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Wetland inundation modeling of Dongting Lake using two-dimensional hydrodynamic model on unstructured grids

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Abstract

To understand the inundation process (wetting and drying) in the bottomlands of Dongting Lake, a two-dimensional hydrodynamic model based on shallow water equations has been developed to model complex flow regime controlled by both the Yangtze River and its own basins. The governing equations are discretized using the finite volume method with the combination of quadrilateral and triangular grids and the mass and momentum fluxes are solved using the approximate Riemann solver, HLLC scheme with high spatial resolution. The processes of wetting and drying are specially treated to simulate the flow routing over dry bed. Verification shows that the proposed method can accurately capture flow propagation over dry bed resulting from suddenly breach of the dam. This performance is preferred for inundation modeling. After theoretical test, we applied the model to simulate the inundation process in Dongting Lake. Setting the calibrated roughness parameters, we successfully simulated flow processes in the lake from 2006 to 2010. The water extent changes rapidly along with the stage fluctuation in the lake. In dry season, water is mainly limited in channels, large parts of bottomlands are exposed and water extent reaches the yearly minimum. The whole lake is inundated in the flood season and the maximum of water extent reaches. After the flood season, the bottomlands expose again along with the gradual decrease of water. Particular hydrological regimes cause the regular zonal distribution of vegetation in Dongting Lake Wetland. Hydrology in the middle Yangtze River Basin is undergoing great changes. This model can be applied to assess possible responses of lake wetland for the changing environment.

Keywords: Wetland hydrology; Inundation process; Hydrodynamic model; Dongting Lake

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1. Introduction

Physical processes of wetland, such as inundation, greatly impact the structure and function of wetland ecosystem [1]. They are of critical importance for the biogeochemical and ecological processes in wetlands. Influenced by the climate changes and human activities, regional hydrology is experiencing changes. These changes directly or indirectly threaten the ecological processes and cause the succession of vegetation and then the possible damages of wetland function. To quantitatively assess the responses of wetland changes to the changing hydrology, in-depth understanding and accurate prediction of the physical processes in wetland are essential prerequisites.

Inundation process is one of important physical ones of wetland, which mainly determines the distribution of wetland vegetation. There are many studies for wetland inundation based on the in-situ measurement and remote sensing data. Because of the limitation of the data availability, such a method usually has no sufficient data with the desirable temporal and spatial resolutions to predict and assess the changes of wetland [2]. Numerical models are the efficient tools to predict the inundation process of wetland [3]. They can help to quantitatively analyze the responses of wetland ecology to global climate changes and local human activities and identify the contributions of them. However, it is still a challenge for the accurate modeling of inundation process, i.e. the wetting and drying in wetlands. The modeling of flood routing over dry bed in the inundation modeling is also an open problem in computational hydraulics.

Dongting Lake located at the middle Yangtze River is a large seasonally lake with annual stage fluctuation about 12.9 m. The particular hydrological conditions foster rich biodiversity and is recognized as an important eco-region for global conservation. In spite of its importance, the altering of hydrological regime resulting from the human activities (e.g. the Three Gorges Reservoir, TGR) and global climate changes is threatening the ecosystem of wetland. In this paper, we have developed a two-dimensional model based on shallow water equations with accurate water front tracking performance. The model was applied to simulate complex inundation process in Dongting Lake. Then its implication for wetland vegetation was analyzed.

2. Modeling method

2.1. Shallow water equations

We use the two-dimensional (2D) hydrodynamic model based on shallow water equations to simulate water flows in wetlands. The conservative form of 2D shallow-water equations are formulated as:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{F}(\boldsymbol{U})}{\partial x}+\frac{\partial \boldsymbol{G}(\boldsymbol{U})}{\partial y}=\boldsymbol{B}(\boldsymbol{U}) \tag{1}$$

where x and y are Cartesian coordinates; $\boldsymbol{U}=(h,hu,hv)^{\mathrm{T}}=(h,q_x,q_y)^{\mathrm{T}}$ is the state variable vector of the equation (where h is water depth, and u and v are the velocities in x and y directions, respectively); $\boldsymbol{F}=(hu,hu^2+0.5gh^2,huv)^{\mathrm{T}}$ and $\boldsymbol{G}=(hv,huv,hv^2+0.5gh^2)^{\mathrm{T}}$ are, respectively, the flux vectors in x and y directions, where g is the gravitational acceleration; $\boldsymbol{B}=\left[0,gh(S_{0x}-S_{\mathrm{fx}}),gh(S_{0y}-S_{\mathrm{fy}})\right]^{\mathrm{T}}$ is the vector of the source term, where $\gamma=\rho g$; $S_{0x}=-\partial_x Z_{\mathrm{b}}$ and $S_{0y}=-\partial_y Z_{\mathrm{b}}$ are, respectively, the bottom slopes in x and y directions (where Z_b is the bed elevation); $S_{fx}=\rho n^2 uh^{-4/3}\sqrt{u^2+v^2}$ and $S_{fy}=\rho n^2 vh^{-4/3}\sqrt{u^2+v^2}$ (where n is the Manning roughness coefficient) are, respectively, the roughness slopes in x and y directions.

