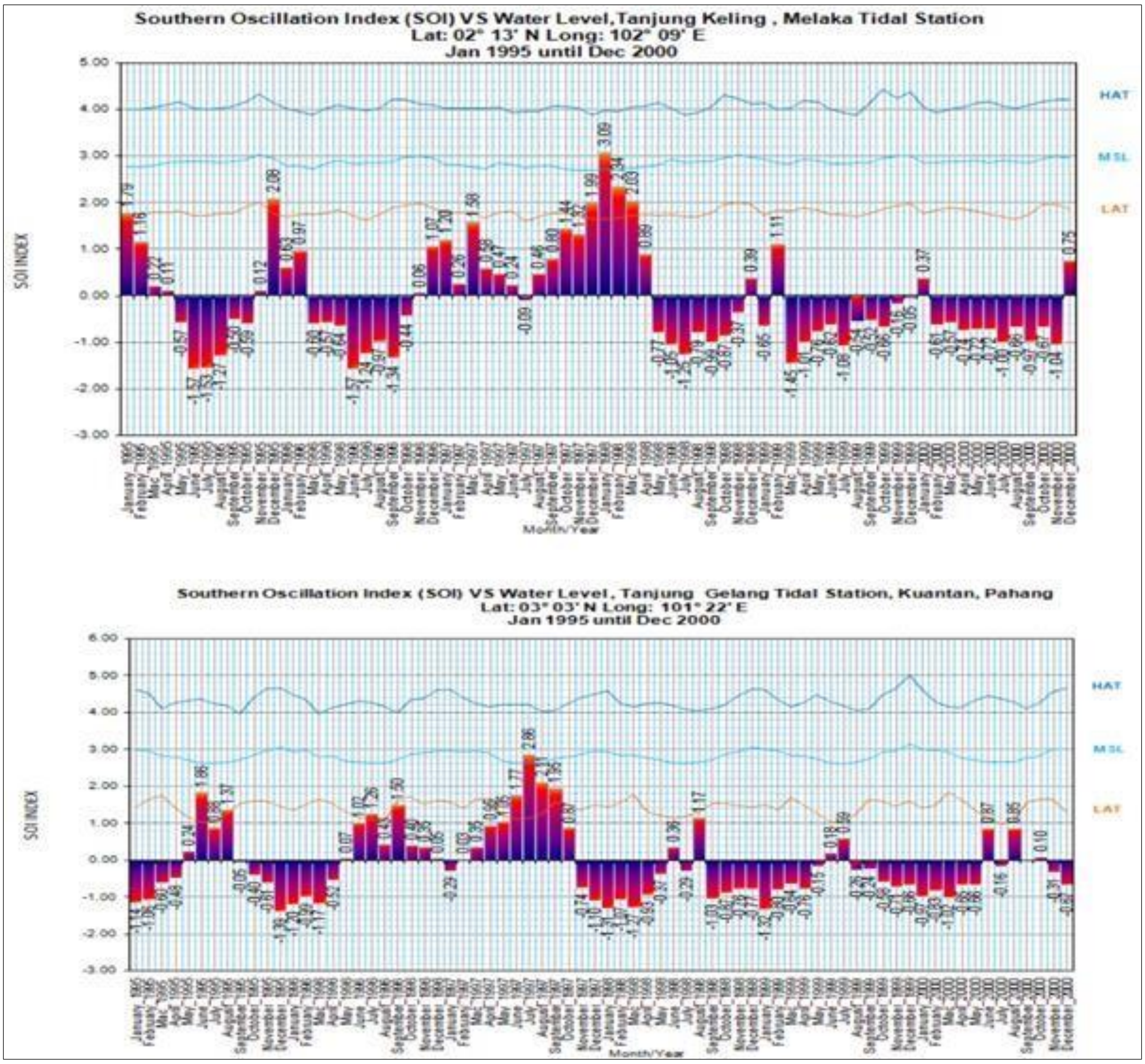

Figure 3.16: Southern Oscillation Index (SOI) vs. water level – Tg. Keling (top) and Tg. Gelang (bottom) (Hilmi et al., 2015)

A trend in storm surge pattern has their own localise characteristics and subjected to geographical location of the observation point. In the eastern coast of PM (ECPM) for instance, the northern part of the ECPM (Kelantan coast) is aligned towards north-northeast orientation, going south then orientated towards northeast (45 degN, Chendering), eastward in southern coast of Terengganu and so on as shown in Figure 3.17. The variance in the orientation of the coast projected different storm surge height. Furthermore, coupled with the continental shelf fronting the coast along ECPM varies in distance and width, has indirectly contributed to various degree of upsurge generated by far away storm genesis towards the shoreline.

Earlier, the trends analysis on the storm surge along the ECPM has been studied by Mohd Anuar et al. (2018) and their investigation leads to an increasing trend and fall out due to ENSO effects at five (5) tidal observation stations starting from the north, at Paknam Bangnara (PB) in southern most Thailand, Geting (GT), Chendering (CH), Tg. Gelang (TG) and Tioman

Island (TIO) in Malaysia, respectively. The trends in storm surge varied with each of the stations. The magnitudes of extreme storm surge generally increase from north to south, with typically high amplitude surge north of Kelantan and lower surge to the south. Though, storm surge is dependent on the intensity and the tracks of the tropical cyclone across the South China Sea. The amplitude of the surge can be contrary if a storm blow across the southern coast before travelled northward. And, test on the correlation or dependency has shown a variation of strength of correlation between the paired stations. For this study, the availability of other neighbouring observation data is limited. Thus, the results produced by Mohd Anuar et al. (2018) is considered valid and significant for the purpose of this study.

Figure 3.17: Coastline orientation along 5 tidal stations

The correlation (r) between observed data was performed between stations and a confidence level of 95% was used in their study, as given in Table 3.7. The PB and GT is moderately correlated with storm surge height of both stations reflecting the existence of an interrelationship of a concurrent surge event. In another words, when high surge is experienced in GT, the probability of PB getting high or slightly higher surge than GT is possible. Continue with GT and CH, the dependency is weak due to different geo-location (coastal orientation as well as sea bottom topography control the receiving surge near the coast), but stronger correlation between southern paired stations. Contrariwise, when southern coast is first hit by severe storm, gradually adjacent northern coasts will experience the same storm but moderate to weaker intensity, hence a minor surge is observed. The results of each paired station are shown in Figure 3.18.

Table 3.7: Correlation test, *r*, on paired stations (Mohd Anuar et al., 2018)

Station	Paknam Bangnara	Geting	Chendering	Tg. Gelang	Tioman Island
Paknam Bangnara		0.611	0.21	0.161	0.155
Geting	0.611		0.126	0.055	0.055
Chendering	0.21	0.126		0.815	0.825
Tg. Gelang	0.161	0.055	0.815		0.948
Tioman Island	0.155	0.055	0.825	0.948	

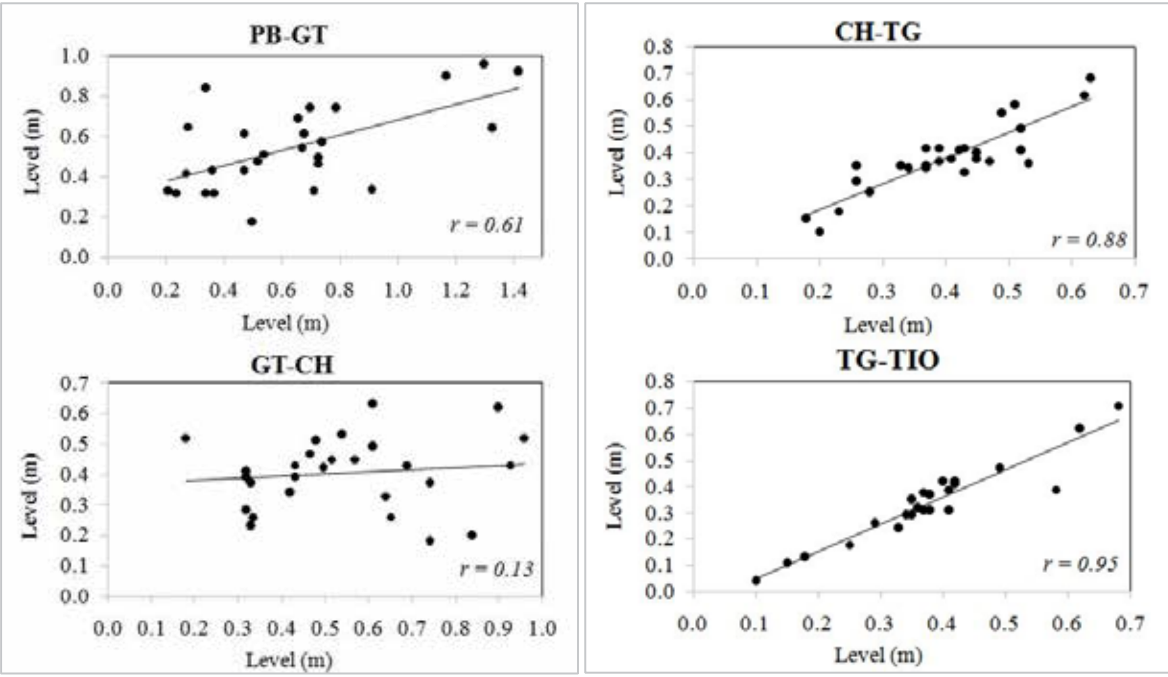

Figure 3.18: Strength of correlation between paired stations (Mohd Anuar et al., 2018)

Linking coastal erosion to natural climate patterns, such as El Niño/Southern Oscillation and the Southern Annular Mode, can be challenging. Coastlines of Malaysia is particularly dynamic, especially in the east coasts as they are exposed to storm waves generated often thousands of miles away. This research is of particular importance as it can help east coast coastal communities prepare for the effects of changing storm regimes driven by climate oscillations like El Niño and La Niña. Characters of ENSO effects may differ in the Strait of Malacca. To help us complete the puzzle, for the next step we would like to look at coastal regions in the Straits of Malacca (SM) using Tg. Keling tide data.

3.4.2 Tg. Keling Station

Tg. Keling located about 190 km north from Tg. Piai at the narrowest part of the Strait of Malacca (Figure 3.19). Flank by Sumatera island in the west and Riau archipelago in the south, has restricted the passage for stronger incoming storm waves from the east, southeast and northwest. Malacca in general is not boasted of severe marine climate conditions, either from waves, currents or even offshore storm winds. Assessment on an offshore hindcasted wind-wave data (GRW) located just offshore Lumut a bit further north from Tg. Keling shown a variation in wind speed during NEM (from 345° to 5°N window) and SWM (from 150° to 180°N window) period as given in Figure 3.20.

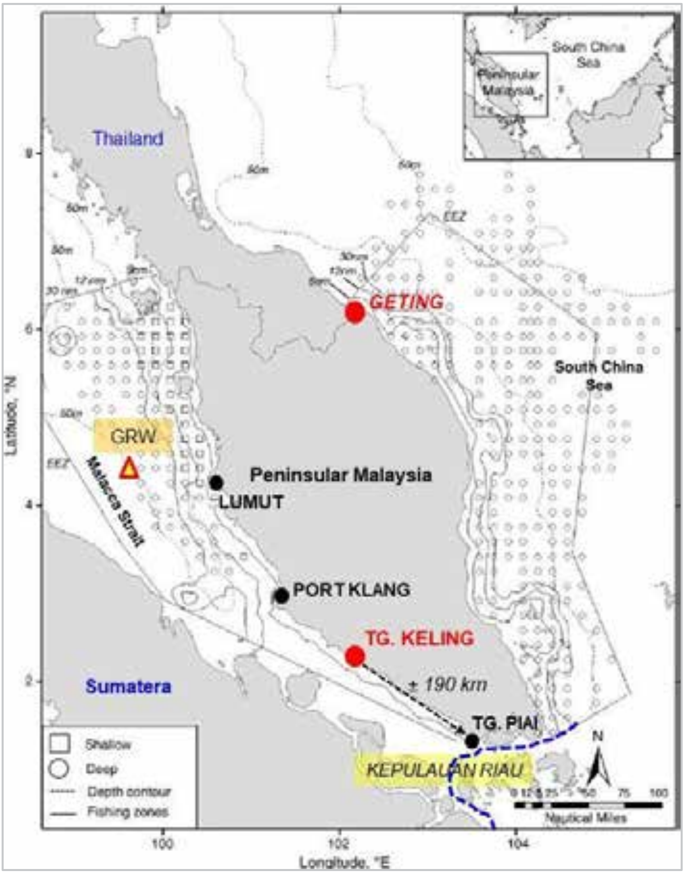

Figure 3.19: Tg. Keling station and offshore wind-wave (GRW) data location

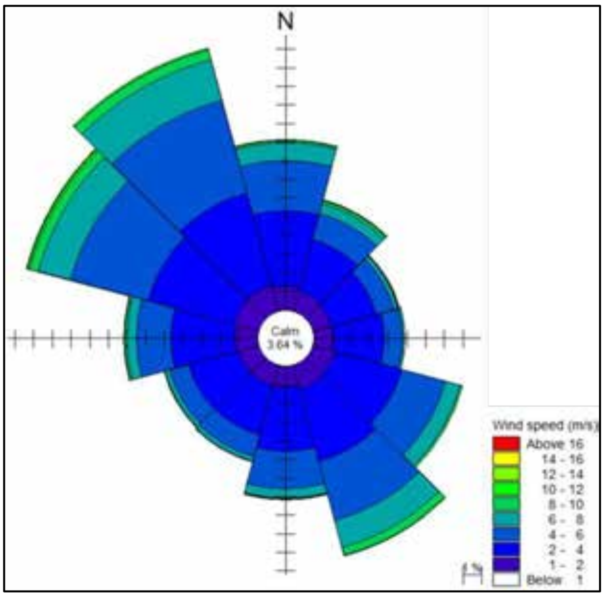

Figure 3.20: Offshore wind rose from 34-year data (1979-2012)

The most significant weather phenomenon during the SW Monsoon is the occasional occurrence of late-night and early-morning thunderstorm squalls known as “Sumatras”. These storms usually give rise to southwest and northwest winds gusting to 13.9 m/s that normally accompanied by heavy rain. A strong Sumatras may produce a gust of up to 26 m/s or higher. Although the storm occurrence is sudden with seldom persist more than one or two hours but moderate to light rain may continue several hours. Thus, the “squalls” or “gust wind” may likely influenced the abnormal upsurge in residuals amplitude in Tg. Keling.

