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Saline Water Intrusion through Rajang River Network due to Sea Level Rise

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Abstract: *Rise in sea levels is one of the disastrous effects of climate change. A relatively small increase in sea level could affect natural coastal systems (Ami et. al., 2019). The main objective of this study is to assess the saline water intrusion through Rajang river network due to Sea Level Rise (SLR) at the year 2100. To carry out the study, several numerical modelswere developed through a proper calibration process to make the models more reliableand useful. At first, Hydrological Model was developed which providesthe flow contribution in Rajang river network fromrainfall-evaporation dataset. After that, well calibrated Coastal Hydrodynamic and Salinity Model were developed which produce flow pattern and salinity profile respectively within the South China Sea and Rajang estuary . Concurrently, river Hydrodynamic and Salinity Model were developed based on the boundary condition from Hydrological,Coastal Hydrodynamic, and Coastal Salinity model. Evidently, from study findings that 1ppt salinity contourcan travel up to 96km from the rivermouthof Rajang river whereas it can travel up to 44km in BatangIgan river as compared when there is no SLR. A study by NAHRIM, UKM and CSIRIO revealed that sea level rise near Rajang estuary wouldbe about 0.72m under scenario RCP 8.5 (Mclnnes et. al., 2017) which is almost same as Global highest sea level rise stated in AR5.Then,salinity analysis was carried out based on 72cm SLR where the study found out that 1ppt salinity countermight intrude 107km along Rajang river and 53km along BatangIgan river. So, it can be concluded that 1ppt salinity counter may intrude further up to11km along Rajang river and 9km along BatangIgan river due to 72cm SLR.Serious remarks on the salinity line fluctuation level changes inside both Rajang and Igan river may affect the ecosystem function within the 11km and 9km river ecosystem for both Rajang and Igan river respectively. Hence, now isthe high time to start practicing adaptive measures in coping with gradual sea level rise which has already been happening and the consequences have begun to alter livelihood of the river inhabitants and their socio-economic activities.*

Keyword*: Sea level rise, numerical model, salinity, Rajang river, BatangIgan*

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I. Introduction

According to Ami et al. (2019), rise in sea level is one of the disastrous effects of climate change nowadays. A relatively small increase in sea level could affect the natural or existing coastal systems. The increase of anthropogenic activities has triggered global sea level rise threatening many low-lying and unprotected coastal areas in the world. Without measures, global sea levels will continue to rise at an accelerating rate in the 21st century (Amalina et al., 2016). A study by NAHRIM, UKM and CSIRO revealed that sea level rise near Rajang estuary will be about 0.72m (Mclnnes et al., 2017) under scenario RCP 8.5 which is almost same as Global highest sea level rise stated in AR5. It is indicatedin this study how severe the impact of SLR, especially on saltwater intrusion by the year 2100. The most severe impacts of SLR at the low-lying coastal areas are coastal flooding and salinity intrusion. The main objective of this study is to assess the saline water intrusion through Rajang river network due to SLRin 2100.

II. Study Area

The study area covers the Rajang River network and its estuary in the South China Sea. In addition to that, itfalls under Sunda Shelf, a bio-geographical region of Southeastern Asia that was exposed during the last Ice Age. According to the co-tidal chart described by Zu et al. (2008), the value of M_2 is quite high, which is about 1.4 to 1.6m, whereas the value of K_1 is about 0.6m. On the other hand, the value of S_2 and O_1 are 0.25m and 0.4m, respectively. The seasonal circulation pattern in the South China Sea and its adjacent seas has been investigated by several authors (Dale 1956; Wyrtki 1961; Xu et al., 1982; Pohlmann 1987; Shaw and Chao

1994). According to them, wind stress climatology during SW Monsson (June-August) is about $260^{0,}$ and during NE Monsoon (December-February) it is about 45^{0}.

The Rajang River is a river network in Sarawak, Malaysia which originates from Iran mountain and approximate length is about 563km. This is the longest river in Malaysia. A total of 30 species of mammals (Tuen, 2004), 122 species of birds (Tuen, 2004) and 164 species of fish (Parenti and Lim, 2005) were identified in the year 2004. The biggest town by the river is located 80km from river mouth known as Sibu which is cultural, political, economic and educational center of the central Sarawak. The study area is shown in Figure 1.

