Numerical modeling of suspended sediment concentration (SSC) due to water surface fluctuations of the Krueng Langsa estuary, Aceh Province

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Abstract. Krueng Langsa estuary is a meeting zone between the sea and the river that crosses the Langsa city. As a result, the Krueng Langsa estuary had a physical change due to tides and river discharge. The Indonesian Minister of Trade Regulation of Number 24 of 2019 has announced that the Krueng Langsa estuary will resume its activities as international shipping. This indeed becomes an important problem for the continuity of shipping activities. An initial study needs to be carried out related to changes in the physical waters of the estuary due to high and low tides. This study is focused on the estuary physical system—especially in water depth, tidal current, salinity, temperature, and SSC along the estuary due to tidal dynamics processes and river discharge runoff—which are modeled numerically. The influence of the Malacca Strait and the Langsa River flow on SSC at each measurement point have also been observed. In this study, the model results were evaluated using the in-situ measurements. The results show that numerical modeling is capable of providing useful information about the physical condition of the Krueng Langsa estuary and agree well with the measurement data.

1. Introduction

Estuaries are a place where two water masses, interrelated seas, and rivers, are mixed. The mixing of the seas and the rivers causes water to experience changes in the estuary physical system against time, especially in bathymetry (depth and width), tidal currents, temperature, salinity, and suspended sediment concentration (SSC). Due to tides that move towards the river upstream and the river that flows to the sea, estuary becomes a complex environment and could affect water quality including SSC content, which in this case needs to be monitored [1]. UNESCO, 1977 once compiled a list of rivers that flowed into the ocean. Although 260 major rivers flow into the ocean, only 25% have been regularly monitored for water quality. Complex problems from estuary make all fields of science participate in solving problems. In order to solve the problem, the method must be improved, and it takes years—when they are applied [2]. However, the direct measurement process is difficult to see as the estuary's physical state has a complex relationship, so that observations can be made by modeling the interconnected physical parameters. This model also able to provide information in decision making on the estuary physical system that prioritizes estuary quality. Saltwater intrusion in estuaries is influenced by seasons; as a result, [3] conducted a numerical modeling of the Indus estuary in Pakistan in seeing the tidal characteristics in the upstream estuary; in the dry season, the tidal reaches 65 km more than those in rainy season because of the resistance from the river to the sea as a barrier to saltwater intrusion in estuary.
In his study of the Belawan estuary physical system modeling, [4] stated that the main consideration in the estuary was a sedimentation increase, which led to the need for high costs of dredging to achieve the draft requirement of the ship. The increase in sedimentation is common, especially in estuaries, where the upper cross the city and causes an increase in the content of the SSC. [5] studied the flow characteristics of the ebb of saltwater intrusion in areas where there are mangroves or no mangroves around the coast. It was found that the comparison of observations and numerical simulation results in Liao China estuary obtained good results. The continuity of activities in a port and increased resources around the estuary waters have reached alarming levels, especially the Krueng Langsa estuary, which will again become an international shipping channel. Krueng Langsa estuary is predicted to have experienced sedimentation, as evidenced by the large draft vessel unable to enter the port of Kuala Langsa port [6]. With the issuance [7], the waters in the port of Kuala Langsa must fulfill the Indonesian National Port Order. The service requirements for the depth of the primary international port shipping line are at least 12 meters Mean Sea Level (MSL) and for secondary and tertiary international ports, the minimum value is 9 meters MSL [8]. In line with the predictions made, [9] stated that the erosion of the Langsa river basin partially flown to the Krueng Langsa estuary because the estuary-sediment load elevated 10,512.25 m$^3$/year.

The main objective of this study was to determine the physical changes of estuary due to fluctuations in water level by forming a numerical model simulation compared to the measurement data. Thus, numerical modeling is needed to observe the physical characteristics of Krueng Langsa estuary. The model results are then compared with the measurement data based on numerical model validation that has been done by [10] and [11]. Then, the value of the Correlation Coefficient (CC), Mean Error (ME), and Root Mean Square Error (RMSE) were determined to obtain information about the relationship between the results of modeling and measurement data.

