Sediment transport model from Dumai River estuary to the Rupat Strait, Riau Province, Indonesia

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Abstract. The main purpose of this study was to describe a suspended sediment transport model from the Dumai River to the Rupat Strait, east coast of Sumatra Island, Riau Province, Indonesia. Suspended sediment samples were taken from 10 sampling points at 3 different depths (0.2, 0.6 and 0.8 m), in the Dumai River estuary, during low and high tides in August 2020. The suspended sediment transport was simulated using the Mud Transport model. The sediments from the Dumai River Estuary were distributed as far 4.24 km toward the western part of Rupat Strait during the low tide and the concentration of sediments ranged from 8 to 120 mg m^{-3}. Conversely, during the high tide, the sediments were distributed toward the eastern part of the strait as far as 4.40 km from the estuary, with a sediment concentration range of 8 to 112 mg m^{-3}. The sediment deposition can be recognized around Pelelangan Ikan (TPI) Port of Dumai City, which is located at the western part during the low tide. The hydrodynamic models play important role in the suspended sediment transport model in the strait.

Key Words: suspended sediment, current system, hydrodynamic model, tidal currents.

Introduction. The Rupat Strait is separated from the Malacca Strait by Rupat Island, located at the eastern coast of Sumatera Island, Riau Province, Indonesia. The strait is elongated and has northward-southward openings, with a length of about 88 km from north to south and a width of about 8 km. The outlets are leading to Malacca Strait (Rifardi & Badrun 2017; Rifardi et al, unpublished data). The strait is a semi-closed inland sea and it is influenced by mixed tide, predominantly semidiurnal (Nontji 2007; Rifardi et al, unpublished data).

Due to the current system flowing from the Malacca Strait and to the landuse change of the hinterland, the abrasion and sedimentation cause shoreline changes at the strait level. During flood tides, the current from the Malacca Strait flows into the Rupat Strait through the north and east parts of the Rupat Strait, while at ebb tides the current from the Rupat Strait flows into the Strait of Malacca through the north and east of the Rupat Strait (Isty & Rifardi, unpublished data).

The total sediment quantities supplied through river streams and artificial canals from the inland of Dumai City and Rupat Island to the Rupat Strait range between 4,999.312 and 7,013.002 ton $year^{-1}$ (Rifardi et al 2016). Such high transport rates lead to a high sedimentation and to sandbars formation at the estuary of the rivers, as shown by Rifardi & Badrun (2017), who reported a total sediments' transport rate of 926 ton day^{-1} in the Mesjid river, determining the sediment deposits into the estuary area to reach 2.4 cm $year^{-1}$.

The Dumai River Estuary is located in the eastern coast of central Sumatera Island, Riau Province, Indonesia. The estuary is connected to the Malacca Strait by the Rupat Strait. The Rupat Strait is characterized by high sedimentation rates due to the sediment discharged by the current system and the rivers (Rifardi 2001a). One of these rivers is Dumai River which has a rather large drainage area flow into the strait, through the estuary. The drainage area has been rapidly developed and became the the residential, industrial and of agricultural center of the community. About 52% of the riverbanks have become residential areas and the river flow is used for transportation, ports, fisheries and industry activities. Consequently, the river receives sediments from erosion of the drainage area as shown by the high concentration of suspended sediment ranging from 124 to 848 mg L^{-1}. The Dumai River Estuary is strongly influenced by a water discharge of 13.81 m^3 s^{-1} carrying lithogeneous sediments at a transport rate of 4,644.03 g s^{-1} and a sedimentation rate of 0.0175 gr cm^{-2} day^{-1} (Asrori et al 2016).

Since three decades ago, the Rupat Strait and its environs have become one of the most intensively studied area in terms of water quality, marine biology, oceanography and marine sediments by many authors (Rifardi 2001a,b; Rifardi 2009; Rifardi et al 2015; Rifardi 2015) who clarified the relation between the characteristics of sediments and environmental conditions. Studies of the anthropogenic impacts on water quality, sediments and benthic organisms were carried out by Alkhatib at al (2007), Amin et al (2007), Amin et al (2008), Badrun (2008), Amin et al (2009), Purba & Khan (2010), Nedi et al (2010), Wöstmann & Liebezeit (2012), Syahminan at al (2015), Putra et al (2016), Merian at al (2016). A study on the relationship between sediment characteristics, distribution of suspended sediments caused by sedimentation, abrasion and sediment supply, and degradation of Rupat Strait resources was carried out by Rifardi & Syahrul (2013). Significant studies in morphological and oceanographical aspects of the strait and its environs have been carried out by Musrifin (2011), Rifardi & Badrun (2017), Isty & Rifardi (unpublished data), Rifardi et al (unpublished data). However, there is no study concerning the sediment transport model. The main purpose of this study was to describe a suspended sediment transport model from the Dumai River to the Rupat Strait using data of oceanographic observation, sediment analysis and satellite images.

