Application of two-dimensional hydrodynamics numerical modelling in mangrove planting of coastal areas

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Abstract. A two-dimensional numerical model is presented for application in mangrove planting of coastal areas. The model is discretized with finite volume method based on an unstructured mesh and employs the Roe-MUSCL scheme and the predictor-corrector procedure for time stepping. The model is validated primarily by the observed river runoff data at the upstream of the Jiaojiang River and tidal level along the open boundary obtained with the TPXO7.2 global tidal model. It is then applied to study tidal hydrodynamics in the Dachuan River of the Baisha Bay within the Jiaojiang River estuary during the spring, middle and neap tidal cycles in July and August 2016. The model results show well agreements between the predicted and observed tidal level and tidal current process. Finally, referred to existing research on critical tidal level and duration of Kandelia candel planting in coastal areas of the southeast China, a proper planting condition of K. candel seedlings are determined, after adopting the mean tidal level and duration calculated from the model results.

1. Introduction
Mangrove has an important effect on ecological equilibrium, species protection and flood prevention in coastal areas. In various mangrove species, Kandelia candel is widely distributed and can exist in relatively high latitude, and that it is one of the main mangrove species in the coastal areas of the southeast China [1]. Since suitable areas for mangrove have been ruined [2] and global sea level is rising steadily [3], proper planting condition including altitude and soaking duration become critical.

The mangrove is naturally distributed from Sanya, Hainan Province to Fuding, Fujian Province in China. However, artificial introductions to Zhejiang Province, China have been conducted in practice these years. And Zhejiang Province is located in the southeast of China, where mangrove planting has been proved as an indispensable complement to the construction of coastal protection forest system. Jin [4] conducted field and greenhouse experiments to investigate changes of plant growth, adaptation, survival, chilling injury index, photosynthesis and physiological parameters of 10 mangrove species, such as K. candel, Avicennia marina, Sonneratia apetala etc., in responding to key environmental factors, temperature, salinity and planting position. Dan et al. [5] assessed mangrove wetlands resources, conservation status and main threats in Zhejiang Province, with the help of the CBERS-CCD data, 3S technology and field investigation.

Previous research about K. candel were mainly focused on proper planting altitude and soaking duration [6-12]. With the moving boundary problem solved through an improved wetting and drying algorithm, Barros et al. [6] established a two-dimensional hydrodynamics model based on a second-order finite difference scheme in time and a finite element scheme in space to simulate the tidal level process of planting area in Vitória Bay, Brazil. Sheng [10] applied a vegetation-resolving
CH3D-SWAN surge-wave modeling system to examine the role of mangroves and salt marshes along the shore of Biscayne Bay, Florida, USA in buffering surge, wave, and inundation during Hurricane Andrew, 1992. However, applications of tidal hydrodynamic numerical modelling in research on mangrove planting condition are still significant. It is necessary to extend these applications referring to existing research on mangrove planting in coastal areas of the southeast China [13-15].

In this study, investigation has been conducted on proper planting condition of K. candel in the shore along the Dachuan River (DCR), where is located in Baisha Bay, Taizhou of Zhejiang Province. A depth-integrated two-dimensional numerical model is presented for predicting the hydrodynamics process in the DCR. The model is validated against the available observed runoff discharge data obtained from the Jiaojiang River estuary (JRE), China and tidal level data along the open sea boundary provided by the TPXO7.2 global tide model [16]. The validated model is then applied to simulate the tidal level process, from which the average tidal level and duration can be calculated. With referred to existing research on critical tidal level and duration of K. candel planting in coastal areas of the southeast China, the proper planting condition of K. candel seedlings are determined.