2. Methodology

The study area is the Krueng Langsa estuary, where the mouth part is connected to the Malacca Strait and the downstream part is in the Krueng Langsa River. The observation points, which start from the estuary mouth and go upstream, were checked every 1 km by observing the salinity parameters close to 0 mg/L. The estuary mouth was coded as the STA A (0 + 000), and the upstream of the estuary was coded as STA Q (16 + 000), as shown in figure 1.

Measurements were taken at each station point by taking the physical parameters of the estuary, namely, flow depth using Fish Finder GPS MAP 585. Handled GPS is utilized as a station measurement at every 1 km distance. The current meter is used to measure flow rate while salinity and temperature are measured with Handheld IP67. Furthermore, SSC is collected by Van Dorn Water Sample tools at 0.2 h, 0.6 h, and 0.8 h and tested using the evaporation method at the laboratory. Krueng Langsa estuary has no tidal recording data. The tides measurements are examined for 15 days using a gauge through the lowest ebbs and which aims to obtain the amplitude of the solar (A$S_2$) and amplitude of the moon (A$M_2$) through the admiral method.

In this study, the model is simulated by computational programs using the physical computational estuary model given by [2], namely:

2.1 Depth and width of estuary

The first step in numerical modeling is determining the stream depth ($D$) and the width of the Krueng Langsa estuary in an exponential variation from the mouth towards the upstream. This step was determined by dividing each measuring distance to produce a bathymetric geometry form. The formula used in this step was as follows:

$$ \text{Width: } W_x = W_0 e^{-a\left(\frac{x}{L}\right)} \quad \text{and Depth: } D_x = D_0 e^{-b\left(\frac{x}{L}\right)} $$  \hspace{1cm} (1)

With, $W_x =$ the estuary width at the point of measurement, $x$ (m); $D_x =$ the estuary depth at the measurement point, $x$ (m); $W_0 =$ the estuary width at the mouth (m); $D_0 =$ the estuary depth at the mouth.
(m); \( x \) = the distance from the mouth of the estuary (m), \( L \) = the estuary length from the estuary mouth (m); \( a \) and \( b \) are the coefficient of estuary width and depth, respectively.

Figure 1. Observation site locations performed in this study.

Figure 2. Flow chart of the numerical model of the physical estuary.

2.2 Tidal currents
The tidal type is determined with Formzal number according to tidal measurement data for 15 days. The changes in estuary depth \( h(t) \) due to tidal harmonic is stated as follow:

\[
h(t) = A_{S2} \sin\left(\frac{2\pi t}{T_{S2}}\right) + A_{M2} \sin\left(\frac{2\pi t}{T_{M2}}\right) + A_{M4} \sin\left(\frac{2\pi t}{T_{M4}}\right) + DT
\]  (2)
Tidal water when reaching shallow water will experience an increase (in-depth) affected by the $A_{M4}$ component which stated by:

$$A_{M4} = \frac{3x \delta h}{4\lambda T h} = \frac{3x \delta h}{4\lambda T \sqrt{\gamma gh}}$$  \hspace{1cm} (3)

With, $h(t) =$ total water level with time $t$ hour (m); $A_{S2}$ = tidal amplitude due to solar attraction (m); $T_{S2}$ = tidal period due to the sun (12 hours); $2\pi =$ the rotation angle of the moon against earth and earth against the sun; $A_{M2} =$ tidal amplitude due to lunar attraction (m); $T_{M2} =$ tidal period due to the moon (12.42 hours); $A_{M4} =$ amplitude of quarter-diurnal lunar tides (m); $T_{M4} =$ period due to diurnal lunar quarter (6.21 hours); $DT =$ water depth for each measurement point, $D_x$ (m), and g = gravitational acceleration (9.81 m/s$^2$)

The combination of two tidal flows from the sea and the river results in current variations in each distance and time of $U(x, t)$ to be:

$$U(x, t) = \frac{\int_{x=x}^{x} w_x \Delta h_x dx}{\int_{x=x}^{x} w_x dx} - \frac{Q}{w_x}$$ \hspace{1cm} (4)

With, $U(x, t)$ = Estuary current for each distance $x$ and time $t$ (m/s); $\Delta h =$ change in depth due to tides per hour per second (m/s); and $Q =$ River discharge (m$^3$/s).

