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THE EFFECTS OF SEASONAL MONSOON AND COASTAL DEFENCE STRUCTURES ON LITTORAL TRANSPORT OFF THE TERENGGANU COAST (MALAYSIA)

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Abstract: Maintaining natural sandy shoreline behaviour following human intervention is quite challenging. Anthropogenic activities have disrupted sediment transport, leading to insufficient sediment supply, causing a loss of natural beach characteristics. The Terengganu coastline, located on the east coast of Peninsular Malaysia, directly faces the South China Sea, historically featured pristine sandy beaches. Recent observations of beach conditions showed that some of the Terengganu shoreline has been exposed to downdrift erosion, which has increased. There has been increased pressure to find efficient mitigation solutions. The Digital Shoreline Analysis System (DSAS) was used to study the rate of change of the shoreline. Meanwhile, beach profile data and sediment sizes were used to evaluate the beach status on a bi-monthly basis following the seasonal monsoon. A MIKE 21 model was used to understand the relationship between sea-land interactions and responses. The result demonstrates that historical shoreline evolution confirmed the downdrift erosion due to insufficient sediment supply from the updrift beaches. Contrarily, seasonal changes from beach profile, sediment size, and wave modelling evidenced the topographical, grain size, and wave changes, respectively distracts the littoral transport in the study areas. This article intends to discover the relationship between the changes in littoral transport concerning the anthropogenic and natural effects on the Terengganu coastline, especially in Kuala Nerus and Dungun, Malaysia.

Keywords: Beach morphodynamics, sediment characteristics, DSAS, numerical modelling, shoreline protection system.

Introduction

Understanding the coastal dynamics of a region necessitates a comprehensive grasp of longshore sediment transport, a critical aspect of the coastal environment. As waves approach the shoreline at oblique angles, they generate longshore currents responsible for transporting sediment parallel to the coast. Over the past few decades, an extensive body of research has been dedicated to investigate longshore sediment transport, with numerous studies contributing valuable insights (Duc *et al*., 2019; Shetty & Jayappa, 2020). The longshore current can be influenced by the prominent direction of seasonal monsoons that can change the coastal morphodynamics (Amalan *et al*., 2018). Changes in longshore processes can result in shoreline changes that can impact coastal communities. Therefore, knowledge of longshore sediment transport along a coast is vital for understanding a region's coastal dynamics.

In tropical and subtropical regions, the long-term seasonal and inter-annual changes in wind and wave conditions can drive longshore transport (Almar *et al*., 2015; Umamaheswari *et al*., 2023). Besides, the coastal ecosystem is dynamic and is constantly adjusting to large-scale meteorological fluctuation and anthropogenic interventions such as the construction of ports, harbours, and coastal defence structures (Chowdhury *et al*., 2020). These variations are expected to impact the coastal processes, like inundations, erosion, accretion, and sediment transport along the coastline. Anthropogenic and natural effects are usually debated when talking about this matter. However, most of the time, anthropogenic influence is more clearly seen and one cannot deny that it can significantly disrupt the natural stability in the long term (Aouiche *et al*., 2016; Chili *et al*., 2017). A study conducted by Ratnayake *et al*. (2018) found that the constructed breakwater from a harbour expansion project in Sri Lanka had obstructed the natural longshore sediment transport. This has resulted in an increase in coastal erosion due to a lack of sediment deposition on the western coast. While the beach width variations showed a clear relationship between sediment deposition and monsoon seasonality.

Meanwhile, in Terengganu, Malaysia, the state is also facing a similar situation where it has engaged in coastal development intending to attract more tourists and bolster its economic growth. To that end, in 2008 the government extended the airport runway located in Kuala Nerus for a few kilometres to the sea to promote its tourism industry and keep the expansive momentum going from year to year. A problem arose when the airport runway acted as an obstacle for the longshore drift to move and deposit sediment along the beach. As a result, a sediment deficit took place and erosion occurred on the northern side of the airport extension causing a downdrift effect. As an immediate emergency measure, the state authorities built several coastal defence structures including groynes and breakwaters to mitigate erosion damage.

According to Ariffin *et al*. (2016), the construction of the runway extension has significantly changed the coastal processes. The coastal processes on the Terengganu coastline are greatly influenced by the monsoon weather system. The physical phenomenon, including wind, current velocities, and waves can be intense during the northeast monsoon (from November to March) and much calmer during the southwest monsoon (from May to September). During the northeast monsoon, the coast is exposed to strong currents and waves that lead to beach erosion (Ariffin *et al*., 2016). Wave climates, currents, and wind distributions play an important role in coping with the morphology of the Terengganu coastline.

The rhythmic alteration of erosion and accretion process harmonised the shoreface which will stabilise the beach morphology. However, these natural patterns could be changed over time due to the variability of atmospheric activities, as well as an interruption by external factors (grey construction). Therefore, an analysis of the long-term shoreline evolution with comprehensive numerical modelling to simulate the hydrodynamic conditions can help hasten a better understanding of the coastal morphodynamic changes. This article intends to discover the relationship between the changes in littoral transport with regards to the anthropogenic and natural effects on the waters off the coast of Terengganu, Malaysia, especially in the districts of Kuala Nerus and Dungun. Consequently, this study can provide baseline data to address several potential research gaps in geological research, for engineering applications, ecological conservation, and coastal management.

Methodology

Study Area

Two study areas chosen were the streets of Kuala Nerus and Dungun in Terengganu, Malaysia (Figure 1). There are six stations in each area and for each station, perpendicular transects facing seaward for the topographic survey was placed at random intervals with the sites chosen based on its economic and societal importance. Both areas specifically indicate the morphology of the beach. Kuala Nerus was selected for its modified beach, whereas Dungun showed a greater shoreline extension of its natural beach. However, the impact of the erosion on the area differs in which Kuala Nerus has experienced erosion in the north while the Dungun area showed more erosion in the south [Figure 1 (a) and (b)].

Terengganu area is situated adjacent to the South China Sea (SCS). Thus, the influence of the monsoonal regimes is present. Northeast monsoon (NEM) and Southwest monsoon (SWM) will hit the coast annually, usually from November to March and May to October, respectively. However, the impact of the NEM is more than that of the SWM. The direction of the littoral drift for both areas is different and keeps changing in line with the monsoon transition (Rosnan *et al*., 1994; Mirzaei *et al*., 2013; Ariffin *et al*., 2016). In addition, Terengganu is also influenced by the tidal inundation, which is semi-diurnal in the micro to the meso-tidal range. The rate of precipitation is between 1,488 mm and 3,017 mm (Mohd *et al*., 2018). Thus, all of these are the causative factors for the coastal area's behaviour.

This study concerns the morphological evolution on the Terengganu coast, it has adapted a multi-method analyses to attribute the impact on littoral transport following the seasonal monsoon and the influences of coastal structures. Historical shoreline observations spanning from between 2004 and 2019 provide information on coastal mobility. Besides, topographical changes, the sediment output characteristics can delineate the dominant behaviour of the beaches subjected to erosion and accretion events. This is supported by the physical dynamics of the wave action study to relate the phenomenon as it occurs.

Methods

Digital Shoreline Analysis System (DSAS)-Shoreline Evolution

The Digital Shoreline Analysis System (DSAS) was used to measure the changes of the shoreline or boundary from the spatial and temporal aspects (Cohen, 2016). This method has been widely used owing to how easy it is to use and

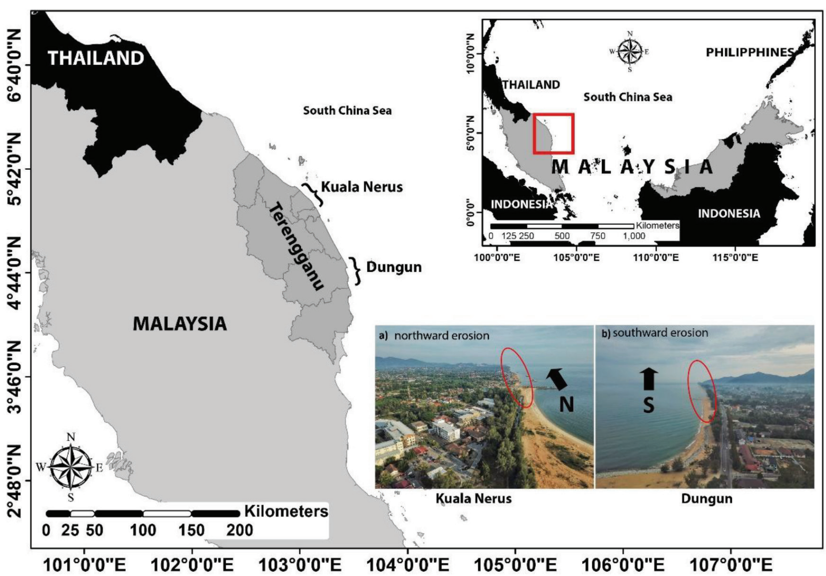

Figure 1: The study area located in Kuala Nerus and Dungun, Terengganu. Aerial image showed northward erosion observed at (a) Kuala Nerus and southward erosion at (b) Dungun

its ability to determine a few years of shoreline changes. DSAS is an extension of ArcGIS software and historical shoreline changes can be statistically determined in a simpler way through aerial images. The aerial images were obtained from a few sources, including Google Earth Pro (GE), Landsat, and drone images (Table 1) to be digitised in the ArcGIS 10.3 projected in UTM48- in which the geometric correction using a Ground Control Point (GCP) was done for the data preparation. A study from Zulfakar *et al*. (2020) used the aerial images from a combination of Unmanned Aerial Vehicles (UAV) and Google Earth (GE) to acquire a fine spatial resolution and a reliable map. The aerial images were processed statistically to get the shoreline track then generate the End Point Rate (EPR), which is depicted in the form of a line graph indicating either positive (accretion) or negative (erosion). Usually at least two years of data is needed for data processing. The baseline is drawn parallel to the shorelines (following the morphology of the shorelines) and transects are perpendicular to those shorelines, producing intersection lines (Figure 2).

