COASTAL INUNDATION SIMULATION IN SELANGOR UTILISING GEOSPATIAL TECHNOLOGY

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KEY WORDS: Coastal inundation, sea level rise, Digital Elevation Model, ArcGIS

ABSTRACT:

Coastal inundation is one of the most visible consequences ofrising sea levels, affecting socioeconomics and human activities. Coastal inundation is the flooding of normally dry land. This is related to the long-term effects of rising sea levels and the short-term effects, such as floods and storm surges. This study aims to establish a coastal inundation simulation of sea level rise in the Selangor coastal areas using satellite altimetry and Digital Elevation Model (DEM) data, as well as Geographical Information System (GIS) software. This study uses robust fit regression method to generate sea level rise trend and projection using multi-mission satellite altimetry data. The combination of altimetric and DEM data is used to simulate areas susceptible to inundation due to sea level rise. In order to construct maps to determine the location of coastal inundation, ArcGIS software is used to demonstrate the inundation areas. The output of this study, particularly the information on sea level projections will be an invaluable element in assisting authorities with future coastal planning and development, as well as helping local government agencies and the general public by providing information on sea-level rise, flood risk zones, and coastal inundation to predict the upcoming sea level and flood discharge. The findings are intended to observe the increment in sea level in coastal areas, therefore, it is possible to anticipate the expected increase in flood areas in the coming year and make preparations in advance.

1. INTRODUCTION

Climate change has been highlighted as a major indicator of the significant impact, particularly in coastal areas and the communities that inhabit the region. Coastal inundation not only caused by tidal range, but also due to the sea level rise. It usually happens when dry, low-lying terrain is flooded by the ocean. Based on its impact on society, natural environment, and coastal ecology, sea level rise is the most prominent threat of climate change (Mohd et al, 2018). In recent years, rising sea level has been clearly identified as a severe concern to society in the 21st century by the Intergovernmental Panel on Climate Change (IPCC) (Solomon et al., 2007; Liverman, 2008; IPCC, 2014). Because of this climate change, sea levels around the world are steadily increasing, endangering many low-lying and unprotected coastal areas (Nicholls and Cazenave, 2010). According to the IPCC, sea level rise, as a result of global warming is one of the most pressing issues affecting coastal populations (IPCC, 2001). The impact of storms on low-lying coastal communities, economic and social severely increase as the sea levels rise. It is critical to take immediate steps to quantify the future sea levels, so that mitigation efforts can begin as soon as possible. Long-term causes of coastal inundation are tied to local-globalsea-level variations. With a large and rapidly increasing population, the impacts on coastal areas are a major concern.

The IPCC (2014) has predicted in its Ar4 that global sea level will increase up to 60 cm by 2100 due to sea level rise and melting glacial (AR4). However, the recently discovered accelerated reduction in polar ice sheet mass increases the prospect of future sea level rise of 1 m or higher by 2100. In a study obtained from IPCC (2019), the average sea level (GMSL) has increased from 2006 to 2015 with an acceleration rate up to 3.6mm/year, which is predicted to be 0.43-0.84 m in 2100 in different Representative Concentration Pathways (RCP) scenarios. According to National Water Research Institute of Malaysia (NAHRIM) (2010), sea-level rise in the Peninsular Malaysia coastal zone is projected to be 0.253 m to 0.517 m by 2100.

Sea level changes in the Malacca Straits over the previous 23 years due to global climate change have been determined using multi-mission satellite altimeter. This study aims to develop a coastal inundation simulation of sea-level rise along the Selangor coast. The approaches mimic the future effects of sea-level rise on the coastal and floodplain within Selangor region. This simulation uses ArcGIS software to execute the hydrodynamic model (bathtub model). The findings of the study will be used to develop long-term inundation mitigation approaches that reduce susceptibility by anticipating future risk implications.

The area of study involves the coastal areas in Selangor, Malaysia. The selected areas for the sea level rise study include Mukim Kapar, Mukim Klang, and Mukim Jugra, specifically located in Klang and Kuala Lumpur districts of Selangor as shown in Figure 1. The study areas are located in the coastal areas of Klang and Kuala Langat, with a total area of 80,966 hectares and further inland. As this study is focused on the coastal areas of Selangor, only Pelabuhan Kelang tide gauge station is included in this study. Table 1 shows the tide gauge station coordinates and period of data.