The trends in Tg. Keling residuals shown an increasing pattern from the start of the observation period in year 1984 (see Figure 3.21). However, the extreme events only happened in year 1988, 1999, 2001, 2004, 2008, 2010, 2011, 2013, 2016 and 2017, respectively, with residual heights all recorded a level of above 0.37 m. By comparing the extreme events with the ENSO years, events in year 2004 and 2013 occurred during normal year, whilst 2010 during El Niño year and others occurred during La Niña year, respectively. Lower residuals with less than 0.37 m occur in various combination of the ENSO year. The future residual is expected to rise and fall under the influence of dominant climate forces such as winds and sea surface temperature which the latter very much controlled the ENSO effects, and the trend is incline towards a rising pattern.

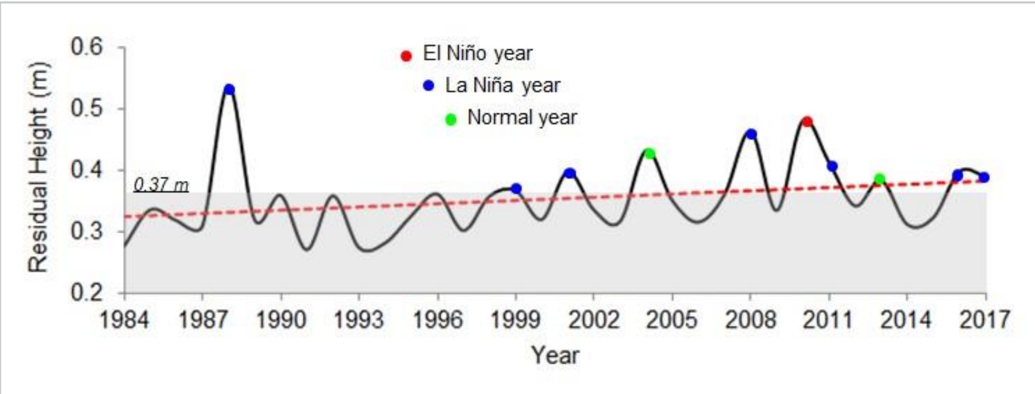

Figure 3.21: Annual residual height coincides with ENSO year – Tg. Keling

Neighbouring station closest in distance to Tg. Keling is Port Klang some 150 km in the north and about 180 km to Kukup near Tg. Piai (south). Port Klang tidal station covered almost 34 years of observed water level data, whilst Kukup only managed to have 9-year gauging records. Correlation analysis for paired station between Tg. Keling (TK) and Port Klang (PK) is sufficient as shown in Figure 3.22, but the resulted r is very low (r = 0.28), an indication that there is no interrelationship between the two events to experience simultaneous extreme at any other time and phase. In contrast with Tg. Keling, Port Klang experienced a recurrence residual height of range 0.3 – 0.5 m and 0.5 – 1.0 m, almost 58% and 98% higher than Tg. Keling, which explained the weak dependency in concurrent events between the pair.

Pairing with Kukup however is unlikely as the station has less than 10 years of data which is insufficient to produce acceptable result. Overall, each station has residuals that dissimilar in amplitudes and period of occurrence and is likely to encounter different climate drivers (wave, winds and currents) which resulted in distinct impact. Location wise, Port Klang (PK) is more accessible to the strong NWestern winds from Andaman and an occasional strong Sumatra squalls from Southwest.

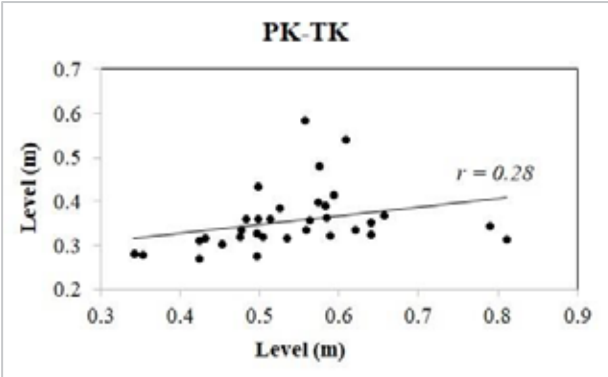

Figure 3.22: Correlation test between Tg. Keling (TK) and Port Klang (PK)

At present, Malacca coastline has been flanked by various magnitude of reclamation land mostly developed and landed by private sectors since the early 1990's. These actions have produced an unwelcome effect to the hydraulic characteristics nearshore. Some of the reclaimed land extended quite a distance which left at present 50 km out of 57 km in year 1994 from Malacca to Pulau Rupat in Sumatera (as shown in Figure 3.23 using Google Earth pictures).

Figure 3.23: Coastline changes along Malacca coastline – waterway passage near Tg. Keling is narrower from year 1994 to 2016 (*Source: Google Earth*)

In comparison to regional impact, the difference may not be significant but the impact is more pronounced locally with severe erosion detected south of Pulau Melaka due to changes in hydraulic meteorological pattern via reclamation activities over the years. As of changes in residual amplitudes, the changes will vary and going through an evolution as future climate changes.

3.5 Storm Surge Probability Periods

Storm surge return periods are useful to land use planners and emergency managers for assessing the likelihood of extreme water depths associated with tropical cyclones. At a given location, it is desirable to determine sound statistical estimates of return periods (typically for 10, 25 and 50-year epochs) and corresponding assessments of uncertainty. The goal is to determine statistical estimates that provide the scientific best prediction of return period. Uncertainties include both limitations in the historical record and effects of parameter estimation. In this report, a methodology is given for forecasting maximum storm surges using the Gumbel distribution method (Gumbel, 1954). This general approach is illustrated with Geting in Kelantan and Tg. Keling in Malacca.

Globally, climatologists have hypothesised that storminess is increasing with climate change, and a series of empirical studies have investigated the evolution in storm climate from the past century until present (Schmidt and von Storch, 1993; IPCC, 2019). Locally, the storminess pattern is somewhat vague with researchers emphasized more in changes in sea level rise rather than the storminess and the resultant surge. Indeed, looking and analysing the in-situ data on surge levels at site for which sufficiently long observational records are available, the magnitude and frequency of storms may increase especially during the past twenty years or so. Which, the analysis on trend has been covered in the previous section.

Frankly, there is no empirical evidence, however, for any corresponding increase in storm surge elevations as the trends in observational data may also be dominated by highly localised effects, especially since tide gauges are often based in estuarine ports which is susceptible to annual or recurring dredging activities. Using statistical approach allow us to describe temporal trends in storm surge characteristics, whilst properly accounting for the effects of natural variability. Using Gumbel Extreme Value Type I developed by E. J. Gumbel in 1954, the Gumbel distribution equation for peak surge estimation at return period, *T*, is:

$$\alpha T = \bar{\alpha} + K\sigma \quad (3)$$

where: αT denotes the magnitude of the return period, *T*-year surge event, *K* is the frequency factor, $\bar{\alpha}$ and σ are the mean and standard deviation of the peak surge respectively. The frequency factor *K* is expressed as:

$$K = Y_T - \bar{y}/S_x \quad (4)$$

In which $\bar{y}$ is the reduced mean, S_x is the reduced standard deviation and reduced variate, Y_T is expressed as:

$$Y_T = -[\{ln(ln(T/T-1))\}] \quad (5)$$

where the *T-year* return level corresponds to the level which is exceeded with probability *1/T* in any particular year, and is used as a design parameter in coastal engineering applications.

The first approach was to establish an annual maxima (AM) series as is typically done in extreme value analysis. The extreme value is used to identify the AM of the surge data, though the method allows only one observation per year. An alternative method such as peak-overthreshold or POT although allow more observations within the specified threshold value, but may not correctly interpreted the term 'extreme' to establish a good estimation of a return level. The choice of threshold value for the POT approach also dependent on the researcher whether to have more numbers of events than the number of years of data, hence the selection is subjective and neglected for this study. However, for comparison purposes, the attempt could be informative for research and in depth understanding on the result, though for future study perhaps.

Exercising the Gumbel method on Geting in ECPM and Tg. Keling in SM, respectively leads to a series of extreme storm surge heights in various return levels. The approach used in this study allows the evaluation of return periods for observed extremes and the extrapolation to longer return periods and larger extremes than those represented in the historical record.

The steps to estimate the design surge or residual for any return period, is as follows:

i) Annual maxima (AM) peak surge/residual was assembled from 1984 to 2017 for Tg. Keling and 1986-2017 for Geting;

ii) From the maximum surge/residual data for n years, the mean, $\bar{\alpha}$ and standard deviation for the sample size, σ are computed using:

$$\bar{\alpha} = \frac{\sum \alpha^i}{n} \quad (6)$$

$$\sigma = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (\alpha - \bar{\alpha})^2} \quad (7)$$

iii) From the Gumbel's extreme distribution table provided by (Subramaya, 1984), with the given N, the value of $\bar{y}$ and S_x are 0.5396 and 1.1255 for Tg. Keling and 0.538 and 1.1193 for Geting, respectively;

iv) From the given return period T, the reduced variate Y_T is computed using Equation (5);

v) Using Equation (4) to compute frequency factor, K;

vi) With the use of Equation (3), the magnitude of surge/residual is computed; and

vii) Using the array of computed surge/residual with their respective return period, interpolate the observed surge/residual return periods.

The observed surge/residual data need to be confirmed if they follow the Gumbel's distribution. In order to performed the task, by assigning the return period for each surge/residual; the reduced variate for each data is computed using Equation (5). The values for a given return period, *T* determined by Gumbel's method can have errors due to limited observed data, especially when larger return period is required for design purposes, an estimate of confidence limits of the estimate is desirable. The confidence probability, *c*, the confidence interval of the variate α_T is bounded by values α_1 and α_2 given by,

$$\alpha_{1/2} = \alpha_T \pm f(c)\, S_e \qquad (8)$$

where f(c) = function of confidence probability c determined by using the table of normal variates (Subramaya, 1984). The probable error, S_e is denoted by,

$$S_e = b\frac{\sigma_{n-1}}{\sqrt{N}} \qquad (9)$$

$$b = \sqrt{1 + 1.3K + 1.1K^2} \qquad (10)$$

K = frequency factor given by Eq. (2)

σ_{n-1} = standard deviation of the sample

N = number of year

The confidence interval taken from Subramaya (1984) for 95% confidence probability is 1.96.

Tables 3.8 and 3.9 shows the computed return period and reduces variate each for Tg. Keling and Geting data respectively. Also, a plot of return periods versus AM of surge/residual was plotted for each stations, which is shown in Figures 3.24 and 3.25. From Table 3.8 the results show the expected surge/residuals at Tg. Keling for return periods as low as 2-yr, 5-yr, 10-yr until 2000-yr Return Period (RP). Values of return periods for observed surge/residual were computed using the above mentioned method with the highest return level of 56-yr Return Period shown in 1988 event. Return Period of 2-yr, ±5-yr and ±10-yr occurred in year 2012, 2001 and 2008, respectively. The analysis on Tg. Keling data shown that the average observed surge/residual magnitude is 0.35 m which is having a return period of 2.3 years.

Whilst in Table 3.9, year 1988 also indicates the highest magnitude of surge height at 0.96 m in Geting station but with lower return period of 20yr compared with Tg. Keling. Then followed by year 1997, 1994 and then 1993 with their respective 10yr, 5yr and 2yrRP, respectively. The 32-years average surge is 0.60 m corresponding to 2.3yrRP.