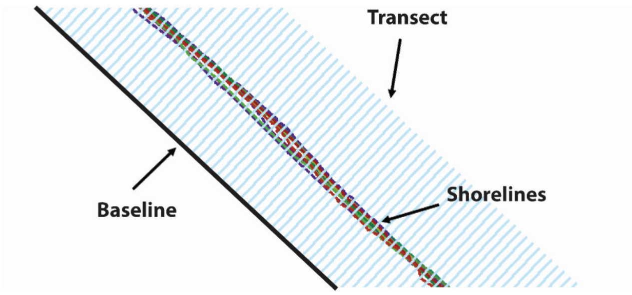

Figure 2: The input needed (baseline, transect, and shoreline) for the statistical calculation of End Point Rate (EPR)

However, before determining the EPR value, the Net Shoreline Movement (NSM) must be determined. NSM can be defined as the distance between oldest and youngest shoreline's in metres (m). The relationship between NSM and EPR are shown below as documented by Quang *et al*. (2021) and Weerasingha and Ratnayake (2022):

$$\text{NSM} = \text{distance between oldest and youngest shorelines} \quad (1)$$

$$EPR = \frac{NSM}{Time\ between\ oldest\ and\ most\ recent\ shorelines} \quad (2)$$

Thus, the determination of shoreline rates or change can be done by having these parameters. Nevertheless, as mentioned above, the calculations are statistically calculated by DSAS add-ins in the ArcGIS software. Other than that, DSAS also can calculate the Linear Regression Rate (LRR), Shoreline Change Envelope (SCE), and others that has its own purpose for calculations towards the shoreline changes.

The digitisation of the shorelines between 2004 and 2019 was conducted with respect to the vegetation mark. According to Anthony *et al*. (2019), the vegetation mark can act as an indicator of shoreline movement trends, which can absolutely support this study. The chosen years of evolution (three series of evolution) were based on the year of installation of the coastal structures on beaches. Thus, evolutionary years differed for both areas since both beaches installed the coastal structures at different periods.

For Kuala Nerus, the series from 2004 to 2016 indicated the year pre-construction of coastal structures, the years between 2016 and 2019 was the period during which the construction of a few coastal structures was undertaken while the period from 2004 to

Table 1: Details of the sources for the DSAS analysis. Details of satellite dataset (acquired via https://earthexplorer.usgs.gov/)

Year of Acquisition	**Source**	**Resolution (pixel size in m)**
2004	Landsat 4–TM	30
2005	GE	30
2006	Landsat 4–TM	30
2007	Landsat 4–TM	30
2008	GE	30
2009	Landsat 5–TM	30
2010	Landsat 5–TM	30
2011	GE	15
2012	GE	15
2013	GE	15
2014	GE	15
2015	Landsat 8–OLI	15
2016	Landsat 8–OLI	15
2017	GE	15
2018	Landsat 8–OLI	15
2019	DJI Mavic Pro (UAV)	13

GE: Google Earth, TM: Thematic Mapper, ETM: Enhanced Thematic Mapper, OLI: Operational Land Imager, UAV: Unmanned Aerial Vehicle

2019 evaluated the post-construction effect on shoreline movement. The same selection for the Dungun area; nevertheless, the evolutions were seen between 2004 and 2015, 2015 and 2019, and between 2004 and 2019. Then, after obtaining all the needed shorelines, the End Point Rate (EPR) was statistically generated and an EPR rate was graphed depicting the positive and negative values. The positive values showed the accretional rate and the negative value for the erosional rate for the respective appended years based on the determined distance. Digitised shorelines were 10 km and yielded 201 transects with an interval of 50 m.

Topographic Survey

The topographic survey by the beach profile was undertaken every other month (8 months in total) from April 2019 until August 2020 during the lowest low tide point with reference to the tide table. The purpose of this survey is to observe the elevation of the beach profile, as well as the volume and slope changes in the study area. There were 12 stations at a random distance for a perpendicular transect in Kuala Nerus and ~2 km distance in Dungun. A total station Topcon GM-Series was used to collect the data from the vegetation area to the waterline. Monitored profiles yielding volumetric and slope parameters, together with beach profiles were analysed using Profiler 3.2 XL Program (Cohen, 2016), which uses an ad-ins extension of Microsoft Excel. The volume and slope of the beach were calculated using Dora *et al*. (2012) formula to determine the loss and gain of the beach sediment through the trapezoid formula (3):

$$Volume\ per\ unit\ length\ \left(\frac{m^3}{m}\right) = A = \left(\frac{L1+L2}{2}\right) * B \qquad (3)$$

where L1 and L2 are the length (m) of each beach profile from a baseline and B is the displacement between two parallel lines in metres (L1 and L2) [Figure 3 (a)].

While the slope of the beach explained the gradient of the beach, applying the right-angle triangle trigonometric formula (4):

$$Sin\ (\theta) = \frac{Opposite}{Hypothenus} \quad (4)$$

where θ is the angle of the beach slope, Opposite is the beach elevation (m), and hypotenuse is the monitored beach profile (m). The adjacent is referring to beach width [Figure 3 (b)]. The hypotenuse value can be obtained through Pythagoras formula (5):

$$(\text{Hypotenuse})^2 = (\text{Opposite})^2 + (\text{Adjacent})^2 \quad (5)$$

Sediment Characteristics

Beach sediments was collected during the same period as the beach profile (bi-monthly sampling), from the backshore to the swash zone, and analysed by applying the dry sieve method in the laboratory using a mechanical shaker (Retsch AS 200 basic B). The sieves were arranged in descending order (large to the small) with mesh sizes of 4,000 µm, 2,000 µm, 1,000 µm, 500 µm, and 63 µm. The weight of retained sediment in each sieve was recorded and further analysed with the Gradistat Program (Blott & Pye, 2001) for the Grain Size Analysis. The Gradistat Program is an easy-to-use Microsoft Excel add-on. The weight of retained sediment was put in the column according to the mesh size. This can be done either for a single sample or multiple samples. Sample statistics will generate and produce results including mean, median, sorting, and skewness following Folk and Ward's (1957) formula. However, only the mean grain size was used for this study.

Numerical Modelling

In this study, MIKE 21 SW by DHI was utilised to simulate wave conditions along the Terengganu coasts. The model was calibrated and validated by comparing the in-situ field data using Acoustic Wave and Current Profiler (AWAC) from a two-year series of deployments comprising the pre and post-construction of coastal structures in the study area in 2014 and 2018, incorporated both long-range wave and numerical shoreline evolution modelling. The simulation domain encompassed Kuala Nerus and Dungun, defined by three open boundaries (south, east, north) and a land boundary. The bathymetry was derived from GEBCO and processed using MIKE ZERO's pre-processing tools.

The model incorporated various boundary conditions, with the open sea boundaries defined as code values 2, 3, and 4 while the land boundary was denoted as code 0. The boundary values were set to differentiate between the open sea and land, the projection angles were based on the region's annual flow, primarily influenced by northeast and south directions. Due to the varying depth, wave-current effect interaction, local wind interaction, and energy

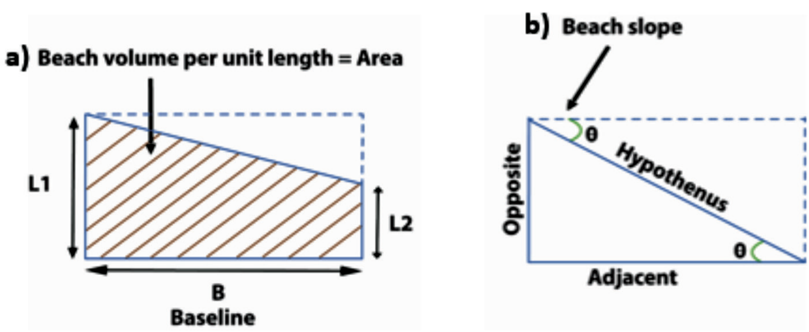

Figure 3: (a) A schematic diagram of beach volume calculation and (b) the beach slope calculation using Pythagoras theorem

dissipation because of the wave breaking and bottom friction will consider the effects of refraction and shoaling process. The input needed for this module was bottom dissipation, wave breaking, wave current interaction, wave current surface elevation, and wind forcing. The input description is tabulated in Table 2.

