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PREDICTION OF SHORELINE CHANGE USING A NEW LONG-TERM SHORELINE EVOLUTION MODEL BASED ON THE CONCEPT OF SEDIMENT BALANCE

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Abstract

A new model that can predict long-term shoreline evolution in response to climate change for the 21st century has been developed. The developed model is an analytical model, capable of simulating coastal processes that contribute to long-term shoreline change, driven by the concept of sediment mass balance. The model was employed to simulate shoreline change along the 53 Km of coastline on the east coast of Peninsular Malaysia, which includes a variety of beach settings. The model was able to produce results close to the actual historical shoreline change for a hindcast period of 10 years, with an accuracy of 90%, indicating an excellent agreement between observed and predicted shoreline changes. Future coastal evolution predicted by the model indicate that by the year 2100, on average, 65% of beaches that are located along the coast of Pahang are going to disappear completely. Primarily due to the effects of long-term coastal sediment misbalance, the beaches are expected to lose roughly twice the amount of gained sediment as a result of the increasing impact of the coastal processes in the next 80 years.

Keywords: Shoreline change, analytical modelling, sediment balance, beach loss, coastal erosion

Abstrak

Model baru yang mampu meramalkan evolusi garis pantai jangka panjang sebagai tindak balas terhadap perubahan iklim untuk abad ke-21 telah dikembangkan. Model yang dikembangkan adalah model analitik capableto yang mensimulasikan proses pesisir menyumbang kepada perubahan garis pantai jangka panjang, didorong oleh konsep keseimbangan jisim sedimen. Model ini digunakan untuk mensimulasikan perubahan garis pantai sepanjang 53 km di pantai timur Semenanjung Malaysia, yang merangkumi berbagai pengaturan pantai. Model ini dapat menghasilkan keputusan yang hampir sama dengan perubahan garis pantai sejarah yang sebenarnya untuk tempoh hindcast 10 tahun, dengan ketepatan 90%, menunjukkan kesepakatan yang sangat baik antara perubahan garis pantai yang diperhatikan dan diramalkan. Hasilnya juga menunjukkan bahawa pada tahun 2100, rata-rata, 65% pantai yang berada di sepanjang pantai Pahang akan hilang sepenuhnya. Terutama disebabkan oleh kesan ketidakseimbangan sedimen pesisir pantai jangka panjang, pantai dijangka kehilangan kira-kira dua kali ganda jumlah endapan yang diperoleh sebagai akibat daripada peningkatan kesan proses pesisir dalam 80 tahun ke depan.

Kata kunci: Perubahan garis pantai, pemodelan analitik, keseimbangan sedimen, kehilangan pantai, hakisan pantai

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1.0 INTRODUCTION

The nature of sandy shores is to frequently change outline or shape, either to retreat or to advance. These fluctuations are triggered by changes in the factors acting on the sandy beaches. Non-explicitly, wave currents that affect the flow of sand, local coastal settings and the availability of native and borrow sand. These factors regulate the direction and pace at which shoreline changes [1]. Shoreline change can be divided into three types: (i) long-term change (ii) short-term change, and (iii) episodic change due to storms.

The long-term change occurs over tens of years. Usually referred to as a chronic change. The long-term shoreline changes are derived from global or large-scale slow-burning factors i.e. global warming, sediment supplement and the relative rise of sea level. On the other hand, the short-term change occurs over a short period of time, habitually season related and perhaps in the opposite direction of the long-term movement. Similarly, episodic changes are quite unpredictable, for a single storm can cause a devastating retreat [2]. This type of shoreline change relates directly to local weather conditions and annual precipitation. While all types of shoreline change occur due to different causes but the fundamental reason is one, and that is the balance between the gained and lost sediment in a coastal system [3].

Sediment balance is a concept that describes the equilibrium between the sediment input and sediment output in a coastal system. This balance theoretically defines the constantly varying shoreline position. When the sediment output rate is higher than the sediment input rate the shoreline experiences a sediment deficit, which drives the shoreline to retreat and lose width, and vice-versa [4].

Sediment gain refers to the sediment that is brought into the coastal system from various sources. Usually referred to as sediment supply or sediment budget. There are major sources that contribute to the volume of sediment supply in a coastal system. Such as river mouths, adjacent coastal systems, beach nourishment and episodic storms. Sediment supply sources depend on the properties, geography, topography, climate, and surroundings of each coastal system [5].

Sediment loss refers to the amount of sediment that is lost from the coastal system due to environmental and coastal drives. The sediment loss is a natural response of the beach to sink or transport the sediment away from the shoreface [6]. The main factors affecting the long-term coastal sediment loss include wave and tide energy, longshore drift, and sea-level rise [7].

The cross-shore process is a highly dynamic region, due to the energy of tides and waves [8]. The cross-shore region is studied by flux-gradient and bulk response models (e.g., Dean [9]). The wave breaking turbulence process in the surf zone is the leading destructive force [9]. The variability of shoreline position in response to the forces of waves and tides vary according to the timescales, which are used to capture these responses. Due to the seasonal wave energy fluctuations, the wave energy can cause the beach to both lose and gain sediment [10].