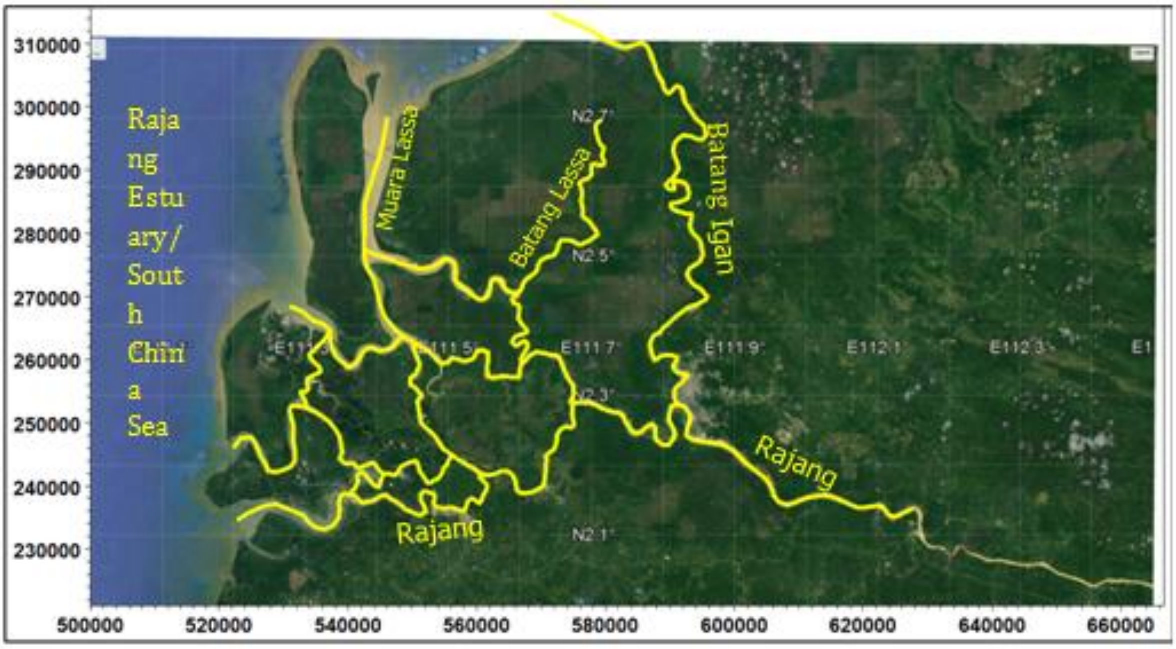


Figure 1: Study Area

III. Methodology

The overall methodology of the study is shown in the following figure. Atthe beginning of the study, a Rainfall-runoff model was prepared to generate the rainfall-runoff in the catchment. This flow was used as an upstream boundary ofRiver Hydrodynamic Model (1D Model) which produced the flow pattern in the tributaries of Rajang river system. After that, Coastal Hydrodynamic and Salinity Model (2D Model) was prepared using flows from the River Hydrodynamic Model and constant salinity as boundary condition. Finally, River Salinity Model was prepared to produce salinity distribution in Rajang River network to establish baseline salinity in the river network. Furthermore, SLR for the year 2100 was adopted and the same simulation sequence were followed to get the salinity intrusion through Rajang river network due to adopted SLR.

