Sediment Transport Modeling at Jelitik Estuary, Sungailiat - Bangka Regency for the Design of Sediment Control Structures

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Abstract. Since 2014 sedimentation at the estuary of Jelitik river, Sungailiat, Bangka has continued to increase. At this estuary, the ship traffic is very busy and there is National Fisheries Port Sungailiat. When the tide is low, the river mouth closes thus disrupting ship traffic. The Bangka Belitung Provincial Government is currently planning to build a sediment control infrastructure to reduce the sedimentation rate. To plan and determine the effectiveness of the jetties requires knowledge of sedimentation patterns around Jelitik estuary. Therefore this study was conducted to determine the pattern of sedimentation (distribution and rate) at the existing and ultimate conditions. The methods are field survey, analysis of field data, and computational modeling of sediment transport. Modeling of sediment transport was done using the Sand Transport Module of MIKE 21. Two scenarios were simulated for the existing and ultimate conditions. Based on this modeling, the sedimentation rate at Jelitik estuary is found uneven. In the existing condition, a large rate of sedimentation occurs on the southern side of the Jelitik River estuary, which reaches a maximum value of 2.75 m/year, with an average of 4.44 cm/year. Whereas in the ultimate condition, the sedimentation rate decreases to 0.0377 m/year.

Keywords: computational modeling, estuary, jetty, sedimentation, sediment control, Sungailiat

1. Introduction

1.1. Background
Jelitik River Estuary lies on the east coast of Bangka Island. The ship traffic on this river is very crowded because the national fishing port (PPN) of Sungailiat is located here. In this area, many industries also use ships as a means of transportation. Based on survey and several studies, sedimentation at the Jelitik River estuary is very intensive and at the lowest tide this estuary is closed, thus disrupting ship traffic. Now, The Bangka Belitung Provincial Government is planning to build a sediment control infrastructure at the Jelitik River estuary to reduce the rate of sedimentation at the river mouth so that ship traffic can run smoothly.
As an initial step in planning the sediment control infrastructure, the understanding of the hydrodynamic and sedimentation processes is needed so that later the design of the sediment control infrastructure can be optimized (effective and efficient). One tool that can be used to understand hydrodynamic and sedimentation processes is computational modeling. Therefore this study is carried out, to determine the pattern of sedimentation (distribution and sedimentation velocity) around the mouth of the Jelitik River as consideration for designing sediment control structures. In addition, this study can determine the effectiveness of the proposed sediment control structure design. The results of this study are expected to provide consideration for sediment control in the Jelitik River estuary.

1.2. Literature review
Some studies state that sedimentation in the estuary is due to changes in land use, especially the increase in community tin mining activities [1]. Community tin mining activity in Bangka Island is suspected to be one of the causes of the erosion in the upstream area and the increasing amount of sedimentation in the downstream area (river mouth) [1]. Besides causing erosion and sedimentation, community tin mining is suspected to degrade the quality of several water sources such as rivers, swamps and groundwater which are the main sources for all companies in Bangka Island [2, 3]. At present, the water quality of the Jelitik River has decreased due to the surrounding mining activities. This is indicated by the increase in turbidity from 5.4 NTU at upstream to > 999 NTU at downstream and has damaged the bank of the river in the middle and downstream with the damaged area of 1,983 ha and 1,663 ha respectively [2].

The study of sedimentation at the mouth of the Jelitik River which is downstream of the Pepabri-Jelitik Sub-watershed was conducted by Maulana, 2011 [4]. This study is based on calculations using the Surfer 8.0 program and the CERC coefficient formula. Based on the results of this study, sedimentation at the mouth of the Jelitik River is around 98% due to mining activities at the inland areas and only 2% is caused by the influence of currents and waves that carry sediment material [4]. Sabri (2017) states that erosion in the Pepabri-Jelitik Sub-watershed is categorized as severe with an erosion value of 270,083 tons/ha/year, while sedimentation in the downstream part of this sub-watershed is 52,753.60 tons/year [1]. Another study conducted in Tanjung Layang, District of Sungailiat, based on this study is known that the average amount of sediment transport caused by waves in Tanjung Layang City of Sungailiat is worth 92,652.24 m³/year [5]. From 2007 - 2008 the eroded coastline was 0.1916 km² and 0.0161 km² accreted with 174,882.7 m³ of sediment transport. From 2008 - 2010 eroded coastline was 0.3263 km² and 0.0039 km² accreted with 186,451.5 m³ of sediment transport. From 2010 to 2014 the beaches experienced abrasion of 0.1359 km² and 0.022 km² accretion with sediment transport about 866,661.92 m³ [5].

