



Effect of projected sea level rise on the hydrodynamic and suspended sediment concentration profile of tropical estuary

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ABSTRACT

Kuala Pahang, an estuary located in the East Coast of Malaysia is projected to experience a 0.03, 0.14 and 0.31 m increase in sea level in the years 2020, 2060 and 2100, respectively. To predict how tide and current speed affect suspended sediment concentration, the MIKE 21 HD and ST models were used to simulate the hydrodynamics and sediment transport at Kuala Pahang. The study is limited to the Southwest Monsoon period and the model was conducted as a localised analysis at the Kuala Pahang estuary. The results of hydrodynamic modelling of 2014 baseline showed the difference in water level between spring and neap tide had influenced the current speed as the maximum flow velocity varies between 0.20 and 1.95 m/s. The Southwest Monsoon affects current flow in two ways, namely through the sea dominated flood tide and through river discharge during ebb tide. Meanwhile rising in sea level had increased 10% of the current speed in year the 2060 based on the 2014 model. Sediment transport modelling showed that the averaged suspended sediment concentration (SSC) fluctuated between 55–1532 mg/l in the year 2014 and could reach a maximum value up to 5091 mg/l in the year 2100, even with an increment of only 0.10 m/s maximum current speed. The profound impact of SLR on hydrodynamics and SSC is significant at the Kuala Pahang estuary and has a direct impact on the socio-economic and livelihood of local communities. This projection model can provide an effective management for the sustainability of estuary ecosystem and is relevant for understanding future hydrodynamic and suspended sediment patterns.

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1. Introduction

The issue of climate change which leads to sea level rise (SLR) has a significant impact not only engineering design and community livelihood but also the morphology of coastal area and the ecosystem of water column (Zhou et al., 2013). Globally, the average SLR is estimated to be 0.17 m in the 21st century with an increment of 1.80 mm/year, although a sudden increase of 3.10 mm/year was observed between 1993–2003 (IPCC, 2007). The Peninsular Malaysia however, is projected to have a higher SLR in the 21st century, an increment between 0.25–0.50 m in a time scale of 90 years (Awang and Hamid, 2013). SLR caused an imbalance in estuaries and had a significant impact on the evolution of coastal morphology (Wegen et al., 2010). Moreover, with a projected increase of 0.30 m in SLR in the year 2050, a

subsequent increase of 20% in tidal current and 28% discharge are expected in a meso-tidal estuary (French, 2008). As a result, erosion and deposition processes, as well as inundation of low-lying areas are expected to occur, and these events are highly likely to be even worse with the energy from tidal current (FitzGerald et al., 2008; Passeri et al., 2015a).

The effects of hydrodynamics on estuarine sediment pattern and processes have received attention including the effect of tidal forcing on subterranean estuary (Robinson et al., 2007), sediment behaviour of a small estuary (Uncles et al., 2014). Furthermore, the dynamic asymmetry of tidal range in a macro estuary tend to create sediment accumulation (Toubanc et al., 2015). Despite exhaustive research and studies, an in-depth understanding of the impact of tidal dynamic on the behaviour of sediment transport has yet to be gained due to the complex estuarine hydrodynamics (George et al., 2006; Sánchez et al., 2014; van Maren et al., 2015). Moreover, SLR is expected to be more likely to alter sediment pattern as current speed and tidal prism also are affected by higher

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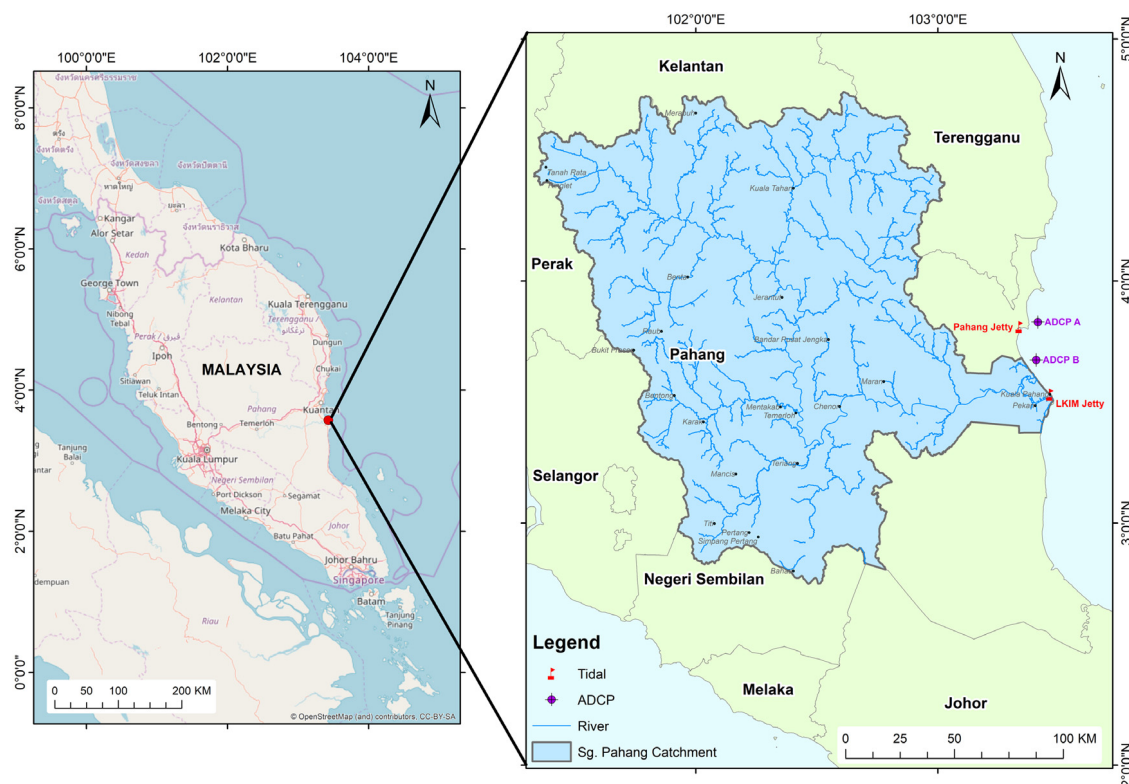


Fig. 1. Pahang River basin, Malaysia. The zoomed image shows the Sungai Pahang catchment area and the location of observation data of tides which are in Pahang Jetty and LKIM Jetty (marked in red colour), and the current speed (namely ADCP A and ADCP B) from Kuantan to the focus area of Kuala Pahang (marked in purple)

SLR. Even so, adverse findings were observed in the work of Ali et al. (2013), where they found with an increase of 0.20 m in sea level, a 10% reduction in the total SSC is predicted. Subsequently, total suspended sediment decreased up to 13% with a 0.50 m rise in sea level. It seems that the effect of SLR could either cause an increase or decrease in suspended sediment concentration in the water column. Nonetheless, SLR is expected to have an impact on estuary system with regard to socio-economics, navigation, and biota system. A sustainable and healthy estuary ecosystem is crucial to increase the production of food supply and preserve the economy of local coastal communities.

About 10% of the world population is faced with serious threat brought by SLR; most of them live in low-lying areas within 10 m elevation from the mean sea level. This includes those in the Asian region, specifically Bombay, India; Shanghai, China; Jakarta, Indonesia; and Bangkok, Thailand (FitzGerald et al., 2008). At the same time, mangrove deforestation is of a real concern in a 300 m strip of Malaysian mangrove area, where it is expected to be lost due to the 0.90 cm/year increase in SLR (MOSTE, 2000). This could alter the morphology of the river mouth and biota system and, most importantly, the natural protection system of the coastline will be compromised. Mangrove acts as a nursery ground for the ecosystem in addition to providing security to humans from most environmental changes (Alongi, 2015). SLR could cause a change in the hydrodynamics and landscape of the coastal area (Passeri et al., 2015a, b).

Even though the effect of SLR on the hydrodynamic and morphology of estuary has been extensively studied, little attention has been given to the potential hydrodynamic and SSC changes in tropical countries. Continuous heavy rainfall during the Northeast Monsoon significantly increased the river flow discharge and subsequently brought higher SSC into the estuary system (Zakariya, 2013). However, the effect of hydrodynamic during monsoon is also significant in mobilising the sediment either from the sea to

the river mouth or vice versa, which is often overlooked. Therefore, this study aims to evaluate the potential impact of sea level rise on hydrodynamics and suspended sediment concentration in Kuala Pahang by using the MIKE 21 software during the Southwest Monsoon season. Hence, the focus of this study is twofold; first, the analysis focuses on the development of the baseline model based on the marine data collected in 2014. Secondly, a projection of how SLR will influence the hydrodynamics and SSC in the years 2020, 2060 and 2100 is made. The results of the simulated model could indicate potential erosion and deposition area by giving the total load magnitude and direction and the rate of change at the bed level (Chee et al., 2014).

