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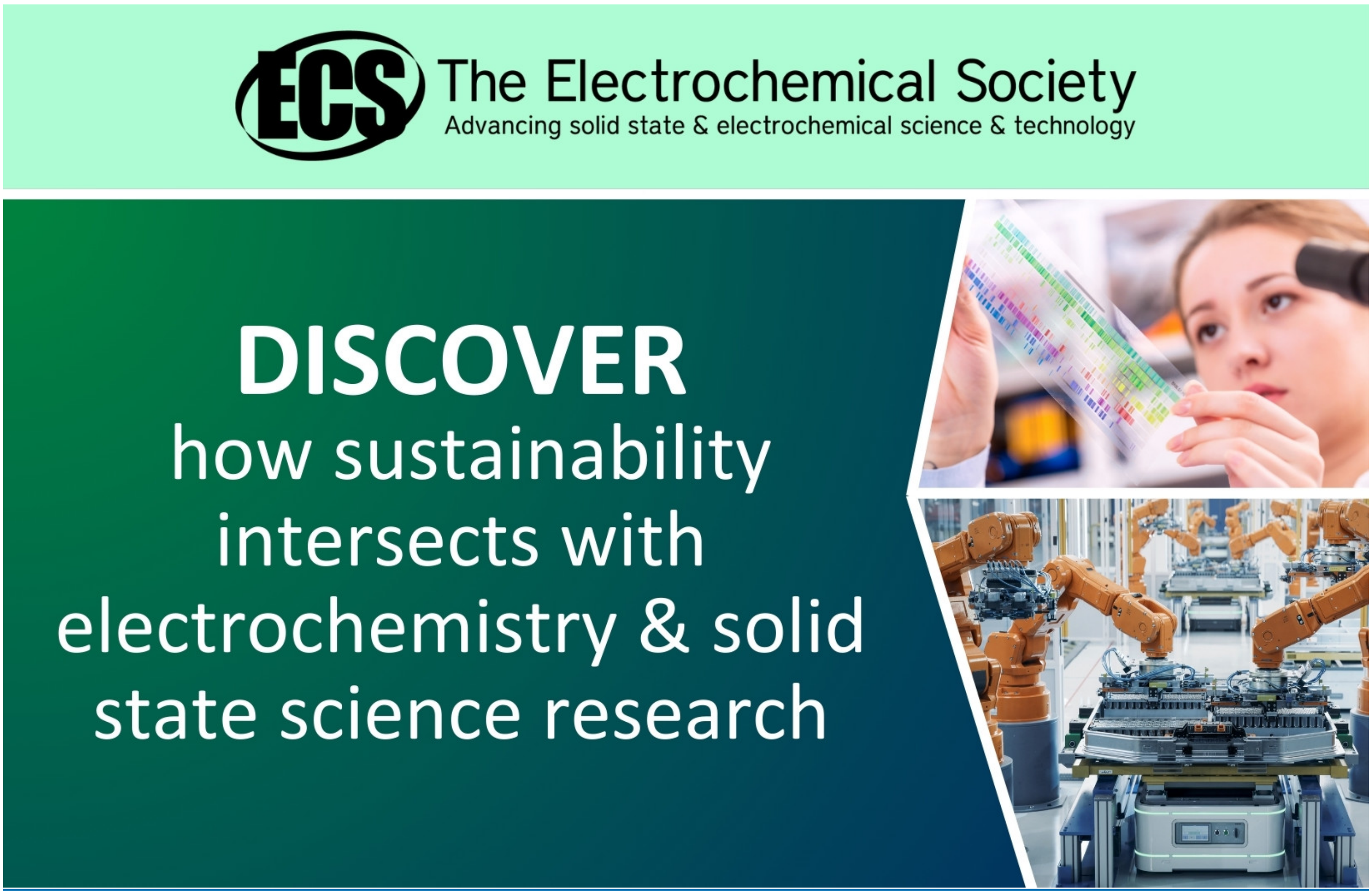

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Wave climate analysis for shoreline management plan in Kelantan, Malaysia