2.3 Temperature and salinity

The distribution of temperature and salinity from the estuary mouth to the upstream of the estuary varies numerically from the temperature distribution of each measurement point ($T_x$) and the salinity of each measurement point ($S_x$). $T_x$ and $S_x$ can be obtained through the following gauss distribution equation:

$$T(x) = (T_R - T_S) \exp \left[ -\frac{x^2}{2\sigma_x^2} \right] + T_S$$ \hspace{1cm} (5)

and

$$S(x) = S \exp \left[ -\frac{x^2}{2\sigma_x^2} \right]$$ \hspace{1cm} (6)

By, $T_S =$ temperature at sea (°C); $T_R =$ temperature on the river (°C); $S =$ salinity in the mouth of the estuary; and $\sigma_x =$ Gauss distribution variance.

2.4 Suspended sediment concentration (SSC)

Due to the exchange of tidal currents and river flow in the estuary, the content of the floating sediment concentration will change with time (t) as the final step of the numerical model predicted by the following equation:

$$C(t) = \left( \frac{C_{Mx} - C_B}{2} \right) \left( 1 + \cos \left( \frac{2\pi t}{6.21} \right) \right) + C_B \ \text{; where:} \ \ C_{Mx} = \frac{M}{S_p \omega_3} \left( \frac{u_{m}^{2}}{u_{cr}^{2}} - 1 \right) + C_B$$ \hspace{1cm} (7)

With, $C(t)$ sediment concentration at each tide time (mg/dm$^3$); $C_B =$ background of floating sediment concentration (mg/L); $C_{Mx} =$ maximum concentration in estuary; $S_p =$ suspension parameters that depend on the type of estuary, $S_p = 2$ (estuary perfectly mixed), $S_p = 4$ (partially mixed estuary), and $S_p = 8$ (estuary start); $u_{cr}$ = critical threshold currents of 0.2 m/s (silt), 0.4 m/s (fine sand) and 0.6 m/s (moderate sand); and $u_m =$ maximum current speed (m/s).

This study also continued from the studio [4] in Belawan estuary with the same numerical model and was not validated, so numerical models were carried out at different estuary locations and validated between the model and field measurements. In general, numerical models on simple estuaries are widely
available, one of them is Box Model/ Finite Segment [12], but it must have complete data to see the intrusion conditions of each point to the upstream of the estuary. While the exponential model used in this model only requires physical data parameters in the estuary mouth, for other conditions, it can directly give an overview of each parameter to the upstream of the estuary.

3. Results and Discussion
The beginning of the measurement was to collect salinity data from the estuary mouth to the upstream in order to find salinity with a value close to 0 mg/L. From the measurement results, salinity with 6.85 mg/L is then used as the final measurement station. The observation points were examined every 1 km, starting from estuary mouth (STA A) toward the upstream (STA Q). The result has shown the length of the estuary (L), which ranges at 16 km. Then, the numerical model is formed on six estuary physical parameters, namely depth, width, tide, current, temperature, salinity, and elevated sediment concentration. The model is carried out from bathymetry (depth and width) using equation (1). Based on measurements in the estuary mouth with width ($W_0 = 1,869$ m) and depth ($D_0 = 8,263$ m), the relationship of the numerical model and in situ measurement is shown in figure 3.

![Figure 3](image_url)

**Figure 3.** Comparison between the numerical model and in situ measurement for depth (left) and width (right) of Krueng Langsa estuary.

The numerical model results are compared with the measurement data by looking at the error value density of Mean Error (ME) and Root Mean Square Error (RMSE) with good Correlation Coefficient (CC) values as shown in table 1.

| Parameter | Coefficient | ME    | RMSE  | CC   |
|-----------|-------------|-------|-------|------|
| Width     | 6.03        | -29.79| 159.34| 0.959|
| Depth     | 1.48        | -5.11 | 8.02  | 0.421|
| Temperature| 10.62       | 0.09  | 0.27  | 0.962|
| Salinity  | 11.19       | -2.07 | 3.98  | 0.941|
| Tide      | -           | -6.06 | 25.12 | 0.830|

Table 1 shows the result of the minimum error value of the width, depth, temperature, salinity, and tide from error density data compared between the numerical model and in situ measurement. The result
of the width coefficient value was 6.03. The value of Coefficient Correlation (CC) equals 0.959 which indicated a good relationship between the model and measurement, as shown in figure 3 (right section). Meanwhile, the depth coefficient value was 1.48 with a low CC of 0.421. This low correlation indicated irregular variation between model and measurement as shown in figure 3 (left section).

