Profile of suspended sediment concentration in narrow channel

Rifardi, Mubarak

Department of Marine Sciences, Faculty of Fishery and Marine Sciences, Riau University, Riau, Indonesia. Corresponding author: Rifardi, rifardi@lecturer.unri.ac.id

Abstract. The objective of this study was to describe the distribution of suspended sediment concentration (SSC) horizontally and vertically in the Rupat Strait as narrow channal. Suspended sediment samples were taken from 60 stations at 3 different depths (surface, middle, and bottom of water column) on the strait in August 2018. The geographic distribution of SSC was mapped using software ArcMap 10.4 and interpolated using IDW tools. The vertical distribution of suspended sediment in the strait varies, indicating that there is no parallel relationship between the difference in the depth of the water column and the SSC. In general, the SSC is higher at the bottom of the water column than at the surface and middle of the column. The type of suspended sediment is a graded (stratified) suspension but is not a gradation caused by differences in the particle size of the sediment, but a graded suspension caused by differences in concentration as a result of bed load erosion due to bottom currents. The horizontal distribution indicates that the northern and eastern parts have lower concentration than in the center part of the Rupat Strait. In the north part (stations 1-18), the SSC range was 36-115.3 mg L^{-1}, while in the center part (stations 19-42) the range was 43.2-180.7 mg L^{-1}, and in the east part the range from 45.3 to 98.1 mg L^{-1}. This condition illustrates that the current velocity in the north and east is higher than in the middle of the Rupat Strait, resulting in sediment transport out of the strait.

Key Words: bottom current, Rupat Strait, sediment concentration, sediment transport.

Introduction. The Rupat Strait is separated from 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 lead to the Malacca Strait (Rifardi & Badrun 2017; Rifardi et al 2020). The strait is a semi-closed inland sea and it is influenced by mixed tide, predominantly semidiurnal (Nontji 2007; Rifardi et al 2020).

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 in Rifardi et al 2020).

Total sediment supply from the inland of Dumai City and Rupat Island to the Rupat Strait through river streams and artificial canals is as large as 4,999,312-7,013,002 ton $year^{-1}$ (Rifardi et al 2016). This condition leads to high sedimentation and sandbar formation at the estuary of the rivers, as reported by Rifardi & Badrun (2017). They clarify that total sediments supplied by the river was of 926 ton day^{-1} hence the sediment deposited into the estuary area was 0.024 m $year^{-1}$.

The Dumai River estuary is located in the eastern coast of central Sumatera Island, Riau Province, Indonesia. The estuary is connected to Malacca Strait by the Rupat Strait. The Rupat Strait is characterized by high sedimentation rates due to sediment discharged by current system and rivers (Rifardi 2001). One of the rivers is Dumai River which has rather large drainage area flow into the strait through the estuary. The drainage area has been rapidly developed and became the center of community residents, industries, and of agriculture. About 52 percent 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 high concentration of suspended sediment range 124-848 mg L^{-1}. The Dumai River estuary is strongly influenced by the mass of water with a water discharge of 13.81 m^3 s^{-1} which carried out lithogeneous sediments of 4,644.03 g s^{-1} and the sediments are deposited as much as 0.0175 g cm^{-2} day^{-1} (Asrori et al 2016).

In the last three decades, the Rupat Strait and its environs have become one of the most intensively studied areas in relation to water quality, marine biology, oceanography, and marine sediments (Rifardi 2001; Alkhatib et al 2007; Amin et al 2007, 2009a, 2009b; Purba & Khan 2010; Nedi et al 2010; Musrifin 2011; Wöstmann & Liebezeit 2012; Rifardi et al 2015; Syahminan et al 2015; Merian et al 2016; Rifardi & Badrun 2017). These studies did not discuss the geographical distribution of suspended sediment concentration (SSC) horizontally and vertically in the strait. The main purpose of this study is to describe the distribution of SSC horizontally and vertically in the Rupat Strait as narrow channal.

Material and Method. This study was conducted in the Rupat Strait in August 2018 (Figure 1). The outlets are leading to Malacca Strait. The studied area has a rather flat bottom topography, under the influence of the water masses from the rivers and Malacca Strait, of the tidal currents and of the antrophogenic activities. The rivers, having rather large drainage areas, flow into the strait.