2. Research on K. candel planting condition
In current research, field and laboratory experiments are both frequently used to investigate proper planting altitude and soaking duration for mangrove seedlings. Liao et al. [17] introduced hypocotyl to the K. candel planting area, and indicated that a suitable planting altitude should be above approximate 1.30 m (using the Huanghai sea level as datum, referred the same in this study) in Chiwan, Shenzhen, China. Chen et al. [18] established artificial tidal tanks to simulate semidiurnal tide under greenhouse and investigated the growth of K. candel seedling. He suggested that 8 h in every tide cycle is a critical soaking duration for normal development of seedlings. Chen et al. [14] conducted experiment in tidal zones of Umbrette Natural Reserve in the Dayu Island of Xiamen, China to investigate the critical tidal level for K. candel forestation, which showed that the tidal level of 1.62 m was optimal for planting K. candel seedlings, the critical tidal level of K. candel seedlings in coastal areas of Xiamen was no lower than 1.31 m, and the soaking duration was no longer than 5.6 h per tide cycle. Qiu et al. [15] made an investigation on the survival rate, growth characteristics and attached barnacles of K. candel seedlings at different elevations in Ximen Island of Leqing, China, and indicated that the critical tidal level for K. candel in the site was 1.66 m, and a proper soaking duration per tide cycle should be shorter than 3.65 h. Table 1 shows the existing research on K. candel planting condition in coastal areas of the southeast China.

| Study domain                  | Critical tidal level (m) | Tidal duration (h) | Refs. |
|-------------------------------|-------------------------|--------------------|-------|
| Chiwan, Shenzhen, China       | 1.30                    | -                  | [17]  |
| Laboratory artificial seawater| -                       | 8                  | [18]  |
| Dayu Island, Xiamen, China    | 1.62                    | <5                 | [14]  |
| Ximen Island, Leqing, China   | 1.66                    | <3.65              | [15]  |

3. Model description
3.1 Governing Equations
It is usually assumed that flow pressure is hydrostatic and the vertical component of velocity can be neglected in coastal areas, and then the two-dimensional shallow water equations (SWEs) can be applied to describe tidal hydrodynamic processes in an estuary. In this study, a depth-integrated two-dimensional SWEs can be written in the following conservation form:

\[\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} = \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} + S\]  (1)
Where $U$ is the vector of conserved variables $(h, hu, hv)^T$, in which $h$ is the water depth and $u$, $v$ are the depth-averaged velocities in the $x$ and $y$ directions, respectively; $E$, $G$ are the convective vectors in the $x$ and $y$ directions, respectively; $\mathbf{E}$, $\mathbf{G}$ are the diffusive vectors related to the turbulent stresses in the $x$ and $y$ directions, respectively; and $S$ is the source term including bed friction, bed slope and the Coriolis force. The detailed expressions of these terms can be found in [19].

### 3.2 Numerical Solution

The model adopts a finite volume method (FVM) based on an unstructured triangular mesh to solve the governing equations. Therefore, a study domain is divided into a set of triangular cells. A cell-centered method has been adopted, in which the conserved variables can be stored at the center of a cell with the three edges defining the interface of this triangular control volume. The calculation of the flow fluxes through an interface between two neighbor cells can be treated as a local one-dimensional problem in the direction normal to the interface, and the convection fluxes can be evaluated by an approximate Riemann solver. Thus, it is a key step to evaluate the convection fluxes for the flow and sediment transport in the FVM. In this model, the Roe-MUSCL scheme is applied to calculate the normal flow fluxes through a cell interface, with a procedure of predictor-corrector time stepping being used to provide a second-order accuracy in both time and space. In addition, the minmod limiter proposed by Roe and Baines [20] is also employed to ensure the solution to remain positive.

With regard to the treatment of the friction term, an explicit discretization may cause numerical instability in the case of shallow water depths. Thus, a semi-implicit scheme is adopted to discretize the friction term, besides which an explicit scheme is still used for other terms such as the bed slope, Coriolis force and surface wind shear stress.