The results of irregular depth at each station from the estuary mouth to the upstream estuary are shown in Table 1. Variation of depth showed that the estuary mouth has an average depth of 8.26 m MSL, which did not satisfy the requirements of the national port standard [4] with a minimum depth of 9 m MSL. Nevertheless, STA D, STA E, and STA F—which located at the port of Kuala Langsa—have significant depth of the shipping channel of 13,287 m, 21,033 m, and 17,763 m MSL, respectively. In general, the Krueng Langsa estuary is proper of being used as an international port but the conservation to achieve shipping line standards is needed especially in the estuary mouth of STA A to C. In order to achieve shipping line stability, a model was formed with \( D_0 = 15 \) m and \( D_0 = 20 \) m, as shown in figure 3 (left section) and table 2.

### Table 2. Comparison of model results and measurements of bathymetry.

| STASIUN | Width Estuary (m) |  | Depth Estuary (m) |  |
|---------|-------------------|---|-------------------|---|
|         | Measured          | Model (Wo = 1,869 m) | Measured | Model (Do = 8.263 m) | Model (Do = 15 m) | Model (Do = 20 m) |
| A       | 1,869.0           | 1869.00 | 8.264           | 8.263 | 15.000 | 20.000 |
| B       | 1,002.0           | 1282.14 | 9.092           | 7.533 | 13.675 | 18.233 |
| C       | 573.0            | 879.55 | 7.913           | 6.867 | 12.467 | 16.622 |
| D       | 456.0            | 603.37 | 13.287          | 6.261 | 11.365 | 15.154 |
| E       | 317.0            | 413.91 | 21.033          | 5.708 | 10.361 | 13.815 |
| F       | 284.0            | 283.95 | 17.763          | 5.203 | 9.446  | 12.594 |
| G       | 383.0            | 194.79 | 9.703           | 4.744 | 8.611  | 11.481 |
| H       | 220.0            | 133.62 | 17.579          | 4.324 | 7.850  | 10.467 |
| I       | 325.0            | 91.67  | 9.296           | 3.942 | 7.157  | 9.542  |
| J       | 295.0            | 62.88  | 23.383          | 3.594 | 6.524  | 8.699  |
| K       | 231.0            | 43.14  | 8.363           | 3.277 | 5.948  | 7.931  |
| L       | 197.0            | 29.59  | 3.683           | 2.987 | 5.422  | 7.230  |
| M       | 94.2             | 20.30  | 3.292           | 2.723 | 4.943  | 6.591  |
| N       | 76.0             | 13.93  | 2.316           | 2.483 | 4.507  | 6.009  |
| O       | 57.2             | 9.55   | 2.263           | 2.263 | 4.108  | 5.478  |
| P       | 45.2             | 6.55   | 1.954           | 2.063 | 3.745  | 4.994  |
| Q       | 24.7             | 4.50   | 1.836           | 1.881 | 3.415  | 4.553  |

The tidal model was done by equation (2). The component was obtained from the admiralty method through tide measurement data for 15 days (21\textsuperscript{st} March to 4\textsuperscript{th} April 2019) yielding \( A_{S2} = 0.143 \), \( A_{M2} = 0.326 \), and \( A_{M4} = 0.00010 \) m. Formzal number (F) was equal to 0.117 (F < 0.25). This indication classified Krueng Langsa estuary as a semidiurnal tidal type with an average sea level (MSL) of 1,561 m. The highest tide average (HWS) equals to 2.27 m, and the lowest tide average (LWS) is 0.85 m.

