COASTAL INUNDATION SIMULATION DUE TO SEA LEVEL RISE IN TERENGGANU, MALAYSIA

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KEY WORDS: Coastal inundation, sea level rise, Radar Altimetry Database System (RADS), Geographical Information System (GIS), shoreline

ABSTRACT:

Coastal Inundation is the amount of water levels that reach above normal level due to flooding in coastal areas. This natural phenomenon is due to the rising of local sea level. This study aims to develop a coastal inundation simulation along the coastline of Terengganu. To ensure the success of this study, the rate and magnitude of sea level rise are calculated using Radar Altimetry Database System (RADS) from multi-mission satellite altimetry data. The rate of sea level rise is computed using robust fit regression technique and overlaid with global Digital Elevation Model (DEM) data, known as TanDEM-X. The overlaid data are utilised to simulate the probable areas to be affected by inundation from year 2040 to 2100 using ArcGIS software. The results obtained from the period of 1993 to 2015 show that the average rate of sea level rise along the Terengganu shoreline is 4.84 mm/year with a standard deviation of 0.49 mm/year. By 2100, the estimated average regional sea level rise is projected to increase by 0.412 m. This study could help coastal development planning, defence, and safety monitoring.

1. INTRODUCTION

A shoreline or coastline is the boundary between land and sea, where their shapes and positions constantly changing due to the environmental conditions. The coastal zone is consistently exposed to threats from the ocean, resulting in coastal erosion and sea-level rise (Rashidi et al., 2021). The other threat that can be considered a serious problem is coastal inundation. Coastal inundation is a natural phenomenon due to the rising local sea level. Coastal zones are drastically experiencing sea level rise; and other than rich with natural resources, these areas are also densely populated and highly developed (Mohd et al., 2018). Therefore, the coastal zone becomes vulnerable to erosion and inundation since they are characterised as low topography. As a result, significant environmental consequences, such as saltwater intrusion into coastal groundwater aquifers and flooding of wetlands and estuaries will continue to occur (Mohd et al., 2018).

East monsoon system and development have a significant impact on coastal activities in Malaysia. It brings high intensity of related physical phenomena, such as waves, current velocities, winds, and high rainfall frequency, in which all of them have impacts on coastal inundation cycle (Ariffin, 2017). Coastal inundation forecasts can benefit many authorities, as it can assist them in well-planned monitoring and preventative measures for future geohazards risk assessment along the coastline.

Since Malaysia is located near the equator, it only deals with tropical climate, hot and humid climate throughout the year, with rainy period during monsoon season. Terengganu is one of the states that experiences extreme impact from this monsoon season. Therefore, Terengganu frequently encounter heavy rainfall that can contribute to flood and has high risk of sea level rise. This problem will significantly impact Terengganu authorities in their infrastructural, economic, environmental, and social development. Hence, the prediction of coastal inundation is crucial to assess the risk of geohazard for the necessities of human and ecological communities.

Coastal inundation forecast can be predicted by simulating the sea level rise with respect to the computation of sea level rate. The data are obtained through Radar Altimetry Database System (RADS) and overlaid with global Digital elevation Model (DEM) data, namely TanDEM-X, to simulate the inundated area. Besides, the airborne remote-sensing platforms can also be utilised to capture the data and offer a better resolution compared to satellite platforms. However, it is very costly in comparison to satellite data (Simon et al., 2018). Furthermore, the amplitude and shape of the returning radar signal from altimetry satellites offer useful information on wind speed and ocean wave height. Radar altimeters also map the topography of the ocean surface with unprecedented accuracy (Simon et al., 2018). Satellite altimeter is a good application, since it is low-cost and provides more accurate data.

Hence, this study aims to estimate the coastal inundation due to sea level rise in Terengganu, Malaysia using satellite altimetry and DEM data. This paper discusses on the derivation of sea level anomaly (SLA) data. A comparison between altimetric data and ground truth (tide gauge) data are also performed for data validation. The findings from this study can benefit various agencies related to the coastal area, such as environmental planning, coastal development, coastal defence, port terminal, and facilities modification.

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2. DATA AND METHOD

2.1 Sea Level Anomalies Derivation from Satellite Altimeter

Satellite altimetry data are extracted from 1993 to 2015 for the derivation of SLA. RADS is used to extract and process monthly mean SLA values over 23 years. Table 1 shows the details of the satellite altimeters used for this study.