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Abstract. Waves climate analysis is of primary concern for several purposes such as maintaining coastal structures, navigation and maritime operations, coastal management, and recreation and tourism. Therefore, understanding the wave climate of a particular region helps in making informed decisions related to coastal and maritime activities, ensuring safety, efficiency, and sustainability. In this paper, wave analysis was conducted for Kelantan State shoreline, Malaysia. The studied shoreline covers around 71 km starting from Pengkalan Kubur to Besut. 5 years data (2014 to 2019) was collected at the location of 6.3N and 102.3E. The analysis was performed under different aspects including, annual wave rose, annual percentage reoccurrence, return period analysis, and closure dept. According to the results, it was found that the predominant waves are coming from the 60 to 90 degrees North sector due to the unlimited fetch in that direction. Besides it was noticed that more than 50% of the waves have periods between 4 to 7 seconds and around 52% have wave heights of less than 1.5m. Also, it was found that the wave depth for a 100-year return period is about 2.75m. Finally, the depth of closure was calculated and found to be 7 m. The outcomes of this study can provide a better understanding of the wave climate along the Kelantan State shoreline and can be used as a reference for future coastal and maritime activities.

1. Introduction

Wave climate describes different wave characteristics and properties such as wave height, direction period, and energy in a particular region [1]. Wave climate is mainly influenced by a combination of factors namely, wind speed, fetch length, wind duration, seabed topography and shoreline terrain, and water depth [2], [3]. Due to changes in oceanic and atmospheric conditions, different locations of the world have unique wave climates. For instance, regions with strong and enduring winds, like the Southern Ocean near Antarctica, frequently experience larger and more intense waves. Regions shielded by land masses or characterized by slow wind speeds, on the other hand, often experience smaller and less powerful waves [1].

According to Mirzaei et. al. (2014) [4] the location between the latitudes of 30º to 60º is experienced the most energetic waves on the earth. while attractive wave climate can be found within ±30º of the equator where the trade winds blow. An atlas of global wave energy was presented by Arinaga and Cheung [5] using 10 years of reanalysis and hindcast data. Based on the obtained results it was noticed

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that the monthly median wave power from wind waves above 30º N ranges from 17 to 130 kW/m while the power below 30º S is steadier throughout the year with a range of 50e100 kW/m.

Peninsular Malaysia's South China Sea (SCS) wave climate is extreme and harsh when compared with other coasts in Malaysia [6]. Mirzaei et. al. (2013) [7] presented the mean significant wave height and 90th percentile wave height for the period 1979–2009 in the South China Sea as shown in Figure 1. According to the presented results the maximum long-term mean wave height was noticed to be in the central region of the SCS at which the wind speed ranges between 5 knots and 40 knots in a matter of hours during the monsoon seasons. On the other hand, the wave height gradually decreases in the northeast–southwest direction towards the Sunda shelf where the values are relatively lower. The wave height at the Gulf of Thailand and southern region of the SCS is relatively lower which ranges between 0.5 to 1 m. The wave height at the coastal region of Peninsular Malaysia and the west coast of Borneo is generally lower than 0.5 m, this was due to the complex bathymetry at those particular regions.

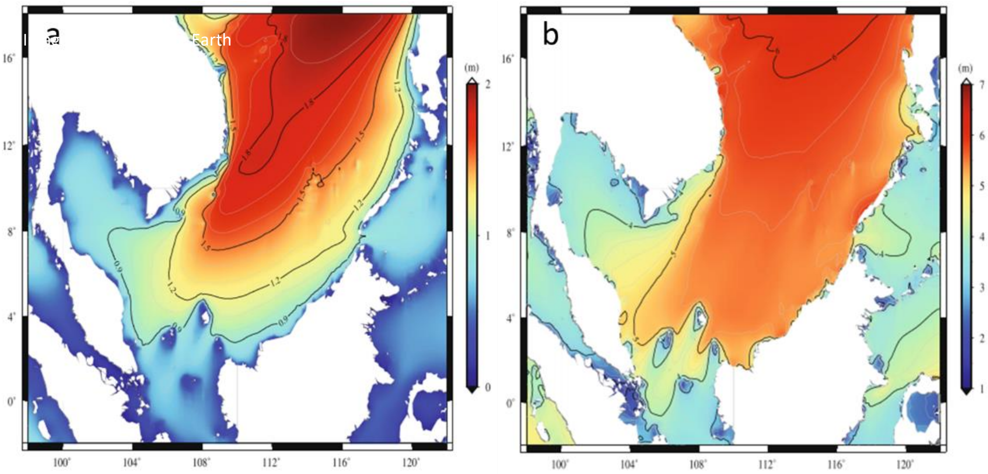

Figure 1. (a) Mean significant wave height and (b) 90th percentile wave height for the period 1979–2009 [7]

Understanding the existing wave climate and the environmental factors that could influence it is important in the context of assessing the long-term and future changes of waves [8]. Also, it helps during the design and operation stages of ocean-deployed structures, such as seawater intake structures, breakwaters, port and harbour structures, shore protection structures, submarine pipelines, open sea loading and unloading terminals, oil terminals, and offshore platforms [9]. The environmental factors could include wave height, wave period, wind speed, and current speed. A lack of knowledge of the environmental factors influencing structure design will either lead to a hazardous structure or an excessively designed and uneconomical structure [10]. Predicting the design wave heights for various return periods is crucial as well which helps to identify the extreme wave climate. Investigating the current wave climate would also yield useful data on the potential effects of waves on coastal zones, such as coastal erosion, floods, and inundation [11].