Based on several studies above, it is known that sedimentation at the mouth of the Jelitik River is quite high. So far, the handling of sedimentation has been carried out by dredging. The Bangka Belitung Provincial Government is currently planning to build a sediment control infrastructure at the Jelitik River estuary to reduce the rate of sedimentation at the river mouth so that ship traffic can run smoothly.

In planning coastal infrastructure, one of the main problems (main issues) from the physical aspects that must be known is the problem of sedimentation and erosion [6, 7, 8]. Erosion and sedimentation are interrelated natural events. The erosion and sedimentation process involves three basic stages: detachment, transport and deposition [9]. The erosion process begins with the release of soil particles from the main rock or aggregate due to strong raindrops and the force of water flow. The greater the intensity of the rain the more soil particles are released [1]. The next process is the transport of soil particles that are eroded by surface water flow which is strongly influenced by the slope and length of the slope, land cover and flow velocity. The last process is sedimentation. Sedimentation is the deposition of soil particles transported and previously held in suspension by flowing water. Sedimentation occurs when the flow decreases to the point where particles can no longer be transported and settle out depending on their weight [9].
The process of hydrodynamics and sediment transport in estuaries is very complex and dynamic. Besides being influenced by river discharge, it is also influenced by tides and waves.

A common problem in the estuary is erosion and deposition where hydrodynamic activity and sediment transport give major influences in terms of erosion and sedimentation phenomena [10]. Interaction between waves, current and sediment transport are very complicated in estuarine water. Understanding this interaction is very useful for designing coastal protection, land reclamation, dredging navigation channels and sedimentation control [11]. Forcing functions and transport processes observed in estuaries such as turbulent flows, tidal mixing, wind stress, wave action, thermal stratifications, and coastal currents and storm surges, are generally three-dimensional in nature [12]. Physical processes associated with sediment transport in and around the breaker zone are highly complex. Varying nearshore topography, wave-induced currents and highly irregular flows make this environment extremely dynamic. Waves breaking near the coast mobilize the sediment around the breaker zone and the currents generated by the waves transport the sediment along and across the coast [13]. In addition to the factors mentioned above, the process of hydrodynamics and sediment transport is also influenced by anthropogenic factors, such as the surrounding human activities [14].

The above phenomenon also occurs at the mouth of the Jelitik River, which is located on the east coast of Bangka Island. Bangka Island Coast has wave currents and longshore transports that are quite large and are affected by the waves of the west wind season and the east wind season [15]. All structures that protrude into the sea will disturb the balance of sediment transport along the coast so the structure can reduce or stop the supply of sediment. Sediment transport along the coast can cause problems such as siltation at ports, coastal erosion and so on, so the prediction of sediment transport along the coast is very important [16, 17]. Sediment transport in the nearshore area consists of onshore-offshore transport and longshore transport. Generally, sediment transport on the coast is limited by sediment cells or only occurs in the same sediment cells.

Sediment cells are spatially discrete areas of the coast within which marine and terrestrial landforms are likely to be connected through processes of sediment exchange, often described using sediment budgets. They include areas of sediment supply (sources), sediment loss (sinks), and the sediment transport processes linking them (pathways) [18].

Prediction of coastal sediment transport can be done by using empirical formulas or by mathematical models to solve continuous equations, energy equations and momentum equations by using finite difference methods or finite element methods [19].

At present, the prediction of sediment transport is easier to do with computational modeling. Computational modeling is a computer-based system for simulating and solving mathematical equations of a coastal process through numerical methods with the help of computer software and hardware [19]. Modern coastal ocean modeling systems are now capable of numerically simulating a variety of coastal and estuarine problems and can provide useful information for managing coastal zones [20].

One of the most reliable software for modeling sediment transport is the MIKE21 Flow Model FM from the Danish Hydraulic Institute (DHI) Denmark, especially the Sand Transport (ST) module. The MIKE 21 Flow Model FM, Sand Transport Module (ST) is the module for the calculation of sediment transport capacity and resulting bed level changes for non-cohesive sediment (sand) due to currents or combined waves-currents [21].