The simulation was carried out with every six-hourly wind and wave data obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) and Era-5 Copernicus database (https://climate.copernicus.eu/) (Copernicus Climate Change Service (C3S), 2020). The model was validated by comparing the simulation outputs with field-measured data using AWAC that covered two series years of pre- and post-construction of coastal structures in the study area in 2014 and 2018. The AWAC was deployed at the nearshore area in Terengganu, Malaysia (5°26'33.936" N, 103°9'37.548" E) [Figure 4 (a) and (b)] in 2014 (pre-construction) for 2 months with 20 minutes intervals while in 2018 (post-construction) for 3 months with 1-hour intervals. Both of the validations showed a good agreement of Root Mean Square Area (RMSE) values of 0.16 and 0.17 [Figure 4 (c)]. RMSE was calculated with the formula as suggested by DHI (2011):

$$RMSE = \sqrt{\sum \frac{(H_{s\,Insitu} - H_{s\,Model})^2}{N}} \quad (6)$$

where H_s is the significant wave height and N is the number of significant wave height readings. The validation values were considered acceptable referring to those of the previous study with 0.28 (Ismail *et al*., 2020) and 0.25 (Shariful *et al*., 2020). Thus, the simulations were carried out afterward starting from April 2019 until August 2020 to simulate the post-construction event.

Statistical Analysis-Spearman Rank Correlation Coefficient

In this sub-chapter, the relationship of all the seasonal evolution parameters including wave, beach profile, and sediment characteristics (d_{50}) will be presented below using a Spearman coefficient. It summarises the characteristics of the dataset and describes the strength and direction of a relationship between two quantitative variables. Higher value of r suggests the parameters have a stronger relationship and complementary data following the spatial and temporal aspects. The correlation measures the non-parametric monotonic relationships between data in which assuming the bivariate normal distribution is not tenable (Artusi *et al*., 2002). The analysis using the formula is as stated below:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad (7)$$

where ρ is Spearman's coefficient correlation, d_i is difference in paired ranks, and n is number of observations.

Table 2: Overview of input data in MIKE 21 SW

Parameter	Description
Module	Spectral wave
Simulation period	1/4/2019 12:00 - 31/8/2020 12:00
No. of time step	1,200
Time step interval	21,600
Bottom dissipation	Nikuradse roughness, constant: 0.04, current friction: 0
Wave breaking	Specified-Gamma: 1, Alpha: 1
Wave current interaction	No current effect
Wave current surface elevation	Constant: 0
Wind forcing	Wind, speed, and direction

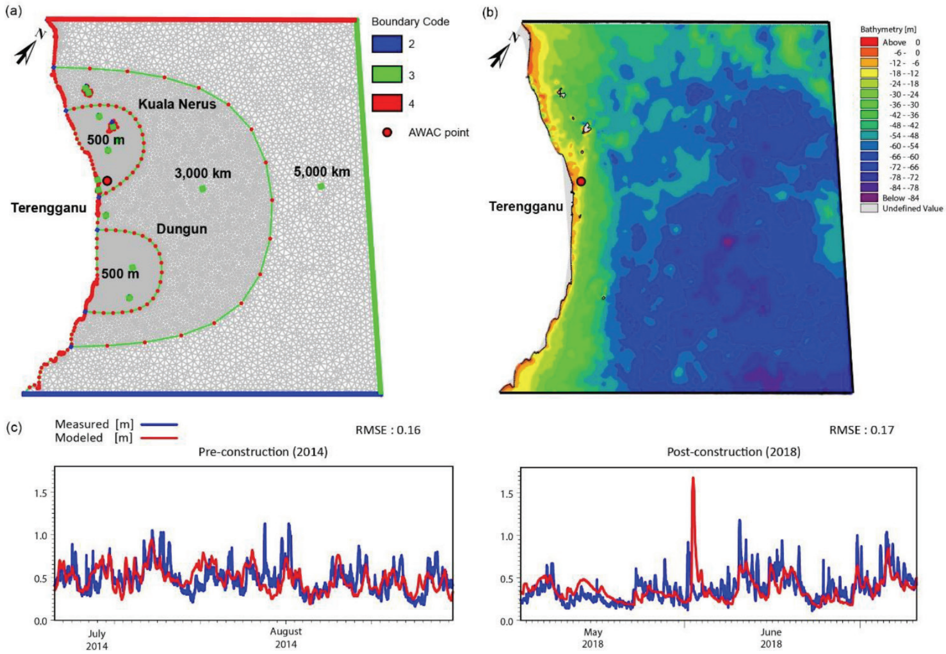

Figure 4: Geomatic model domain and initial bathymetry of the MIKE 21 SW model: (a) The computational mesh and boundary; (b) bathymetry for the model domain of Kuala Nerus and Dungun generated from GEBCO; and (c) wave model validation with in-situ AWAC measurement comprising pre- and post-construction of coastal construction showing the RMSE value

Results

Shoreline Evolution

In this section, the evolution of the shoreline was delineated in the form of End Point Rate (EPR) in Kuala Nerus and Dungun. In Kuala Nerus (Figure 5), the EPR value for all appended years showed a similar pattern; where one side experiences erosion (negative EPR), the other side will balance back the sediment transport and have an accretion (positive EPR). The figure showed a separation trend (Batu Rakit- Mengabang Telipot) on the north side and (UMT 1-Tok Jembal) in the southern region denoted by the dotted grey line. For the series of years between 2004 and 2019, the EPR value showed erosion on the northern side (Batu Rakit, Pengkalan Maras, and slightly Mengabang Telipot), whereas accretion in the south (UMT 1, UMT 2, and Tok Jembal).

Meanwhile, for the series 2004-2016, the pattern of the EPR in the northern areas (Batu Rakit-Mengabang Telipot) showed a positive EPR value illustrating the accretion process and in the south part (UMT 1-Tok Jembal) indicating the erosion problem. Over the 2016-2019 period, there was a change in the EPR values movement. The area specifically at Batu Rakit experienced accretion at almost +30 m. At the same time, the erosional rate discovered at Pengkalan Maras and UMT 3. UMT 1 and UMT 2 had a significant accretion with EPR values of more than +50 m within three years.

Figure 6 shows the rate of change of the shoreline in the Dungun area and was selected for the comparative spatial study of the Kuala Nerus region. Generally, the EPR trend for the selected years was about the same, the areas with accretion and erosion was quite similar to each other. However, the separation trend of EPR in this area was divided into three sections (north,

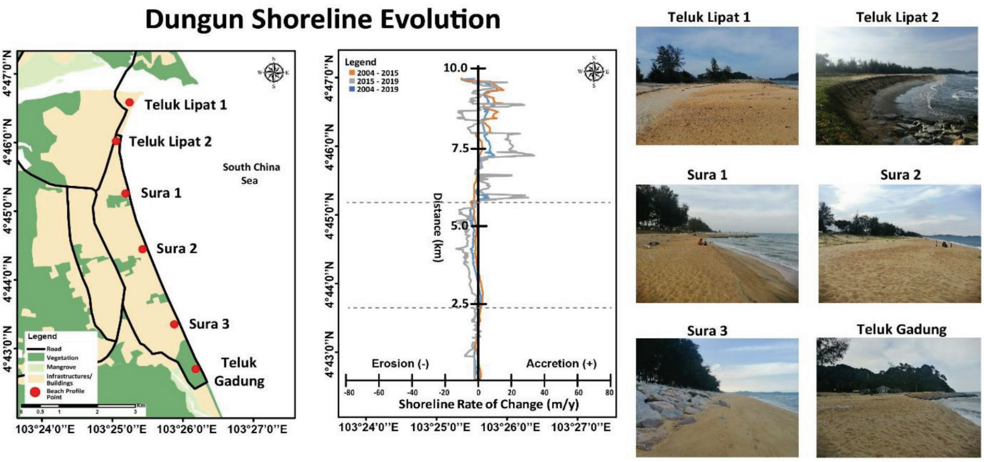

Figure 5: The End Point Rate at Kuala Nerus showing the End Point Rate (EPR) at Kuala Nerus 2004-2019 (all years), 2004-2016 (pre- and during the construction of coastal defence), and 2016-2019 (post-construction of coastal defence)

centre, and south). There were more noticeable differences in the rate of shoreline changes over the period from 2015 to 2019. The 2015-2019 EPR value demonstrated an accretion behaviour in which the intensity kept increasing (accretion process) after the construction of the groynes along the north Dungun coast (Teluk Lipat 1, Teluk Lipat 2, and Sura 1) while at the Sura 2, Sura 3, and Teluk Gadung experienced an erosion of fewer than -20 m within those three years.