2.2. Numerical method

The unstructured finite volume method is flexible to handle the complicated geometry and topography. Hence, it is applied to develop the practical hydrodynamic model for wetland inundation modeling based on Eq.(1). Both quadrilateral and triangular grids are implemented in the model. The HLLC solver [4] is used to compute the normal mass and momentum fluxes. It make the model be capability of simulating the different flow regimes in wetlands, including gradually varied and discontinuous flows, steady and unsteady flows, and subcritical and supercritical flows.

2.3. Wetting and drying treatment

Another advantage of the model is to compute the wetting and drying processes stably and accurately. Wetting and drying processes frequently occur to wetlands. The accurate tracking of flood front is of importance to successful inundation modeling. The modeling of flooding and drying is still a challenge in computational hydraulics. Although many methods have been proposed to simulate this kind of flows in near decades [5], most of them are not independent of model. In this paper, under the framework of the unstructured finite volume method, we dynamically examine the hydraulic condition at cell interface and select the corresponding method to compute interfacial fluxes according to the hydraulic conditions of the considered and adjacent cells at each time step. As conducted by Zhao et al. [6], a tiny water depth, ε is introduced to determine the status of a cell and the hydraulic conditions of the linking cells.

The treatment is summarized as following. First, the water depth, h_L and h_R, on the left and right side of the considered cell are computed. The type of the cell interface is then dynamically determined in each computational time step. The computation methods of fluxes are selected according to the type of interface. There are eight possibilities determined by water depths and bed elevations of considered and adjacent cells. Fig.1 (a)-(d) shows the four cases where the bed elevation of considered cell (or left cell, L) is greater than the adjacent cell (or right cell, R). For the cases when $h_L > \varepsilon$, the empiric formula of broad crested weir is used to compute mass fluxes if $h_R < Z_{bL} + \varepsilon$; and the normal routine of HLLC solver is used to compute both mass and momentum fluxes. For the cases when $h_L < \varepsilon$, the interface are considered as solid wall if $h_R < Z_{bL} + \varepsilon$; and the empiric formula of broad crested weir is used to compute mass fluxes if $h_R > Z_{bL} + \varepsilon$. Fig.1 (e)-(h) shows another four cases where the bed elevation of considered cell (or left cell, L) is less than the adjacent cell (or right cell, R). The computation methods of fluxes are similar with previous cases.