Several previous studies have attempted to investigate the wave climate and predict the waves' extreme values. The first statistical method to predict the extreme values of natural random events was developed by Gumble in 1958 [12]. This method basically depends on the previous annual maximum records for natural events such as wind speed or wave height. Due to its simplicity, the Gumble method is one of the most common methods that is used by the wind engineering community. A detailed discussion on using the Gumble distribution method for predicting extreme wave height was presented by Denis (1969) [13]. In this study, the wave climate of the Kelantan State shoreline was presented and discussed. Wave data from 5 years (2014 to 2019) were collected and analysed to understand the current wave climate and the possibility of the occurrence of extreme events. Firstly, the annual wave rose is presented, and the common direction of the waves is identified. Secondly, the percentage of wave properties re-occurrence is analysed and presented in terms of wave directions, heights, and periods. Finally, return periods are investigated and analysed using the Gumble distribution method.

2. Methodology

2.1. Study area

This study was conducted for Kelantan state shoreline which has a total length of 71km. Figure 2 shows the details of the study area. The necessary data for the wave analysis study was collected from Bouyweather, archive of WavewatchIII for a period of 5 years (2014 to 2019. The collected data is approved by the Department of Irrigation and Drainage (DID) of Malaysia. The wave data was obtained at the location of 6.3N and 102.3E as shown in Figure 2.

Several analyses were conducted at which the return period was studied and defined using the Gumbel distribution method. The annual percentage of occurrence of wave heights, directions, and periods was presented. Depth of closure (DOC) which is one of the most important shoreline processes was calculated and presented as well.

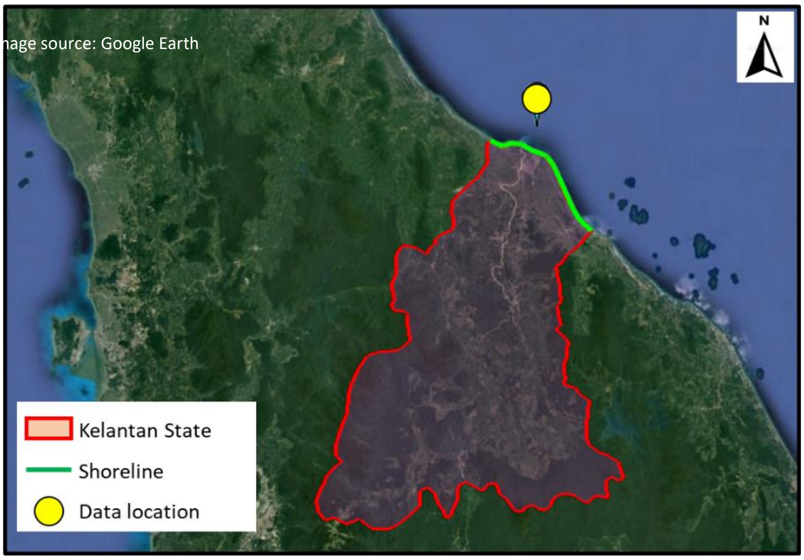

Figure 2. Study area details

2.2. Analysis method

For the purpose of annual wave rose generation and reoccurrence analysis, firstly, the collected data was organized into a format that includes the direction (expressed in degrees) and the frequency (or percentage) of occurrences for each direction for the purpose of plotting the annual wave rose. The wave rose was divided into 12 buns based on a 30° Intervale to represent NNE, NE, ENE, ESE, SE, SSE, SSW, SW, WSW, WNW, NW, and NNW directions. Secondly, statistical analysis was employed to represent the collected data in the form of graphical forms to show the wave height, direction, and period distribution.