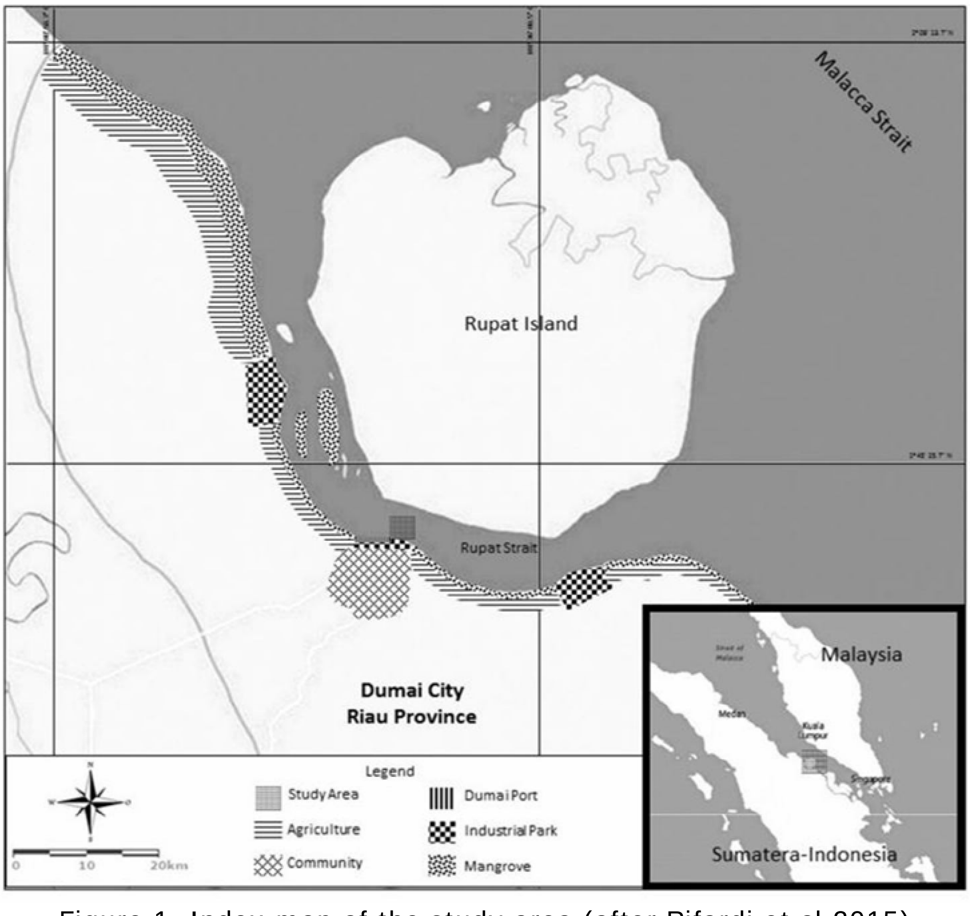

Figure 1. Index map of the study area (after Rifardi et al 2015).

Suspended sediment samples were taken from 60 stations at 3 different depths (surface, middle, and bottom of the water column) using vandorm bottle sampler (Figure 2). Positions of the stations were determined using the global positioning system (Table 1).

Suspended-sediment concentration was analyzed based on analytical method of American Society for Testing and Materials (ASTM) Standard Test Method D 3977-97 which lists three methods that result in a determination of SSC values in water and wastewater samples (Gray et al 2000).

The geographic distribution of SSC was mapped using software ArcMap 10.4 and interpolated using the tools of Inverse Distance Weighting (IDW). The data obtained from the results of the SSC analysis in the physical oceanographic laboratory, department of marine science, Riau University along with its coordinates were inputted into Ms. Excel. Fuhermore, the value of the coordinates was converted from the Degree Minute Second (DMS) format to the Decimal Degree (DD) format. In the next stage, the data was inputted into ArcMap 10.4 software for interpolation using Inverse Distance Weighting (IDW) (Spatial Analyst) tools.