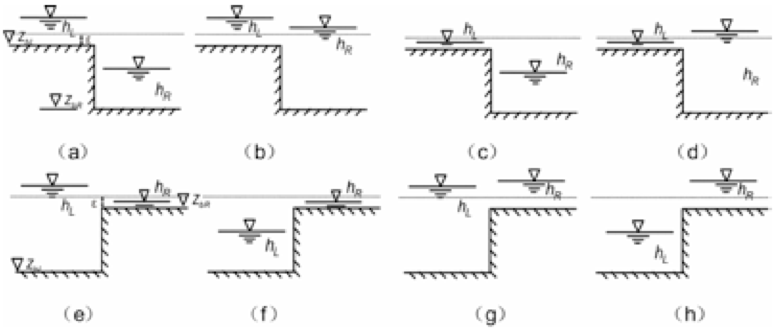


Fig.1 Possibilities of water depth across cell interface

2.4. Verification of flood modeling over dry bed

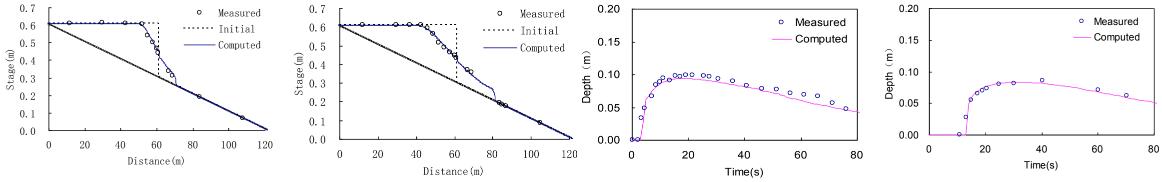
To verify the numerical performance of the developed model and the reliability of the treatment of flooding and drying, the flood routing over dry bed resulting from suddenly breach of the dam is simulated. The data are acquired from the experiment done by the Waterway Experiment Station (WES), US Corps of engineers [7]. The experiment was conducted in a 122 m long and 1.22 m wide flume with bottom slope 0.005. Water was impounded at x = 61.0 m by a dam with a height of 0.305m. Initially, the water stage is 0.61 m at upstream of dam. The downstream channel is dry (no water flow). The computational domain covering the whole flume is discretized using 400*12 rectangular grids. The computational results of the propagation of flood wave over dry bed are illustrated with Fig.2. It shows that the computed profiles of water surface along the channel are very close to the real ones at t = 5 s and t = 10 s, respectively. The good agreement can also be found in the stage hydrograph at x = 68.625 m, 85.4 m and 106.625 m. Successful simulation of the propagation of flood wave suggests that the model can simulate the flows over dry bed well.

3. Model application

3.1. Study area

Dongting Lake (Fig.3), the second largest freshwater lake in China, lies in the middle reaches of the Yangtze River. It is fed by the Yangtze River via Sankou distributary channels in the north, the Lishui and Yuanjiang rivers in the west, and the Zishui and Xiangjiang rivers in the south. Floods are discharged into the lower Jingjiang reaches of the Yangtze River via the unique outlet at the Chenglingji hydrological station. They play very important roles in maintaining water resources of Yangtze River and aquatic ecosystem equilibrium [8]. The main flood season is from June to September and the lake wetland is inundated during this period. The lake stage decreases gradually and goes into the dry season from October. From April of next year, the bottomlands of Dongting Lake flood again. The stage of Dongting Lake fluctuates seriously in one year, about 12.9 m on average from 1955 to 2008.

Dongting Lake also provides a habitat for many protected species. The three natural wetland reserves, East, South and West Dongting Nature Reserves in this area are all recognized as Ramsar sites, which are wetlands of international importance by the Ramsar Convention on Wetlands [9].



(a) profile at t =5 s

(b) profile at t =10 s

(c) stage hydrograph at x=68.625m

(c) stage hydrograph at x=106.625m

Fig.2 Verification of water profile and stage hydrograph for flood wave over dry bed resulting from suddenly dam breach

