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Modelling the Physical System of Belawan Estuary

A P M Tarigan[1*], D Swandana[1] and F Isma[2]

[1] Civil Engineering Department, Faculty of Engineering, University of Sumatera Utara, Jl. Dr. Mansur No. 9 Medan, Indonesia
[2] Civil Engineering Department, Faculty of Engineering, Universitas of Samudra

*nuahptarigan@gmail.com

Abstract. Belawan estuary represents one of the most complex and fascinating mixed environments of sea and land, where not only habitat of rich biodiversity but also international seaport infrastructure are at stake. It is therefore a matter of considerable importance to understand the physical system which characterizes the dynamics of the estuarine water. The purpose of this study is to model the changing water depths, tidal currents, salt, temperature and sediment concentration over a long stretch of Belawan estuary on an hourly basis. The first essential step is to define the bathymetry based on which other physical parameters are simulated. The study is accomplished by building working computer modules which simplify and model the systems complexities. It should be noted that model validation and improvement is the subject of the next study.

1. Introduction

Belawan estuary is a complex and fascinating environment where sea and land borne parameters are mixed intertwined. The estuary is a habitat of rich biodiversity and the location of Belawan International Seaport. Both represent matters of considerable interests, although the former is usually defeated in the name of economy outlook.

However growing concerns on natural resources of the estuary has increased since the wellbeing of the habitat will eventually affect the sustainability of the port. The main problems over the estuary can be described as follows. There is a high rate of sedimentation which causes a lot of effort of dredging with enormous amount of cost. This is a common problem in urban areas as mention in [1]. The Belawan estuarine water has been polluted with a high concentration of metal due to port operation and nearby industrial activities [2]. Frequent flooding over the low laying area of Belawan has been a common condition during the wet rainy period, and this problem is worsened by a high rate of sea level rise causing shoreline erosion [3].

To cope with the problems, it is of considerable importance to understand the nature of the characters of Belawan estuary. The purpose of this study is to gain understanding of the physical system of the estuary. The objective is to be attained by modelling the changing water depths, tidal currents, salt, temperature and sediment concentration over a long stretch of Belawan estuary on an hourly basis. Figure 1 is the map of the study site.

Figure 1. Map of study side

2. Basic Theory and Scope

The basic theory in this study is based on the concepts and applications described by Hardisty (2007) [4]. The first step in the modeling is to have a geometric shape for bathymetry which is expressed as follows [4].

$$W_x = W_o e^{-a\left(\frac{x}{L}\right)} \tag{1}$$

and

$$D_x = D_o e^{-b\left(\frac{x}{L}\right)} \tag{2}$$

where W_x = the estuary width (m), W_o = the estuary width in the mouth (m), D_x = the estuary depth (m), D_o = the estuary depth in the mouth (m), x = distance from the mouth (m), L = the estuary length (m), a and b are bathymetry coefficients.

The water depth, h(t) is estimated using a harmonic function of the three components of the tides as follows.

$$h(t) = A_{S2} \sin(2\pi t/T_{S2}) + A_{M2} \sin(2\pi t/T_{M2}) + A_{M4} \sin(2\pi\, t/T_{M4}) + DT \tag{3}$$

where h(t) = the depth of water at time t (m), A_{S2} = the amplitude of solar semi diurnal tide (m), T_{S2} = the period of solar semi-diurnal tide (12 hours), A_{M2} = the amplitude of lunar semi-diurnal tide (m), T_{M2} = the period of solar semi-diurnal tide (12.42 hours), A_{M4} = the amplitude of lunar quarter-diurnal (m), T_{M4} = the period of lunar quarter-diurnal (6.21 hours), and DT = the estuary depth (m).

Estuary water is composed of riverine and sea waters. The current U(x,t) is expressed as follows [4].

$$U(x,t) = \frac{\int_{x=X}^{x=L} W_x \, \Delta h_t \, dx}{W_x D_x} - \frac{Q}{W_x D_x} \tag{4}$$

where U(x,t) = the tidal flow at time t and distance x from the mouth (m/s), Δh_t = the change in tidal depth per second (m/s), and Q = the freshwater discharge (m^3/s).

