Fundamental applications of the Bruun model to project land loss of coastal cities: A case study of Kuala Terengganu, Malaysia.

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Abstract

Shoreline erosion is a topic of high urgency in coastal cities that suffer from climate change induced sea-level rise and inundation. Knowledge is needed to protect ecologically sensitive coastal areas with high social and economic value such as the Kuala Terengganu area in Malaysia. The current study applies environmental geospatial modeling to evaluate the impact of changes in sea level on shoreline erosion in Kuala Terengganu. We present an analysis and framework for model formulation adopting the Bruun model for coastal areas that can serve as a blueprint for other studies. The goal was to assess the rate of shoreline erosion and to predict erosion based on changes in sea level. Key assumptions in the model include the beach profile and its equilibrium. We identified several areas at greatest risk for erosion including Kuala Nerus and Pengadang Buluh and discuss measures and challenges for erosion mitigation. The findings of this study can enhance the planning, policy, and decision-making for climate change adaptation in shoreline and coastal areas.

Introduction

Concerns are growing about the ability of coastal ecosystems to withstand increasing stresses from human development and changes in climate. Around 70% of the world's beaches are receding, while only 20% are steady and 10% are advancing (O'Riordan and Pollock, 1995). Climatic conditions, sea-level rise, storm surge, and cyclical events like El Niño and La Nina have intensified coastal erosion problems, resulting in dramatic retreats of shorelines and loss of properties which has made hazard management more important than ever (Mimura, 2013). To minimize impacts and manage threats, local governments as first responders require adaptation strategies and plans (Zilberman et al., 2018). Although the development of adaptation strategies and plans is stipulated under the Malaysian National Climate Change Policy 2009, their implementation and practice is still lacking which makes Malaysia extremely vulnerable to the consequences of climate change [Rao and Mustapa, 2021]. In this research we present the case of the coastal city of Kuala Terengganu in Malaysia. The complexity of risk presented by climate change combined with non-climate influences has not been thoroughly discussed for any of the Malaysian cities although much of the coastline is under immediate threat (Ukaejiofo, 2020).

One of the most serious consequences of climate change and global warming is the rising of sea levels (Tangang et al., 2012). Research on long-term monitoring of sea level rise reveals that global sea levels rise by 3.32 mm/yr. This reflects an acceleration in rates (Doukakis, 2004), increasing from 1.7 mm/yr during the 1901–2010 period to 3.2 mm/yr during the 1993–2010 period. Because of the high and growing population concentration, commercial development, and the prominence of marine habitats in the coastal regions, questions have been raised globally on the possible consequences of sea-level change. Rising sea levels pose a serious danger to coastal ecosystems with direct and indirect impacts on the socio-economy of coastal cities. Under a scenario of a 1-m sea-level rise, more than 50 million people are likely to be displaced globally (Dasgupta, 2007). Sea-level rise, climatic trends, hurricanes, and cyclical disasters such as El Niño and La Nina, intensify the problems of protracted ocean coastal flooding, triggering major property and shore damages as well as accentuating exposure to hazards

(Boesch et al., 2000). Here we focus on shoreline retreat in Kuala Terengganu, an issue that is highly relevant to Malaysia and other countries worldwide as the landward shift of coastlines remains one of the central effects of climate change related sea-level rise (Stive et al., 2002). The projected sea-level rise in Peninsular Malaysia approximates 0.25–0.5 mm/yr, with the low-lying Northeast and West coast areas of the peninsular (Kelantan and Kedah) reaching the maximum value (Awang and Abd. Hamid, 2013).

The analysis of shoreline change is complicated because of the conceptualisation and diversity in the definition of shoreline change, the variety of factors influencing it, as well as its spatio-temporal variability. Two main concepts are generally considered with the first concept relating to the volumetric change (gains and losses of sediment) in the Three-Dimensional (3D) shoreline, whereas the second concept indicates the displacement of the Two-Dimensional (2D) shoreline location landward and seaward. Although both are interconnected, to investigate shoreline change using the correct technique, it is essential to distinguish between them. Here, we chose the Bruun model that accommodates both concepts for three reasons: (1) The approach finds consistent application in coastal change studies for coastal planning and management (DMRS and PAGASA, 2014); (2) Similarly, it finds consistent use in environmental studies (Kask et al., 2009); (3) It requires only a small quantity of data compared to other approaches (Rosati et al., 2013). Overall, the Bruun model has been extensively applied to model shoreline erosion triggered by sea-level rise (Mather and Stretch, 2012).

Other models that have been applied in this context include the Shoreline Translation Model (STM). This model integrates diverse parameters to specify how the geologic framework influences shoreline change caused by sea-level rise. However, STM can only be applied to forecast long-term variation in coastline morphology (Stolper et al. 2005). Then, Thieler et al. (2000) developed the latest model known as the Geomorphic Model of Barrier, Estuarine, and Shoreface Translations (GEOMBEST). This model represents a rule-based geomorphic shoreline change model that can predict the reaction of barrier islands to sea-level rise. Further, through the extrapolation of quantitative historical trends rates in shoreline change can be determined. Accordingly, historical shoreline data are extracted from Global Position System (GPS) data, coastal maps and charts, aerial photographs, and from different remote sensing data (Fountain et al., 2010). Linear regression and endpoint rate statistics are incorporated to measure the shoreline change rate as well as to forecast future shoreline sites (Dolan et al., 1991). This technique has been applied by coastal managers and planners to ascertain coastal development setback lines (Crowell et al., 1997). It uses the traditional transect-based approaches for the measurement of shoreline change. Nowadays, the utilization of computer-based GIS software particularly Digital Shoreline Analysis System (DSAS) has enhanced the measurement of shoreline change rates (Fenster, 2005). The historical trend extrapolation technique is based on the assumption that future shoreline development would be remedied by a similar process presently influencing the shoreline. The two shortcomings of this technique include: (1) it assumes that present trends are typical of future trends; and (2) it necessitates long-term historical observations across the study area that are unbiased by short-term man-made or natural variations such as beach nourishments or seasonal variability (Thieler et al., 2005).

Finally, the sediment budget model is based on the sediment budget balance (gains and losses) for a particular coastal section (Yates et al., 2011). Thus, this method quantifies and measures the volume of gain and loss in sand via beach volume change considering beach profiles from a given time (Komar, 1996). The geometric variance between sources of sediments and sinks in every cell of the sediment budget should thus be identical to the rate of change in the sediment quantity occurring in that section while accounting for potential engineering undertakings. It can be expressed through variables of volume or as the volumetric rate of change. However, one major shortcoming and restriction in the application of this technique is how challenging and costly it is to collect the necessary data for dunes, cliff positions, and beach profiles that also need to be captured with a high level of accuracy (Gutierrez et al., 2011). In addition, the Monte Carlo simulation method has been utilized to develop a simple shoreline change model (Komar, P. D. 1998). It is typically based on a direct one-line model that connects shoreline change to the height of the wave and the characteristics of sediment. This model is no longer in use at is too simple and does not incorporate sea-level change.

Conversely, the Bruun model is the model of choice and most widely applied among coastal scientists. This model analyses 2D (vertical and horizontal) shoreline change using sea-level rise (Reeve and Fleming 1997). The beach profile and its equilibrium are the main assumptions in this model. The Bruun model has been extensively applied to model coastal erosion triggered by sea-level rise, particularly in the US (Cowell et al., 1995). Cooper and Pilkey (2004) noted that the Bruun Rule provides the foundation for theoretical models of coastal reaction to sea level rise, and it is fundamental to several modern coastal management applications. Commonwealth science and industrial research organizations (2008) posited that the Bruun Rule "*does not account for longshore interactions and assumes the wave climate is steady and hence the equilibrium profile remains the same simply translated landwards and upwards with the rise in mean sea level*". Some coastal researchers (e.g., Addo et al., 2008) declared some reservations with this method thereby limiting its use. Furthermore, this model cannot be utilized in non-sandy beach coastlines. Notwithstanding the above-stated merits and demerits of the Bruun model, coastal scientists have developed numerous models founded on the Bruun rule (Komar, P. D., 1996).

Methodology

Methodological framework to develop the shoreline erosion model

This study applies both the Bruun model and statistical methods to investigate coastal hazards. The Bruun model connects the sea level rise with erosion retreat processes in three dimensions. Erosion and recession are frequently used interchangeably in this research. Thus, recession refers to the landward displacement of shoreline whereas erosion denotes the disintegration of land and volumetric change in the coast, albeit recession could be a consequence of shoreline erosion. The Bruun model was applied on data from 20 transects in the Kuala Terengganu sandy beach area to predict the evolution of sandy beach relative to sea-level rise. The sandy beach erosion model depends on predicted rates of sea level change, coastal measurement data and historical data of shoreline change. The use of statistics and computer-based approaches alongside the predicted and observed data enhance the forecasting of erosion with a simple mathematical model (Bruun model). This section discusses the diverse methods and techniques which are applied in this study to evaluate coastal erosion.

Figure 1 illustrates the four components of our methodology. Firstly, beach data were collected along transects in Kuala Terengganu's sandy beach region. Samples from each transect were analyzed for particle size as the Bruun model can only be used for sand (Gale and Hoare, 2012). Also a beach profile was produced for each transect. Secondly, we developed the structure of the Bruun model and forecast erosion for the sandy beaches. Thirdly, sand transportation was estimated for each transect. Finally, we validated the results of the Bruun model using historical and statistical data.

Study area

Terengganu is a state of Peninsular Malaysia. The coastal city of Kuala Terengganu is located by the Terengganu River estuary about 500 km Northeast of Kuala Lumpur on a promontory surrounded on three sides by the South China Sea. It is the state and royal capital as well as the largest city in Terengganu, providing home to a population of 286,317 residents. Kuala Terengganu is the tourism gateway to the East Coast Economic Region (ECER) and thus holds great economic importance for the area. Figure 2 shows our transects and erosion locations.

The Kuala Terengganu coastline in Malaysia is impacted on by natural forces largely governed by the Southwest monsoon (May to September) and the Northeast monsoon (October to March). The Northeast monsoon triggers Malaysia's major rainy season and powerful waves, with monsoon winds impacting the volume and direction of the waves (Maged and Ibrahim, 1996). Natural forces including waves, wind, and currents move unconsolidated soils and sand up the coast which leads to rapid variation in shoreline positions (Morton, 2005). The tidal range along Peninsular Malaysia's east coast, as well as the yearly variations in the average sea level, are estimated to be in the order of 1–2 meters, with wave not exceeding a height of more than 1.8m (Husain et al., 1995a). The variations in beach profile that occur between non-monsoon and monsoon seasons have proven useful in explaining the sequential changes that occur on beaches during monsoon seasons (Rosnan et al., 1995). The east coast of Peninsular Malaysia is more vulnerable to coastal changes, owing to the greater influence of the Northeast monsoon compared to the Southwest monsoon. Kuala Terengganu is one of the locations along Malaysia's east coast that is threatened by significant coastline erosion (Ariffin and Helmy, 2017) as the whole Peninsular is susceptible to sea-level rise (Chalabi et al., 2006; Ibrahim and Wibowo., 2013). Several studies have been conducted by National Hydraulic Research Institute of Malaysia (NAHRIM) around this issue yielding coastal vulnerability assessments and inundation maps (Awang and Abd. Hamid, 2013). Ishak et al. (2014) noted that over 70% of Terengganu was classified as a low-lying coastal area of less than 200 m in altitude, and about 30% of the area was considered vulnerable to flash floods. The Northeast monsoon has also triggered flooding in Southern Thailand and other parts of Malaysia (Gasim et al., 2007), exacerbating the potential vulnerability, hazard, and risk to coastal cities in these countries. Thus there is great need for research on coastal assessments and analysis, shoreline alterations, historical mapping, and shoreline position forecasting to support the planning of coastal development setbacks.