Table 3.8: Calculation of T and Y_T, expected and observed – Tg. Keling

Return Period, *T*	**Expected Surge/ Residual (m)**	**Observation Year**	**Observed Peak Surge/ Residual (m)**	**Peak Surge/ Residual in ascending order (m)**	**Reduced variate, Y_{Tob}**	**Return Period, T_{ob}**
1.01	0.24	1984	0.28	0.27	-1.3021	1.0
1.1	0.28	1985	0.34	0.27	-1.0567	1.1
1.5	0.32	1986	0.32	0.28	-0.9479	1.1
2	**0.34**	1987	0.31	0.28	-0.7662	1.1
3	0.37	**1988**	**0.54**	0.30	-0.3361	1.3
4	0.39	1989	0.32	0.31	-0.2316	1.4
5	**0.41**	1990	0.36	0.31	-0.1932	1.4
6	0.42	1991	0.27	0.32	-0.1454	1.5
8	0.43	1992	0.36	0.32	-0.1355	1.5
10	**0.45**	1993	0.27	0.32	-0.1104	1.5
15	0.47	1994	0.28	0.32	-0.1044	1.5
20	0.48	1995	0.33	0.32	-0.0929	1.5
25	0.50	1996	0.36	0.32	-0.0214	1.6
30	**0.51**	1997	0.30	0.33	0.0384	1.6
35	0.51	1998	0.36	0.33	0.2022	1.8
40	0.52	1999	0.37	0.34	0.2207	1.8
45	0.53	2000	0.32	0.34	0.2291	1.8
50	**0.53**	**2001**	**0.40**	**0.34**	0.3306	**2.0**
55	0.54	2002	0.34	0.35	0.5728	2.3
60	**0.54**	2003	0.32	0.36	0.7541	2.7
65	0.55	2004	0.43	0.36	0.7711	2.7
70	0.55	2005	0.35	0.36	0.7866	2.7
75	0.56	2006	0.32	0.36	0.8151	2.8
80	0.56	2007	0.36	0.36	0.8333	2.8
85	0.56	**2008**	**0.46**	0.37	0.9498	3.1
90	0.57	2009	0.33	0.38	1.2309	3.9
95	0.57	2010	0.48	0.39	1.3223	4.3
100	**0.57**	2011	0.41	0.40	1.4151	4.6
200	0.61	**2012**	**0.34**	**0.40**	1.4215	**4.7**
300	0.63	2013	0.38	0.41	1.5910	5.4
400	0.64	2014	0.31	0.43	2.0651	8.4
500	**0.66**	2015	0.32	**0.46**	2.4733	**12.4**
1000	**0.69**	2016	0.40	0.48	2.9335	19.3
2000	0.73	2017	0.39	**0.54**	4.0156	**56.0**
Observed Level (m)		***Surge/ Residual***				***RP (yr)***
Minimum		***0.27***				***1.0***
Maximum		***0.54***				***56***
Average		***0.35***				***2.3***

Table 3.9: Calculation of T and Y_T, expected and observed – Geting

Return Period, *T*	Expected Surge/ Residual (m)	Observation Year	Observed Peak Surge/ Residual (m)	Peak Surge/ Residual in ascending order (m)	Reduced variate, Y_{Tob}	Return Period, T_{ob}
1.01	0.28	1984	-	-	-	-
1.1	0.38	1985	-	-	-	-
1.5	0.50	1986	0.95	0.35	-1.0045	1.1
2	**0.57**	1987	0.89	0.37	-0.9068	1.1
3	0.65	**1988**	**0.96**	0.39	-0.7548	1.1
4	0.70	1989	0.53	0.42	-0.5146	1.2
5	**0.74**	1990	0.44	0.44	-0.4029	1.3
6	0.77	1991	0.65	0.44	-0.3993	1.3
8	0.82	1992	0.49	0.44	-0.3860	1.3
10	**0.86**	**1993**	**0.58**	0.46	-0.2563	1.4
15	0.92	**1994**	**0.74**	0.48	-0.1981	1.4
20	0.97	1995	0.46	0.48	-0.1638	1.4
25	1.00	1996	0.68	0.49	-0.1546	1.5
30	**1.03**	**1997**	**0.86**	0.49	0.0311	1.6
35	1.05	1998	0.39	0.52	0.1055	1.7
40	1.07	1999	0.61	0.53	0.1082	1.7
45	1.09	2000	0.42	0.53	0.2477	1.8
50	**1.11**	2001	0.48	0.55	0.4125	2.1
55	1.12	2002	0.35	**0.58**	0.4156	**2.1**
60	**1.13**	2003	0.44	0.58	0.6134	2.4
65	1.15	2004	0.55	0.61	0.7556	2.7
70	1.16	2005	0.48	0.61	0.7879	2.7
75	1.17	2006	0.49	0.62	0.8115	2.8
80	1.18	2007	0.52	0.65	1.0634	3.4
85	1.19	2008	0.53	0.66	1.1198	3.6
90	1.20	2009	0.62	0.68	1.2140	3.9
95	1.20	2010	0.73	0.73	1.4692	4.9
100	**1.21**	2011	0.77	**0.74**	1.4786	**4.9**
200	1.32	2012	0.61	0.77	1.7761	6.4
300	1.38	2013	0.44	0.81	2.0298	8.1
400	1.42	2014	0.81	**0.86**	2.2689	**10.2**
500	**1.46**	2015	0.37	0.89	2.3846	11.4
1000	**1.56**	2016	0.58	0.95	2.9095	18.9
2000	1.67	2017	0.66	**0.96**	2.9645	**19.9**
Observed Level (m)		***Surge/ Residual***				***RP (yr)***
Minimum		***0.35***				***1.1***
Maximum		***0.96***				***20***
Average		***0.60***				***2.3***

From Figure 3.24 and Figure 3.25, with the trend line resulted in r = 0.99 for Tg. Keling and r = 0.987 for Geting, both observed mean surge/residual are close to the expected mean surge/residual values with percentage in variance calculated at 4.1% and 5.8% for Tg. Keling and Geting data respectively. The plots follow a narrow trend line concur with the Gumbel's distribution method and is suitable for predicting expected surge/residual in Tg. Keling and Getting stations. Further calculation on a 100yr RP, Tg. Keling and Geting each gave a 0.60 m and 1.32 m surge height, thus the possibility of occurrence is present based on the fitted distribution.

Although return periods have been provided for the (reasonable fit) distributions utilized herein, clearly some distributions fit better than others and therefore are preferable when used for design and/or cost benefit analysis. While it is seen that the surge magnitudes are similar for low return periods in practically all of the distributions utilized, there is a wide discrepancy in the surge magnitudes for the different distributions at large return periods critical to project design. Hence, a critical judgement is called for in deciding a profundity approach to be taken.

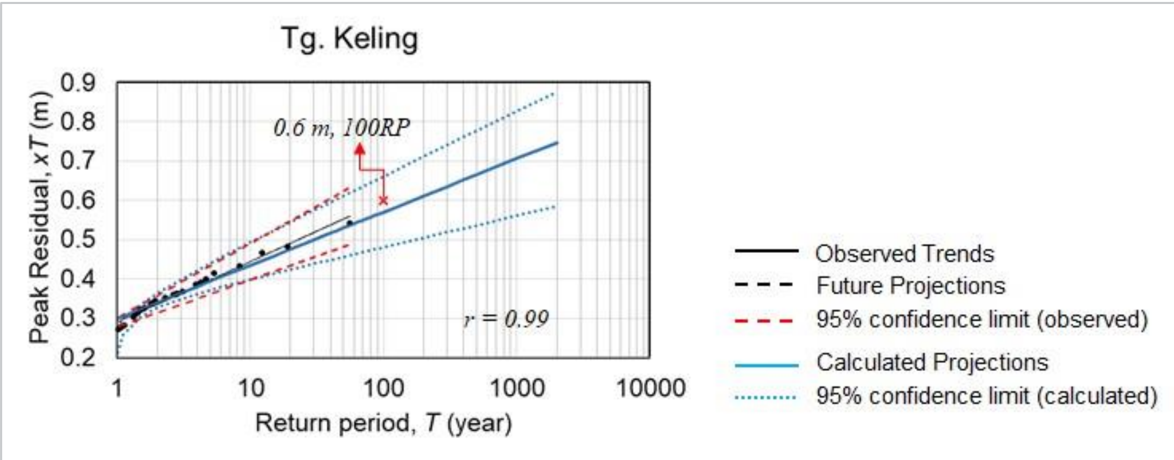

Figure 3.24: Return period vs. Peak residual for Tg. Keling

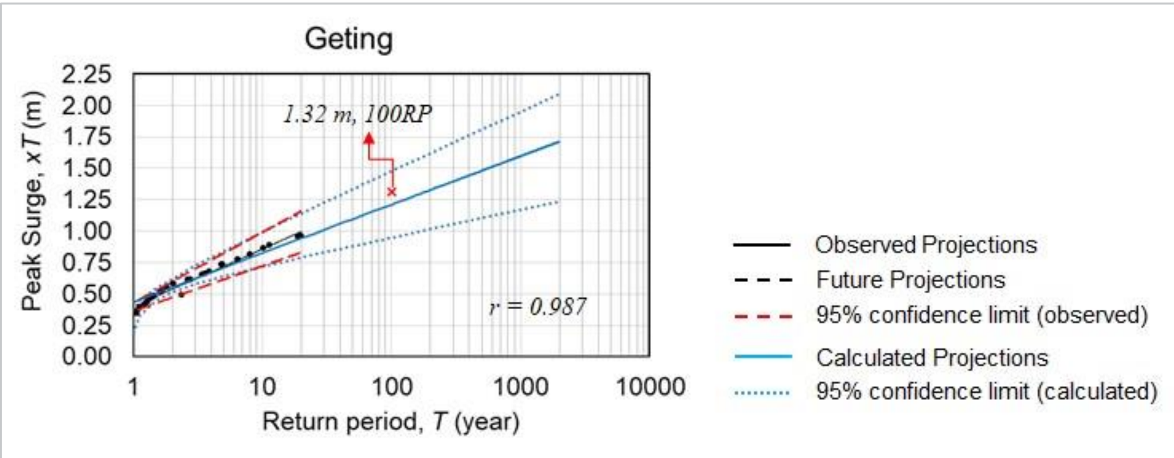

Figure 3.25: Return period vs. Peak Surge for Geting

3.6 Storm Surge Risk Assessment

Storm surge, as explained earlier is the increased sea surface elevation resulting from a tropical cyclone traverse from a far fetch distance moving towards adjacent coast, a fair distance from Malaysia. Historically, tropical cyclone (TC) records compiled by Hong Kong Observatory (HKO), Japan Meteorological Agency (JMA) and Joint Typhoon Warning Center (JTWC) in West North Pacific including South China Sea, from as early as 1945 until 2018 is impressive. However, the TC genesis numbers that moving into the South China Sea closer to the ECPM is less. Notwithstanding the numbers, the offshore or far away distance genesis and tracks which indirectly made an impression on the sea surface elevation along the ECPM is increasing in numbers as the sea temperature rises globally (IPCC, 2019). Table 3.10 list out the native distance of TC genesis with respect to storm surge events in ECPM from 1986 to 2012 investigated by Mohd Anuar et al. (2019). Note that overall the TC native distance to ECPM and the respective storm surge is not in linearity. Nonetheless, the surge magnitudes were significant and more likely will reduce the coastal structure lifespan and a beach resiliency to recover.

Table 3.10: Storm surge event with respect to nearshore and offshore TC genesis in the ECPM (Mohd Anuar et al., 2019)

Name	**Month Yr**	**Storm Surge (m)**				**TC speed (m/s)**	**Distance (km)**	**TC air pressure (hPa)**
		GT	**CH**	**TG**	**TIO**			
TD	Nov-86	0.96	0.39	0.27	0.20	16	844	1002
TD Ogden	Nov-87	0.90	0.67	0.63	0.62	13	1260	1003
STS Tess	Nov-88	0.93	0.43	0.44	0.48	36	1110	970
TS Gay	Nov-89	0.52	0.45	0.42	0.42	18	159	1000
TD Forrest	Nov-92	0.51	0.42	0.41	0.39	16	230	995
TS Manny	Dec-93	0.57	0.45	0.38	0.39	18	1285	995
TS Owen	Apr-94	0.20	0.19	0.20	0.17	23	1700	996
STS Linda	Nov-97	0.44	0.31	0.32	0.27	25	330	985
TD	Dec-99	0.62	0.63	0.68	0.71	16	1045	1000
TD Durian	Dec-06	0.50	0.54	0.58	0.52	23	680	985
STS Hagibis	Nov-07	0.25	0.29	0.26	0.27	31	1215	975
ST Megi	Oct-10	0.74	0.37	0.34	-	49	2140	940
TD	Nov-12	0.65	-	0.52	-	16	660	1002

Notes: TD = Tropical Depression
TS = Tropical Storm
STS = Severe Tropical Storm
ST = Severe Typhoon

Differ from storm surge that affected the coast of Philippines, the alleged storm surges were caused by tropical cyclone that made landfalls near or at the coast, which the impacts were devastated and often cause enormous damage and losses to coastal regions, in particular the loss of life. The numbers of TCs over the years and as far as predicted by global researchers, are increasing in intensity though not in parallel in numbers or frequency (Elsner et al., 2008; Webster et al., 2005, Wang et al., 2007) with stronger storm intensify from 2% to 11% by 2100 (Knutson et al., 2010) and China top the most risk area to be affected by storm surges among the East Asia and Pacific region by 39.4% (Dasgupta et al., 2009b).

As planning and management of coastal zone is an ongoing and continuous processes, among the coping strategies to be decided by government, risk assessment in storm surge is seldom being dealt with and thus should be a primary work undertaken along other marine climate hazard, i.e. waves and currents. Therefore, understanding the characteristics of risk associated with TC storm surges for the coastal regions along the Kelantan, Negeri Sembilan and Malacca is of great interest in this study. Lin et al. (2010) indicated that storm surge risk assessment is the basis for decision making and mitigation recommendation purposes and others utilized different approaches and opinions which subjected to their objectives in interpreting the risks associated with storm surges (Webster et al., 2013; Brecht et al., 2012).