The temperature and salinity are formulated using Gaussian distribution [4].

$$\text{for } T_S > T_R,\quad T(x) = (T_S - T_R)\exp\left[-\frac{x^2}{2\sigma_x^2}\right] + T_R \tag{5}$$

$$\text{for } T_R > T_S,\quad T(x) = (T_R - T_S)\exp\left[-\frac{x^2}{2\sigma_x^2}\right] + T_S \tag{6}$$

and

$$S(x) = S_o \exp\left[-\frac{x^2}{2\sigma_x^2}\right] \tag{7}$$

where $T(x)$ = the estuarine temperature (°C), T_S = the sea temperature (°C), T_R = the river temperature (°C), σ = the variance, $S(x)$ = salinity (‰), and S_o = salinity at the mouth (‰). Finally, the sediment concentration is expressed.

$$C(t) = \left(\frac{C\max - C_b}{2}\right)\left(1 + \cos\left(\frac{2\pi t}{6.21}\right)\right) + C_b \tag{8}$$

where C (t) = the concentration of SPM (Suspended Particulate Matter) at time t (mg/dm^3), C max = the maximum concentration (mg/dm^3), and C_b = the background concentration (mg/dm^3).

The scope of study is described in Figure 2. The stretch of the estuary under study is from x = 0 at the mouth to x = 18 km upstream. The point of observation is interval at 2 km from point A at the mouth to point J at the most upstream [4].

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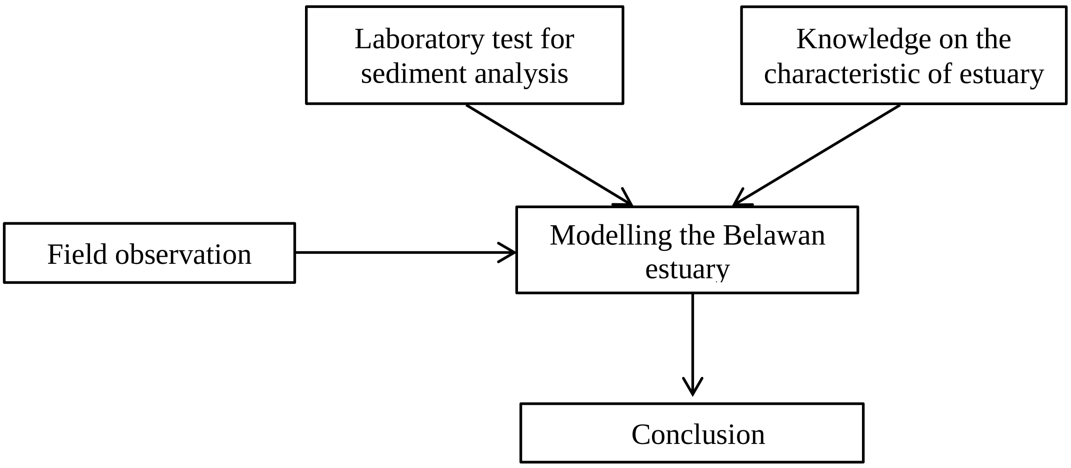
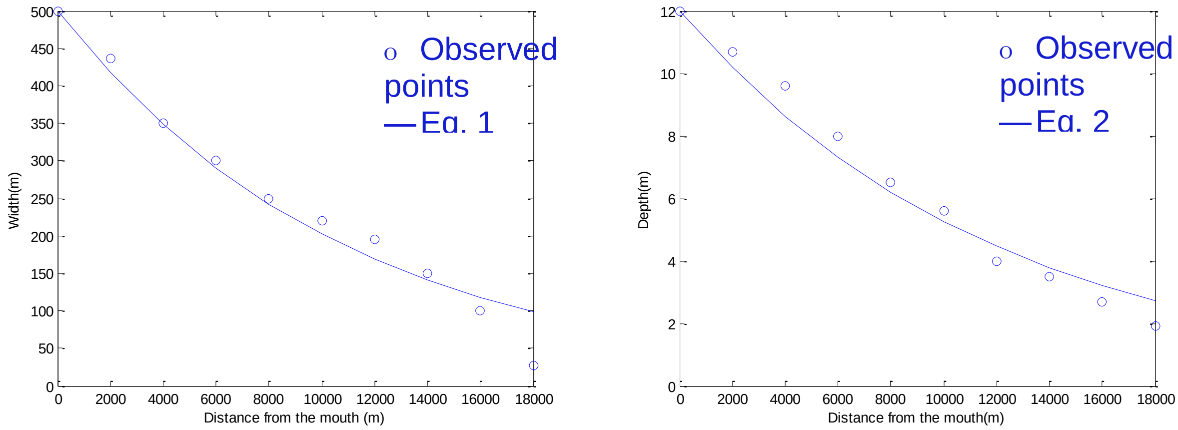