Data collection

Data from various sources were obtained as per Table 1. Field data were collected during the Northeast (NE) monsoon from 6th October to 26th October 2015. The 20 transects were chosen because they are prone to severe erosion (DMRS and PAGASA, 2014).

Table 1
Bruun model data collection and sources.

Type of data	Beach and Marine Data		Resolution	Source
Primary data	20 transects and GPS-surveyed data	Beach Measurement data For 20 transects	-	Fieldwork survey Kuala Terengganu
	Land-based photo data for each transect	-	-	Fieldwork survey Kuala Terengganu
	Sand particle size data for each transect	-	-	Fieldwork survey Kuala Terengganu
Secondary data	Spatial data	Topography 2005 and Hydrographic 2005 Maps	1:50000	JUPEM and Navy
		Air photos of 1980 and 2005	1:5000 1:10000	JUPEM
	Non-spatial data	Oceanographic data	-	Report from some agency of Malaysia
		Technical report	-	Report from some agency of Malaysia

All data were collected during low tides for each of the 20 transects. Clinometers were used to measure the angle, sand samples taken for particle size measurements, transect distances measured, a Garmin eTrex used to collect coordinates of each transect (GPS accuracy: 15 m, 95% typical, and velocity: 0.05 m/s steady state, DGPS (WAAS) accuracy) and photographs taken of all transects (Fig. 3). The sand samples (weighing between 2.5 and 2.8 kg each) were taken from the center of each transect line using a stake, slender, and hammer and analysed in the laboratory for particle size measurement.

To determine particle size a sand sieve analysis was carried out using a conventional dry sieving process. The material was washed and dried in a laboratory oven set to 105 to 110°C. Following that, 20 dry sand samples of a known weight were passed through a set of 5 suitable sieves with a known mesh size. For ten minutes, the sieves were mechanically shook. Finally, the researchers calculated the weight of sand retained on each sieve as a percentage of the total weight of the sand sample (Bruun, 1962).

Using the following method in Excel (Eqs. 1 and 2), we computed the slope and elevation for each transect using measured distance and angle obtained during fieldwork:

Slope = Distance * Cosine [Radian (Angle)] (1)

Elevation=Distance * Sine $[\text{Radian (Angle)}]$ (2)

By using slope, elevation, and distance, we drew the beach profile for each transect in Excel.

The Bruun model

The Bruun model signifies a simple profile transition technique that was proposed for the estimation of the net sand loss on the profile of beaches (Fenster, 2005). Dubois (1992) first proposed that contemporary beach erosion rates are caused by rising sea levels, and as a result, the Bruun model (Bruun, P., 1954) illustrates the relationship between rising sea levels and coastal retreat, and captures the percentage of horizontal to vertical active profile measures (Dolan, 1991). The Bruun model links the two-dimensional shoreline reaction (vertical and horizontal) to sea-level rise. It has offered the scientific and engineering communities a valuable technique of interpreting shoreline changes and proved a valuable tool for planning beach stabilization projects (Schwartz, 1967). The Bruun model had been validated in field tests and literature as examined by Bruun (1988). The model is also referred to as the Bruun's rule (Zhang, 1998).

According to the model, as sea level rises the cross-shore form of the beach profile takes on an equilibrium shape that turns landward and upward (Eq. 3). According to the bathymetry map and offshore wave, the first segment of this model is used to compute the extent of the depth of the closer (h*) active zone (L) near the coastline. The second section inspects the extent of the shoreline retreat under various sea-level rise scenarios. The coastline shift predicted in this research is based on the outcome of the rise in sea level, which is explained in Chap. 3.

The following is a mathematical representation of the model:

$$\mathrm{R} = \mathrm{G}.\frac{\mathrm{L}}{\mathrm{B}+\mathrm{h}^{*}}.\mathrm{S}\ (3)$$

where R represents the shore's horizontal retreat; h^{*} signifies the depth of closure or depth where the residue interchanges between the shoreface and inner shelf which is presumed to be marginal; B represents the berm's height;L signifies the beach profile's length to h^{*}; S represents the vertical sea level rise and G signifies the inverse of the eroded material's overfill ratio (Fig. 4) (Coelho and Veloso-Gomes, 2006). If the whole research area is a sandy beach, the eroded material (G) is equal to one, according to the Bruun model and prior studies on coastal erosion. As a result of the particle size examination, it was discovered that all 20 transects are indeed sandy. It is necessary to identify the active sediment transport area on the native beach to appropriately determine the requisite volumes for beach nourishment. Anders and Hansen (1990) noted that the distance to closure enhances the determination of the seaward degree of sediment movement.

The depth of closure (DoC) is a practical metric for determining the seaward limit of significant cross-shore sediment movement on sandy beaches. Coastal engineering makes considerable use of it. As a result, the precise position of closure is determined by the depth change criterion used to characterize closure from a set of dimensions. Closure is generally described in terms of measurement accuracy, however there are only a few models that can forecast closure. Nicholas et al., (1998) developed a widely used and well-validated formulation of severe wave conditions in a generalized time-dependent model to calculate the yearly depth of closure (h*) on sandy beaches (Eq. 4). It is given as follows, as updated by (List et al., 1997):

$$\mathrm{h}^{*} = 2.28{*}\mathrm{H}_{\mathrm{et}} - 68.5{*}\left(\frac{\mathrm{H}_{\mathrm{et}}^{2}}{\mathrm{g}{*}\mathrm{T}_{\mathrm{et}}^{2}}\right), (4)$$

where h^{*} represents the closure's predicted depth obtained from the observation's time length t regarding the Mean Low Water (MLW); H_e signifies the non-breaking greatest local important wave height which ensues for over 12 hours per t years; T_e represents the connected wave period with (H_e); and g signifies the acceleration that occurs because of gravity. This technique specifically knows that the movement of some sediment will happen seaward of h^{*}(Fig. 4). The Northeast monsoon has a propensity to erode a larger portion of the beach profile due to rising offshore bottom currents and sediment transport, whereas the Southwest monsoon has a tendency to replenish the top profile. Literature shows that there are four seasons in Malaysia including the main season (Northeast monsoon season), low season (Southeast monsoon season), and two interval seasons. The main season is fundamental for the assessment of erosion and flood hazard in coastal regions in Malaysia. Based on the recent (DMRS and PAGASA, 2014), the Peninsular Malaysia East coast suffers from severe erosion during the main season (Northeast monsoon season). Following DoC and some information supplied by the bathymetric map (2005) in Kuala Terengganu, we estimated the active zone of 20 transects. As several transects had berm, the berm height was measured using a beach profile measurement approach. Because the erosion rate for the sandy beach zone is governed by the rate of sea level rise, sea level rise is a critical element in the Bruun model calculation.

The Accuracy of Shoreline Prediction

The Bruun model conclusion may be verified and validated by comparing observed coastal erosion rates to model generated rates (Crowell et al., 1991). The historical coastline data used in this study was derived from JUPEM's historical data of high-resolution air photographs. GIS software was used to do a specific analysis of the historical coastline, which involved geo-referencing using historical images based on a topographical map with a Planimetric Accuracy (x, y) of 25.00 m, and an Altitude Accuracy (z) of 10 m (Arshad 2014). For 1980 and 2005, the calculated RMSE in geo-referencing is around 0.098 and 0.078, respectively. The rates of coastal erosion were calculated using historical data and the Bruun model's simulated data. It is necessary to choose a uniform coordinate grid system to compare mapped shorelines and other mapped or air photo-derived shorelines for all maps and air photos to be appropriately aligned to ensure the most precise determination of previous shoreline movement.

It is necessary to identify numerous solid and permanent locations or features on the map for which exact and current geographic coordinates are established in order to align maps to a certain coordinate system (Khamis and Abdullah, 2014). The prediction error, as well as the explanation of the validation between the predicted and observed data, are frequently used to explain performance evaluation (US Army, 1989). For assessing the performance of erosion in the sandy beach zone, a variety of accuracy assessment methods are used. Here the model's performance was evaluated using the Mean Square Error (MSE) and Correlation determination (R2), which represent the most generally accepted or recognized statistical methods.

Sand Transport Rate on the Long Beach

The rate of transport of littoral material alongshore in the surf zone caused by currents generated by obliquely breaking waves is referred to as the Long Shore Sand Transport (LST) rate. To calculate the whole LST rate, the entire LST rate is considered to be comparable to extended shore energy flow in the surf zone, which is indicated by the Eq. (5) (Bhuiyan and Siwar 2011):

$$Q = \frac{K}{\left(\rho_s - \rho\right) * g * a'} * P_{ls} \quad (5)$$

where (K) represents a dimensionless empirical sand transport coefficient (K = 0.39 if substantial breaking wave height is utilized to compute Pls); (ρs) represents sand density (ρs = 2.650 kg/m3); (ρ) signifies water density (seawater at 20° C, ρ = 1,025 kg/m3); (g) denotes the acceleration caused by gravity (g = 9.81 m/s2); (a') represents the proportion of the volume of solids to overall volume (accounting for the porosity of the sand (a' = 0.6)), and (Pls) denotes the longshore wave energy flux factor.

Results

We created 20 transects and determined 18 erosion locations based on the researcher's observations and the reports of different departments (NAHRIM and DID). Figure 5 shows the classification of the beachfront into four reaches (R1, R2, R3, and R4) and nine sub-reaches (R1E1, R1E2, R1E3, R1E4, R1E5, R2E1, R3E1, R3E2, and R4E1) from Marang Kchil to Kuala Merang, a distance of 68.84 km.

Particle Size Analysis

Sand samples were collected from each of the 20 transects using a standard cylinder. All transects are sandy, according to particle size analyses, with a maximum of 94.12 percent (T6) and a minimum of 64.04 percent (T18). Figure 6 depicts the sand size and cumulative percent for each transect. The particle size distributions are represented graphically in this diagram. Because the Bruun model can only be used to sandy beach regions, the primary goal of particle size measurement was to demonstrate that the study area was sandy.

Bruun model analysis

Results obtained from the Bruun model specified erosion of shoreline due to sea-level rise along the sandy beaches of Kuala Terengganu (Fig. 7). Erosion was predicted for four areas: Kuala Terengganu, the UMT area, Kuala Ibai, and the Bt. Gendering area. These were chosen because of their importance for future development (DID. 2010), ECER plans, some reports (DMRS and PAGASA, 2014; Byrnes and Hiland, 1994) and government investments (oil, gas, and coastal construction). The mentioned areas are also subjected to a high rate of erosion. The erosion rates were calculated via the Bruun model and the most eroded area determined. The estimated average projected erosion rate in 5 years (2015–2020) for all 20 transects was 1.48 m/year, with a minimum rate of -4.87 m/year and a maximum rate of 5.34 m/year, which is connected to the rate of sea level rise in Kuala Terengganu.

The time and day of data collection are critical for beach measurements since the distance between low and high water lines must be measured. As a result, all transects were measured in the afternoon from 3:15 pm to 5 pm (6/10/2013 to 26/10/2013) based on the heights and times of higher and lower water sea level, covering a period from 1985 to 2012 (historical data) at Kuala Terengganu Chendering station given by JUPEM's Geodetic Survey Division. The position of each transect was chosen using GPS (Garmin with an accuracy of 3 meters). Beach profiles evaluate the form of the beach using a combination of distance and angle data. At all times, a straight transect line from the sea's edge to the active beach end must be followed (e.g., existence of vegetation). Every transect was then subdivided into six smaller parts that could be measured based on where the slope angle changed.