### 3.3 Treatment of key problems

In this model, a traditional free-slip boundary condition is used. Thus, the normal velocity and normal gradient of water level to the wall boundary are both assumed to be zero. An inflow uniform along both the width and depth is given by observed runoff discharge from the Haimen Station (HS) downstream of the Jiaojiang River (JR) for the upstream open boundary. As the downstream open boundary, a tidal level process along the open sea boundary is specified from the TPXO7.2 global tide model, in which the main tidal components of $M_2$, $S_2$, $K_1$, $O_1$, $N_2$, $P_1$, $K_1$, $Q_1$ and long-term tidal components of $M_f$ and $M_n$ can be predicted properly. Thus, a reliable tidal level process can be structured in the following expression:

$$\zeta_0(x) = \zeta_p + \sum_{i=1}^{10} A_i(x) \cdot \sin(\omega_i t + \alpha_i(x))$$

(2)

Where $\zeta_0$ is tidal level relative to a specified datum; $\zeta_p$ is the mean tidal level; $i$ is an integer ranged from 1 to 10, which represents different tidal components; $A_i$, $\alpha_i$ are the amplitude and phase lag of a certain $i$ tidal component, respectively; $\omega_i$ is the angular frequency of a certain $i$ tidal component.

Besides, an efficient treatment of the wetting and drying fronts proposed by Xia et al. [21] is introduced to solve the moving boundary problem in this model.
4. Model validation

The hydrodynamic process in JRE are complex due to irregular land boundary, high tide range and runoff-tide interaction in the estuary. According to observed data from the HS downstream of the JR, the annual mean tidal range and tidal level approach 4.14 m and 0.25 m, respectively. Figure 1 shows a map of the study domain in the area south to Kanmen (KM), north to Damutu (DMT) and offshore within the depth contour of -70 m. Covered a plane water surface area of about $1.95 \times 10^4$ km$^2$, the model domain is divided into a set of computational mesh with 75617 nodes and 39138 cells. The bathymetry of the study domain, locations of observation points and set of computational mesh are also shown in figure 1. To obtain a better simulation accuracy, the grid is refined locally to give a higher resolution around the area of the DCR. In this mesh, space step ranges from 1800 m to 6000 m in the open sea, and the maximum values are limited to 150 m and 10 m for the area of the JR and DCR, respectively.

The tidal level and tidal current are both validated against the observed data during the spring, middle and neap tidal cycles in July and August 2016. The Manning roughness coefficient is calibrated to be about $0.021 \, m^{-1/3}/s$ for deep channel zones and $0.027 \, m^{-1/3}/s$ for floodplain zones. In the meantime, the average time step is set around 0.2 s after validation.

The detailed validation analysis is limited to the comparisons between the calculated and observed tidal level process at Haimen (HM) and Toumendao (TMD) observation points during the spring, middle and neap tidal cycle, respectively (see figure 2). It can be seen that the predicted tidal level hydrographs agree closely with the observed values. The maximum calculation error is no more than 0.08 m while the mean error is about -0.01 m.
Figure 2. Validation comparisons between the calculated and observed tidal level process

(a) spring tidal cycle
(start from 7/20)

(b) middle tidal cycle
(start from 7/24)

(c) neap tidal cycle
(start from 7/27)

Figure 3. Validation comparisons between the calculated and observed tidal current process

(a) spring tidal cycle
(start from 7/20)

(b) middle tidal cycle
(start from 7/24)

(c) neap tidal cycle
(start from 7/27)

Figure 3 shows the comparisons between the calculated and observed tidal current process at V2 and V5 during the spring, middle and neap tidal cycle, respectively. The predicted and observed tidal current are in well agreement, and the calculation error is within ±20% of the observed data.

Generally, with practicable and reliable predictions on both tidal level process and tidal current process, this model can be applied in research on tidal hydrodynamic process.
5. Model application

5.1 Calculation condition
Since the mean tidal level during July and August 2016 is close to the annual mean tidal level based on statistical analysis of data over the years at the HS, the observed data are representative in this period. The observed data during the spring, middle and neap tidal cycles in July and August 2016 are applied to the application simulation as well. The validated two-dimensional tidal hydrodynamic model is used in the investigation on the predictions of tidal hydrodynamic process in the DCR. Besides, a bathymetry generalization of the DCR region with actual elevation is also conducted.

5.2 Results analysis

5.2.1 Tidal level process of the DCR
Three tidal level monitoring points D1~D3 are selected from north to South in the DCR (see in figure 1). Figure 4 shows the calculated tidal level process during the spring, middle and neap tidal cycles, respectively, and the statistics analysis results of tidal duration can be seen in table 2.

