Jurnal Kejuruteraan 35(3) 2023: 635-645
https://doi.org/10.17576/jkukm-2023-35(3)-11

Hydrodynamic Modelling: Estuary Dynamic Implication to Morphological Changes

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Received 5 August 2022, Received in revised form 2 November 2022
Accepted 3 December 2022, Available online 30 May 2023

ABSTRACT

Estuaries are transition zones between the sea and inland rivers, where oceanic tidal waves and fluvial flows control hydrodynamic processes. However, these natural changes and implications are not thoroughly understood, particularly in tropical estuaries. The interactions between tidal and riverine flows in the Kuala Pahang Estuary were examined using numerical modelling techniques applying TELEMAC2D. Our results model demonstrate that prolonged heavy rainfall significantly impacted water levels in the estuary system during the neap tide cycle. Moreover, the results show that the tidal range and current speed significantly influenced estuary morphological changes. The flood-ebb current can affect sediment transport near the river bank, leading to erosion. Meanwhile, the ebb-flood current significantly affected the bed sediment and suspension in the estuary mouth area while deposition happens during the slack water, either flood or ebb. Our results have a major impact on estuary morphology and sediment transport in the estuary water column, which will lead to a reduction in estuary water quality and the local economy, particularly fisheries.

Keywords: Estuary; Hydrodynamic; Heavy rain; TELEMAC2D; Neap tide; Morphology

INTRODUCTION

Climate change is a significant obstacle to sustainable development. The increase in weather and climate extremes has had irreversible consequences, pushing natural and human systems beyond their ability to adapt (Pörtner et al. 2022). Furthermore, changes in precipitation and temperature cycles are altering ecosystems, not only forests, agricultural land, mountain areas, and seas, but estuaries, the plants, animals, and humans that dwell in the system. The warming of the Earth's atmosphere is creating changes in the global climate system that jeopardise the livelihoods (Morufu Olalekan Raimi et al. 2021) of large portions of the population in developing countries (Ahmed et al. 2019; Md. Ashiqur Rahman, 2018), while infrastructure and some economic sectors in wealthier countries are particularly vulnerable to the hazards of climate change (Ghazali & Osman 2019; Schipper 2020).

Estuaries are incredibly dynamic where transitional location between the river and the sea (Robins et al. 2014) exhibits complex and dynamic environments with significant temporal and geographical variations in physical factors (Azhikodan & Yokoyama 2018, 2018; Beck 2019; Grasso & Le Hir 2019; Leuven et al. 2019; Matte et al. 2019). According to Osburn et al. (2019), in their study, extreme precipitation events may exacerbate the dynamics of mixing between river water and seawater, which increases the dissolved organic matter (DOM) in the estuaries system. Moreover, the world's climate impact on rainfall profoundly impacts the velocity, depth, and transport of sediment and even water flow.

Hydrologists and water managers continue to be concerned about changes in watershed responsiveness due to climate change and variability (Abdi & Ayenew 2021; Marshall & Chen 2022). Precipitation is also recognised as an essential climatic variable that influences both the geographical and temporal patterns of water availability (Hettiarachchi et al. 2018; Tang et al. 2020). As a result, it is becoming evident that analysing precipitation changes is critical in evaluating the effects of climate change on water resource planning and management. According to Pörtner et al. (2022) in the Sixth Assessment Report (AR6) of the Intergovernmental Panel of Climate Change (IPCC), the future impact of climate change would be fairly severe, indicating that an increase in precipitation will increase flood risks. Furthermore, the documented increases in the frequency and severity of climate and weather extremes, particularly hot extremes on land and in the ocean, and heavy precipitation events, have resulted in the risk of food and water security due to rising temperature extremes and rainfall unpredictability.

Any change in the rain pattern will have a flow effect as it is directly proportional. Higher maximum rainfall may lead to extreme flood events, which can create an extreme event of river discharge depending on the rainfall intensity. Heavy rains lead to flooding and other seasons exhibit water shortages to meet the needs, especially irrigation (Anie John & Brema 2018). With an increase in rainfall rate of more than 100 years, low-lying areas close to the river will undoubtedly be affected and suffer severe major flooding. The flood can be seen in the case in the state of Pahang itself, wherein in 2014, 2020, and the latest event occurred in 2021, a series of significant floods occurred and produced a high flow of water to be released into the estuary when heavy rain happened. As a result, the impact from the upstream had significant morphological changes in the estuary system and surrounding it.

Even though much research had done on the assessment of rainfall trends in the context of climate change, the unpredictable impact on the estuary system due to increased precipitation and climate change needs attention when predicting the response of estuaries to global climate change remains speculative (Scanes et al. 2020). Therefore, good estuary management is essential to creating a balanced ecosystem in the estuary (Li1 et al. 2020). Hydrodynamic modelling is essential for estuary and coastal management (Mardani et al. 2020). These advancements have given researchers and estuary system managers, particularly stakeholders, various alternatives for analysing and planning for estuarine ecosystems' long-term and short-term preservation. Climate change impacts and risks are becoming increasingly complex and more challenging to manage (Pörtner et al. 2022). Understanding the interaction of estuaries with tides, river currents, and estuary geometry necessitate using high-resolution hydrodynamic models (Matte et al. 2017), which will provide precise environmental management tools for detecting and forecasting the environment. Therefore, the modelling method is suitable for this study in analysing the effects of extreme rainfall on the estuary. Furthermore, the impact of extreme rainfall on parts of the estuary is rarely said as the effect on the upstream is more pronounced and easier to see. In connection with that, this study will focus on developing a model for Kuala Pahang using TELEMAC2D and analysing the impact of heavy rain on estuary hydrodynamic during neap tide by gaining a more thorough understanding of the flow dynamics in a tropical estuary.

PAHANG RIVER ESTUARY

The Pahang River Estuary, as shown in Figure 1, is located in Pahang state's Pekan sub-district, east of Peninsular Malaysia. With a length of around 435 kilometres, Sungai Pahang is Peninsular Malaysia's longest river. The Sungai Pahang Basin is formed by the confluence of two equally large and long rivers, approximately 304 kilometres from the river mouth in the central north (Ghani et al. 2016). Considering the enormous expanse of the Pahang River catchment region, this area is prone to recurring flood outbreaks. Other factors contributing to flooding include low topography, monsoon season, river overflow, and tidal behaviours. Economic activity and subsequent developments in the upstream and downstream regions have also risen fast. The climate is tropical, with air temperatures ranging from 24^{o}C to 28^{o}C all year with an average humidity of 80% (Ahmad et al. 2019). Because of a scarcity of accessible space and rapid expansion upstream, it is increasingly positioned on territory vulnerable to hazards, especially climate change, so potential economic vulnerability has grown over time, including the downstream area. In addition, The Pahang estuary is situated downstream and is known to be one of Malaysia's most productive natural ecosystems and provides food for various organisms (Mohamamad & Jalal 2018) and is vulnerable to climate change. Moreover, Ismail et al. (2018), in their study, said Pekan is one of the targeted areas for the Special Economic Zone, which is envisioned to be the critical engine of economic growth, including the estuary zone area. The potential for morphological changes and water quality issues is high if the estuary area at Kuala Pahang has a tremendous development and is not well planned.