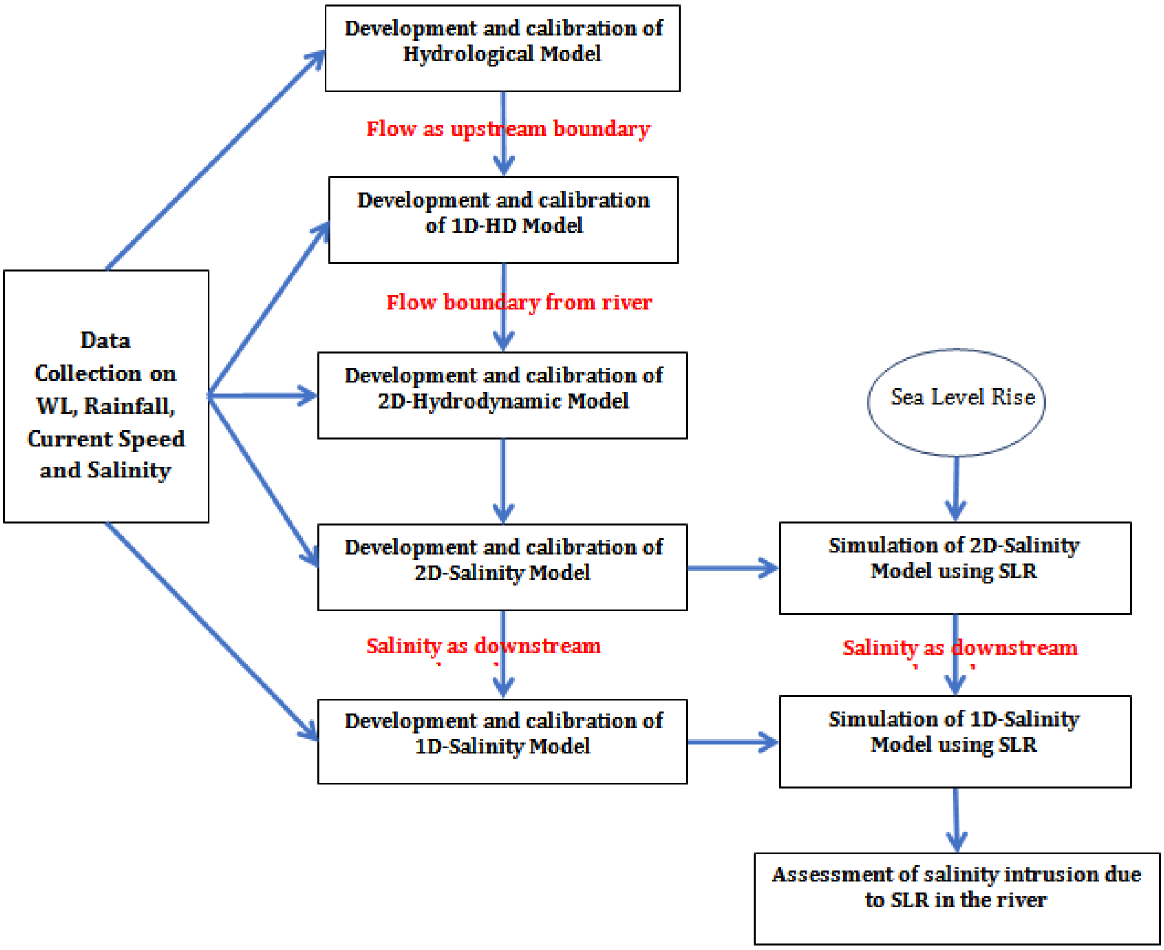


Figure 2: Study flow diagram

IV. Numerical Models

1.1 Hydrological Model (Rainfall-Runoff)

1.1.1 Introduction

Accurate calculation of rainfall-runoff is essential to carry out a hydrological model which finally can be used as an upstream boundary for River Model Hydrodynamic/Salinity Model. The Rational Method [McPherson 1969], Soil Conservation Service- Curve Number Method [Maidment 1993], and Green and Ampt Method [Green and Ampt 1991] are the widely known rainfall-runoff models identified. The Genetic Danish MIKE11 NAM (1972) is one of the complex models identified which should provide better runoff estimation [Supiah and Normala 2002], and this model has been used under this study.

MIKE11 NAM is a rainfall-runoff model which is part of the MIKE11 RR module. It is a well-proven engineering tool that has been applied to several catchments around the world [Resfsgaard and Knudsen 1996, Thompson et al. 2004, Keskin et al.2007, Liu et al. 2007, Kamel 2008 and Makungo et al. 2010], representing many different hydrological regimes and climatic conditions.

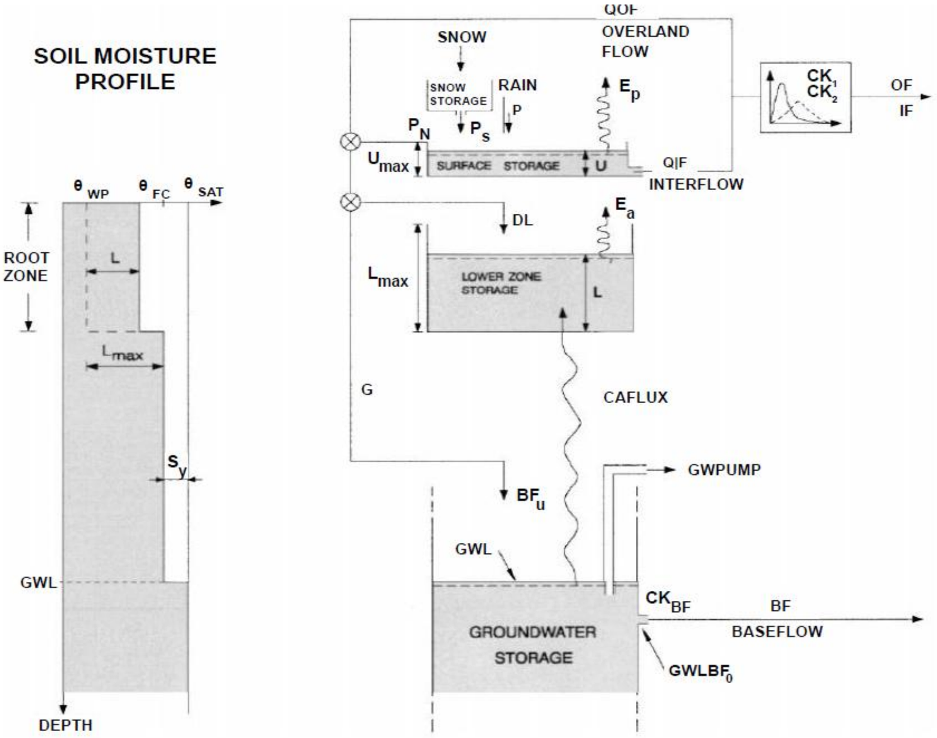


Figure 3: Flow diagram of rainfall-runoff model

1.1.2 Model Setup

Catchment delineation of Rajang river system was carried out based on the topography of the study area. The final catchment distribution is furnished in Figure 4. The entire basin was divided into sevencatchments, and the total area is 52,500 km^2. The key input for Hydrological Model is rainfall. Data from 21 rainfall station within the delineated catchment were collected.