In reach E2, UMT covers the left bank of Terengganu International Airport and UMT & Kg. T. Gelam to Kg. Seberang Takir over a distance of 10.63 km. Based on 2015–2020 data, T12 (Jalan Fikri Seberang Tkir 2) is expected to have the highest rate of erosion, with an average erosion rate of 3.20 m/year, a maximum erosion rate of 11.53 m/year, and a sand transportation rate (using Eq. 5) of 10,489.07 m^3/year. T10 (Kg.T.Gelam) shows an average erosion rate of 2.97 m/year, a maximum erosion rate of 10.73 m/year, and a sand transport rate of 10,345.98 m3/year. T11 (Jalan Fikri Seberang Tkir 1) shows an average erosion rate of 2.72 meters per year, a maximum rate of 9.82 meters per year, and a sand transport rate of 9,622.82 m/year. As for T13 (Jalan Fikri Seberang Tkir 3), the average erosion rate is 1.83 m/year, the maximum rate is 6.59 m/year, and the sand transportation rate is 11,239.42 m^3/year (Fig. 8a). The above-mentioned areas are low-lying areas that are challenging for coastal management. The result also proves that the International Airport of Terengganu located close to T10 is exposed to the highest erosion rate after T12. This suggests that the airport might be in risk of flooding and erosion.

Figure 8a shows the erosion rates determined by the Bruun model for shoreline change and coastal erosion in the past (1980–2014) and future (2015–2020). Figure 8b shows the beach profile for each transect. T10 signifies the high-risk area for erosion.

Beach profiles were created for T10, T11, T12, T13. Likewise, the results of the Bruun model enabled the development of a new beach profile (after erosion) from 2015-2020 (Figure 8b). According to the predicted sea-level rise, T10, T11, T12, and T13 will be eroded by 2.97, 2.72, 3.20, and 1.83 m/year, respectively. These areas would suffer from more land loss and erosion compared to other transects of our study area.

The second study area in Kuala Terengganu includes Kg. Seberang Takir to Gong Merbau, covering a distance of 5.36 km in reach E2 and E3 (Fig. 9). As the biggest area in this study it encompasses the Kuala Terengganu River with some of the most severe coastal erosion. In the north of the Terengganu River, the beach and nearshore profile is quite steep, contrasting with the gentle profile in the south. During the Northeast monsoon, the surf zone exceeds 200 m based on the national coastal erosion study (DMRS and PAGASA, 2014). The projected result suggest that T14 (Jalan Pantai Batu Burok 1) would experience the most severe erosion from 2015 to 2020, with an average erosion rate of 1.75 m/year, a maximum erosion rate of 6.30 m/year, and a sand transportation rate of 12,503.32 m3/year. Transect T15 (Jalan Pantai Batu Burok 2) follows, with an average erosion rate of 1.41 m/year, a maximum erosion rate of 5.09 m/year, and a sand transportation rate of 12,119.45 m3/year (Fig. 9a). It is expected that the T14 Left Bank of Kuala Terengganu experiences a greater erosion compared to T15 in reach 2.

Past (1980 to 2015) and present predictions (2015 to 2020) for coastal erosion and shoreline change based on the Bruun model are presented in Figures 4.20a and 4.21b. The initial data collection in the field supports the beach profile production (before erosion) for transects 14 and 15. Likewise, the results of the Bruun model generate new beach profiles (after erosion) from 2015-2020 (Figure 9b).

The third study area is Kuala Ibai which extends from Gong Merbau to the right bank K. Ibai, covering a distance of 5.46 km to reach E3. This area has only one transect with a high rate of erosion noted at T16 (Jalan Tok Adis), which is expected to be 5.13 m/year, with a mean rate of 1.42 m/year and a sand transportation rate of 13,227.97 m^3/year (Fig. 10). The fourth part is Bt. Chendering which extends from the right bank of K. Ibai to the left bank of Kuala Marang over a distance of 9.96 km, and reaches E3 and E4. This bay is hook-shaped. This area was progradational in the past based on a national coastal erosion study (DMRS & PAGASA, 2014). It features a steeper beach and nearshore gradient at its downdrift end compared to at its up-coast end, similar to other hook-shaped bays. The size of the sand gets smaller as you get closer to the bay's concave-shaped upshore. Since 1982, the coastline in this area has responded quickly to the barrier building at Bt. Chendering. This breakwater essentially shifted the headland's placement to the south. In the past, this region exhibited near-maximum embayment indentation.

According to the findings, the projected average rate of erosion at T17 (S.K.Chendering) between 2015 and 2020 is 1.03 m/year, the maximum rate of erosion is 3.73 m/year, and the sand transportation rate is 10,735.35 m3/year. The average erosion rate of Transect T18 (Kampung Aur) is at 1.17 m/year, with a maximum erosion rate of 4.24 m/year and a sand transportation rate of 12,471.02 m3/year (Figs. 11 and 12). Therefore, the region of Kampung Aur is anticipated to experience a higher erosion and sand transportation rate compared to S.K Chendering. The data from the pace of coastal retreat and the volume of sand carried may be used to best sight and design a building to prevent sedimentation in the harbor and provide a disposal area for sand.

Lastly, by comparing the four parts of the study area, the strongest erosion is expected to occur between Kg.T.Gelam and Right bank. The result obtained from the sand transportation is somewhat consistent with Raj's study (1982 and 2002) on the East Coast of Peninsular Malaysia. Based on Raj study, in Kuala Terengganu, Kuala Ibai, and Bt. Chendering, the sand transportation rates are 3,375, 15,625, and 15,625 m3/year, respectively. In comparison, the rates of sand transportation in Kuala Terengganu, Kuala Ibai, and Bt. Chendering are 12,310.38, 13,227.97, and 11,589.20 m3/year, respectively. Apart from the influence of sea-level rise, greater rates of human activity (coastal development), other climatic variables (rainfall, wave, and northeast monsoon wind), and hazards will all exacerbate erosion in these regions (flood). The aforementioned variables may have an influence on land usage in Kuala Terengganu's coastline area.

As sea-level rise is an increasing concern in the study area, the results of this study can assist when creating a new shoreline change map in the GIS environment to identify at-risk regions the risks and prioritize conservation activities.

Bruun model validation

To validate the Bruun model, the model's simulated data for the years 1980 and 2005 were compared to historical data from aerial pictures taken in 1980 and 2005 (the only historical data available). Arial photos for the years 1980 and 2005 were sourced from the Geospatial Data Development Section, JUPEM, and the National Geospatial Database Division. Both sets of photographs (Orthophoto) are vertical black and white images. It is impossible to apply a universal coastline because of the local and regional geomorphology, the study's spatiotemporal scale, the type of data available, shoreline mapping technology, and the main objective for studying shoreline erosion (Leatherman, 2003).

There are several types of coastal morphological classifications, each with its own set of appropriate geomorphic markers. The vegetation line was used as an indication in coastal digital image processing, according to previous studies. A flat sandy beach, a muddy tidal flat, or a rocky tidal flat can all be identified by the vegetation line. Based on the particle size analysis, the vegetation line was chosen as an indication since most of the Kuala Terengganu coastal regions consist of flat sandy beaches.

After determining the optimum indication, air pictures (Orthophoto) must be georeferenced since JUPEM alone can change the two historical maps. These maps were geo-referenced with RMS between 0.087

and 0.098 using a topographic map (2003) as a base map and a GIS georeferencing tool. As a result, the historical coastline was digitized from air pictures, and two historical shoreline alterations based on observed data for 1980 and 2005 were generated (Fig. 13). The study verifies the Bruun model performance by extracting historical coastline data and estimating the rate of shoreline change for the years 1980 and 2005 using observed data.

Results of the validation test and the correlation coefficients for observed and simulated data are shown in Fig. 13. In 1980, the R2 value and MSE for observed and predicted data were 0.81 and 0.0558, respectively, whereas in 2005, the R2 value and MSE were 0.79 and 0.1192, respectively. In conclusion, the high R2 and low error value confirm that the result of the Bruun model simulation is acceptable. Thus, the findings of the predicted shoreline change data are valid and can be used to assess the coastal erosion risk in Kuala Terengganu, as detailed in the Conclusion. We will first however proceed by presenting measures to prevent coastal erosion in cities.

Coastal City Erosion Control

Coastal city erosion control measures for Kuala Terengganu

Coastal erosion has serious impacts on landforms, land use, and property ownership with direct and indirect implications for the social, economic, and physical value of land. A proper Coastal City Erosion Control (CCEC) program aims at keeping these consequences within acceptable limits. In some cases, this requires preventing erosion altogether; however, most often this is not necessary. The definition of acceptable limits is a matter of public policy, and yet effective coastal erosion control requires the concerted effort and expertise of engineers, scientists, and economists. The central part of a CCEC program is the management plan that devises individual projects and management measures.

Erosion control measures may include structural approaches that change the physical characteristics of the shoreline, offer a physical barrier to the sea and sharply define the defended area. They require considerable budgets for construction and are known to have long-term environmental impacts. Structural approaches particularly appropriate for Kuala Terengganu include seawalls, jetties, breakwaters, revetments, and groins:

Seawalls separate land and water areas to prevent damage from waves to the upland retained by them (Fig. 14a). Seawalls are massive, free-standing structures designed to resist the full force of attacking waves. Seawalls are not apt to be cost-competitive with revetments in most locations in Malaysia but may be appropriate where special conditions prevail. Like revetments, sea walls must be secured against undermining and flanking. Additionally, the use of seawalls often requires acceptance of accelerated erosion of the shore in front of the seawall.

Jetties improve mainly navigation but incidentally they also control erosion in parts of the river estuary in Kuala Terengganu. They limit one particular consequence of erosion as shown Fig. 13b. As jetties extend seaward at the river mouth to confine and direct the river and tidal flows, they protect the shoreline of the navigation channel.

Breakwaters are structures designed to protect shores, harbors, and basins by intercepting waves. A typical section for a rubble mound breakwater is shown in Fig. 14c. Protection of shore areas to control erosion is a relatively recent addition to the traditional role of breakwaters in navigation improvement. Breakwaters control erosion by reducing or excluding wave energy. They are sited offshore and differ from seawalls in that they neither retain land nor separate land from water. Like seawalls, breakwaters are massive, free-standing structures that oppose the force of the waves. The reduction of wave energy reaching the shore in the lee area of a breakwater prevents erosion from the force of waves and eliminates sediment transport by currents, thereby causing sediments to be deposited in the breakwater. The cumulative effect is accretion which can make breakwater and shore merge where conditions are favorable. Such joining can be precluded by appropriate design. An offshore breakwater is a functionally suitable erosion control structure for most areas of the East Coast of Malaysia especially Kuala Terengganu. However, breakwaters are typically more costly than revetments and other alternatives. Special circumstances that could make breakwaters attractive alternatives are higher than usual waves, steeper than usual near-shore sea bottom slopes, sand trapping objectives, and navigation improvement objectives in combination with erosion control objectives.

Revetments armor in the form of stone or concrete protects embankments or structures against erosion from waves and currents. A typical rock revetment section is shown in Fig. 14d. Revetments rest on the surface that they protect and depend on it for support. They are relatively light structures and are well suited to locations free of strong wave attacks. Revetments can be constructed of several materials that are readily available in Malaysia.