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No	Tide Gauge Station	Latitude	Longitude	Period of Data
1	Pelabuhan Kelang	2°58'48.3"N	101°24'18.9"E	1993 - 2015

Table 1. The location and data period of Pelabuhan Kelang tide gauge station

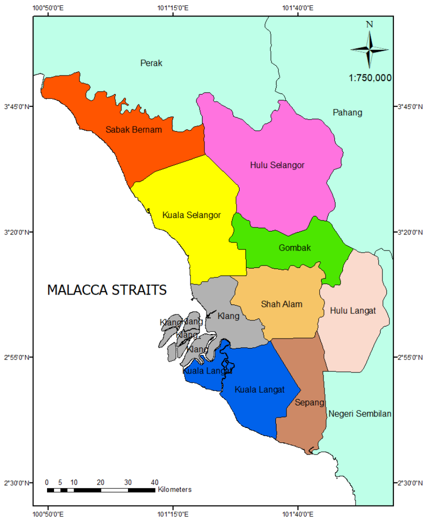

Figure 1. Selangor map with a red circle for the coastal area

2. DATA AND METHOD

2.1 Data Acquisition

Satellite altimetry data are derived from Radar Altimeter Database System (RADS) from 1993 to 2015. The satellite missions used are TOPEX/Poseidon, Envisat-1, ERS-1, ERS-2, Jason-1, Cryosat-2, and SARAL. Tidal data for Pelabuhan Kelang station are retrieved from the Permanent Service for Mean Sea Level (PSMSL) website from 1993 to 2015. DEM from TanDEM-X data is used to simulate the inundation area due to sea level rise. The DEM data are obtained from an open-source website.

2.2 Derivation of Sea Level Anomaly from Multi-mission Satellite Altimeter

The fundamental principle of satellite altimeter is it measures the time taken by the microwave energy of satellite range to travel back and forth. The microwave pulse is transmitted by the satellite radar to the sea surface and reflected back from the sea and received again on-board. A secondary tracking system determines the satellite's three-dimensional position with respect to a fixed Earth coordinate system. These two numbers yield sea-level elevation or profile relative to the projected ellipsoid. This study utilises satellite altimetry data from seven multi-mission: TOPEX/Poseidon, Jason-1, ERS-1, ERS-2, Envisat-1, Cryosat-2, and SARAL to determine sea level anomaly (SLA). This study relies on 23-year records of monthly average SLA values from 1993 to 2015. RADS software is used to derive the absolute sea-level rise. SLA data processing in RADS involves several steps, starting with cross-over adjustment for each multi-mission satellite, then information gridding for data flattening, and ultimately, regular extraction of sea level data from each selected point (Hamden et al., 2021).

Altimeter adjustment and bias removal phases of data processing involve region-specific models. This is due to the fact that the default RADS correction models are designed for global instead of local use. Prior to the SLA generation, all altimetric data in this study are corrected relative to the range measurements using atmospheric and geophysical corrections. Table 2 describes the geophysical corrections implemented in this study.

Correction/Model	Editing (m) Min	Editing (m) Max	Description
Orbit/gravity field			All satellite: EIGEN-GL04S ERS: DGM-E04/D-PAF
Dry Troposphere	− 2.4	− 2.1	All satellites: atmospheric pressure grids
Wet troposphere	− 0.6	0.0	All satellites: radiometer measurement
Ionosphere	− 0.4	0.04	All satellites: smoothed dual-frequency, ERS: NIC09
Dynamic atmosphere	− 1.0	1.0	All satellites: MOG2D
Ocean tides	− 5.0	5.0	All satellites: GOT4.10
Load tides	− 0.5	0.5	All satellites: GOT4.10
Solid Earth tides	− 1.0	1.0	Applied (elastic response to tidal potential)
Pole tides	− 0.1	0.1	Applied (tide produced by polar wobble)
Sea state bias	− 1.0	1.0	All satellites: CLS non-parametric ERS: BM3/BM4 parametric
Reference	− 1.0	1.0	DTU13 mean sea surface height
Engineering flag			Applied
References surfaces			TOPEX, Jason-1 Jason-2

Table 2. The RADS correction for altimetric data processing

2.3 Sea Level Trend and Projection in the Selangor Coastal Areas

On the basis of predicted sea-level rise and elevation data, the influence of rising sea levels in the Selangor coastal areas is evaluated to prevent the potential of submerged land areas in the future. Figure 2 shows the projected sea level trend along the coast of Selangor from 2040 to 2100 using robust fit regression analysis.