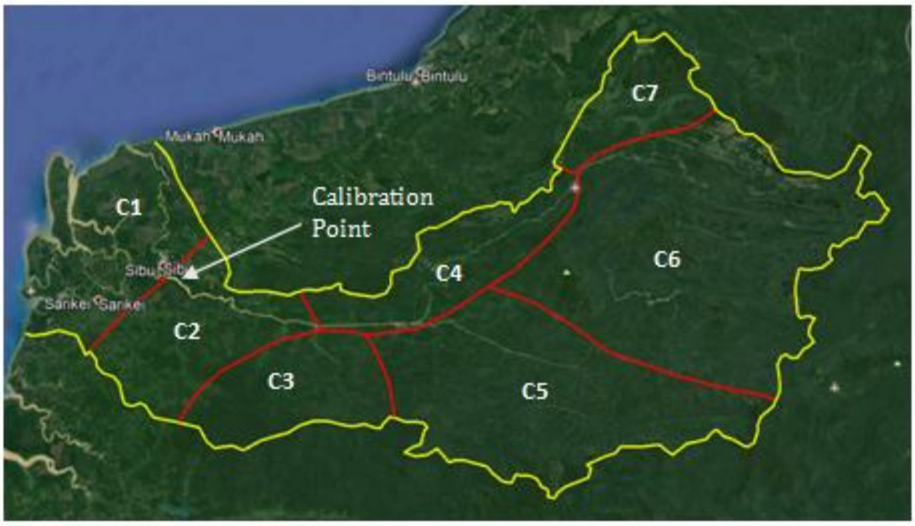


Figure 4: Rajang river catchment

1.1.3 Model Calibration

Calibration is the process under which the model parameters and/or structure are determinedbased onthe measurement and prior knowledge [Beck 1987]. For any model, field/measured data can be used to calibrate the model at a given time by adjusting model parameter values until an acceptable correlation is achieved [Ditmars 1988].The model was then calibrated against measured flow in the upstream of Rajang river and was found quite good agreement between measured data and simulated data.

1.2 Hydrodynamic Model (River)

The physically-based hydrodynamic modelling system MIKE11 has been used for carrying out surface water modelling work under this study. The hydrodynamic model was developed integrating all the drainage channels and rivers of the study area using the hydrodynamic module of MIKE 11 modelling system of DHI Water & Environment. The upstream boundary condition were defined by time series discharge, and downstream boundary were defined by tidal variation, and it was generated from the measured data of standard tidal station or by simulating the CoastalModel. The contribution of flow from rivers were included as flow time series from the rainfall-runoff model result. The model wasthen calibrated and validated against measured water level and current speed to ensure its reliability to generate field conditions. The validation was made for a different set of data at different location than what being used forcalibration, which will ensure a reliable hydraulic model. Figure 6 depicted the process of developing and validating a river model.

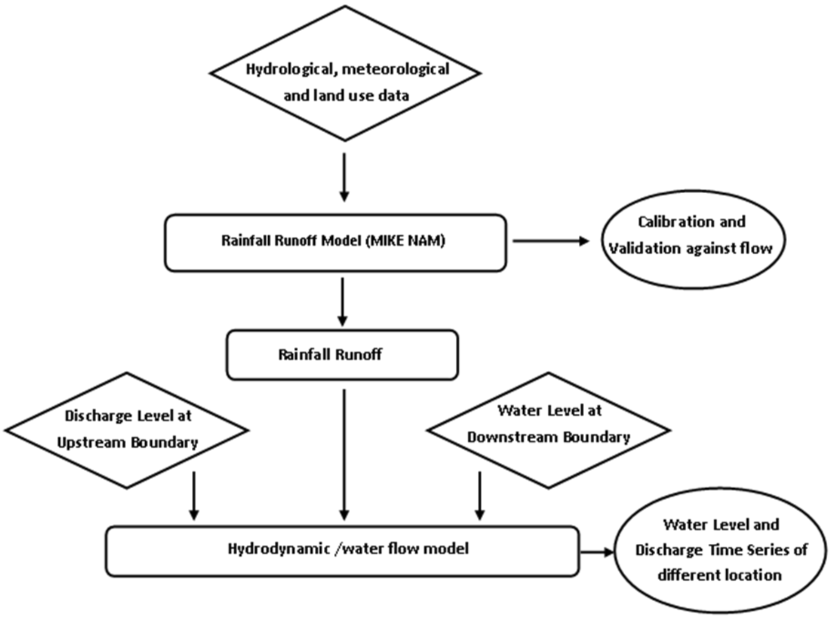


Figure 5: Schematic diagram One-Dimensional river model

1.2.1 Model Setup

At first, a river network (6) was developed by identifying major river/tributaries in the Rajang river basin such as Rajang, Igan, Batang Lassa Muara Lassa,and so on. After that, boundary condition was defined by using water level at the downstream and flow boundary at the upstream. The downstream boundary condition was extracted from calibrated Coastal Hydrodynamic Model of South China Sea, and Rajang Estuary and flow boundary was derived from Hydrological model result. The model was then simulated to produce variation of flow and water level in Rajang river network (Figure 6).

1.2.2 Model Calibration

River Hydrodynamic Mode was also calibrated against measured flow data at Rajang river and BatangIgan river and furnished in Figure 7. From the measurement, it shows the agreement between simulated and measured are quite satisfactory.

