ASSESSMENT OF THREE-DIMENSIONAL BAROCLINIC CIRCULATION MODEL FOR THE MUSI COASTAL AREA

KAJIAN MODEL SIRKULASI BAROKLINIK TIGA-DIMENSI UNTUK KAWASAN PESISIR MUSI

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(Received 02 February 2023; in revised from 09 February 2023; accepted 11 July 2023)

DOI : http://dx.doi.org/10.32693/bomg.38.2.2023.811

ABSTRACT: The hydrodynamics of the Musi estuary ecosystem is influenced by the flow of water discharge from the river, tidal circulation within the estuary, and complex bathymetry. Numerical modeling is one of the best ways to explain the characteristics and processes occurring in the estuary. However, the obtained model requires validation to ensure its accuracy despite the complexity added by variability in tidal and bathymetric conditions, making the validation process more challenging. This difficulty can be overcome by using high-resolution data, which provides a refined understanding of the river-to-sea estuary flow and its variability. The validation process involves the use of conductivity-temperature-depth (CTD) instruments and mooring tidal stations. The validated model is considered capable of accurately simulating tidal propagation as it represents the temperature-salinity-density properties within the estuarine environment. The development of this model demonstrates the effective implementation of these parameters within the Musi estuary ecosystem domain. The 3D model simulation is used to consider the vertical discretization in the river-estuary-sea channel, which enhances the representation of temperature-salinity-density in the water column. The obtained results suggest that the 3D-MIKE modeling is well-suited for operational purposes, including the prediction of hydrodynamics and the management of estuarine areas, specifically in the Musi estuary ecosystem.

Keywords: hydrodynamic, validation model, baroclinic circulation, Musi estuary, and coastal area

***ABSTRAK**: Hidrodinamika ekosistem muara Musi dipengaruhi oleh aliran debit air sungai, sirkulasi pasang surut di muara, dan batimetri kompleks. Untuk menjelaskan karakteristik dan proses kejadian di muara, salah satu cara terbaik yang dapat dilakukan adalah dengan menggunakan model numerik. Model yang diperoleh perlu divalidasi agar teruji keakuratannya. Variabilitas saat kondisi pasang surut dan batimetri akan meningkatkan kompleksitas aliran yang menyebabkan proses validasi menjadi lebih sulit. Hal ini dapat diatasi dengan menggunakan data resolusi tinggi sehingga aliran dan variabilitas alur sungai-muara laut menjadi lebih jelas. Validasi dilakukan dengan menggunakan instrumen conductivity-temperature-depth (CTD) dan penempatan mooring tidal station. Model yang telah divalidasi dianggap mampu menyimulasikan propagasi pasut secara akurat yang mencerminkan sifat temperatur-salinitas-densitas di muara. Pengembangan model ini menunjukkan bahwa parameter-parameter tersebut telah terimplementasikan dengan baik pada domain ekosistem muara Musi. Hasil simulasi model 3D digunakan dengan mempertimbangkan diskritisasi vertikal pada kanal hulu-muara-lautan untuk memperoleh representasi suhu-salinitas-densitas yang lebih baik dalam kolom air. Hasil yang diperoleh menunjukkan bahwa pemodelan 3D-MIKE cukup baik digunakan pada level operasional, antara lain untuk memprediksi hidrodinamika dan mengelola kawasan estuari, khususnya di ekosistem muara Musi.*

***Kata Kunci:** hidrodinamik, validasi model, sirkulasi baroklinik, muara Musi, dan wilayah pesisir*

INTRODUCTION

Estuaries are an important ecosystem that provide breeding, shelter and feeding grounds for numerous species. Gradient distribution in temperature, salinity, vegetation, bathymetry and sediment parameters in these ecosystems create diverse habitats. These parameters can undergo changes as a result of both human activities and natural processes, such as climate change. The influence of these factors on estuary ecosystems has turned them into a research topic that has attracted researchers (Wagner et al., 2011; Brown et al., 2016; Jeffries et al., 2016). Temperature is one of the critical parameters for estuarine ecosystems and directly impacts the habitat, existence and growth rate of species. Various studies have indicated that high temperatures can cause stress and even mortality in a species (Brown et al., 2013; Ralston et al., 2015). Several factors that can affect temperature include river flow, heat exchange by the atmosphere, and flow interaction with the sea or ocean adjacent to the estuary area (Monismith et al., 2006).

The study area is located on the east coast of Sumatra which is directly adjacent to the Bangka Strait (2.1^0S – 2.25^0S and 104.4^0W – 105.6^0W), It was conducted in the Musi-Banyuasin estuary, South Sumatra. The area consists of the ROFI zone (Freshwater Influence Area), including the Banyuasin, Musi and Upang estuaries, which are downstream of the densely populated Palembang city (Figure 1),

The Musi coastal area represents the largest estuary in the South Sumatra province characterized by a central body extending 30 km and connected to the Bangka Strait with a depth range of 0 to 15 m. The lithological units of study area generally consist of quaternary alluvium (gravel, sand, silt and clay) and swamp deposits (mud, silt, and sand) (Gafoer, et al., 1995). This area features a narrow platform heavily influenced by tides. Research conducted by Surbakti (2012) and Nurisman et al., (2012) found that the Musi River estuary shows a single (diurnal) tidal type, with tidal currents dominating at a speed of 10.1 cm/s. Three significant geomorphological features dominate this area, including Payung Island located in the middle of the Musi estuary, the convergence of three estuaries, and the narrow strait linking the Natuna and Java seas. The flow at the study site is related to the tidal amplitude resulting in a mixing process within the estuary. The main driver of circulation at the mouth of the Musi River is tides, with other factors such as river discharge and wind also having an effect (Rodrigues, 2015).

It is important to know the modeling of coastal systems, especially in estuaries, influenced by fresh water, such as in the Musi estuary and its surrounding coastal areas, to understand the unique physical processes that characterize them. Measurement of several in situ environmental variables or time-limited studies is not sufficient to translate coastal processes because coastal systems are complex (Restrepo et al., 2018). The combination of interacting physical factors, such as bathymetry, coastline, outflow of estuaries and distribution of flow fields makes the coastal system a complex hydrodynamic system (Murthy et al., 2008; Iglesias et al., 2020). Therefore, the coastal system must be decomposed into smaller systems and one way to determine the structure of the coastal system is to use a numerical model approach. Models enable a better understanding of the interactions between the various components in the system. They are also needed to define scenarios and answer scientific questions (Petihakis et al., 2012). Therefore, it will result in a precise understanding of coastal processes, including spatiotemporal variations. This is valuable for the development of more comprehensive and integrated coastal management plans. The hydrodynamic model plays a significant role in the formation of current and density patterns as a basis for transport models. Given the importance of advection and/or diffusion in studies closely related to coastal systems.