The longshore drift is enabled by the incoming waves in the diagonal direction, generating a wave-driven current, which travels parallel to the coastline along the surf zone. The general direction of longshore currents is resolved by the prevailing wind that reflects on the direction of the striking waves [11]. The longshore drift plays a dual role in the shoreline evolution. The longshore currents transport and distributes sediment between adjacent beaches, in addition to contributing to transporting the sediment from the supply sources to the coastal systems. [12].

The main cause of the sea level rise is the thermal expansion of oceans that are being continuously stimulated by global warming. The global sea-level rise caused by the thermal expansion was estimated at 1.6 – 6.6 mm per year [13]. Sea level facilitates shoreline sediment transport since it allows more high-energy waves to travel further up-shore dragging sediment seaward [14]. Modelling the shoreline erosion due to sea-level rise is a topic that arises conflict in means of modelling methodologies [15].

Many models are dedicated to simulating shoreline evolution and each model has its advantages and disadvantages. Analytical models are straightforward and efficient, e.g., Bruun rule [16], equilibrium shoreline models [17, 18]. These models are often applied to estimate shoreline change, though, they rely upon assuming a single dominant physical process to evaluate shoreline change. However, the actual shoreline change is influenced by multiple physical processes as opposed to one dominant process. These unaccounted-for secondary processes contribute to coastal evolution. Thus, inevitably these models are subject to many errors and inaccuracies [19]. Process-based models, e.g., Delft3D [20], XBeach [21], Mike21 [22, 23], and ROMS [24] primarily function based on the conservation of mass and momentum of fluid and sediment, morphology, and hydrodynamics. Although these models account for nearly all of the physical processes involved in shoreline change, they are generally used for simulating small-scale, short-term beach evolution events [26]. Using these models to simulate large-scale and long-term events such as shoreline change is complicated, with high computational cost. In addition, the results do not show high improvement over the simple analytical models [27, 28].

This research aims at developing a shoreline change model that is based on the sediment balance concept and accounts for all the necessary coastal processes, including sea-level rise. And considers both the long-shore and cross-shore coastal zones. The developed model shall be capable of predicting the long-term shoreline change for sandy beaches accurately.

2.0 MODEL DEVELOPMENT

The developed model is titled "MESE" an acronym for Multi-process, sediment Equipoise, Shoreline Evolution. The model is built on including the factors neglected by Bruun [16]. The new model considers multiple factors that drive shoreline change. These factors are mainly wave energy, sediment misbalance and sea level rise. Each of these factors split into multiple sub-factors as described further in the next sextions. This model combines all the main processes that directly influence shoreline change and theorize that shoreline change is governed by the movement of sediment in and out of the coastal system in both cross-shore and long-shore zones and directions.

2.1 Wave Energy Driven Shoreline Change

Sandy shores are constantly losing and gaining sediments in reaction to the varying waves' properties. The zone at which this process occurs is referred to as active beach profile, and it is defined as the cross-shore coastal zone that is highly dynamic due to the energy of tides and waves. The variability of shoreline position in response to the forces of waves and tides (hydrodynamic force) is simulated using a model suggested by Yates *et al.*, [18].

The model simulates sequential changes of the cross-shore position for different elevations using an equilibrium approach. Shorelines progress to steadiness as a function of the intensity of the wave forcing and the imbalance between the present and equilibrium conditions together, which causes the shoreline to erode or accrete [18, 29]. The mathematical expression is given in Equation (1) as

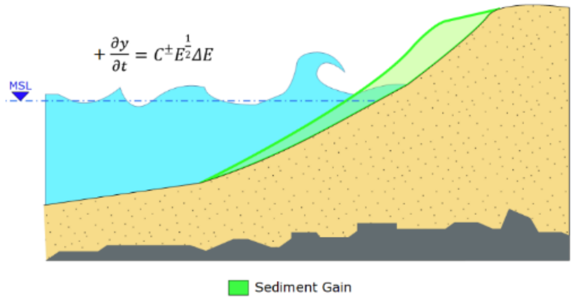
$$\frac{\partial y}{\partial t} = C^{\pm}E^{\frac{1}{2}}\Delta E. \qquad (1)$$

C signifies the rate of shoreline change, E is the instantaneous wave energy that is related to the wave height, H given by $E{=}H2$.