Gumbel distribution which is known also as the Type I Extreme Value distribution was employed for return period analysis purposes. The cumulative distribution function (CDF) of the Extreme Value Type I or Gumbel distribution is given in Equation (1).

$$F_x(x) = \exp\left[-exp\left(-\frac{x-u}{\alpha}\right)\right] \quad (1)$$

Where x is the observed data, and u and α are the calculated parameters of the distribution which can be calculated using Equations (2-3).

$$\alpha = \frac{\sqrt{6}s_x}{\pi} \quad (2)$$

$$u = \bar{x} - 0.5772\alpha \quad (3)$$

Where $\bar{x}$ is the average value of the observed data while S_x can be calculated using Equation (4):

$$s_x^2 = \frac{1}{(n-1)}\sum_{i=1}^{n}(x_i - \bar{x})^2 \quad (4)$$

The depth of closure range is important in coastal management and beach nourishment projects. It helps determine the appropriate depth and volume of sand required for beach replenishment and maintenance. Understanding the depth of closure range also aids in assessing the impact of coastal structures, dredging activities, and climate change on the sediment transport and stability of coastal areas [14]. It's important to note that the depth of closure range is specific to each beach or coastal area and can vary depending on local conditions and factors. It is typically determined through field measurements, numerical modeling, and analysis of sediment transport data. In this study, the depth of closure is determined by Equation (2) which was developed by Robert Hallermeier in 1980 [15].

$$D_c = 2.28\,H_s - 68.5\left(\frac{H_s^2}{gT^2}\right) \quad (5)$$

Where D_c is the closure depth, H_s is the nearshore storm wave height that is exceeded only 12hr in a year, T is the associated wave period, and g is the gravity [15].

3. Results and discussion

3.1. Annual wave rose

The annual wave rose is a graphical form representing the wave patterns or heights over the course of a year. This graphical form helps to understand where the waves commonly come from and the size of the waves corresponding with each direction. Wave roses are utilized by sailors, navigators, and maritime planners to understand the prevailing wind patterns and plan routes accordingly. They provide information about favourable and unfavourable wind directions for shipping, boating, and other marine activities [16], [17].

After analysing the 5 years data, it was noticed that the predominant waves are coming from the 60 to 90 degrees North sector as shown in Figure 3. This is because the Gulf of Thailand creates a limited fetch for winds from the North and North North East (30 degrees North). The wind from North East East (60 degrees North) has unlimited fetch as shown in Figure 4. Thus, the waves from this sector are much higher compared to the other sectors.

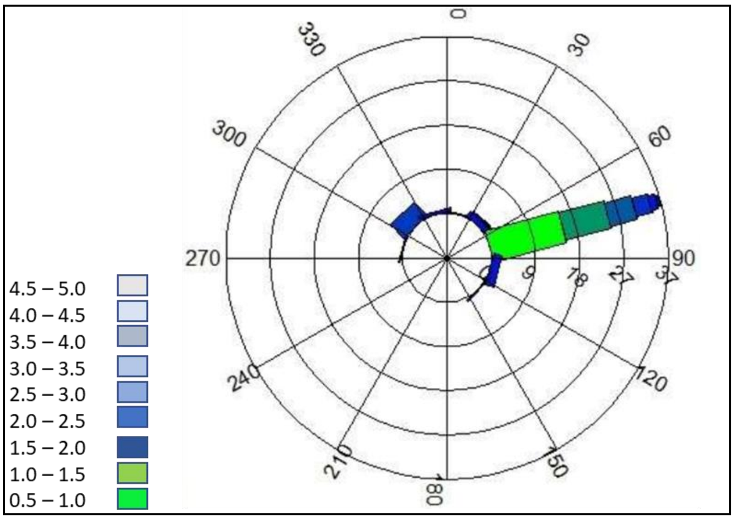

Figure 3. Annual wave rose, wave direction (degree) vs wave height (m)