Several types of numerical models have been used to simulate hydrodynamic processes in coastal systems. MIKE 3D is one of these models, known for its capability to simulate two dimensions in 2D and 3D, in sigma, cartesian or lagrangian vertical coordinates and spatial dimensions. It can also combine formulations in each process. The flexibility possessed by MIKE 3D facilitates its application in various types of systems and for research purposes or undertaken work. Indeed, in the last 10 years the model has been applied in several studies in Musi estuaries; Sari et al., (2013) used the 2D SMS model for distribution of salinity, while Syarifudin et al., (2016) employed the MIKE 21 model to simulate sediment transport. In the coastal system consisting of the Musi estuary, Banyuasin estuary and Upang estuary, the study is focused on the vertical structure of the water masses. In order to apply the model output, the constructed model must be built properly and scientifically. Validation is needed to demonstrate the degree of confidence that can be shown in the model results. Model validation is a process that aims to explain that specific models can be simulated with a considerable degree of accuracy at certain locations (Williams & Esteves, 2017).

The validity of the model is confirmed by comparing the simulation results with in situ observations. The MIKE 3D model is regularly used and validated, but no published work has yet focused specifically on the Musi estuary. As the model application is baroclinic, the validation must also consider the seawater temperature and salinity. This study will provide better insight regarding the validation of model results in the estuary area, especially in the Musi and its surroundings. The objective is to determine the vertical structure within the Musi estuary domain from a vertical-temporal perspective using the 3D MIKE model. The model results will be compared with in situ measurements of the CTD. This study is the first to conduct a validation process using CTD for the Musi estuary domain. The main results of the model are expected to represent the coastal physical processes, reliable during its use in real-world operational settings, and its forecast ability that will be useful for coastal environmental management.

METHODS AND MATERIALS

Data collection occurred between September 1-10, 2016, and data processing extended from October 2019 to February 2020. It comprises of two cross-sections (red dotted line): cross-section A1-A2 from the mainland to the Upang estuary and longitudinal cross-section B1-B2 from upstream to the sea, passing through the Musi River. The tidal data capture station (BIG) is represented by the black point. The wind data collection station is marked by the black triangle. CTD measurements were taken at two locations, denoted by black pinpoints (St.1 and St.2). The mooring point is the same as that of St.2.

Tidal data used in this study were obtained from three sources with a 1-hour time interval during data processing. The initial tidal data was derived by predicting EMB bathymetry which was processed using MIKE 3D software as the boundary and initial condition hydrodynamic model. Furthermore, tidal data were gathered from the results of mooring measurements at station 2 (St.2) over 3 days, from September 7-9, 2016 with 1-hour intervals and tidal model extraction data at the same time and location, both of which were used for model verification. Wind data retrieved from Copernicus (https://resources.marine.copernicus.eu/products), was employed to understand existing wind patterns in the area, with daily u10 specifications at the surface layer. The u10 wind data represented one month in September 2016 and used to identify dominant pattern and speed at the study site. Discharge data was obtained from field current measurements at three locations: Telang, Musi, and Upang Rivers. Current data was obtained using a current meter with a mooring procedure for 72 hours with 1 hour data interval at each location. This data was then used to calculate the flow rate, determined by the river flow velocity (m/s) and wet cross-sectional area (m2). The wet cross-sectional area was determined using the mid-section model from Chow (1989). The discharge can be obtained through the equation:

$$Qf = v \times A \quad (1)$$

where:
Qf= River discharge (m^3/s)
A= Cross-sectional area (m^2)
v= Flow velocity (m/s)

Bathymetry data in the study area were acquired from the Hydro Oceanographic Service of the Indonesian Navy No. 160 with a scale of 1: 50,000 and BIG in 2015. This data was digitized using Qgis 3.8 software to obtain water depth and coastline with latitude, longitude and depth output. Salinity, temperature, and turbidity data were obtained from measurements, using Conductivity-Temperature-Depth (CTD) instrument that taken at low tide, and from scientific publications. The measurement data consists of two stations to represent the transverse and longitudinal cross-sections taken during and at low tide (Figure 2).

The created model consists of a baroclinic 3D hydrodynamic model. Its initial are based on the average input of tidal values from 5 sources, including the Musi, Telang, Upang, and Banyuasin rivers, and the Bangka

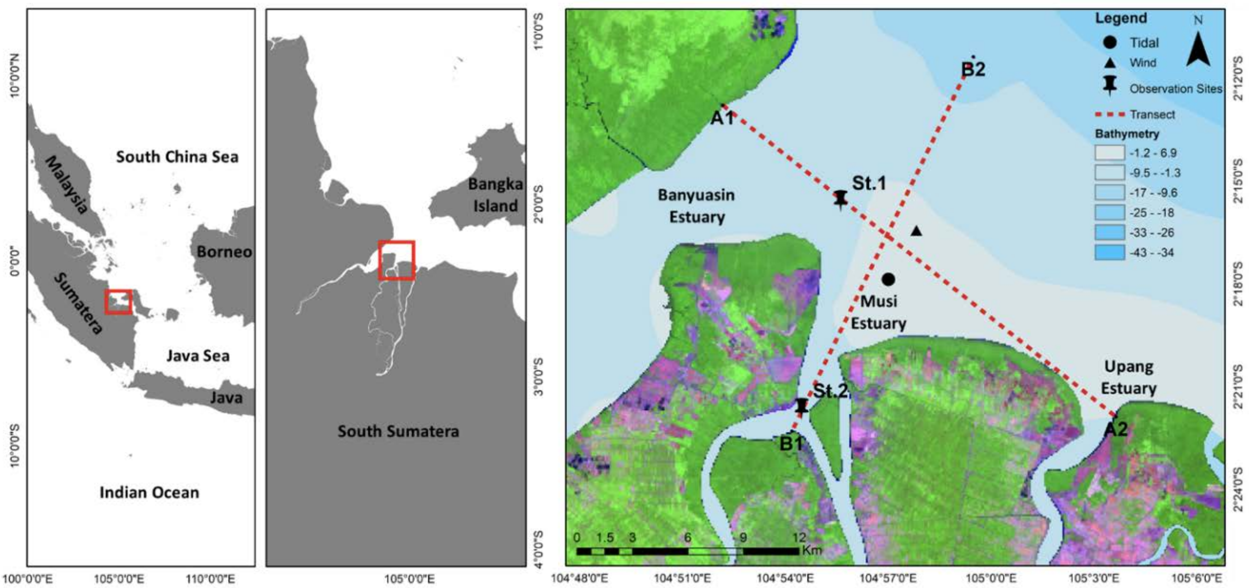

Figure 1. Research Location Map with two cross-sections (red dotted line): cross-section A1-A2 from the mainland to the Upang estuary, and longitudinal cross-section B1-B2 from upstream passing through Musi River to the sea. Black circle denotes the tidal data capture station owned by Geospatial Information Agency (Badan Informasi Geospasial (BIG), black triangle is wind data collection station, black pinpoints (St.1 and St.2) at two locations marked the decreasing CTD, and mooring point is at the same location as St.2.