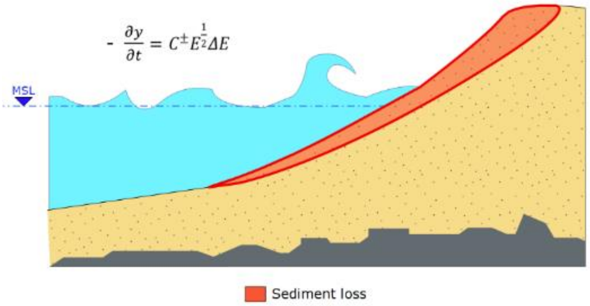
ΔE, as expressed in Equation (2) is the disequilibrium between the instantaneous wave energy, E and the wave energy related to the equilibrium shoreline position Eeqi. E_{eqi} is the wave energy that does not cause the shoreline position to change. It is given by a linear function $Eeqi{=}aY{+}b$, where Y is the initial shoreline position, a is the slope and b is the intercept point.

$$\Delta E = E - E_{eqi} \qquad (2)$$

The model is presented with four free parameters C+, C-, a, b. Parameters a and b determine the equilibrium energy (E_{eqi}) for each cross-shore position, and C+ and C- are the accretion and erosion coefficients, respectively. The free parameters C± and a relate wave characteristics to variations in shoreline position, and therefore, are similar at different sites with similar grain sizes with different wave climates. The optimal values of these parameters can be used as grain size-dependent coefficients. However, the free parameter b relates the shoreline variations to the initial shoreline position, which is required to be defined independently at each site. Therefore, it is not similar or transportable between locations [30]. Figure 1 shows the cross-shore advancement and cross-shore retreat processes as described by Yates *et al.*, [18].



(a) Cross-shore advancement +ve ΔE



(b) Cross-shore retreat -ve ΔE

Figure 1 Shoreline changes in the cross-shore position due to wave energy

2.2 Sediment Misbalance Effects on Shoreline Change

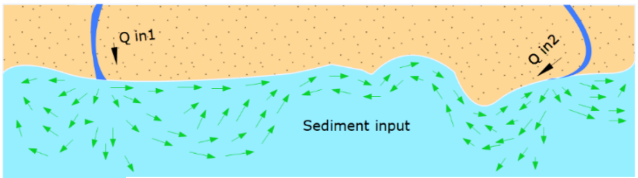
The longshore currents play a dual role in the shoreline evolution. These currents trigger the longshore drift, which is a phenomenon that erodes beach materials in the swash zone away from the beach, the longshore currents do not only cause the beach to lose its sediment but, also supplies the shoreline with sediments transported from different sources. Therefore, the two-dimensional longshore sediment balance is considered as a function of sediment volume balance as expressed in Equation (3).

$$\partial V_e = \partial V_{in} - \partial V_{out} \qquad (3)$$

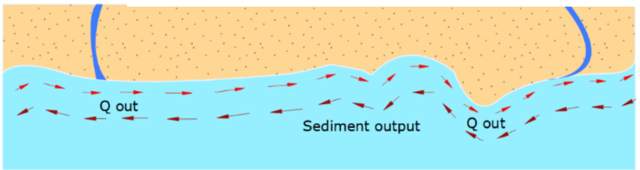
Where ∂Ve represents the sediment equilibrium or the net sediment volume in a coastal system. V_{out} is the sediment volume loss, that is eroded by the longshore drift away from the shore, and V_{in} is the sediment volume gain, delivered from the supply sources to the shore by longshore currents. Figure 2 shows the schematic diagram of sediment supply and sediment loss.

Assuming that the sediment volume transport occurs over a measurement period that is denoted as ∂t, and since the discharge, Q is equal to volume, V over a period, T, then the expression of sediment balance rate can be given as:

$$\partial Q_e = \frac{\partial V_e}{\partial t} = \partial Q_{in} - \partial Q_{out} \qquad (4)$$



(a) Sediment supply



(b) Sediment loss

Figure 2 The concept of two-dimensional sediment supply and loss rate

Equation (4) relates to the volume of sediment transported at a given time, however, it does not directly link to shoreline position. Therefore, if the coastal system is to be visualized in three-dimensional space, more variables are needed such as width and depth. Figure .3 portrays that concept in which the depths are represented by the berm height (Db) and the closure depth (Dc), respectively whereas the width (Dy) signifies the shoreline position.

The volume is a function of depth, width, and length, as well as the function of discharge rate over time, hence:

$$\partial V = \partial y\,(Dc + Db)\,\partial x \qquad (5)$$

$$\partial V_e = \partial Q_e\,\partial t \qquad (6)$$

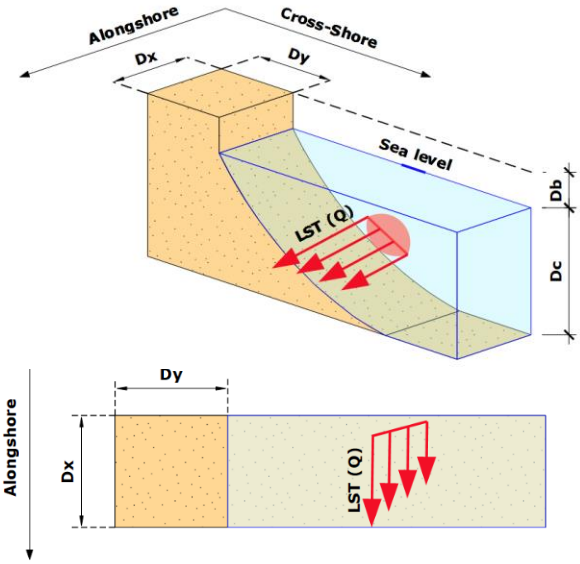


Figure 3 Spatial visualization of long-shore sediment transport (LST)