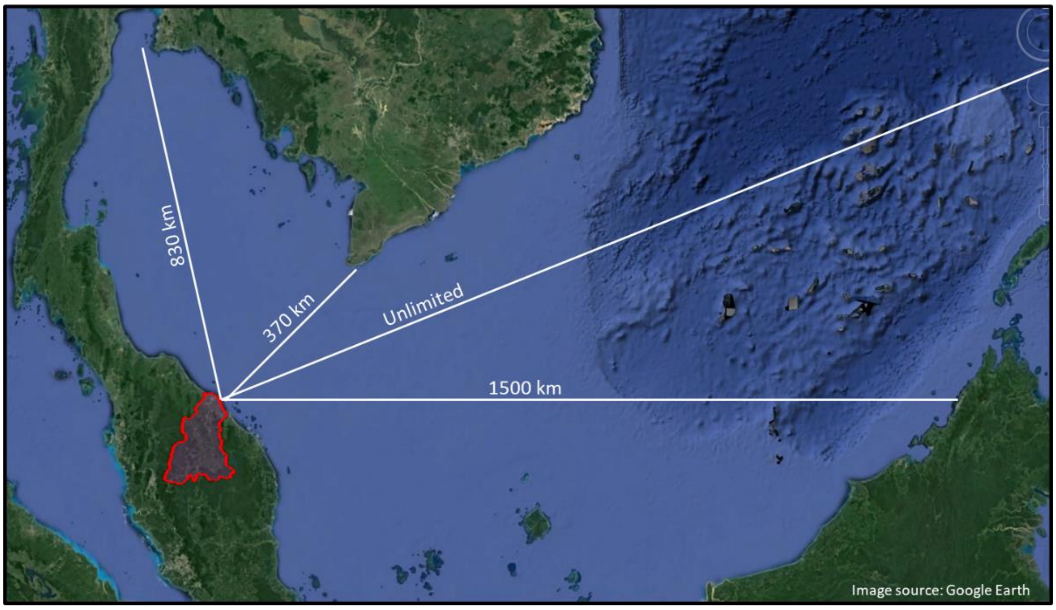

Figure 4. Fetch length

3.2. Waves parameters percent of occurrence

The collected data was further analysed to understand the annual percentage of occurrence of wave depth, wave period, and wave direction. It was found that more than 80% of the waves come from the 60 to 90 degrees sector. More than 50% of the waves have periods between 4 to 7 seconds and around 57% have wave heights between 0.5 to 1.0m. Figures 5a, 4b and 4c show the annual percentage of occurrences of wave direction, period, and height respectively.