2. Methodology

2.1. Study area

Pahang River is the longest river in Peninsular Malaysia and is 459 km long (Gasim et al., 2013) with a 29,137 km² catchment area (Kar, 2014). It flows from the Titiwangsa Range to Kuala Pahang, as shown in Fig. 1. Located at latitude 3° 31' 50.4" N and longitude 103° 27' 44.0" E, Kuala Pahang receives 1755.24 tons/km²/year suspended sediment concentration and is significantly affected by the two monsoon seasons, namely the Northeast and Southwest Monsoons (Toriman et al., 2010). In addition, NAHRIM (2010) projected that the sea level rise in Pahang waters will be the third highest in the East Coast of Malaysia after Kelantan and Terengganu, and is projected to reach up to 0.31 m in the year 2100.

In predicting the morphological changes caused by the effect of sea level rise, three projection years of 2020, 2060 and 2100 were analysed. NAHRIM (2010) projected that the sea level will increase by 0.03 m in 2020, 0.14 m in 2060 and 0.31 m in the year 2100 respectively.

Table 1
Location of ADCP and tidal data measurement.

Location	Latitude	Longitude
Location of ADCP		
Pahang ADCP A	3° 49' 49.0" N	103° 24' 47.3" E
Pahang ADCP B	3° 40' 25.4" N	103° 24' 23.6" E
Location of tidal data measurement		
LKIM Jetty	3° 31' 50.4" N	103° 27' 44.0" E
Pahang Jetty	3° 48' 35.6" N	103° 20' 09.8" E

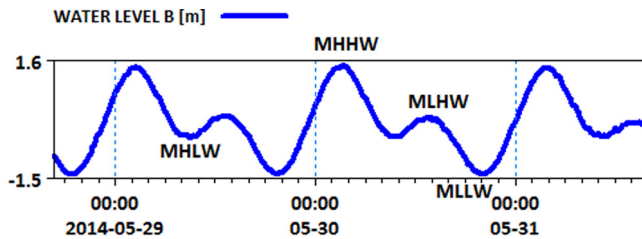


Fig. 2. Measured data of mixed semidiurnal tides in Kuala Pahang at LKIM Jetty, located at the river mouth of Pahang River.

2.2. Data collection

Collection of bathymetry, current, and tide data, as well as soil samples data, were conducted by trained personnel and technicians from the National Hydraulic Research Institute Malaysia, (NAHRIM). The measurement campaign was done for 15 days between 23rd May 2014 and 7th June 2014, covering one complete neap and spring cycle. Data were collected along the 15 km shoreline from Kuantan to Kuala Pahang (as shown in Fig. 1), including the estuary area. Single beam bathymetry surveys were conducted from Beserah, Kuantan to Kampung Alur Pasir, Kuala Pahang for 2 weeks. Data were collected in a 250 km² study area with an extension of 5 km from shoreline seaward. The bathymetric point data were gridded to 3 m from shoreline to sea and 500 m point to point from south to north of shoreline for bedform analysis.

Table 1 shows the location where the current speed and tidal data was collected during the field work measurements. Current speed data was collected at two locations using Acoustic Doppler Current Profiler (ADCP), here shown in Fig. 1. Velocity configuration and current direction were set at a time interval of 10 min. Tidal data was collected in two locations using the 520P Aquatec meter water logger based on the mean sea level datum at a 10-min interval. The shoreline area from Kuantan to Kuala Pahang is exposed to mixed semidiurnal tides which experienced two high and two low tides of different heights in a day. The maximum tide level during Mean Higher High Water (MHHW) is 1.4 m and the lowest tide is −1.4 m during Mean Lower Low Water (MLLW) from the mean sea level. The maximum tidal range is approximately 2.8 m during MHHW and MLLW events while during MLHW and MHLW, the variation in tidal range is lower and varied between 1.00 m and 1.20 m. The mixed semidiurnal tides are as shown in Fig. 2. Bed samples were taken at a depth of 10 cm from bed surface using a 20 kg grab sampler. The sediment in Kuala Pahang is predominantly sand which comprises 53.7% of the sediment mixture; as such, the MIKE ST module was adopted to simulate sediment transport model. A mean sediment size of 0.20 mm, obtained from particle size distribution analysis (of the collected surficial bed samples at the estuary) was used in the model.

2.3. Model configurations and boundary conditions

2.3.1. Model computational grid, bathymetry and initial conditions

Recall that this study focused only on the estuary mouth area of Kuala Pahang and analysed the hydrodynamic characteristics

due to the projected sea level rise during the Southwest Monsoon. To study the potential impact of SLR on morphological changes in the study area, the model domain includes the area from Kuantan to Kuala Pahang by taking into consideration the effect of hydrodynamics from the South China Sea. The land elevation and bed morphology of the study area, where low-lying areas in Kuala Pahang are 2.50 m below the mean sea level. The model includes bathymetry data as well as terrain data of land (from Kuantan to Kuala Pahang) provided by the Department of Survey and Mapping Malaysia, (JUPEM).

The model used interpolated bathymetry generated from a combination of fieldwork bathymetry data with electronic admiralty charts (C-map) in MIKE ZERO. The tidal elevation was specified on the open boundaries of the model, which consist of global tide data and was applied over the entire model domain. The hydrodynamic simulation was run for 30 days with a time step interval of 60 s, and the model frequency was set to store simulated results at a 10-min interval. The numerical solution of MIKE21 is two dimensional incompressible of Reynolds averaged Navier–Stokes equation thus, the model consists of continuity, momentum, density, and turbulence equations. The parameters setting used for the hydrodynamic simulation in MIKE21HD (HydroDynamic) are shown in Table 2. The mean size of sediment and settling velocity were set as control parameters of sediment properties in MIKE21 ST (Sediment Transport). In this model, based on the mean grain diameter, d_{50} which is 0.2 mm, porosity of 0.40, relative density of 2.65 and degrading coefficient of 1.10 were used.

2.3.2. Model calibration and validation

Parameters of water level, current speed, and current direction were used for calibration and validation. The flow, current speed, and current direction model showed good results with the measured fieldwork data. Fig. 3(a), (b) and (c) show the calibration output, whereas Fig. 4(a), (b) and (c) show the results of the validation. The calibrated model has a bottom roughness range between 0.005 and 0.020. The statistical parameter of Root Mean Squared Error (RMSE) was calculated for water level, current speed, and direction for both calibration and validation models. RMSE values for calibration model were 7.50 (water level), 15.52 (current speed) and 13.82 (current direction), whereas RMSE for validation model were obtained at 8.62 (water level), 13.50 (current speed) and 15.75 for current direction, respectively.

2.3.3. Projection modelling

Numerical model provides established trends and projection of future scenarios, particularly when SLR is of concern (Pereira et al., 2013). As such, prediction of SLR's impact on the hydrodynamics and SSC in Kuala Pahang provides a useful and holistic picture of future local coastal scenario, particularly for years 2020, 2060 and 2100. The projection model was done by increasing SLR by 0.03, 0.14 and 0.31 m for 2020, 2060 and 2100, respectively. Further analysis is discussed in Section 3.2.

3. Results and discussion

3.1. Tide and current speed in 2014

In this study, the tidal effect was investigated based on the tidal range and tidal current. A difference in tidal range will result in a different pattern of sediment transport, which will lead to accumulation and erosion in locations where equilibrium of sediment supply from the sea to the estuary is affected by tidal asymmetry (Kirwan and Guntenspergen, 2010). In this section, the tidal and current speed is discussed for different tides in each flood and ebb situation. Figs. 5 and 6 show the temporal and spatial changes in current speed at different water levels during the measurement

Table 2
Parameters setting in the model.