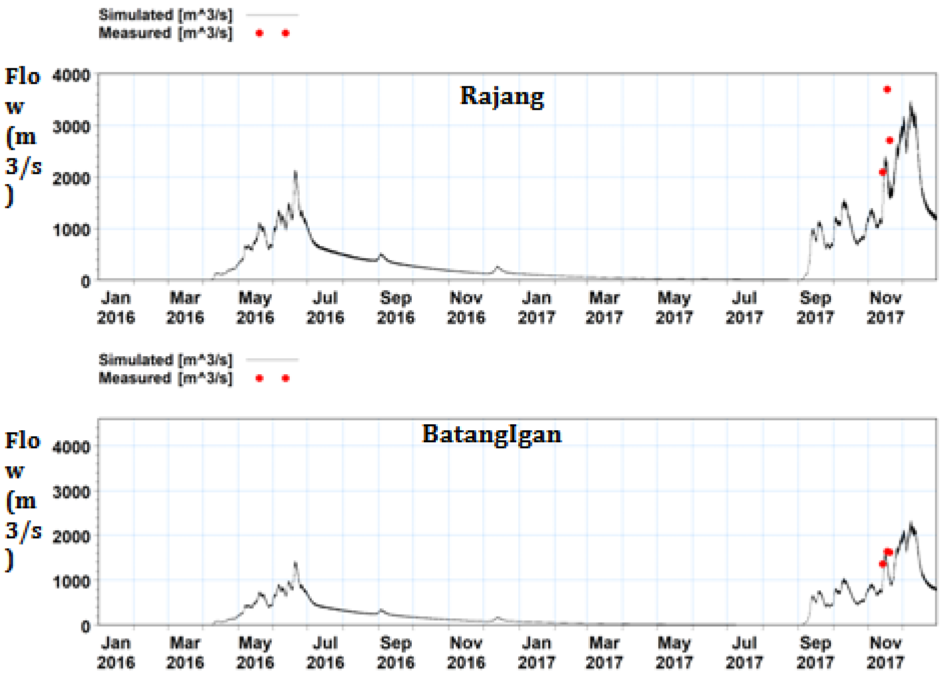


Figure 7: River Model calibration at Rajang and BatangIgan

1.3 Hydrodynamic Model (Coastal)

Hydraulic modelling is a proven and tested technology which can be applied for any hydraulic study either for river or sea. A well calibrated and validated Hydrodynamic model is the pre-requisite for other models such as wave model, salinity model, morphological model, etc. In this study hydrodynamic model was developed as a pre-requisite of salinity model. MIKE 11 and MIKE21 modelling system have been applied for hydraulic modelling

A 2D Hydrodynamic Model was developed using the model domain showed in theFigure 6. The boundary in the sea was taken from Global Tide Model of MIKE and upstream river flow was taken from River model.

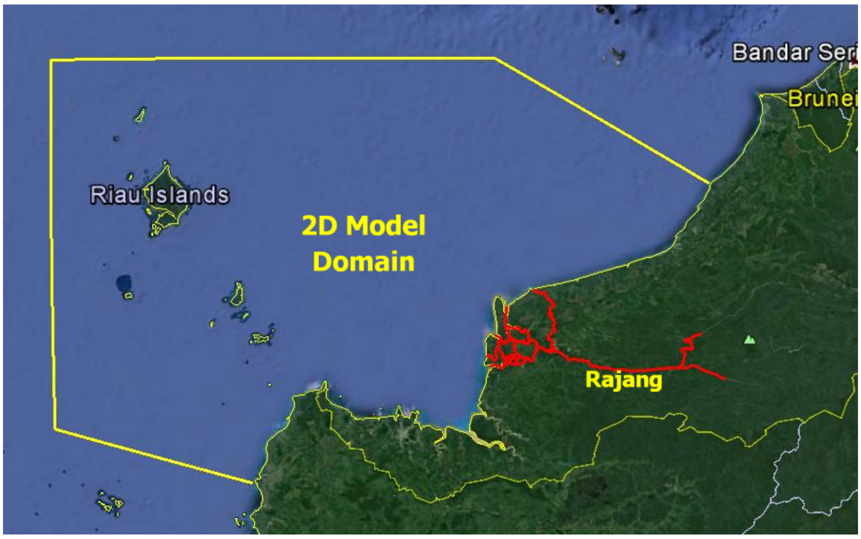


Figure 6: Domain of 2D model for Rajang Estuary

1.3.1 Model Setup

Flexible mesh for the study was prepared and presented in Figure 7. It is found from the figure that coarse resolution was used near the boundary and the fine resolution was used near Rajang estuary. The model bathymetry was produced using field measurement, data from C-MAP, and ETOPO2v2. MIKE C-MAP provides access to an abundance of bathymetric data and, combined with an electronic chart database. It can make the setup of model bathymetries easy and consistent. On the other hand, ETOPO2v2 is available in both a downloadable cell-centered version, named ETOPO2v2c (pixel registered, where the cell boundaries are lines of even minutes of latitude and longitude, centered on intersections of lines of odd minutes of latitude and longitude) and a grid-centered, version, available via design-a-grid (with cell boundaries defined by lines of odd minutes of latitude and longitude, meaning that cells were centered on the integer multiples of 2 minutes [even minutes] of latitude and longitude). The cell-centered grid is the authoritative version. The final version of the bathymetry has been shown in Figure 8.