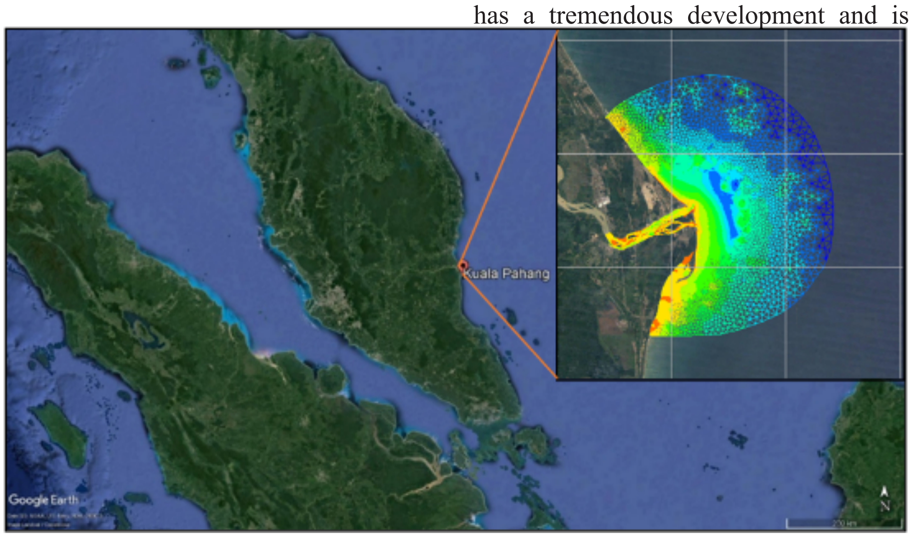

FIGURE 1. Location and unstructured mesh on study area with bathymetry applied.

MATERIALS AND METHODS

RESEARCH METHOD

Within the study context, a vast quantity of data was collected, including the information of hydrological data and estuary were required to create the estuary model. The Saint-Venant Equation is used in this model to solve the hydrodynamic equations using the finite element method. Its domain is discretised using a non-structured grid of finite elements (triangular elements), allowing for a more significant concentration of elements in regions of interest and major bathymetric fluctuations and lower resolutions in regions of more homogenous bathymetry, reducing calculating time. The data required in this study are bathymetry data, tidal data, current data, as well as hydrological data. The bathymetry of Kuala Pahang estuary and the adjacent coastal region was obtained from various sources which are including the Department of Irrigation and Drainage (DID), National Hydraulic Research Institute Malaysia (NAHRIM), open sources data from the British Oceanographic Data Centre (BODC) also including historical data from nautical charts from the Directory of Hydrography and Navigation Malaysia. The data had been blended in the BLUE KENUE software and had produced a better depth elevation of the study area.

Model Setup

The BLUE KENUE Software was employed in this study to produce the triangle components' unstructured bathymetric grids. An unstructured triangular mesh in BLUE KENUE to determine the hard and broken lines preserved during node and element construction. Moreover, grid optimisation was performed on the complicated morphology and shallow parts inside the estuary and nearby coastal regions, allowing for improved resolution in the areas of interest (Figure 1). The model comprises a triangular mesh of 605252 nodes and 1196776 elements with a minimum mesh size in the river estuary area from upstream to a distance of 4 km to the shore, with node spacing varying from 3 m to 5 m. Furthermore, Blue Kenue is used not only as a pre-process networking model but also provides a state-of-the-art interface and combines geospatial data with model input and results from data that support a complete set of data types and deliver direct results of TELEMAC2D model results.

TELEMAC2D's open-source limited element system has been used to simulate a wide range of hydrodynamic and morphodynamical situations such as waterways, curved channels, recirculation flows, and wave-induced littoral transportation. This 2D shallow water flow model is chosen based on its strengths such as geometric flexibility, availability of different solution schemes and turbulence closure models and being an open-source code (Mali et al. 2020). The open boundary in the South China Sea using the astronomical tides, TPXO binary data (TPXO data is provided by Egbert & Erofeeva, CEOAS, Oregon State University, USA). Wind data with spatial and temporal resolutions of 0.75° and 6 hours were obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts) and Meteorological Department. Meanwhile, the mean discharge data for upstream Kuala Pahang, located about 14 km from the river mouth, was considered constant at 596 m^3s^{-1} based on DID historical data for the current month of analysis in 2008.

Model Calibration and Validation

Analysis framework of study shown in Figure 2 can be devide by three sections which are data collection process, modelling setting and modelling analysis. In the data collection process, data collected from various sources such as DID, MET Malaysia and open sources data. In model setting, the development of model by creating mesh structure and steering code file and done the calibration and validation. Furthermore, modelling analysis as shown in Figure 2, the modelling calibrated output will be analysed by incorporating the rainfall data whereby a heavy rain scenario, based on classification set by the meteorology department, as shown in Table 1. The data was selected because the simulation model is for the neap tide condition, where the rainfall rate is considered to occur for two days. In addition, the rainfall intensity of 96 mm/day is acceptable for the northeast monsoon situation. The study also performed calibration and validation exercises to demonstrate the ability of the model to reproduce the observed environmental conditions. The calibration tests were carried out by comparing the simulated result with actual data from the study area. The tests were conducted with the main physical parameters with Nikuradse = 0.32 as the law of bottom friction.