According to Brooks (2003), the vulnerability and adaptation of a community to the risk it presented due to climate change encompassed and applicable to a wide range of contexts, systems and hazards. Whilst the definition of risk specifically in natural disaster can be classified into two categories: (i) the probability of the occurrence of a hazard that acts to trigger a disaster or a series of events with an undesirable outcome, and (ii) the probability of a disaster or outcome combining the probability hazard event with a consideration of the likely consequences of the hazard. Here, Brooks (2003) implicitly tie the vulnerability with risk which also defined by Stenchion (1997) and UNDHA (1992). In simple understanding, the vulnerability of a coast depends on the probability of occurrence of a hazard (surges) and the social vulnerability of the exposed system, which will determine the consequence of the hazard.

Sea level rise will raise various degrees of implications socially and economically to coastal community resides in Negeri Sembilan, Malacca and Kelantan. The implication mostly associated with coastal erosion and coastal flooding due to breached of coastal protection structures or an erosion of a natural beach dunes, apart from anthropogenic inclined causes (dredging, mangrove deforesting, unscheduled development, etc.). The possible change in water level intrusion due to SLR to the present coast has been evaluated comprehensively by NAHRIM through hydrodynamical modelling using MIKE 21 model using the latest 2017 SLR projections.

The information gathered is significant especially for coastal development planning, risk evaluation on flooding and evacuation inclusive of the structural integrity and vulnerability. Thus, we look at the possibilities of flood intrusion along the coast of study via hydrodynamic model results in each projection years, followed by the beach dune sustainability and coastal structures integrity under design aspects to face the change in climate impact. From there on, a storm surge risk levels (indicated by Total Physical Vulnerability Index, PVI) are assigned into different categories where the risk assessment integrates the inundation hazard and the coastal structure vulnerability as the main indicator, in the zone of study.

The structures are either a natural or man-made coastal protection structures inclusive of natural beach. The storm surge risk assessment focus on the physical aspects of the coastal mitigation structures or beach. The assessment leans toward the integrity of the coastal structures and the sustainability of the present beach dune in withstanding the continuous impact of storm surge and waves with the assistance of SLR through an optimum design crest level.

3.6.1 Vulnerability Index

Coastal Vulnerability Index (CoVI) study of Malaysian coast which has been accomplished by NAHRIM in 2014, is adopted and 2017 SLR projections are employed. The storm surge level of risk is represented by a physical vulnerability index computed based on the average of two indicators, coastal structure and beach dune, after which each of them was adjusted based on a certain proposed weightage as follows:

Coastal structure (CS) – 40 %
Beach dune (BD) – 60 %

Greater weightage towards beach dune as compared to the other indicator reflects greater concern on the impact of the livelihood of the people affected. The scaling factors adopted for CS and BD are given in Table 3.11. The combined PVI is then computed according to the weightages that have been described earlier.

$$PVI = \frac{(A_1 \text{ x } W_1) + (A_2 \text{ x } W_2)}{2} \quad (11)$$

where,
A_1 = Crest level for coastal structures
A_2 = Crest level for beach dune
W_1= weighting factor for coastal structure
W_2 = weighing factor for beach dune

Hence, $$PVI = \frac{(A_1 \text{ x } 0.4) + (A_2 \text{ x } 0.6)}{2}$$

Table 3.11: Scaling for coastal protection and beach dune crest level

Description	Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)
A_1 (m MSL)	> 4.0	3.0 - 4.0	2.0 – 3.0	1.0 - 2.0	< 1.0
A_2 (m MSL)	> 3.0	2.0 – 3.0	1.5 - 2.0	1.0 – 1.5	< 1.0

The Physical Vulnerability Index (PVI) is total up according to the range given in Table 3.12.

Table 3.12: The total PVI score for the study area

Rank	1	2	3	4	5
Vulnerability	Very Low	Low	Moderate	High	Very High
Range	$x \leq 0.5$	$0.5 < x \leq 1.0$	$1.0 < x \leq 1.5$	$1.5 < x \leq 2.0$	$x > 2.0$

As mentioned earlier, the present numerical model on Kelantan, Negeri Sembilan and Malacca coasts were choreographed using the 2017 SLR projections in accordance with IPCC AR5 RCP 8.5. The year 2100 SLR projections (SLR study in year 2017) indicated a lesser magnitude than the study in year 2010 which utilized a satellite altimetry data with larger range of uncertainty due to the interannual cycle (NAHRIM, 2017). The 2017 study on SLR projections used both satellite altimetry and tide gauge observation data, and they veered towards smoother regional patterns aligned with global projections using latest scientific understanding reported in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (Church et al., 2013). In reference to the 2017 SLR study, the magnitude of the mean SLR is unchanged in west and east coast of PM for year projection 2030 at 0.11 m, but increase slowly in year 2100 with 0.69 m in Tg. Keling and 0.70 m in Geting, respectively. Figure 3.26 shows the mean SLR projection for year 2030, 2050 and 2100, respectively. The regional SLR pattern is gradually increasing and differ only at about 0.1 – 0.2 m from north to south Peninsular Malaysia under similar RCP 8.5. Risk assessment for Tg. Keling and Geting adopted the SLR magnitude from these three projections only.

Figure 3.26: Averaged SLR in Peninsular Malaysia under 2030 (black), 2050 (blue) and 2100 (red) projections (NAHRIM, 2017)

3.6.2 Design Crest Level

The design crest level of the structure is the main component in determining the level of risk, whether the current design is sufficient or require an upgrade to overcome future marine climate extremes. The height of a coastal structure in Malaysia for many years has been based on the highest known flood level that could be remembered since there is no inventory list was produced to co-related the two parameters (structural crest height and flood level or resultant damage). The extreme estimations often based on relatively short periods of observations, mostly have to extrapolated into regions far beyond the field of observations. And seldom based on overall marine climate drivers (often, storm surge is neglected). The following equation is the standard design water level (DWL) formula employed by broader coastal practitioners:

$$DWL = MHHW/MHWS + \text{Wind Set-up} + \text{Wave Set-up} + SLR \quad (12)$$

where,

MHHW = Mean Higher High Water (ECPM)
MHWS = Mean High Water Spring (WCPM)

and,

$$\text{Crest Level (CL)} = DWL + \text{wave run-up} \quad (13)$$

To cater for the probability of an increase in storminess and its' associated storm surge, Equation 10 is added up with storm surge level of respective return period. The highest tide level historically in Kelantan, Negeri Sembilan and Melaka were taken from the annual tide table data published by DSMM. East and west coast are represented with different tidal range with the east coast is more inclined to seasonal variations impact due to longer fetch and strong monsoonal winds/storms. Table 3.13 shows the tidal variance for station Geting and Tg. Keling based on DSSM long term tide level assessment. Wind set-up and wave set-up magnitudes were taken from previous study provided by NAHRIM.

Table 3.13: Tide level variance – Geting and Tg. Keling stations

Station	**Tide Level (mCD)**						
	HAT	**MHHW**	**MLHW**	**MSL**	**MHLW**	**MLLW**	**LAT**
Geting	1.78	1.27	0.95	0.74	0.52	0.20	0.00
	HAT	**MHWS**	**MHWN**	**MSL**	**MLWN**	**MLWS**	**LAT**
Tg. Keling	2.65	2.10	1.51	1.19	0.88	0.29	0.00

The likelihood of a coastal structure or beach dune to be overtopped, breached, failed or eroded is estimated using two storm surge return levels, the 25-year and 50-year storm surge. With a 25-year storm as the baseline, increasing the severity of this storm leads to a less likely but possible 50-year storm; similarly, reducing the severity of the 25-year baseline storm offers a candidate representative for a 10-year storm. Since changes in a particular storm's characteristics (track, intensity, forward speed and so forth) can have considerable impact on storm surge, the present approach lends itself to considerable debate.

Intuitively reasonable arguments may support the selection of a specific storm as the "25-year" storm based on the observed data, but an assessment of the uncertainty in the storm surge associated with this storm is unclear and uncovered in any similar investigation lead by (Mohd Anuar et al. 2018, 2019). A further difficulty emerges, if the 25-year time frame were replaced by a 50-year or 100-year time frame, the risk is likely to escalate. Despite these difficulties, a surge-specific approach is a reasonable start at identifying the level of risk. Such definitions are absolutely critical to make full and intelligent use of the historical storm surge set, which can estimate the level of risk of storm surges for a given location.

Hence, for the purpose of estimating the level of storm surge risk distribution in the study area, the selected return levels of 25-yr RP and 50-yr RP are employed herein until other more suitable approach (storm surge simulation) is established. The simulation model for the study areas were set-up in MSL, thus the resultant surface elevation (SE) used in the calculation of DWL need to incorporate the difference between the MHHW and MSL. Means that the extra difference between MSL and MHHW will have to add separately in the calculation of the DWL.

The bathymetry model was set-up under zero surface elevation mode to replicate the MSL conditions purposely for present and future impacts comparison analysis. Thus, the baseline model employed a zero-level elevation and subsequently, additional surface elevation with respect to individual projections were employed in each case models. A Digital Elevation Model (DEM) data was utilized only in small part of the study area due to insufficient data acquired from DSMM. For Kelantan, the DEM area only covered from Sg. Kelantan to Sg. Kemasin, whilst the area in Geting is not covered. Thus, the SE at Geting can only be applied as a rough estimation.

In Negeri Sembilan-Malacca, the DEM data starts from Port Dickson in Negeri Sembilan to Tg. Keling, thus the estimation of SE in Tg. Keling is not an issue and can be extract straightforwardly. Nevertheless, the DEM data acquired only covered certain part within the coverage area. For example, a detail inland elevation data covered only along the shoreline. At Sg. Linggi, the DEM covered from the river mouth up to approximately 3 km upstream but only close to river bank (both sides). Therefore, the inundation impact or flood intrusion was not projected as intended, which in general is not sufficient to represent the overall inundation impacts of the study sites due to SLR. Nevertheless, the risk assessments made are perceived as best as the data is presently made available.

The spatial resultant of surface elevations under year 2018 (baseline) and the respective projection year for Kelantan are shown in Figures 3.27 to 3.30, whilst Negeri Sembilan-Malacca in Figures 3.31 to 3.35, respectively.

As for crest level (CL) estimation, the wave runup was calculated based on the dominant nearshore wave results extracted from previous study. As all is considered, the following Table 3.14 shows the DWL and CL calculated for Kelantan, Negeri Sembilan and Malacca sites, respectively.

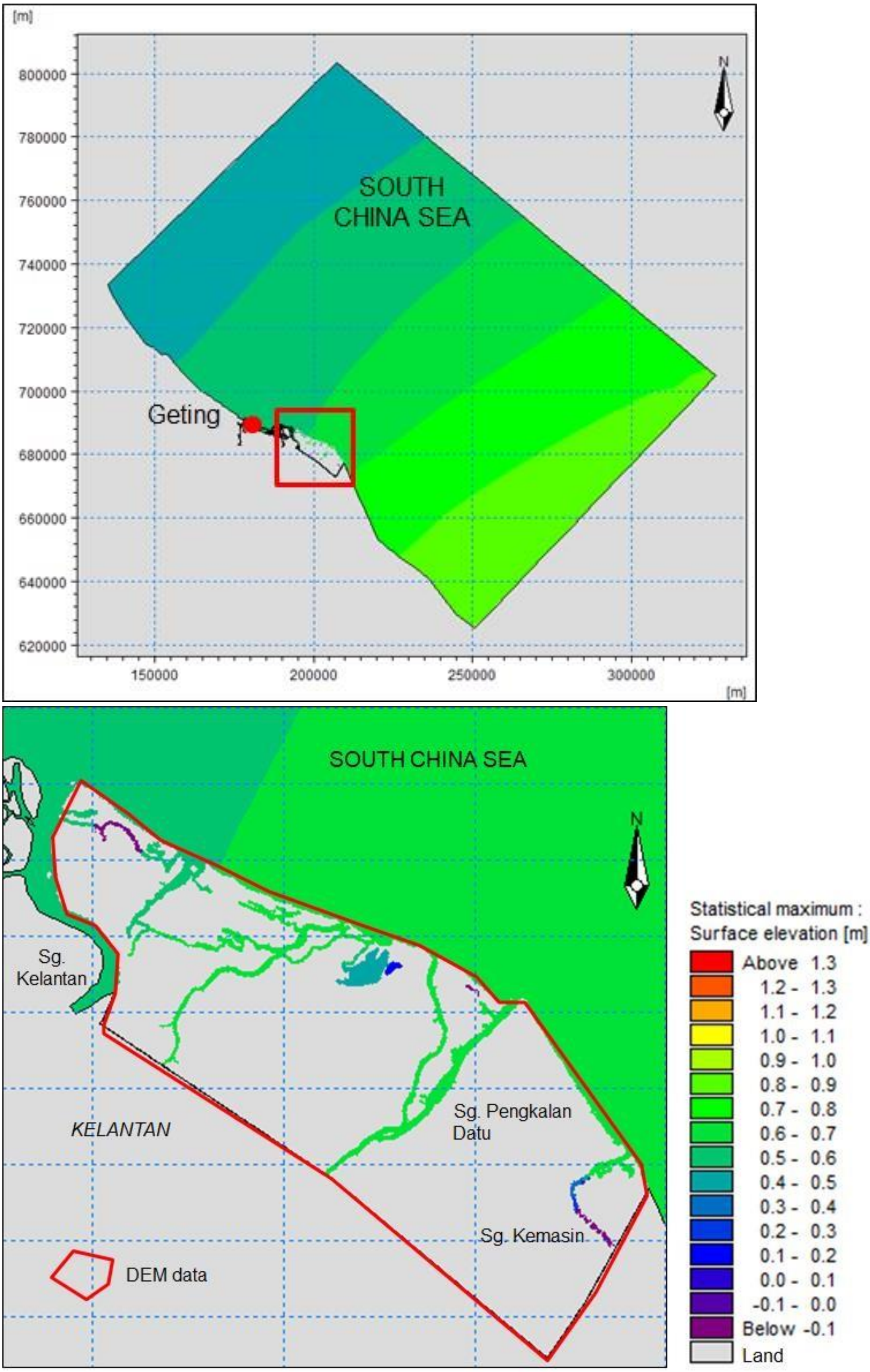

Figure 3.27: Max. surface elevation in Kelantan – baseline (2018). Model area (top). Close-up view on the DEM coverage area (bottom) identify in big model area (red box)