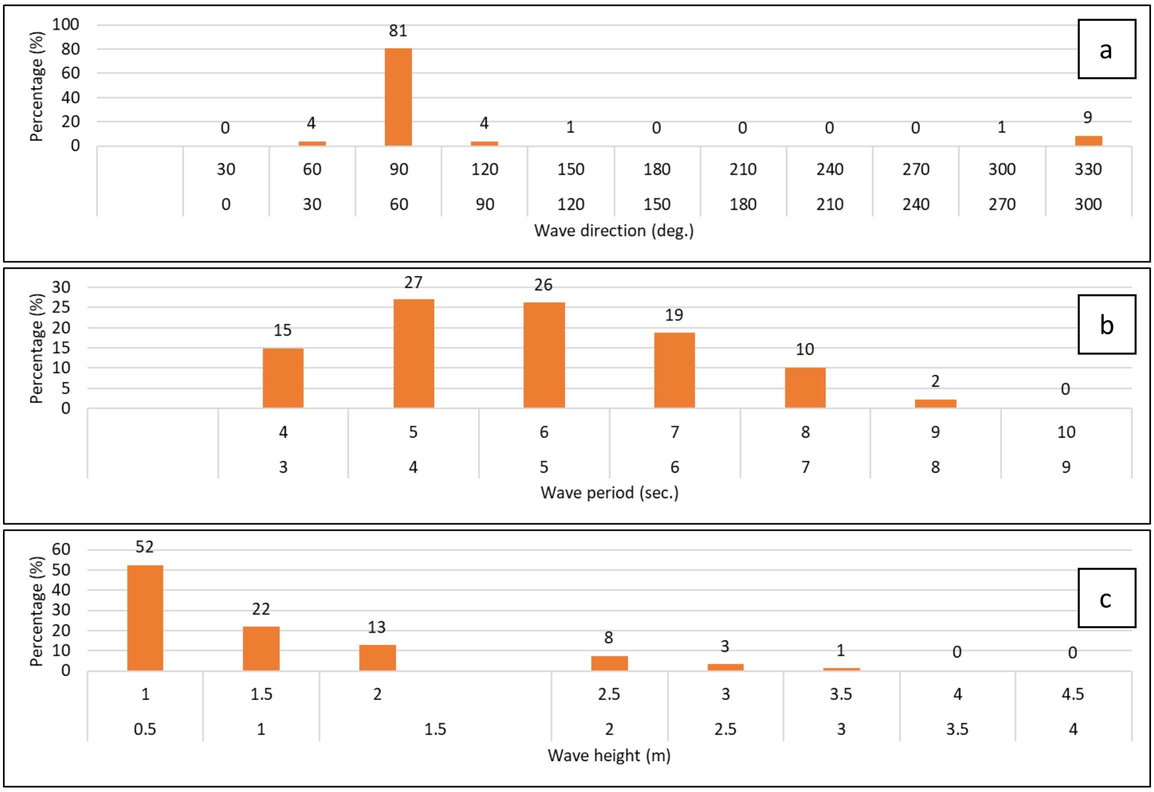

Figure 5. Annual percentage of occurrences of wave direction, period, and height

The annual number of occurrence relationships between wave period, height, and direction were presented in a matrix form as shown in Figures 6, and 7, respectively. It can be seen that from the total number of the recorded waves, 290 waves have a height range between 0.5m and 1m with a period of 5 to 6 seconds. On the other hand, a total of 455 waves were noticed to be coming from a 60 to 90-degree direction for the same height (0.5m - 1m). A summary of the annual percentage of wave occurrence for all directions at different heights is presented in Table 1.