At present, MIKE21 ST module has been widely used and applied to solve erosion and sedimentation problems. In 2003, Siege modeled the dynamics of the sandbar on Teignmout, Teign River, Devon-UK with excellent results. The results of this modeling are coupled and validated with remote sensing data [22]. MIKE21 ST also succeeded in modeling coastal erosion in Baydara Bay - Russia. The model was calibrated using the available data. The model results were found to be in good agreement with the collected data [23]. The ST MIKE21 module also produced a very satisfying model when used to analyze the effect of a breakwater on sedimentation in Pozm Bay-Oman [11]. This module is also used to model the effect of sea-level rise on sedimentation in the Tien River.
Estuary in South Vietnam. The results of the model are morphological evolutions of the Tien River Estuaries showed the same trend as the existing processes [24].

Other use of ST MIKE21 module is modeling sediment transport and morphological change in the Pentland Firth and Orkney Waters [25], modeling of sediment transport at Lampusatu Beach, Papua [26], modeling of sediment transport at Hanstholm Harbour, Denmark [27], evaluation of sediment transport at di Naiband Gulf, Iran [28], modeling of sediment transport at Mangalore Coast [29], modeling of sediment transport at mouth of Musi River, Palembang-Indonesia [30], and scour modeling around coastal protective structure (groin) [31].

1.3. Objectives
The objectives of this study are:
- To determine the pattern of sedimentation (distribution and rate of sedimentation) at existing condition, as consideration for designing sediment control structures.
- To assess the effectiveness of sediment control structures proposed to be built.

1.4. Location of study
The location of the study is in the seawaters around the estuary of Jelitik River. The coordinates are 623853 mE - 641572 mE, 9790000 mN - 9808010 mN, which is in the UTM 49S zone.

Figure 1. Location and area of study.

2. Method
Based on survey and laboratory analysis, it is known that the texture of the sediment is classified as fine sand - medium sand with \(d_{50}\) ranging from 0.10 mm - 1.5 mm with a fairly large gradation coefficient between 1.62 – 4.08 [32]. Therefore the process of sediment transport in the Jelitik River estuary was assessed using Sand transport (ST) modeling in MIKE 21 software. The ST model in MIKE 21 is a transportation model application for non-cohesive sediment types. The ST model is run by coupling with MIKE 21 Hydrodynamics Flexible Mesh (HD FM) and spectral waves [33]. One of the strengths of the MIKE 21 HD FM model is the ability to create a flexible grid so that complex domain contours can be described as a whole. This model shows a good correlation for the seabed which has a high Manning number value (50 m⁹/³/s) and is suitable for areas where sediment transport is primarily affected by the presence of waves so that the wave and currents compilation model gives more realistic results [23].

2.1. Stages of study
The stages of activities start from measurements in the field to modeling of sediment transport (see Figure 2).
2.2. Governing Equations

Sediment transport is calculated as:

\[ q_t = q_b + q_s \]

(1)

Where \( q_t \) is the total sediment transport, \( q_b \) the bedload transport and \( q_s \) is the sediment transport in suspension.

This study uses the Sand Transport (ST) model with the combined driving force of wave and current and the type of bedload and suspended load transport. The development in time of the boundary layer in combined wave-current motion is described by the following first-order differential equation, Fredsøe, 1984 [34]:

\[
\frac{\partial z}{\partial t} = \frac{z(1+\alpha-e^z)}{e^z(z-1)+1} \frac{\partial U_0}{\partial x} + \frac{30K}{k} \left( \frac{K^2 U_0^2 + U_f^2 + 2K U_f U_0 \cos \gamma}{e^z(z-1)+1} \right)^{1/2}
\]

(2)

where:

\( K \) : von Karman constant
\( t \) : time

Figure 2. Scheme of activity stages.
$z$: a parameter related to the boundary layer thickness

$U_0$: the near-bed wave orbital velocity

$U_{f0}$: the friction velocity due to the current inside the wave boundary layer is

$\gamma$: the angle between the current and wave

$k$: the bed roughness, taken to be equal to $2.5d_{50}$ for a plane bed, and $2.5d_{50} + k_R$ for a ripple-covered bed

$d_{50}$: the median grain size

$k_R$: the ripple-related roughness

The vertical sediment transport values in this module are calculated using the diffusion equation (equation 3) as follows:

$$\frac{\partial c}{\partial t} = w \frac{\partial c}{\partial y} + \frac{\partial}{\partial y} \left( \varepsilon_s \frac{\partial c}{\partial y} \right)$$

(3)

where:

$\varepsilon_s$: turbulence coefficient

$c$: suspended sediment concentration

$w$: vertical velocity

2.3. Modeling scenarios

Modeling is done using 2 scenarios, namely the existing condition and ultimate condition (after the port is built and the channel is dredged -6m) (see Figure 3 and Table 1).

| No | Scenario | Information | Simulation Period | Domain (km) | Forcing and Input Data |
|----|----------|-------------|-------------------|-------------|------------------------|
| 1  | Existing | Current conditions (existing), with 8993 elements and 4794 nodes | July 2017 to June 2018 | 17 x 18 | The tides and currents from Hydrodynamic Model. The waves from the Spectral Wave Model. Sediment Properties from Generation of Q3D Sediment Table Module |
| 2  | Ultimate | The condition after jetties have been built (with a length of about 360 m on both sides of Jelitik River), navigation channel dredged -6 m with a width of 110 m. The number of elements is 9335 and nodes are 4991. | | | |

Figure 3 below shows the modeling domain for existing and ultimate condition. The ultimate condition is the condition after jetties have been built (with a length of about 360 m on both sides of Jelitik River), navigation channel dredged -6 m with a width of 110 m.
2.4. **Input Data**

Numerical model results with high accuracy require good model set-up supported by the high quality of field survey data. The better the data quality and set-up, then the results obtained will also be satisfactory [35]. Input data needed in this ST modeling include:

- Wind data obtained from NOAA (National Oceanic and Atmospheric Administration) - Direction-Speed data per 3 hours [36].
- Tidal Data generated from TMD (Tide Model Driver) for input i.e. surface elevation at open boundary [37].
- Shoreline data far from the river mouth is obtained from the Google Earth imagery.
- Tidal data are taken for the period 15 April - 15 May 2018 at 1-hour intervals [38].
- Current data using ADCP (Acoustic Doppler Current Profiler) and flow track [38].
- The coastline data near the river mouth were updated using aerial photography using UAV (Unmanned Aerial Vehicle) [38], which then combined with shoreline data digitized from Google Earth.
- Bathymetry data around the mouth of the Jelitik river is taken using a single beam echosounder (Ceeducer) [38]. This data is then assimilated with secondary bathymetry data from GEBCO [39].
- Bed resistance: Manning Number constant 32 m$^{1/3}$/s [40].
- Sediment properties (grain size and gradation)[32].
• Sediment transport table: which illustrates the distribution of sediment transport value.
• Time series of River Jelitik discharge [38].

3. Results and Discussion

3.1. Validation of hydrodynamic modeling result
Validation of the hydrodynamic model is done by comparing the elevation of the water level from the modeling results with measurement data (see figure 4). Figure 4 shows that the elevation of water level results oh the modeling is very similar to the the results of measuring in the field. The tidal measurement coordinates are 625994, 9794478 (UTM 48S). Comparisons were made for the measurement period between April 24, 2018 and May 09, 2018. Based on the analysis, the value of NRMSD (Normalized Root Mean Square Deviation) between the results of modeling and measurement is 9.383%.

![Figure 4. Comparison of water level between measurement and modeling result.](image)

3.2. Sedimentation pattern at existing condition
Based on the results of modeling for 1 year (July 2017 - June 2018) it can be seen that significant erosion and sedimentation occur inside the mouth of Jelitik River (green, yellow, orange and red colors indicate sedimentation while blue and purple colors indicate erosion) (see Figure 6). After a
simulation of one-month (figure 6.a), erosion and sedimentation began to appear at the mouth of the Jelitik River. The depth of erosion could reach around -0.4 m and sedimentation reached 0.5 m. After a three-month simulation at the tip of the southern river estuary, intense sedimentation occurred with the bed level change value reaching 2 m. Besides, sedimentation also occurred at around 0.4 m to the north of the river mouth. Conversely, at the northern tip of the estuary and in front of the river mouth erosion occurred with the bed level change value reaching -0.5 m and erosion in the middle of the river channel of -0.1 m (Figure 6.b). After a six-month simulation at a relatively similar location, the depth of erosion continues to reach -0.6 m, while sedimentation reaches 3 m at the southern tip of the river mouth (figure 6.c).