Figure 2. Scope of the study

3. Results and Discussion

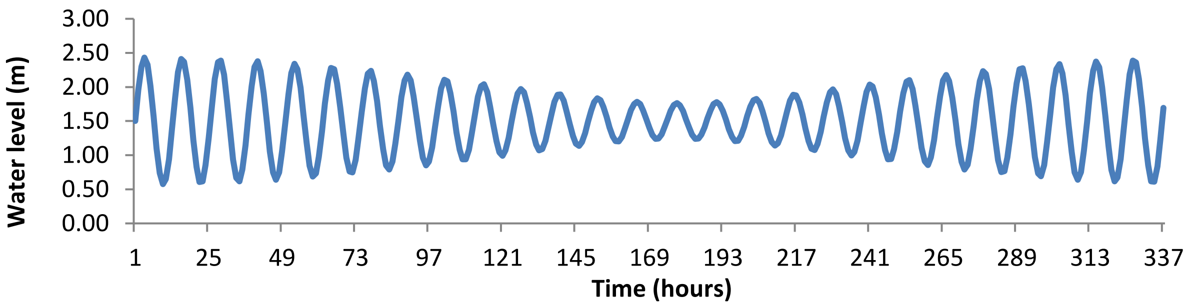
Based on the equations given in the previous section, the following results can be obtained through a computer program. There are 6 models described here including bathymetry, tides, current, temperature, salinity and sediment. First, the model for bathymetry is demonstrated in Figure 3. It can be seen from the figure that exponential geometry can depict the depth and the width of the estuary fairly well. The values of the coefficients in Eq. 1 and Eq. 2 are a = 1.63 and b =1.48.



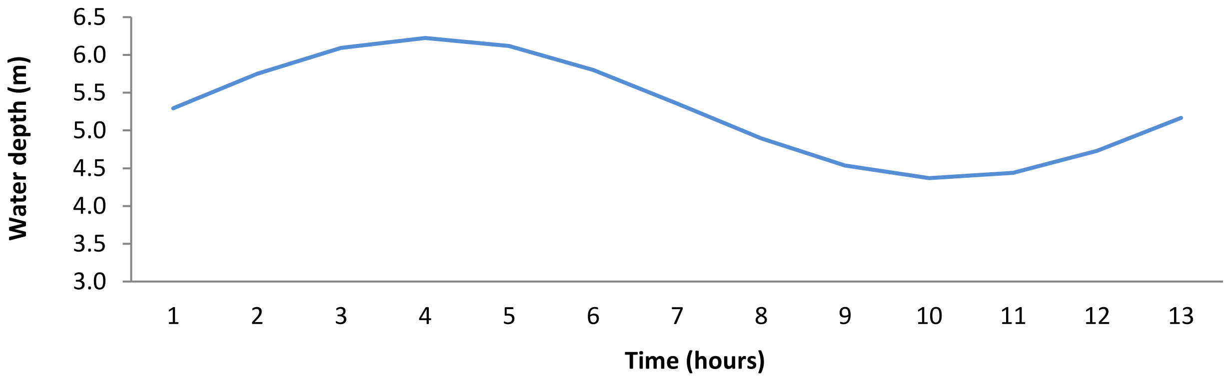
(a) (b)

Figure 3. The model for estuary width (a); the model for estuary depth (b)

The tide is modeled using Eq. 3 with A_{S2} = 0.335 m, A_{M2} = 0.597 m. Figure 4.a describes the tides composed of A_{S2} and A_{M2} for 15 days showing the semidiurnal character of the tides and the variation between spring and neap tides. Meanwhile Figure 4.b describes the total components of the tide at point E (10 km from the mouth) for a half day. Note that $A_{M4} = \frac{3 \text{ x } A_{M2}^2}{4\,h\,T_{M4}\sqrt{g\,h}}$ which is 0.0031 at point E with water depth h = 5.3 m and the value of A_{M4} increases with decreasing depths h.