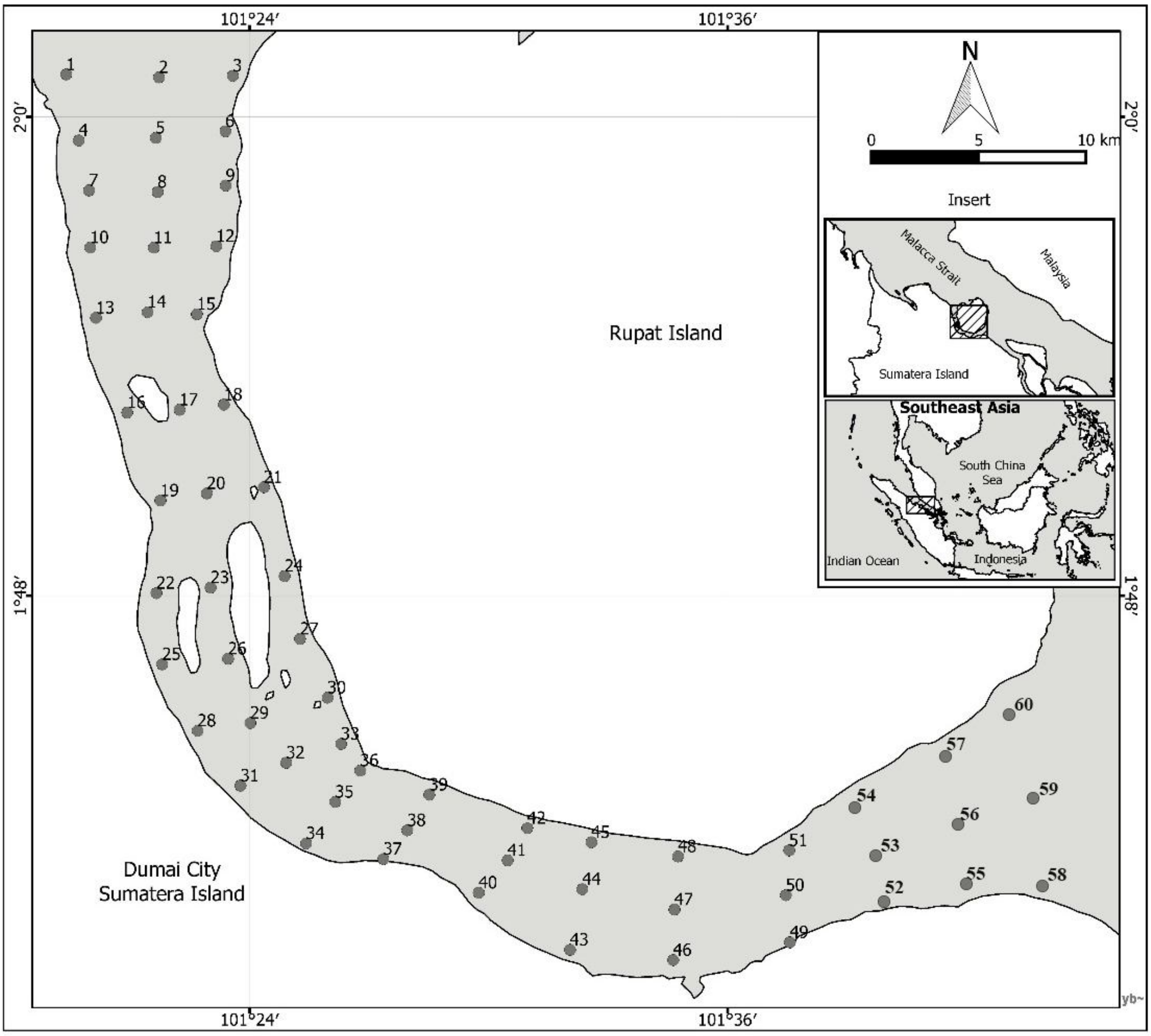

Figure 2. Map of the stations for SSC samples and oceanographic observation.

Table 1

The geographic coordinates (longitude and latitude) of the stations

Station	*Latitude (N)*	*Longitude (E)*	*Station*	*Latitude (N)*	*Longitude (E)*
1	2°0'31.2092"	101°19'37.6431"	31	°43'6.0001"	101°23'50.2348"
2	2°0'29.0677"	101°21'36.4972"	32	1°43'40.2643"	101°25'4.6525"
3	2°0'25.8554"	101°23'24.6437"	33	1°44'18.3626"	101°26'14.8734"
4	1°59'14.1147"	101°19'37.6431"	34	1°42'19.208"	101°24'34.0288"
5	1°59'14.1147"	101°21'35.8547"	35	1°42'56.8986"	101°25'44.2705"
6	1°59'14.1147"	101°23'31.4966"	36	1°43'38.0157"	101°26'51.0857"