Groynes are designed to trap sediments transported along the shore by littoral currents or to prevent sediment transport to or away from an area (Fig. 14e). They have a limited effect on the movement of sediments transported in suspension. Groynes are useful for the sandy shores of Kuala Terengganu where littoral transport of sand occurs parallel to the shore. The prevalence of sand spits at the river estuary indicates that sand transport does parallel the shore in many areas. In other areas however, the straight beaches between headlands indicate that little or no shore parallel sand transport occurs, and the same is the case for some of the ‘pocket’ beaches.

Evaluation of the existing erosion control measures in Kuala Terengganu

Various structural control measures have been employed along the Kuala Terengganu coastline. The measures used are generally designed to harden and armor selected areas against the force of waves. Groynes for instance were designed to trap sediments and alter longshore transport from north Kuala Terengganu to the Mengabang Telipot beach in Batu Rakit. However, construction for the mitigation works did mostly not follow a comprehensive plan and occurred rather haphazardly without consulting various stakeholders and interest groups. The existing works shown in Table 2 were evaluated for their effectiveness and to judge their suitability for use in Kuala Terengganu. The survey was undertaken at reconnaissance level and did not include a review or analysis of engineering design or design criteria. The results of expert choice and fieldwork observation are summarized in Table 2. The distribution is probably more indicative of the level of development in these coastal regions rather than reflecting the severity of erosion.

Table 2
Existing coastal protection structure for the Kuala Terengganu shoreline

No	Structure	Location	Suitable	Effective	Remarks
1	Jetty and Rock revetment	Right bank Kg. Merang	Yes	No	Rocks displaced
2	Timber seawall and Breakwater	Right bank International Terengganu Airport and UMT(Behand)	Yes	No	Timber not suitable for permanent use, partially collapsed
3	Concrete pipe seawall	Kg. Seberang Takir	No	No	Collapsed, overtopped
4	Breakwater	Left bank Kuala Terengganu	Yes	Yes	Flanked, undermined
5	Breakwater	Right bank Kuala Terengganu	Yes	No	Rock displaced
6	Concrete seawall	Left Bank Kuala Ibai	Yes	No	Timber not suitable for permanent works
7	Bakau pipe seawall	Right Bank Kuala Ibai	No	Yes	• Gabion is not suitable for permanent works • Part of gabion failed
8	Gabion seawall and Breakwater	Left Bank Bukit Chendering	Yes	No	• Gabion is not suitable for permanent works • Overtopped • Undermined
9	Stonemasonry seawall and Breakwater	Righ Bank Bukit Chendering	Yes	No	Stones displaced
10	Rock revetment	Left Bank of Kuala Marang Terengganu	Yes	No	Overtopped

In our assessment of existing erosion control measures we considered suitability separately from effectiveness. Works were judged suitable if the conceptual solution was sound, which means that the used structure was appropriate. Works were considered effective if the structure exhibited no structural or functional inadequacy when surveyed. From Table 2 above, seawalls tend to accelerate erosion and scour at their bases. Unless toe protection is provided, foundation failure is likely for most seawalls. Seawalls also tend to accelerate erosion at the ends of the wall. Unless the wall allows for this erosion, the wall will be flanked and ultimately destroyed from the landward side. Common causes for failures of rock revetments are rocks not heavy enough to withstand wave action, along with the omission of a filter system between the armor and the protected slope, omission of toe protection, and overtopping. Properly designed and constructed rock revetments are effective, long-lived, structures that require minimal maintenance, as can be seen at the recently added revetments at the beach near UMT where it replaced timber seawalls.

Revetments and groynes especially can be reinforced and fortified with natural vegetation, traditionally known by the local communities as sand binders and natural armor against beach erosion such as *Vitex trifolia* and *Ipomoea pescaprae*. These endemic creeping plants spread quickly over the rock revetments and stabilise the soil and rocks against strong waves. Through the cohesive reinforcement between the hard and soft parts, the life span of groynes and revetments can be prolonged, and new beaches may be recreated through sand accretion. Several coastal areas in the East of Kuala Terengganu demonstrate this natural symbiosis.

Erosion control and ways forward for Kuala Terengganu's most impacted areas

Malaysia appears to be at the verge of erosion impacts reaching their unacceptable limits. A call needs to be made for studies to more precisely define and quantify the costs and effectiveness of mitigation measures to underpin decisions on investments to protect beaches and infrastructure. Here we presented research for six areas in Kuala Terengganu to determine priorities for action: Kuala Nerus, Pengadang Buluh, Merang, Batu Rakit, Manir, and Rusila. Three groups have emerged with different priorities to act against erosion. The most urgent measures need to be taken in Kuala Nerus and Pengadang Buluh in Kuala Terengganu. These recreational resorts near Gong Merbau and Left Bank. K. Ibai are well known for their sandy beaches and recreational facilities such as resort housing and food stalls. Erosion has impacted strongly here so that the remaining beach is only 30 to 40 m wide and a swimming pool has been destroyed. There are alternate beaches in the vicinity and recreation could relocate to those without great inconvenience. However, people are accustomed to frequenting Kuala Nerus and Pengadang Buluh and these habits are difficult to change. Therefore social impacts need to be considered and a feasibility study needs to compare erosion measures.

In contrast, Right Bank Kg. Merang, Kg. Seberang Takir, Left Bank of Kuala Marang in Kuala Terengganu are located in a fishing village. The primary access road to the village have been destroyed by erosion. There is an alternative path, but although it passes through the village it is much less convenient than the primary road. The impact of erosion on transportation is therefore considered to be moderate. A large rock has been placed to protect part of the shore, which has not been very effective. Gabion walls have been used to protect other parts of the shore but only offer temporary protection. Houses consist of temporary structures that are easily threatened. The sandy beach that once fronted the village has been eliminated by erosion. Because this area only has minor potential for recreation, impacts in regards to that are minor. However the cumulative economic effect of all physical losses is moderate. If the houses were of a more permanent type, the economic impact would be high rather than moderate. Nonetheless, the pending dislocation of many families and the loss of the primary access road combined factor strongly into social impacts. Because of the high social impacts and the moderate economic impact predicted for the next 3 to 5 years, a feasibility study for erosion measures is urgent here too.

Conclusions

The current study applies environmental geospatial modelling to evaluate the impact of changes in sea level and other environmental factors on shoreline erosion in the Kuala Terengganu coastal area in Malaysia. We presented an analysis and approach for model formulation adopting the Bruun model for coastal areas. The goal of the study was to assess the rate of shoreline erosion and to predict erosion based on changes in sea level along the Kuala Terengganu coast from 2015 to 2020.

Numeric forecasts of future shoreline evolution in eroding regions are critical for effective coastal management and planning. Essential information like rates of land subsidence, existing rates of land loss (erosion), and flood return periods is often missing or inadequately captured. Longer-term models are required that account for coastal evolution (e.g., sea level rise), shoreline response to sea-level rise and potential human adaptations such as beach nourishment. This study appears to be the first to analyse future shoreline change in the coastal city of Kuala Terengganu. It improves our understanding of digital and numerical data of historical and observed shoreline positions of Kuala Terengganu to assist the analysis of future shoreline change. The study presents a model framework for evaluating the effect of sea-level change on the Kuala Terengganu coastal area. It can therefore serve as a blueprint for developing mathematical models to predict shoreline behaviour for sandy beaches at the local level.

Several limitations exist for shoreline erosion modelling in coastal city areas, like Kuala Terengganu: (1) The lack of coastal engineering data as well as the lack of sources of frequently measured shoreline data collected accurately and at sensible time intervals. (2) Short history of reliable shoreline imagery data makes long-term modelling impossible. (3) In some undeveloped coastal areas, the location of appropriate ground control points (GCPs) for geo-referencing uncoordinated shoreline imagery data is too challenging, especially in sandy beach areas. (4) In the Bruun model, one of the main limitations is the prediction and analysis of coastal erosion according to the two dimensions and the horizontal movements of a defined shoreline proxy. (5) In specific coastal sites, finding consistently and identifiably defined shoreline indicators in aerial photographs proved problematic and, in some cases impossible. (6) This study relied on restricted coastal city maps and data. It can therefore only offer a broad overview of environmental risks for the Kuala Terengganu coastal area. Nonetheless in this research we introduced a model formulation process that can guide future studies in this field.

The use of the Bruun model to assess the physical vulnerability of the Kuala Terengganu coastal city region allows for the identification of areas at risk of coastal erosion as a result of sea-level rise. The results show that using the Bruun model to predict future shoreline positions may be more appropriate than using statistical approaches since the model explains the process. The most sensitive areas to coastal erosion are zones 3 and 5 according to the results obtained from the shoreline change map and the Bruun model. From Merang Kecil to UMT (Universiti Malaysia Terengganu), our model predicts that the coastal city of Kuala Terengganu is likely to experience the highest erosion between 2015–2020. The sandy beaches on the left and right banks of the Kuala Terengganu coastline are exposed to higher recession rates and shoreline erosion. Economic impacts in these areas will be high because of their importance for tourism and the reliance upon this sector by many city residents.

Local governments and the general public might use the estimated rate of coastal erosion to select acceptable places for future development and to make choices about erosion risks. Our mathematical model utilized vertical point prediction (from the shoreline) for each transect along the shoreline. It is simple to implement and understand by coastal planners and managers. Erosion control measures such as soft maintenance (e.g, dune restoration and beach replenishment) and hard structures to reduce wave energy and protect urbanized areas were presented. Our research can inform plans and policies needed for the long-term management of erosion in these vulnerable areas to conserve the ecological, social, economic, and national value of this land.

Declarations

Ethical Approval: Not applicable.

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Asma Wan Talaat, Isabelle D. Wolf; Visualization, Milad Bagheri, Zelina Z Ibrahim; Supervision, Milad Bagheri, Zelina Z Ibrahim, Latifah Abd Manaf; Project Administration, Milad Bagheri, Zelina Z Ibrahim, Latifah Abd Manaf; Funding Acquisition, Milad Bagheri, Mohd Fadzil Akhir, Wan Izatul Asma Wan; supervision Milad Bagheri;

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Figures

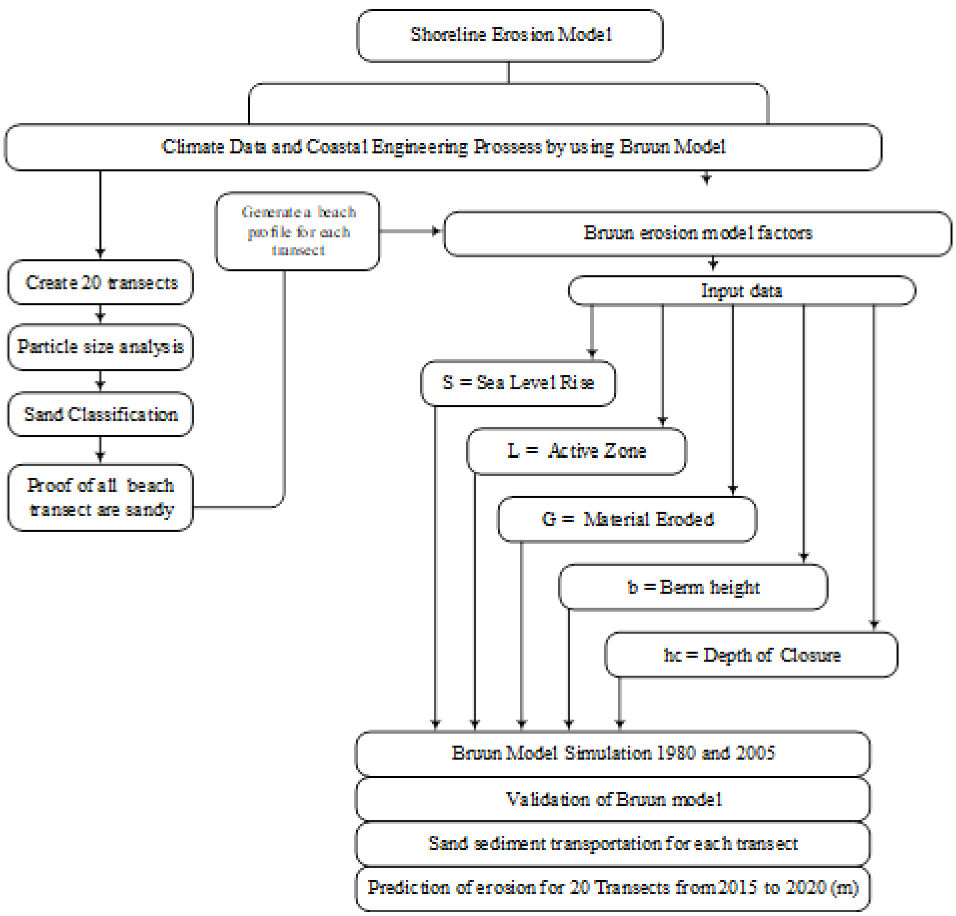

Figure 1

Shoreline erosion model building process.