Parameter	Type	Value	Recommended value
Solution technique	Low order fast algorithm	CFL 0.9	CFL < 1
Flood and dry	Drying depth	0.005 m	Default
	Flooding depth	0.05 m	$H_{dry} < H_{flood} < H_{wet}$
	Wetting depth	0.1 m	
Eddy viscosity	Smagorinsky formulation	0.28 m ² /s constant	Default
Bed resistance	Manning number	25–60 m ^{1/3} /s	20–40 m ^{1/3} /s
Wind forcing	Constant	9 m/s, 60°	NCES 1985
Boundary condition (BC)	BC 1	Land	
	BC 2–4	Global tide model	

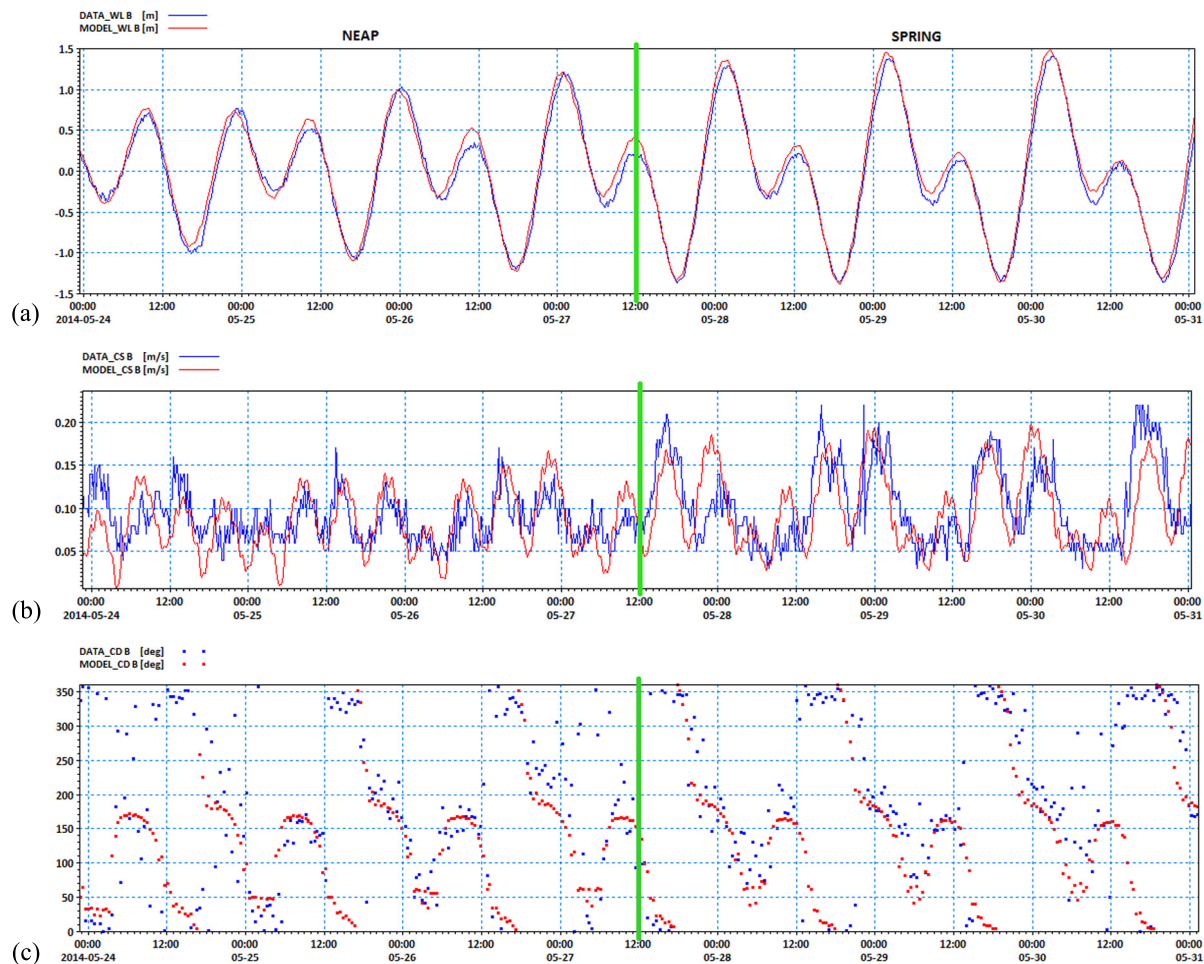


Fig. 3. Performance of calibrated model with measured data for (a) water level at LKIM Jetty, (b) current speed, (c) current direction at ADCP B data during neap and spring tide. The blue and red solid lines and points represent model output and measured data, respectively. Meanwhile, the green line acts as the separator to visually distinguished between neap and spring. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

period of spring tide. Meanwhile, Figs. 7 and 8 show the temporal and spatial changes during neap tide. The tidal current in the South China Sea flows in the northeast direction of Kuala Pahang into the estuary mouth during flood tide (Fig. 5). The high-intensity current speed in the estuary during higher high water, HHW, and transition between lower low water, LLW to HHW, covered the entire estuary mouth as shown in Fig. 5(a) and (c). Fig. 5(b) and (d) show a slack tide which occurred during lower high water, LHW, and transition period from higher low water, HLW to LHW. The tidal current flows from the river towards the sea during ebb tide (as shown in Fig. 6). From the analysis of Figs. 5 and 6, it is clear that a strong tidal current speed during HHW was observed ranging from 0.67 m/s to a maximum of 1.83 m/s, while LHW flood current shows a much lower maximum current speed between 0.30 to 0.45 m/s.

The Southwest Monsoon influenced the domination of ebb current during HLW and LLW, where the flow velocity ranged between 0.67 and 1.30 m/s. The detailed current speed during both HHW and LHW events (covering neap and spring tides) is presented in Fig. 9 which will be discussed later.

Based on the spatial analysis result from Fig. 7, the current speed intensity is high during the transition between LLW to HHW at the river mouth (Fig. 7(d)). However, the current speed during neap tide shows the current speed is consistently high for all four different situations. This is due to the water level during neap tide is low with a tidal range of 2 m (as shown in Fig. 7). Meanwhile, Fig. 8 shows the current pattern and magnitude during neap tide for low and ebb tide situations. The current speed of Fig. 8(a) and (b) during HLW and LLW respectively, were found varied between