7	1°57'46.7409"	101°20'3.3413"	37	1°41'26.3125"	101°26'51.6211"
8	1°57'46.7409"	101°21'37.1397"	38	1°42'8.6075"	101°27'33.916"
9	1°57'49.3107"	101°23'22.5022"	39	1°42'58.3977"	101°28'13.5341"
10	1°56'21.9369"	101°20'12.3357"	40	1°40'38.6638"	101°29'41.8716"
11	1°56'24.5067"	101°21'37.1397"	41	1°41'19.7809"	101°30'20.4188"
12	1°56'27.0765"	101°23'10.938"	42	1°42'6.8942"	101°30'55.5397"
13	1°54'57.1329"	101°20'17.047"	43	1°38'49.0183"	101°33'17.7363"
14	1°55'0.131"	101°21'38.4246"	44	1°39'59.26"	101°33'9.1702"
15	1°54'58.8461"	101°22'40.1002"	45	1°41'23.2073"	101°33'0.6041"
16	1°52'1.5287"	101°21'7.5868"	46	1°38'38.739"	101°36'8.2008"
17	1°52'38.791"	101°22'19.5417"	47	1°39'58.4034"	101°35'45.9291"
18	1°53'1.9194"	101°23'12.2229"	48	1°41'9.5016"	101°35'21.9441"
19	1°50'4.602"	101°22'4.6367"	49	1°39'54.1203"	101°38'54.3824"
20	1°50'29.1866"	101°23'12.4799"	50	1°40'41.6654"	101°38'18.6009"
21	1°50'51.4583"	101°24'28.2039"	51	1°41'27.4054"	101°37'43.9968"
22	1°47'59.2805"	101°21'48.7038"	52	1°40'23.0315"	101°40'36.0461"
23	1°48'11.273"	101°23'12.6512"	53	1°41'23.3365"	101°39'46.7484"
24	1°48'37.8278"	101°24'54.5873"	54	1°42'19.3157"	101°39'11.6276"
25	1°46'1.0689"	101°22'9.2624"	55	1°40'32.24"	101°42'10.5726"
26	1°46'19.0576"	101°23'23.7871"	56	1°41'51.0477"	101°41'29.4555"
27	1°47'1.8879"	101°25'13.4327"	57	1°43'11.5687"	101°40'46.6252"
28	1°44'5.4271"	101°23'7.5116"	58	1°40'42.5192"	101°43'58.5049"
29	1°44'34.5517"	101°24'35.742"	59	1°42'25.7403"	101°42'59.3991"
30	1°45'28.5179"	101°25'46.8403"	60	1°44'5.5349"	101°42'16.5688"

Results. The results of suspended sediment samples analysis from 60 stations at 3 different depths (surface, middle, and bottom of the water column) are shown in Table 2.

Table 2

Suspended sediment concentration at 3 different depths (surface, middle, and bottom of the water column)

Station	*Surface (mg L^{-1})*	*Middle (mg L^{-1})*	*Bottom (mg L^{-1})*	*Average (mg L^{-1})*	*Station*	*Surface (mg L^{-1})*	*Middle (mg L^{-1})*	*Bottom (mg L^{-1})*	*Average (mg L^{-1})*
1	56.4	91.6	116.6	88.2	31	47	64.2	83.4	64.9
2	28.8	53	26.2	36.0	32	61.6	45	69.2	58.6
3	42.6	33	36	37.2	33	78.8	90	106.2	91.7
4	71.6	79.4	161.8	104.3	34	46.8	88.4	114.8	83.3
5	85.2	71.6	189	115.3	35	46.4	73.6	74.2	64.7
6	67	72.8	77.4	72.4	36	57	66.6	117.2	80.3
7	67	75.2	131.6	91.3	37	73.6	88.2	158.4	106.7
8	64.2	68.4	93.8	75.5	38	55.8	74.8	61.8	64.1
9	63	72.8	78	71.3	39	77.8	86.6	95	86.5
10	61.6	72	94.4	76.0	40	100.8	150.2	291	180.7
11	69	86.8	89.4	81.7	41	90.6	107	110	102.5
12	53.8	63.8	73.8	63.8	42	80.8	75.6	117	91.1
13	46.2	70.6	146.4	87.7	43	72.6	100	121.8	98.1
14	47	74.2	215.6	112.3	44	52.4	76	79.4	69.3
15	67.8	68.4	56.2	64.1	45	41	78.4	109.6	76.3
16	66.4	81.2	92.2	79.9	46	49.2	57.4	94.8	67.1
17	65	48.8	50.2	54.7	47	44	54.2	85.6	61.3
18	39.4	74	76.8	63.4	48	44.2	67	40	50.4
19	56.8	53	77	62.3	49	38.8	63.2	107	69.7
20	61.8	62	78.6	67.5	50	69.2	57.8	56	61.0
21	60	63	89.8	60	51	73.2	86	106.2	88.5
22	59.4	76.6	106.2	59.4	52	50.2	59.8	74.8	61.6
23	41.4	85.6	73.2	41.4	53	62.4	51	59.4	57.6