By rearranging the terms, yields the governing equation for the shoreline position change due to sediment equilibrium misbalance, where ∂y/dt is the fraction of shoreline change given by:

$$\frac{\partial y}{dt} = \frac{1}{Dc+Db}\,\frac{\partial Q_e}{\partial x} \qquad (7)$$

Substituting Equation (7) in Equation (4), the positive and negative shoreline change equations can be written as:

$$\frac{\partial y^+}{dt} = \frac{1}{D}\left(\frac{\partial Q_{in}}{\partial x}\right) \qquad (8)$$

$$\frac{\partial y^-}{dt} = \frac{1}{D}\left(-\frac{\partial Q_{out}}{\partial x}\right) \qquad (9)$$

Where *D* is the total sediment transport depths including *Dc* and *Db*. *Dc* is the closure depth, at which sediments are mainly transported in the vertical direction, and *Db* is the berm height of the beach profile. Sediment input sources are different from one beach to another, with a minimum of zero supply source to n, number of sources contributing to a single beach where $n \geq 0$. Thus, the sediment input fraction $\frac{\partial Q_{in}}{\partial x}$ in Equation (8) can be further adjusted as a function of summation of all sources as given in Equation (10)

$$\frac{\partial y^+}{dt} = \sum_{i=0}^{n} \frac{1}{D_{(n)}}\,\frac{\partial Q_{in(n)}}{\partial l_{(n)}} \qquad (10)$$

The sediment loss rate (Q_{out}) can be estimated as a mean value between CERC formula [31] and Kamphuis formula [32]. An intermediate value of longshore sediment transport rates between the two equations gives a more realistic estimation of the actual sediment transport rate [33, 34, 35].

Sediment supply rate (Q_{in}) is the volume of sediments brought into the coastal system from various sources, at time (t), usually referred to as sediment income or sediment input. It is very difficult to quantify in a real case scenario since coastal systems can be extremely dynamic and unpredictable. However, there are major supply sources that are responsible for the foremost amount of sediment supplied. The amount of sediment supplied by each of these sources depends on the properties, geography, topography and climate of each coastal system [5]. The primary sediment supply sources include erosion of upland by rivers, longshore transport from adjacent coastal compartments, erosion of the older beach and shore-face deposits, and erosion of older deposits on the inner shelf.

2.3 Sea Level Rise Effects on Shoreline Change

Bruun [16] proposed that the rising sea level had an indirect but significant effect on the rate of coastal erosion. Hence, Bruun developed an analytical approach to calculate the shoreline retreat as a function of sea level rise rate. The model of Bruun estimates shoreline erosion as a unit length of recession (loss in width). This mathematical relation is known as Bruun rule, which was the first formula to link between sea-level rise and coastal recession. Bruun proposed that the equilibrium beach profile (EBP) is an active profile where sediment erosion and deposition processes happen at successive locations. In the sense that, the volume of sediment eroded from within the critical depth in a beach profile is equivalent to the volume of sediment deposited in the same profile. Furthermore, the nearshore bottom rise (as a result of sediment deposition) is identical to the sea level rise [36]. The model is given in Equation (11).

$$\frac{\partial y}{\partial t} = \frac{S * yc}{Dc + Db} \tag{11}$$

yc is active profile length in the horizontal direction and S is the sea level rise for the projected year, Dc and Db is closure depth and berm height, respectively.

As development progressed, the Bruun model met criticism. Researchers pointed out that the Bruun rule lacks accuracy due to its two-dimensional nature of work. Other researchers criticized the model's assumptions. Bruun [16] assumes the existence of a closed system of sediment in every beach profile. In other words, the beach can neither lose nor gain sediment outside of its two-dimensional cross-shore profile which automatically suggests that the model assumes that beaches will constantly always have the same amount of sediment. Besides, since the model functions in a two-dimensional mode, the alongshore sediment transport is completely ignored in Bruun's theory. These assumptions lead to a non-solid concept since actual shorelines exchange sediments constantly in all directions. Sediment transport in coasts is a three-dimensional process and cannot be simulated in two-dimensional mode [37, 38, 39, 40].

