Numerical simulation of tidal bore in Kampar river: a preliminary study

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Abstract. Tidal bore is a very rare natural phenomenon, in which the flow of the river goes upstream. It usually happens close to the estuary. In Indonesia, it happens at Kampar river, Riau province. Some factors that cause this phenomena are tides waves and water bottom topography. In this paper, we simulated the propagation of tidal bore in the Kampar river based on shallow water equations (SWE). We used the staggered grid conservative scheme to discretize the SWE. Next, we apply bottom topography of Kampar river and tides elevation profile there into our scheme. Finally, we present numerical simulation of tidal bore propagation along the Kampar river. The result shows that the river discharges have a quite significant effect on increasing bore elevations. The friction coefficient has an important role on wave attenuation of tidal bore propagation.

1. Introduction

Estuary is kind of interest place to observe many natural phenomena. One of them is contraflow between tidal flows and river discharges that pushes the river upstream which is known as the tidal bore. Tidal bore is a very rare natural phenomenon because it does not occur in all rivers. It is such a huge wave that propagates upstream along the river. There are some factors that generate the tidal bore such as tidal range and river discharge, but the most important thing that influences the occurrence of the tidal bore is the physical characteristics of the estuary [1].

In Indonesia, tidal bore only occurs in Kampar river, Riau province, Indonesia (see Figure 1). This phenomenon is forced by tides waves from Malacca straits [2]. Local people usually call it Bono waves. The uniqueness of Kampar river is there is a small island near the estuary known as Muda island. Some hypotheses relate Muda island to the formation of Bono waves in Kampar river. The biggest Bono usually occurs during the rainy season, when the water discharge is quite large (around November and December). Bono may cause destruction effect, because the tidal range typically may reach 4-5 meters with the velocity more than 10 m/s. The wave can destroy everything in front of it.

Several researches about numerical simulation of tidal bore can be found in [3, 4, 5, 6]. They discussed about numerical simulation based on the shallow water wave model in Qiantang river, China. Another research is also taken in the same place but using a different model i.e. Boltzmann equation [7]. However, there is still little research on tidal bore in Kampar river, Indonesia. In [8], they investigated the environmental effect of tidal bore propagation in Kampar river using Korteweg and De Vries (KdV) equation. While for analysis of bathymetry and wave tides as the generator of an undular bore in Kampar river can be seen in [9].

In this paper, we simulated tidal bore in Kampar river (Figure 1) based on nonlinear shallow water equation using staggered grid conservative scheme. This scheme was proposed in [10] and successfully applied to simulate various shallow water flow see [11]. We applied water bottom topography of Kampar river and open boundary condition in the mouth of the river into our scheme. Next, we
presented the result of numerical simulation on several points along the Kampar river to see the influence of river discharge and friction coefficient on tidal bore propagation.

![Figure 1. The location of Kampar river in Riau Province, Indonesia](image)

2. **Numerical model**

2.1. **Governing Equation**

We consider the governing equation of this numerical simulation is nonlinear shallow water equations (Figure 2)

\[
\begin{align*}
\frac{h_t}{h} + (hu)_x &= 0, \\
u_t + uu_x + g\eta_x &= - C_f \frac{|u|}{h}
\end{align*}
\] (1)
(2)

where \(h(x,t)\) denotes total water height, \(\eta(x,t)\) surface elevation, \(u(x,t)\) horizontal velocity component, \(x\) and \(t\) are spatial and time domain respectively, \(C_f\) friction coefficient, \(g\) gravitational acceleration and subscripts refer to partial derivatives.

2.2. **Numerical procedure**

We use staggered grid conservative scheme to discretize (1) and (2). First, we define numerical staggered grid of spatial domain \(0 < x < L\) with partitions \(0 = x_{1/2}, x_1, x_{3/2}, \ldots, x_{N/2}, x_{N+1/2}, \ldots, x_{N-1}, x_N, x_{N+1/2} = L\) where \(j = 1, 2, \ldots, Nx\). Values of \(u\) will be evaluated on the centered of grid \(x_{j-1/2}\) with \(j = 1, 2, \ldots, Nx + 1\). Meanwhile, values of \(h\) and \(\eta\) will be evaluated on the full grid \(x\) with \(j = 1, 2, \ldots, Nx\). The details of illustration is shown in Figure 3. For instance, the red cell denotes momentum cell and the blue cell denotes mass cell.