24	70.8	92.6	39.2	70.8	54	61.4	65.4	90.2	72.3
25	41	46.4	42.2	41	55	49	98.4	105.8	84.4
26	67.8	81.4	104.2	67.8	56	72.4	58.4	71	67.3
27	106.2	94.4	122.8	106.2	57	64	69.8	71.6	68.5
28	51.4	71	87.4	51.4	58	33.2	64	70.4	55.9
29	50.2	92.4	177.6	50.2	59	38.4	56.4	41	45.3
30	63.4	71.6	73	63.4	60	68.8	60.4	128.2	85.8

The vertical distribution of suspended sediment in the waters of the Rupat Strait varies and shows no parallel relationship between the difference in the depth of the water column and the concentration of suspended sediment in each water column. However, in general the concentration of suspended sediment is higher at the bottom of the water column than at the surface and in midlle of the column. There are only 5 (five) stations that have a higher concentration in the surface layer of water compared to the middle and bottom layers of the water, namely stations 3, and 17 located adjacent to the northern coast and stations 50, 53 and 56 located along the strait in the eastern part of the Rupat Strait (Table 2 and Figure 3) and their distribution can be seen in Figure 4.

Higher suspended sediment concentrations in the middle than at the surface and bottom of the water column were found at only 7 (seven) stations, namely stations 2, 15, 23, 24, 25, 38 and 48 (Table 2), and the distribution can be seen in Figure 5. Stations 2 and 15 are located in the north and stations 23, 24, 25, 38 and 48 are located along the center of the Rupat Strait.

The suspended sediment concentration was dominantly (78.33%) higher at the bottom than at the surface and middle of the water column. The difference in concentration indicates that the type of suspended sediment in the strait (narrow channel) is a graded suspension.

The type is assumed due to the energy of the bottom current is stronger for transporting sediment compared to the energy of the solidity of the sediment. In other words, the current erodes the bottom sediment into suspended sediment. Rifardi & Mubarak (2013) explained that bottom surface sediments were eroded by strong bottom currents causing the sediments to become suspended sediments. The distribution of suspended sediment on the bottom of the waters can be seen in Figure 6.

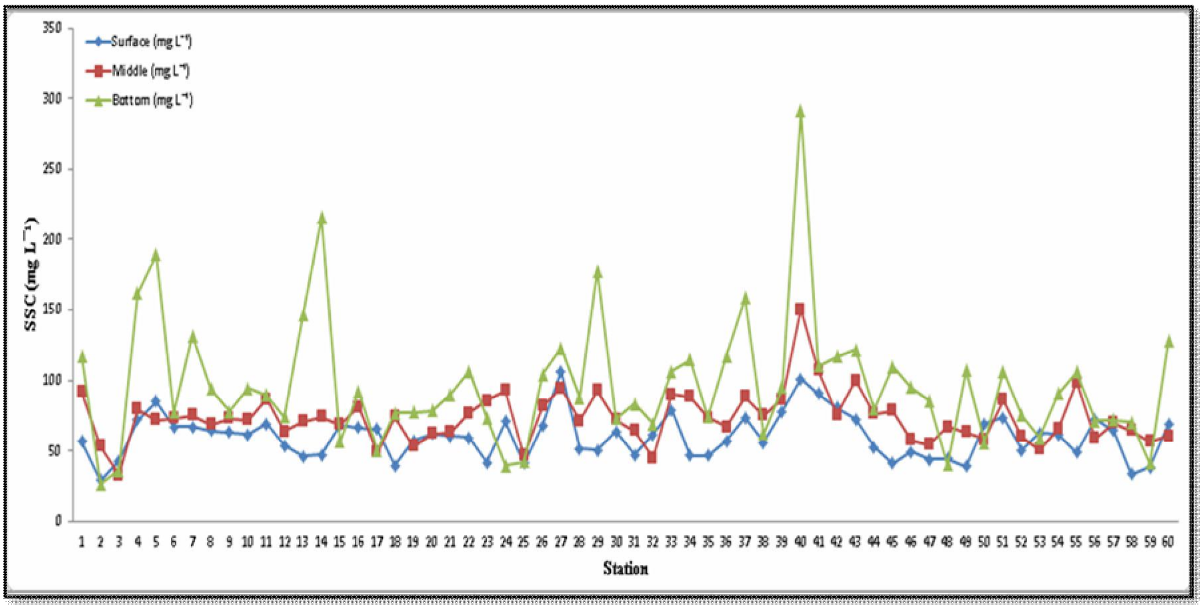

Figure 3. The variation of SSC at 3 different depths (surface, middle, and bottom of the water column) each station.