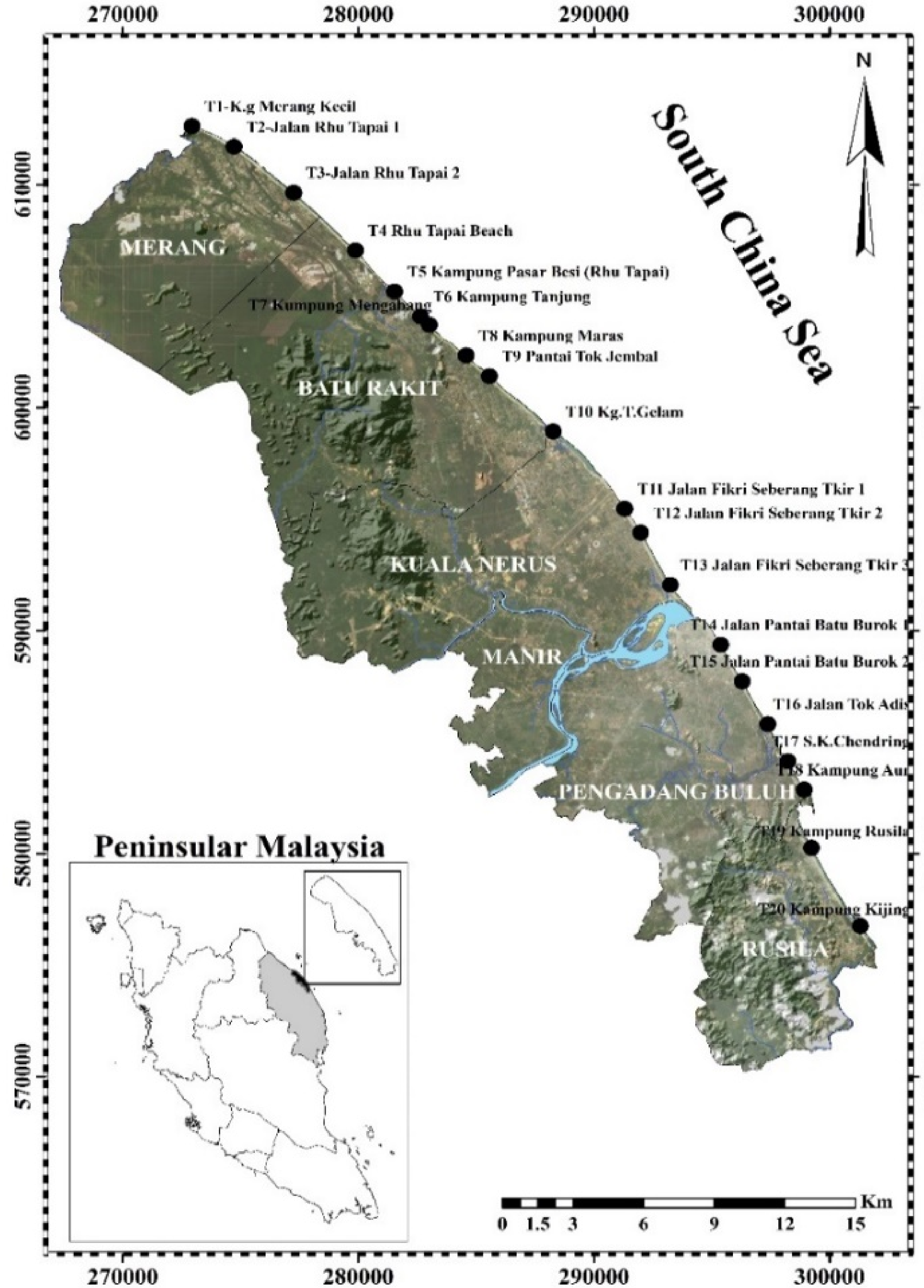

Figure 2

The *Kuala Terengganu study area in Malaysia and transect points on the shoreline area*

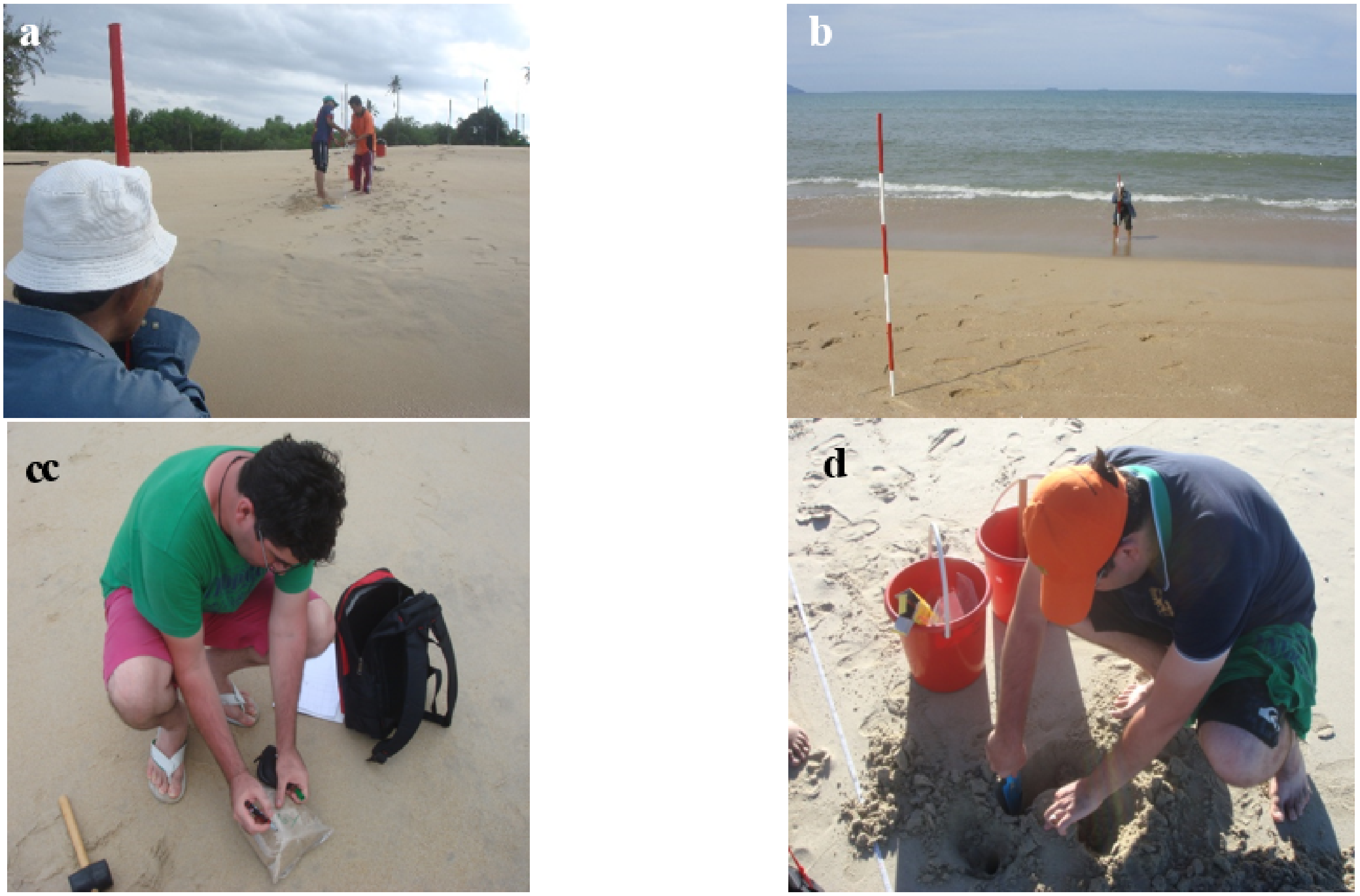

Figure 3

(a) Creating transects on the beach; (b) Measuring the angle for the first point using clinometers; (c) Measuring the distance between two points (d) Collecting sand samples for particle size analysis.