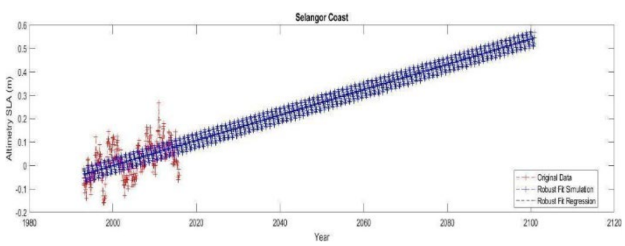

Figure 2. Projected sea level trend in Selangor area in years 2040, 2060, 2080, and 2100 using robust fit regression method

2.4 Bathtub Concept in Inundation Simulation

Sea level rise is one of the most severe consequences of climate change. In order to effectively estimate the possible hazards posed by increasing sea levels to the local regions of interest, it is required to analyse the patterns and unpredictability of sea level. As aresult of these effects, numerous low-lying areas along the Malaysia coast are at risk of damage. All contemporary approaches to determine the depth and extent of inundation are dependent on the quality of DEM. By using hydrological modelling and inundation mapping, flood information, such as inundation extent and water surface level are forecasted. Some methods of sea level modelling techniques can predict dry and wetland land loss caused by coastal flooding. The bathtub inundation model predicts that low-lying areas will flood like a bathtub. Two ways to replace the "bathtub" are via or without hydrological connectivity. In ArcGIS setting, any DEM cells with elevations below the predicted sea level are considered to be flooded. Since only elevation data are necessary, calculations can be made even when the hydrological data are missing (often the case). A location must be hydrologically connected to the origin of inundation (e.g., the ocean or river) to be inundated according to bathtub models that account for hydrological connection, such as flowing water between cells (Yunus et al., 2016). As depicted in Figure 3, certain strategies, such as the "zero-side rule," "four-side rule," and "eight-side rule" are utilised to simulate the circumstances of flooding. (Khalid et al., 2021).

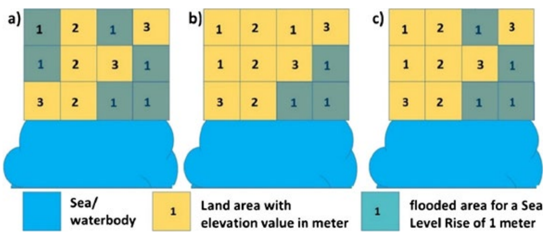

Figure 3. Three different designs of bathtub: (a) Zero or no connectivity indicates practically all 1 m raster grid cells are inundated; (b) 4-side connectivity with 1 m elevation indicates all grid cells are flooded if they are directly or indirectly related to a water body; and (c) 8-side connectivity with 1 m height, means all grid cells could be inundated if linked to a water body or waterway. (Yunus et al., 2016)

2.5 Inundation Modelling

In coastal flooding research, multiple variables must be addressed, including sea level, velocity, depth, and duration. A flood simulation of Selangor beaches is now being constructed to forecast sea level rise over the next century. This study uses TanDEM-X data to assess the effects of coastal flooding along Malaysian coastlines in 2040, 2060, 2080, and 2100. The raster elevation dataset can be visualised by subtracting the sea level rise from the present elevation of the grid, where the negative values are assumed to be below sea level. The bathtub method is utilised to depict regional changes in sea level and hydrological connections.

3. RESULT AND DISCUSSION

3.1 Sea Level Trend from Satellite Altimetry and Tidal Data

SLA is calculated from sea surface height (SSH) data relative to the mean sea surface (MSS). The MSS can be determined using the average of SSH values for a particular time period. The SLA value is calculated as follows (Anderson and Scharroo, 2011; Hamid et al., 2018):

$$SLA = H_{SALT} - R_{SALT} - MSS \qquad (1)$$

where

H_{SALT} = Height from satellite orbit,
R_{SALT} = Range of satellite altimeter,
MSS = mean sea surface.

The rate of sea level from altimetry data in Pelabuhan Kelang is depicted in Figure 4. The figure also shows the original data (red line) and the simulation of robust fit (blue line). The rate is 5.17 mm per year with a standard deviation of +/- 0.54 mm per year.