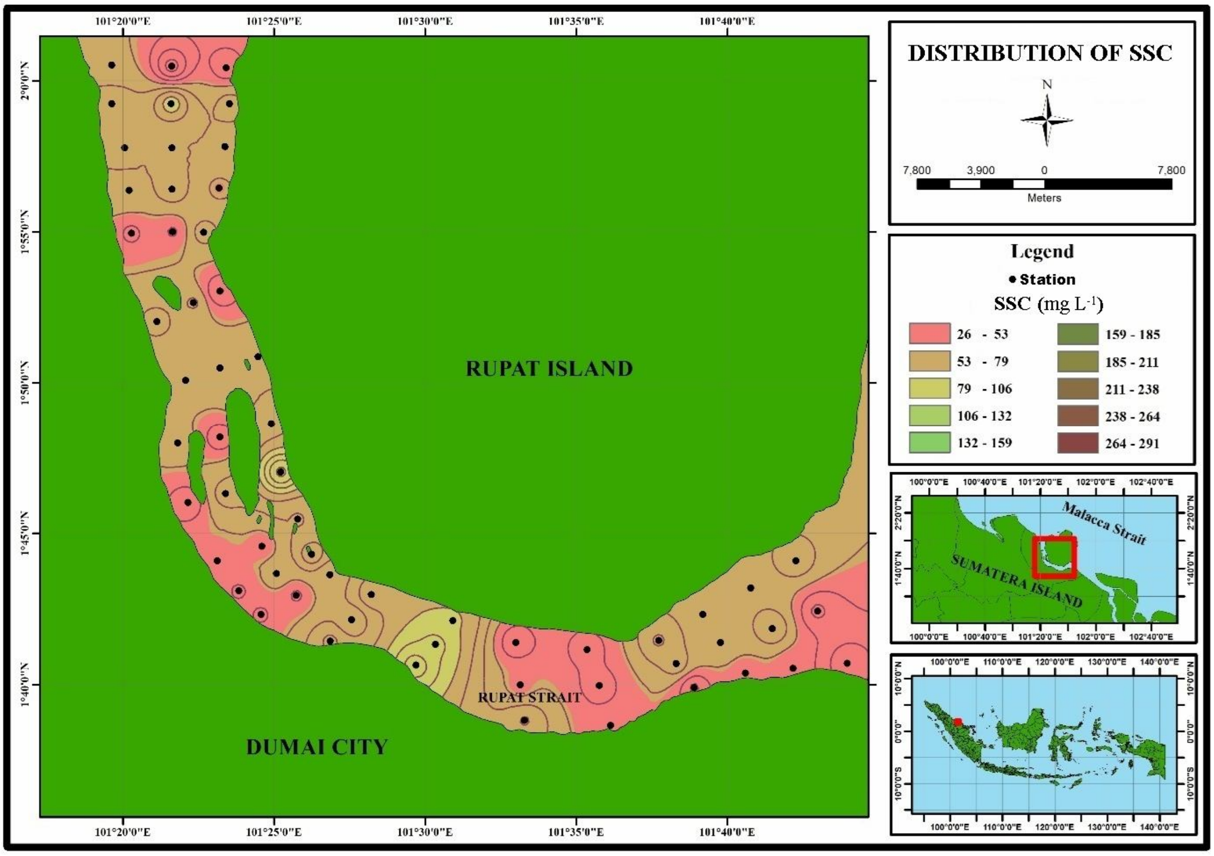

Figure 4. Geographical distribution of SSC at the surface of the water column.