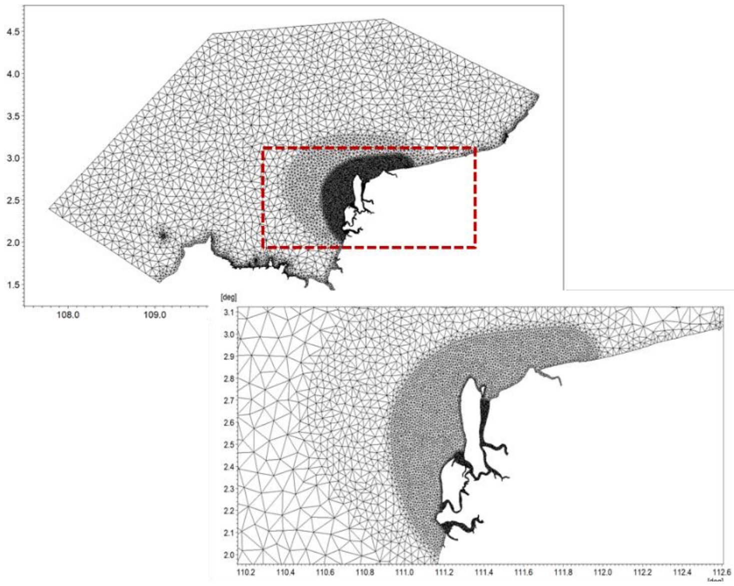


Figure 7: Distribution of flexible mesh

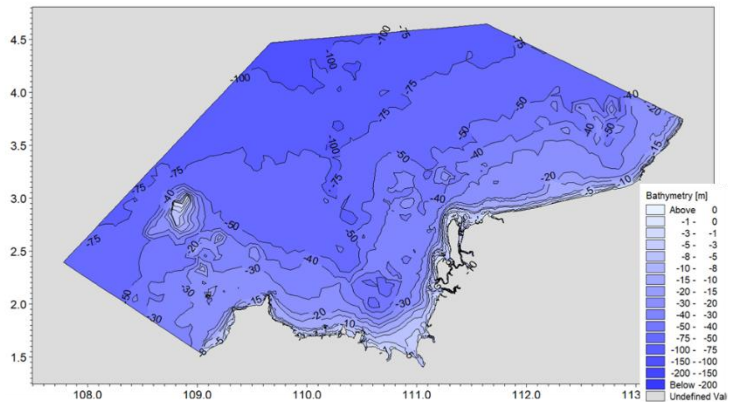


Figure 8: Estuary and sea bathymetry

1.3.2 Model Calibration

The Coastal Model was calibrated against predicted water level (13 stations) and measured data water level and current speed) in Rajang estuary. Quality Index for each calibration was calculated and furnished in

Table 1. It is evident from the table that all the results satisfied the criteria of JPS. Quality Index (ρ) was calculated based on the following equation.

me_i *Measured Value*

mo_i *Model Value*

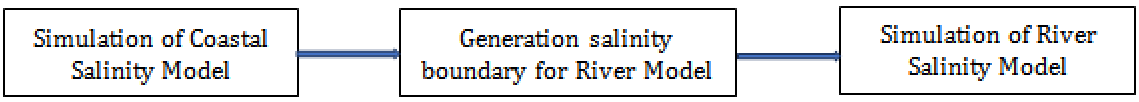
$$\rho = \frac{\sum_{i=1}^{N}(me_i - \overline{me})(mo_i - \overline{mo})}{\sqrt{\sum_{i=1}^{N}(me_i - \overline{me})^2 \sum_{i=1}^{N}(mo_i - \overline{mo})^2}}$$

Table 1: Model performance

Stations	Item	Quality Index	JPS Guideline	Stations	Item	Quality Index	JPS Guideline
Kuala Bintulu	Water Level	0.98	0.9	Santubang	Water Level	0.98	0.9
Kuala Tatau	Water Level	0.99	0.9	Pulau Satang Besar	Water Level	0.99	0.9
Kuala Balingian	Water Level	0.99	0.9	Sematan	Water Level	0.97	0.9
Kuala Mukah	Water Level	0.99	0.9	TanjungSerabang	Water Level	0.98	0.9
Kuala Oya	Water Level	0.98	0.9	ADCP-1	Water Level	0.98	0.9
Igan	Water Level	0.98	0.9	ADCP-2	Water Level	0.98	0.9
Kuala Paloh	Water Level	0.98	0.9	ADCP-1	Current Speed	0.83	0.8
Rajang	Water Level	0.98	0.9	ADCP-2	Current Speed	0.86	0.8
PulauLakei	Water Level	0.98	0.9				

1.4 Salinity Model

In general, salinity movement in any river depends on the flow condition from upstream and any abstraction and addition of water in the river system. The temporal and spatial variation of the salinity along Sg. Rajang was assessed for existing conditions and future condition (SLR condition) using numerical modelling techniques. Two different salinity models were developed,which is CoastalSalinity Model (2D) and River Salinity Model (1D). Initially,,Two-Dimensional Salinity Model was developed and after that One-Dimensional salinity model wasestablished by using salinity boundary from Coastal Salinity Model. A Flow diagram for the salinity model is shown in the following diagram.



1.4.1 Coastal Salinity Model

Costal Salinity Model were developed by using flow boundary from River Hydrodynamic Model and salinity level along sea boundary. The model was then simulated to produce the salinity variation in Rajang estuary which can be used as a boundary for River Salinity Model.

1.4.2 River Salinity Model

River network under Hydrodynamic Model (Figure 6) were used for salinity model, and boundary points are also the same. Downstream boundaries (five) were taken from Coastal Salinity Model, and upstream boundary was considered as zero. Salinity data at two locations along Rajang river were collected to understand the salinity condition in the Rajang River and for calibration purpose. Modelcalibration were carried out for the period from December 2017 to January 2018.