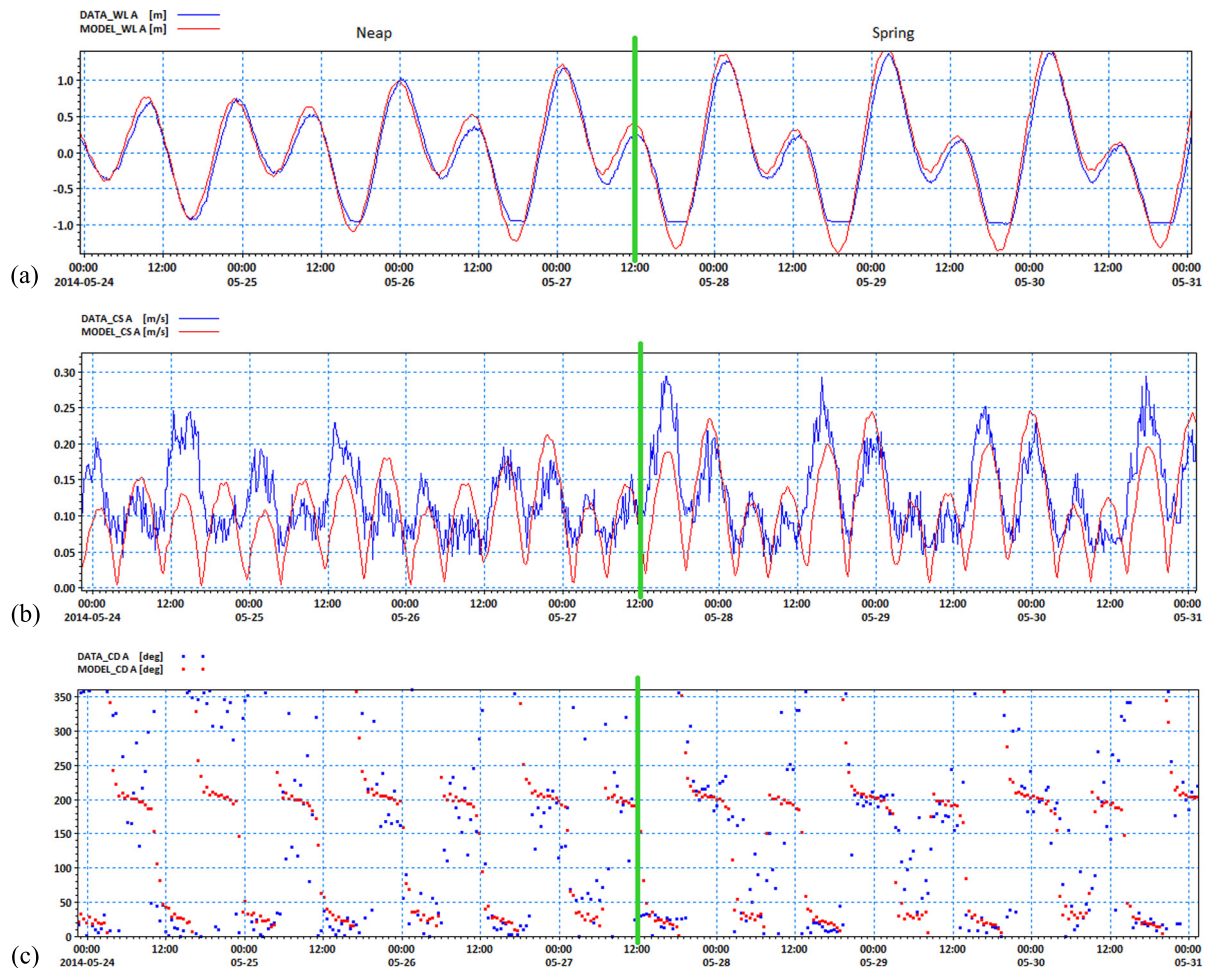


Fig. 4. Validation model with measured data for (a) water level at Pahang jetty, (b) current speed, and (c) current direction at location ADCP A during neap and spring tide. The blue and red solid lines and points represent model output and measured data, respectively. Meanwhile, the green line acts as the separator to visually distinguished between neap and spring. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.40 to 1.00 m/s. However, the current speed during the transition from HHW to HLW (Fig. 8(c)) increased to a higher range of 1.00 to 1.80 m/s, although the current speed during LHW to LLW has a similar value with HHW to HLW, the intensity of current speed was visibly observed at the middle of the river mouth as shown in Fig. 8(d). The obtained tidal profiles during neap and spring tides showed and proved that the neap tide had higher current speed compared to the spring tide even though with lower tidal range.

Figs. 6 and 8 showed that ebb current dominates in all situations with high intensity of current speed. This is due to the difference in water column depth and the profound effect of river discharge during ebb tide. Significantly, with a decrease in depth, current speed produced higher turbulence intensity which promotes the increased concentration of suspended matter in the water column (Bolaños et al., 2012). The mixed semidiurnal tide resulted in different current speed during neap and spring tides.

Model analysis demonstrated that the maximum current speed lies in between of 1.60 m/s to 2.00 m/s occurs in the middle of the river mouth, here shown in Fig. 9. Data evidently showed that the maximum current speed at three different locations inside the river mouth occurred during the spring tide. The averaged current speed is only 50% of the maximum speed. However, current flow is high during the Southwest Monsoon for both flood and ebb tides. Even though the hydrodynamic influence is not as profound during the Northeast Monsoon, ebb current is significantly high due to shallow water depth at the river mouth. Based on the Hjulstrom chart, it is expected that the area will experience deposition and

sediment suspension in the water column at 0.10 to 0.20 m/s current speed. However, at a higher maximum current speed of 1.80 to 2.00 m/s in the area, finer sediment is expected to be entrained and transported to the sea.

3.2. Impact of sea level rise

The simulation of SLR scenarios was generated by increasing the SLR rate for each SLR scenario based on the 2014 baseline model. Due to the complexity and dynamic activities in the estuary system, the projection of SLR significantly increased the tidal level and current speed (Kuang et al., 2014). Furthermore, direct inundation and erosion due to sea level rise resulted in sediment transport and morphological changes of estuaries (Wetzel et al., 2012). The effect of SLR on current speed and suspended sediment will be discussed in the following section. As the hydrodynamic directly influenced the behaviour of sediment transport, the discussion starts with characteristics of current speed.

3.2.1. Current speed

Fig. 10 shows the difference in residual maximum current speed calculated between the predicted values for the years 2020, 2060, and 2100. The residual maximum current speed was chosen to immediately show the change in speed for the projected years. For the year 2020, the model shows that the 0.03 m increase in sea level resulted in an increase in current speed at the river mouth to 0.85 m/s and can be reached up to 1.80 m/s. Data shows that the residual

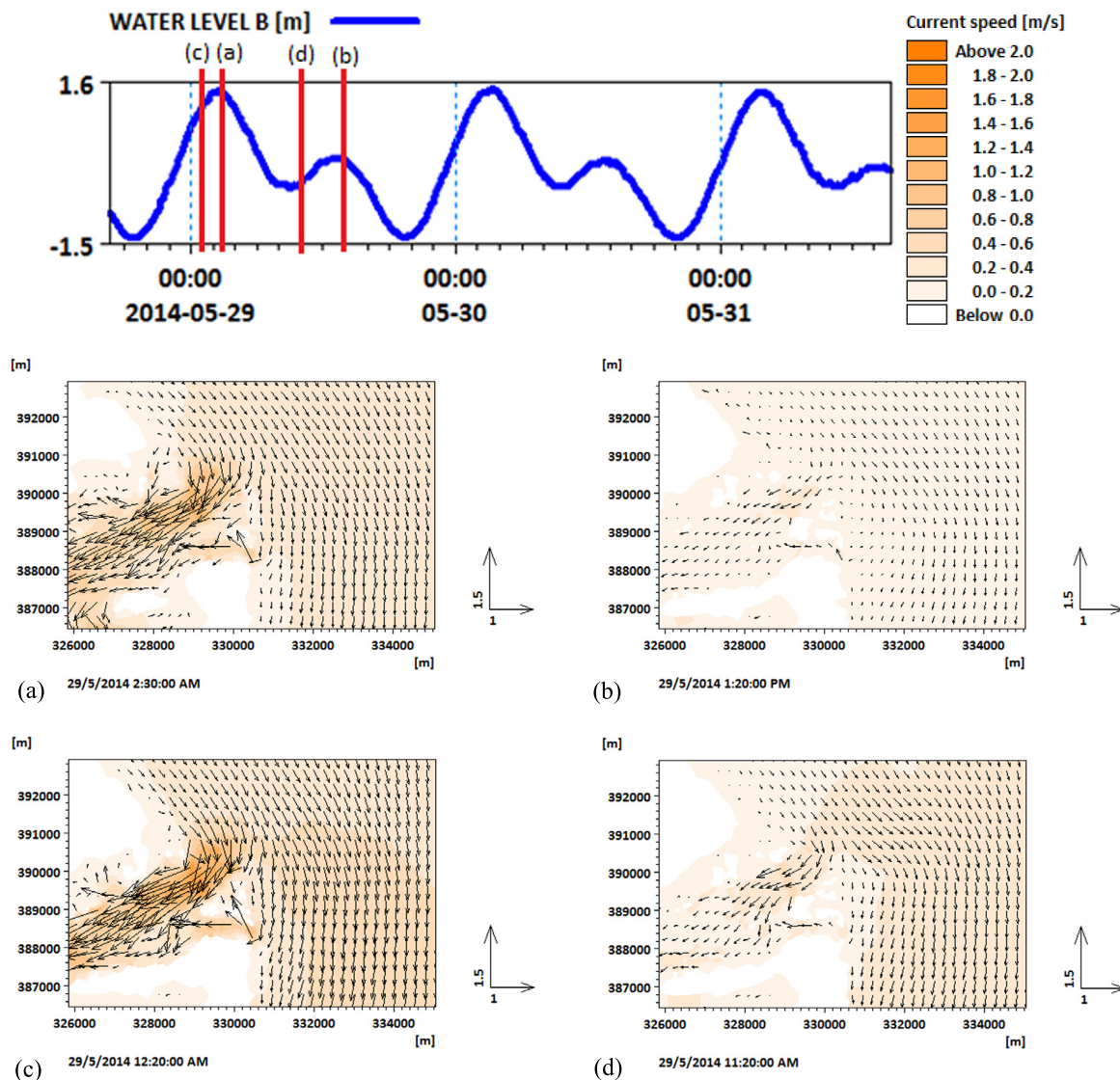


Fig. 5. Current pattern and magnitude in a mixed semidiurnal tidal cycle during spring tide; (a) and (b) during high tide, (c) and (d) during flood tide. The solid line shown at the water level plot represents the time position associated with the velocity vector plots. The arrow scale shows the maximum current speed of 1.5 m/s for all figures including Figs. 6–8.

current in the study area varied and ranged between 0.01 to 0.05 m/s. The residual current speed in the middle of the river mouth ranged between 0.01 and 0.04 m/s, which is 0.63% to 4.38% higher than the maximum current speed obtained for the year 2014. Subsequently, on a smaller temporal scale, a 0.03 m rise in sea level resulted in a less significant change in the current speed. However, suspended sediment could still be transported, especially during ebb tide. As the depth of the water column decreases, the speed increases and becomes strong enough to mobilise the particles and create suspension events.