Beach Profile

An analysis of the beach profile set a dynamic change within all 12 sampling stations. Most of the Kuala Nerus sampling stations experienced erosion during NEM and accretion during the SWM (Figure 7). Additionally, sediment enhancement could also be seen during NEM. The stations included Mengabang Telipot, UMT 1, UMT 2, and Tok Jembal. The Tok Jembal station data was considered exceptional due to its revetment since the armour rock protected the beach from erosion.

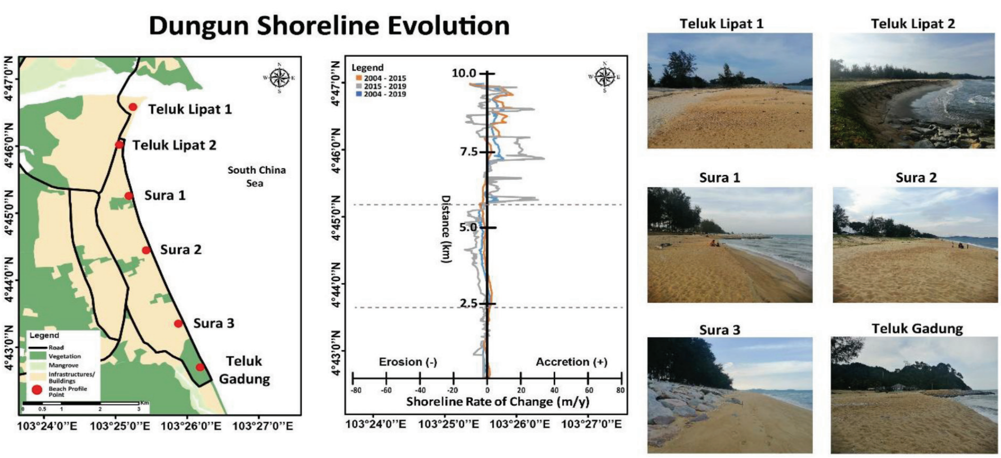

Figure 6: The End Point Rate at Dungun area 2004-2019 (all years), 2004-2015 (pre- and during the construction of coastal defence), and 2015-2019 (post-construction of coastal defence)

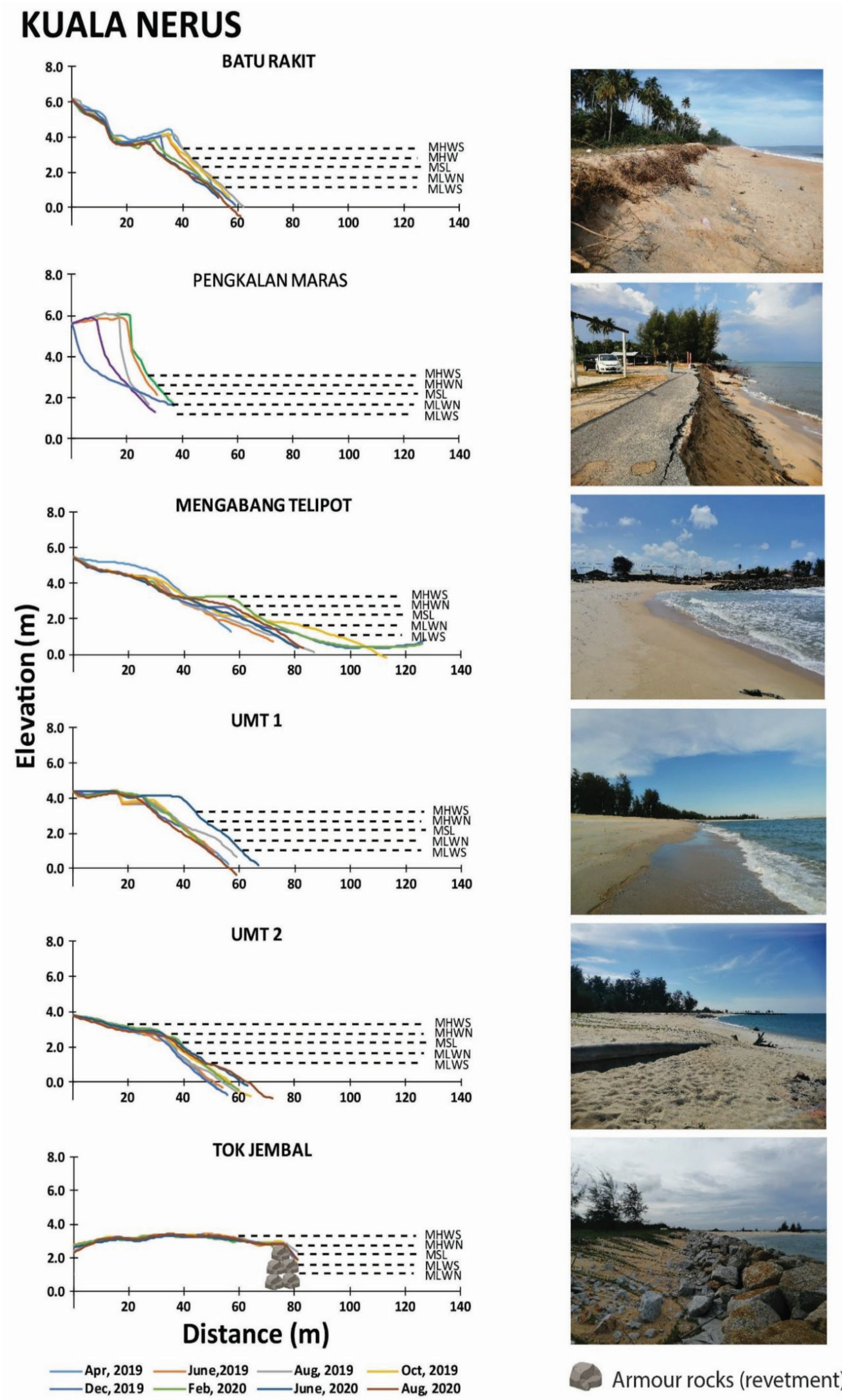

Figure 7: The beach profile of the Kuala Nerus area and the pictures taken during the survey activity

Unlike the scenario at Kuala Nerus which has a nearly straight shoreline (315° orientation), Dungun has a concave beach morphology (Figure 8). Both ends of the Dungun littoral cell have a natural headland influenced directly by coastal processes. Most of the stations experienced erosion during SWM and accretion during NEM, which is in opposition to the natural process at Kuala Nerus. Based on the bi-monthly observations, only Teluk Lipat 1 station showed the same pattern of beach profiling process as that of the Kuala Nerus station; other than that, it was dynamic, it had sediment degradation within the NEM period and accretion from June to August. Meanwhile, the other stations (Teluk Lipat 2, Sura 1, 2, 3, and Teluk Gadung) showed erosion during the SWM period. Interestingly the most dynamic station, Teluk Gadung, once experienced edge failure and berm destruction in August 2019, but recovered from October 2019 until the end of the observation period (Figure 9).

Figures 5 and 6 show that Tok Jembal, Sura 3, and Teluk Gadung have a revetment structure to secure their shoreline. When compared with other stations where the structures are located nearer to the beach profile point, the three stations have revetment structures on their profiles. Regardless of the revetment's function to retain the profile, the overtopping of waves still occurs behind the armour rocks. Both Tok Jembal and Sura 3 stations displayed an eroded backshore profile and scouring effect even though it has not significantly impacted the profile in a short-term period, but over time, a future flunking edge of the berm might occur. Meanwhile, the Teluk Gadung emergency revetment was completely buried by incoming sediment deposition built in August 2019. From this aspect, the authorities emergency mitigation measures were well executed with a proper understanding of the littoral transport there as the revetment stabilised the profile without berm destruction as before in August 2019.

Besides, volume and slope changes are the two parameters related to each other. The higher value of slope degree will impact the volume (Figure 10). For spatial difference, northern Kuala Nerus experienced more negative volume, indicating more sediment loss when compared to the southern region. This is much supported by the increasing degree of slope changes, especially at Batu Rakit, Pengkalan Maras, and slightly Mengabang Telipot area. Most of the beaches in UMT and Tok Jembal showed volume increment and decreasing slope.

Meanwhile, north of the Dungun area experienced volume increment as well as slope decrement. However, since the morphology of Dungun is a kind of concave beach, the centre part undergoes the most impact resulting in more erosion. The volume difference since the first sampling period reached up to -45 m^3 and the slope increased by 21°. Besides, at the Teluk Gadung site, there was a peak of volume reduction accompanied by an additional slope degree between August and October 2019.