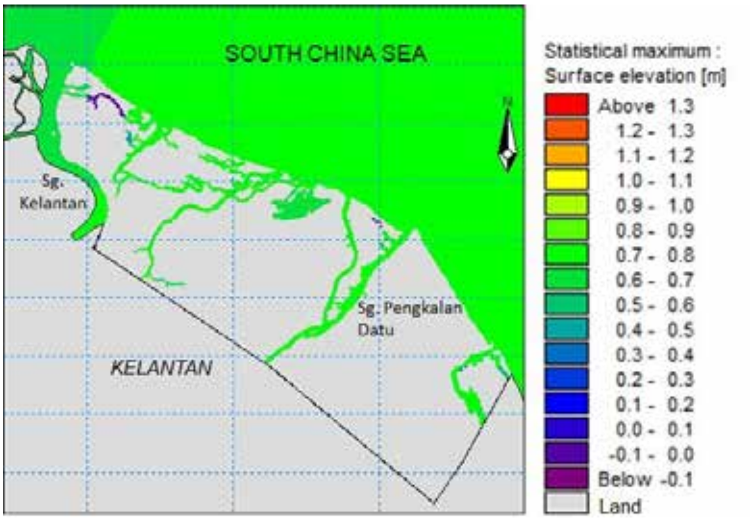

Figure 3.28: Max. surface elevation in Kelantan – projection year 2030

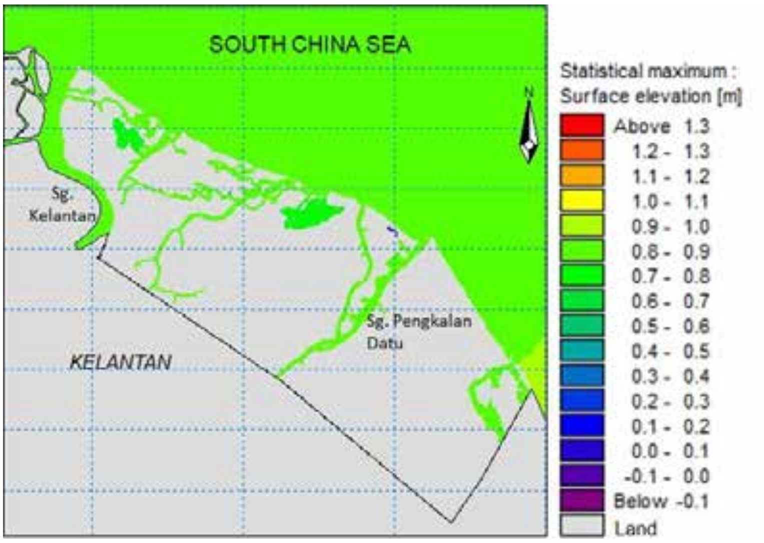

Figure 3.29: Max. surface elevation in Kelantan – projection year 2050

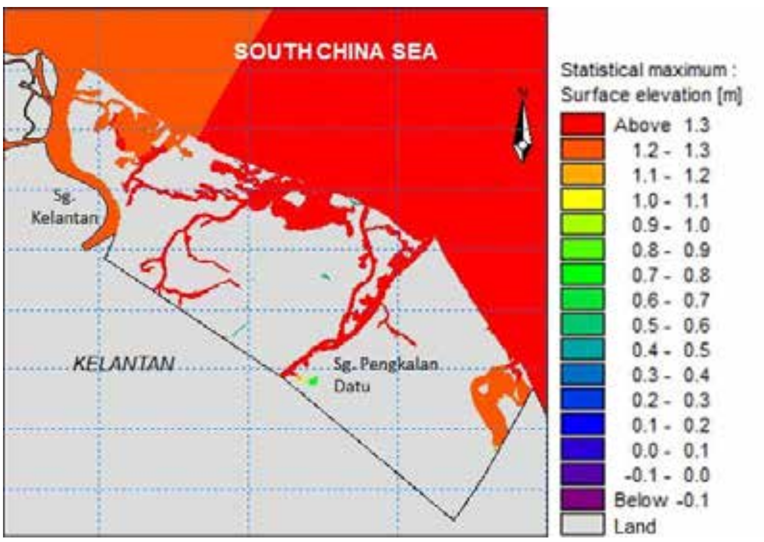

Figure 3.30: Max. surface elevation in Kelantan – projection year 2100

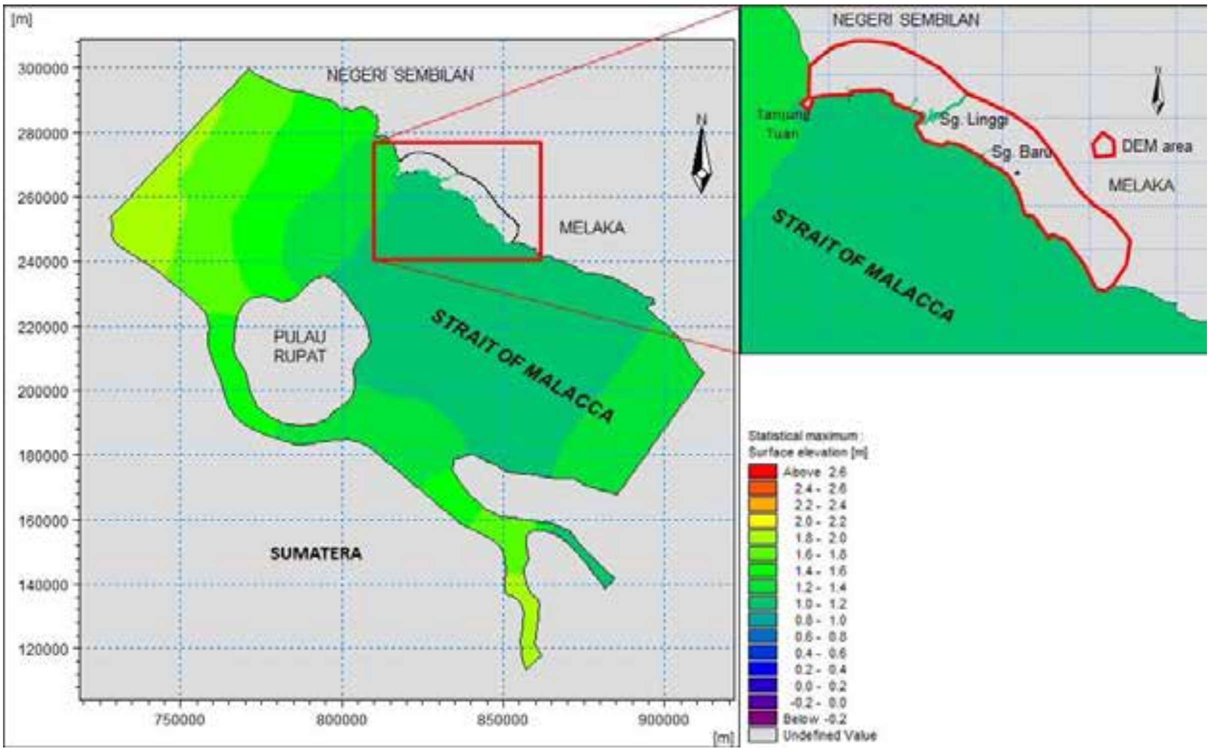

Figure 3.31: Max. surface elevation in Negeri Sembilan/ Malacca – baseline (2018). Model area (left) and close-up view of DEM area (top right)

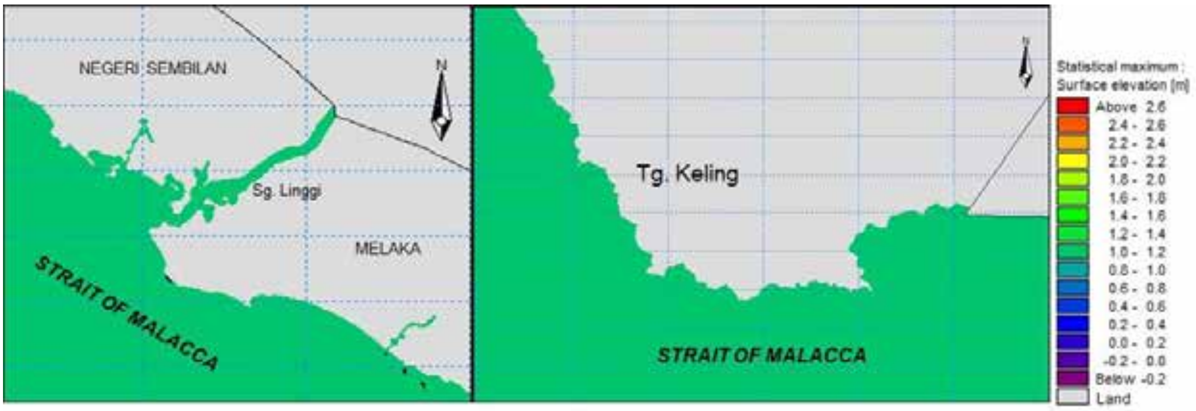

Figure 3.32: Max. surface elevation at Sg. Linggi and Tg. Keling – baseline (2018)

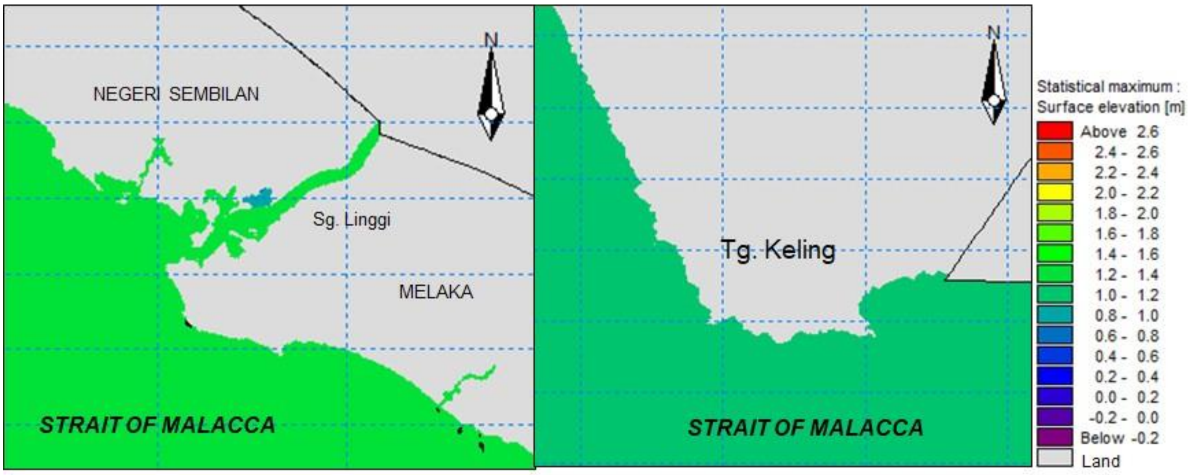

Figure 3.33: Max. surface elevation in Negeri Sembilan/ Malacca – projection year 2030

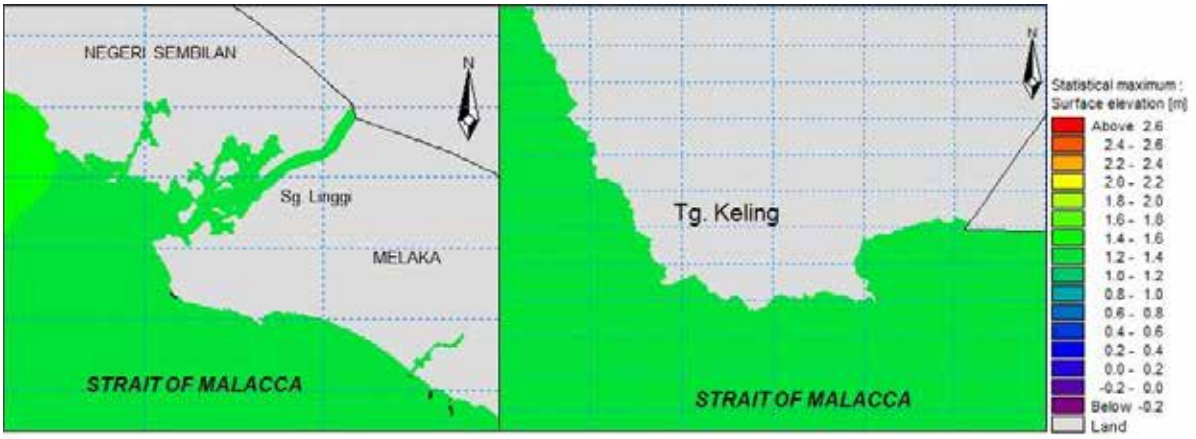

Figure 3.34: Max. surface elevation in Negeri Sembilan/ Malacca – projection year 2050