Satellite	Phase	Product	Time Period	Cycles
TOPEX/ Poseidon	A, B, N	NASA	Jan 1993- Sept 2002	11-364
Jason-1	A, B, C	NASA	Jan 2002- Dec 2015	01-425
ERS-1	C, D, E, F, G	ESA	Jan 1993- Jun 1996	91-156
ERS-2	A	ESA	April 1995- Jul 2011	01-169
Envisat-1	B, C	ESA	May 2002- April 2012	06-113
Cryosat-2	A	ESA	Jul 2010- Dec 2015	04-74
SARAL	A	ESA	Mar 2013- Dec 2015	01-30

Table 1. Selected multi-mission satellites with time period data

In RADS processing, there are several steps to retrieve SLA data. Firstly, crossover adjustment is applied for every multi-mission satellite, followed by data gridding and smoothing of daily solution. Crossover adjustment is an integrated data processing from multi-mission satellite altimeters to eliminate satellite orbital errors and inconsistencies in satellite orbit frame (Hamden et al., 2021). Range and geophysical correction are applied using region-suitable models before SLA values are determined.

2.2 DEM Data Source

The potential of coastal inundation events has attracted global attention in recent years, requiring observations or time-series from coastal tide gauges or altimetry data and high-quality DEM (Fraile-Jurado and Ojeda-Zújar, 2013; Din et al., 2017; Kamaruddin et al., 2017). DEM datasets are widely available worldwide, providing latitude, longitude, and height information in a specific reference coordinate system for continuous topographic surfaces.

This study uses the TanDEM-X mission to produce digital elevation data. Spatial resolution of 3 arc second (90 m x 90 m) data are downloaded from the Earth Observation Centre of the German Aerospace Centre (Jalal et al., 2020). The impact of coastal inundation can be simulated by overlaying the magnitude of sea level rise with DEM data; therefore, identify the inundated areas. Figure 1 shows the DEM data for coastline in Terengganu from the TanDEM-X mission using ArcGIS software.

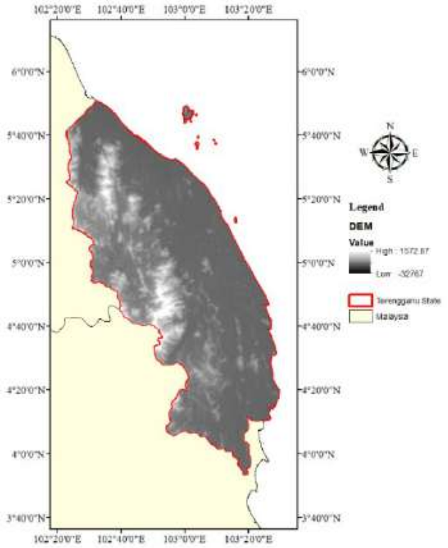

Figure 1. DEM spatial data for Terengganu state

2.3 Estimating Sea Level Trends Using Robust Fitting Method

The sea level trend in this study is calculated using the robust fitting method. The SLA time series are projected using linear function while removing the outliers using Iteratively Re-Weighted Least Squares (IRLS) techniques (Holland and Welsch, 1977). With an estimated rate value, the sea level rise is projected via robust fit analysis for the next 85 years, from 2016 to 2100. Figure 2 indicates the sequence of obtaining sea level rise projection.

Figure 2. The sequence of determination sea level rise projection

2.4 Coastal Inundation Simulation using GIS software

The increment of sea level is one of the factors that triggers floods in low-lying areas. The ArcGIS software is utilised to develop the simulation modelling system to detect the possible inundation areas. Inundation depth and extension within the study area is mapped using raster DEM data by overlaying the predicted magnitude of sea level rise.

DEM data are used as a base layer to simulate the inundation map for production of water flow. By utilising water level or flood analysis tools, the water flow can be simulated by allowing the water to flood or raise the water level over a predetermined height. For instance, zero (0) is for sea level. The sea level rise value is deducted with the current elevation value to simulate the elevation raster dataset. Note that below zero or negative values represent values below sea level. This method known as the Bathtub approach, depicting hydrological connection and regional sea level variation (Khalid et al., 2021).