For the year 2060, the residual maximum current speed considerably changed (due to the rise of 0.14 m in water level), which varied between 0.20 and 0.88 m/s. Note that this is a 10% increase from the baseline 2014 model. In general, SLR increased the residual current speed in the estuary mouth, although some of the area marked green which indicate a decrease in current speed (see Fig. 10(b)). It is speculated that this could be due to the increase of depth in that area, where erosion occurred due to the equilibrium in the conservation of mass in the sediment transport process and water column for sediment below than 0.20 mm.

The change in maximum current speed between the years 2014 and 2100 is shown in Fig. 10(c). Interestingly, the figure shows a

similar pattern to the profile obtained for the year 2020. However, the residual maximum current speed (see Fig. 10(c)) within the estuary area showed a different set of results where the speed increased by approximately 0.04 m/s or more. Thus, the increase in SLR resulted in either a spatial increase or decrease in the current speed. Fig. 10(c) also illustrates the change in morphology due to the wide range of temporal scale, where the land area and the nearby island will be inundated. The data shows a significant increase in current speed due to SLR. The rise in the maximum current speed showed that ebb tide dominated the process and that current flow was higher during ebb tide in comparison to flood tide. Furthermore, the current is more ebb dominant with an increase of 0.05 m/s in tidal velocity.

3.2.2. Suspended sediment concentration

With regard to suspended sediment concentration (SSC), it was observed that there is a linear relationship between current speed and suspended sediment concentration as a result of an increase in SLR. The increase in current speed in each projection creates maximum turbidity by decreasing the depth of river mouth (shown in Fig. 11). The maximum turbidity, in turn, creates a trapping

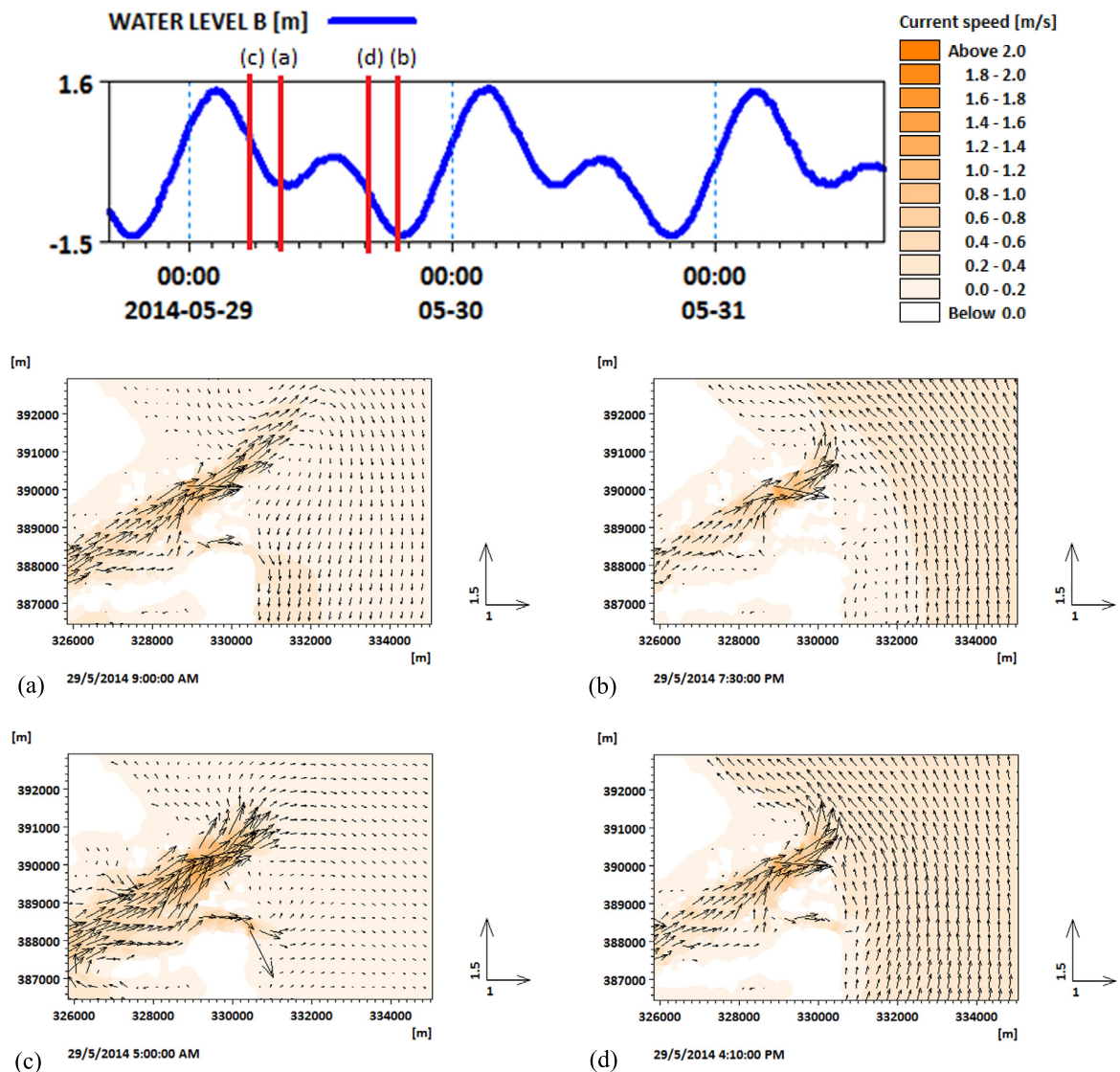


Fig. 6. Current pattern and magnitude in a mixed semidiurnal tidal cycle during spring tide; (a) and (b) during low tide, (c) and (d) during ebb tide. The solid line shown at the water level plot represents the time position associated with velocity vector plots.

system in the water column where SSC is higher in the upper and middle reaches of river mouth (Kim and Voulgaris, 2008; Wu et al., 2012). Fig. 11(a) shows that the suspended sediment concentration is between 55 and 800 mg/l and can reach up to 2000 to 5000 mg/l in 2014. Although spatial results from Fig. 11(b) and (c) indicate that the suspended sediment concentration is increasing with SLR for both projection years, higher concentration and distribution of suspended sediment was found at the river mouth for the year 2100 projection as shown in Fig. 11(c). The concentration showed a significant increase as current speed increased in each projection at 94.20%, 105.70% and 154.60% in the years of 2020, 2060, and 2100, respectively.

The results of the present study established that SLR actively induced hydrodynamic process, increased both current speed and turbulence intensity, which then caused an increase in SSC (as depicted in Fig. 11). Interestingly, this finding echoes the conclusion from the studies of Kim and Voulgaris (2008) and Nordstrom and Jackson (2012). Increasing water level subsequently affected the current speed and accelerates the suspension process (Nordstrom and Jackson, 2012). The interaction between horizontal current speed and turbulence velocities forced the sediment bed material and fine particles to be entrained in the water column, particularly

at the river mouth, creating maximum turbidity seaward (Kim and Voulgaris, 2008). Furthermore, SLR pushed the stratification layer further upstream of the estuary towards the river. The shear stress between the two layers of fresh and saline water in the water column increased, thereby increasing the turbulence. As a result, the amount of suspended sediment increases and remains suspended due to the high and consistent upward forces.

The relationship between the maximum current speed and SSC is shown in Fig. 12(a). It shows that while the maximum current speed remained the same for six years between the years 2014 to 2020, the increase in SSC is obviously high. The projections also showed that SSC increased slightly with an increase of 0.10 m/s in the maximum current speed in the year 2060. Similarly, for the next 40 years (from the year 2060), the SSC is projected to substantially increased even though the current speed remained the same at 1.90 m/s as projected in the year 2020. This indicates that the effect of SLR on estuary system is not only short term, but the effect might be on a long temporal scale.