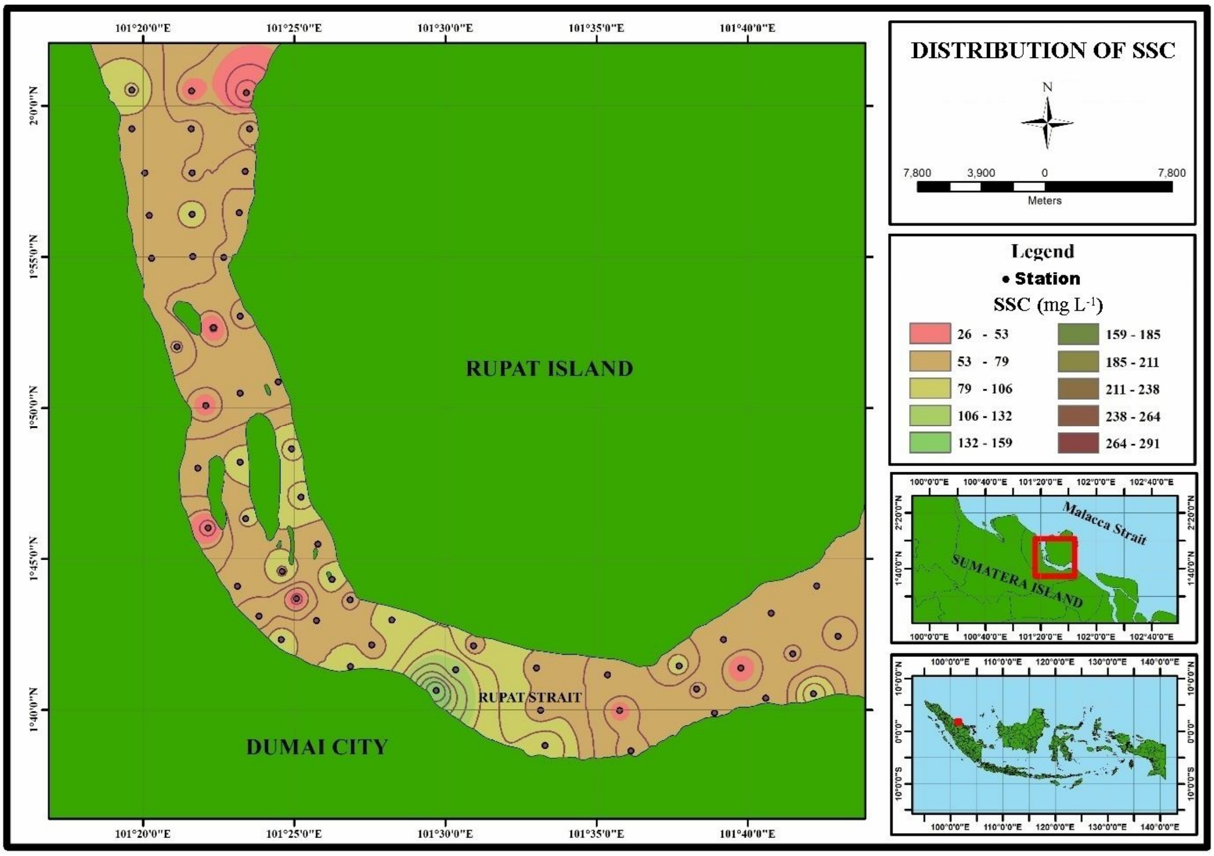

Figure 5. Geographical distribution of SSC in the middle of the water column.