Material and Method

Study location. The area studied is restricted to the Dumai River Estuary and its surrounding area in the Rupat Strait, located within the lines of 01°41'15''N and 01°43'40''N latitude and 101°26'0''E and 101°26'30''E longitude (Figure 1). The studied area has a rather flat bottom topography, which gets gradually deeper northeastwards, under the influence of the water masses from the Dumai River and Malacca Strait, of the tidal currents and of the antrophogenic activities. The river, having rather large drainage areas, flows into the estuaryzone.

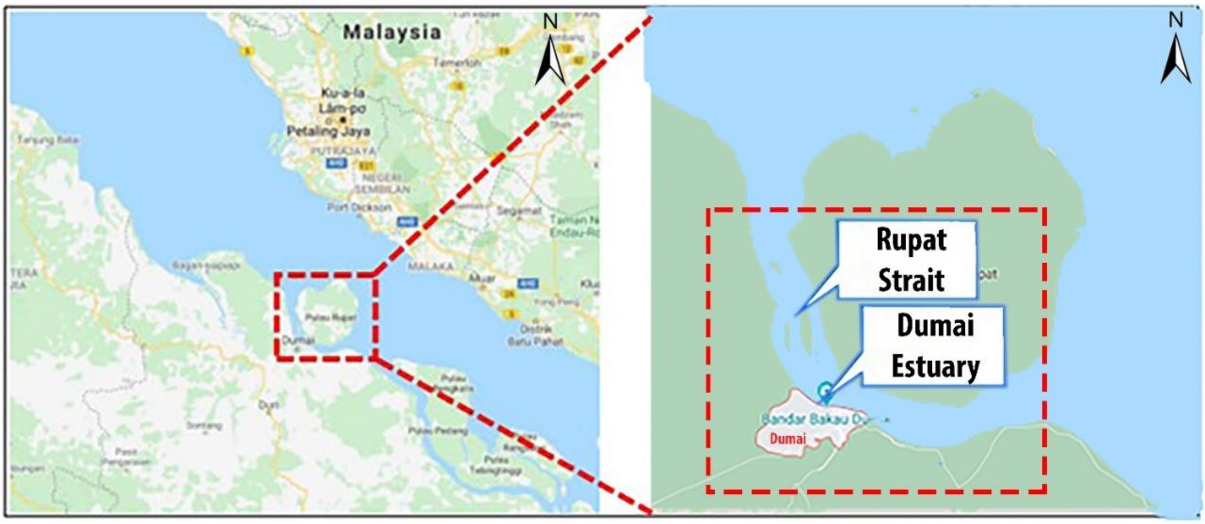

Figure 1. Index map of the study area.

The present study was conducted in the Rupat Strait from July to August 2020. The Dumai River Estuary was used as the location for observation and sampling points. These data included: suspended sediments, sediment supply from the Dumai River and oceanographic parameters. The sediment transport model followed a two-dimensional system, in which the vertical direction concentration is assumed to be uniform.

The satellite data processed in this study consisted of time series for 22 years, recorded within the P127/R59 study area (according to the Worldwide Reference System-2 path/row system), by using the Landsat Level 1 imagery, namely records from the Landsat 5 Thematic Mapper and from the Landsat 8 Data Continuity Mission. The analysis and interpretation of the data model consisted of: creating a mesh boundary, time series and point series. Area boundaries were made based on the area of study by entering coastline data and water bathymetry data.

Furthermore, the time series were the result of tidal elevation predictions which were saved in dfs0 format to create ocean currents models, while the point series were the result of a simulation that displays tidal data, current velocity and current direction, used to verify the model with field measurement data. The current hydrodynamic modeling was made using MIKE 21 fm software.

Data obtained from observations and measurements, such as oceanographic and coastal slope, are presented in a tabular form, while shoreline changes, ocean flow modeling, surface sediment distribution and suspension are presented in the form of two-dimensional (2D) maps, both of which are then discussed descriptively.

The Mud Transport (MT) module is an application for sediment transport simulation using clay as a base material. The Mud Transport (MT) module is devoted to non-cohesive modeling. The two-dimensional transport equation of the MT model is based on the convection-diffusion equation (Rizal et al 2012), namely:

$$\frac{\partial C}{\partial t}+\bar{U}\frac{\partial C}{\partial x}+\bar{V}\frac{\partial C}{\partial y}=\frac{\partial}{\partial x}\left(Dx\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(Dy\frac{\partial C}{\partial y}\right)+\alpha_1 C+\alpha_2$$

Where:
C-sediment concentration;
U and V-zonal and meridional velocity, respectively;
Dx and Dy-dispersion coefficient in x (zonal) and y (meridional) direction, respectively;
α1-decay coefficient;
α2-a sediment source.

The suspended sediment samples were taken from 10 sampling points at three different depths (0.2, 0.6, and 0.8 m) in the Dumai River estuary, at low and high tides (Figure 2).