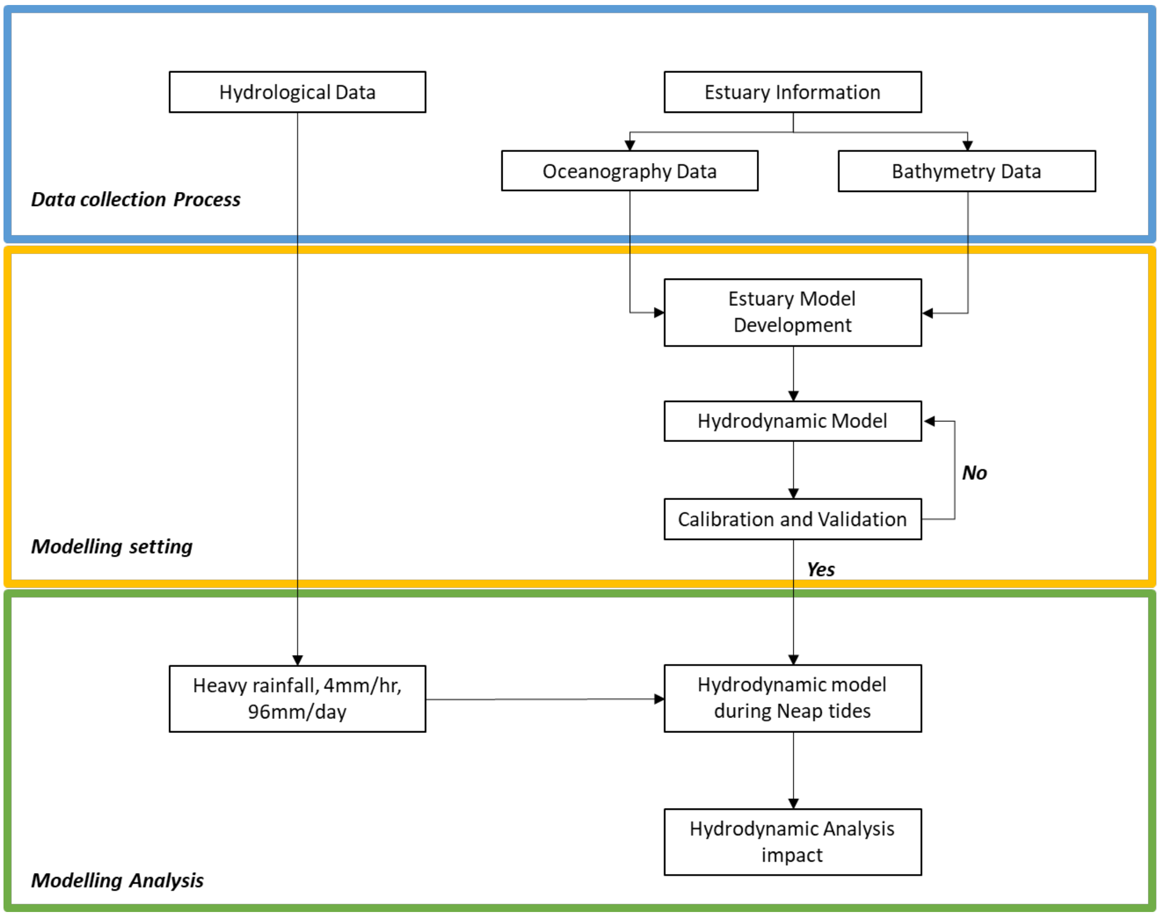

FIGURE 2. Analysis framework of the study

TABLE 1. Classification of rain intensity (MET Malaysia, 2021)

Classification	Intensity
Drizzle	Flushing rate less than 0.5mm per hour
Moderately heavy rain	The Flushing rate ranges from 0.5mm to 4.0mm hourly
Heavy rain	Flushing rate over 4.0mm per hour
Drizzle	Flushing rate less than 2.0mm per hour
Moderately heavy rainfall	The Flushing rate ranges from 2.0mm to 10.0mm hourly
Heavy rainfall	The Flushing rate ranges from 10.0mm to 50.0mm hourly
The rain is very heavy	Flushing rate over 50.0mm per hour

Figure 3 shows a well-fitted performance between model and observation data for both condition tides, which are neap and spring. From Figure 3, calibration was done for data in 2008, and the available data was from DID observation data. Even though the analysis uses the 2008 data, the analysis still can be used for calibration to make sure the mesh structure and the steering file used are correct and can be used for prediction analysis. Moreover, the model performance was evaluated by comparing the modelled and measured tidal using the root mean square error (RMSE), the coefficient of determination (R^2), the relative mean absolute error (RMAE) and index of agreement (IOA). Antonio et al. (2020), in their study, stated that based on RMAE, the model performance was classified as excellent when the values of RMAE were smaller than 0.2; good, when values were between 0.2 and 0.4; reasonable, when values were between 0.4 and 0.7; poor, when values were between 0.7 and 1; and bad, when values were greater than 1. Based on RMAE, the model calibration tests for both scenarios resulted in excellent model performances for the tidal time series with RMAE = 0.137 during neap and 0.159 during spring. The calibration also gives good performance with RMSE=0.18 and 0.21, R^2=0.92 and 0.96, and IOA=0.975 and 0.983, respectively, as shown in Table 2 where the root means square error (RMSE) near 0 represents a very little error, R^2 with a more significant number indicates less variation and IOA with a value of 1 indicates a perfect match of the model. In contrast, a value of 0 indicates no match.

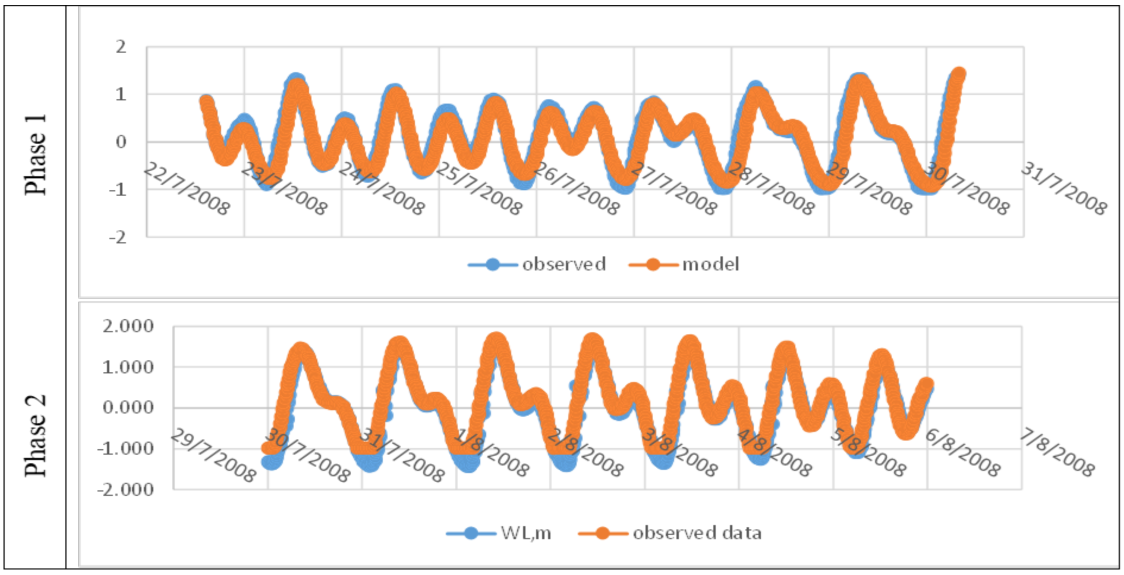

FIGURE 3. Calibration exercise for phase 1 during neap tides and phase 2 during spring tides