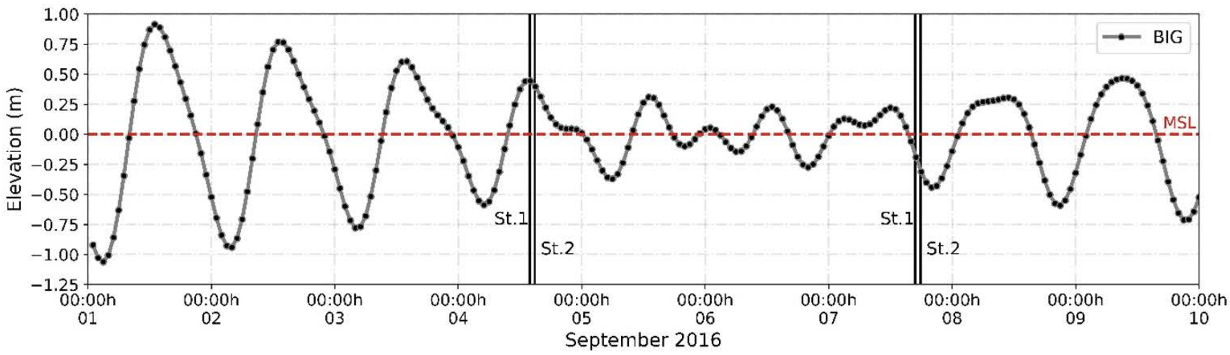

Figure 2. Water level elevation during CTD data collection and tidal mooring based on calibrated BIG data. CTD data at each station is taken twice during flood and ebb.

Strait. Tidal values are predicted using on the MIKE 3D device based on the bathymetry conditions of the waters. The model domain is illustrated in Figure 3. In the baroclinic 3D model, the initial conditions are made based on the minimum, maximum and average values of temperature and salinity. Furthermore, boundary values are set using source data of temperature and salinity with a constant value. The hydrodynamic model describes the flow conditions at the study site which are simulated using tides, discharge and bathymetry. The model is simulated for 21 days to describe flood and ebb tide conditions. The model configurations used are listed in Table 1.

The hydrodynamic model provides the basis for simulating movements in the waters. It formulates the movement of currents, tides over time intervals. The momentum and continuity equations are used to determine the motion of water influenced by various forces. The following describes the equations used, based on the MIKE module of DHI (2012).

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S \quad (2)$$

Momentum equation:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} = fu + g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_0}\frac{\partial \rho_a}{\partial x} - \frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz + F_u + \frac{\partial}{\partial z}\left(v_t\frac{\partial u}{\partial z}\right) + u_s S \quad (3)$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} + \frac{\partial wv}{\partial z} = -fv + g\frac{\partial \eta}{\partial y} - \frac{1}{\rho_0}\frac{\partial \rho_a}{\partial y} - \frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial y}dz + F_v + \frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right) + v_s S \quad (4)$$

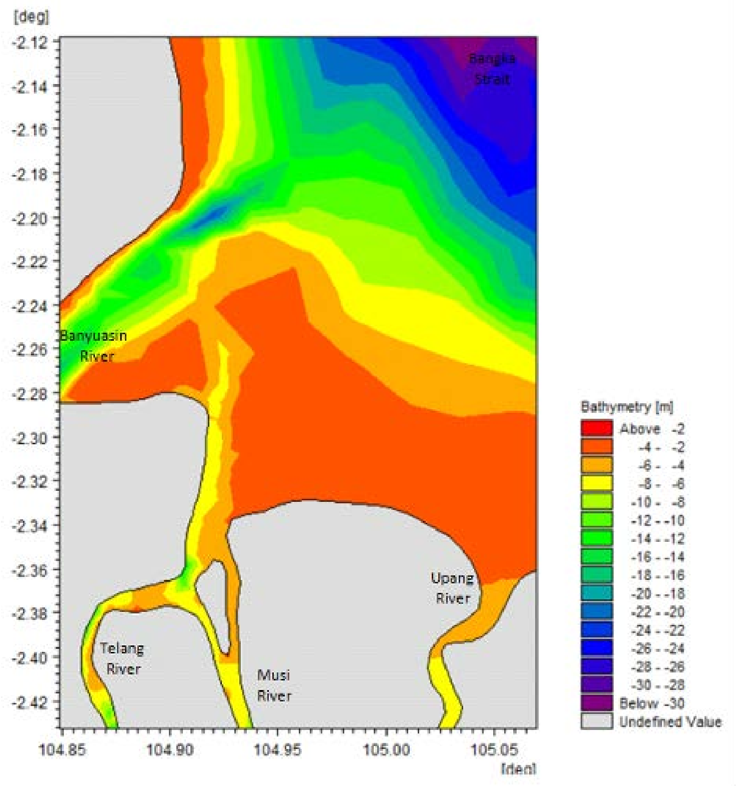

Figure 3. The bathymetry of the Musi estuary as a model domain

Table 1. Musi coastal area model configuration.

Parameter	Application of Simulation	
Model Characteristics		= 3D-Baroclinic
Simulation Time	Number of step	= 6048
	Time step interval	= 300
	Simulation period	= 01/09/2016 01:00:00 – 22/09/2016 23:00:00
Area	Maximum Element Area	= 0.0005 $(deg)^2$
	Angle Mesh	= 26 (deg)
Grid	Origin	= 105.081E -2.105S
Mesh Boundary	1. PUSHIDROSAL bathymetry data (2015) 2. BIG bathymetry data (2015) 3. Field tide data (2016)	
Discharge	Telang River	= 142.6 m^3/s
	Musi River	= 202.15 m^3/s
	Upang River	= 211.7 m^3/s

$$\frac{\partial v}{\partial t}+\frac{\partial w^2}{\partial z}+\frac{\partial uw}{\partial x}+\frac{\partial wv}{\partial y}=-fw+g\frac{\partial \eta}{\partial z}-\frac{1}{\rho_0}\frac{\partial \rho_a}{\partial z}-\frac{g}{\rho_0}\int_z^n\frac{\partial \rho}{\partial z}dz+F_w+\frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right)+w_sS \quad (5)$$

$$\rho_a = \rho_0 g\eta + \rho_0 \int_{-z}^{0} Bdz \quad (6)$$

$$B = B = \frac{\rho-\rho_0}{\rho_0}\, g \quad (7)$$

The horizontal stress section is described using the stress-gradient relationship, which is simplified to:

$$F_u = \frac{\partial}{\partial x}\left(2A\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right) \quad (8)$$

$$F_v = \frac{\partial}{\partial y}\left(A\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial y}\left(2A\frac{\partial u}{\partial y}\right) \quad (9)$$