For the temporal changes, NEM seasons exhibited the highest volume degradation and together with the slope increase, especially at Batu Rakit and Pengkalan Maras stations. As expected, the UMT area and Tok Jembal experienced stable slopes throughout the sampling period. In Dungun, the volumetric and slope changes were significantly seen at the central part, which is Sura 1 station. The volume loss and steep slope here are quite severe when compared to the other beaches. As aforementioned, most of the stations are installed at coastal structures except for this station. Thus, as the littoral transport moves southward, this beach technically receives a less than expected supply of sediment causing it to experience a sediment deficit, leading to an erosion of its beach profile which affects the onsite grain size distribution.

Mean Grain Size Based on the Littoral Transport

The mean grain size at Kuala Nerus (Table 3) ranged from coarse to fine sand while Dungun (Table 4) showed very coarse to fine sand. In terms of spatial difference, the Dungun area has coarser sediment ranging between -0.085 ϕ and 2.361 ϕ and Kuala Nerus dominantly had

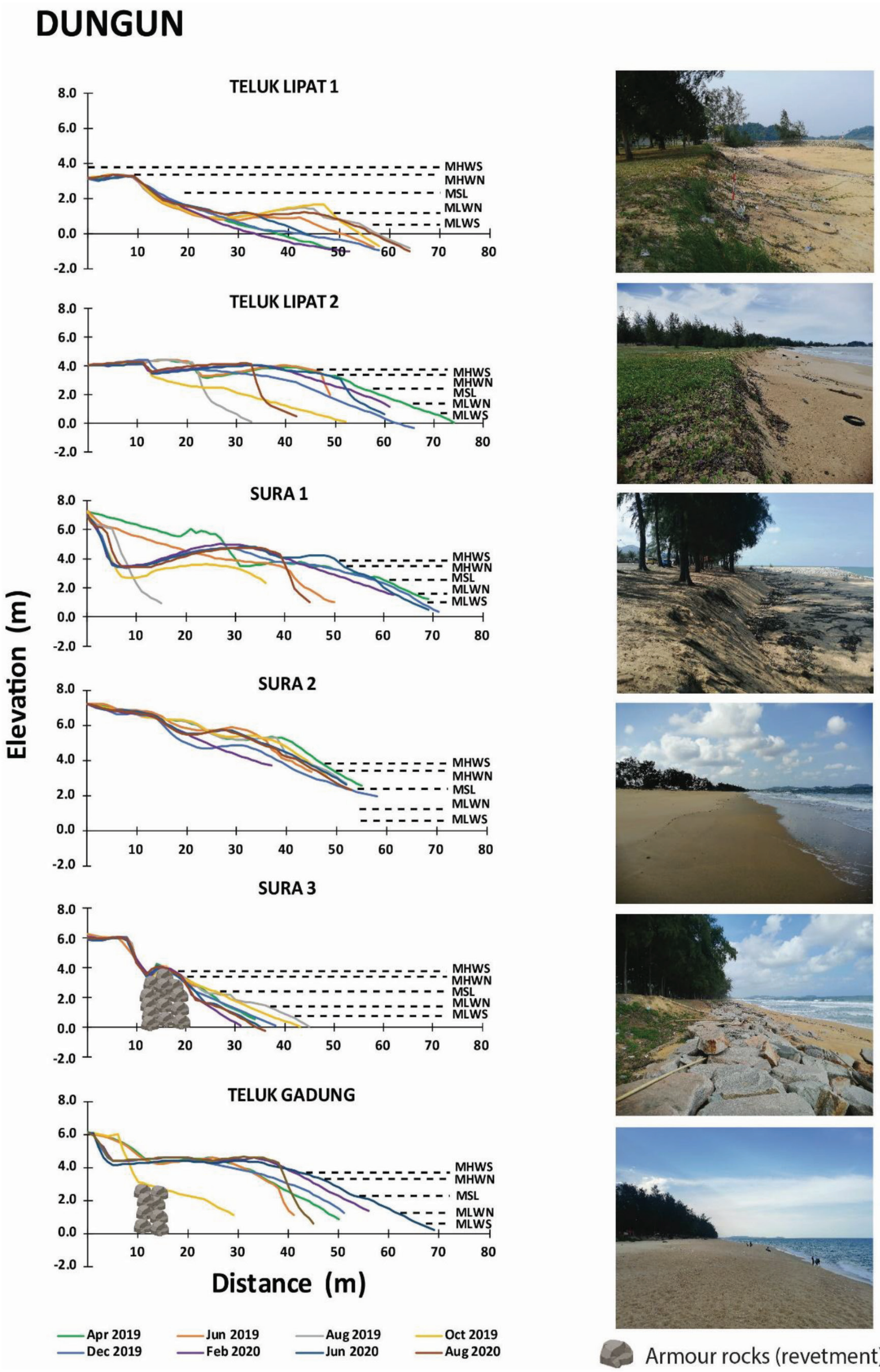

Figure 8: The beach profile of the Dungun area and the pictures taken during the survey activity

Figure 9: Substantial beach morphodynamic changes due to anthropogenic and natural seasonal activities at Teluk Gadung station in April 2019 (left), August 2019 (centre), and August 2020 (right)

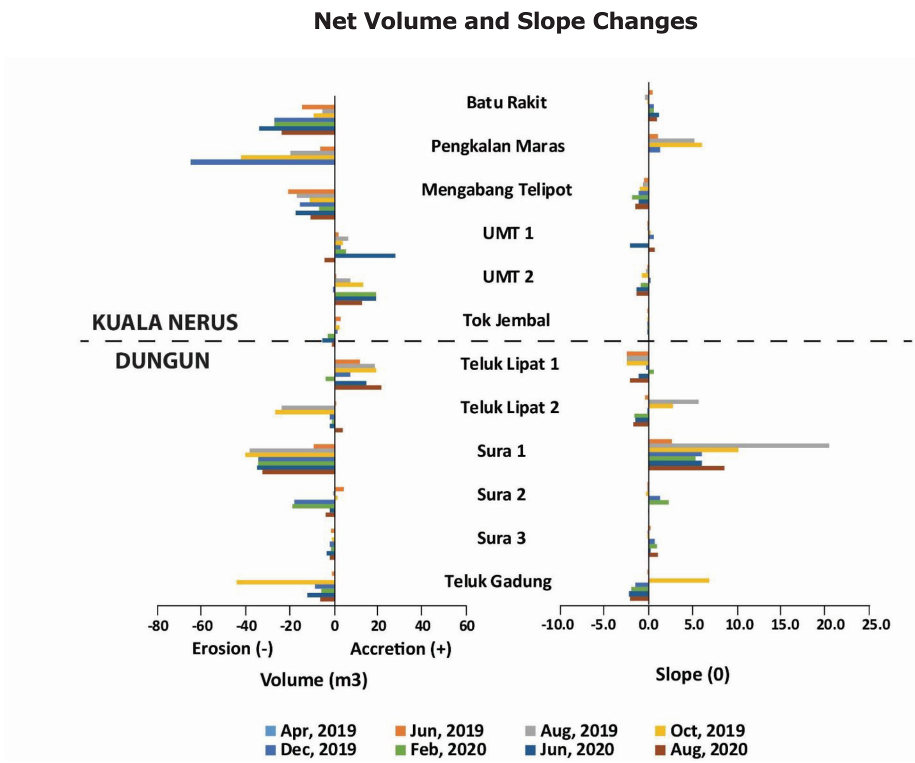

Figure 10: The beach volume and slope for both stations

finer sediment (between 0.288 ϕ and 2.561 ϕ). It can be observed that SWM impacted Dungun by yielding quite coarser sediment within this season. However, NEM showed a stable pattern (coarse to fine) of distribution at Kuala Nerus.