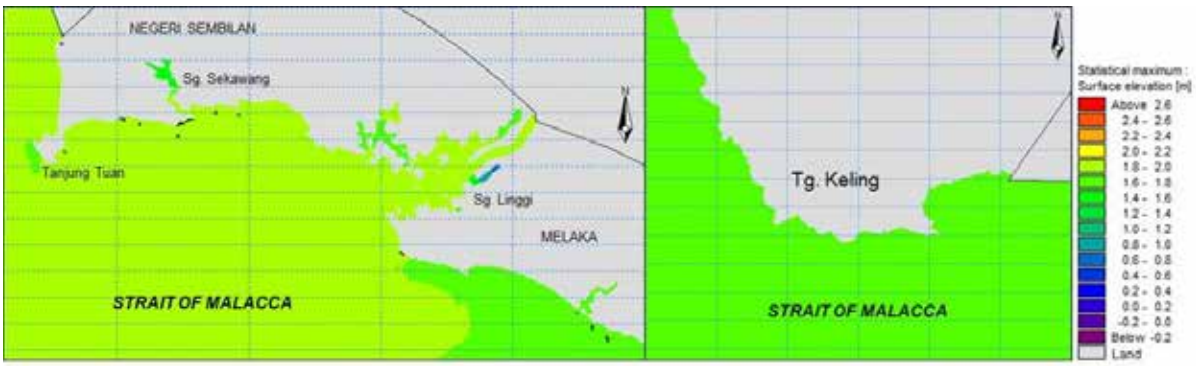

Figure 3.35: Max. surface elevation in Negeri Sembilan/ Malacca – projection year 2100

Table 3.14: Design parameters for Kelantan, Negeri Sembilan and Malacca study area

Item	**Kelantan**				**Negeri Sembilan/ Malacca**			
MHHW (m)	0.53				0.91			
Model @ MSL	2018	2030	2050	2100	2018	2030	2050	2100
Mean SE (m)	0.00	0.12	0.23	0.70	0.84	0.88	0.93	1.13
Max. SE (m)	0.55	0.67	0.78	1.25	1.06	1.17	1.28	1.74
Wind set-up (m)	0.02	0.02	0.02	0.02	0.10	0.10	0.10	0.10
Wave set-up (m)	0.70	0.70	0.72	0.80	0.30	0.30	0.32	0.35
SS25	1.00	1.00	1.00	1.00	0.49	0.49	0.49	0.49
SS50	1.11	1.11	1.11	1.11	0.53	0.53	0.53	0.53
Mean DWL25	2.25	2.37	2.50	3.05	2.64	2.68	2.75	2.98
Mean DWL50	2.36	2.48	2.61	3.16	2.68	2.72	2.79	3.02
Max. DWL25	2.80	2.92	3.05	3.60	2.86	2.97	3.10	3.59
Max. DWL50	2.91	3.03	3.16	3.71	2.90	3.01	3.14	3.63
Wave Runup	4.00	4.10	4.20	4.40	2.00	2.00	2.10	2.30
Mean CL25	6.25	6.47	6.70	7.45	4.64	4.68	4.85	5.28
Mean CL50	6.36	6.58	6.81	7.56	4.68	4.72	4.89	5.32
Max. CL25	6.80	7.02	7.25	8.00	4.86	4.97	5.20	5.89
Max. CL50	6.91	7.13	7.36	8.11	4.90	5.01	5.24	5.93

Note: SS25 – 25yrRP storm surge
DWL – design water level under 25yrRP storm surge
CL25 – crest level under 25yrRP storm surge

From the baseline model results shown in Figures 3.27 and 3.32, all model indicates an inland flooding at low lying area (DEM bathy area) with maximum SE reached above 0.5 m and no change in other part of the model space. The inundated area is spread even wider and the flood level increased from 0.8 m in year 2030 to above 1.2 m in year 2100 in Kelantan. Whilst in Negeri Sembilan and Malacca, the inundation area is small and concentrated along Sungai Linggi (the only area covered by extensive DEM data). Here, along Sg. Linggi the flood level is about 1.2 m, 1.4 m and above 1.8 m for year 2030, 2050 and 2100, respectively. Whilst in other part of the model inland area, at Sg. Sekawang, Port Dickson, the SE is above 1.4 m in year 2100. The coastline in Tg. Keling indicated a SE more than 1.5 m in year 2100, and more than 1.0 m in both year 2030 and 2050, respectively. Hence, future development especially a reclamation platform must be sufficiently enough to withstand the increase in SLR and other stronger marine climate energy.

3.6.3 Storm Surge Risk Level

3.6.3.1 Kelantan

Kelantan coastline is furnished with natural beach dune, mangrove foliage and coastal protection structures. However, in the hydrodynamic simulation model, the DEM data employed in the model bathymetry only covers about 2 km inland from the original land-water boundary (based on crude regional sea bed depth data supported by MIKE21 C-Map). The rest of the model depths are coarse especially in offshore area. With limited DEM and survey data the model was set-up in part as a sea wall (no breaching and erosion occurred) in area that is not covered by the DEM or survey information. Thus, the bed profile at the nearshore point may be overestimated and careful justification is required to assess the level of risk occupying the coast of study. In this case, to assist in determining the possible sea bed depth, a plan view taken from Google Earth service is used to justify the type of physical features aligning the coast of Kelantan. So that a vulnerability ranges that best represents the area of interest can be defined.

Five locations along the study area are selected for sea bed profile extraction via the model bathymetry to investigate the SLR impact (see Figure 3.36). Among the five profiles, only location at profile no. K1 and K5 are classified as beaches. Whilst profile at location no. K2, K3 and K4 are line-up full stretch either with coastal revetment, groyne or breakwater. Figure 3.37 shows some of the coastline features along Kelantan coast. The actual crest level for the structures are an estimation based on previous study done in adjacent coast since a current inventory data on the existing structures were not available.

The calculated DWL for year 2100 SLR and 25yr RP storm surge is plotted for each profile to identify whether the selected coastal area is well above the level of inundation or vice versa (Figures 3.38 to 3.42). Calculation on the PVI at each profile indicated a variety of risk level, from Moderate to Very Low risk of inundation. The PVI ranking at each point changes with SLR projections. The higher the rise in sea level, the risk level is increased. Table 3.15 gives the PVI for K1 to K5. Based on the PVI results, K1 and K5 will be subjected to moderate level of risk of inundation, whilst K2, K3 and K4 are subjected to Very Low PVI level. Figure 3.43 shows in detail the severity of Kelantan coast when subjected to 2100 SLR projection.

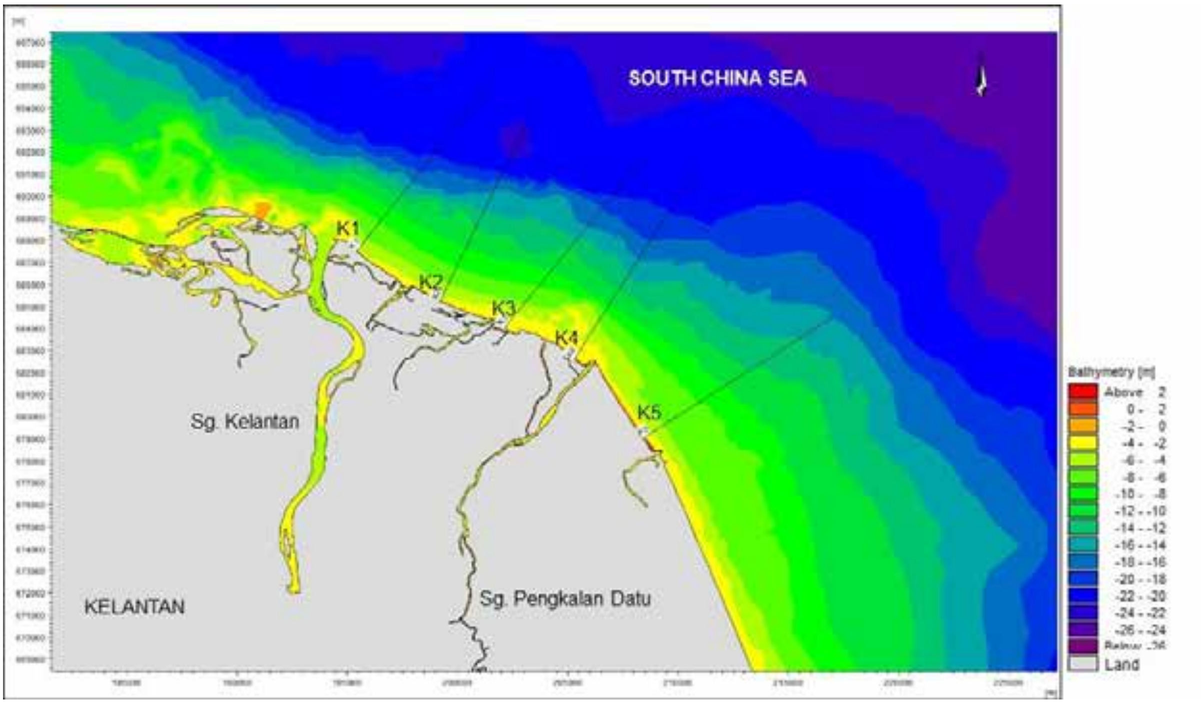

Figure 3.36: Extraction points for sea bed profile at Kelantan coast

Figure 3.37: Coastline features along Kelantan coast

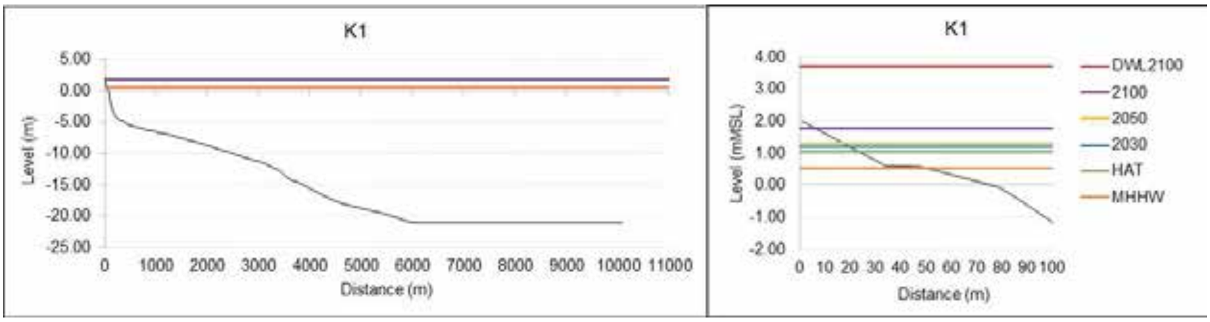

Figure 3.38: Profile K1 - in various SLR projections and DWL = 3.71 m (2100 SLR)

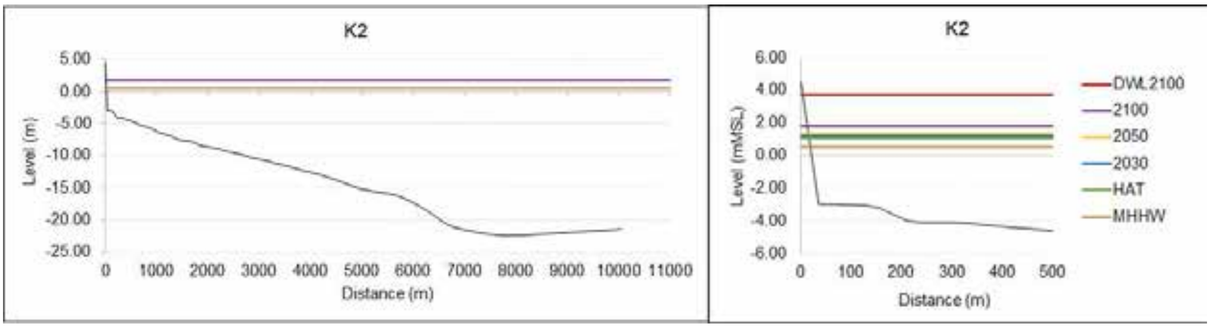

Figure 3.39: Profile K2 - in various SLR projections and DWL = 3.71 m (2100 SLR)

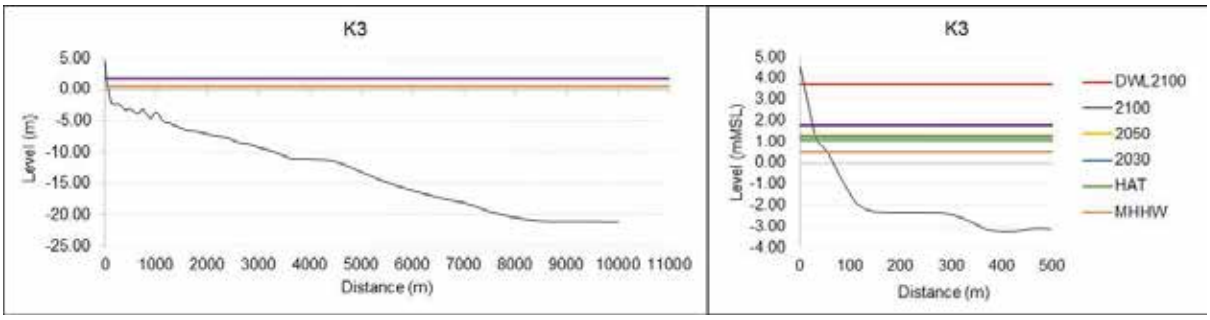

Figure 3.40: Profile K3 - in various SLR projections and DWL = 3.71 m (2100 SLR)