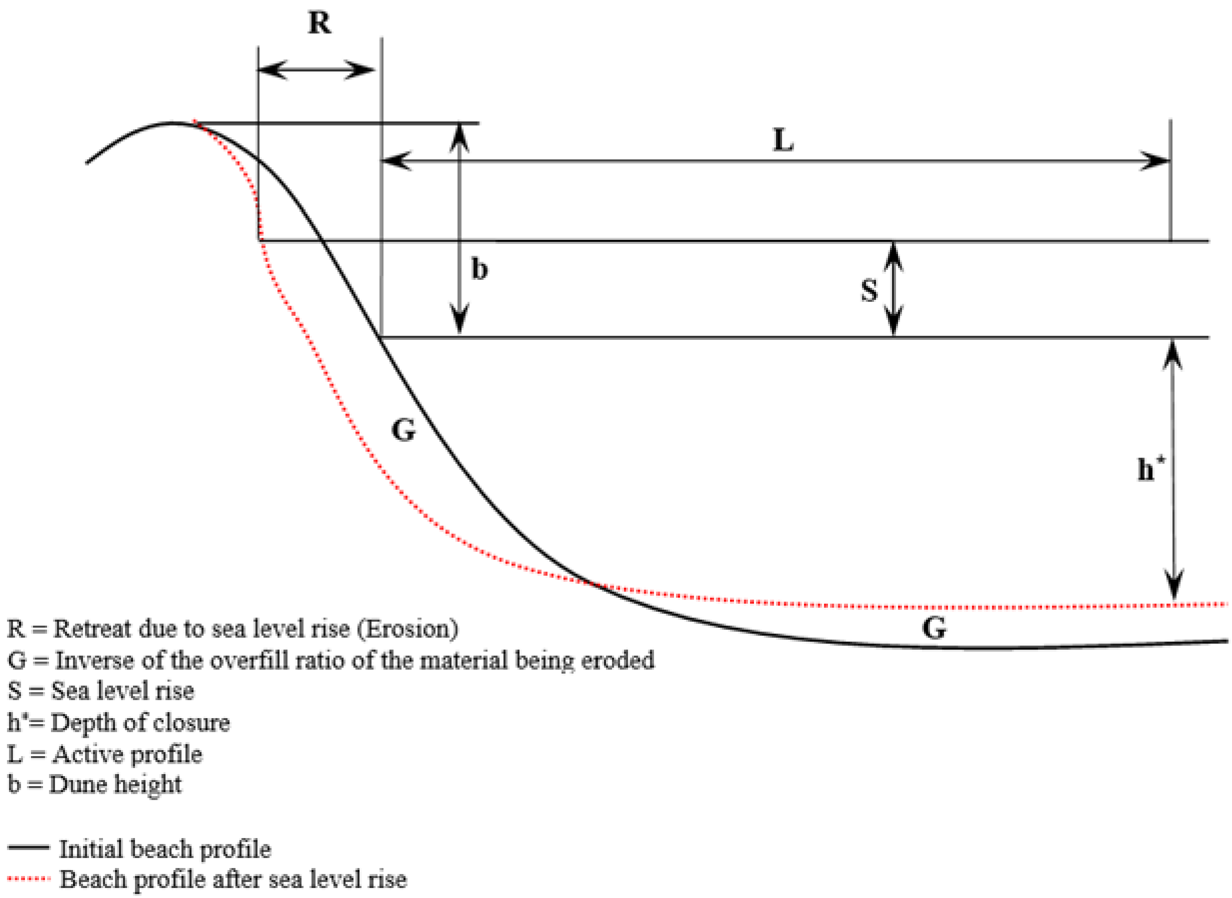

Figure 4

The simplified model of landward coastal retreat under sea-level rise (based on the Bruun Rule) The Bruun model structure and the two basic dimensions of the shore that are used as model inputs (Source: Authors).

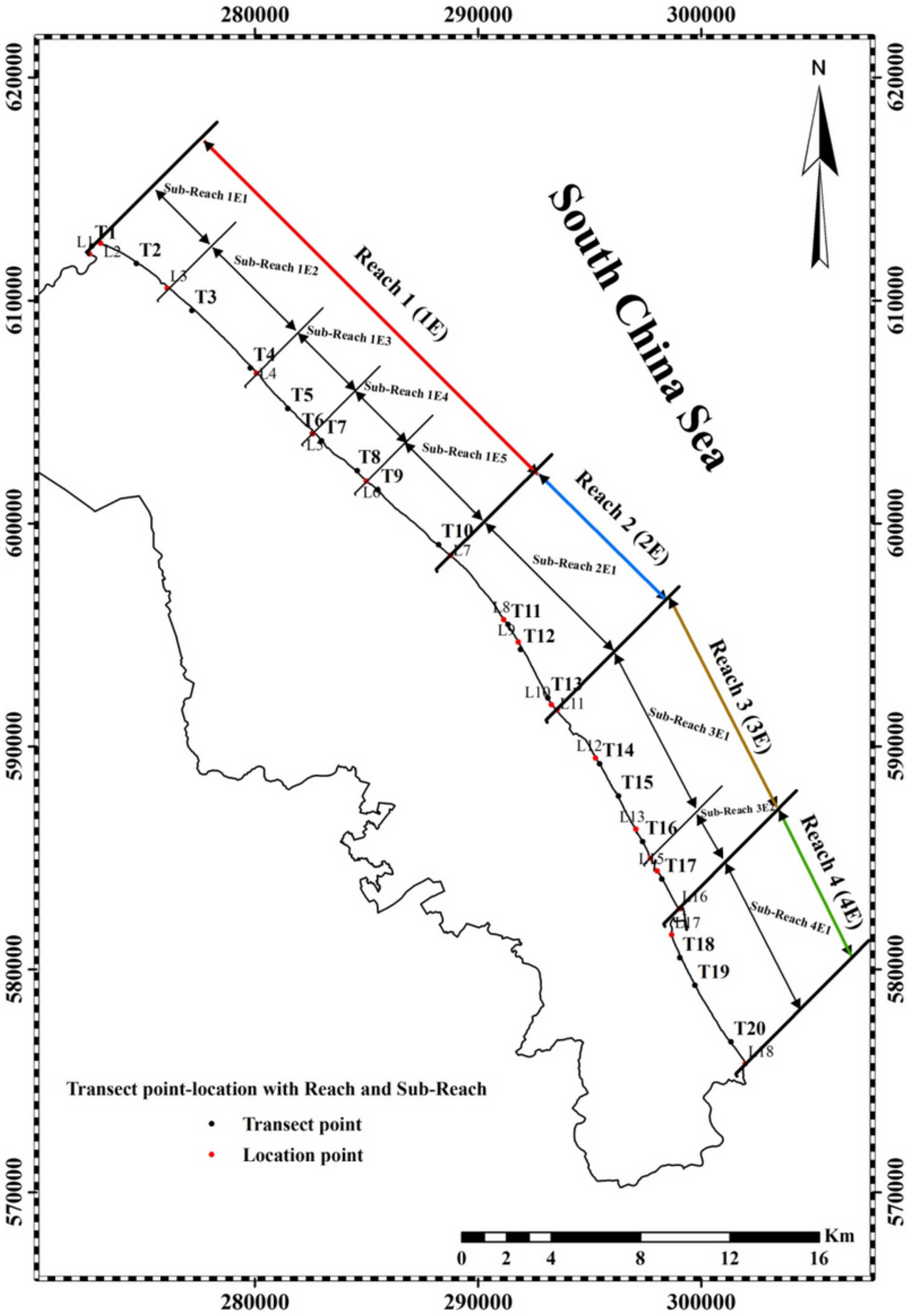

Figure 5

Reach and sub-reaches with transects and location points.

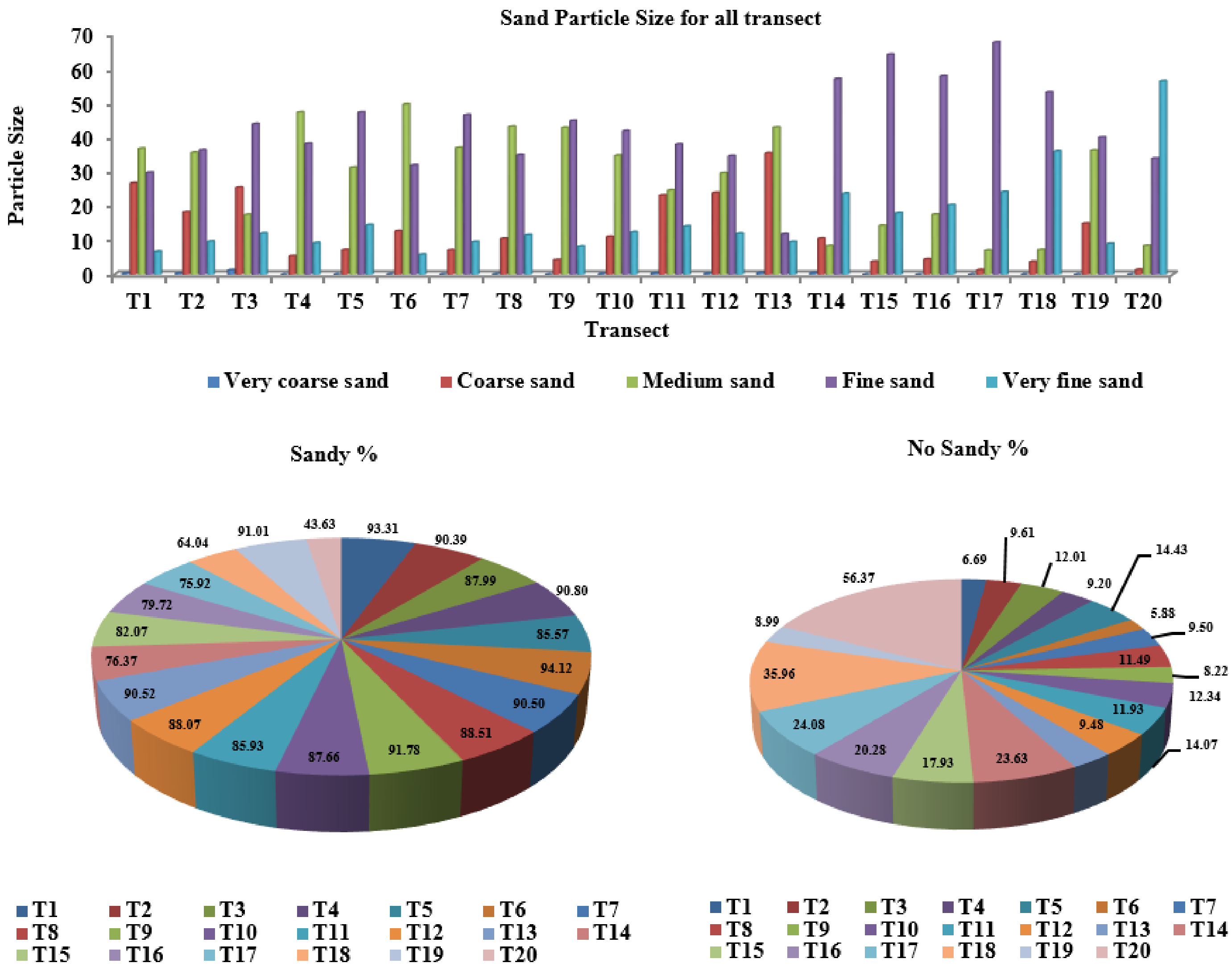

Figure 6

Sand size (%) for all 20 Kuala Terengganu transects

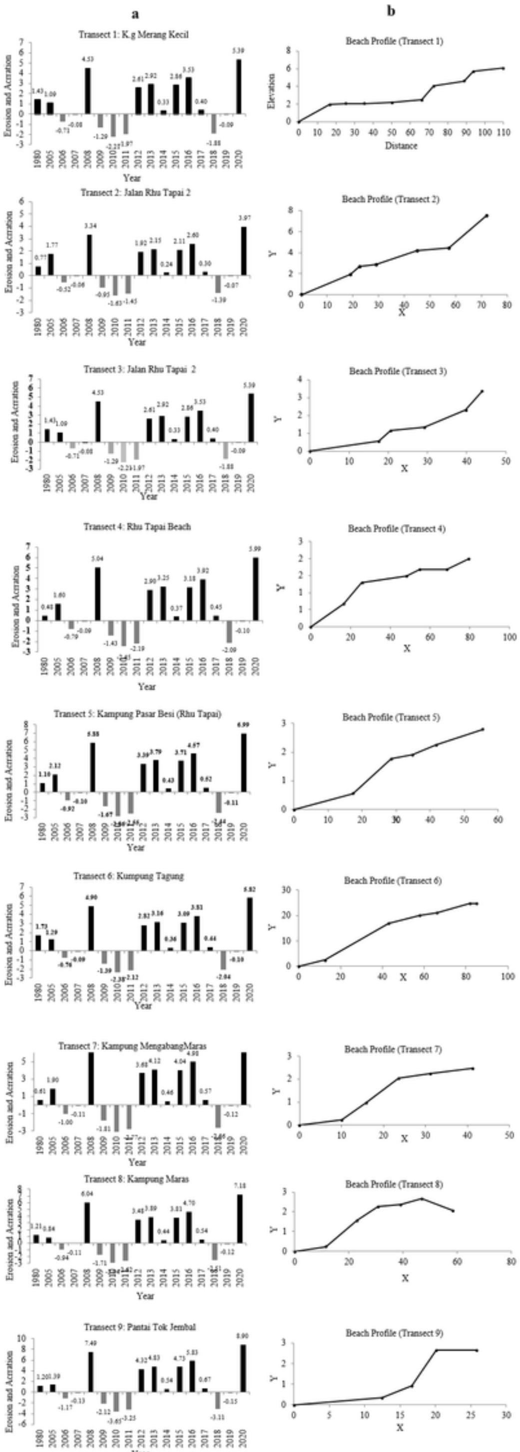

Figure 7

Study transect 1-9: (*a*), *Rate of shoreline erosion from 1980-2020 for Kuala Terengganu. (b) Beach profiles after erosion.*