(a)



(b)

Figure 4. Tides due to $A_{S2} + A_{M2}$ (a); water depth due to total components at point E (b)

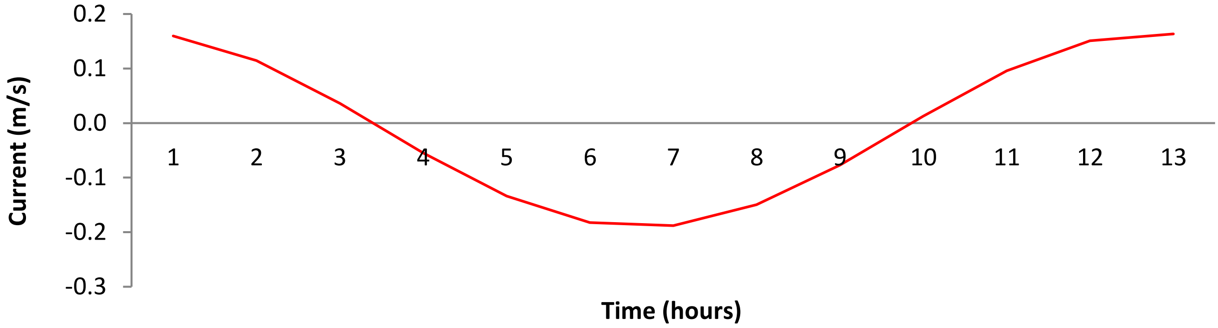
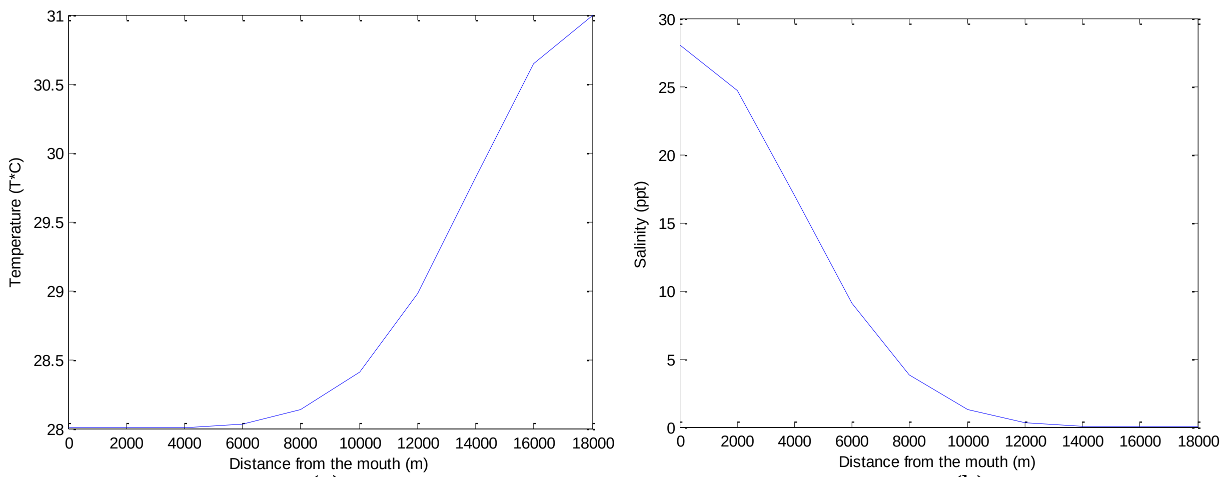


Figure 5. The current at point E

The current is represented using Eq. 4 and the result at point E is depicted in Figure 5 for a half day. It can be seen in this Figure and Figure 4.b that the slack waters occur at the proximities of the highest and lowest water levels. Meanwhile the maximum in minimum currents occur near the middle of high and low tides. Notice in Figure 5 that positive values represent currents going to upstream, while negative currents going to downstream. Negative currents tend to become more significant toward the upstream.