Wave Parameters

Results from Figure 12 and Figure 13 illustrate the output of the wave parameter depicted a higher significant wave height, H_S during NEM at Dungun, which recorded more than 1.5 m. For Kuala Nerus, the H_S range was between 1.2 m and 1.35 m. This indicated that the Dungun area tends to have higher wave height. As the wave reached the shallower shoreline, the wave height gradually decreased. Both wave distribution maps discovered the coastal structures caused the H_S to be reduced when compared to the wave height in front of the coastal region with less or no structure (Fitri *et al.*, 2019). Behind the

Table 3: The mean grain size for the Kuala Nerus stations

Month	Stations											
	BR		PM		MT		UMT 1		UMT 2		TJ	
Jun, 19	1.885	MS	1.968	MS	1.738	MS	1.463	MS	2.037	FS	1.244	MS
Aug, 19	1.468	MS	1.421	MS	0.8	CS	1.118	MS	1.346	MS	1.397	MS
Oct, 19	1.718	MS	1.306	MS	1.867	MS	1.325	MS	0.757	CS	0.907	CS
Dec, 19	1.787	MS	2.394	FS	1.632	MS	1.127	MS	2.084	FS	1.372	MS
Feb, 20	2.132	FS	2.561	FS	1.158	MS	0.728	CS	1.703	MS	1.045	MS
Jun, 20	2.277	FS	2.079	FS	1.399	MS	1.806	MS	2.306	FS	0.288	CS
Aug, 20	2.387	FS	-	-	1.303	MS	1.310	MS	1.998	MS	0.903	CS

FS: Fine Sand, MS: Medium Sand, CS: Coarse Sand

Table 4: The mean grain size for the Dungun stations

Month	Stations											
	TL1		TL2		S1		S2		S3		TG	
Jun, 19	1.908	MS	0.225	CS	0.345	CS	1.380	MS	1.646	MS	1.646	CS
Aug, 19	1.462	MS	0.435	CS	0.332	CS	1.703	MS	1.118	MS	-	-
Oct, 19	2.311	FS	1.559	MS	-0.085	VCS	2.302	FS	1.890	MS	0.280	CS
Dec, 19	1.796	MS	0.338	CS	0.498	CS	1.404	MS	0.317	CS	0.152	CS
Feb, 20	1.045	MS	0.072	CS	0.072	MS	1.529	MS	1.594	MS	0.325	CS
Jun, 20	2.361	FS	0.156	CS	0.960	CS	1.643	MS	0.927	CS	0.015	CS
Aug, 20	1.429	MS	0.349	CS	0.720	CS	1.902	MS	1.120	MS	0.262	CS

FS: Fine Sand, MS: Medium Sand, CS: Coarse Sand, VCS: Very Coarse Sand

breakwater structure, especially at Mengabang Telipot and UMT beaches, the maximum H_S only reached 0.15 m. However, for the Batu Rakit area, the wave height could still reach up to 0.90 m (Figure 11).

Overall, during the SWM, the H_S was higher, which showed that Dungun area had domination on the impact on the beach morphodynamics (Figure 12). This situation also demonstrated that the Dungun area exhibited high dissipation characteristics during this season and sediment transport would be more prevalent than deposition events. Higher dissipative energy will lead to the reduction in the transport threshold values, thus much finer sediment will be transported rather than deposited. That is why coarser sediment is predominantly present at Dungun and finer materials at Kuala Nerus. On the contrary, the Kuala Nerus area was subjected to less influence. In addition, higher H_S specifically over the SWM period triggered beach erosion in the area. Higher wave heights caused a berm failure, leading to the eroded sediment being transported to adjacent beaches.

Relationship of Wave, Current, Beach Profile, and Sediment Characteristics

The relationship of all the seasonal evolution parameters including wave, beach profile, and sediment size (d_{50}) presented below by using Spearman coefficient as stated above. For Kuala Nerus, all parameters only exhibited a very weak to moderate correlation and not significant ($p > 0.05$) during NEM (Table 5). However, during SWM beach elevation versus wave and beach slope against beach volume depicted significant

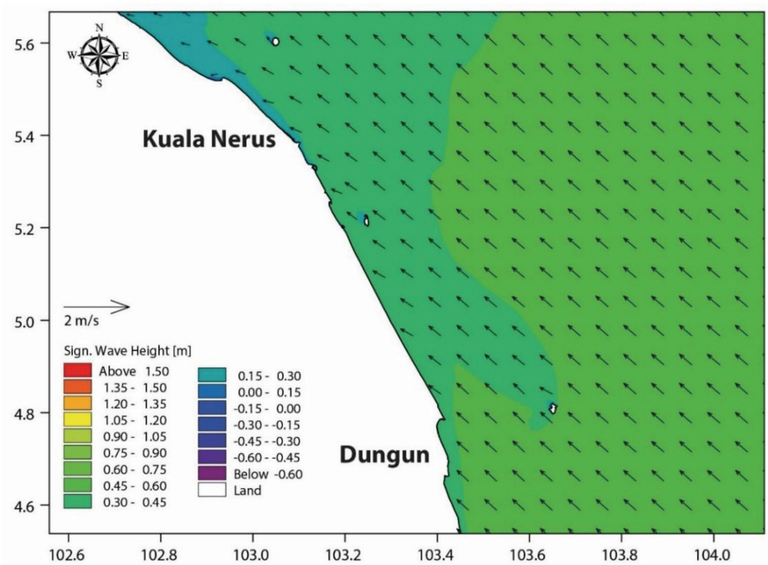

Figure 11: Distribution map of significant wave height during SWM at Kuala Nerus and Dungun

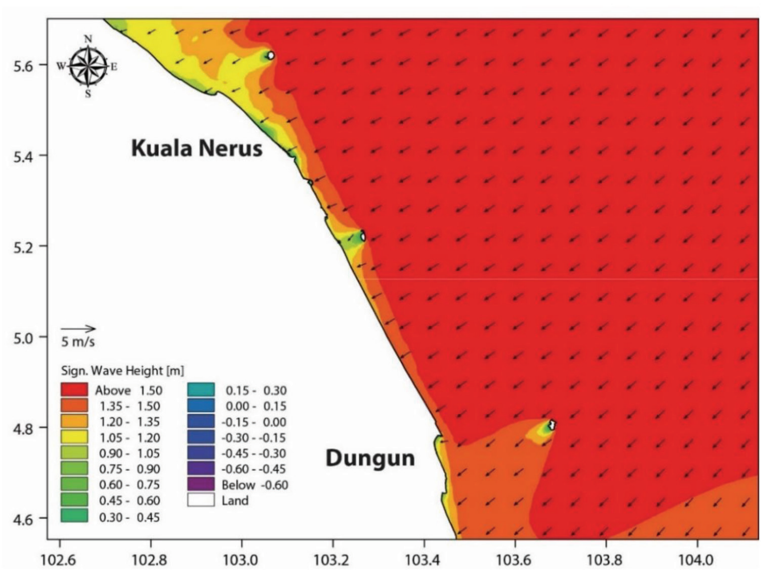

Figure 12: Distribution map of significant wave height during NEM at Kuala Nerus and Dungun

and strong correlation in which r = 0.612, $p < 0.001$ and r = -0.516, $p = 0.004$, respectively (Table 6). In Dungun, the analysis also presented strong and negative correlation (r = -0.644, p = 0.124) during NEM (Table 7). Meanwhile, SWM season evidenced slope versus volume were strong and negatively correlated (r = -0.780, $p < 0.001$) (Table 8). On the other hand, three relationships including volume versus elevation (r = 0.502, p = 0.005), slope versus elevation (r = 0.497, p = 0.005), and d_{50} versus elevation (r = 0.413, p = 0.023) were positive and had strong correlation.

Table 5: Spearman correlation between significant wave height (H_S) and other morphodynamic factors at Kuala Nerus during NEM

Parameters	H_S (wave)	Beach Elevation	Beach Volume	Beach Slope	d_{50}
H_S (wave)	1.000	-0.193	-0.266	-0.340	-0.483
Beach elevation		1.000	-0.088	0.444	-0.231
Beach volume			1.000	-0.346	0.406
Beach slope				1.000	0.106
d_{50}					1.000

** Correlation is significant at the 0.01 level (2-tailed).

Table 6: Spearman correlation between significant wave height (H_S) and other morphodynamic factors at Kuala Nerus during SWM

Parameters	H_S (wave)	Beach Elevation	Beach Volume	Beach Slope	d_{50}
H_S (wave)	1.000	0.612**	0.034	0.059	0.035
Beach elevation		1.000	-0.164	-0.015	-0.177
Beach volume			1.000	-0.516**	0.130
Beach slope				1.000	-0.180
d_{50}					1.000

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 7: Spearman correlation between significant wave height (H_S) and other morphodynamic factors at Dungun during NEM

Parameters	H_S (wave)	Beach Elevation	Beach Volume	Beach Slope	d_{50}
H_S (wave)	1.000	0.290	0.000	-0.024	-0.314
Beach elevation		1.000	0.189	-0.312	0.343
Beach volume			1.000	-0.644*	0.186
Beach slope				1.000	0.149
d_{50}					1.000

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Discussion

Shoreline Rate of Change

The historical shoreline evolution over a 15-year period showed that at the natural beach, recovery processes had occurred following seasonal changes. However, disturbances in coastal areas could lead to erosion issues, which would make it harder to achieve the coastal dynamic equilibrium. Northern areas were not yet disturbed in the early stages, except at UMT 1 towards the southern region, where the coastal modification had started. The extension

Table 8: Spearman correlation between significant wave height (H_S) and other morphodynamic factors at Dungun during SWM

Parameters	H_S (wave)	Beach Elevation	Beach Volume	Beach Slope	d_{50}
H_S (wave)	1.000	-0.153	-0.035	0.160	0.063
Beach elevation		1.000	0.502**	-0.497**	0.413*
Beach volume			1.000	-0.780**	0.021
Beach slope				1.000	0.051
d_{50}					1.000

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

of the airport runway is one of the factors for the coastal erosion that occurs today (Ahmad *et al*., 2014; Soh *et al*., 2019). It is undeniable that the presence of the runway extension that juts out seaward blocks the longshore drift pathway (Ariffin *et al*., 2016). This has disrupted the normal transport of the sediment. Erosion at Pengkalan Maras is proof that an erosional rate of more than -10 m can occur in just four years.