TABLE 2. Root mean square error (RMSE), the coefficient of determination (R^2), the relative mean absolute error (RMAE), and index of agreement (IOA) computed for phase 1 during neap tides and phase 2 during spring tides

Phase	RMSE	R^2	RMAE	IOA
Phase 1	0.18	0.92	0.137	0.975
Phase 2	0.21	0.96	0.159	0.983

The validation process is conducted by quantifying model accuracy in water levels and current speed aiming at reproducing the dynamic patterns observed in the field data. Figure 4 compares observation and modelled water elevation data and the current speed at Kuala Pahang Estuary for validation exercise. The illustration showed a well-fit result for both water level and current speed with validation model performances analysis showed an excellent result as shown in Table 3. The high value of the index of agreement, IOA=0.977 for water level and 0.911 for current speed gives the impression that the model is much better. The illustration and the performance analysis for RMSE, RMAE and IOA model reveal a good agreement between the model and collected data; therefore, the hydrodynamic model for Kuala Pahang estuary is considered successfully calibrated and validated.

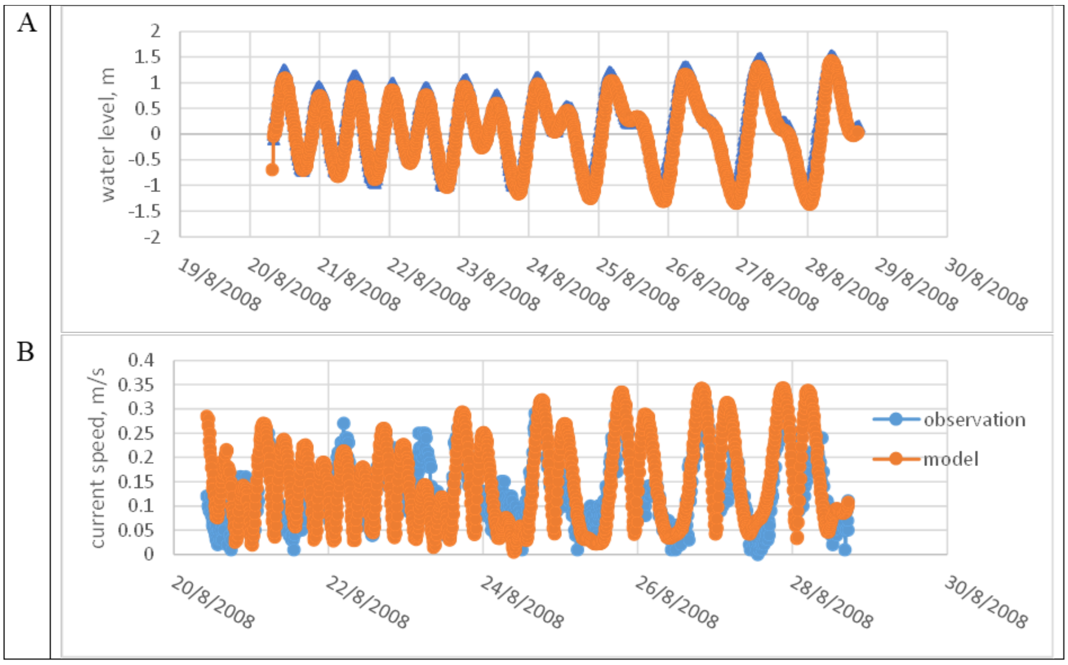

FIGURE 4. Validation exercise comparison between modelled (orange line) and observation (blue line) for water level (A) and current speed (B) with the duration of 10 days from 20/8/2008 till 28/8/2008.

TABLE 3. Validation simulation goodness-of-fit criterion results

Validation	RMSE	RMAE	IOA
tides	0.17	0.156	0.977
Current speed	0.07	0.057	0.911

RESULTS AND DISCUSSION

HYDRODYNAMIC MODEL ANALYSIS

Tides in Kuala Pahang were mixed semidiurnal, with tidal ranges spanned 0.58 to 1.75 m during neap and 1.5 to 4m during spring tide. Figure 5 shows the water level and current speed during neap tides at the mouth of the river. The analysis showed that the current speed is high during the interval from the ebb to flood and vice versa. From the Figure 5, we analysed the percentage of tidal range when the current speed increases. In section (a), the graph showed almost the same percentage of tidal range for the current speed reaching the maximum speed, which is 27.56% during ebb to flood and 27.70% during the flood to the ebb with a tidal range of 1.56m and 1.48m. For section (b), the percentage of the tidal range is lower with 16.27% during ebb to flood with a tidal range of 0.75m and 6.90% during the flood to ebb with a tidal range of 0.58m. meanwhile, for section (c), (d), (e) and (f) the percentage is 29.82%, 21.77%, 26.25% and 22.86% during ebb to flood and 23.68%,15.94%, 29.68% and 17.78% during the flood to ebb respectively. Results showed that the higher tidal range had almost the same percentage; meanwhile, with a lower tidal range, the current speed is at a maximum below 20% of the tidal range. Results also showed that the current speed could affect the estuary dynamic during 80% to 85% of the tidal range during the monsoon season.

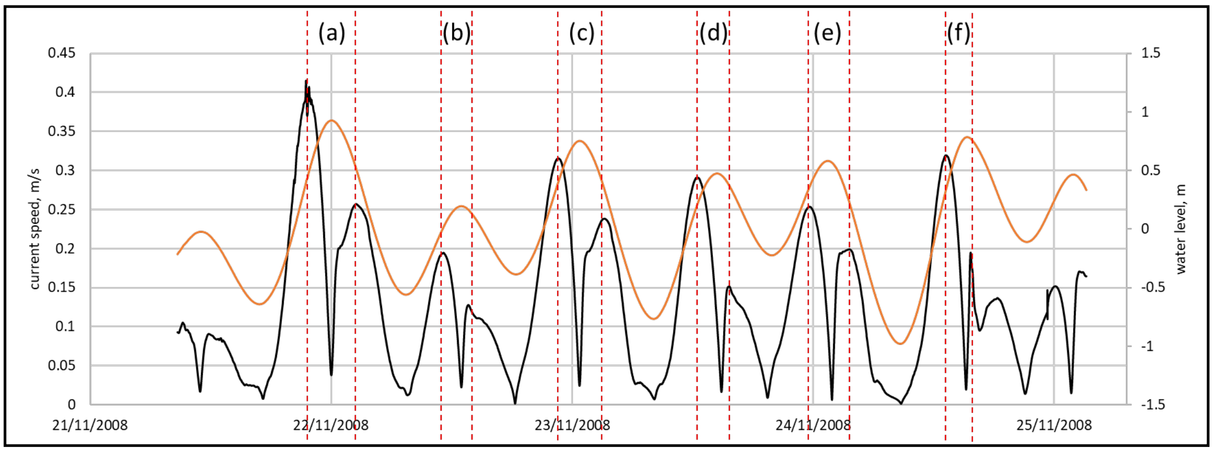

FIGURE 5. Comparison between water level (orange line) and current speed (black line) for neap tides. The red dot line showed the maximum current speed for each tidal range.