Model Calibration

River Salinity Model is the final tool to assess the impact on salinity intrusion due to SLR condition. That is why it is essential to carry out a good quality calibration. To quantify and qualify model performance we used goodness criteria by Moriasi et al. (2007) given by the formula

PBIAS(%) = (Measured mean – Model Mean)*100/Measured mean

General performance rating then is quantified in

Table 1.

Table 2: Model performance rating

PBIAS <±10	very good
±10≤ PBIAS ≤ ±15	good
±15≤ PBIAS ≤ ±25	satisfactory
PBIAS≥ ±25	unsatisfactory

Salinity model has been simulated for the period from December 2017 to January 2018 and mean salinity and PBIAS at the two measured locations were calculated. All the values are tabulated in Table 3. From the table, it is evident that model performance in the upstream and downstream fall under “Very Good” category. The model is now ready for further assessment. A baseline map of maximum salinity level along

Rajang River was prepared and furnished in Figure 9.From the results that maximum intrusion of 1ppt saline line is about 96km along Rajang river and 44km along BatangIgan river.

Table 3: Mean value from model result and measurement and PBIAS

Location	Mean value from measured data (PSU)	Mean value from simulated value (PSU)	PBIAS (%)	Performance
Location-1 (upstream)	0.184	0.166	9.8	Very Good
Location-2 (downstream)	2.62	2.81	-7.2	Very Good

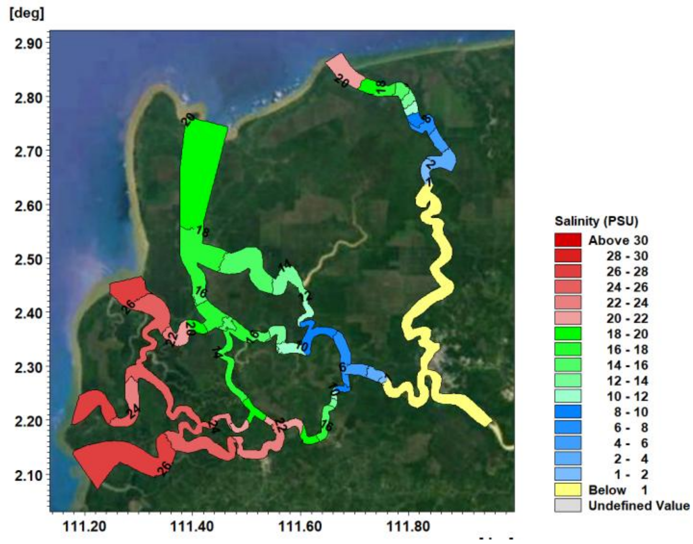


Figure 9: Salinity pattern in Rajang river network

V. Impact Assessment Due To Slr

1.5 Selection of SLR

A studycarried out by National Hydraulic Research Institute of Malaysia (NAHRIM), UniversitiKebangsaan Malaysia (UKM) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) to assess the regional sea level rise around Malaysia. The study finding is furnished in Figure 10. It is evident from the figure that near Rajang river estuary the sea level rise during 2100 is 0.72m. As this study gives the regional value of sea level rise, these values were used to simulate the models to assess salinity intrusion due to sea level rise.

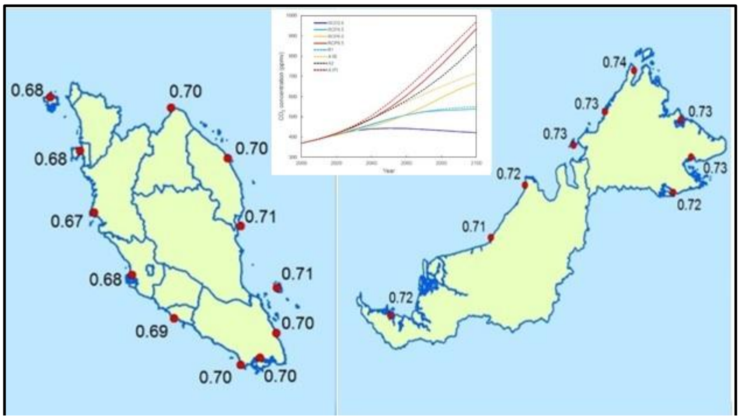


Figure 10: SLR during 2100 around Malaysia

1.6 Impact on Salinity Intrusion due to SLR

To assess the impact of SLR on salinity intrusion, Coastal Salinity Model was simulated with SLR condition which produced the downstream salinity boundary for River Model. Finally, river salinity model was simulated with SLR associated downstream boundary from the 2D model and zero salinity at the upstream boundary.The flow diagram of the salinity model is furnished in Figure 11.