The temperature expressed in Eq. 6 is depicted in Figure 6.a. It was measured during the day that the temperature at the estuary mouth might reach up to T = 31 ^{o}C, while far upstream in the river of Belawan the water temperature was T = 28 ^{o}C [5][6]. The salinity expressed in Eq. 7 is depicted in Figure 6.b. Likewise it was measured during the day that the salinity at the estuary mouth might reach up to S = 28 ‰, while far upstream in the river of Belawan the water salinity was S = 0 [5] [6].



(a) (b)

Figure 6. The Gaussian distribution of the estuary temperature with σ = 4.00 (a);
The Gaussian distribution of the estuary salinity with σ = 4.00 (b)

Based on Eq. 8 the model for sediment concentration is depicted in Figure 7. Referring to Figure 4.b and 5, it can be explained that the minimum sediment concentration in Figure 7 occurs near the slack waters. Meanwhile the maximum sediment concentration occurs in the middle between high and low tides. It should be noted the sediment model is not capable of showing any intra-tidal variability and sediment stratification within a tidal cycle as shown by Wang and Wang (2010) [7].

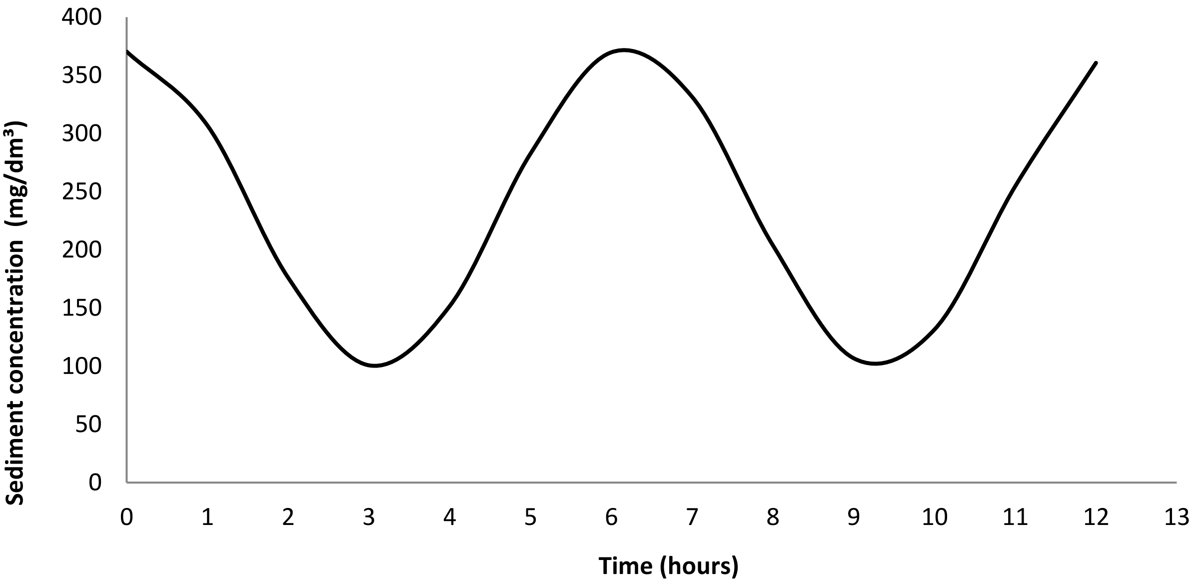


Figure 7. The concentration of SPM (suspended particulate matter) at point E

4. Conclusion

It can be concluded that the models described in this study have fairly well demonstrated the physical system of Belawan estuary including bathymetry, tides, current, temperature, salinity and sediment. Hence basic understanding on the characters of the estuary has been gained. In order to confirm the robustness of the models more field data are needed for validation to be planned in the further study.

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