The semidiurnal tides in the study area had produced two flood tides (higher high water, HHW and lower high water, LHW) and two ebb tides (higher low water, HLW and lower low water, LLW) per day. In Figure 6, the illustration and graph show the current speed analysis during each ebb tide for neap tide conditions. Figure 6(a) shows the current speed of higher low water at the top and the bottom during lower low water. Meanwhile, Figure 6(b) shows the current speed during lower high water on top and bottom is the current speed during higher high water, where the current speed is below 0.05m/s. However, due to the difference in tidal range for each segment, the current speed illustration showed that the tidal current speed for the whole simulation area is different for each tidal range. For the ebb tides, the current speed from the river discharge dominates in the estuary mouth, with the current speed lying between 0.185m/s to 0.05m/s.

The northern South China Sea tidal current had a more significant influence than the southern South China Sea tidal current. Meanwhile, during the flood tides, the tidal current is much more robust, affecting the mouth area and the study region with a current speed between 0.095m/s to 0.275m/s. Furthermore, the difference in duration of slack water periods after high tide and after low tide (i.e., short time around the turn of the tide during which flow velocities are near to zero) is evidence of horizontal tidal asymmetry. Because of the deposition of fine grain size, suspended sediment is directly connected to the duration during which velocity is low, and particles can settle. High water slacks induce a residual transport of fine sediments in the flood direction, whereas low water slacks induce a residual transport of fines in the ebb direction.

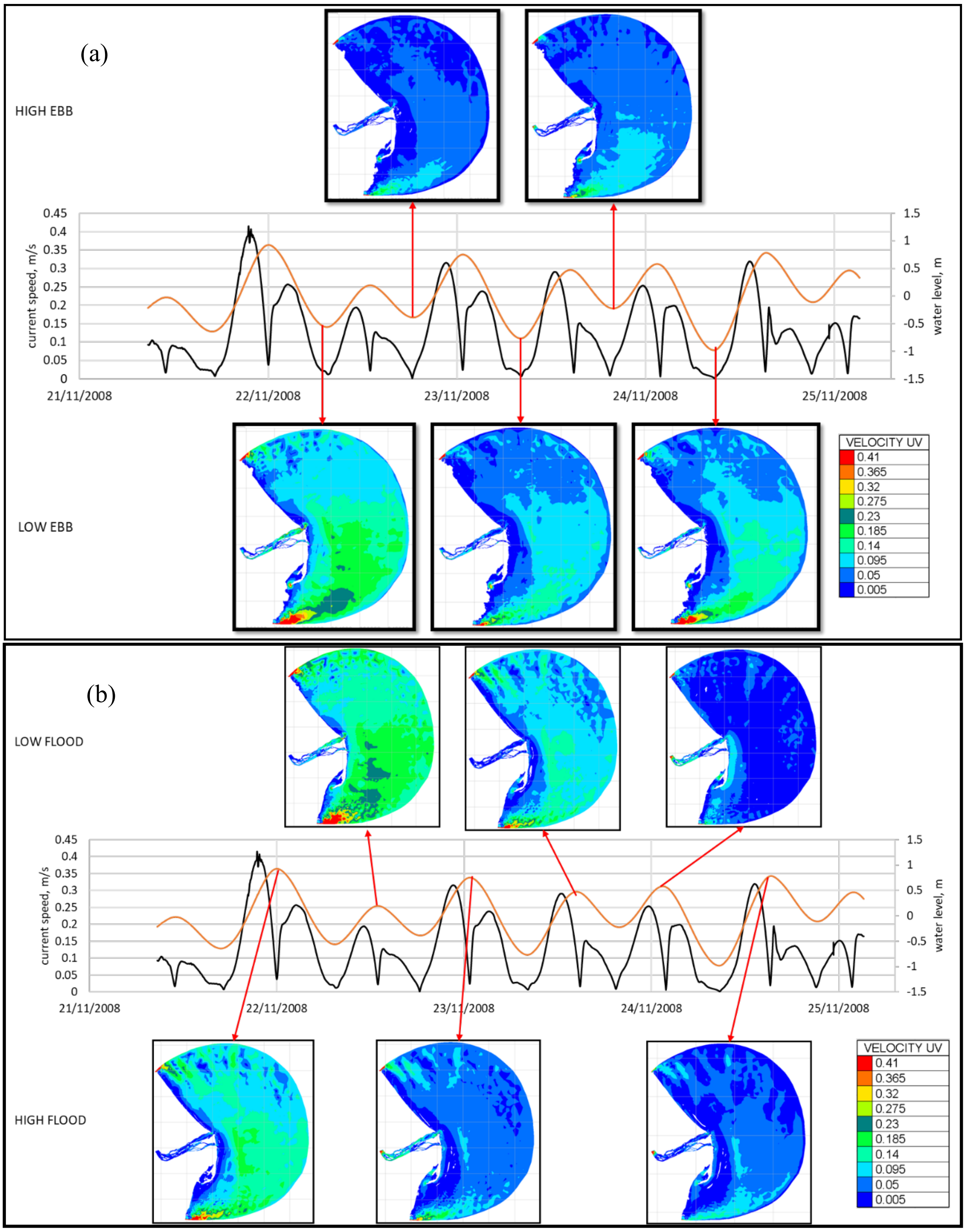

FIGURE 6. (a)Current speed during ebb tides, and (b) Current speed during flood tides where the black line is current speed and the orange colour is water level at the estuary mouth.