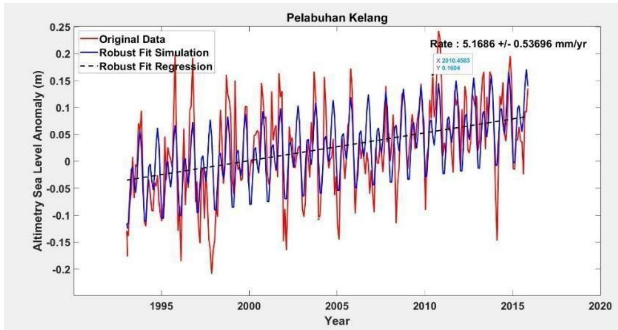

Figure 4. Sea level trend at Pelabuhan Kelang from satellite altimetry data

The tidal data obtained from the PSMSL website range from 1993 until 2015. Robust fit regression technique is utilised to assess the data and estimate the trend of sea level rise over the past century. Figure 5 illustrates the time series of sea level trend at Pelabuhan Kelang derived from tidal data using robust fit regression method. Based on the tidal SLA, the sea level rate is estimated to be 3.29 mm per year with a standard error of +/- 0.68 mm per year.

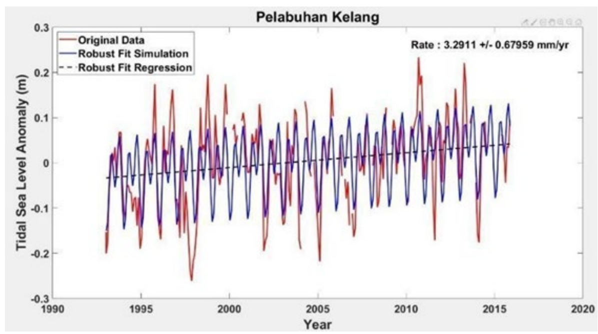

Figure 5. Sea level trend at Pelabuhan Kelang from tidal data

3.2 Analysis of Sea Level Pattern

Peninsular Malaysia is divided into two areas facing distinct seas: South China Sea and Malacca Strait. Since this study focuses on Selangor area, only the Pelabuhan Kelang tide gauge station facing Malacca Strait is considered in this study. The tidal data, which is in monthly solution is used to calculate the relative SLA, whereas the SLA derived from altimetric data is known as absolute sea level. Time series of both relative and absolute SLA at Pelabuhan Kelang station are plotted as illustrated in Figures 6 and 7 to better visualise the sea level pattern.

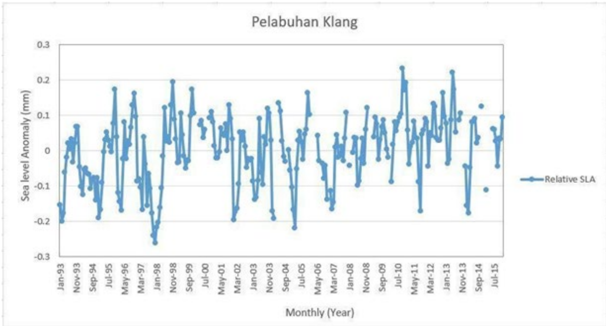

Figure 6. Sea level pattern of monthly tidal data at Pelabuhan Kelang station

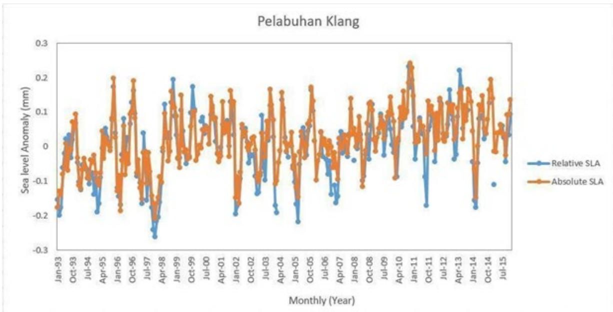

Figure 7. Sea level pattern of relative and absolute SLA derived from tidal and altimetric data

3.3 Projection of Sea Level Trend using Robust Fit Regression

This study explores the projected sea level trends in Malaysian waters. Multiplying the trend rate of sea level rise by the anticipated time period yields the predicted rate of sea level rise across the coasts of Selangor. The projected number is obtained by excluding the external impact of several events that could affect future forecasts of sea level rise on Selangor coastlines. This analysis forecasts sea level rise for Selangor waters for every 20-year increment in the twenty-first century, for the years 2040, 2060, 2080, and 2100 (see Table 3 and Figure 8).