To determine the possibility of coastal flooding areas, the water level rate is converted into polygons to determine which area has hydrological connectivity to the ocean (Khalid et al., 2021). The raster and polygons are identified explicitly using visualisation methods, where any polygon that touches the coastline are considered as inundated area. The polygon produced represents the area affected by sea level rise that are susceptible to inundation.

2.5 Data Validation: Tide Gauge versus Satellite Altimetry

Tide gauge data are used to validate the accuracy of satellite altimetry data. Located in Terengganu, Cendering tide gauge station is selected for data assessment. Three analysis methods are used to validate the data, which are the correlation coefficient (R) analysis, the Root Mean Square Error (RMSE), as well as the trend and magnitude of two datasets. The RMSE formula shown in Eq. 1 is used to calculate standard deviation of the residuals (prediction errors):

$$RMSE = \sqrt{\frac{\sum_{=1}^{n}(p_i - a_1)^2}{n}} \qquad (1)$$

where;
p_i = Satellite altimeter data
a_i = Tidal data from tide gauge
n = Total no. of data
i = No. of data

Small value of RMSE indicates the less error between two variables. From the calculation of R, the values that fall within 0.7-1 are considered to have a strong correlation between the two datasets. This analysis is carried out to assess the reliability of SLA derived from satellite altimeters; thus, satellite altimeter-measured sea level is compared with the tidal data.

3. RESULT AND DISCUSSION

3.1 Satellite Altimetry versus Tide Gauge

To ensure that satellite altimetry data are reliable and applicable, data validation between altimetry and tidal data is conducted. Cendering station is selected in this study to serve as the point of comparison between these two types of data. This tide gauge station is located at 103.18 E, 5.27 N, continuously recording tidal measurement (Hamid et al., 2018). Meanwhile, according to Trisirisatayawong, (2011) and Din et al., (2014), satellite altimeter passes Cendering tide gauge only thrice per month, and in worst-case scenario, only once.

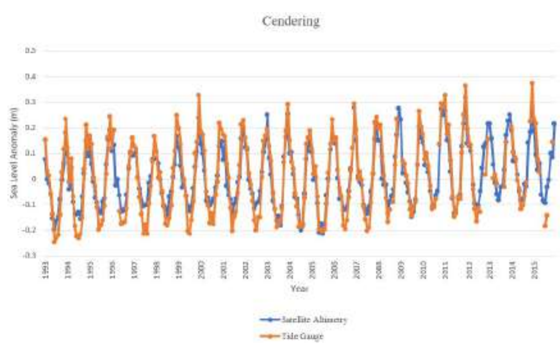

Figure 3. Graph of sea level anomaly changes at Cendering station from 1993 to 2015

In Figure 3, SLA time series derived from both satellite altimeter and tige gauge are plotted from 1994 to 2015. The orange line indicates the data from the tide gauge and the blue line represents the data from satellite altimeter. From the figure, a good pattern between these two types of data is observed in the time series, where the SLA derived from altimetric and tidal data shows similar fluctuations. Referring to Figure 4, showing the SLA time series of (a) altimetric and (b) tidal data, there are some missing data as emphasised by the red circles. Even though the absence of altimetric and tidal data are on the different timeline, it is still acceptable as the short data gap is still beyond threshold.

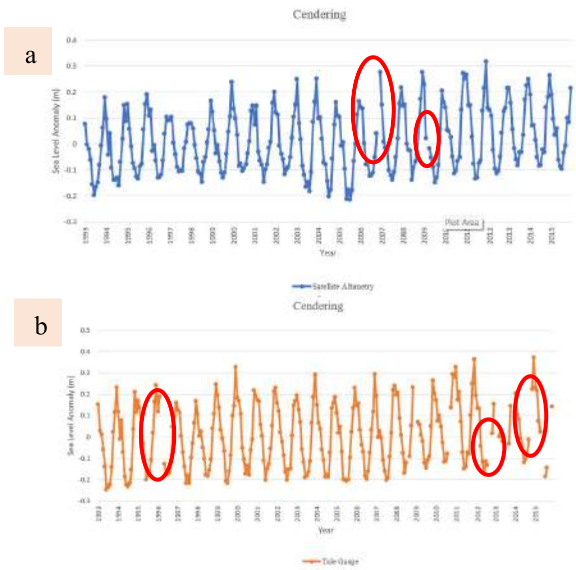

Figure 4. Graph of sea level anomaly pattern from (a) satellite altimetry and (b) tide gauge. Red circles show the data gap