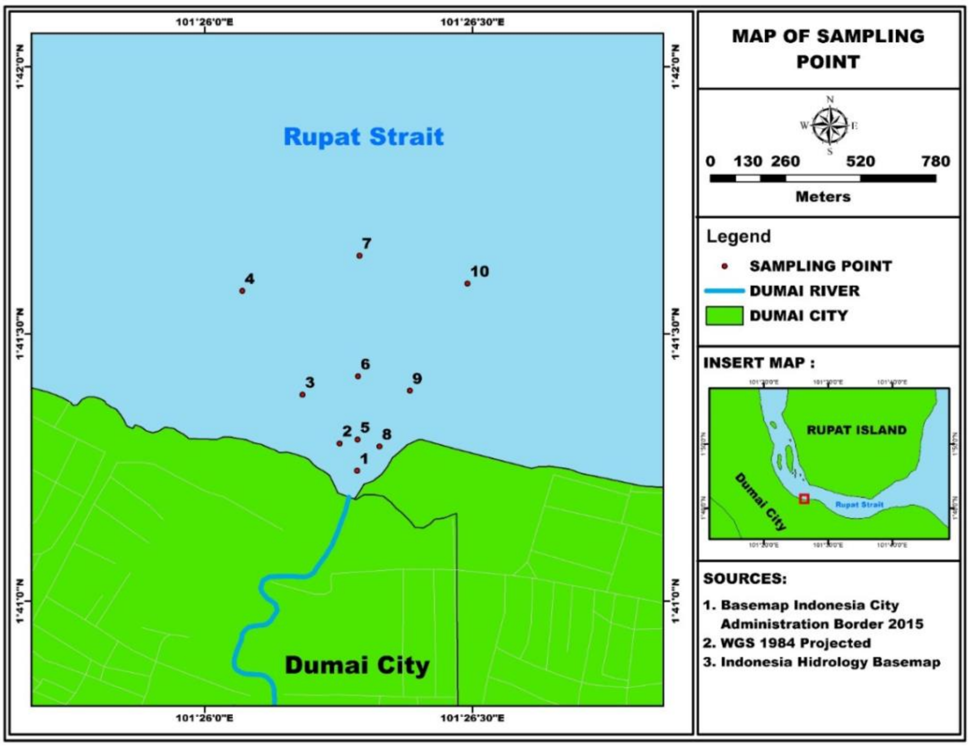

Figure 2. The sampling for total suspended sediments.

Tidal current were measured on 16-22 August 2020, using current drouge and tide bars. The data of currents and of suspended sediments were used as model input data and results of model validation are simulated using flow models. Model results' validation was performed using the Root Mean Square Error (RMSE) formula as following:

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(yi-y)^2}}{n}$$

Where:
yi-result of model;
y-result of field measurements;
n-total amount of data.

Results

Tidal model. Based on the tide chart in Figure 3, it can be seen that the Dumai River Estuary is influenced by the semidiurnal tide, where the high tide reaches 1.26 meters and the low tide -1.37 meters.

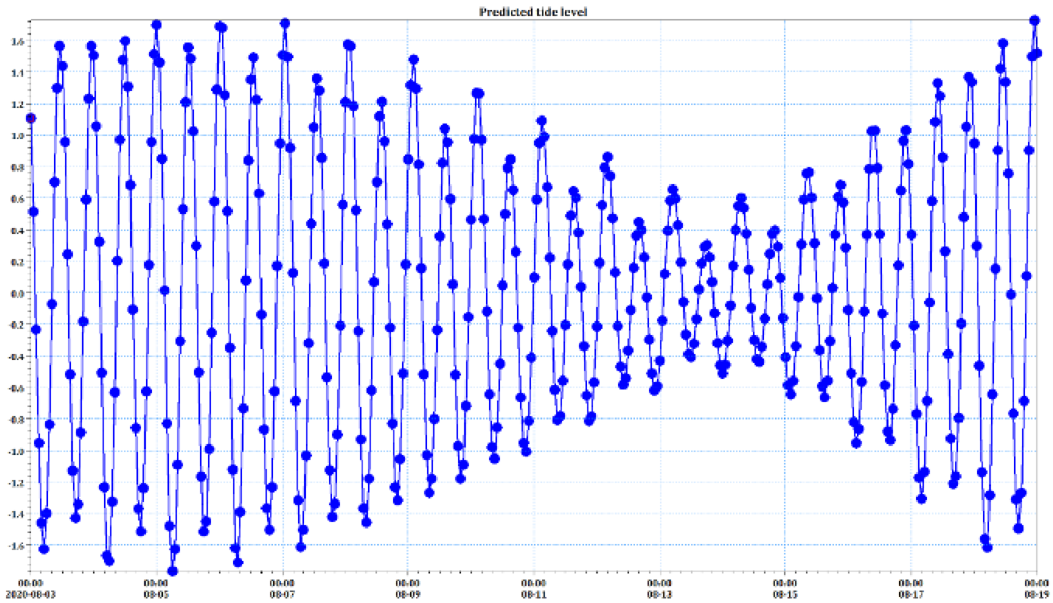

Figure 3. Tidal graph of the Dumai River Estuary.