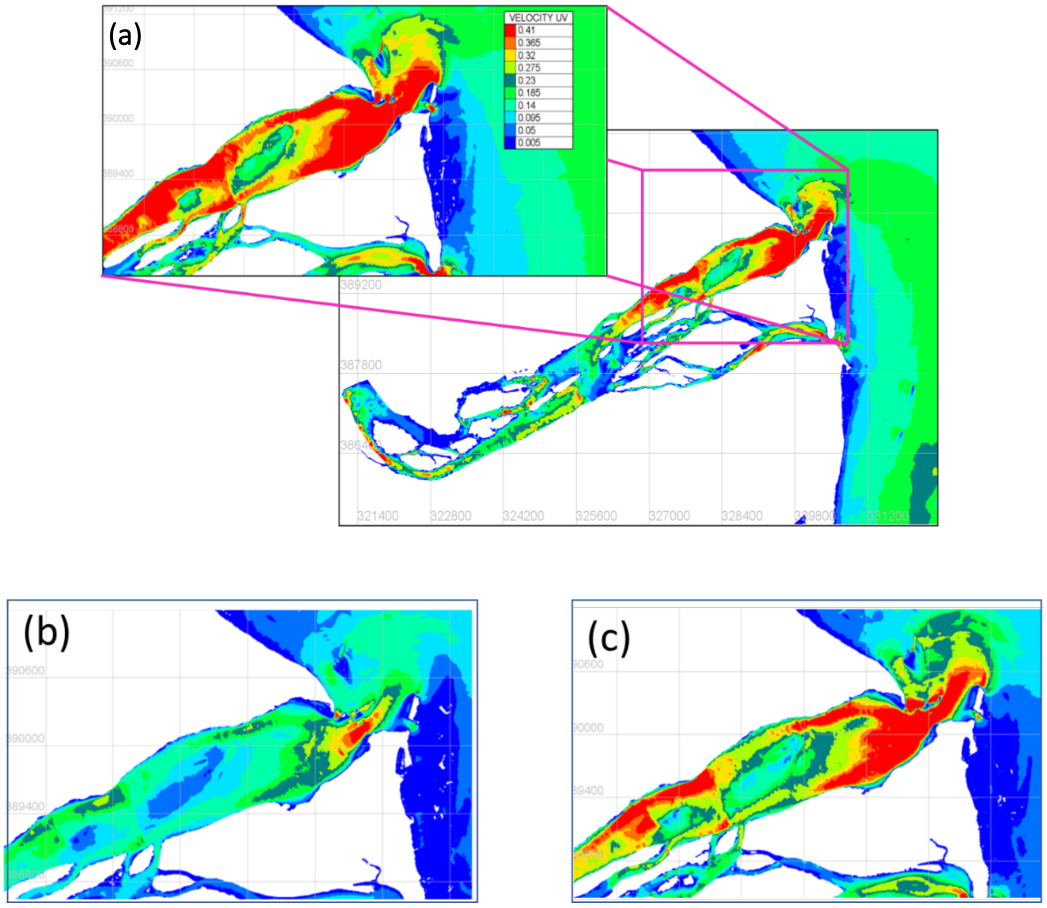

FIGURE 7 Current speed pattern for each segment of transition from ebb to flood, where (a) zoom of estuary mouth from the study region where the current speed during high tidal range as well as (c), (b) the current speed during shallow tidal range.

The current speed during the transition from low water to high water is clearly seen in Figure 7. Figure 7(a) and (c) showed during the transition of the current speed from the LLW to HHW, where the tidal current dominated the estuary mouth with a speed range starting with 0.23m/s and a maximum of 0.41m/s, and it can flow up to 4km from the estuary mouth. Meanwhile, in Figure 7(b), due to the shorter tidal range from HLW to LHW, the influence of the tidal current only affected the neck of the estuary mouth, with the tidal current lying between 0.23m/s till 0.41m/s. According to the Hjulstrom curve, a 0.41m/s tidal current inside the estuary mouth will carry sediments from clay to coarse sand with grain sizes ranging from 0.001mm to 2mm as suspended sediment and bedload transport. Hence, it gives signification to coastal erosion and morphological changes wherein morphology evolutions under maximum current speed conditions are significantly influenced by transporting sands from the size of 2mm to 0.063mm, which in Samad et al. (2013) study the estuary mouth are dominated by sands.

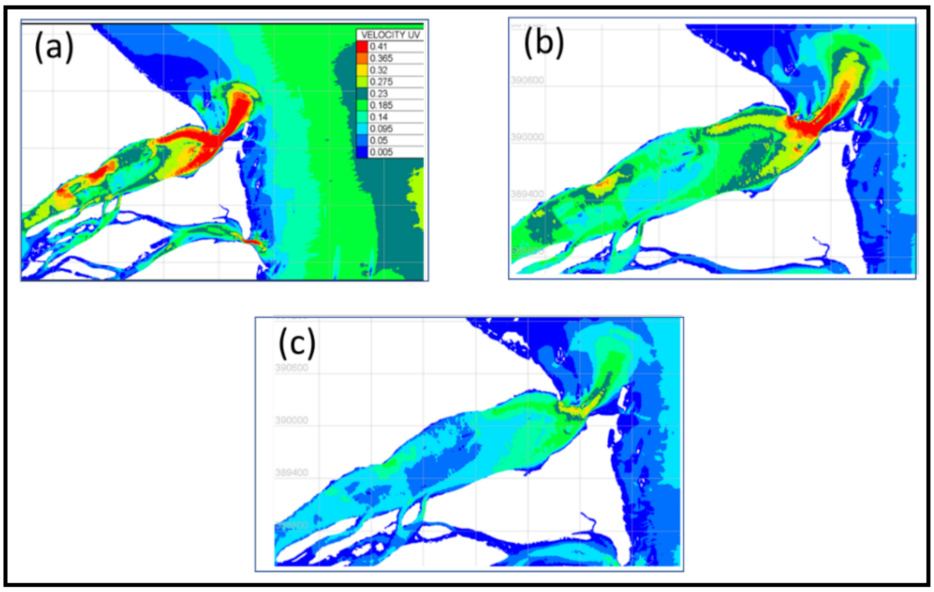

FIGURE 8. Current speed direction flow pattern during the interval of flood to ebb.

The river discharge dominates the current speed during the interval from flood to ebb, which is shown in Figure 8. In Figure 8(a) and (b), when the HHW transition to LLW, the result shows the current speed flowing out from the estuary to the mouth. The current speed much higher at the Y shape of the pattern in Figure 8(a) and (b) with max current speed from 0.365m/s to 0.41m/s, 0.275m/s to 0.365m/s respectively. The current speed is higher at the river mouth boundary due to the shape of the river mouth with a small opening and flowing out to the larger open area. The hydrodynamic force influenced the shear stress. As the flow accelerates at high speed, the shear stress increases in the water column, transporting the sediment and eroding the river bank at the mouth area. Meanwhile, Figure 8(c) demonstrates the river discharge had a dominant influence with the lower range of current speed between 0.095m/s to 0.32m/s with an average of 0.1m/s. Hence, the sediment will be in a suspension state and dominate during the lower tidal range of transition from flood to ebb.