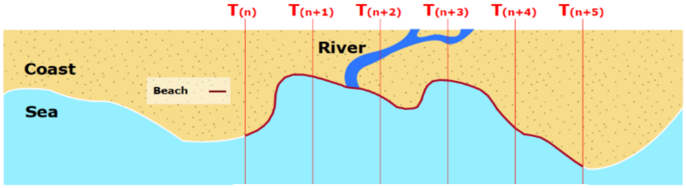
2.4 The Establishment of a New Model

Considering the significant processes that affect long term shoreline change as discussed in previous sections. The developed model is titled "MESE" an acronym for Multi-process, sediment Equipoise, Shoreline Evolution. The model represents a 3D analytical approach, driven by the main nearshore coastal processes that contribute to shoreline change and built on the concept of sediment and fluid mass balance to effectively simulate shoreline evolution and predict long-term shoreline change. By summing Eqs. (1), (8), (9) and (11), yields the relationship:

$$\frac{\partial y}{\partial t}\frac{1}{\varpi} = \left(C^{\pm}E^{\frac{1}{2}}\Delta E - \frac{1}{\tan \propto}\frac{\partial S}{\partial t}\right) + \left(-\frac{1}{D}\frac{\partial Q_{out}}{\partial L}\sum_{i=0}^{n}\frac{1}{D_{(n)}}\frac{\partial Q_{in(n)}}{\partial L_{(n)}}\right) \tag{12}$$

where ϖ is a correction factor, which is discussed further in Section 3. This model can be divided into two terms i.e cross-shore and long-shore. The first term as in the left bracket is used to obtain the shoreline change caused by alterations in the cross-shore position, and it operates by using transects taken along the beach length. A transect is a cross-sectional slice that runs orthogonal to the shoreline. Each transect is analysed as an individual slice of the beach. The results obtained from all transects taken per beach combined represent the shoreline change in the cross-shore position for that single beach. The more transects taken per beach, the more accurate the estimations of the first term are.

The longshore term as in the right side brackets simulates the effect caused by the sediment loss and sediment gain on the shoreline position. The results acquired from the two terms are then combined to produce a value for the long-term shoreline change $\frac{\partial y}{\partial t}$. Figure 4 shows the procedures for the two phases of the model for a hypothetical coast.



I- Cross-shore phase

II- Long-shore phase

Figure 4 The developed model analytical phases, where T(n) is a hypothetical transect

2.5 Study Area

The majority of the east coast of Peninsular Malaysia recorded higher coastal vulnerability index scores than other coasts in Malaysia, making them the most vulnerable to erosion [41]. Also, Pahang state coasts located on the east coast of Peninsular Malaysia showed a higher projected sea-level rise rate compared to other parts of Malaysia [42]. Therefore, Pahang coasts are classified as highly vulnerable to long-term shoreline change, hence are selected to be the study location of this research. The study area includes six beaches extended from Pantai Balok beach (3o55'43''N-103o22'17''E) located in Kuantan district until Tanjung Agas beach (3o30'39''N-103o28'24''E) in Pekan district, stretches approximately 53 kilometres along the east coast of Peninsular Malaysia. Figure 5 shows the locations of study area.

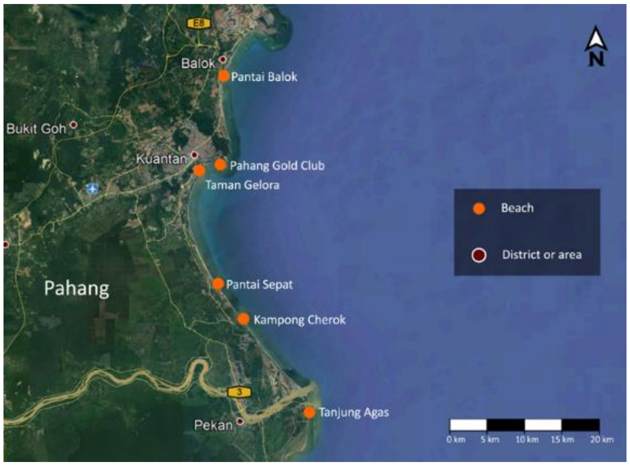


Figure 5 The locations of the study area. Six beaches along the Pahang coastline are selected

3.0 RESULTS AND DISCUSSION

The MESE model is then applied to compute the long-term sediment budget, to project and assess shoreline change and beach loss rates for the year 2100.

The forecasts provided by the developed model indicated that the leading factor contributing to shoreline change is owed to the long-term disturbance of beaches' coastal sediment balance. From the main three primary coastal processes involved in the MESE model, 46% of the shoreline retreat is contributed from the sediment balance effect, 30% is contributed by the sea level rise effect, and 24% is from the wave energy effect.

The sediment loss rate will be greater than the sediment gain rate, which will place these beaches under a substantial sediment deficit for 80 years, making this the primary factor leading to long-term shoreline change. The sediment loss/gain rates do not only depend upon the net amount of sediment entering and exiting in a coastal system but also on the capability of different shorelines within the coastal system to hold or release sediment.

Figure 6 illustrates an aerial view of the projected sediment loss rate, sediment gain rate, and projected shoreline retreat by 2100. The overall shoreline change is governed by the net sediment exchange (loss and gain) rate in a coastal system, and not by the sediment loss rate alone.