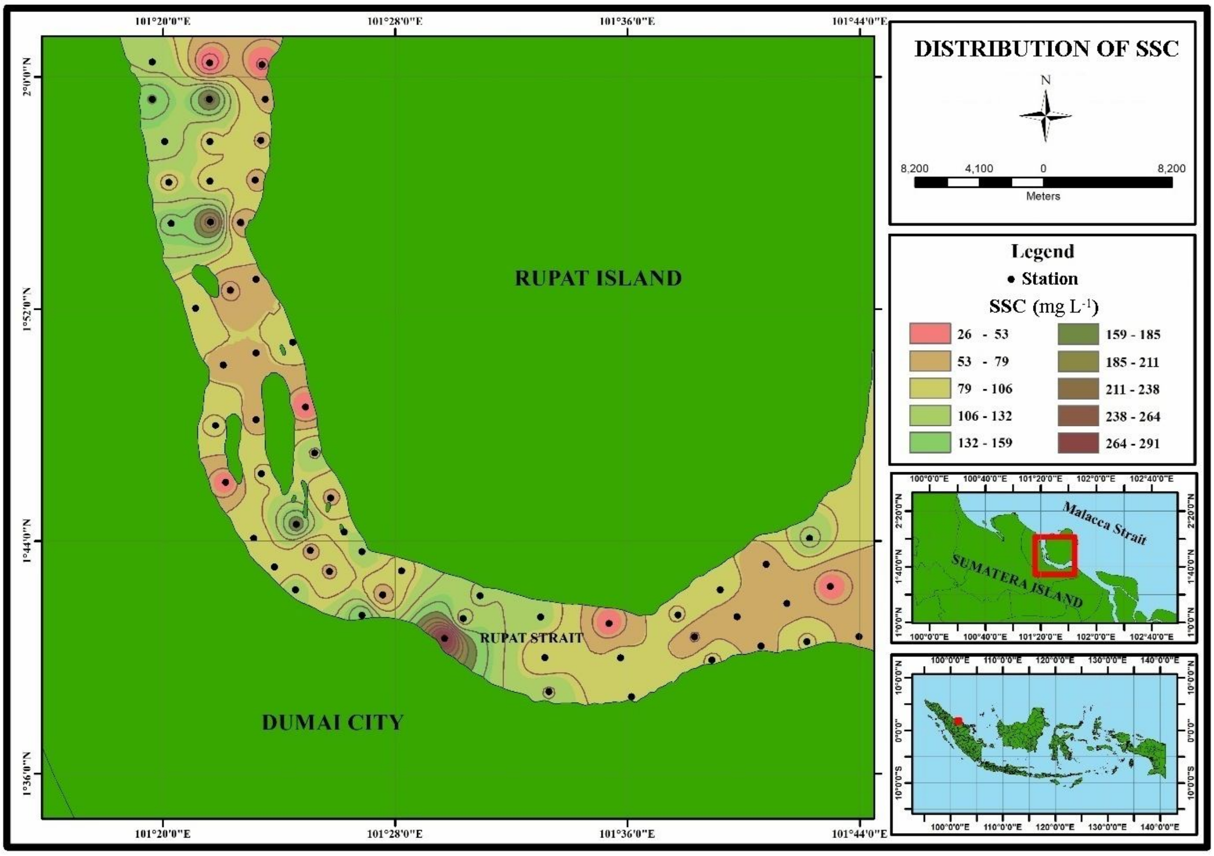

Figure 6. Geographical distribution of SSC at the bottom of the water column.

Discussion. In general, higher SSCs were found at the bottom of the water column compared to the concentrations at the surface and middle. This illustrates that the type of suspended sediment in Rupat Strait is a graded (stratified) suspension where the concentration is lowest at the surface, low at the middle and high at the bottom of the water.

This type is caused by the energy that transports sediment from incoming and outgoing currents in the form of tidal and ebb currents through the Rupat Strait which is higher at the bottom of the waters then decreases towards the surface waters. Rifardi (2012) explains that currents transport sediment physically through two opposite mechanisms based on two types of load, namely 1) suspended load, current energy disperse fine sediment particles such as silt and clay and sand size, then move in the flow, 2) bed load or load that is not continuously in the form of suspension or solution, such as larger and heavier particles (boulder, pebbles and gravel) being rolled along the bottom of the water.

The difference in the distribution of suspended sediment in the north, central, and east is thought to be due to differences in current velocity in the Rupat Strait. The current velocity in the north and east is higher than the central part of the Rupat Strait, resulting in sediment transport out of the strait. According to Rifardi et al (2018), the northern and eastern parts of the Rupat Strait are deeper due to sediment transport out of the strait by tidal currents, while the central part is shallower due to sediment deposition due to the confluence of two water masses during the transition from high tide to low tide or vice versa.

The Rupat Strait is influenced by tidal conditions, the maximum current speed occurs at full tide which reaches 1.84 m s^{-1}. At high tide, the current from the Malacca Strait flows into the Rupat Strait through the north and east of the Rupat Strait, while at low tide, the current from the Rupat Strait flows into the Malacca Strait through the north and east of the Rupat Strait. Further explained, this current pattern causes the meeting of two water masses in the central part of the Rupat Strait. This section is characterized by weak currents and high sedimentation resulting in silting. 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).

Azizul et al (2017) clarify that currents play a role in the distribution and direction of sedimentation in a water. The clarification is strengthened by the results of research by Satriadi (2013) which described that the results of sediment transport modeling show the distribution pattern of sediment concentration, its movement is influenced by currents dominated by tidal currents.

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 (Rifardi et al 2020).

Conclusions. The distribution of suspended sediment in the narrow channel (Rupat Strait) varies both vertically and horizontally due to the unequal difference in current velocity in each layer (vertical: surface, middle and bottom) of the water coloum. The type of suspended sediment is a graded (stratified) suspension but is not a gradation caused by differences in the particle size of the sediment, but a graded suspension caused by differences in concentration as a result of bed load erosion due to bottom currents. Thus, this gradation is not caused by the process of particle deposition (sedimentation).

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Conflict of interest. The authors declare that there is no conflict of interest.

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Authors:
Rifardi, Riau University, Department of Marine Sciences, Faculty of Fishery and Marine Sciences, Kampus Bina Widya Sp. Panam Pekanbaru, 28293 Riau, Indonesia, e-mail: e-mail: rifardi@lecturer.unri.ac.id
Mubarak, Riau University, Department of Marine Sciences, Faculty of Fishery and Marine Sciences, Kampus Bina Widya Sp. Panam Pekanbaru, 28293 Riau, Indonesia, e-mail: mubarak@lecturer.unri.ac.id

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