Fig. 12(b) shows the averaged and maximum SSC rate for years 2060 and 2100. The SSC rate was obtained for a 40-year period (i.e. from 2020 to 2060 and 2060 to 2100). The analysis which was conducted based on the maximum SSC rate from the 2014

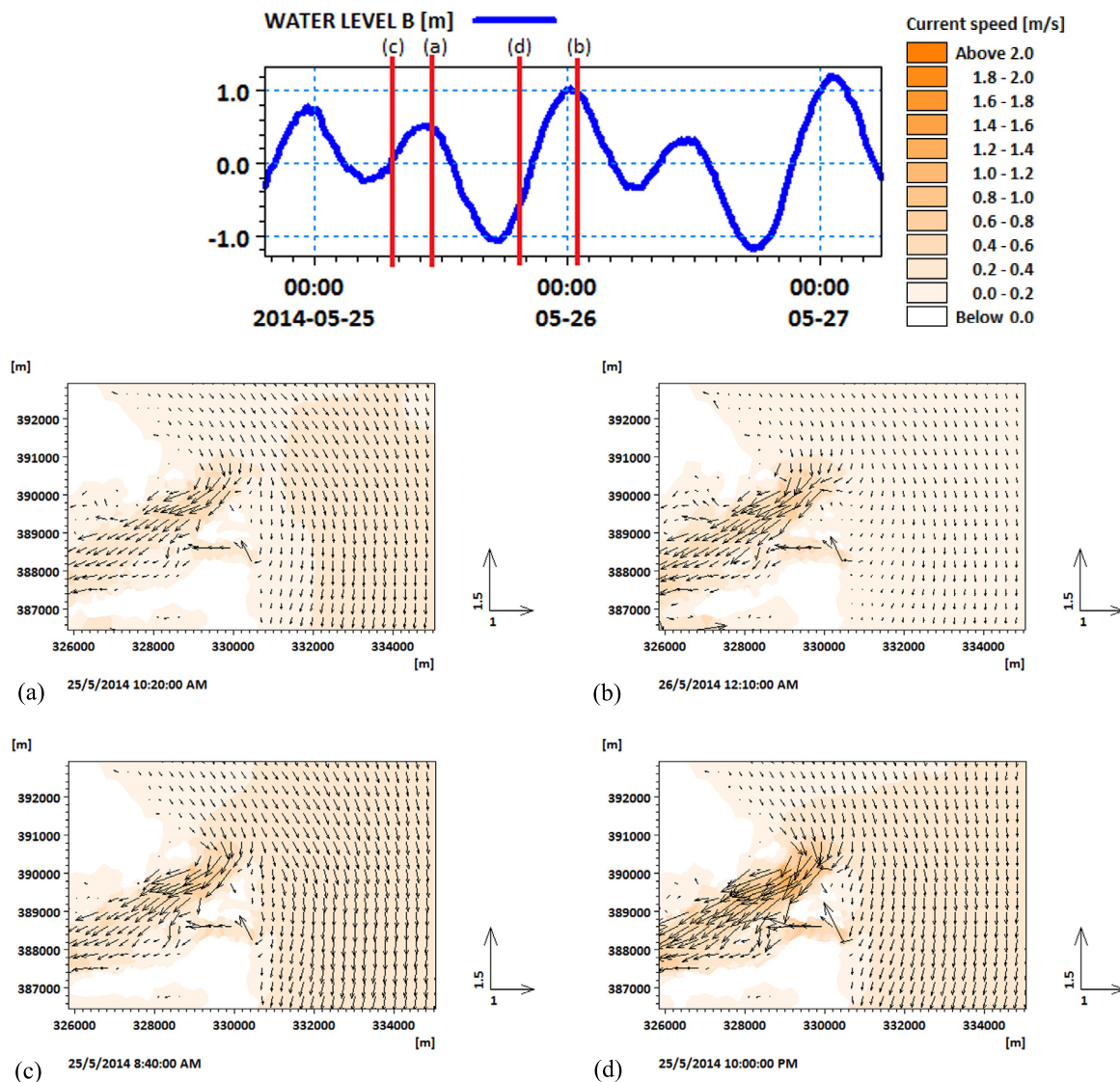


Fig. 7. Current pattern and magnitude in a mixed semidiurnal tidal cycle during neap tide; (a) and (b) during low tide, (c) and (d) during flood tide. The solid line shown at the water level plot represents the time position associated with velocity vector plots.

baseline showed in the year 2060, SSC dramatically increased from the averaged SSC (i.e. 11.54 mg/l/year) to a maximum SSC of 45.93 mg/l/year. The SSC rate for the year 2100 steadily increased from the averaged SSC of 17.17 mg/l/year to a maximum rate of 35.94 mg/l/year. The temporal scale used in the model to predict the SSC rate plays an important role where prediction from the baseline model in the year 2100 (an 86-year different) showed a lower SSC rate increment compared to when was calculated from the year 2060. Relatively, the SSC rate in the year 2060 (based on the 40-year time scale) showed that the maximum SSC rate (i.e. 5.75 mg/l/year) is 52.96% less than the averaged SSC rate (i.e. 12.23 mg/l/year). This could be related to the slight increase in maximum SSC (as shown in Fig. 7(b)) from the year 2020 to 2060, where the increment seems to be almost constant in each year. In the 21st century, the averaged and maximum SSC rate only showed a small variation, from 23.65 mg/l/year to 24.45 mg/l/year. Interestingly, the contrasting results for years 2060 and 2100 demonstrates that even with increasing sea level, SSC remains almost unchanged or only a small increase in the water column.

Meanwhile, Sarkar et al. (2014) studied the effect of SLR on the coast of Peninsular Malaysia and found that an increase in sea level of 0.20 cm/year and 0.50 cm/year is not significant for tidal

inundation. However, the result of this study shows a contrary impact. One reason for this could be that the previous simulated model was done on a big macro scale and was therefore unable to capture the localised effect. Sarkar et al. (2014) analysed the biophysical impacts caused by sea level rise in the year 2100 based on varying rates of increase, namely of 0.20 cm/year, 0.50 cm/year and 30.70 cm/year. The effect of such rates on SLR obtained from the macro scale model was compared with the results of the present study which adopted localised simulation. This finding is evidently in contrast with their work which reported no significant impact.

The acceleration in SLR in the 20th century has profound biophysical and socio-economic impacts on coastal population, ecosystem, and morphology of coastal zones. The analysis shows that SLR could potentially change hydrodynamic characteristics, the concentration of suspended sediment and bed morphology. SSC instantaneously increased in the water column with a higher current speed of between 0.02 m/s and 0.10 m/s. The results of this model indicate that the exchange between importing and exporting sediment into estuary mouth has increased SSC in the water column, which subsequently influenced the changes in estuary morphology.