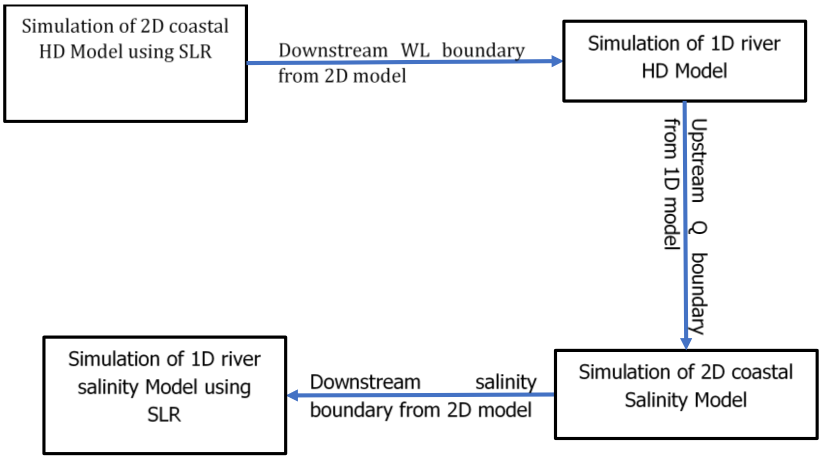


Figure 11: Flow diagram to calculate salinity intrusion through Rajang river

Figure 12 shows the comparison of salinity level along Rajang and BatangIgan river for zero SLR and 72cm SLR condition. It is evident from both the figures that there is a possibility of salinity intrusion in the Rajang and BatangIganriver due to sea level rise. It also found from the model result that 1ppt saline will intrude about 11km towards upstream in Rajang River and 9km in BatangIgan river if SLR is about 72cm increment.

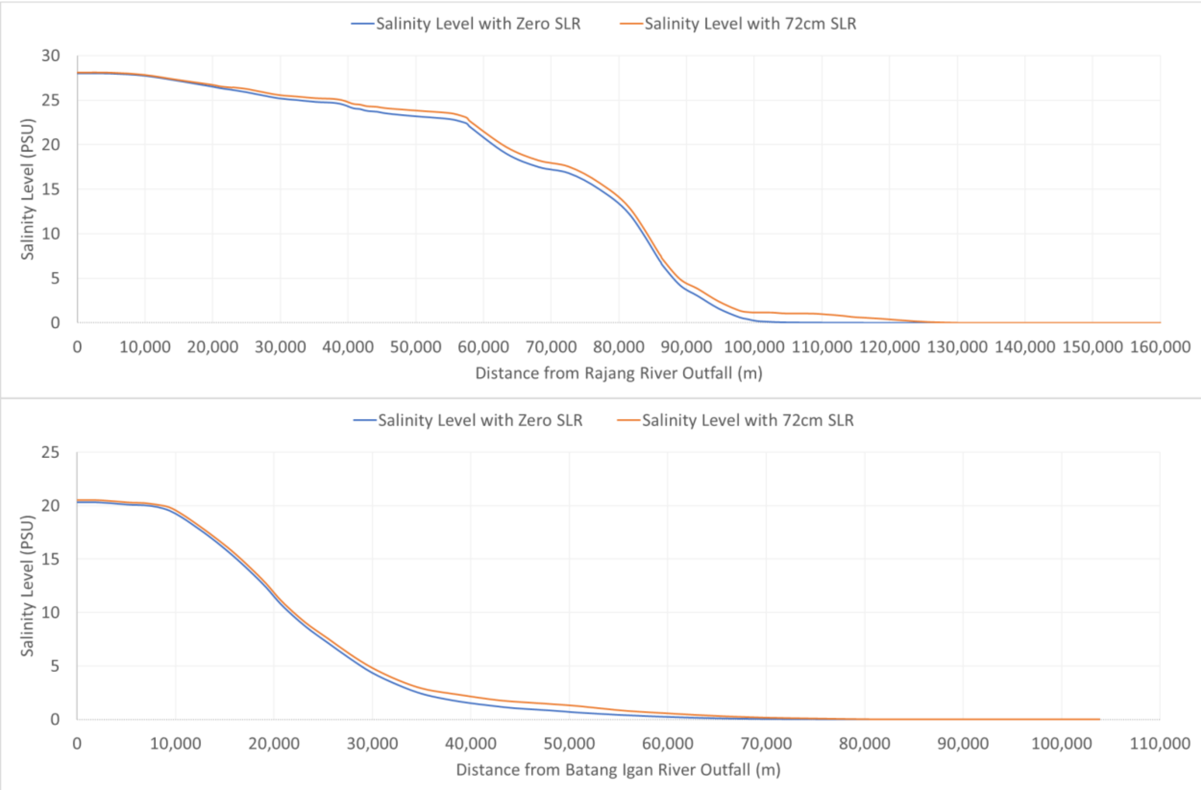


Figure 12: Salinity level along Rajang and BatangIganriver with and without SLR

VI. Conclusion

The main objective of the study is to assess the intrusion of saline water through Rajang river system due to SLR. The main tool which helps to carry out the study is numerical modelling approach. According to the World Economic Forum's *Global Risks Report 2016*, Climate change disaster is the biggest threat to global economy, and sea level rise is the most critical component under climate change issue. Sea level rise is accelerating and could reach 72 centimeters by century's end, and astonishingly it falls and applies withinour study interest area. It has been proven from the study findings that 1ppt of salinity contour will intrude further of11km towards upstream along Rajang river and approximately 9km in BatangIgan river due to 72cm SLR. It is a strong indication that saltwater intrusion might protrude further in the event of severe drought since the large area of Rajang and BatangIgan delta are low lying area. As a conclusion, without procrastinating, relevance body should start to visit the existing coastal infrastructure and to come out suitable and workablemitigation measures to make a climate resilient coastal environment.

Acknowledgement

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