Temperature Function:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}\left(K_v\frac{\partial T}{\partial z}\right)+\frac{\partial}{\partial x}\left(A_H\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial T}{dy}\right) \quad (10)$$

Salinity Function:

$$\frac{\partial s}{\partial t}+u\frac{\partial s}{\partial x}+v\frac{\partial s}{\partial y}+w\frac{\partial s}{\partial z}=\frac{\partial}{\partial z}\left(K_v\frac{\partial s}{\partial z}\right)+\frac{\partial}{\partial x}\left(A_H\frac{\partial s}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial s}{dy}\right) \quad (11)$$

where:
t = time
x,y,z = cartesian coordinates
u,v,w = flow velocity components
g = gravitational acceleration (m^2/s)
ρ = density
ρ_0 = reference density (1024.78 kg m^{-3})
η = elevation
f = *coriolis* parameters
S = amount of discharge from the source

A_V *dan* K_V = vertical eddy viscosity and vertical diffusion coefficient (*log law formulation* (1.8e^{-6} m^2/s))
A *dan* A_H = vertical eddy viscosity and horizontal diffusion coefficient (*smagorinsky formulation* (0.28 m^2/s))
B= buoyancy
T= temperature
s= salinity

Model verification was carried out to determine the accuracy of the data by comparing field tide data and statistical simulation results (Zaman & Syafrudin, 2007). The verification method used is the average relative error (MRE < 50%: Accepted, MRE > 50%: Re-simulation) with the following equation:

Relative Error (*RE*) $\frac{|X-C|}{X}$ x 100 % (12)

Mean Relative Error (*MRE*) $\sum_0^n \frac{RE}{n}$ x 100% (13)

where:
c = simulation results data
x = field data
n = amount of data

RESULTS

The Musi-Banyuasin estuary is the place where four rivers are located, namely the Upang River, Musi River, Telang River, and Banyuasin River, which directly face the Bangka Strait. The flow in the estuary originates from the dynamics of tides and river discharge. The tides enter through propagation from the South China Sea to the north of Bangka and the Java Sea, which enters through the south of the Bangka Strait. The tides in the Musi-Banyuasin estuary are of the diurnal type, occurring once a day, with a Formzhal number of 3.06, in accordance with the results of previous studies (Surbakti et al., 2022; Radjwane et al., 2018). During high tide, water from the sea enters the estuary, while during low tide, the water flows out of the estuary. The river discharge flow comes from the Banyuasin River and the Musi River, which have three branches: the Telang River, the Musi River, and the Upang River. Heltria et al. (2021) has calculated the flow rate for each river. The Musi River discharge is known to be 202.15 m^3/s, the Upang River discharge is 211.7 m^3/s, and the Telang River flow rate is lower than that of the Musi River, at 142.6 m^3/s. The Musi River and Upang River originate from the same stream, which then separate due to a delta. Although the current velocity is assumed to be the same in both rivers, the flow rate is calculated based on the cross-sectional area of each river. The Banyuasin River estuary has a large cross-sectional length of approximately 6 km, making tides play an important role in the flow at this location. The visualization of the direction of movement of the dominant wind in the waters of the Musi estuary is shown by the wind rose diagram. The dominant wind direction moves from south to north with a speed ranging from 1.3 to 5.2 m/s, as shown in Figure 4.

The 3D bathymetry obtained from the PUSHIDROSAL and BIG data in Figure 5 shows the seabed morphology of the Musi-Banyuasin estuary waters. The Banyuasin estuary, with a larger cross-section, has a varying depth range of 0.2 m - 22 m, which is deeper than the Musi estuary. The depth range of the Musi estuary, where the Musi and Telang rivers originate, is 0.2 m - 12.9 m. The morphology of the waters is formed by sediment deposits from rivers that flow into this estuary. As the water reaches the Bangka Strait, the water depth increases to 38 m, which is considered shallow water.

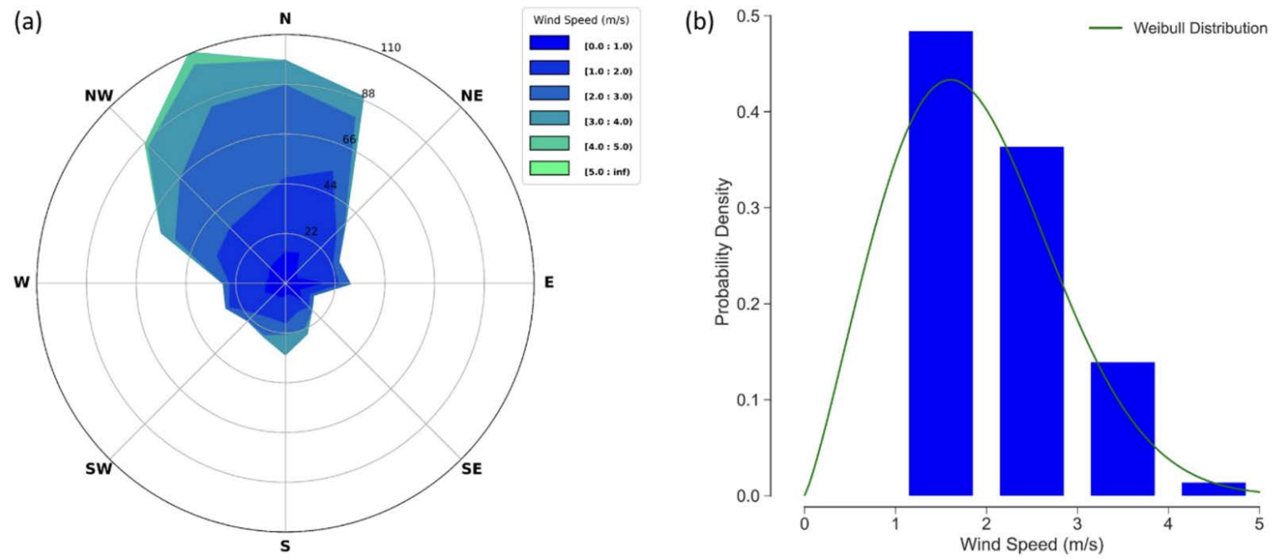

Figure 4. Wind distribution with respect to (a) direction and (b) speed on the Musi coast. Blue to green in (a) indicates low to high speed.