According to Hyndman and Koehler (2006), by computing the RMSE value, the standard deviation of the residual can be determined to identify the error value, while the R-value demonstrates the constancy of the datasets pattern (Glantz et al., 1990; Hamden et al., 2021). In this study, the R-value is calculated to identify the relationship between altimetric and tidal data. The R-value calculated for these two datasets is 0.903, indicating a strong data agreement. Table 2 shows the classification of the R-value, whereas Figure 5 shows the R graph of SLA derived from satellite altimeter against SLA derived from tidal data. The RMSE value of 0.062 m is also exhibited in the figure.

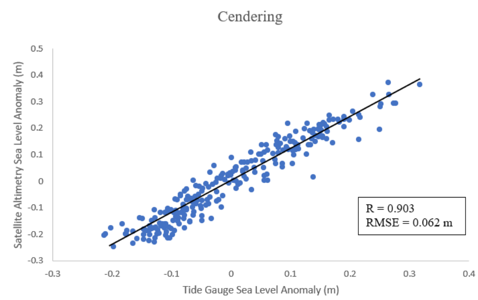

Figure 5. Correlation coefficient graph with a positive linear line indicates a good correlation between satellite altimetry and tide gauge data

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To briefly summarise, the SLA derived from altimetric and tidal data as visualised in Figure 3, has a similar pattern of sea level fluctuations based on the data span from 1993 to 2015. Additionally, the statistical results obtained from the R and RMSE values also indicate that the SLA data derived from satellite altimeter is reliable and can be used for further processing.

R-Value	Description
1	Perfect
0.7 – 0.9	Strong
0.4 – 0.6	Moderate
Less than 3	Weak

Table 2. Classification of R-values (Dancey and Reidy, 2004).

3.2 Sea Level Rise Rate and Magnitude

In this study, the rate of sea level rise in the Terengganu coastal area is projected using robust fit regression analysis. The sea level rate is estimated for the next 85 years, from 2016 to 2100 based on the SLA derived from satellite altimeter. The projection of sea level rise is quantified until 2100 due to the fact that it can identify a reliable fit link between the increases in regional sea level (Hamid et al., 2018).

Figure 6 illustrates the rate of sea level at Cendering tide gauge station relative to altimetric data. The fluctuation of SLA at Cendering station shows a consistent pattern with an increase rate of 3.615 ± 0.376 mm/year. According to Hamid (2018), the SLA at South China Seas represents a stable pattern with an increase rate of 3.88 ± 0.05 mm/year, whereas in Malacca straits, sulu sea, and the Celebes Sea show irregular patterns. This is due to the extended land of the Malaysian west coast (Yan et al., 2017), causing the Malacca Strait to become narrow and the enclosed sea at the Sulu Sea and the Celebes Sea (Wang et al., 2006; Md Din et al., 2015, Hamid et al., 2018) trigger high rate of sea level rise in these three places.

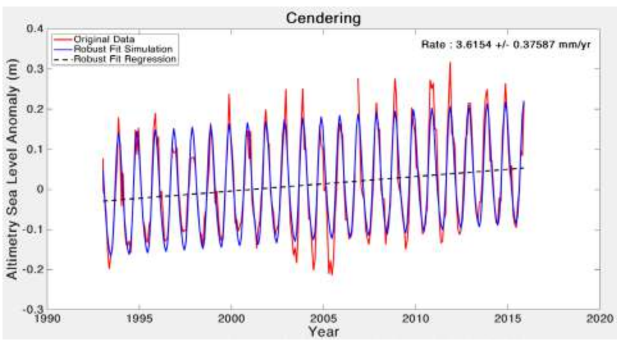


Figure 6. The sea level trend derived from altimetry data at Cendering tide gauge station

Regarding Figure 7, the red circles indicate the areas affected by a drastic rate of sea level rise. In contrast, the South China Sea does not experience drastic sea level changes because the ocean itself is a semi-closed sea coupled with the existence of numerous straits and channels (Choi et al., 2013). Related to this statement, Cendering station shows a stable pattern of sea level rise as it is located facing the South China Sea.