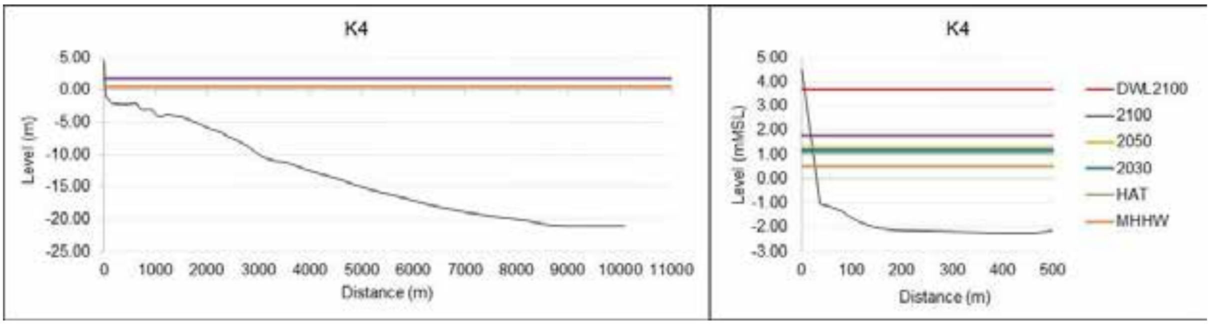

Figure 3.41: Profile K4 - in various SLR projections and DWL = 3.71 m (2100 SLR)

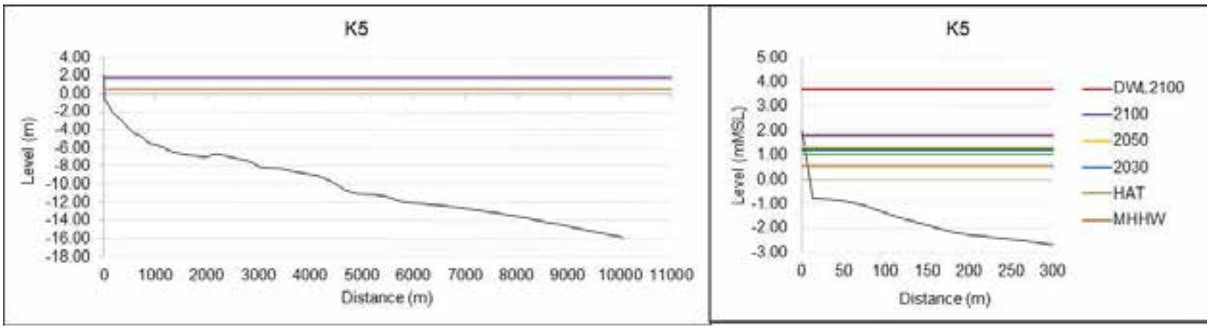

Figure 3.42: Profile K5 - in various SLR projections and DWL = 3.71 m (2100 SLR)

Table 3.15: PVI for profile K1 to K5 under various tidal range and SLR projection

Area	Kelantan				
Point	K1	K2	K3	K4	K5
A1	1	1	1	1	1
A2	3	1	1	1	3
PVI	1.1	0.5	0.5	0.5	1.1
Rank	3	1	1	1	3
MSL	moderate	very low	very low	very low	moderate
MHHW	very low	very low	very low	very low	very low
SLR 2030	moderate	very low	very low	very low	moderate
SLR 2050	high	low	low	low	high
SLR 2100	very high	moderate	moderate	moderate	very high

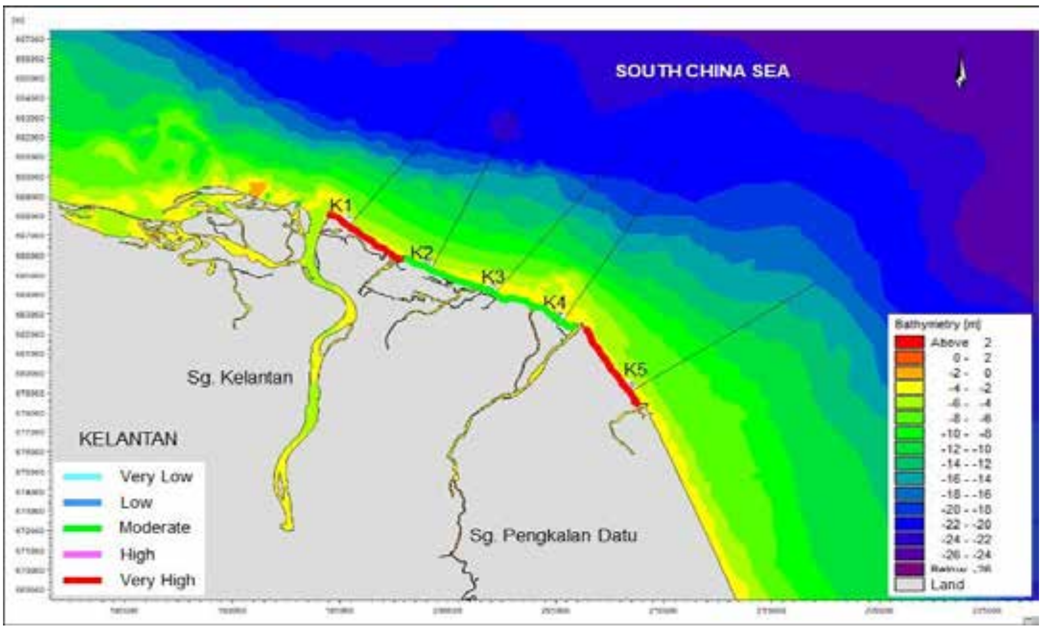

Figure 3.43: Storm surge risk map for Kelantan coastal study area - 2100 SLR

3.6.3.2 Negeri Sembilan- Malacca

Reviewed on the coastline features in Negeri Sembilan - Malacca indicated a combination of beaches, headland, revetment and rock groynes. There are six profiles extracted along the coastline of the two states (N1 to N6) as shown in Figure 3.44. N1 is classified as rock headland, N2 and N3 are a mix in between sandy and rocky beach, N4 is sandy beach with rock groynes, N5 is rock revetment with Petronas Lube Plant jetty and finally N6, a seawall with Malacca jetty. Figure 3.45 shows several pictures of coastline features taken at site in Malacca. No site pictures for Negeri Sembilan area is available for viewing. Moreover, the freeboard level of the jetties was not made available for this study, thus the risk assessment on the structures are omitted. Only the coastal protection structures such as rock revetment and groyne are assessed. Again, the information regarding the actual crest level of the structures are not present, hence crest level is estimated based on previous study done at adjacent area.

The calculated DWL and design CL for year 2100 SLR and 25yr RP storm surge are plotted for each profile as illustrated in Figures 3.46 to 3.51). Calculation on the PVI at each profile indicated a variety of risk level, from Very Low to Very High risk of inundation. Table 3.16 gives the PVI for N1 to N6. Based on the PVI results, whichever points that features a headland, revetment or groyne, they will be subjected to moderate to low level of risk of inundation. Whilst coastline that featured a sandy beach will be subjected to High to Very High risk of storm surge impact and inundation. The PVI ranking at each point is subjected to changes in SLR projections. The higher the rise of the sea level, the higher the ranking and the associated risk level. Figure 3.52 shows in detail the severity of Negeri Sembilan - Malacca coast when subjected to 2100 SLR projection.

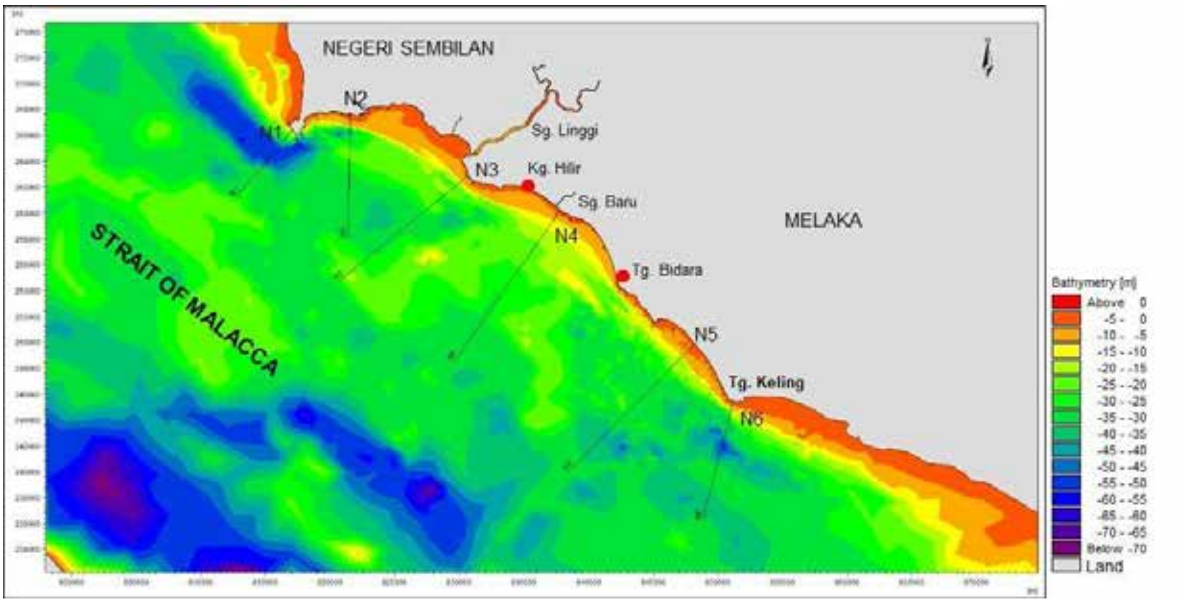

Figure 3.44: Extraction points for sea bed profile at Negeri Sembilan- Malacca coast

Figure 3.45: Coastline features along Negeri Sembilan-Melaka coast - Kg. Hilir (left), Kuala Sg. Baru (middle) and Tg. Bidara (right)

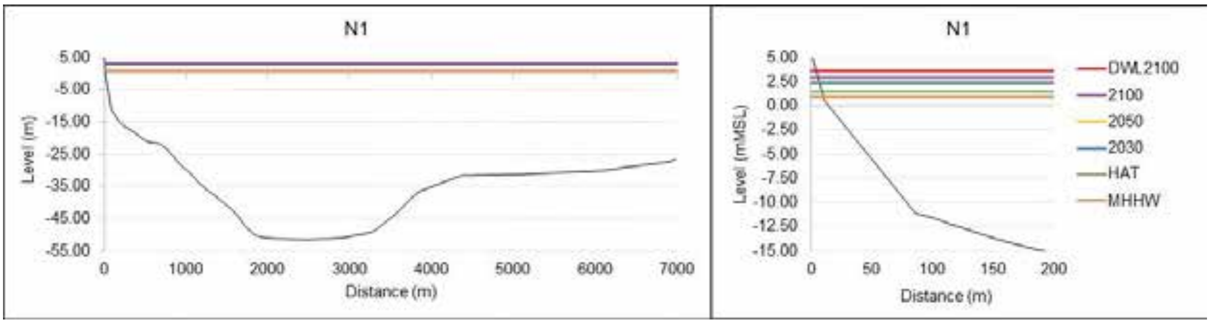

Figure 3.46: Profile N1 - in various SLR projections and DWL = 3.63 m (2100 SLR)

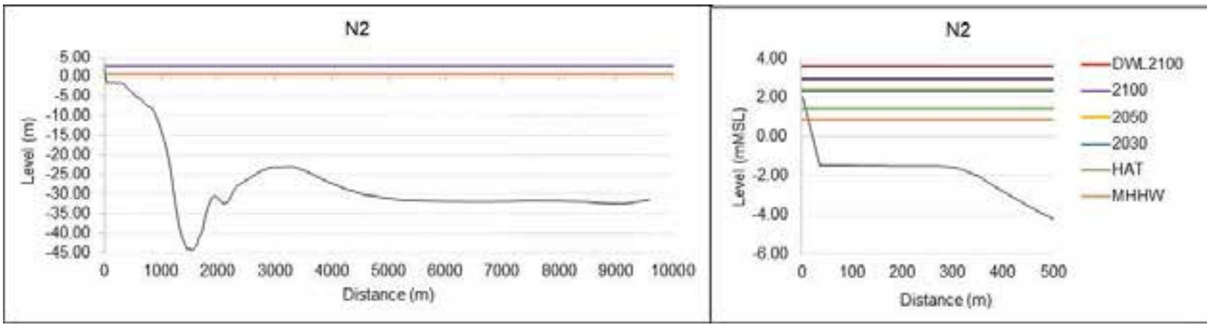

Figure 3.47: Profile N2 - in various SLR projections and DWL = 3.63 m (2100 SLR)

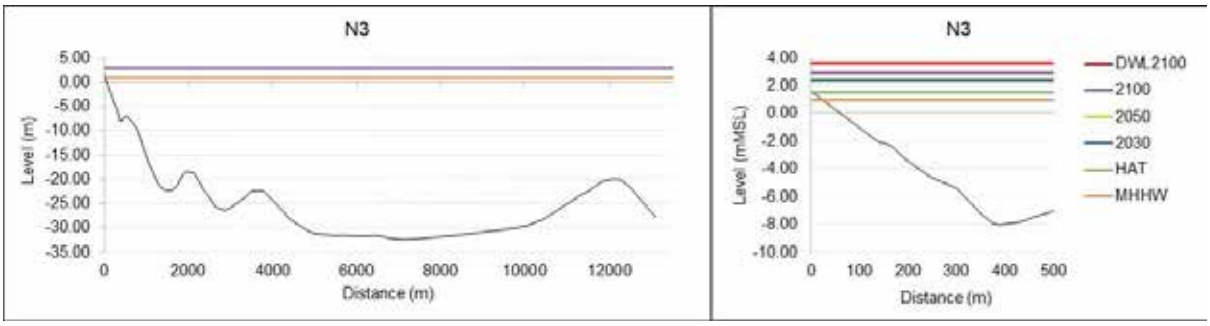

Figure 3.48: Profile N3 - in various SLR projections and DWL = 3.63 m (2100 SLR)