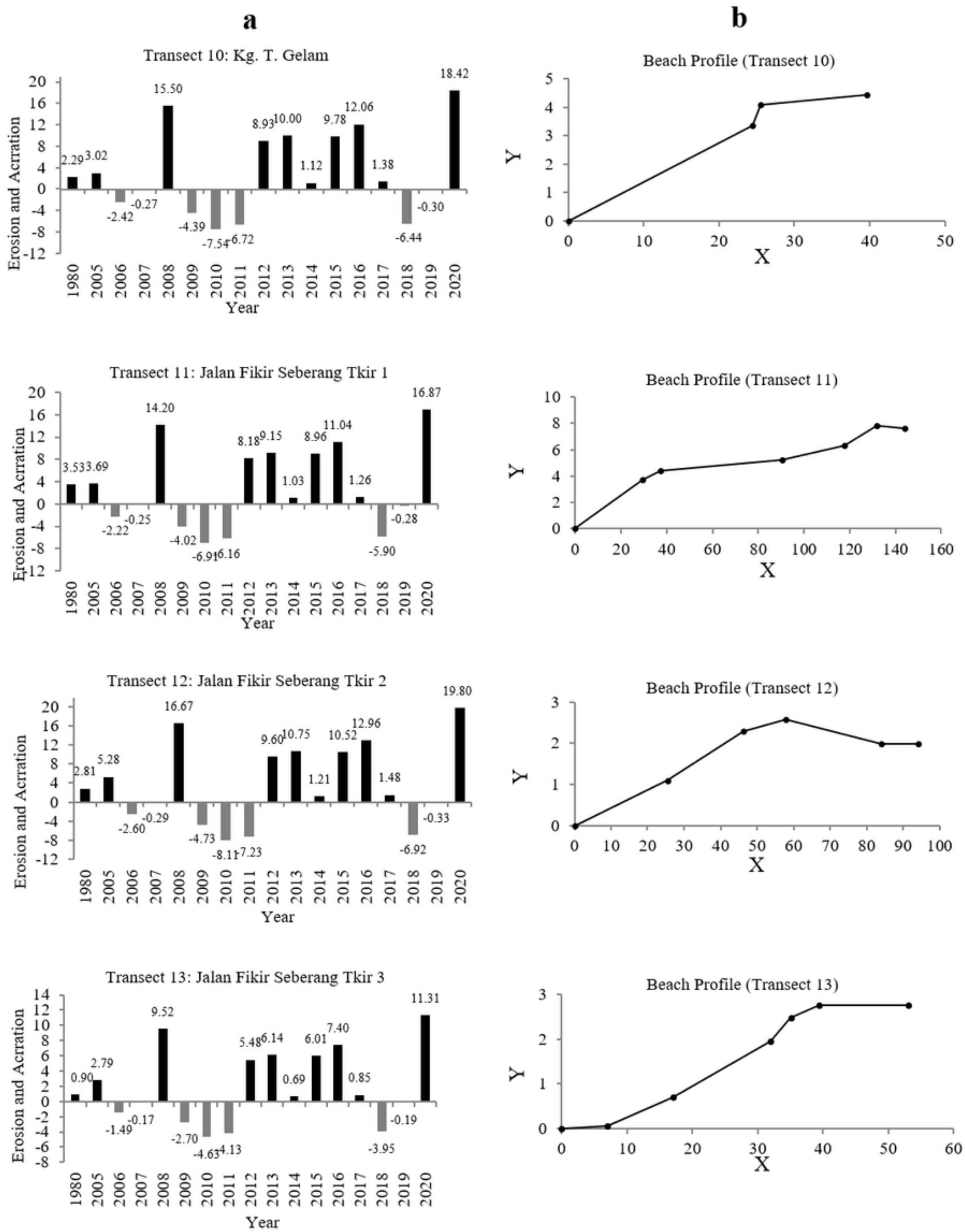

Figure 8

Study transect 10-13: (a), Rate of shoreline erosion from 1980-2020 for Kuala Terengganu. (b) Beach profiles estimation after erosion.

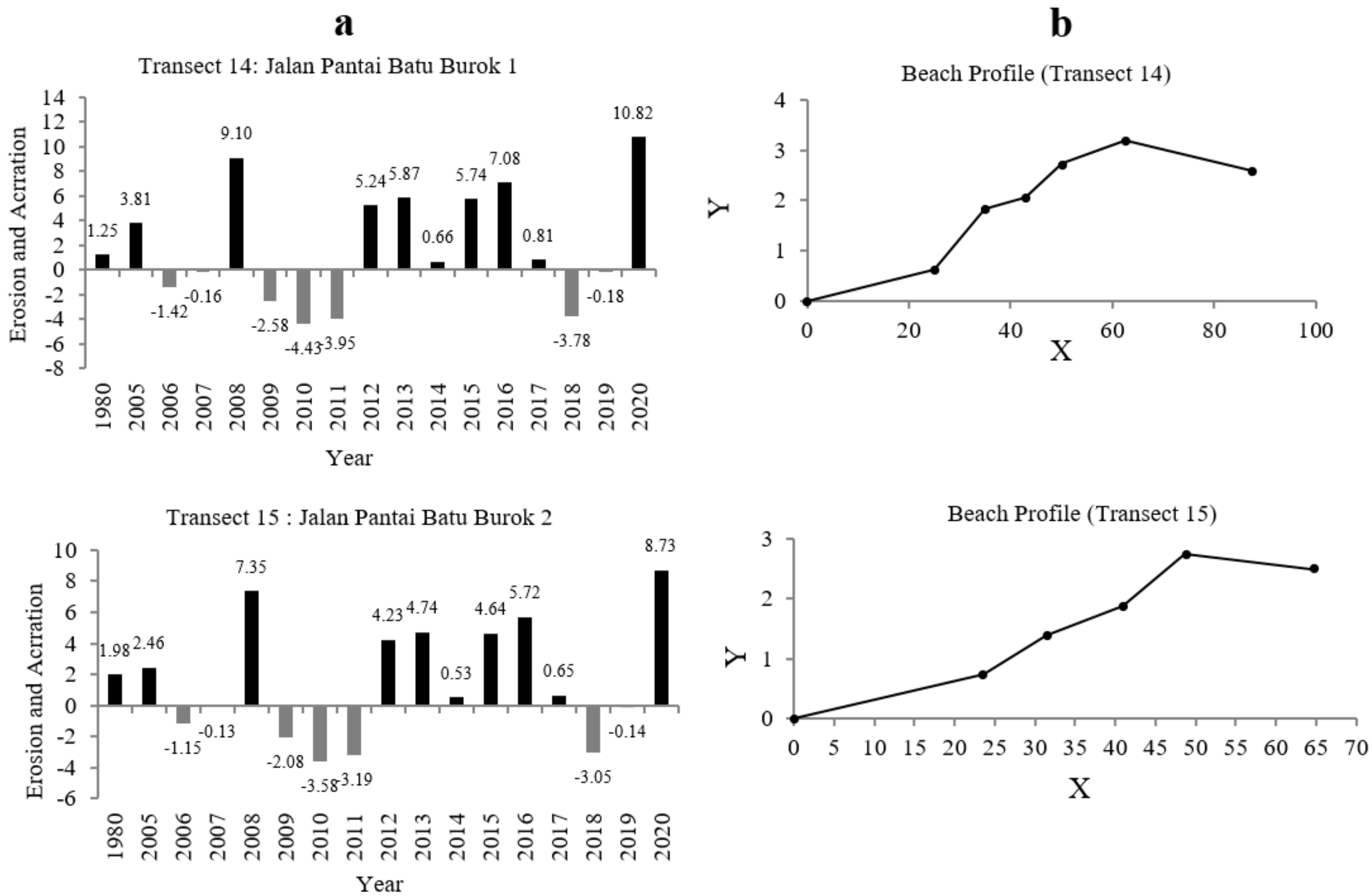

Figure 9

Study Transect 14 and 15: (a) Rate of shoreline erosion from 1980-2020 for Kuala Terengganu. (b) Beach profile estimation after erosion.

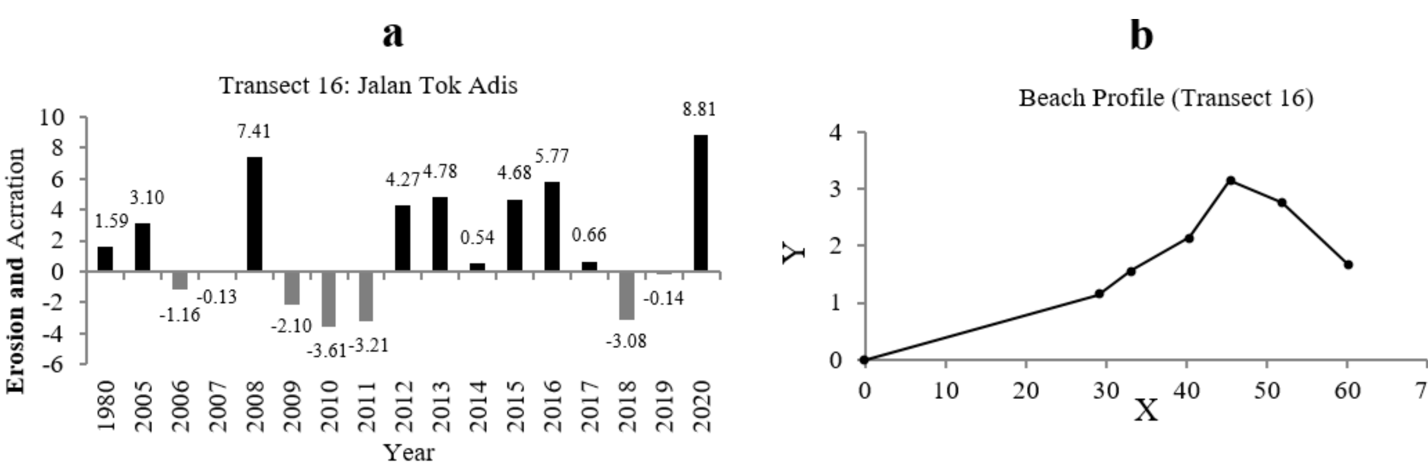

Figure 10

Transect 16: (a) Rate of shoreline erosion from 1980-2020 for Kuala Terengganu. (b) Beach profiles estimation after erosion