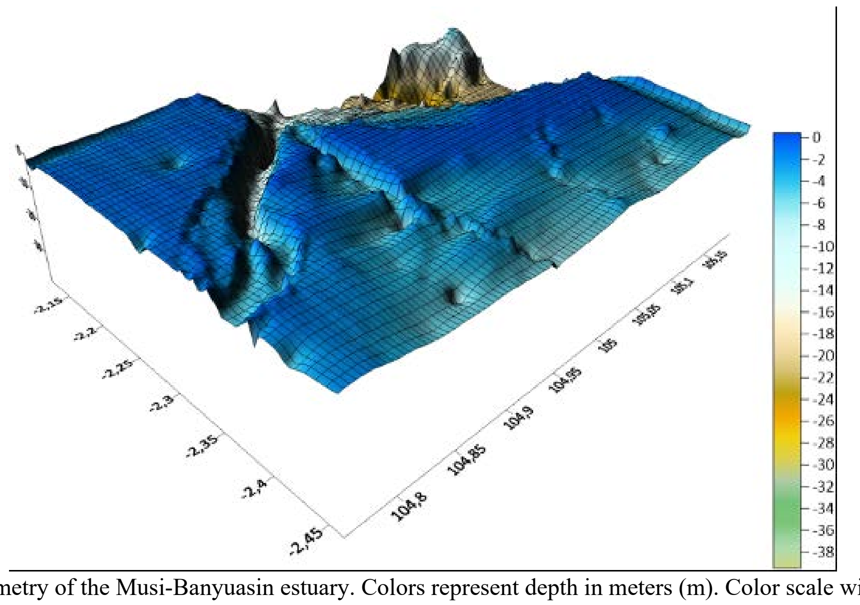

Figure 5. 3D Bathymetry of the Musi-Banyuasin estuary. Colors represent depth in meters (m). Color scale with 2m intervals.

The validation of the hydrodynamic and salinity models is known through the verification value of the mean relative error (MRE). The verification value of the hydrodynamic model uses tidal data, namely tides at the same point in the model and measurement results in the study area (Figure 6). The resulting model MRE value is 30.74%, which means that the model results adequately represent the hydrodynamic conditions in the study area. The verification method used is the verification of the average relative error (MRE < 50%: Accepted; MRE > 50%: Re-simulated). Sugianto (2012) in his model verification obtained a value of <35% and was still acceptable for further analysis. Insitu data collection right at the mouth of the estuary shows the formation of two peaks at high tide. The mass of sea water and riverine inflow towards upstream causes the buildup, indicating an increase in water mass during high tide. As the tide recedes, the sea water continues to enter, maintaining the formation of peaks. The mass of sea water entering the estuary weakens at the lowest tide. The error value obtained may be influenced by other factors, such as tidal currents and water conditions during field measurements. Adding more to the complexity of bathymetry in the field, there are differences in tides between model simulation and field results, which is smoother for model simulation result.

Figure 7 presents a comparison between temperature and salinity values obtained from observation data and model data during high and low tide. The data from station-1 was collected at the estuary's mouth, which is directly connected to the Bangka Strait. Here, water masses receive direct input from the Musi and Banyuasin estuaries. On the other hand, the data from station-2 was acquired at the confluence of the Telang and Musi rivers, near Payung Island.

The range of station-1 temperature values at high tide in the observation data is 29.36℃ – 29.93℃, and for the model data, it is 29.65℃ – 29.97℃. The correlation between the two datasets shows a good value, namely R2 = 0.97 at high tide. The biggest difference is at a depth of 3.34 m, which is 0.31℃, with a maximum depth of 6.64 m. At low tide, the temperature value range for the

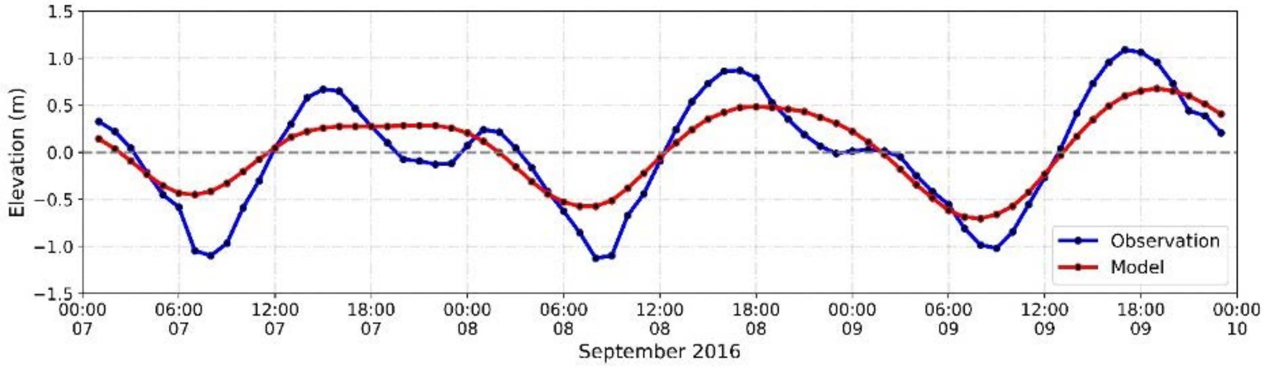

Figure 6. Data validation using tidal mooring data (observation) with the results of the hydrodynamic model running.

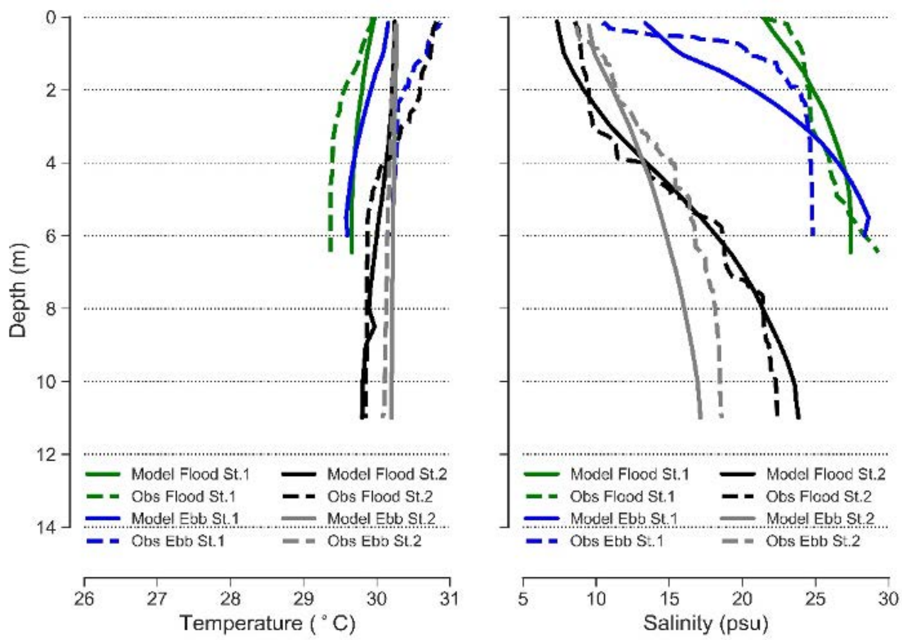

Figure 7. Data validation using observational data (CTD) with model data sampled at station 1 and station 2 (according to CTD location).

observation data is 30.20°C – 30.26°C, and for the model data, it is 29.58°C – 30.15°C. The correlation between the two datasets at low tide is smaller than at high tide, namely R2 = 0.91, with a maximum difference of 0.70°C at a depth of 0.17 m. At station-2, the range of temperature values for the observation data at high tide is 29.85°C – 30.81°C, and for the model data, it is 29.80°C – 30.24°C. The correlation between the two datasets is smaller than that of station-1, namely R2 = 0.77, with a maximum difference of 0.57°C at a depth of 0.12 m and a maximum depth of 11 m. At low tide, the temperature range for the observation data is 30.08°C – 30.26°C, and for the model data, it is 30.20°C – 30.27°C. The correlation between the two datasets is R2 = 0.97, with a maximum difference of 0.11°C at the maximum depth of data collection.