Because it is possible for a beach to have a moderately low sediment loss rate, but a significantly low sediment gain rate, this could lead to a more serious beach loss when compared to a beach that has a high sediment loss rate but also a high rate of sediment gain. That unnoticed gain rate can be compensated for the high rate of sediment loss and hence causes less beach loss.

The output obtained from the model back up that theory, where Tanjung Agas showed the lowest rate of sediment loss among all the other locations, however still experienced the highest projected long-term beach loss as can be seen in Figure. 6. This is owed to the fact that, although Tanjung Agas showed a low rate of sediment loss, it also exhibited extremely low levels of annual sediment gain. This gap in sediment gain/loss rates severely disturbed the long-term sediment balance and gave rise to a significant sediment deficit. A similar event took place at Pantai Balok, where the main influence of beach loss arises from low sediment gain rates.

On the other hand, at Kampung Cherok, the sediment loss rate is considered the highest among other locations, but also, the sediment gain rate is relatively high, which indemnified the high loss rate. This phenomenon resulted in a more steady long-term sediment misbalance and prompt less beach loss. Moreover, Pahang Golf club displayed a slightly positive rate of sediment misbalance, which kept the beach at a minor sediment surplus during the projection time and that consequently led to the least long-term beach loss, which is majorly driven by sea-level rise and hydrodynamics effects.

3.1 Shoreline Change Driven by Sea-Llvel Rise

The developed model accounts for shoreline retreat caused by sea-level rise by utilizing the Bruun rule as an integral part of the model's general equation since the sea level rise is not the only factor that influences shoreline change. Therefore, simulating shoreline change using the Bruun rule alone is considered lacking. To acknowledge the contribution of the Bruun rule, a comparison of results was done. Figure 7 shows a comparison between the results obtained by the MESE model and the Bruun model for all the six beaches (projected for the year 2100). Sea level rise rate projection for the year 2100 is taken as 32 cm for all beaches. MESE model projects that shoreline retreats caused by sea-level rise represent only 30% of the total shoreline retreat under a forecast period from 2020 to 2100. Figure 7 also shows that shoreline change caused by sea-level rise is only 11% of the total shoreline change at Tanjung Agas. This suggests that dynamic beaches are less influenced by sea-level rise than stable beaches. Therefore, the shoreline position of dynamic beaches is heavily influenced by short-term factors that tend to influence most of the shoreline change.