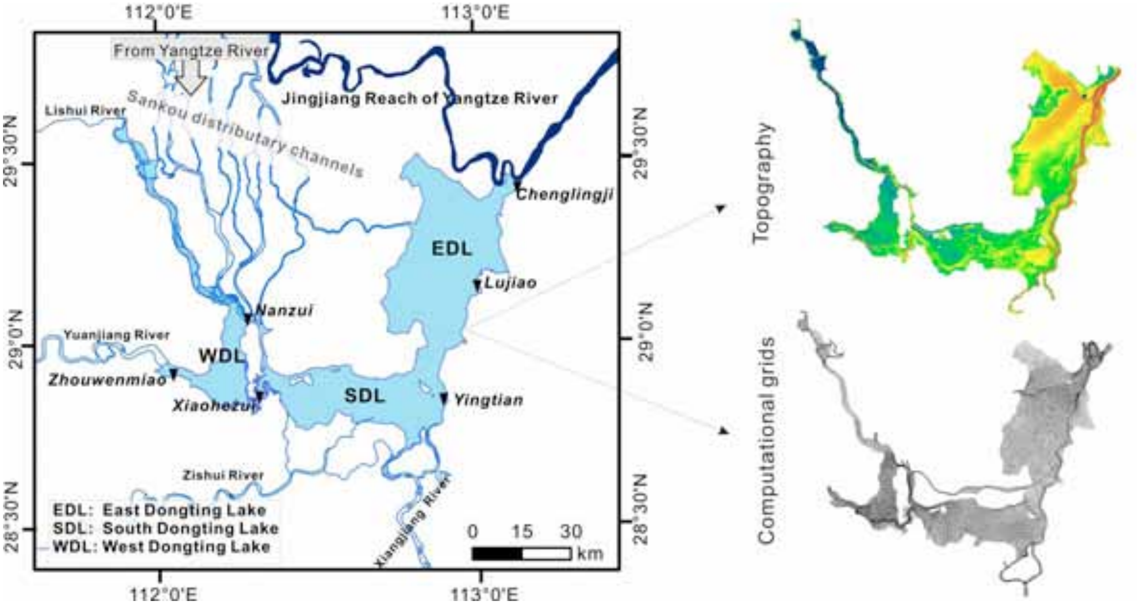


Fig.3 Water system, topgraphy of Dongting Lake and its computational grids

3.2. Model setup

The inundation extent of Dongting Lake greatly varied with water stage. In dry season, the water is only limited the narrow channels in the lake. In order to model hydrodynamic and dynamic storage capacity of the lake precisely, the hybrid quadrilateral and triangular grids with varied sizes are generated for resolving the main channels in the lake. The computational grids are consisted of 10676 nodes and 10324 cells in total (Fig.3). The length of cell interface ranges from 20 (narrow channels) to 2000 m (large water area with little changes of bed elevation) to depict the lake topography in detail. It helps the model to simulate the real flows of the lake, as well as the lake storage capability. It is particularly true for the flow in dry season.

The bed elevations of computation grids in Dongting Lake are extracted from the topographic data surveyed in 1995 and partly updated in 1998 (Fig.3). Given initial and boundary conditions, we can model the flow dynamic in the lake. Initial conditions are here set to the steady flows driven by the inflow discharge at initial time instant. The boundaries of the model include the inflow discharge boundaries given by the discharges of the Xiangjiang, Zishui, Yuanjiang and Lishui rivers. The discharge hydrographs of the inlets from the Yangtze river and the stage hydrograph of the outlet at Chenglingji Station are obtained by the integration with the 1D unsteady flow model. The details of the linking between 1D and 2D model can be referred to Lai et al. [10].

3.3. Model parameters

The main parameters of the proposed model are the Manning roughness coefficients, n. The computational domain is separated into five blocks including main channel, three kinds of floodplains with carex, reed and woods, and large open water area in Dongting Lake according to land covers. n is computed using the expression $n = n_0 h^{\alpha}$ for considering that it varies with water depth h in each block.

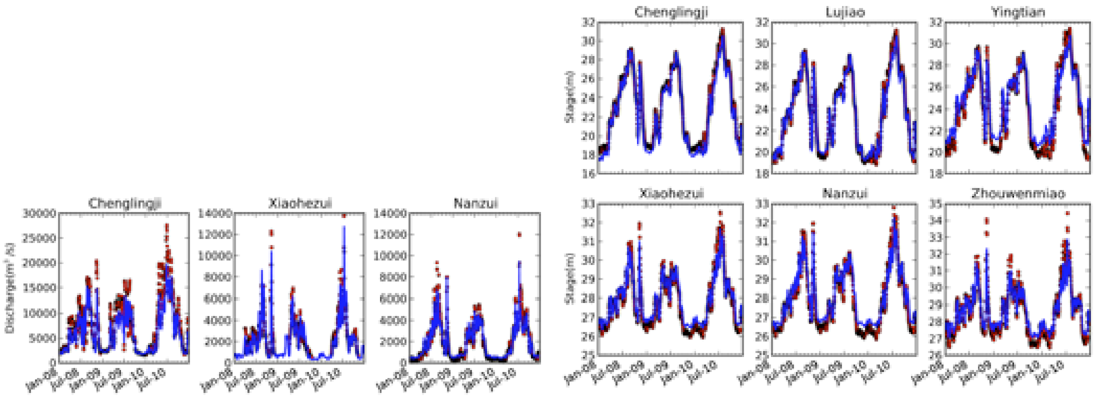
The model was calibrated by the water regime data of the year of 1998. The calibrated *n* values are listed in Table 1.

Table 1 The calibrated Manning roughness coefficients, *n* corresponding to land blocks

Land blocks	Manning roughness coefficients, n
Main channel	0.020
Open water area	0.020
Floodplain: carex and sand	0.025
Floodplain: reed	0.028
Floodplain: wood	0.032

3.4. Validation

We computed the water regimes of Dongting Lake from 2008 to 2010. As shown in Fig.4(a), the computed discharge hydrographs are consistent with the measurements at the outlet of Dongting Lake (Chenglingji Station), the north and south outlets of from West Dongting Lake to South Dongting Lake (the Nanzui and Xiaohezui stations). The computed stage hydrographs of Dongting lakes at the Chenglingji, Lujiao, Yingtian, Nanzui, Xiaohezui and Zhouwenmiao hydrological stations all fit well with measurements. The values of Nash-Sutcliffe efficiency (NSE) at the examining stations are all over 0.9. Successful simulation suggests that the model is suitable to simulate the water regime of Dongting Lake.