At station 1, the range of observed salinity data values is greater than the model data, explicitly 23.07 Psu – 29.30 Psu compared to 21.75 Psu – 27.40 Psu, respectively. Station-1 is located in zone 1, which is classified as the polyhaline zone with a salinity range of > 18 Psu – 30 Psu, according to Heltria et al. (2022). The correlation between the two datasets is R2 = 0.77, with a maximum difference of 1.91 Psu at the maximum depth of data collection. During low tide, the range of observed data values is 10.41 Psu – 24.82, while the model data is 13.35 Psu – 28.62 Psu. The data correlation is smaller, specifically R2 = 0.67, with a maximum difference of 5.13 Psu at a depth of 1.25 m. The salinity value at station-2, during high tide, shows a correlation value of R2 = 0.98, with a maximum difference of 1.64 Psu at a depth of 3.87 m. The salinity range is lower than at station-1, as the mass flow of fresh water dominates and falls within the mesohaline zone (Heltria et al., 2022). The range of observed salinity data is 8.55 Psu – 22.36 Psu, while the model data is 7.33 Psu – 23.83 Psu. During low tide, the range of observed salinity data values is 8.64 Psu – 18.57 Psu, while the model data is 9.50 Psu – 17.12 Psu. The correlation between the two datasets is R2 = 0.97, with a maximum difference of 2.28 Psu at a depth of 4.94 m.

DISCUSSIONS

Modeling is capable of reproducing several temperature-salinity-density stratifications. Stratification in the estuary area occurs due to variations in the input of freshwater from upstream and seawater in the estuary. The surface layer typically has lower salinity than the layer beneath it due to its lighter mass. This finding is supported by Surbakti et al. (2022). Patty (2013) also suggests that depth and shape of the bottom topography of the waters are internal factors that influence the distribution of temperature, salinity, and density.

Figure 8 depicts the vertical pattern of temperature, salinity, and density during the ebb tide. Specifically, Figure 8.a-b-c represents a cross-section across A1-A2 (Banyuasin estuary – Musi estuary – Upang estuary). On the other hand, Figures 8.d-e-f represents a cross-section on B1-B2 (upstream – ocean). In the cross-sections A1-A2 and B1-B2, the modeling results clearly show the presence of temperature-salinity-density stratification at the study site.

From cross-section A1-A2, the Banyuasin estuary exhibits the strongest stratification. This estuary has a deeper depth compared to the other estuaries. Meanwhile, the Musi and Upang estuaries show more homogeneous temperature-salinity and density simulations, indicating less stratification. The Banyuasin estuary, which is adjacent to the Musi estuary, is situated in a relatively deep section of the Banyuasin River. The model results reliably demonstrate that temperature-salinity and density stratification in this area is the strongest compared to other estuaries. During low tide, when the intrusion of seawater is minimal and the majority of water outflows from rivers into the sea, the model successfully reproduces the temperature-salinity-density stratification. The temperature-salinity-density model in the Musi and Upang estuaries clearly differs, which is characterized by warm temperatures, as well as low salinity and density.

Stratification of temperature-salinity-density was revealed in cross-section B1-B2, as shown by the model results (Figure 8.d-e-f). This stratification can also be seen both in the model and at the time of measurement during data verification. During periods of high and low tides, stratification can be captured by the model. Stratification occurs on a small and sometimes a large scale depending on the period of occurrence and location. The highest temperature observed in the surface layer is located in the middle of the Musi River, close to the mainland, and is complemented by low salinity. The surface temperature is higher, especially in shallow waters because solar energy is more effective in increasing seawater temperature (Maharani et al., 2014). The salinity on the surface has a smaller value due to the input of fresh water from upstream towards the sea, while seawater infiltrates the estuary through the bottom layer. The model shows a gradient of temperature-salinity from the upstream region to the ocean region. The temperature seems to gradate smaller as it heads towards the ocean, while the salinity and density increase as it heads towards the ocean. In the estuary stratification area, the dominance is influenced by salinity, which also causes differences in density (Beer, 1997).

In cross-section B1-B2, intrusion from the sea is stuck in the middle of the cross-section with a distance of 0.1 deg from point B1, specified by the temperature 29.88-29.94°C (light green in Figure 8.d), salinity 27-28 Psu (brick red in Figure 8.e), and density 12.5-14 (brownish yellow in Figure 8.f). This intrusion from the sea spreads through the bottom of the waters, although in the upper section, it is still dominated by water from the mainland (rivers). This happens because during low tide, sea water heads to the ocean so that water from the mainland with a large discharge goes to the sea. Meanwhile, there is no visible intrusion of sea water masses can be seen in cross-section A1-A2, in which the model looks homogeneous.