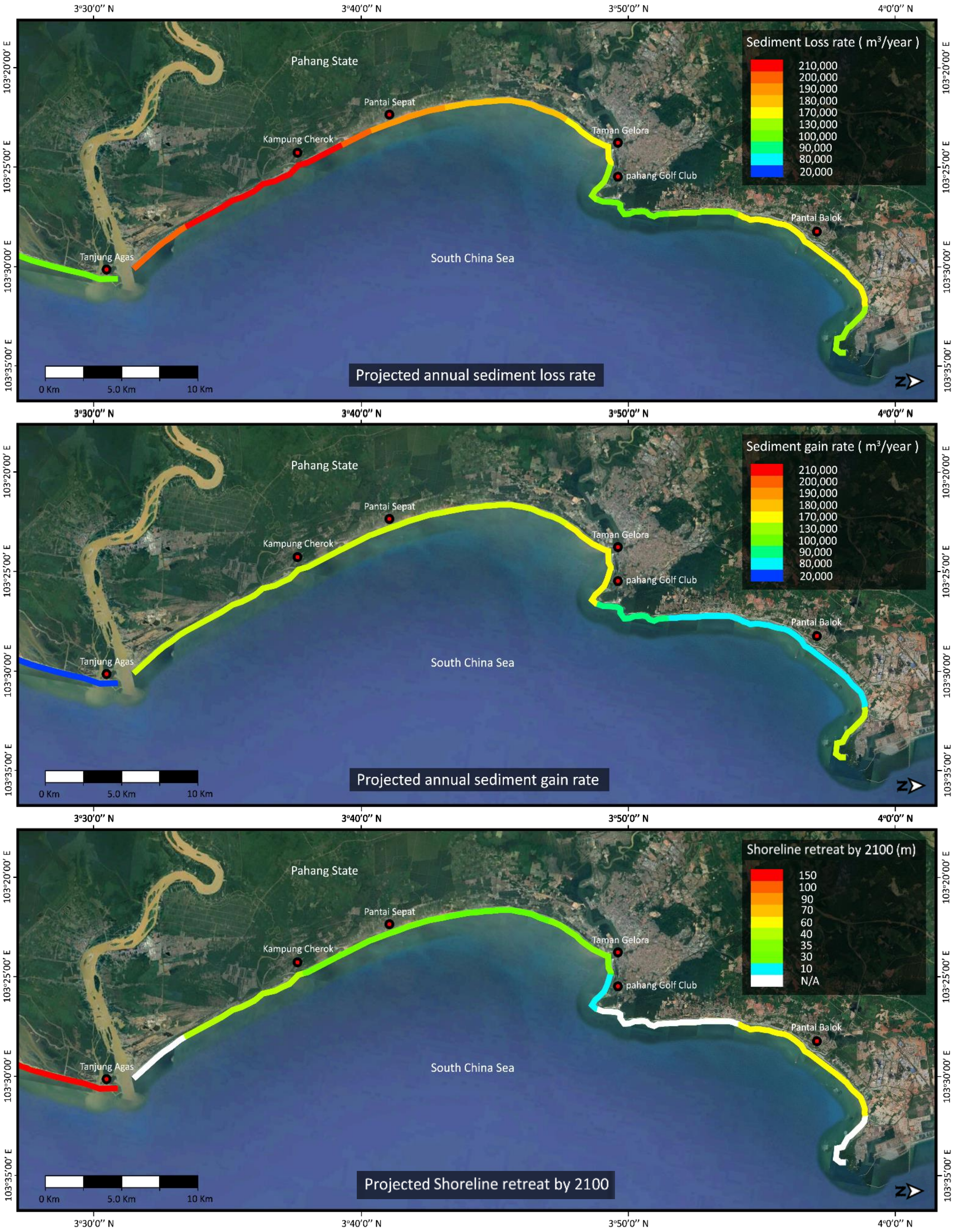


Figure 6 Projections of sediment loss rate, sediment gain rate and beach loss, the analysis are carried out using the developed model's Equations (12) and (13) along 53 km of the east coast of Malaysia on Pahang state coast. Base maps from Google Earth, Data SIO, NOAA, U.S. Navy, NGA, and GEBCO. Image © 2020 CNES / Airbus, Image © 2020 Maxar Technologies

The developed analytical model is tested via back-testing, specifically by running the model with data settings of historical records to obtain results of the current state of shorelines. This method is known as hindcasting. The obtained results from the model are then compared with the actual observed shoreline change rates for the same testing period. The difference between the shorelines is recorded as the historical shoreline change. This procedure is repeated for all other beaches and then standardized on a decadal scale. The historical observed shoreline change rates are obtained from satellite imagery. Figure 8 shows the shoreline positions of 2006 and 2017 that are both overlaid on satellite images of 2016 and 2017. The landward migration of shoreline from 2006 to 2017 can be clearly seen, indicating that the shoreline recession has occurred in the past.

Figure 7 Projected shoreline change (for the year 2100). A comparison between MESE model and the Bruun rule

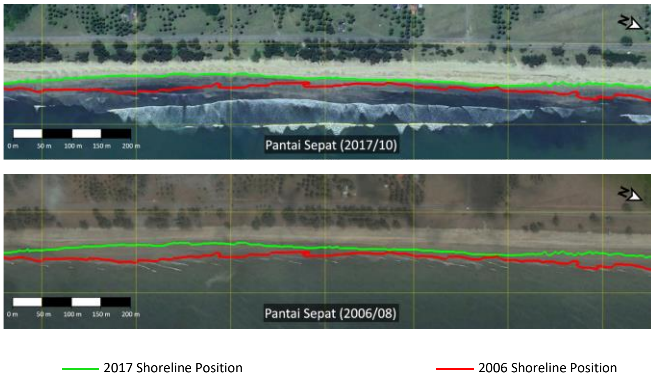


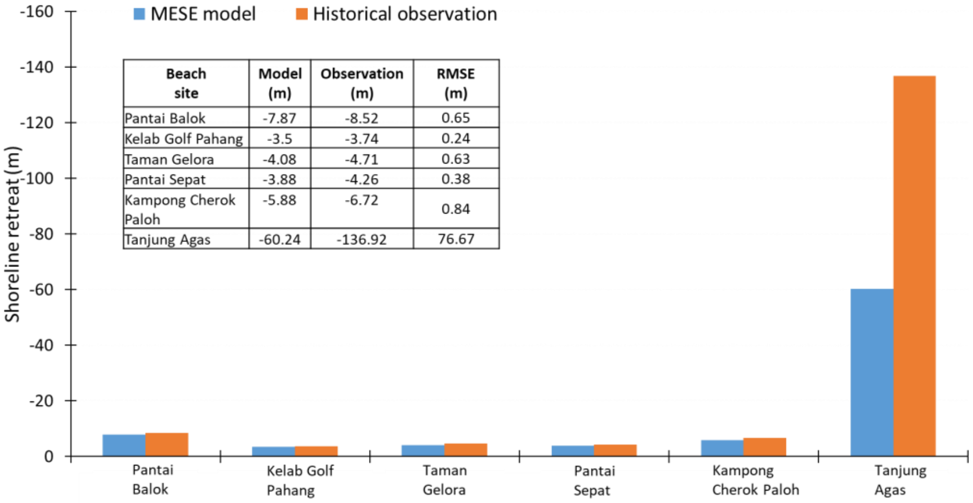
Figure 8 Digitization of historical shoreline change data from aerial images via shoreline position comparison. This map represents only a small portion of the actual shoreline of Pantai Sepat. Base maps from Google Earth Engine, Image © 2020 CNES / Airbus, Image © 2020 Maxar Technologies