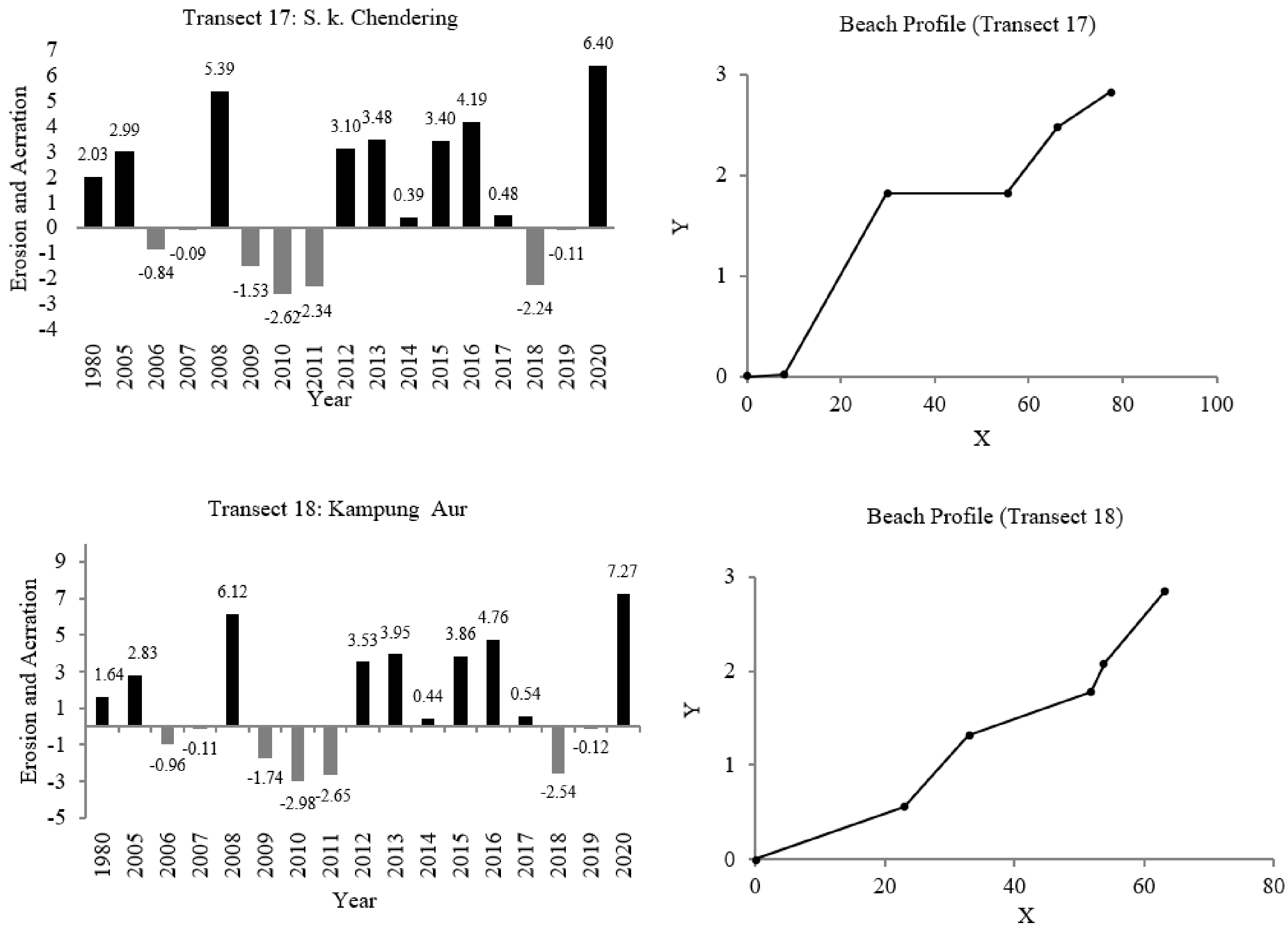

Figure 11

Transect 17 and 18: (a) Rate of shoreline erosion from 1980-2020 for Kuala Terengganu. (b) Beach profiles estimation after erosion.

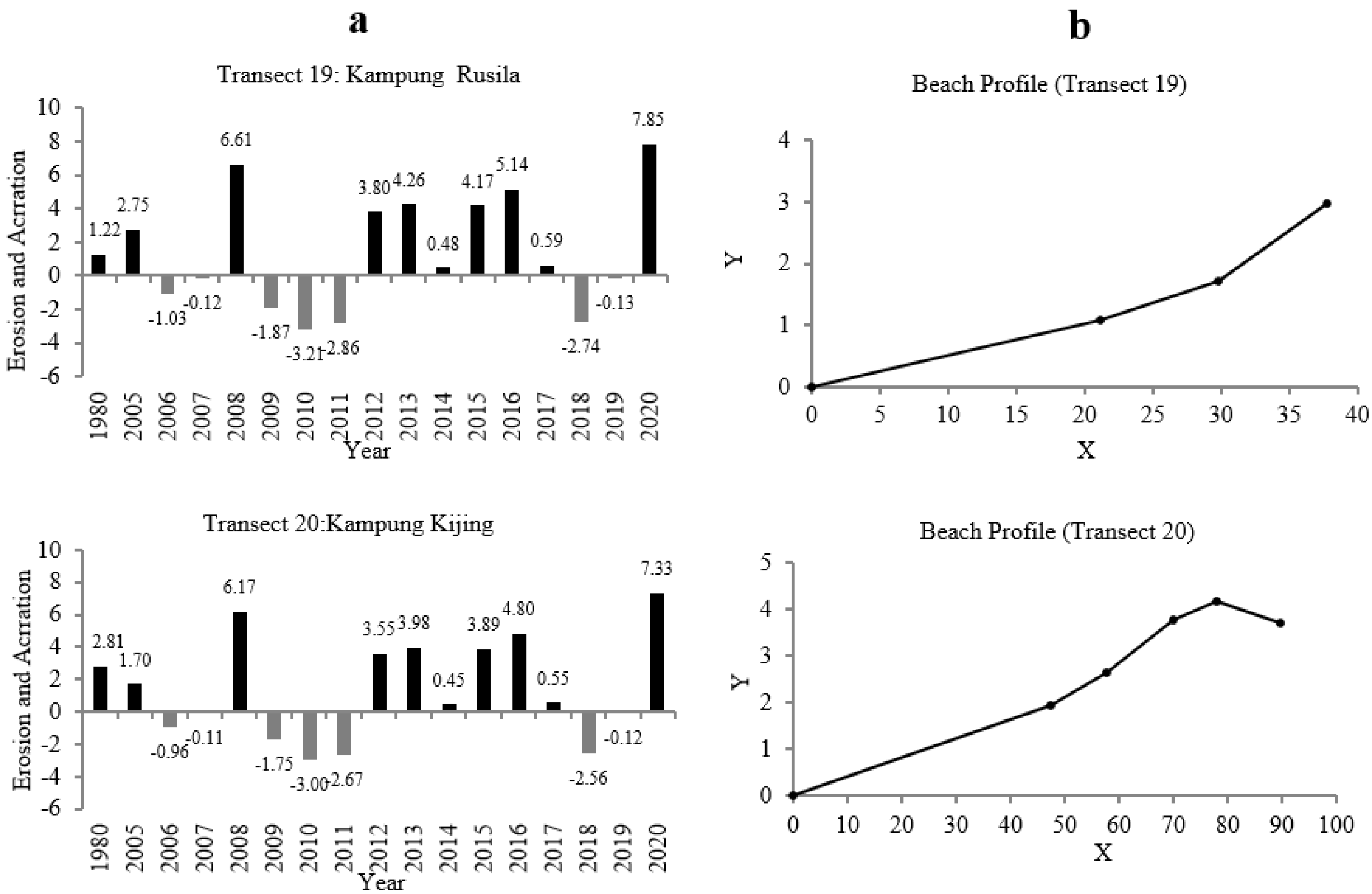

Figure 12

Transect 19 and 20: (a) Rate of shoreline erosion from 1980-2020 for Kuala Terengganu. (b) Transect 19 and 20, Beach profiles estimation after erosion

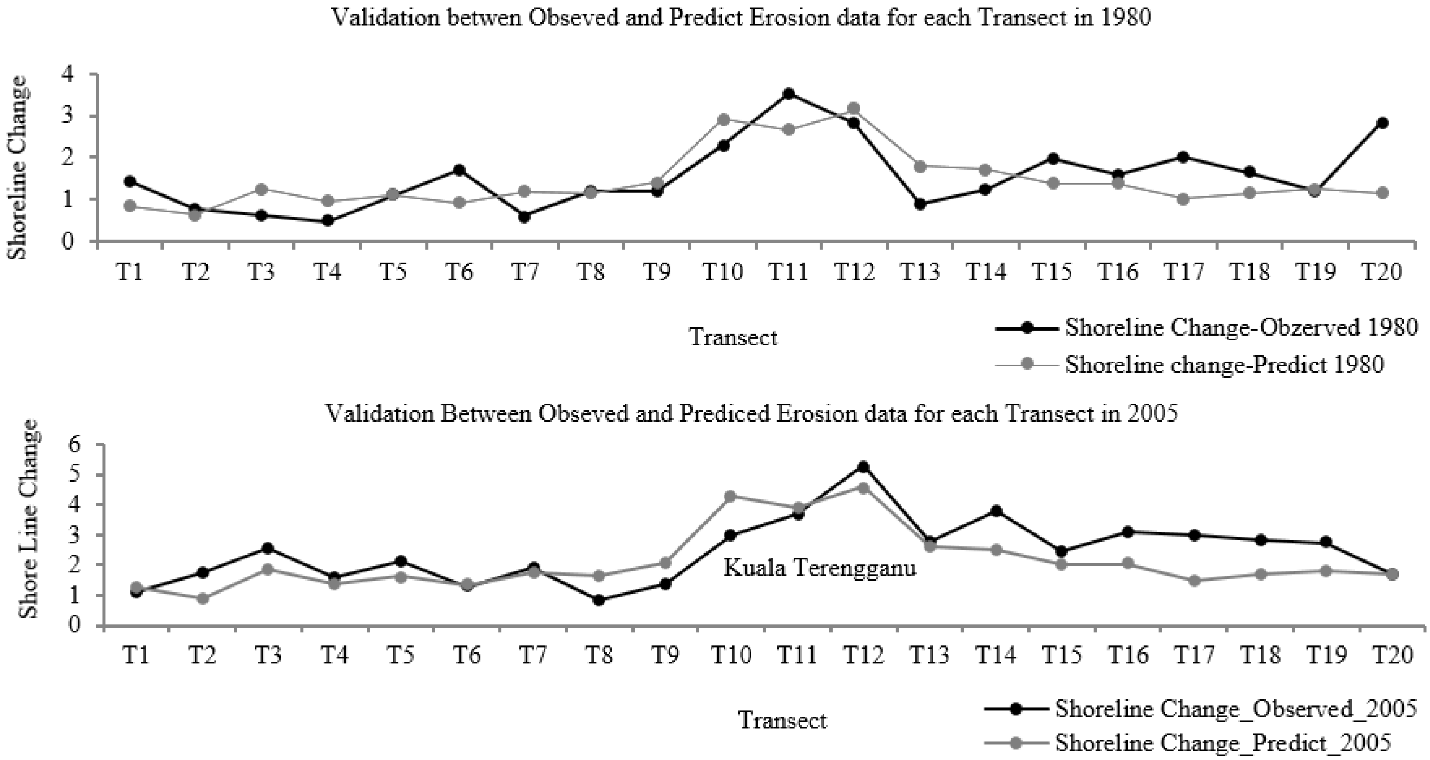

Figure 13

Observed and simulated shoreline change for 1980 and 2005.

Figure 14

Structural approaches proposed for the protection of the Kuala Terengganu coastal area in Malaysia to mitigate coastal erosion: (a) seawall, (b) jetty, (c) areal-view section of breakwater, (d) revetment armor, and (e) groyne.