![Figure 2. Sketch and notations for shallow water equations.](image)
Next, let $q = uh$ denotes horizontal flux, $\Delta x$ and $\Delta t$ denotes uniform spatial spacing and time spacing respectively. Discretization of (1) is given by the following expression

$$\frac{\eta_j^{n+1} - \eta_j^n}{\Delta t} + \frac{q_j^{n+1/2} - q_j^n}{\Delta x} = 0,$$

where

$$\eta_j^{n+1} = \eta_j^n - \frac{\Delta t}{\Delta x}(q_j^{n+1/2} - q_j^{n-1/2}), \quad j = 1, 2, \ldots N_x.$$

Note that the values of $h$ are missing in $x_{j+1/2}$ (indicated by $^*$). Here we approximate these values by using upwind method (based on flow direction) as follows

$$^*h_{j+1/2} = \begin{cases} h_j & \text{if } u_{j+1/2} \geq 0 \\ h_{j+1} & \text{if } u_{j+1/2} < 0 \end{cases}$$

when the flow direction is to the right ($u_{j+1/2} \geq 0$), then we choose $h_j$ as value of $h$ in $x_{j+1/2}$. When the flow is going to the opposite direction ($u_{j+1/2} < 0$), then we choose $h_{j+1}$ as value of $h$ in $x_{j+1/2}$. Next, discretization of (2) yields

$$\frac{u_j^{n+1} - u_j^n}{\Delta t} + \frac{\eta_j^{n+1} - \eta_j^n}{\Delta x} + \frac{q_{j+1/2}^n}{\Delta x} = -C_j^\eta \frac{pn}{h} |x_j^n|,$$

(3)

Here, handling of advection term $uu_x$ is the most important thing to concern. To approximate this term, we rewrite $uu_x$ into the following expression

$$uu_x = \frac{1}{h} \left( \frac{\partial (pu)}{\partial x} - u \frac{\partial q}{\partial x} \right)$$

(4)

Discretization form of (4) yields

$$uu_x \big|_{j+1/2} = \frac{1}{h_{j+1/2}} \left( \tilde{q}_{j+1} * u_{j+1} - \tilde{q}_j * u_j - u_{j+1/2} (\tilde{q}_{j+1} - \tilde{q}_j) \right)$$

(5)

where

$$\tilde{h}_{j+1/2} = \frac{1}{2}(h_j + h_{j+1}) \quad \text{and} \quad \tilde{q}_j = \frac{1}{2}(q_{j-1/2} + q_{j+1/2})$$

Here, we use the average values to approximate $h$ in $x_{j+1/2}$ and $q$ in $x_j$ (indicated by $\tilde{\cdot}$). Note that the values of $u$ are missing in $x_j$. Again we apply upwind method to approximate these values as follows.
Approximation of $u$ in $x_j$ (indicated by $\ast$) depends on direction of $\bar{q}_j$.

In handling the nonlinear friction term in (3), we use picard linearisation ie

$$u[|u|^n \approx |n^n|u^{n+1}$$

For a more detailed explanation about the derivation of staggered grid conservative scheme of shallow water equation see [10] and [11].

3. Model set-up

The model set-up was designed as close as possible to the real situation in Kampar river. We considered the variation of water bottom topography and boundary conditions into our model. In this section, the explanation of our model set-up is presented.

3.1. Domain and boundary conditions

The domain of this simulation starts from the mouth of Kampar river and ends at the middle of the river with total length about 77 km ($A < L < B$), white color symbolizes river channel and green is for the land, the circled numbers indicate the point that we observe (Figure 4). We use 5 points to observe, the first point is in front of Muda island 20 km far from the left boundary (point A), the second point is in the middle 30 km from the left boundary, the third point is in the backside of Muda island 50 km from the left boundary, and the last two points are on the other side of Kampar river 60 km and 70 km from the left boundary respectively. The small side channels along our domain are neglected, due to it has no significant effect on tidal bore propagation. In this simulation, we use two open boundaries. On the left boundary (mouth of the river/downstream) is given by tidal elevation profile with dominant tidal constituents. According to [9], the dominant tidal constituent in the mouth of the Kampar river is $M_2$ with 12.42 hour of the period, 1.13 meters of amplitude, and 3.377 radians of phase differences. On the right boundary condition (upstream) is given by setting proportional velocities that depend on river discharges.