Sea	Year			
	2040	2060	2080	2100
Selangor Coast	0.1163	0.2094	0.3024	0.3955

Table 3. Selangor coastline sea level rise and projection (unit is in metre).

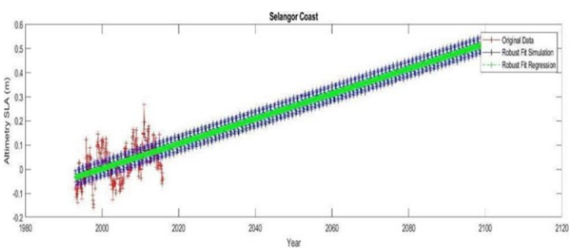

Figure 8. Sea level trend and projection from 2016 to 2100

Robust fit regression is a method used to determine the solution and identify outliers. In this method, an iteratively Reweighted Least Square (IRLS) procedure is used to customise a linear trend to annual sea level trend for each station. When values depart from the long-term trend, the respective weights of those values are adjusted. Then, the trend line is re-fitted. The procedure is repeated until better outcome is achieved. The observed results (wi) are reconstructed utilising the bi-square weight function, which interacts with the normalised residuals (ui). It is represented as (Holland and Welsch, 1977; Din et al., 2015):

$$wi = \begin{cases} (1-(u_i)^2)^2 & |u_i| < 1 \\ 0 & |u_i| \geq 1 \end{cases} \quad (2)$$

where,

$$u_i = \frac{r_i}{K.S.\sqrt{1-h_i}}$$

r_i : Residuals,
h_i : Leverage,
S : Mean absolute deviation divided by a factor 0.6745 to make it an unbiased estimator of standard deviation,
K : A tuning constant, which default value of 4.685 provides for 95% asymptotic efficiency as the ordinary least squares assuming Gaussian distribution.

3.4 Prediction of Sea Level Rise with DEM Data

The development model approach for the sea level simulation begins with a starting event, such as the predicted sea level rise for every two decades. The bathtub inundation model has been used in conjunction with GIS software to simulate a number of different sea level rise scenarios with varying degrees of amplitude along the coastlines of Selangor in 2040, 2060, 2080, and 2100. Although the bathtub modelling is a straightforward method that could be conducted using commercially available geospatial data interpretation, the coastal inundation floor may be erroneous due to the incapability of DEM to identify the scattered land borders, which can impede interior water flow to the shore (Murdukhayeva et al., 2013). Using the coastline inundation map, it is possible to determine the flood inundation area and the future implications of a sea level rise along the shoreline for early precautions. Prior to the execution of inundation mapping procedures, the ArcGIS Mosaic to New Raster Dataset tool is utilised to aggregate the elevation model dataset into four files, which are spatial relevance matches to the four research areas. This geographical data processing and mapping are projected with respect to World Geodetic System 1984 (WGS84) coordinate system. The administrative bounds of these study regions are then employed to trim the predicted file, rendering it accurate and space-applicable.

To estimate the rise of sea levels in the study area, the 30 m-resolution elevation data from TanDEM-X is used. Lowlands and floodplains surrounding the state of Selangor, particularly in Kuala Selangor and Klang regions, have a high probability of inundation by 2100 based on the sea level rise projection. Figures 9 to Figure 12 show the prediction of sea level rise at the Selangor coast for every twenty years.

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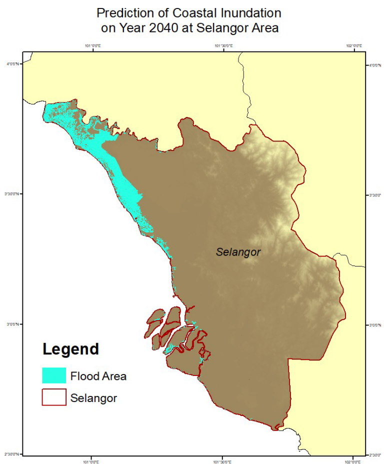

Figure 9. Prediction of inundation area at Selangor coastal in the year 2040 with an increment of sea level rise by 0.1163 m