When one place has eroded, the adjacent areas will also be affected. According to Putro and Lee (2020), the eroded sediment will follow the direction of the longshore drift which is linearised with the shoreline shape. The counter-balance process of shoreline change study demonstrated that the littoral transport will always bring the sediment along to a favourable site. For instance, Batu Rakit benefited from the additional sediment volume during the 2016-2019 evolution due to the erosion at UMT. However, the resultant evolution over the period from 2004 to 2019 had a negative EPR because the whole littoral cell there experienced the most accreted area in the south, as a result the northern area (Batu Rakit) saw serious erosion.

The littoral transport for the Dungun area is moving southward, which will keep changing following the monsoons. Dungun is influenced mostly by natural processes. Only in the north (the updrift area), where the bell-shaped groynes were installed and at Sura 3, which has a rip rap structure the natural processes lessened or curbed coastal flooding and edge failure. The low-lying area in Dungun makes it prone to coastal changes which makes the area a high-risk zone for coastal dwellers (Ismail *et al*., 2022). From the overall result of the Dungun EPR value, the trend was not too different but with a significantly different intensity rate of the EPR value. The 2015-2019 EPR value had the highest rate for both erosion and accretion along the coastline, but the latter was much more prominent, especially in the area with the groynes. The amount of river discharge can be the reason for the abundance of the sediment there, which displayed a morphological adjustment and the presence of the groynes obstructing the sediment littoral transport supply to the south area.

In addition to those above, a study from Zamri *et al*. (2021) elucidated that the Dungun river flow has been altered and has slowed significantly. The slowing of the river flow has impacted the amount of river discharge at the shoreline area. This condition was different from what was seen at Kuala Nerus as the Dungun river is situated just behind the Teluk Lipat 1's groyne. Thus, it has been the primary source of sediment, other than what is brought in from offshore. However, since the flow rate slowed down and also a series of shoreline constructions blocked the natural sediment movement, which has had a devastating impact on the beach profile.

Beach Profile

Coastal dynamic processes have a close relationship with the natural and anthropogenic influences. Both areas knowingly have the same influences from a strong Northeast Monsoon (NEM) and a series of coastal defence structures. However, the intensity of the storm that hit the coastal region varies due to different morpho-structural implementations. The area with coastal structures (emerged breakwater now known as tombolo-breakwater) seemed stable along the season and has only seen a slight change. The structures have successfully maintained the beach morphology for a certain period in certain locations. However, the beach without coastal protection was subjected to erosion. Updrift accretion and downdrift erosion could possibly have occurred with the presence of this breakwater (Saengsupavanich *et al*., 2022).

Pengkalan Maras station experienced significant erosion due to its location at the downdrift pathway. More than -20 m loss of beach width was recorded from April to December 2019 due to the Pabuk storm (Shariful *et al*., 2020) to undergo the natural process of substantial erosion and accretion, together with the repercussions of coastal structures. A temporary benchmark was lost as the beach keeps encroaching upon the inland area. Data stopped being recorded from that point on. While Batu Rakit (which is shielded by the Pengkalan Maras station) has undergone dynamic changes showing erosion during the NEM and accrete during the SWM. Thus, from observation, it is confirmed that the beaches with coastal structures were more stable and rarely suffer from erosion.

As mentioned before, the littoral drift for Kuala Nerus is moving to the north and will keep changing following the monsoons. When coastal structures for the mitigation measures were installed such as groynes and breakwaters, significant accretion was observed at UMT 1 and UMT 2 and sediment accumulation took place due to a few detached breakwaters that eventually led to the tombolo-breakwater formation. These structures not only intensified the rate of erosion in the northern area (due to decline in sediment supply) but also changed the inclined angle of the waves that hit the coastline. The changes in the angle of the waves can lead to confusion of the cross-shore and blockage of the littoral drift direction. This indirectly influences the sediment transport and sediment budget to be yielded in the adjacent areas (Prodger *et al*., 2017).

In addition, the morphology of the concave beach at Dungun was due to the presence of natural headland in both the north and south areas forming a crenulate-shaped shoreline. Natural headlands are a morphological tool to trap sediment, as a result, the area will experience less erosion. Of note, for both Kuala Nerus and Dungun shorelines, there was an obvious form, where a wider beach in the updrift areas and narrower beaches at the downdrift areas [Figure 1 (a) and (b)]. The justification for this is that to achieve stability and prevent an edge failure, erosion would keep happening until an ample amount of sediment deposits helped it recover from the sediment loss. The mentioned figures demonstrated that the installed revetment in Tok Jembal and Sura 3 was located below the Mean High Water Spring (MHWS) or specifically, at Mean Sea Level (MSL). Supposedly, the structures were located at or above the MHWS so that the impact of wave overtopping can be minimised (Figure 7 and Figure 8).

For Dungun area, the inconsistency of the topographic changes occurred but generally, SWM led to the erosion season, and in contrast, NEM is the season for the depositional event. For instance, Sura 1 showed an unsteadiness profile. This was mainly in April 2019, when beach nourishment was done and the next month until August, when the berm failure kept occurring, which was beyond doubt due to the insufficient sediment supply from the north. The recovery process happened after October 2019 when there was a dramatic erosion event in

August 2019 at Teluk Gadung, where the beach profile was lost beyond the benchmark point and impacted the volumetric and slope magnitude.

The decreasing volume value will lead to the increasing of the beach slope. Increment of the beach slope will tend to cause beach instability, thus, allow more erosion to occur. This is because, a higher slope will cause the instability of the beach profile, thus, resulting in the unconsolidated sediment being winnowed away by coastal drift from the shoreline area. This hypothesis was consistent with Bon and Sousa (2018) considering that as the beach face becomes steeper, the average of the beach width will reduce accordingly in which the volume reduction took place. As aforementioned, most of the stations are installed with the coastal structures except for this station (Sura 2). Therefore, as the littoral transport moves southward, this beach technically receives less than expected supply of sediment causing it to experience a sediment deficit, leading to the narrower cross-shore profile directly affecting its grain size distribution.

Sediment Distribution

In the sediment analysis study, the mean grain size was used to determine the trend of the littoral transport that brought along the sediment. The grain size provides a literal indication of the environment that shows the depositional/transportation pattern, hydrosedimentary transport as well as the wave energy present. As such, the determination was based on the seasonal changes as well as the anthropogenic influences such as the installation of coastal structures and beach nourishment accordingly to the sampling stations.

Essentially, the movement of the sediment is driven by the longshore transport that moves parallel to the shoreline and cross-shore drift, which can lead to beach erosion or accretion. Sediment starvation could occur when the net sediment received by a particular beach is less than expected, conversely the reverse happens during sediment enhancement. However, erosion issues are a more worrying and a dangerous phenomenon experienced by coastal countries all around the world. As a result, the characteristics of the sediment is an important aspect to be understood and studied especially when related to the wave action that significantly impacts the sediment distribution (sediment budget) in the area. An interesting relationship was discovered between littoral transport, the mean grain size as well as coastal defence structures. As mentioned before, the littoral transport at Kuala Nerus is from the south to the north, which brings the sediment along. Based on Figure 9, the average grain size was as clearly illustrated, that of a coarse-medium pattern from Tok Jembal to Batu Rakit. The sample collected at Tok Jembal station were solely from the nourishment project and not involved in littoral transport. According to de Schipper *et al*. (2021), sediment obtained from beach nourishment activities will have coarser material and is believed to adjust the steepness of the beach configuration, thus, creating a post-nourished dry beach. This is consistent with Bitan *et al*. (2020), who posited coarser sediment should be used for beach longevity as long as it is effective and economic in the long term.

However, as the littoral transport moved more to the north, another few coastal structures (breakwater and groyne) slowed down the movement, which led to some of the sediment being deposited and transported to the adjacent beaches. This is supported by Fitri *et al*. (2019), who showed that the presence of breakwaters has successfully reduced the wave height at the lee side of the structures. A lower wave regime basically will bring finer sediment to the beach (Elshinnawy *et al*., 2017; Joevivek *et al*., 2018; Perera *et al*., 2023).

Meanwhile, the fine material changed back to coarser-grained due to the groyne structure (UMT 1). A study in the Bengal Basin demonstrated coarser sediment that tended to be deposited near groyne structures, especially at the tip side while leaving finer grains in the backside of it (Fitri *et al*., 2019). Later, the sediment size became fine again as the regions Batu Rakit and Pengkalan Maras have no coastal structures installed therein. This can be justified by the fact that the farther the sediment travels, the finer the sediment becomes (Yaacob *et al*., 1994; Yaacob & Hussain, 2005; Waznah *et al*., 2010).