The tidal prediction data obtained the Dumai River Estuary were processed using the Admiralty method, with observation data of the tidal for 15 or 30 days. The results can be seen in Table 1.

Table 1

Tidal harmonic components

Component	*Amplitude*	*Phase difference*
S0	123.27	MSL
M2	88.53	-185.09
S2	26.30	2.73
N2	40.46	-79.94
K2	6.05	2.73
K1	10.24	326.82
O1	14.43	-71.14
P1	3.38	326.82
M4	5.31	-443.20
MS4	7.26	-192.58

The results of tidal data processing using the Admiralty method obtained tidal harmonic constants, namely S0, M2, S2, N2, K1, O1, M4, MS4, K2, P1 (Table 1). Based on the processing, the type of tide in the Rupat Strait showed the Formzhal number value of 0.215 indicating a semidiurnal tide, meaning that high tide as well as low tide occur two times a day.

Field/observation data was verified through a numerical model and the result indicated the extent of the deviation from the simulation. A model can be considered to be valid if the results of the simulation have a pattern that is consistent with field data. In this model the tide data was verified against field data by comparing the tide elevation data from Deshidros and the measured values, at each sampling point, as shown in Figure 4 and Figure 5.

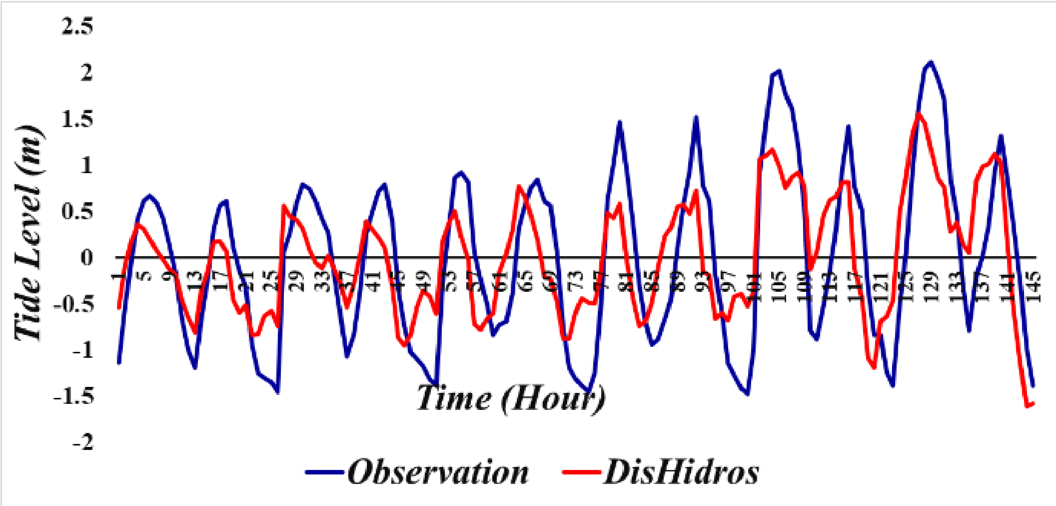

Figure 4. Result of validation of tidal data.

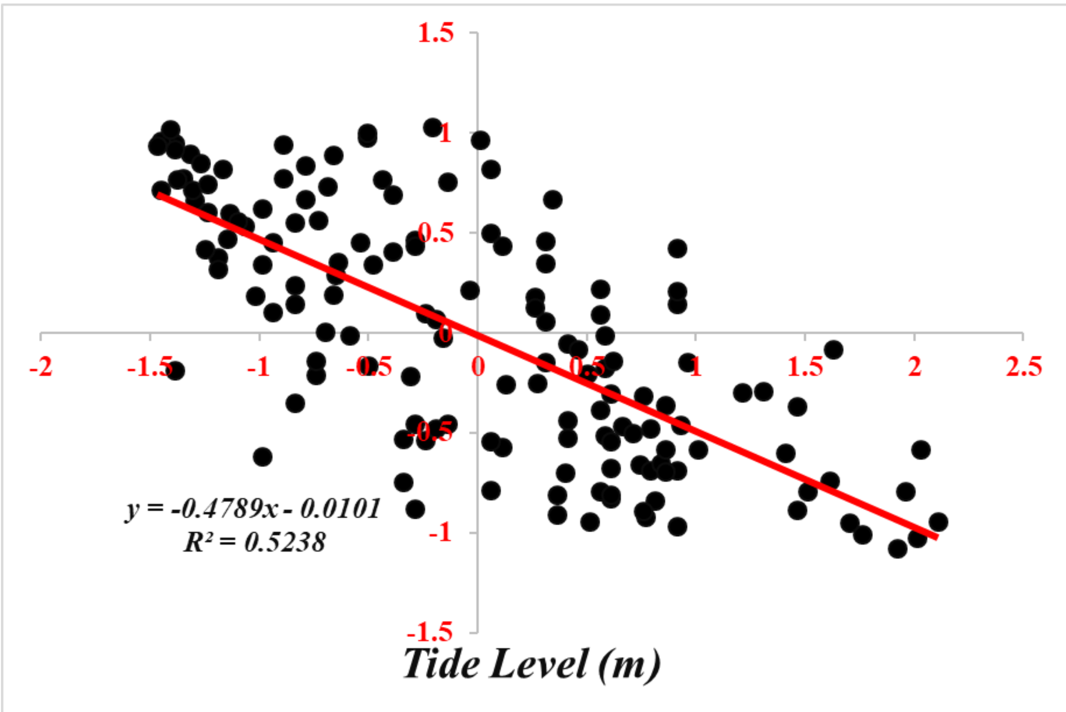

Figure 5. Scatter plot graph of tide level of model and of observation.