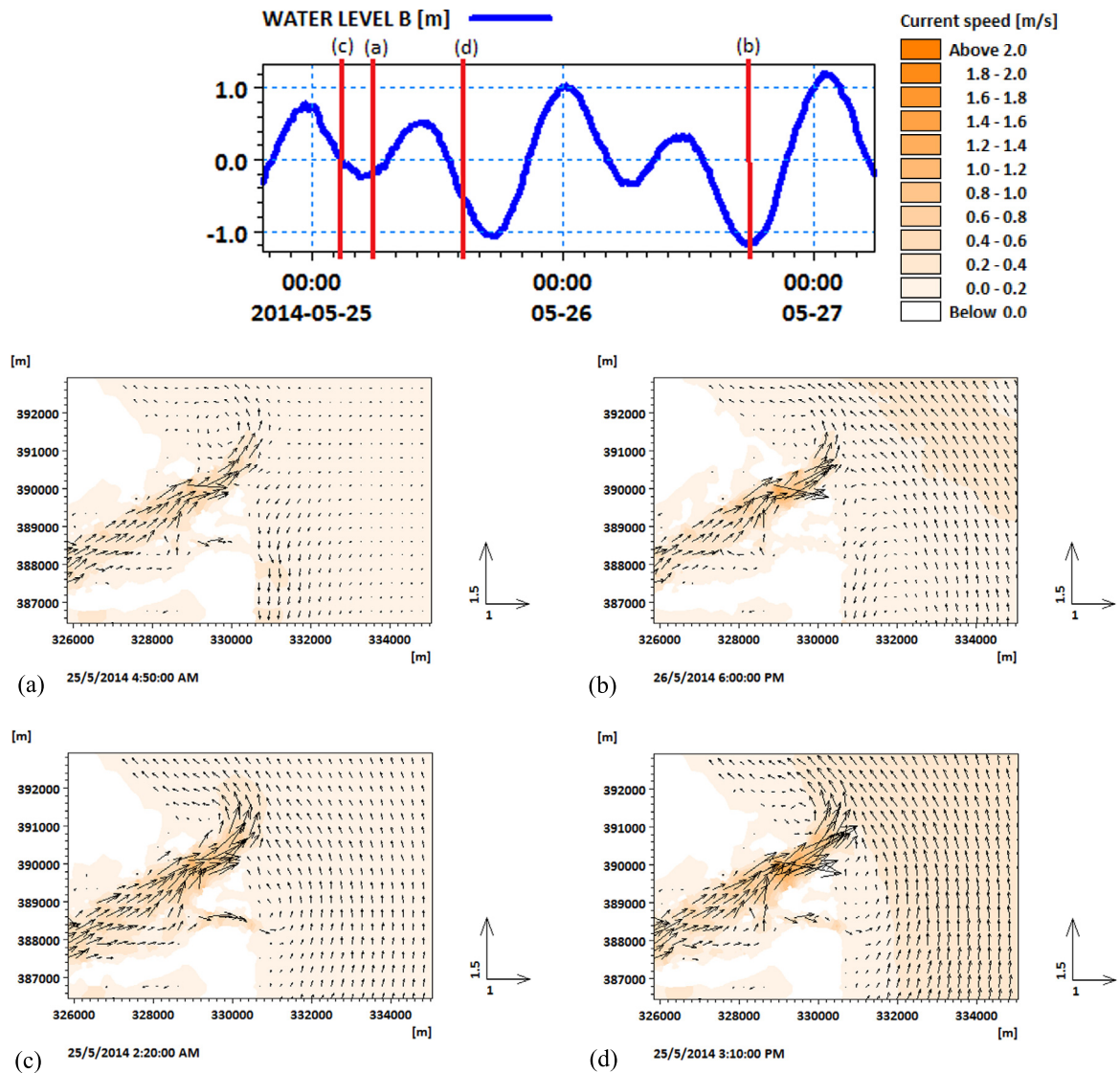


Fig. 8. Current pattern and magnitude in a mixed semidiurnal tidal cycle during neap tide; (a) and (b) during low tide, (c) and (d) during ebb tide. The solid line shown at the water level plot represents the time position associated with velocity vector plots.

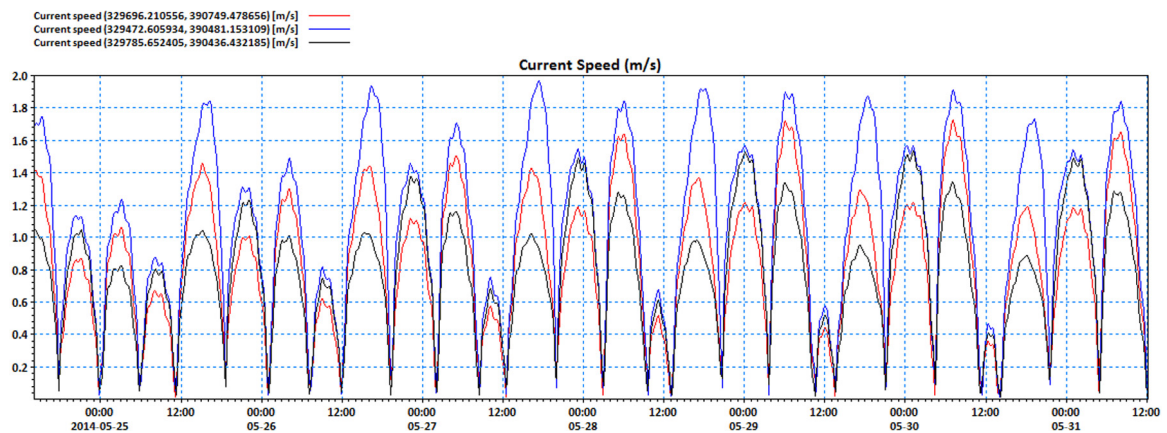


Fig. 9. The maximum current speed of 2014 baseline in the middle of the river mouth. The red, blue and black lines showed the maximum current speed at three different locations inside the river mouth. Meanwhile, the green line separates the neap (i.e. from 24th May till 27th May 2014) and spring tides (i.e. from 28th May till 31st May 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

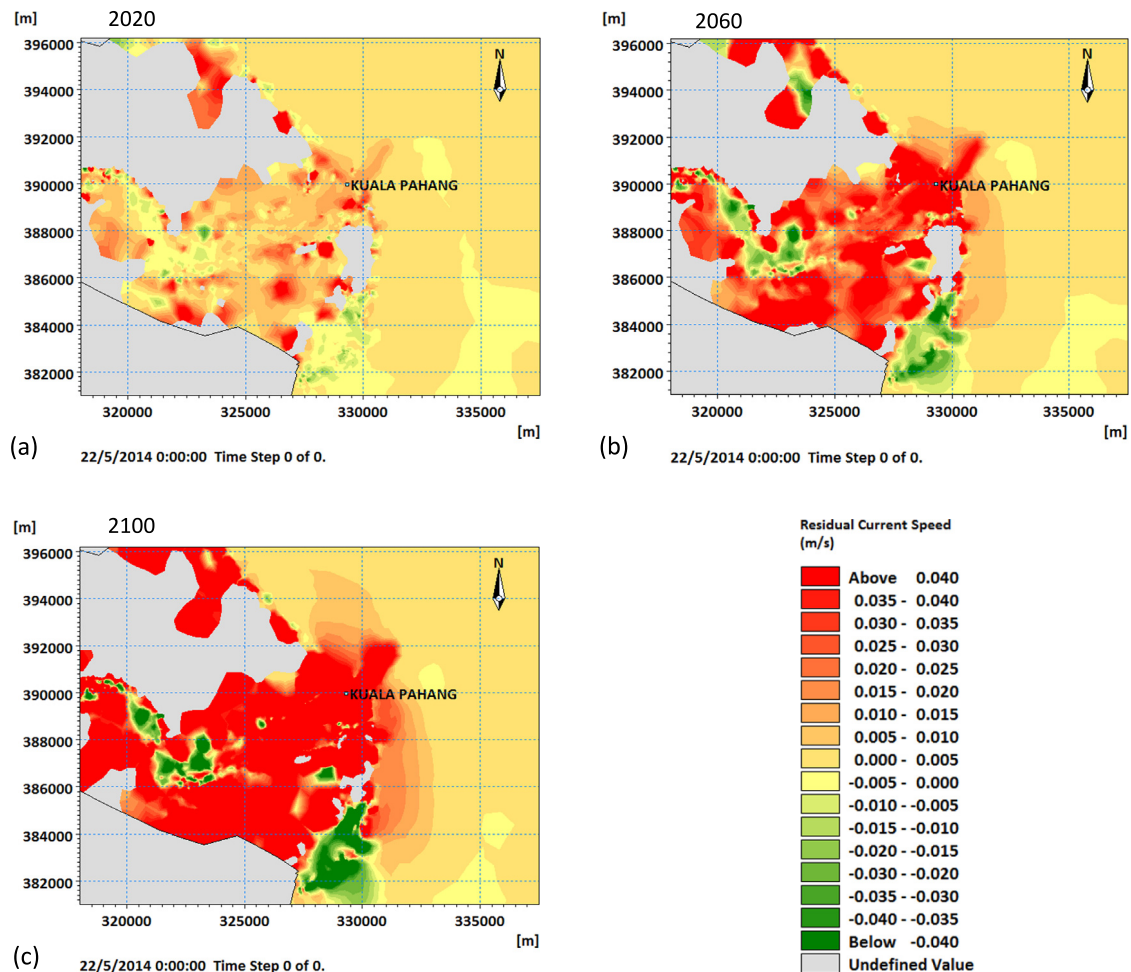


Fig. 10. Comparison of the projected maximum residual current speed (m/s) for years of (a) 2020, (b) 2060, and (c) 2100. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Results from this study showed that the ebb tide dominates the current speed and SSC distribution whereas flood tide too can be a major factor (Dissanayake et al., 2012; Van Maanen et al., 2013). Flood and low flow (during dry periods) also resulted in the SSC altering bed morphology by transporting finer particles (as erosion) or deposition (increasing the sediment volume). Furthermore, a rise in sea level changes the source of sediment in the estuary mouth where tidal current is not the only agent transporting sediment. Littoral transport too occurs and induced wave to attack erodible cliffs (Sorensen et al., 1980). The increase in water depth allows the wave and current to accelerate the erosion process further up landward, where the refraction from offshore wave brings alongshore-sediment transported into the estuary system. Passeri et al. (2015b) found that SLR influenced the tidal range, tidal prisms, surge height, and inundation process. They also found that tidal prism increased by 28% due to a 0.30 m rise in sea level. The influence of SLR towards the tidal range and current flow lead to a high possibility for the flood tide to be dominant. This possibility had been reported by Dissanayake et al. (2012) and Van Maanen et al. (2013), where sediment transport is dominant when the tidal range is less than 1.50 m. Ultimately the exporting process will turn into an importing process or vice versa. The effect of flood dominance may increase erosion since the boundary of the river mouth is shifted landward.