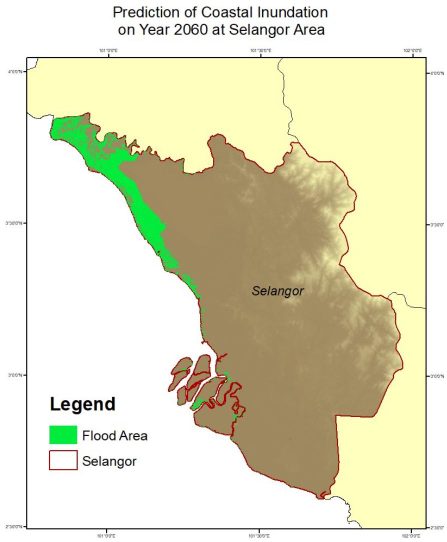

Figure 10. Prediction of inundation area at Selangor coastal in the year 2060 with an increment of sea level rise by 0.2094 m

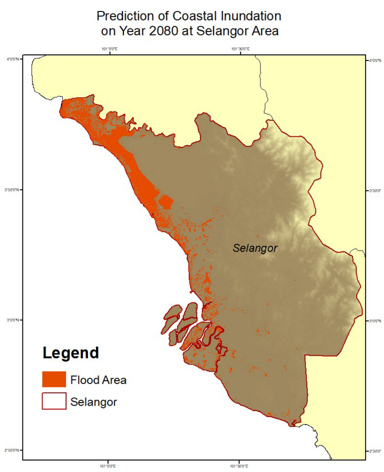

Figure 11. Prediction of inundation area at Selangor coastal in the year 2080 with an increment of sea level rise by 0.3024 m

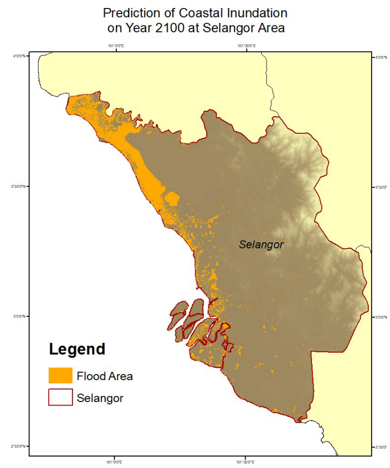

Figure 12. Prediction of inundation area at Selangor coastal in the year 2100 with an increment of sea level rise by 0.3955 m

The predicted values of the area to be inundated are depicted in the figure above based on the magnitude of sea level computed at the latitude and longitude coordinates of Selangor coastline. The area that will be affected by flooding for every 20 year in the future will experience a sea level rise of 0.09 m. What can be concluded from this is that sea level continues to rise faster and higher than expected, which predicted by the sea level and climate change forecasters like IPCC. Referring to the projection made in the Selangor area from 2040 to 2100, the sea level is estimated to increase by 0.09 m for every 20 year. According to the IPCC, sea levels are unlikely to exceed 1 meter by 2100. However, based on a researcher from the University of Copenhagen’s Niels Bohr Institute, he stated that sea levels will rise sharply by 1.35 m by 2100 (McVeigh, 2021).

3.5 Evaluation of the Potential Coastal Inundation at Pelabuhan Kelang Areas

Globally, the sea level has been rising continuously. According to the studies of more than 100 researchers, the seas rising rate is faster than previously thought, and it could reach one metre by the turn of the era if global emissions are not reduced. The IPCC (2021) stated that the global sea level has increased from 2.4 to 3.8 mm/year. In contrast, the study by NAHRIM on the impact of the rising sea level in Malaysia in 2010 indicated that in comparison to sea level rise patterns from the preceding two decades, sea level rise trends in the current two decades had increased substantially.

A study by Ehsan et al. (2019) has determined the annual rise in sea level at 30 tide gauge stations in Malaysia is between 2.73 to 7.00 mm/year (1993 to 2010). Figure13 shows that the sea level rise in the Kuala Selangor area is higher than the sea level rise around the Klang area in year 2040. As Kuala Selangor consist of natural resources, it is more prone to the impact of sea level rise leading to the flooding of low-lying areas of the coastal zone. This is because, among the main causes of coastal inundation are sea level rise, erosion, wetland changes, saltwater contamination of surface and groundwater, and increase groundwater surface (McLeod et al., 2010; Nicholls, 2011; Brown et al., 2013; Wong et al., 2014; Jamaluddin et al., 2016; Mucerino et al., 2019; Hamid et al., 2019; Hamid et al., 2021).