Tidal pattern simulation. Current velocity in Dumai River Estuary is influenced by the position of the sampling point, weather, wind and waves. At high tide the current flows from Rupat Strait toward the North-East (the estuary) with a velocity ranging from 0.017 to 0.73 m s^{-1}, whereas at low tide it flows from the estuary toward the South-West of the strait with a velocity ranging from 0.1 to 0.28 m s^{-1}, as shown in Table 2.

Table 2

Comparation the velocity and direction of current between the model and field observations at each sampling point

Sampling point	Model				Field observations			
	Velocity ($m\ s^{-1}$)		*Direction (degree)*		*Velocity ($m\ s^{-1}$)*		*Direction (degree)*	
	High tide	*Low tide*	*High tide*	*Low tide*	*High tide*	*Low tide*	*High tide*	*Low tide*
1	0.36	0.18	30	275	0.40	0.18	45	257
2	0.10	0.15	122	329	0.12	0.16	45	317
3	0.25	0.24	120	271	0.21	0.23	45	270
4	0.56	0.16	90	220	0.73	0.16	45	223
5	0.35	0.39	67	303	0.25	0.10	45	303
6	0.28	0.26	45	263	0.25	0.26	45	265
7	0.25	0.21	45	217	0.17	0.23	45	225
8	0.24	0.29	45	292	0.27	0.28	45	297
9	0.32	0.30	45	263	0.10	0.28	45	225
10	0.15	0.28	45	223	0.06	0.26	45	225

The results of hydrodynamic modeling of tidal currents in the Rupat Strait can be seen in Figures 6 and 7. Based on the simulation results of the hydrodynamic model, it is known that the current direction in Rupat Strait cause waters flowing back and forth during high and low tide, respectively. The model also shows that the current velocity in the Rupat Strait ranges from 0.06 to 0.84 m s^{-1} during high tide and from 0.04 to 0.60 m s^{-1} at low tide. The results of the present study are different from the results of Mubarak et al (2017), which report tidal current velocities ranging from 0.2 to 0.45 m s^{-1} in the Rupat Strait and from 0.04 to 0.33 m s^{-1} in the Dumai River Estuary.

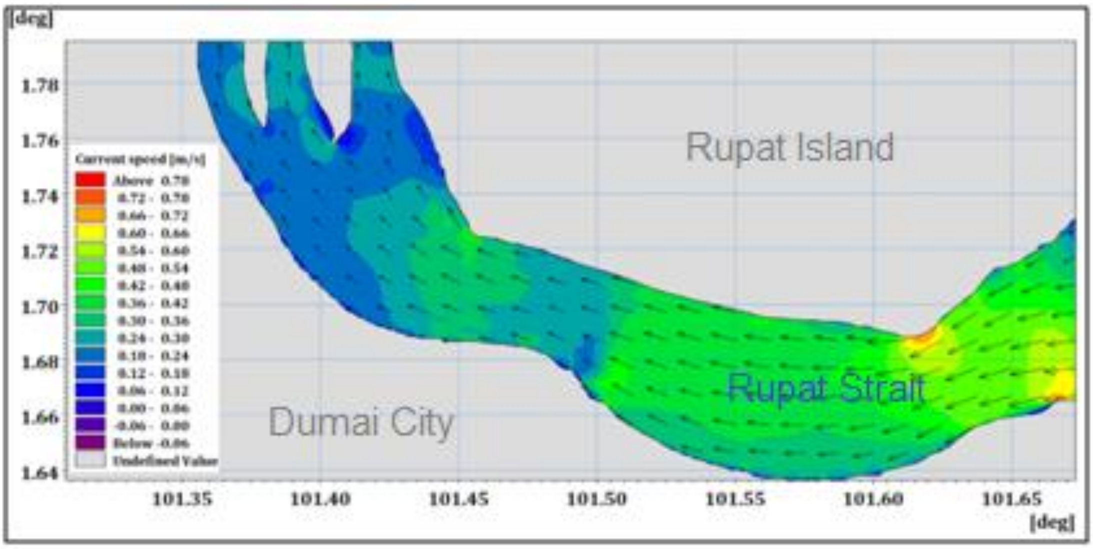

Figure 6. Hydrodynamic model at low tide.