The root mean square error (RMSE) is then applied to compute the error between the model and the historically observed shoreline retreat. Figure 9 shows the comparison between the shoreline retreat simulated by the model and the shoreline retreat from the historical observed for all six beaches. The RMSE errors for all beaches are acceptable as the values are below 1.0 m, expect Tanjung Agas. The RMSE for Tanjung Agas is 77 m. The reason behind this declination in validity at Tanjung Agas is due to three main reasons. First, Tanjung Agas is located at the river mouth of Pahang river (see Figure 6) making the beach dynamic and highly unstable. Second, based on the obtained aerial images, during the hindcast period, the beach's surroundings was undergoing coastal construction works i.e. river mouth improvement, that influenced the course of sediment transport and consequently affected the observed shoreline change rate. This phenomenon is not captured by the model. Third, data unavailability, as there were not enough historical data spans to support a long-term trend of the observed shoreline data, unlike other beaches, as a result of that, there might have been inaccuracies in the estimation of the observed shoreline retreat.

For other beaches, the model showed a RMSE value of less than 1.0 m. This error is expected due to uncorrected tidal height differences, uncertainties within the coastal system and unaccounted minor events for sediment sources or sinks.

Nevertheless, the empirical-fit validation of the model is sound for a model that is designed for long-term prediction. However, this accuracy can be raised if a correction factor is used. The unitless coefficient of Varpi (ϖ), as applied in Equation (12), is introduced as a location-dependent factor that is considered to account for the anthropogenic impact and the uncertainties within the coastal system. It is calculated as a ratio of modelled value divided by the actual observed shoreline change.

For all five beaches (Pantai Balok, Kelab Golf Pahang, Taman Gelora, Pantai Sepat, and Kampung Cherok Paloh), ϖ coefficient ranges from 1.07 to 1.15 which is not a weighty rate and does not pose a significant change in the results. On the other hand, for Tanjung Agas, ϖ coefficient is considerable at 2.27. Therefore, it is safe to assume that the correction factor can be neglected for beaches that undergo evolution without human interference and it is only vital to use the correction factor when studying beaches that are exposed to anthropogenic impact.



Beach site	Model (m)	Observation (m)	RMSE (m)
Pantai Balok	-7.87	-8.52	0.65
Kelab Golf Pahang	-3.5	-3.74	0.24
Taman Gelora	-4.08	-4.71	0.63
Pantai Sepat	-3.88	-4.26	0.38
Kampong Cherok Paloh	-5.88	-6.72	0.84
Tanjung Agas	-60.24	-136.92	76.67

Figure 9 Comparison between the results estimated by the MESE model and actual observed shoreline retreat on a decadal scale

4.0 CONCLUSION

The new model developed in this study is primarily used to predict long-term shoreline change. However, it can be rearranged to provide accurate estimations for long-term coastal sediment exchange for large-scale study areas. The model was tested and evaluated using a statistical cross-validation approach between the data hindcasted by the model and the actual long-term shoreline change rates obtained from the historical aerial imagery. The accuracy of the developed model is 90% for beaches that are stable without human intervention. That accuracy is enhanced by employing a site-specific correction factor that accounts for the factors that the model oversees. The model predicted that the 53 km long coast extending from Pantai Balok to Tanjung Agas along the Pahang state coast will experience an average shoreline retreat of 54 meters by the year 2100. The highest shoreline recession rate of 145 meters is expected to occur at Tanjung Agas and the lowest shoreline recession rate is expected to occur at Pahang Golf Club with a loss of 12 meters wide.

Coastal sediment balance is the equipoise between sediment gained and sediment lost by a coastal system. When the rate of sediment loss is greater than sediment gain and vice-versa, the coastal system enters a state of sediment imbalance. The long-term effects of coastal misbalance cause the beaches within the coastal system to either experience sediment surplus or deficit, causing beaches to change shape.

Based on the results obtained from the model, the majority of the long-term shoreline change is driven by the effects imposed by the long-term coastal sediment misbalance. This factor is usually ignored in other models that are used for shoreline evolution assessment such as the Bruun rule [16] making these models highly inaccurate. A comparison between the new developed model and Bruun model showed that Bruun model could only estimate around 11% of the total magnitude of beach loss for highly dynamic beaches. On average, the sea level rise drives around 30% of the total long-term shoreline change.

By comparing the current beach width with the projected total shoreline recession rates, the projected percentage of the shoreline retreat by 2100 is obtained. Surprisingly, 80% of Pantai Balok will be lost, also, 28% of Pahang Golf Club, 85% of Taman Gelora, 52% of Pantai Sepat, and 44% of Kampong Cherok Polah. Finally, 100% of Tanjung Agas beach will be gone. These values suggest that by the year 2100, on average, 65% of beaches that are located along the coast of Pahang state are going to vanish completely.

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