The relationship between the model and measurement in figure 4 indicated a good agreement with CC = 0.830. Therefore, the model can be used to predict the occurrence of tides in the Krueng Langsa estuary. The measurement of salinity parameters in the estuary mouth was 38 mg/L, where the temperature in STA A (estuary mouth) was 30 °C and in STA Q (Langsa river) was 32.08 °C. So, the temperature of the river (\( T_R \)) > temperature of sea (\( T_S \)). The distribution of salinity and temperature
parameters is formed in numerical models through the gaussian distribution equations (5) and (6). The relationship between the model and measurement data of salinity and temperature parameters shown in figure 5.

![Figure 4](image.jpg)

**Figure 4.** Comparison between the model output and measurement data for tides and lows of Krueng Langsa estuary.

![Figure 5](image.jpg)

**Figure 5.** Comparison between the model and measurement data for salinity (left) and temperature (right) of Krueng Langsa estuary.

The $\sigma_x$ value as the gaussian distribution variance every 1 km is calculated based on $T_x$ and $S_x$. The model results and the measurement data show good agreement with the value of CCs are 0.96 for
temperature and 0.94 for salinity, as shown in table 1. This value expressed the numerical model. In situ measurements are correlated. As a result of the exchange of saltwater (sea) and river freshwater, temperature and salinity parameters in the estuary zone will continue to change in harmony due to tidal currents and river discharge.

The current model was formed using equation (4). From the measurement data of Langsa river, flow velocity was 0.353 m/s at point Q with a width of 24.7 m and depth of 1.836 m resulting in river discharge (Q) of 16 m$^3$/s. The each-point river flow towards the estuary mouth and tide currents are obtained from the difference of the depth ($\Delta h$: $h_{i+1}$ - $h_i$) and the upstream volume of ($V_{ut+1} = \Delta_1 W_x / 106 + V_{ut}$). The hourly tidal current conditions at STA A state that the peak tidal current is 0.008 m/s, the lowest current is 0.010 m/s, the maximum tide current is 0.028 m/s and ebb-tides are 0.0270, as shown in figure 6.

The modeling of sediment concentration was formed using equation (7). Based on laboratory tests of sediment for each station, $C_B$ is equal to $C_B$ of 379 mg/L. The distribution of sediment grains at the bottom of the Lago Palm estuary is classified as sedimentary sand—$u_{cr} = 2$ and $\omega_S = 0.1$ m/s. $C_{Max}$ value obtained at STA A is equal to 0.454 kg/m$^3$. Then, SSC was formed every hour due to the tide of the floating sediment concentration pattern as shown in figure 6. The figure explained that the pattern of SSC during peak tides is 0.379 kg/m$^3$. During the maximum tides, the value of SSC is greater at 0.453 kg/m$^3$ and the max (tide) current of the SSC value also increases by 0.451 kg/m$^3$. These phenomena explain that the higher current will cause an increase in SSC in the Krueng Langsa estuary. By the value of $CC = 0.83$, it means that the relationship of increasing current is in line with the increase in SSC.

The tidal current pattern and SSC from figure 6 stated that tidal currents in the estuary mouth showed that the river flow upstream of the estuary is 0.353 m/s to 0.001 m/s at STA A. This occurrence is due to greater estuary cross-section so that the river flow does not affect the tidal current as a current total.
Meanwhile, for STA which are located upstream, such as STA D, STA H, and STA Q, river flow affected the tidal current. So that, during low tide conditions, the total current increases together with the tidal current; when a tide occurs, the total current decreases from the tide current. The current pattern also explained the condition of the SSC content in the Krueng Langsa estuary, where during low tide conditions, there is an increase in SSC and slack water conditions during tides and low tide.

4. Conclusion
Numerical modeling was applied to observe the characteristics of the physical properties of the Krueng Langsa estuary, especially in water depth, tidal currents, salinity, temperature, and SSC. Then, numerical modeling was evaluated using measurement data. The observation point consists of 17 stations at every 1 km starting from the estuary mouth (STA A) toward the upstream (STA Q). The results show that the correlations between the model results and observations are quite good for most physical parameters that are modeled where CCs are ranged from 0.42 to 0.696. The correlation between currents and SSCs shows CC of 0.83, which indicates good utility. As a result, it can be concluded that increasing the current will increase the content of SSC in the Krueng Langsa estuary.

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