Figures 13 to 16 show the significant differences in flooded areas in 2060, 2080, and 2100. Due to the melting of ice, experts advise coastal communities to be prepared to face the effects that will occur sooner than expected as the sea level rise could reach 5 m by 2300 (Watts, 2020).

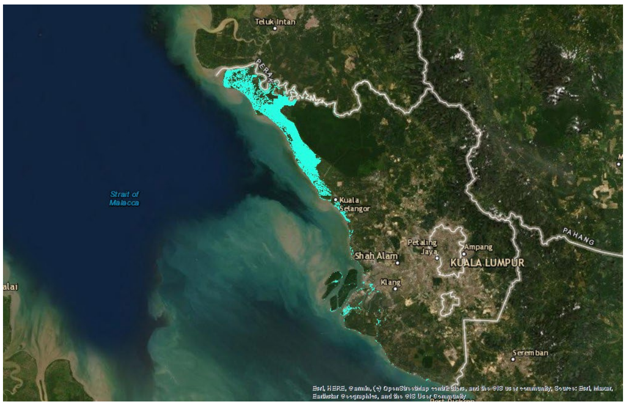

Figure 13. Expected flood areas around Selangor in 2040

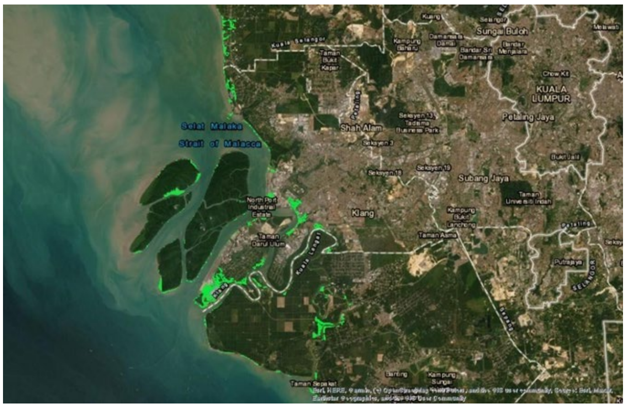

Figure 14. Expected flood areas around Klang in 2060

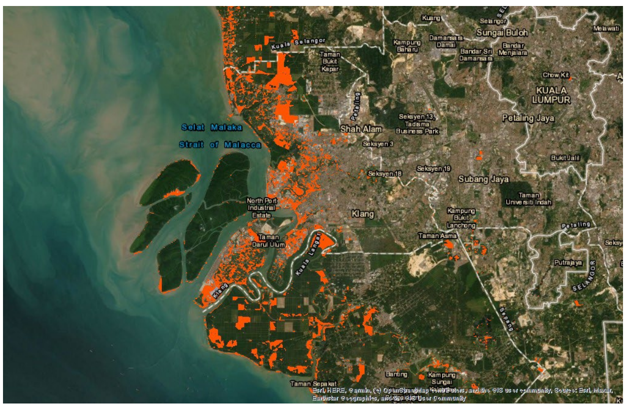

Figure 15. Expected flood areas around Klang in 2080

Figure 16. Expected flood areas around Klang in 2100

4. CONCLUSION

In the 21st century, the sea level along Malaysian coastline is projected to rise rapidly and reach significantly higher levels. Therefore, this study is conducted to forecast the sea level rise patterns along the coast of Selangor using robust fit regression method. The anticipated sea level patterns in the study region from 2040 until 2100 indicate that the rate of sea level rise is accelerating. The sea level around the shoreline of Selangor is projected to increase by 11.63 cm, 20.94 cm, 30.24 cm, and 39.44 cm in 2040, 2060, 2080, and 2100, respectively. In the 21st century, the highest rise might reach 39.55 cm. This work demonstrates a simulation model to generate inundation maps based on the land area affected by various sea-level rise magnitudes. The maps are generated using ArcGIS software. The findings from this study are expected to provide better comprehension to authorities and coastal communities of how the coastline will change in the future and how global and regional rising sea levels will affect us. However, it is difficult to minimise the damage induced by rising sea levels without a detail future map of susceptible coastal floods. Consequently, inundation has been considered as the most damaging natural disaster, although it is in slow phases. Therefore, authorities should have comprehensive plans and preventive measures to mitigate the effects of coastal flooding.

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