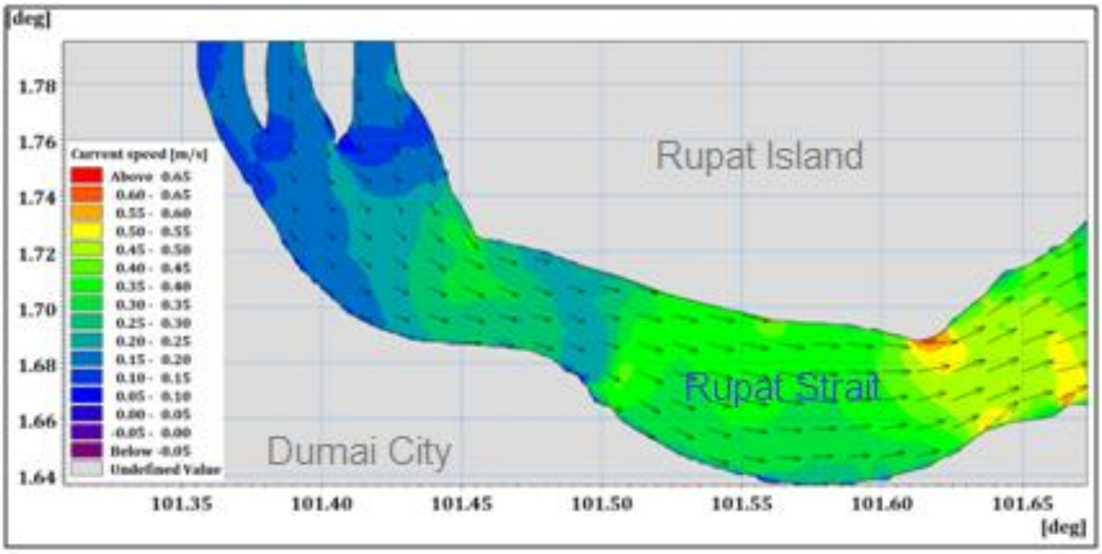

Figure 7. Hydrodynamic model at high tide.

Based on the hydrodynamic model (Figure 6 and 7), the current from Malacca Strait flows into the Rupat Strait through the east to west parts during low tide, and during high tide the current flows through the west to east parts of the Rupat Strait. This current pattern dominantly influences the distribution pattern of suspended sediments, causing the suspended sediment transport model to be different during high and low tides. The distribution of the sediments derived from the Dumai River Estuary into the Rupat Strait depends on the spatial gradients of the river.

Model of suspended sediment transport. In general, suspended sediment concentration (SSC) ranges from 119 to 848 mg L^{-1} during high tide and from 124 to 235 mg L^{-1} during low tide, as shown in Table 3.

Table 3

Suspended sediment concetration (SSC: mg L^{-1}) at sampling point in each depth

Sampling point	*High tide*				*Low tide*			
	Depth (m)	*SSC 0.2 m*	*SSC 0.6 m*	*SSC 0.8 m*	*Depth (m)*	*SSC 0.2 m*	*SSC 0.6 m*	*SSC 0.8 m*
1	2.74	203	195	160	3.2	139	144	150
2	3.8	624	153	119	3.5	160	150	160
3	6.72	165	143	128	8.48	147	141	153
4	18.6	176	180	160	15.5	133	131	124
5	3.7	241	212	190	3.67	150	142	151
6	13.8	229	265	196	10.2	143	148	148
7	22.5	130	215	350	15.8	147	142	159
8	6.52	848	221	241	4.67	142	148	235
9	18.3	295	231	269	8.2	156	157	132
10	25	271	249	277	15.7	145	160	199

The suspended sediments derived from the Dumai River Estuary distribution into the Rupat Strait is a function of the velocity and direction of the tidal currents, meaning that the suspended sediment transport models are strongly affected by the hydrodynamic model. The models at high and low tides are shown in Figure 8 and 9, respectively.