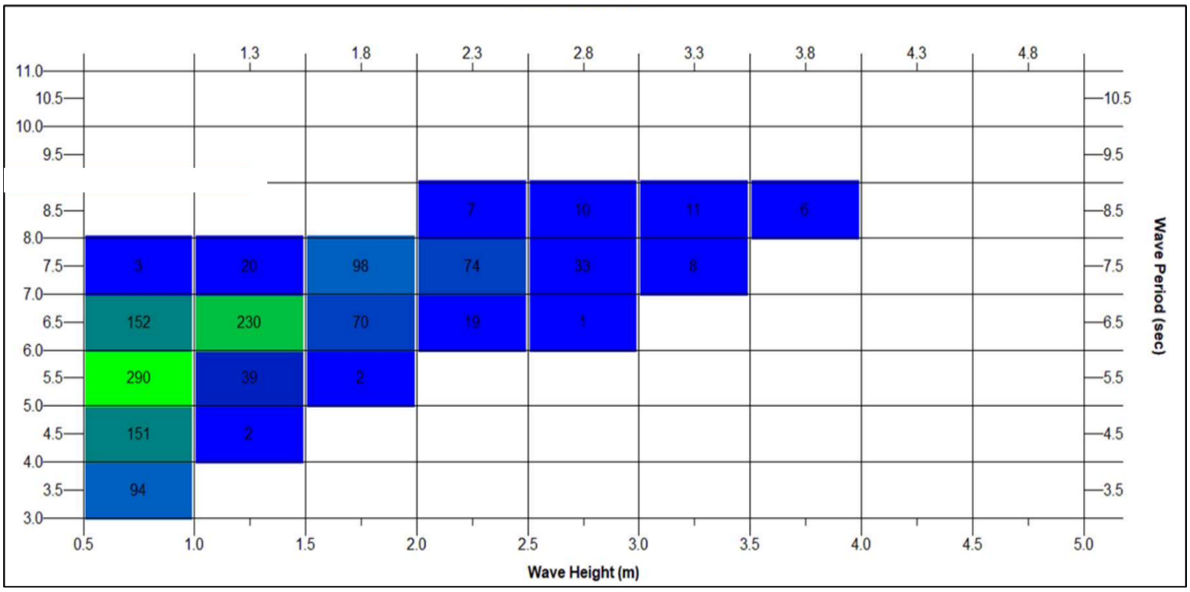

Figure 6. The annual number of occurrences with respect to wave period and heigh

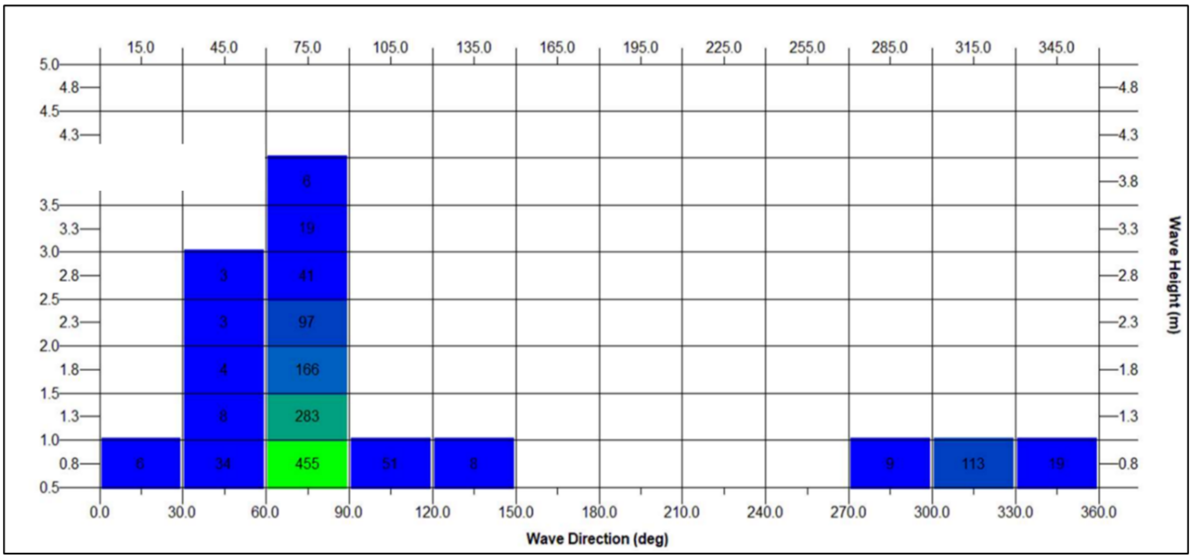

Figure 7. The annual number of occurrences with respect to wave height and direction

3.3. Retune period

Gumbel distribution was used to define the wave retune periods based on the whole wave data of the 5 years as shown in Figure 8. Gumbel fit, also known as extreme value distribution, is a statistical method used to estimate the parameters of the Gumbel distribution for a given dataset [18]. The Gumbel distribution is commonly used in extreme value analysis to model the distribution of extreme events, such as floods, wind speeds, wave heights, or maximum temperatures [19]. It was noticed that the likelihood of wave of a significant wave height exceeded in a given time during the study period. For this location, the return period of a 2.75m wave event is approximately 1 year. This means that a 2.75m wave has a 100% chance of occurring in 1 year. Although Gumbel fitting shows that a 1:100-year wave height is 5.5m, it is important to use this data with caution as the physics of the wind blowing over the South China Sea may not create such high waves.

Table 1. Summary of the annual percentage of occurrence for all directions and heights

Wave direction (deg.)	Wave height (m)								
	0.5 - 1	1- 1.5	1.5 - 2	2 - 2.5	2.5 - 3	3 - 3.5	3.5 - 4	4 - 4.5	4.5 - 5
0 -30	0	0	0	0	0	0	0	0	0
30 - 60	3	1	0	0	0	0	0	0	0
60 - 90	34	21	13	7	3	1	0	0	0
90 - 120	4	0	0	0	0	0	0	0	0
120 - 150	1	0	0	0	0	0	0	0	0
150 - 180	0	0	0	0	0	0	0	0	0
180 - 210	0	0	0	0	0	0	0	0	0
210 - 240	0	0	0	0	0	0	0	0	0
240 - 270	0	0	0	0	0	0	0	0	0
270 - 300	1	0	0	0	0	0	0	0	0
300 -330	9	0	0	0	0	0	0	0	0
330 - 360	1	0	0	0	0	0	0	0	0
Total %	**52**	**22**	**13**	**8**	**3**	**1**	**0**	**0**	**0**