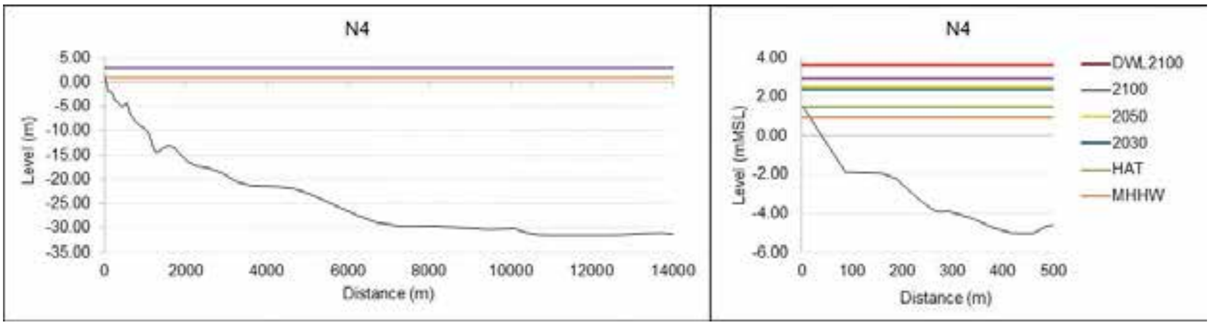

Figure 3.49: Profile N4 - in various SLR projections and DWL = 3.63 m (2100 SLR)

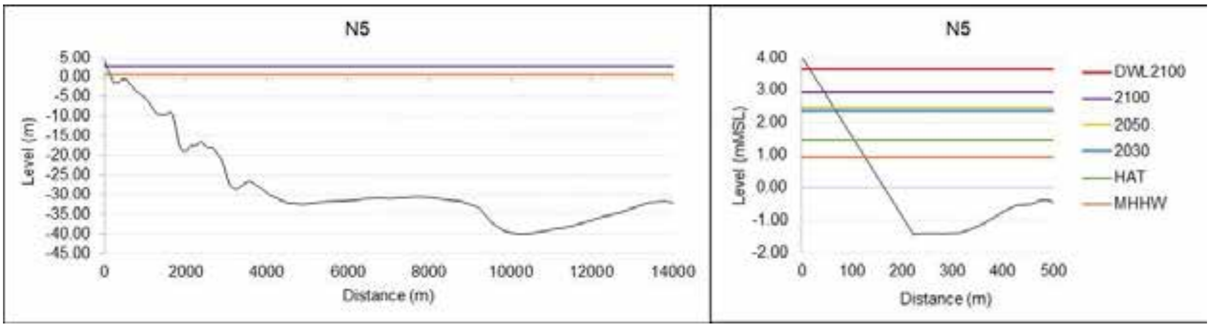

Figure 3.50: Profile N5 - in various SLR projections and DWL = 3.63 m (2100 SLR)

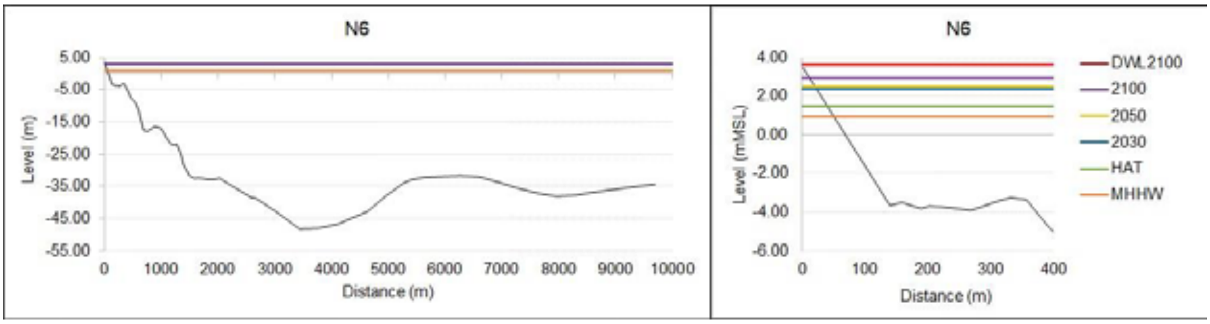

Figure 3.51: Profile N6 - in various SLR projections and DWL = 3.63 m (2100 SLR)

Table 3.16: PVI for profile N1 to N6 under year 2030, 2050 and 2100 SLR projection

Area	**Negeri Sembilan - Malacca**					
Point	N1	N2	N3	N4	N5	N6
A1	1	3	5	5	2	2
A2	1	3	4	4	1	2
PVI	0.5	1.5	2.2	2.2	0.7	1
Rank	1	3	5	5	2	2
MSL	very low	moderate	very high	very high	low	low
MHHW	very low	moderate	high	high	low	low
SLR 2030	low	very high	very high	very high	low	moderate
SLR 2050	moderate	very high	very high	very high	moderate	moderate
SLR 2100	moderate	very high	very high	very high	high	high

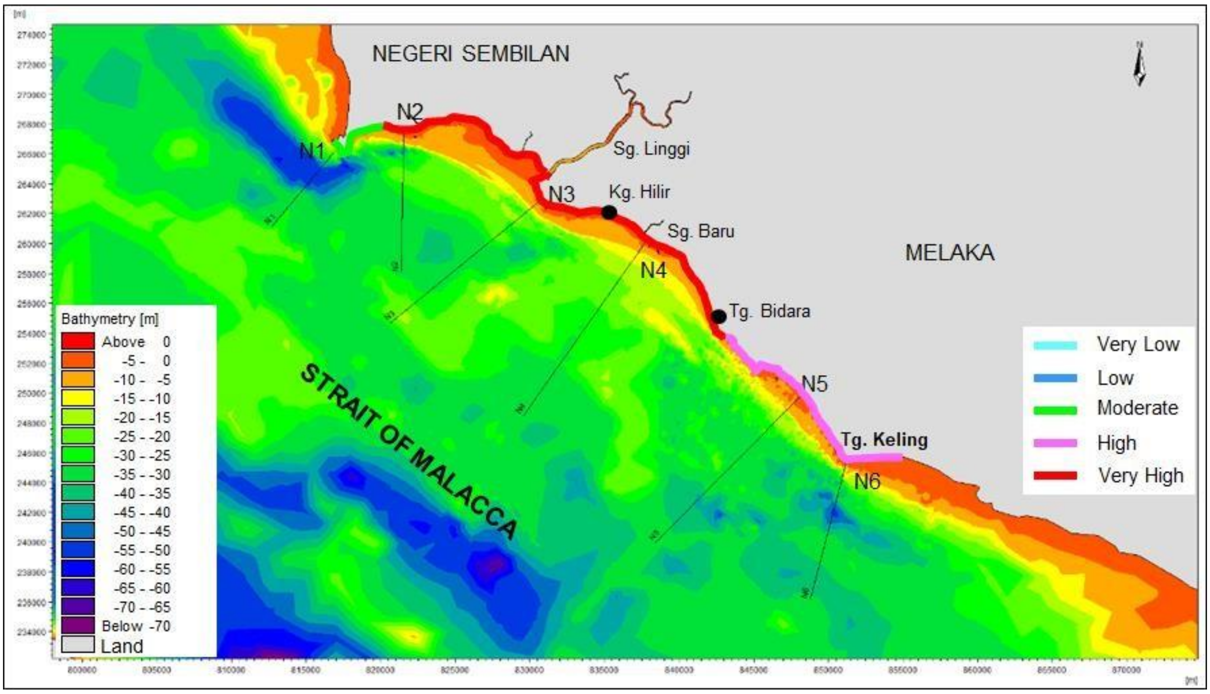

Figure 3.52: Storm surge risk map for Negeri Sembilan-Malacca coastal study area – 2100 SLR

CHAPTER 4.0 CONCLUSIONS AND DIRECTIONS

In this study, historical storm surge events in Kelantan, Negeri Sembilan and Malacca have been investigated using theoretical and statistical approach. Appreciatively, additional data from completed hydrodynamical study by NAHRIM for SLR study is applied. The examination of more than 25 years of sea-level data in East Coast and West Coast of Peninsular Malaysia indicates that storm surges occur year round, but in various magnitudes. In west coast, the variation of surges is much smaller and normally acknowledged as tide residual. In east coast, the surge magnitudes can reach up to a metre, and is more common in cold Northeast monsoon. About 75% of the surge belonged to above 0.5 m height category and the trends of higher surge is increasing parallel with the change in marine climate conditions globally. It is an expected outcome concur with assessment made by AR5 study by IPCC working group in 2019.

Nevertheless, unlike countries such as Philippines, Vietnam, Japan, China, US and European region, storm surge in Malaysia is less common than flash flood in urban areas due to heavy rain or high waves in coastal areas, but they are potentially more damaging because of the intense rainfall and high waves that accompany them and which, can produce severe coastal flooding. Indeed, one such event, which occurred in late December 2014, were responsible for the 7th highest ranking in storm surge of 0.81 m in Geting, which is the worst flooding over the Kelantan state in recorded history. The frequency of storminess and its' associated surges in east coast is more proclaimed during the northeast monsoon but not withholding the impact to west coast under similar monsoon period, but with lesser degree of impact. The west coast however, has frequency of surge/residual heights of lesser magnitude (< 0.3 m) that almost equal in percentage of occurrence between the northeast and southwest monsoon, which numbers of researches indicated that the western coast is more dominated by waves. Not to negate the assumption, the variance in wave run-up is bigger between east and west coast by 2.0 m. As it is, the location of the site of interest with respect to the receiving waves should thereby need to be considered.

Moreover, in standard practice, the 1-in-100 year return period of design sea level heights is commonly used for planning purposes by DID and general coastal engineering practitioners. But seldom storm surge is included in the design as one of the main parameters, as many has acknowledged it as a wave set-up. Whilst in meteorological term, the generation of storm surge is due to a decline in atmospheric pressure and increase in storm speed, which is partly similar to wave only by the facts that both parameters are due to the act of wind. Thus, the assessment of coastal area due to storm surge is investigated by employing a 1-in-25 year and 1-in-50 year storm surge event to investigate the vulnerability of the coastal area in the study domain. The level of vulnerability varies with SLR projections. For each rise in sea level, the risk and vulnerability of the coastal area to the storm surge is increasing. Results of assessment indicates the increased vulnerability of a coast in northern Kelantan from moderate to very high risk in year 2100. Similar case could be said in the west coast, with moderate level rise to very high level of vulnerability under parallel year. Hence, future coastal zone management should at least make a leeway on the impact of storm surge in the design.

As in present, the direction of the study veered towards making full use on the available data and information gathered, acquired and screened. The judgement on the results may be on the critical side of acknowledgment by some researchers and scholars. However, the lack of significant data pertaining to the comprehensiveness of this study should be made aware first upon reclaiming any critical view. In all, the assessment made is partly through numerical model by the hydrodynamic water level generation in various SLR projections, and the rest in simple analytical and statistical analysis on the tide level to produce storm surge magnitudes. An applause to the long-term collection of tidal data which enable this study to employ a sound results, though the same could not be said to other tide gauge station in Malaysia, for example, Kukup station only established less than 10 years of water level data.

Overall, a general comment can be made regarding the use of these results, however. It would be unwise to rely on the estimates of return periods based on theoretical and statistical analyses to rule out the level of risk that we face today. This is because planning requires that conservative assumptions are made, and the estimation of return period based on the current approach would by definition have about a 50% chance of being incorrect. The conclusions of this report are also affected by a number of sources of uncertainty in these results that are independent of the correctness of the information applied here. The first concern the current elevation of inland structures and beach dunes along the study region. This may lead to an underestimation or overestimation of the vulnerability level assesses and concluded. Others, an insufficient tide data could also lead to an overestimation of surge return level, which most of our tide data is under 30-years period.

This report is considered only a start of more comprehensive storm surge analysis and forecasting model frame work. As a continuous research activity, it is foreseen that a spatial resolution approach is more in favour to produce agreeable results of future storm surge trends to match with the modelled SLR completed by NAHRIM in 2017. Hence, the next step is to run a dynamic storm surge model to simulate sea level resulting from a large number of randomly selected cyclones and tides, to examine the nature of surges that occur in Malaysian region. To date, the propose approach has been widely applied in a wide variety of previous modelling studies in other Asian countries (Thailand, Mynmar, Vietnam and Philippines).

The model should then able to arrive with an algorithm to serve as an estimation guideline for emergency responders, planners, engineers and insurers as the basis for response, recovery and mitigation. A risk level associated to storm surge under various SLR projections can assist in producing a graphical imager to illustrate flooding extents to both scientific audiences and the general public. A typhoon-induced storm surge flood risk map in various degree of storm surge return levels and SLR projections, in hope shall provide a significant head start for authority, decision makers and planner to manoeuvre a plausible and constructive planning and management and cost estimation for coastal hazard and risk reduction.

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