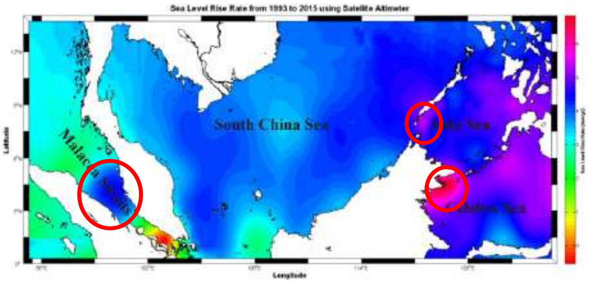


Figure 7. Map of sea level rate over Malaysian Seas (Hamid et al., 2018)

The estimation of sea level rate in Terengganu waters, is calculated using the sea level trend lines at the selected coordinate in the years 2040, 2060, 2080, and 2100. The same robust fit regression method is adopted to project the sea level trend. As shown in Figure 8, the sea level is projected to continue to rise from 2016 until 2010.

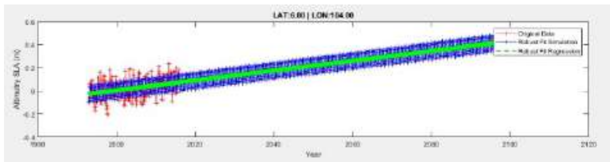


Figure 8. Projected sea level trend at a selected coordinate in the Terengganu coastline using robust fit regression in the years 2040, 2060, 2080 and 2100

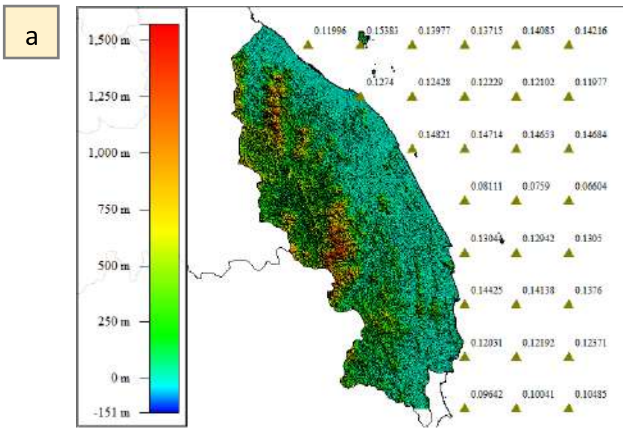
Figure 9 represents the distribution map of the sea level rise for each twenty-year increment around the Terengganu coastline. The lowest sea level rise projected in 2040 are located at 104 E, 5 N with an increase value of 0.066 m, while the highest projected value of sea level rise in 2040 is located at 103 E, 5.75 N with an increase value of 0.149 m. In the next 20 years (2060), the lowest projected sea level rise with a value of 0.119 m is recorded at 104 E, 5 N, meanwhile, the highest value of 0.277 m is measured at the 103 E, 5.25 N.

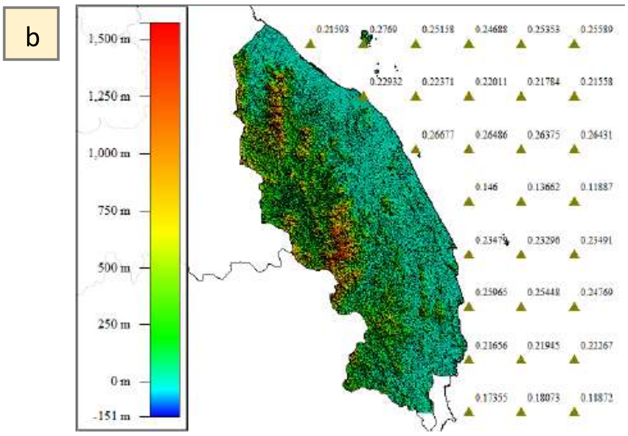
In 2080, the lowest increment is expected to occur at 104 E, 5 N with a value of 0.171 m, whereas the highest sea level rise at 103 E, 5.75 N is 0.400 m. Moreover, the shoreline of Terengganu water is anticipated to have the greatest influence on sea level rise in 2100, with the lowest increment of 0.224 m at 104 E, 5 E and the highest increment of 0.523 m at 103 E, 5.75 N.