At the end of the simulation or after a 1-year simulation at a relatively similar location, the depth of erosion continues to increase and reach -1 m, and sedimentation at the southern tip of the estuary reaches 3 m. Overall along the coast facing the open sea in the southern part of the river mouth, there was sedimentation of about 0.5 m and on the north side of the river mouth, there was an erosion of about -0.4 m (figure 6.d). This is likely related to the results of Sagala's research (2015) which states that during 2010-2014 there were sediment transported about 866,661.92 m$^3$ [5]. This result also related with Sabri (2017) that state sedimentation in the downstream of the Pepabri-Jelitik Sub-watershed is 52,753.60 tons/year [1]

The occurrence of abrasion and retreat of the coastline north of the river mouth is consistent with observations from Google Earth imagery where during the period 2004 - 2018 there was a significant abrasion or coastline retreat where in the north the river mouth retreated around 47 m. The occurrence of sedimentation on the south side of the river mouth is the opposite of the observation of Google Earth imagery, which is likely due to the sand dredging and hoarding of human sand.

![Figure 6. Snapshot of modeling results at existing conditions.](image)

3.3. Sedimentation pattern at the ultimate condition
Based on the results of modeling for 1 year from July 2017 to June 2018 (see figure 7) it appears that in the ultimate conditions, there is an erosion of $\pm$ 0.5 m/year around the southern jetty, shown in purple. Sedimentation processes occur along the coastline, especially in the southern mouth of the
Jelitik River (1.3 m/year) which is shown in green. Sedimentation also occurs on the coastline inside the jetty and around the northern jetty, with sedimentation rates between 0.1 - 1.4 m/year.

In the navigation channel between jetties, the largest sedimentation occurs near the base of the jetty, ranging from 0.5 to 1.4 m/year. Whereas in the channel, the eroded area was around 61,605 m² with an average erosion of around 0.1158 m/year, the area experiencing sedimentation was 75,918 m² with an average sedimentation of around 0.1037 m/year.

Related to the maintenance of navigation channels between the jetties and those in the river channel, the location that needs special treatment is the area near the base of the jetty, since the sedimentation rate reaches 1.4 m/year.

The results show that for the condition where navigation channel is dredged as deep as 6 m, there is sedimentation with an average speed of 0.1 m/year (1 m/10 years) at certain parts of the channel, and the maximum sedimentation speed reaches 0.4 m/year (but with less area of 300 m²).

Overall, on the navigation channel based on the results of the extraction area, it is found that the average sedimentation speed is 0.0067 m/year (0.67 cm/year). So for the maintenance of the channel (assuming the channel can be traversed by ships with a 4 m draft), the volume of sediment that must be dredged is only around 921 m³ per year.

**Figure 7.** Snapshot of modeling results at ultimate conditions.

3.4. **Comparison of modeling results between existing dan ultimate condition**

In general, the results of modeling for 1 year between the existing and ultimate conditions are very different, especially the area within the jetty. To quantify the bed level change, especially in jetty and river channel, area extraction is needed. The location of the extraction area is presented in the following Figure 8.
Figure 8. The location of extraction area at (a) existing condition and (b) ultimate condition.

Based on the results of the area extraction it is known that the average bed level change of the existing conditions is 0.0444 m/year, while the ultimate condition is 0.0067 m/year for 1 year. This shows that the jetty can reduce sedimentation by 0.0376 m/year (about 84.83% compared to existing conditions). In other words, the jetty can reduce bed level change by 6.6 times compared to existing conditions.

To see the changes in bed level in more detail, especially at the mouth of the Jelitik River and the navigation channel, then extraction was carried out on 3 lines (transverse profile). A comparison of modeling results for 1 year between the existing and ultimate conditions in the 3 line extractions is presented in figure 9-11 below.

Figure 9. Bed level change comparison between existing & ultimate condition at profile A-B.
Figure 10. Bed level change comparison between existing & ultimate condition at profile C-D.

Figure 11. Bed level change comparison between existing & ultimate condition at profile E-F.

4. Conclusions
Modeling results at existing conditions indicate that there are significant erosion and sedimentation inside the mouth of the Jelitik river. The dominant direction of total load sediment is to the West-Northwest. However, in the north of the estuary, some are also directed to the southeast. There is large sedimentation on the southern side of the Jelitik estuary with bed level change reaching 2.75 m/year.

Modeling results at the ultimate condition indicate that sedimentation still occurs on the coastline between the jetties, with sedimentation rates between 0.1 - 1.4 m/year. The mean bed level change at the existing condition is 0.0444 m/year, whereas at ultimate condition is 0.0067 m/year. Therefore, the structures can reduce sedimentation by 0.0377 m/yr (about 84.83% reduction compared to existing conditions).

For navigation channel maintenance, the volume of sediment that must be dredged is around 921 m$^3$/yr.

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