Figure 4(a) shows the results in the spring tidal cycle. The tidal level rises up from the outlet to inlet of the DCR in the flood phase, which is represented that D3, D2 and D1 occurring increasing of the tidal level in turn, and particularly in the initial flood phase the tidal level is relatively higher at D3 downstream the DCR while it is lower at D1 upstream the DCR. Similarly, the tidal level ebbed down from the outlet to inlet of the DCR in the ebb phase, which is represented that D3, D2 and D1 occurring decreasing of the tidal level in turn, and particularly in the final ebb phase the tidal level is relatively lower at D3 downstream the DCR while it is higher at D1 upstream the DCR. The same pattern can be concluded in figure 4(b) and figure 4(c) for the middle tidal cycle and neap tidal cycle, respectively.

The analysis results in table 2 indicate that the durations of tidal level above 0.5 m, 1.0m, 1.5 m and 2.0 m are no longer than 5.80 h, 4.88 h, 4.08 h and 3.13 h, respectively, which are compared among D1~D3 in the spring tidal cycle. In the middle tidal cycle, the durations are no longer than 5.70 h, 4.63 h, 3.63 h and 2.02 h, respectively, while the durations of tidal level above 0.5 m, 1.0m and 1.5 m are shorter than 5.23 h, 3.65 h and 1.47 h, respectively, in the neap tidal cycle.

![Figure 4. Calculated tidal level process of the monitoring points along the DCR](image)

![Table 2. Tidal duration statistics of the monitoring points along the DCR](image)

| Tidal level (m) | D1  | D2  | D3  |
|----------------|-----|-----|-----|
| >0.5           | 5.73| 5.78| 5.80|
| >1.0           | 4.85| 4.88| 4.88|
| >1.5           | 4.07| 4.08| 4.07|
| >2.0           | 3.13| 3.13| 3.12|
5.2.2 Tidal level process of the planting area and determination of K. candel planting condition

Furthermore, three tidal level monitoring points R1~R3 in the planting area along the DCR are also selected (see in figure 1). Figure 5 shows the calculated tidal level process in the planting area during the spring, middle and neap tidal cycles, respectively, which is similar to figure 4 particularly in the final ebb phase. The analysis results of tidal duration can be seen in table 3. The average duration among the spring, middle and neap tidal cycle when the tidal level above 1.5 m are shorter than 3.33 h, 3.26 h and 3.39 h, respectively, in R1–R3.

According to the existing research, a proper planting altitude of K. candel is generally greater than 1.30 m in coastal areas of the southeast China, while soaking duration is shorter than 8 h. It should be noted that Qiu et al. [15] presented a proper altitude of K. candel above 1.66 m with soaking duration no longer than 3.65 h in Ximen Island, which is located close to the JRE. Thus, in this study, the proper planting altitude along the DCR is suggested above 1.50 m where soaking duration is no longer than 3.4 h.

| Tidal level (m) | R1    | R2    | R3    |
|----------------|-------|-------|-------|
| Spring >1.5    | 4.57  | 4.33  | 4.67  |
| >2.0           | 3.20  | 3.12  | 3.30  |
| >1.5           | 3.97  | 3.98  | 4.02  |
| Middle >2.0    | 1.42  | 1.42  | 1.43  |
| >1.5           | 1.47  | 1.47  | 1.50  |
| Neap >1.5      | 3.33  | 3.26  | 3.39  |

6. Conclusions

This study presents a two-dimensional numerical model, which employs a finite volume method based on an unstructured mesh, and it is used to investigate a proper planting condition of K. candel in shore along the DCR. The model is then validated against the available observed runoff discharge data.
obtained from the JRE and tidal level data along the open sea boundary provided by the TPXO7.2 global tide model, which proves a reliable ability to simulate the tidal hydrodynamic process. The validated model is then applied to simulate the tidal hydrodynamic process, from which the average tidal level and duration can be calculated. Finally, a proper tidal level and duration for planting *K. candel* seedlings along the DCR are proposed.

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