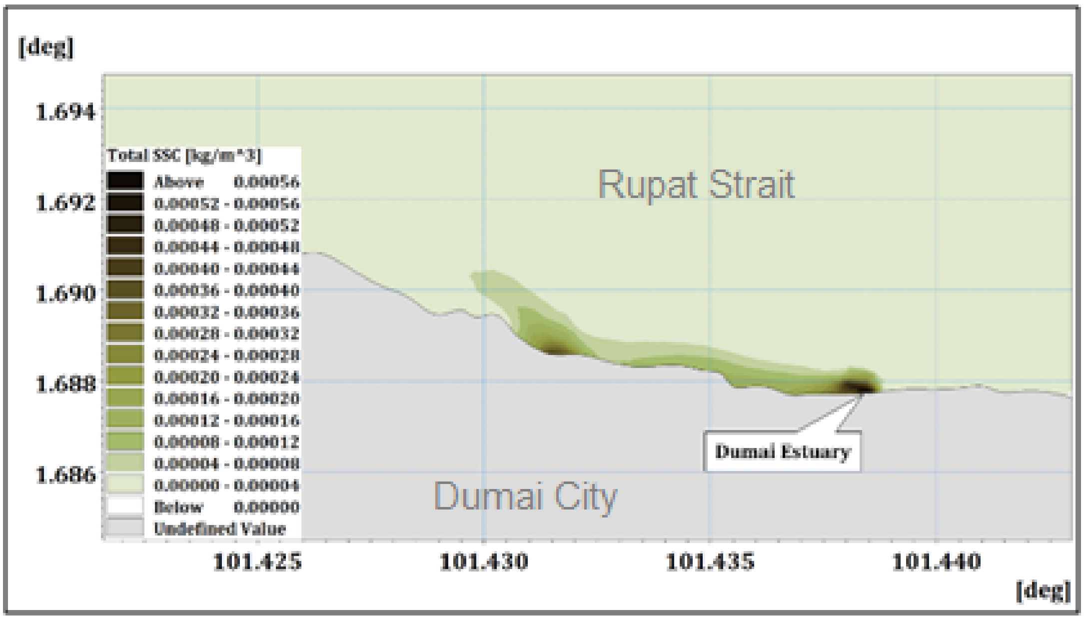

Figure 8. Model of suspended sediments at low tide.

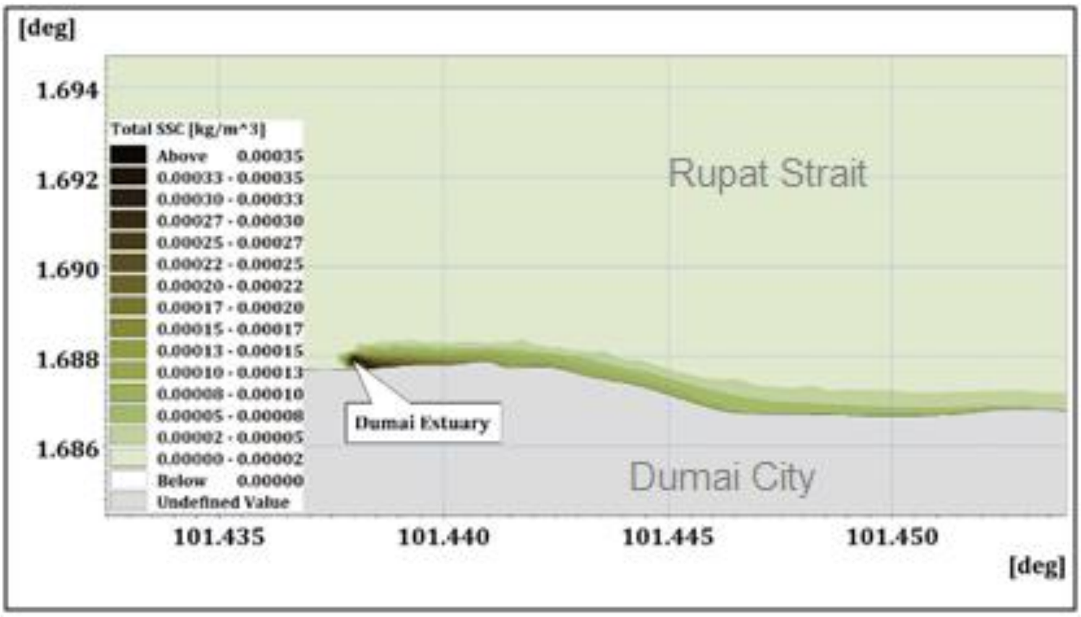

Figure 9. Model of suspended sediments at high tide.

The sediments from the Dumai River Estuary are distributed as far as 4.24 km toward the western part of Rupat Strait during the low tide, and the concentration of sediments range from 8 to 120 mg m^{-3}. Contrastingly, during the high tide, the sediments are distributed toward the eastern part of the strait as far as 4.40 km from the estuary with a sediment concentration ranges 8 to 112 mg m^{-3}. The sediment deposition can be identified around TPI Port of Dumai City which is located at the Western part during the low tide (Figure 10).