TABLE 4. Percentage of water level based on each tidal range during neap tides.

	HHW to LLW	LLW to LHW	LHW to HLW	HLW to HHW	HHW to LLW	LLW to LHW	LHW to HLW	HLW to HHW	HHW to LLW	LLW to HHW
Tidal range (m)	1.474	0.747	0.577	1.119	1.495	1.236	0.697	0.796	1.546	1.758
Tidal range observed (m)	1.403	0.500	0.399	1.030	1.350	0.868	0.433	0.706	1.252	1.457
% Of the increase in tidal range	5.06	49.4	44.61	8.64	10.74	42.40	60.97	12.75	23.48	20.66

From Table 4, the data showed the increase of water level during neap tides for each tidal range. As shown in the Table 4, 96mm/day of rainfall for 48hrs of simulation significantly influenced the tidal range, which also increased the water level. The transition of either HHW to LLW or LLW to HHW had an increase of 5.06%, 10.74% and 23.48% tidal range; meanwhile, the transition of LLW to LHW and LHW to HLW tidal range increased about 49.4%,44.61%, 42.40% and 60.97% respectively. Hence, the 96mm/day of rainfall for 48hrs can slightly increase the water level. The rising tide implies more substantial flood velocities with the increasing water level, whereas the falling tide implies higher ebb velocities. Based on the findings, it can be concluded that the influence of climate change, namely heavy rainfall, affects the estuary's dynamics. The model developed for the research area is a localised analysis. However, a higher impact is expected if the model analysis incorporates rainfall-runoff from upstream to the estuary and is done in the whole catchment region for the river estuary. Moreover, the effects of high rainfall based on ARI 100yrs and sea level rise due to climate change will influence hydrodynamics, the transfer of estuarine sediments, and the estuary's morphology.

HYDRODYNAMIC IMPACT ON ESTUARY MORPHOLOGY

The remarkable flood-ebb current asymmetry was determined during the study period by the influence of heavy rainfall. The 48hrs of prolonged heavy rainfall had influenced the tidal and current speed in the estuary system, which may lead to morphological changes. Morphological changes can have profound implications for coastal habitats, particularly estuaries, commonly used for commercial, recreational, and industrial purposes. The estuary hydrodynamics can reshape the estuarine morphology, whereas bedload sediment and suspended sediment concentration are highly related to the strength and duration of the flood and ebb current velocity in the present study. Hence, investigations of the impact of heavy rainfall on the dynamic of tidal and current speed during the neap tides in the northeast monsoon season will help us to understand the estuary hydrodynamic and estuary morphology comprehensively. The flood-ebb tidal asymmetry exhibits remarkable spatial variation in the Kuala Pahang Estuary. The spatial variation makes the ebb-flood current in the estuary mouth more robust. It dominates the overall area of the estuary, which influences the estuary bed in transporting the bed sediment and suspension. Meanwhile, the flood-ebb current is much stronger near the river mouth bank, leading to bank erosion and reshaping the inside of the estuary mouth morphology.

CONCLUSION

The goal is to develop a hydrodynamic and sediment transport model for Kuala Pahang using TELEMAC2D. This study specifically aims to analyse the impact of heavy rain on estuary hydrodynamic during neap tide and their effects on the river mouth morphological changes. The evaluation was done to explore responses of the estuary hydrodynamics due to heavy rainfall's impact to understand better the impact of rainfall on estuary tidal range and current speed. According to model results, prolonged rainfall significantly impacted the estuary dynamic, which will raise the estuary water level, tidal range and current speed. Moreover, results showed that river discharge dominated the current speed during the interval from flood to ebb; meanwhile, the tidal current significantly influenced the estuary mouth from ebb to flood. Besides, slack water during ebb had an impact on the morphology where the current speed lies between 0.05m/s to 0.14m/s, which can transport the sediment in suspension for clay and silt (0.001mm till 0.067mm) and transported as sediment bed for the fine and medium sand size of 0.07mm till 0.7mm. Morphological changes can significantly affect coastal habitats, particularly in estuaries, places of significant commercial, recreational, and biological significance. When the flood-ebb current is from 0.275m/s to 0.365m/s, and the ebb-flood current exceeds 0.23m/s to 0.41m/s, higher suspended sediment concentrations are expected in the water column as well as bedload transport, and they increase with increasing current velocity. Studies were done only during the neap cycle; however, evaluating the hydrodynamic and morphology changes of the estuary necessitates an assessment of the complete tidal cycle. Hence, to assess estuary morphology, additional research should be conducted to examine the influence of seasonal variation on sediment transport processes during the northeast and southwest monsoon, which may have a significantly different range of tidal and current speeds.

ACKNOWLEDGEMENT

The authors thank the Department of Drainage and Irrigation (DID), Department of Meteorology Malaysia and National Hydraulic Research Institute Malaysia (NAHRIM) for extensive data support and their assistance in data acquisition.

DECLARATION OF COMPETING INTEREST

None

REFERENCES

Abdi, D. A., & Ayenew, T. 2021. A scenario-based modeling of climate change impact on the hydrology of Ketar watershed, Central Rift Valley Basin, Ethiopia. Modeling Earth Systems and Environment 2021, 1–14. https://doi.org/10.1007/S40808-021-01314-1

Ahmad, Z., Kassim, Z., Mohd Rosli, N. S., & Shammodin, M. S. 2019. Mapping mangrove degradation in pahang river estuary, Pekan Pahang by using remote sensing. *Science Heritage Journal* 3(2): 01–05. https://doi.org/10.26480/gws.02.2019.01.05

Ahmed, I., Ayeb-Karlsson, S., van der Geest, K., Huq, S., & Jordan, J. C. 2019. Climate change, environmental stress and loss of livelihoods can push people towards illegal activities: a case study from coastal Bangladesh. Https://Doi.Org/10.1080/17565529.2019.1586638, 11(10), 907–917. https://doi.org/10.1080/17565529.2019.1586638

Anie John, S., & Brema, J. 2018. Rainfall trend analysis by Mann-Kendall test for Vamanapuram river basin, Kerala. *International Journal of Civil Engineering and Technology* 9(13): 1549–1556.