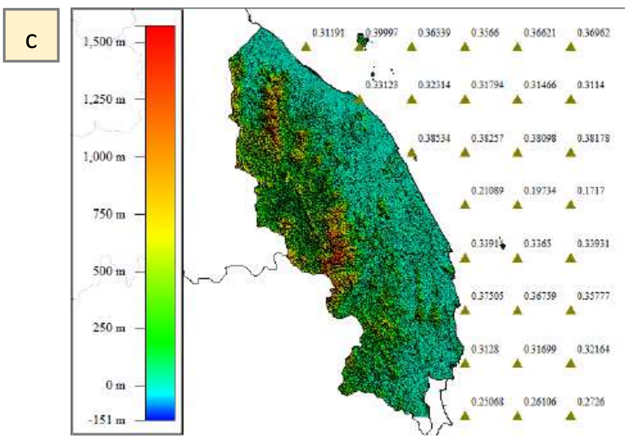
Based on the data measurement period from 1993 to 2015, the average of absolute sea level rise along the Terengganu shoreline is tabulated in Table 3. By the end of 2100, the estimated average of sea level rise is projected to increase by 0.412 m.

Sea	Year			
	2040	2060	2080	2100
Terengganu Coastline	0.121	0.218	0.315	0.412

Table 3. The average of sea level rise projection (in m) along the Terengganu shoreline







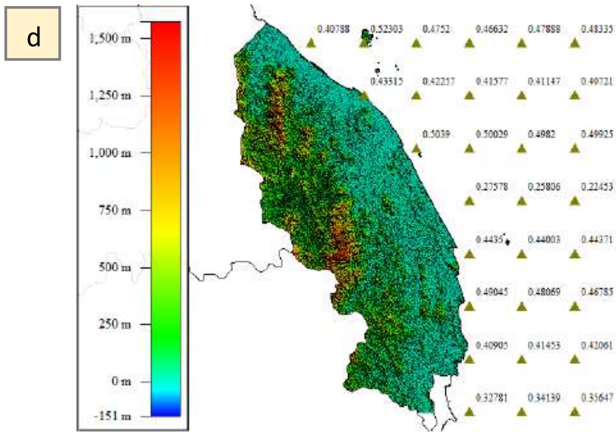


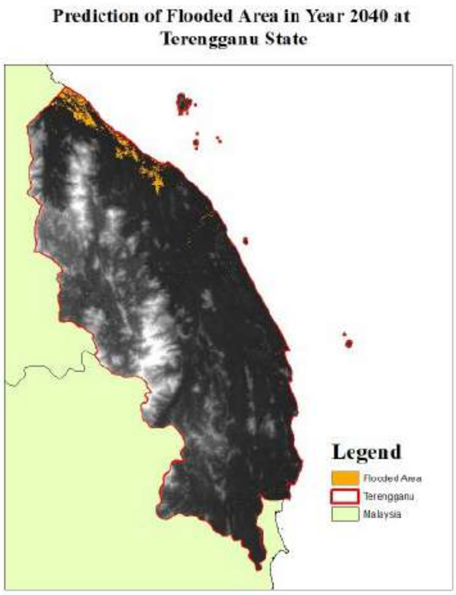
Figure 9. Maps of the distribution of sea level projection in South China Sea around Terengganu coastline in year (a) 2040, (b) 2060, (c) 2080, and (d) 2100, in unit metre

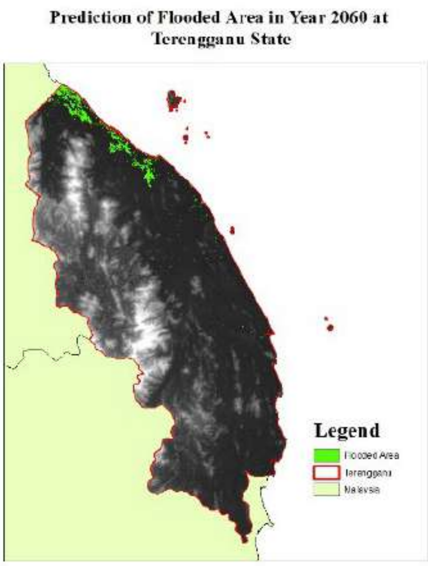
3.3 Coastal Inundation Simulation using GIS Software