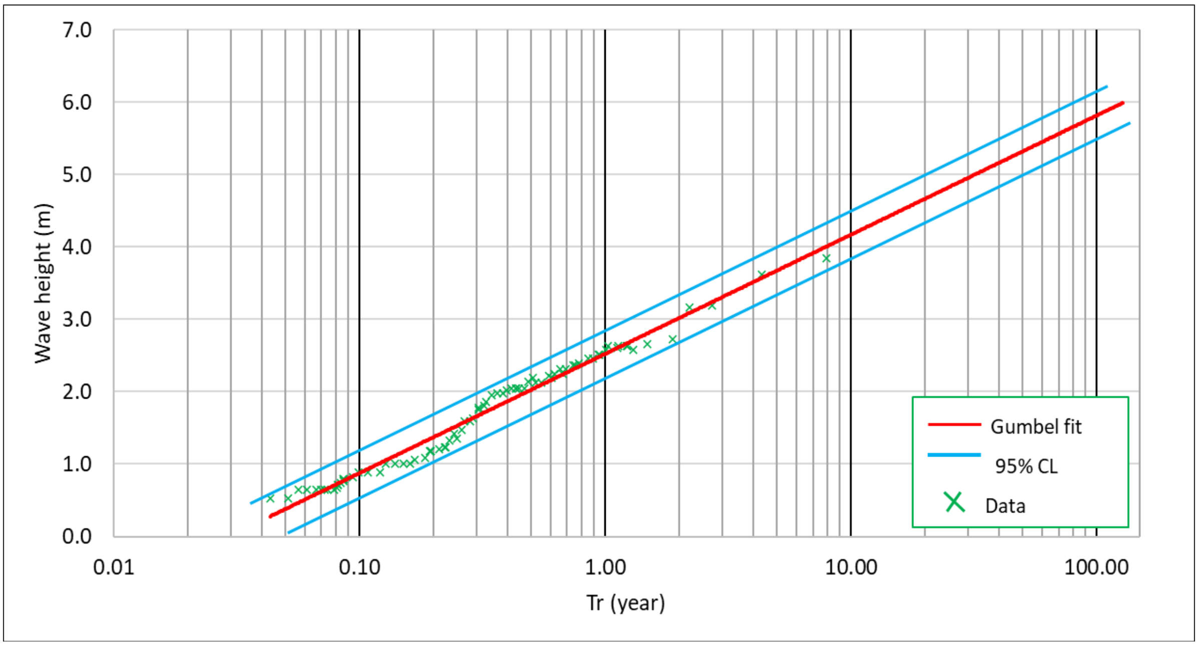

Figure 8. Wave Height Return Period

3.4. *Closure depth*

The depth of closure refers to the depth at which waves and currents no longer cause significant sediment transport along a beach or coastal area. It is an important concept in coastal engineering and coastal management as it helps determine the stability and equilibrium of a beach profile [20]. A schematic view of the depth of closure is shown in Figure 9.

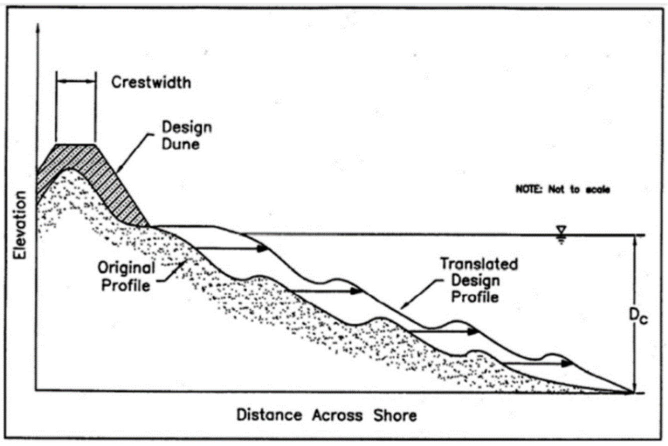

Figure 9. Schematic view of closure depth [21]

The depth of closure range refers to the range of water depths over which sediment transport is significant and can affect the beach profile. This range is typically defined by a lower depth of closure and an upper depth of closure. The lower depth of closure represents the minimum water depth at which sediment transport is significant. Below this depth, waves and currents are not energetic enough to transport sediment, and the beach profile is relatively stable. The lower depth of closure is influenced by factors such as wave energy, sediment characteristics, and bottom slope [22].

The upper depth of closure represents the maximum water depth at which sediment transport is significant. Beyond this depth, waves and currents are too weak to transport sediment, and the beach profile becomes relatively stable. The upper depth of closure is influenced by similar factors as the lower depth of closure [22]. The range between the lower and upper depth of closure is the depth of closure range. It indicates the water depths within which sediment transport processes are active and can cause changes to the beach profile.

According to the available data (Hs= 4m and T= 7 seconds) and by using Equation (5) which was developed by Robert Hallermeier in 1980 [15], the value of the closure depth was found to be 7 m.

4. Conclusions

In this paper, wave climate analysis for the Kelantan State shoreline was performed to understand the nature of the waves in that particular region. The assessment was conducted based on 5 years data ranging between 2014 and 2019. The wave climate assessment was mainly focused on wave rose analysis, the annual percentage of reoccurrence, return period, and closure depth. It was found that the waves are primarily originating from the area between 60 and 90 degrees North sector. Additionally, it was noted that 52% of the waves have a height of less than 1.5 m, and more than 50% of the waves have periods between 4 and 7 seconds. The wave depth for a 100-year return time was also noticed to be approximately 2.75 m. Finally, the closure depth which indicates the region of shoreline instability in terms of sediment transport was calculated to be 7m. In future studies, it is recommended to conduct further analysis on wave climates at the Kelantan shoreline using longer periods of data and consider more than one location for data collection.

Acknowledgment

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