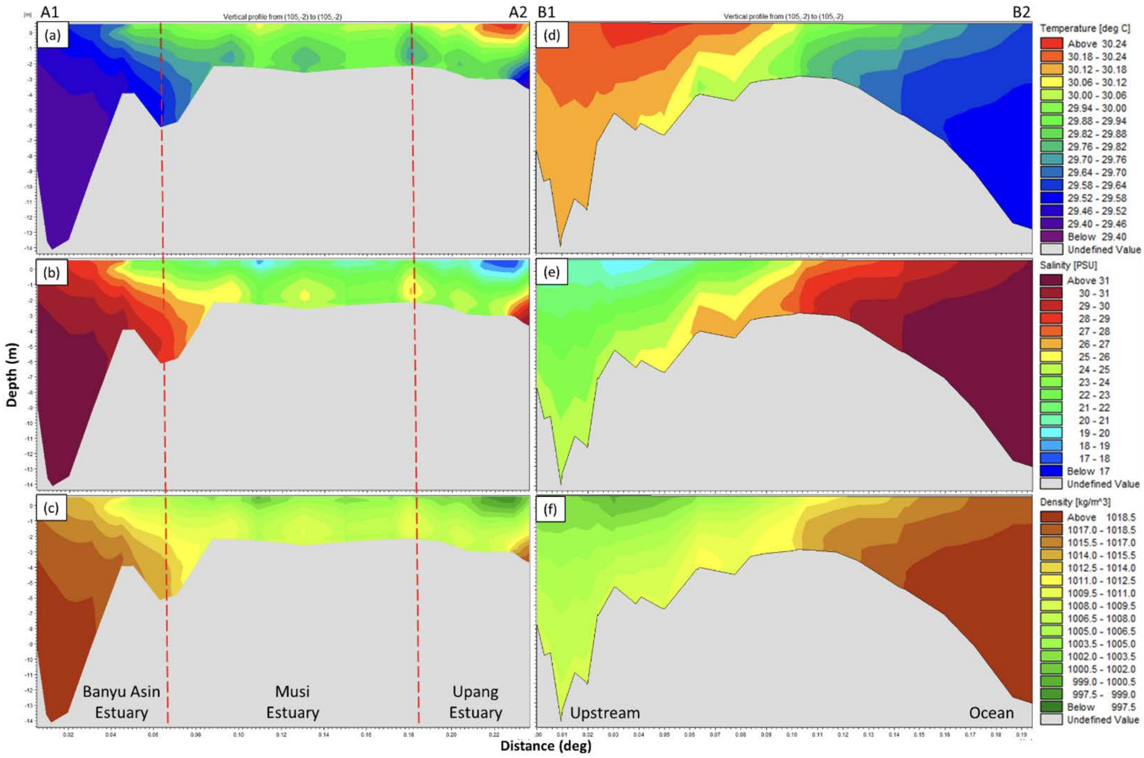

Figure 8. Vertical distribution of (a) temperature (b) salinity (c) density of cross-section A1-A2 (divided into the Banyuasin estuary-Musi estuary-Upang estuary); and (d) temperature (e) salinity (f) density of cross-section B1-B2 during low tide.

Vertical salinity stratification can signify the type of estuary in the Musi-Banyuasin estuary, that is, there is a strong push by the mass of seawater which pushes the mass of freshwater so that high salinity is in the bottom layer and lower salinity is in the upper layer. Having the mixing, the estuary can fall into the type of partially mixed estuary. This is in line with research conducted by Heltria et al. (2022) at the same location and Duxbury (2002), which stated that the partially mixed estuary type is characterized by a strong mass flow of seawater, horizontal mixing at the bottom of the waters, and a combination of vertical mixing.

Figure 9 shows the vertical pattern of temperature, salinity, and density during the flood tide. Specifically, Figure 9.a-b-c is a cross-section across A1-A2 (Banyuasin estuary - Musi estuary - Upang estuary), while Figure 9.d-e-f represents transverse cross-section on B1-B2 (upstream – ocean). The flow of water in the river is observed to be in one direction, flowing from upstream to downstream until it reaches the estuary and then flows into the sea. This flow appears to form two types of flow sources, namely surface water flow (from the river) and underwater flow (from the sea), which converge in the estuary area. The magnitude of this flow varies depending on the area of the watershed, geomorphology, and the amount of rainfall, subsequently affecting the river discharge. The modeling results reveal a significant stratification of temperature-salinity-density parameters during high tide. In cross-section A1-A2, the weakest stratification is observed in the Banyuasin estuary, which tends to be homogeneous and persistent, and consistent with conditions during low tide, particularly in the deeper layers. This is influenced by the depth of the Banyuasin estuary, which is deeper than the Musi estuary, resulting in a dominance of high salinity from seawater in the bottom layer. The Musi and Upang estuaries exhibit well-stratified model results from temperature-salinity-density simulations. It is evident from the model results that the temperature-salinity-density stratification in this area is fairly uniform, with a gradation observed in each parameter from the surface layer to the bottom layer of the water. The model accurately reproduces the temperature-salinity-density stratification during the tides, particularly when the tides intrude from the ocean, bringing in a massive water mass. In the Banyuasin estuary, a clearer stratification pattern depicting the layers of water mass, was formed due to the mixing at high tide, compared to at low tide.

In cross-section B1-B2, results from modeling during high tide show stratification of temperature-salinity-density (Figure 9.d-e-f). At high tide, stratification occurs both towards the sea in the surface layer and towards the land in the bottom layer of the water. The highest temperature is found in the surface layer, which is located in the middle of the Musi River close to the mainland. Its area is wider during low tide. Low salinity was also observed in the surface layer, indicating fresh water mass. The model results during the high tide period

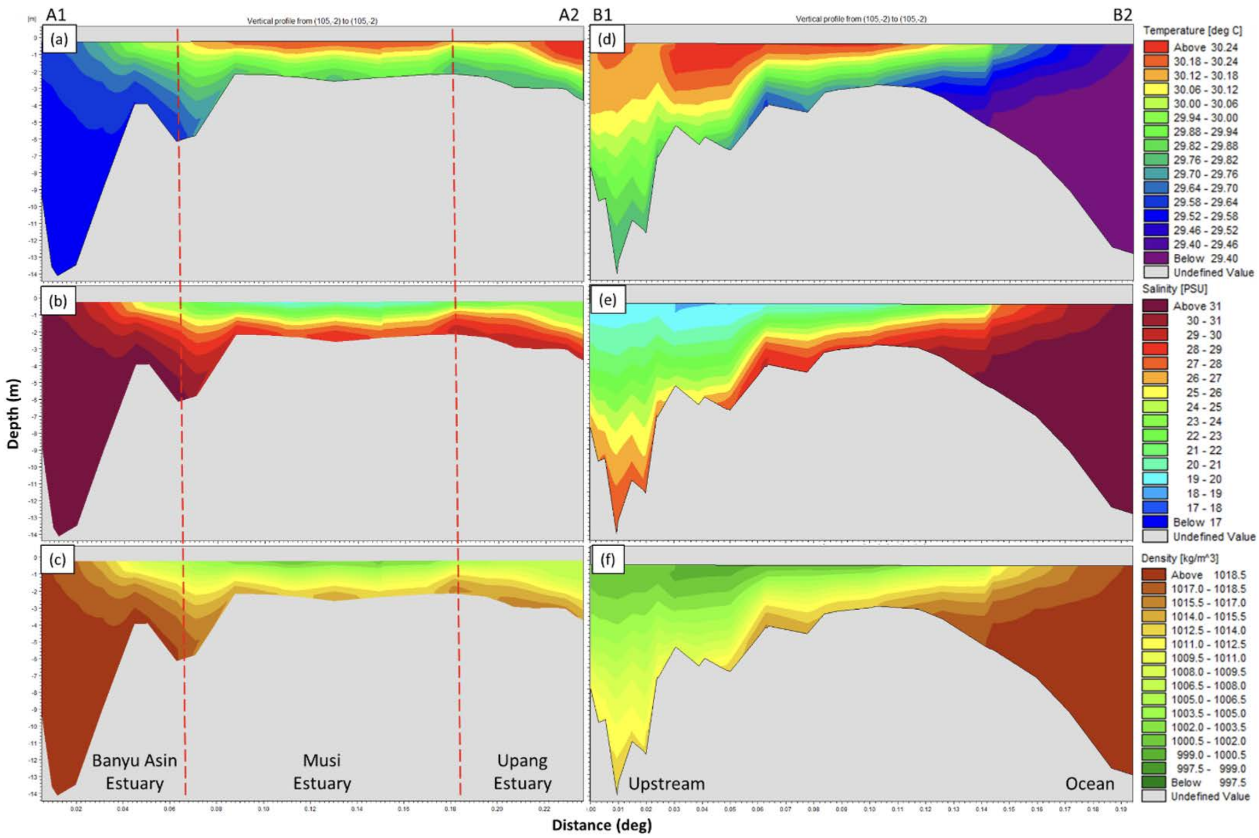

Figure 9. Vertical distribution of (a) temperature (b) salinity (c) density of cross-section A1-A2 (divided into the Banyu Asin estuary-Musi estuary-Upang estuary); and (d) temperature (e) salinity (f) density of cross-section B1-B2 at flood time.