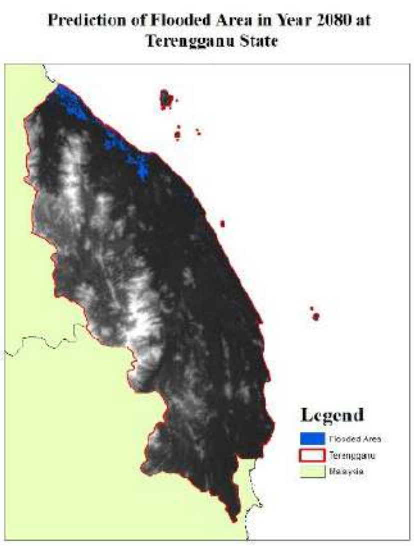
In this study, ArcGIS software is used to map the differences in the magnitude of sea level rise events from 2040, 2060, 2080, and 2100 along the Terengganu shoreline, as shown in Figure 10. By using spatial elevation data and spatial sea level projection, the inundation map of the Terengganu shoreline has been produced to identify the inundation risk zones. Analytic tools in ArcGIS software are utilised to map the coastal areas at risk of inundation.

From the coastal inundation map, areas prone to inundation are determined. The inundation risk zone is determined based on the sea level increment. Therefore, with the inundation map simulation, the precautionary decision can be taken. In the processing, the spatial data within the study area are trimmed to be precise and physically relevant in accordance to the administrative borders. Figure 10 depicts the simulated inundation area in the Terengganu state by overlaying the DEM data with the magnitude of sea level rise values.

By the end of year 2100, Besut district is predicted to be severely affected by flood. As shown in Figure 11, the area within 2-3 km buffer zone from the coast will experience inundation. This might occur because Besut district is located in a low area compared to the other districts in Terengganu.







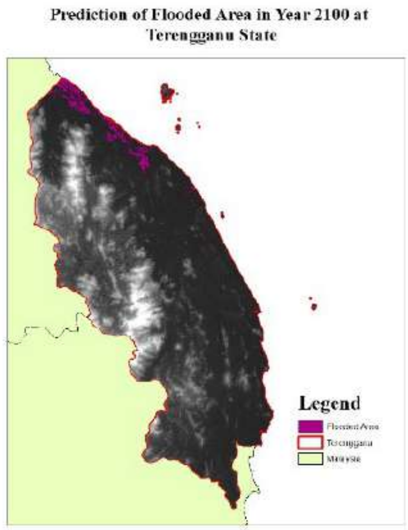


Figure 10. Maps of the affected areas over Terengganu state for the years 2040, 2060, 2080 and 2100

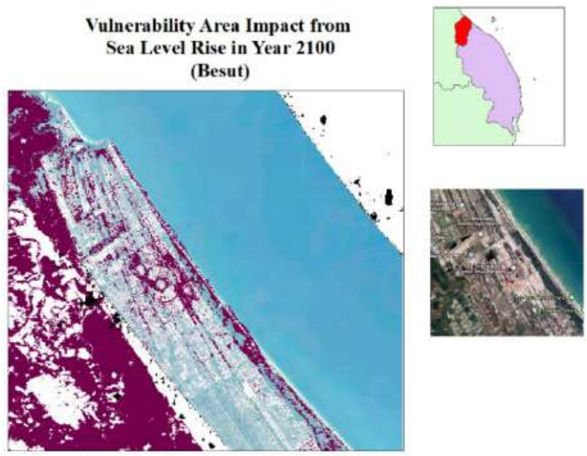


Figure 11. Simulation of inundation areas in Besut district

4. CONCLUSION

The potential threats of coastal areas have been confirmed by the coastal flooding simulation caused by the sea level rise along the Terengganu coastline. The combination of information from altimetric and DEM data beginning from 1993 to 2015 (23 years) are used to investigate the coastal vulnerability to the threat of sea level rise. This study successfully produces inundation maps with different magnitudes within 100 years using ArcGIS software. The results show that the district of Besut in Terengganu is the most susceptible area to inundation compared to other areas. It is expected that the predicted inundation maps produced will help authorities and coastal communities to better visualise the areas that are prone to coastal inundation. In conclusion, the information from this study is anticipated to help the relevant parties concerned with inundation risk assessment and levels of planning and preparedness in Terengganu coastal areas, particularly regarding coastal development planning, defence, and safety monitoring.

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