This study has shown that sea level rise not only changes the hydrodynamic process but also the behaviour of suspended sediment in estuaries. Moreover, it is expected that the socio-economic status of local communities will be affected since local coastal

areas, particularly low-lying areas, might become inhabitable as the sea advances closer to their homes.

3.3. Impact of SLR on coastal resources

The results of localised simulation showed adverse impacts in the increase of sea level at 0.31 m/year, which has a profound impact on tidal inundation especially at low-lying areas, including the areas in the estuary mouth. Furthermore, the ebb dominated tide in Kuala Pahang increased the potential for flooding and thus, accretion is expected as higher tidal current flows into the estuary. Based on Figs. 5–8 presented above in Section 3.2, the current speed direction is parallel to the shoreline which longshore current is occurring on the coastline. The presented figure showed the longshore current will be promoted the longshore transport either erosion or accretion during 2014 analysis. It is believed that with increasing of sea level it will increase the sediment longshore transport into the river mouth which in turn resulted in shallower depth in the estuary system. The rising sea level creates wider water boundaries due to the inundation effect, which may re-suspend the finer particles previously deposited in the area that used to be a floodplain.

4. Conclusion and recommendations

In this study, the result of numerical modelling to investigate the hydrodynamics and associated effect of SSC caused by SLR at

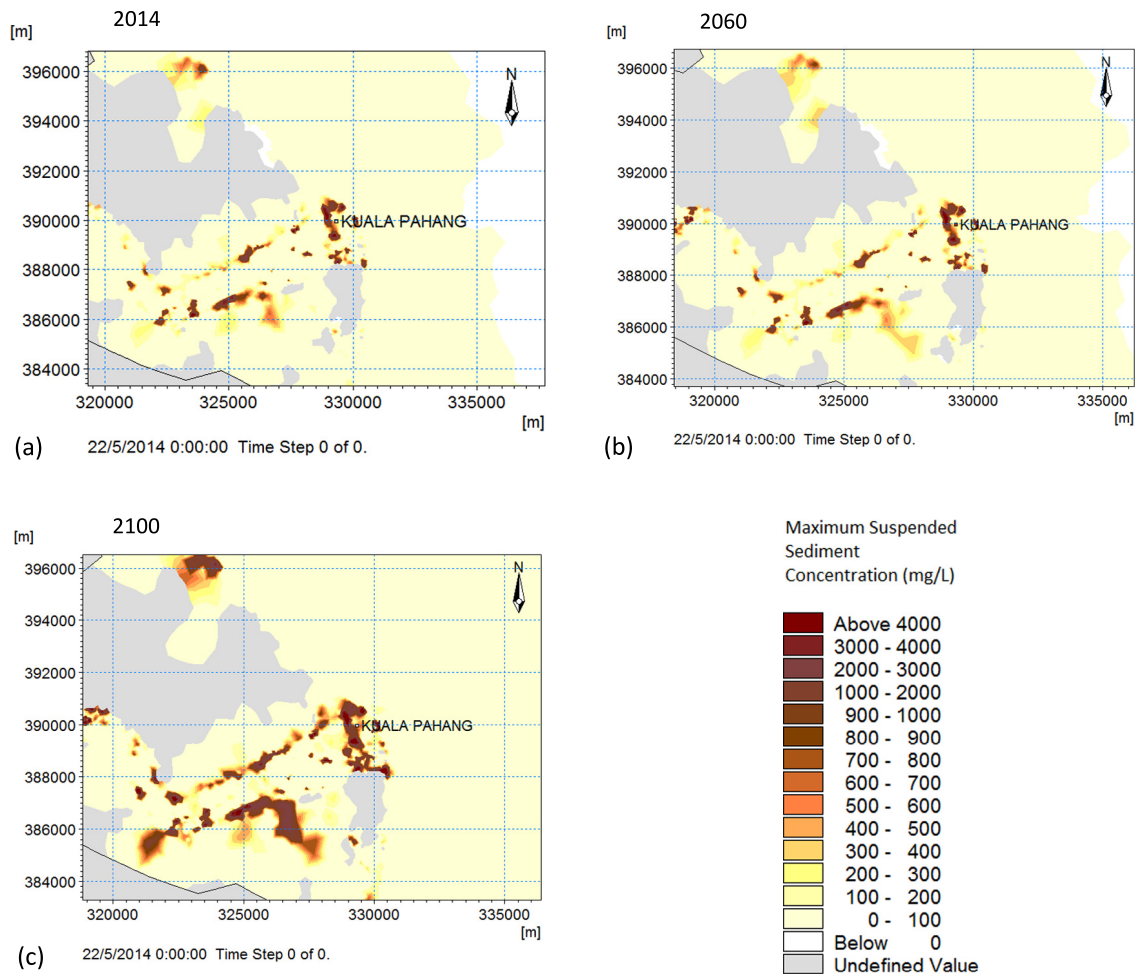


Fig. 11. Illustration of maximum suspended sediment concentration for the year (a) 2014, (b) 2060 and (c) 2100, respectively.

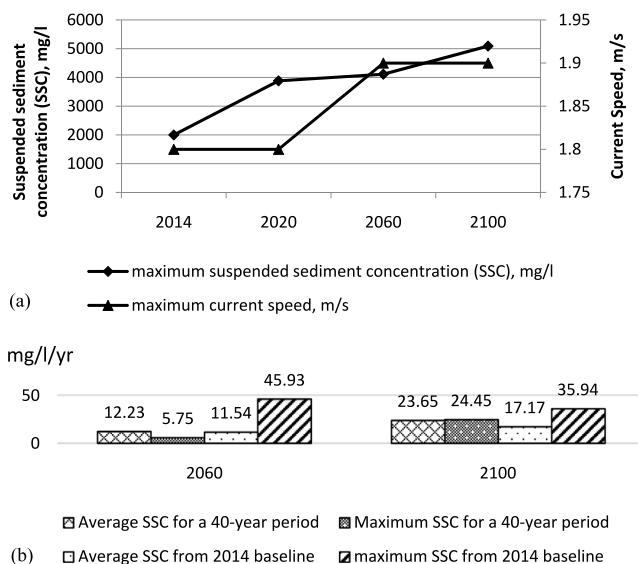


Fig. 12. (a) Relationship between the maximum SSC and current speed at Kuala Pahang with projected SLR for years 2020, 2060 and 2100 and (b) Averaged and maximum SSC rate on a 40-year time scale (mg/l/year), obtained from the baseline 2014 model for the projections in years 2060 and 2100.

the Kuala Pahang estuary is presented. The model looks at the effect of tide on suspended sediment. Analysis shows that tide changes the current speed of Kuala Pahang estuary. Ebb tide for both spring and neap tides dominates the current flow pattern which transport and carry sediment from the sea to the river mouth. Current flows from river discharge determine the sediment transport process during flood tide. SLR increases the intensity of tidal current and consequently increase SSC. The slight increase in the average current speed in the 21st century has significantly increased SSC. The result for residual current shows that SLR not only promotes erosion at the cliff and river mouth bank but also accretion in the estuary mouth. The longshore transport increases sediment supply in the estuary during ebb tide, hence reducing the depth of the water column. It is believed that the effect of decreased depth along with increased SLR will create greater inundation, which will have an adverse impact on local communities in Kuala Pahang. We even believe that with the rising sea level during the Northeast monsoon will result in a higher impact than the Southwest monsoon where the Northeast monsoon is more significant to change the hydrodynamic in Kuala Pahang. In addition, the original stratification layer is pushed upstream of the river mouth and induces turbulence; this results in an increase in SSC in the water column. This study also finds an irregular increase in SSC rate in 2060 and 2100, which is believed to be caused by river discharge and longshore transport. Localised simulation has been shown to provide better illustration and prediction of estuaries. The non-linear interaction between hydrodynamics, sediment transport, and bathymetry show an interdependent characteristic. The equilibrium of the ecosystem in the estuary shows that evolution is

significantly affected by sediment transport and the effects of tidal current.

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