![Figure 4](image)

**Figure 4.** Domain of numerical simulation (A is the left boundary and B is the right boundary).

3.2. Bottom topography

Bottom topography of this simulation is based on dataset point as seen by down arrow in Figure 4. We interpolate these points to get full water bottom topography along simulation domain (see Figure 5). We obtain the dataset of water bottom topography by using General Bathymetric Chart of the Oceans
30 arc-second grid. Since the depth at every location along the domain is known, then average water depth can be calculated.

\[ \eta(t) = 1.13 \cos(\omega t + \theta) \]

where \( \omega \) denotes angular velocity \( \omega = \frac{2\pi}{T} = \frac{2\pi}{44712} \) radian/second and \( \theta \) denotes phase difference \( \theta = 3.377 \) radian. We use gravitational force \( g = 9.81 \) m/s\(^2\) and uniform friction coefficient \( C_f = 10^{-5} \). We divide our simulation in two cases. Case 1 presents simulation with given proportional velocity on the upstream boundary. Meanwhile, to see the effect of friction coefficient \( (C_f) \) we present case 2 with larger \( C_f = 10^{-3} \).

For convenience in comparison, we also present numerical simulation without proportional velocity on upstream boundary as reference simulation. The result of reference simulation, case 1 and case 2, is shown in Figure 6, Figure 7 and Figure 8, respectively.

As seen in Figure 6, in this simulation we present evolutions of tidal bore propagation along the Kampar river without given proportional velocity, the tidal bore propagation is only influenced by water bottom topography and tidal waves from the left boundary (downstream). At the beginning of the time, the elevation profile of each figure (6a-6e) still looks random. Until in a quite long time, the bore starts to form. The tidal range of this reference simulation can reach 4.5 meters and the highest elevation of bore occurs at observation point 5.

**Figure 5.** Cross section of bottom topography.
Figure 6. Evolution of tidal bore elevation of reference simulation in 5 different locations. (a) at observation point 1. (b) at observation point 2. (c) at observation point 3. (d) at observation point 4. (e) at observation point 5.

Figure 7 presents evolutions of tidal bore propagation along the Kampar river with given proportional velocity on the upstream boundary. As we can see that the elevation of tidal bore increases and reaches the highest at observation point 5 figure (7e). At this point, tidal range can reach 5 meters, larger than reference simulation (Figure 6). It means that the effect of proportional velocity is quite significant on tidal bore propagation. The proportional velocity depends on the river discharges.
In Kampar river, the largest river discharges occurs during the rainy season, normally from November to December. The volume of the river is greatly increases and suddenly the mouth of the river becomes wider at that moment. This condition is encouraged the generation of a huge tidal bore.

\[\text{Figure 7.} \quad \text{Evolution of tidal bore elevation of case 1 in 5 different locations. (a) at observation point 1. (b) at observation point 2. (c) at observation point 3. (d) at observation point 4. (e) at observation point 5.}\]

In case 2, we change the value of the friction coefficient to see how this parameter influences the tidal bore propagation. The boundary condition is the same as the reference simulation, without given any proportional velocity on the upstream boundary. As shown in Figure 8, the result of case 2 is significantly different in comparison from the reference simulation, as we can see that the elevation of tidal bore is extremely smaller than reference simulation. The tidal range can only reach less than 2 meters. It means that the higher friction coefficient will give wave attenuation effect on tidal bore propagation. Based on [8], this kind of friction will be influenced by the environmental condition such
as bottom sediment resuspension and bed erosion. The environmental issue still plays an important role in the existence of natural phenomena. Therefore, one way to keep the existence of Bono waves is by protecting the environment of the Kampar river.

Figure 8. Evolution of tidal bore elevation of case 2 in 5 different locations. (a) at observation point 1. (b) at observation point 2. (c) at observation point 3. (d) at observation point 4. (e) at observation point 5.

5. Conclusion
The staggered grid conservative scheme was successfully implemented for simulating tidal bore in Kampar river based on nonlinear shallow water equation. Based on our result, the tidal range of these simulations could reach 5 meters. It took quite a long time until the bore was formed. The river discharges had a quite significant effect on increasing bore elevations. The friction coefficient had an important role on wave attenuation of tidal bore propagation. Due to the physical characteristics of the
river that had an important effect on tidal bore propagation, to gain a better model, the width and the length of river variables could be added to the model.

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