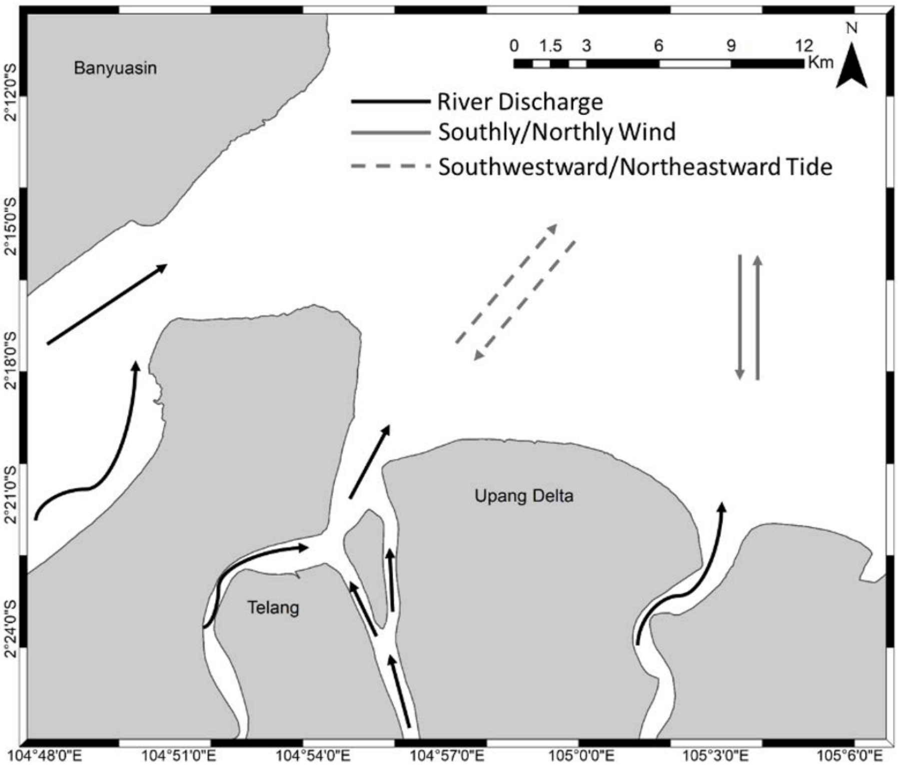

Figure 10. Schematic of stream transportation routes in estuaries: the black solid line represents the river discharge flowing to the sea, the gray solid line represents the to-and-fro path of wind flow in September, and the gray dashed line represents the direction of in-and-out tidal circulation at the study site.

imply a gradient of the temperature-salinity-density layer that protrudes from the upstream area to the ocean. The surface layer is dominated by water masses from rivers, flowing from the mainland towards the ocean. Whereas,

the bottom layer consists of water masses from the ocean. The intrusion of the incoming waters from the sea spreads through the bottom to the very back of the basin, close to the land. This intrusion, characterized by a temperature of 29.88-29.94°C (light green in Figure 9.d), salinity of 27-28 Psu (brick red in Figure 9.e), and density of 12.5-14 (brownish yellow in Figure 9.f), enters the mainland quite far, almost reaching point B1. This occurs because during high tide, sea water moves onto the land with significant pressure, pushing water from the ocean to flow towards the land. there is an. The intrusion of water masses that spreads through the bottom of the water also can be observed in cross-section A1-A2, which appear stratified. Based on the model results obtained in cross-section B1-B2, the salinity gradient increases due to the intrusion of salty and low-temperature water mass into the estuary, which is the characteristic of seawater.

Circulating water flow can be controlled by complex interactions between tides, wind pressure, and fresh water discharge from rivers (Vaz et al., 2009). Winds are likely to contribute to the circulation of water flows and vertical stratification. The process relies on heat exchange when water interact with the atmosphere, as well as advection of salinity in the water. At this location, the wind predominantly blows towards the north, added as a significant influence along with the effects of tides and river flow. Estuaries are often considered an area that all the processes mentioned above can mix well, and this well-stratified area can be observed at different time periods during the high and low tide cycles (Rodrigues & Fortunato, 2017).

Currents from rivers to estuaries induce flow paths, which are mainly controlled by fresh water discharge (Vaz & Dias, 2014). The flow path of the Banyuasin, Musi, and Upang Rivers is mentioned as the main driving force behind the flow. This flow controls the outflow in various areas of the estuary (Figure 10). River discharges from the land to the sea can spread and transport property through river canals. The outflow of the Banyuasin, Musi, and Upang Rivers carries properties, especially on the surface, which is seen in the middle area of the Musi-Upang estuary as a significant area to be traversed due to the shallow bathymetry. The tides that enter and exit in the estuary mouth make this area very influenced by tides, as seen clearly from the pattern derived in the model.

CONCLUSSIONS

Coastal areas and estuaries are areas where freshwater sources from land and sea meet. Here, the characteristics of physical processes often overlap with water masses, resulting in a complex ecosystem. This ecosystem is influenced by factors such as river water discharge, tides, and bathymetry. Due to its broad and complex nature in spatiotemporal scale, relying solely on in situ and/or spatial data is insufficient to explain the processes occurring in this area. To address this limitation, a numerical model can be used to estimate and approximate the reality on the ground. This model helps in understanding the properties of water masses in terms of space and time, as well as the interactions between different components of the system. It is also valuable for monitoring and managing related resources. The model's accuracy is validated through field measurements at various points, yielding reliable values for further analysis. Overall, during low tide, the salt intrusion from the sea is confined in the middle of the cross-section. Conversely, during high tide, salt intrusion can enter the mainland at a secure location near the island.

ACKNOWLEDGEMENTS

Special thanks are extended to Denny Alberto Satrya Gumay and Lerma Yuni Siagian for their invaluable contribution in providing field data. We would also like to express our gratitude to PUSHIDROSAL and BIG for generously providing us with the necessary data for this research and for letting us use the Python program for the analysis and graphing conducted in this paper. Finally, we would like to thank all those who provided valuable input and suggestions during the writing process.

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