Antonio, M. H. P., Fernandes, E. H., & Muelbert, J. H. 2020. Impact of jetty configuration changes on the hydrodynamics of the subtropical Patos Lagoon Estuary, Brazil. *WATER* 12(11). https://doi.org/10.3390/w12113197

Azhikodan, G., & Yokoyama, K. 2018. Sediment transport and fluid mud layer formation in the macro-tidal Chikugo river estuary during a fortnightly tidal cycle. *Estuarine, Coastal and Shelf Science* 202(March): 232–245. https://doi.org/10.1016/j.ecss.2018.01.002

Beck, T. M. 2019. Tracking Sediment Bypassing, Geomorphological Analysis, and Regional Sediment Management at Tidal Inlets (Issue July).

Ghani, A. A., Chang, C. K., Puay, H. T., & Ismail, W. R. 2016. Flood inundation analysis for large scale river using hydrodynamic and sediment transport model – Case study of Sungai Pahang's December 2014 flood Flood inundation analysis for large scale river using hydrodynamic and sediment transport model – Case st. December 2014.

Ghazali, N. H. M., & Osman, S. 2019. Flood Hazard Mapping in Malaysia: Case Study Sg. Kelantan river basin. *CATALOGUE OF HYDROLOGIC ANALYSIS: Flood Hazard Mapping* 1: 1–30.

Grasso, F., & Le Hir, P. 2019. Influence of morphological changes on suspended sediment dynamics in a macrotidal estuary: Diachronic analysis in the Seine Estuary (France) from 1960 to 2010. *Ocean Dynamics* 69(1): 83–100. https://doi.org/10.1007/s10236-018-1233-x

Hettiarachchi, S., Wasko, C., & Sharma, A. 2018. Increase in flood risk resulting from climate change in a developed urban watershed - The role of storm temporal patterns. *Hydrology and Earth System Sciences* 22(3): 2041–2056. https://doi.org/10.5194/HESS-22-2041-2018

Ismail, I., Haron, H., & Yusof, N. A. Z. M. 2018. Sustainable fishing village business model: Case study of Kuala Pahang Malaysia. *International Academic Journal of Social Sciences* 05(02): 1–22. https://doi.org/10.9756/iajss/v5i2/18100022

Leuven, J. R. F. W., Pierik, H. J., van der Vegt, M., Bouma, T. J., & Kleinhans, M. G. 2019. Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nature Climate Change* 9(12): 986–992. https://doi.org/10.1038/s41558-019-0608-4

Li1, J., Claude, N., Tassi, P., Cordier, F., Crosato, A., & Rodrigues, S. 2020. Implementation of a novel approach accounting for the influence of vegetation on sediment transport in GAIA. 2020 TELEMAC-MASCARET User Conference, October.

Mali, V. K., Veeranna, B., Parik, A., & Kuiry, S. N. 2020. Experimental and numerical study of flood dynamics in a river-network-floodplain set-up. *Journal of Hydroinformatics* 22(4): 793–814. https://doi.org/10.2166/hydro.2020.160

Mardani, N., Suara, K., Fairweather, H., Brown, R., McCallum, A., & Sidle, R. C. 2020. Improving the accuracy of hydrodynamic model predictions using lagrangian calibration. *Water* 12(575): 1–20. https://doi.org/10.3390/w12020575

Marshall, A. M., & Chen, J. M. 2022. Impacts of changing snowfall on seasonal complementarity of hydroelectric and solar power. *Environmental Research: Infrastructure and Sustainability* 2(2): 021001. https://doi.org/10.1088/2634-4505/AC668F

Matte, P., Secretan, Y., & Morin, J. 2017. Hydrodynamic Modeling of the St. Lawrence Fluvial Estuary . II : Reproduction of Spatial and Temporal Patterns. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 143(5): 1–13. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000394.

Matte, P., Secretan, Y., & Morin, J. 2019. Drivers of residual and tidal flow variability in the St. Lawrence fluvial estuary: Influence on tidal wave propagation. *Continental Shelf Research* 174(December 2018): 158–173. https://doi.org/10.1016/j.csr.2018.12.008

Md. Ashiqur Rahman. 2018. Governance matters: climate change, corruption, and livelihoods in Bangladesh. Climatic Change. https://doi.org/https://doi.org/10.1007/s10584-018-2139-9

MET Malaysia. 2021. *MetMalaysia: Iklim Malaysia*. Malaysian Meteorological Department. https://www.met.gov.my/pendidikan/iklim/iklimmalaysia

Mohamamad, A., & Jalal, K. C. A. 2018. Macrobenthic diversity and community composition in the Pahang Estuary, Malaysia. *Journal of Coastal Research* 82(4): 206–211. https://doi.org/10.2112/SI82-030.1

Morufu Olalekan Raimi, Tonye Vivien Odubo, & Adedoyin Oluwatoyin Omidiji. 2021. Creating the healthiest nation: Climate change and environmental health impacts in Nigeria: A narrative review. *Sustainability in Environment* 6(1). https://doi.org/http://dx.doi.org/10.22158/se.v6n1p61

Osburn, C. L., 1#, J. N., Boyd, T. J., & Montgomery. 2019. Antecedent precipitation influences the bacterial processing of terrestrial dissolved organic matter in a 1 North Carolina estuary 2.

Pörtner, H.-O., Roberts, D. C., Poloczanska, E., Mintenbeck, K., Craig, M., & Andrew Okem. 2022. Climate Change 2022 - Impacts, Adaptation and Vulnerability - Summary for Policymakers. In Ipcc. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

Robins, P. E., Lewis, M. J., Simpson, J. H., Howlett, E. R., & Malham, S. K. 2014. Future variability of solute transport in a macrotidal estuary. *Estuarine, Coastal and Shelf Science* 151: 88–99. https://doi.org/10.1016/j.ecss.2014.09.019

Samad, A. S. A., Ali, C. A., & Mohamed, K. R. 2013. Delta zoning based on sediment dispersal in Pahang River Delta. AIP Conference Proceedings, 1571(December 2013), 438–444. https://doi.org/10.1063/1.4858695

Scanes, E., Scanes, P. R., & Ross, P. M. 2020. Climate change rapidly warms and acidifies Australian estuaries. *Nature Communications* 11(1): 1–11. https://doi.org/10.1038/s41467-020-15550-z

Schipper, E. L. F. 2020. Maladaptation: When adaptation to climate change goes very wrong. *One Earth* 3(4): 409–414. https://doi.org/10.1016/J.ONEEAR.2020.09.014

Tang, X., Fan, S., Du, M., Zhang, W., Gao, S., Liu, S., Chen, G., Yu, Z., & Yang, W. 2020. Spatial and temporal patterns of global soil heterotrophic respiration in terrestrial ecosystems. *Earth System Science Data* 12(2): 1037–1051. https://doi.org/10.5194/ESSD-12-1037-2020