Unlike at Kuala Nerus, the Dungun site showed the southward movement of littoral transport, bringing a sediment supply from the Dungun river. A sequential medium-very coarse-medium-very coarse sand trend can be observed spatially from Teluk Lipat 1 to Teluk Gadung. Originally, the mean grain size at Teluk Lipat 1 was composed of medium sand, similar to Yaacob *et al*. (2018) study. As the littoral transport moves downdrift, a groyne structure at Teluk Lipat 2 trapped some of the sediment making this area start to have coarse sediment (same case as at UMT 1). As expected, Sura 1 station experienced coarser sediment than Teluk Lipat 2 as this station has no structures installed. It is speculated that profile adjustment occurred here as the mean grain size obtained was most probably from the flunking berm (backshore erosion, see Figure 8 at Sura 1 station) as well as from the travelled sediment from the north.

Although, the pattern returned to medium with the presence of groyne structures at Sura 2 before changing back to coarser sediment at Teluk Gadung. Here, weathering process at Sura 3 from the rip rap structures resulted in Teluk Gadung receiving the larger sediment size (very coarse) besides the rocky headland that acts as a natural groyne to entrap the southward moving sediment. Surprisingly, the patterns of the mean size sediment changed at every station, both Kuala Nerus and Dungun, confirmed the evolutionary trend shown in Figures 5 and 6, which shows the pivotal role of the coastal processes in controlling the erosional/transport pattern in the area.

Wave Parameters

Waves were also a reason for the morphology of the beach. The Dungun area is known to have a concave or embayed beach. This feature allows for external forces like waves to make landfall more to the centre of the beach cell (Figure 13). Such the natural headland at the tip end regions in the northern and southern areas which results in the engraving of the shoreline. Model

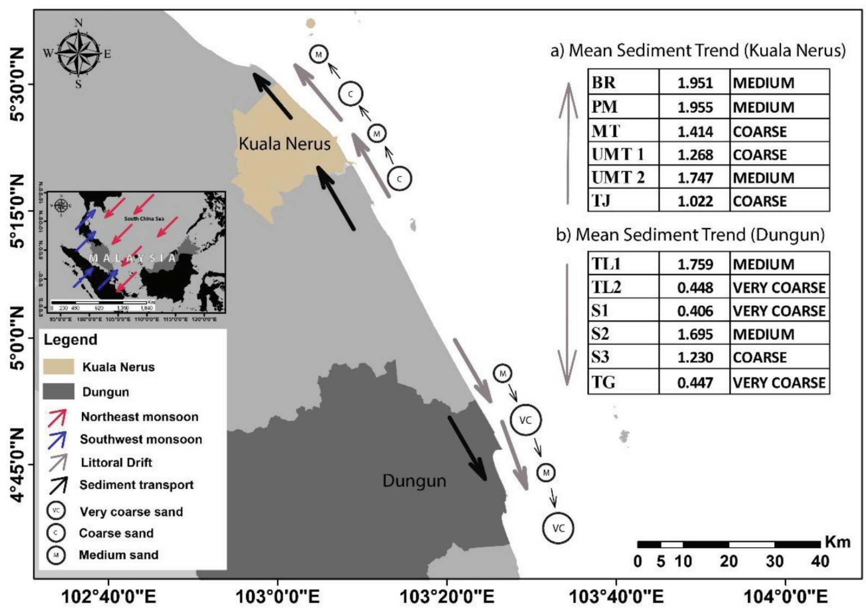

Figure 13: The different littoral drift for both areas, which is northward for Kuala Nerus and southward for Dungun. When the Northeast monsoon (NEM) season changes to Southwest monsoon (SWM), the littoral drift direction will also change

simulations from the study by Hurst *et al*. (2015) defined the impact of the wave's direction at different oblique angles toward the evolution of the shoreline change with the presence of two headlands on the coast well. Starting from a straight coast, a crenulated shoreline bay can be created by the waves in order for the shoreline to achieve an equilibrium. The model explored a single direction of the waves and the spread of the erosion significantly impacted the northwest end of the beach, creating a balanced morphology. Comparing Kuala Nerus to Dungun, seasonal winds from the NEM and SWM lead the bi-directional waves from the northeast and southwest every other season. Of note, the impact to the Dungun shoreline will indeed be more heavily affected as described by Hurst *et al*. (2015) when compared with Kuala Nerus.

This is because the central part of the Dungun shoreline exhibited a deprivation of sediment in order to come to an equilibrium. Sura 2 station which has less coastal structures tends to experience shoreline degradation more than any other station. In terms of spatial variability, Kuala Nerus has more island protection. During the SWM, wave energy was propagated by Tengol and Kapas islands while Bidong island protected the Kuala Nerus shoreline during the NEM. In Dungun, cover is only available during the NEM, Tengol island assisted to reduce the Hs. Thus, the role of the islands as a barrier in Dungun area was not justified. The presence of the islands knowingly can lessen the wave energy due to the dampening process in which the island shields the shoreline from being hit directly by strong waves (Mirzaei *et al*., 2013; Ismail *et al*., 2020; Shariful *et al*., 2020).

Correlation of Wave, Beach Profile, and Sediment Characteristics

The results show that the changes in Kuala Nerus beachside and coastline morphology is closely related to changes in the wave and beach profiles. Dungun on the other hand is mostly influenced by waves, its beach profile, and sediment size. When considering the situation in Dungun, wave conditions are much stronger when compared with those at Kuala Nerus. These stronger hydrodynamic conditions can lead to modifications in the native sediment behaviour. This explains why the correlations in the Dungun area had a significant relationship with the sediment characteristics. It is worth noting, Kuala Nerus exhibited deposition process more than Dungun, but sediment transport is more likely to occur at Dungun when compared to Kuala Nerus. Nevertheless, finer sediment will never be forever one type. The distribution can experience modification in a matter of time where, for instance for the coarser sediment, the transport process cannot maintain its magnitude and vector, which causes the transport rate to be reduced, as a result the transfer function also changes. Coarser sediment will be deposited and over time, it will also become fine. Each parameter shows a clear inter-connection to the other parameters which affects the result. However, the Spearman bivariate analysis demonstrated Kuala Nerus morphology is more closely related to the changes in the wave and beach profile than due to the depositional environmental influences such as accretion which surpassed erosion. Dungun on the other hand is mostly influenced by wave, beach profile, and sediment deposits because of its transport environment, where more sediment has been transported than deposited due to the dynamic environment in Dungun.

Recommendation for the Coastal Management

Having access to current data and knowledge of the intricate dynamics between land and sea interactions, particularly concerning the Terengganu coast is paramount. For instance, the study by Ariffin *et al*. (2020) revealed that the 2013-2017 period of beach morphodynamics at Kuala Nerus results show the role of coastal structures were somewhat controversial as erosion still occurs although some beaches experience landward redevelopment. This information serves as the foundation upon which various stakeholders and authorities can base their decisions and actions. It is crucial for them to engage in collaborative efforts with researchers and experts to address the multifaceted challenges that this region faces. Managing an environment that is both vulnerable and under constant threat is a complex endeavour, which requires a comprehensive approach.

Successfully navigating these complexities demands a profound understanding of the coastal ecosystem, its unique challenges, and the underlying factors contributing to its vulnerability. Moreover, it necessitates a spirit of cooperation among all relevant parties, including government agencies, local communities, environmental organisations, and scientific institutions. In practice, this cooperation is instrumental in developing effective and sustainable strategies for the conservation and protection of the Terengganu coast.

In such endeavours, it is important to acknowledge that not every aspect of planning and execution will proceed exactly as anticipated. Challenges and unforeseen obstacles can arise, making it imperative for stakeholders to remain flexible and adaptive in their approach. Even when faced with setbacks or unexpected turns, a commitment to the broader goals of preserving the coastal environment is crucial. Taking immediate and systematic action, guided by the best available knowledge is of utmost importance. Such actions can help mitigate and minimise the risks that threaten the Terengganu coast. By doing so, the destructive impact on this cherished natural resource and the communities that depend on it can be substantially reduced. In essence, a proactive and collaborative approach is not only essential and holds the potential to safeguard the long-term health and vitality of the Terengganu coast for future generations.

Conclusions

The beach evolutionary process, beach profile, sediment grain size, and wave action are sensibly correlated to each other. Every component mentioned above is vital in which overlooking any one parameter will lead to coastal destruction. The morphodynamic processes of the coastal areas are an unprecedented subject to be studied. It will never be the same as the foregoing event keeps changing following the surrounding factors over time. From this, it can be learned that (1) any modification to coastal areas will lead to the littoral transport disruptions, (2) coastal defence structures should not be site-specific mitigations as it reduces the erosion impact in a particular area, but will cause greater erosion in the downdrift region, (3) natural events including monsoon regime could lead to the coastal instability during the reversal seasons, and (4) the coastal structures must be placed at the right location in order for it to function effectively.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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