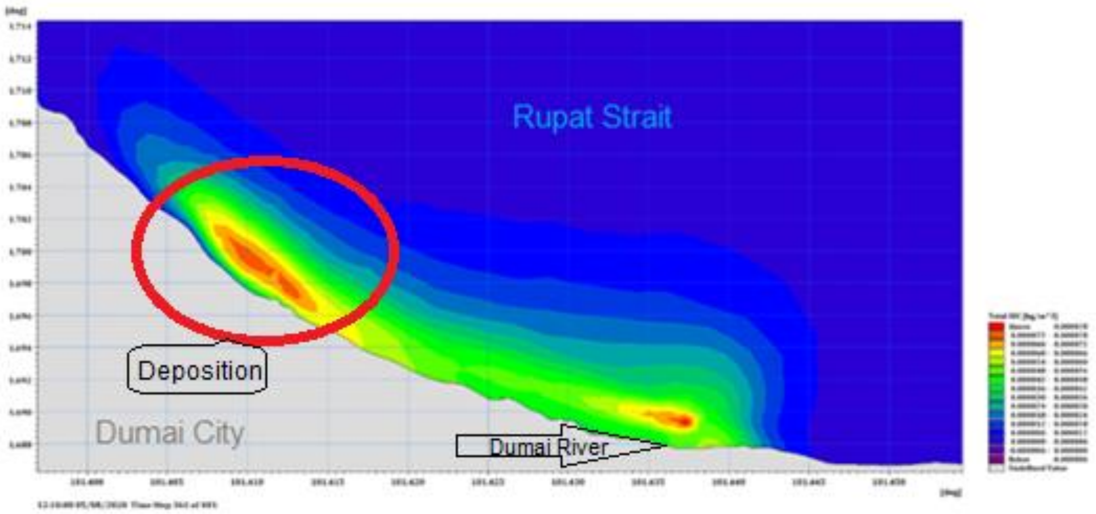

Figure 10. Sediment deposition derived from Dumai River.

Discussion. The Rupat Strait is characrized by semidiurnal tides, as shown by a Formzhal Number of 0.215. The results of this study are in harmony with Mubarak et al (2017), who explain that there are two daily tides and ebbs in this strait, although they differ in the current velocity as explained above. This variation is thought to be caused by differences in oceanographic patterns that occur in the strait and estuary.

The hydrodynamic models (Figure 6 and 7) show the same models which were found by Nedi (2010) and Tarigan et al (2014), who explain that current from Malacca Strait flows through the Rupat Strait from the east to west and turns to the north during the ebb tide, and reverses during the flood tide.

The current pattern is also influenced by the depth of the waters: shallower waters with higher elevations causea higher current velocity than deep water. This pattern also occurs in the Rupat Strait and Estuary of the Dumai River. Rifardi et al (1998) explained that tidal currents in strait waters are influenced by the water depth and affect the distribution of bottom sediments. Pelling et al (2013) explain that changes in bathymetrics cause changes in the sea level elevation and affect the tidal velocity and changes in coastal sediment transport capacity. The depth of Rupat Strait has increased to 1.5-2.7 m in 28 years, even though the strait receives a great amount of fine grained sediment discharged by rivers and channels from the hinterland of Dumai City and Rupat Island. The rapid development of the city of Dumai and Rupat Island resulted in large erosion of surface soil, the latter being eventually transported through these rivers and canals (Rifardi & Syahrul 2013, 2014; Rifardi 2015).

The suspended sediment transport models in the Rupat Strait are strongly influenced by the hydrodynamic model built by the current pattern as described above. The suspended sediments originating from the Dumai River Estuary are transported into the Rupat Strait, their distribution's spatial patterns (direction and distance) depending on the velocity and direction of tidal currents as expalined above. Most of the sediment does not settle on the bottom of the strait but are further transported to the strait by tidal currents flowing from the Malacca Strait (Rifardi et al, unpublished data). At the low tide, the sediments are distributed as far as 4.24 km toward the western part of Rupat Strait with the concentration of sediments ranging from 8 to 120 mg m^{-3}, due to a current with a velocity ranging from 0.04 to 0.60 m s^{-1}. Contrastingly, during the high tide, the sediments are distributed toward the eastern part of the strait as far as 4.40 km from the estuary with a sediment concentration ranging from 8 to 112 mg m^{-3}, due to a current with a velocity ranging from 0.06 to 0.84 m s^{-1}. Transport directions of sediments are mostly controlled by current circulation (Wei et al 2004; Lobo et al 2008). The sediments resuspension and deposition occur continuously until finally settling in an area that is protected from waves (Bainbridge et al 2012). The feature is also found by Setiady & Ediar (2015) in surficial sediment of the Rangsang Island Indonesia, under the influence of tidal currents flowing from the Malacca Strait, shown by the presence of fine to coarse grained sediment indicating that the island is under the influence of moderate to strong currents and waves, causing the sediment to be transported along the coast to offshore areas. Tidal current dynamics and waves have a dominant effect on the sediment distribution and deposition (Galib & Rifardi 2020).

The sediments from the Dumai River Estuary are distributed to the Rupat Strait during the low tide and deposited in the western part of the strait, around the TPI Port of Dumai City, which is characterized by stable hydrodynamics and low sediment transport rates (Afrizam et al 2015). The western part of the Rupat Strait has the lowest current velocity at low tide (Isty & Rifardi, unpublished data). The western part is also characterized by a weak sediment transport flow resulting in bathymetry changes due to the high sedimentation rate. This pattern is confirmed by the still ongoing process of small island clusters formation in the western part of the Rupat Strait.

Conclusions. The current patterns play an important role in the distribution of suspended sediments, which is explained by hydrodynamic and suspended sediments' distribution models in the Rupat Strait. The sediments from the Dumai River Estuary are transported toward the western part during the low tide and toward the eastern part of the strait during the high tide. The models comparison reveals that suspended sediment transport models are strongly influenced by the velocity and direction of the tidal currents.

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