(a) discharge hydrograph

(b) stage hydrograph

Fig.4 Discharge and stage validation in Dongting Lake from 2008 to 2010

3.5. Wetland inundation of Dongting Lake and its implication for wetland vegetation

Resulting from the rainfall of Monsoon weather, the water regime fluctuates annually. Fig.5 shows the inundation extent and water depth on March 1, 2010 before the flood season, July 30 during the flood season with high water stage and October 10 after the flood season with significant impact of TGR. It clear shows that Dongting Lake has an annual hydrological cycle with wetting and drying resulting from the Monsoon weather. The inundation extent and depth of Dongting Lake wetland vary with the water stage. In dry season, the water is mainly limited in channels, most of bottomlands are exposed and inundation extent reaches the minimum in one year. Along with the flood water pouring from upstream, the inundation extent increases rapidly and the bottomlands are inundated from June to September. The maximum of water extent reaches during this period. After the flood season from October to March of next year, the water returns to main channels and the bottomlands are exposed once again. The mean inundation depths of water areas are respectively 1.62 m, 5.84 m and 3.21 m at 8:00 of March 1, July 30 and October 10, 2010. Inundation days, as an indicator of flooding frequency of wetland are also examined and illustrated with Fig.6. In Dongting Lake, main channels and some internal lakes (depression) are always filled with water. But, the inundation days in the most of bottomlands vary from 0 to 9 months depending on their elevations and local hydraulic conditions.

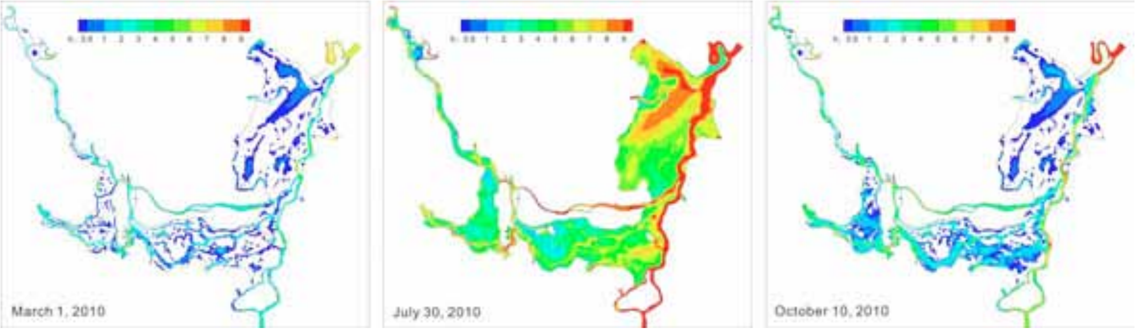


Fig.5 Inundation extent and depth in Dongting Lake before, during and after the flood season

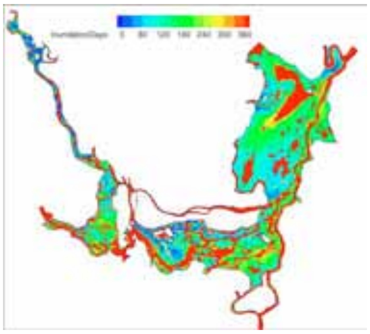


Fig.6 Spatial distribution of inundation days in Dongting Lake

Wetland plants of Dongting Lake have clear zonation, mainly woods in high bottomland, reeds in moderate bottomland, carexs in low bottomland, and submerged vegetation in shallow water. This type of distribution of wetland plants is attributed to particular hydrological regimes, especially regular intra-annual fluctuation in Dongting Lake. However, human activities (e.g. the Three Gorges Reservoir, TGR) and global climate changes may cause the great changes of hydrological regimes, then the habitat conditions of wetland vegetation, and finally whole ecosystem of wetland.

4. Conclusions

In this paper, we develop a two-dimensional hydrodynamic model based on shallow water equations to simulate complex flow regime of Dongting Lake. The equations were discretized using the finite volume method with the combination of quadrilateral and triangular grids. The approximate Riemann solver, HLLC scheme with high spatial resolution is used to compute the mass and momentum fluxes. The processes of drying and wetting are specially treated to catch the flow routing over dry bed accurately.

Inundation process of Dongting Lake from 2008 to 2010 is then simulated using the proposed model. The inundation extent and depth of the bottomlands in Dongting Lake fluctuate with the water stage. The water extent changes rapidly along with the stage fluctuation, especially in the beginning of the flood season. In dry season, water is mainly limited in channels, large parts of bottomlands are exposed and water extent reaches the yearly minimum. The whole lake is inundated in the flood season and the maximum of water extent reaches. After the flood season, the bottomlands expose again along with the gradual decrease of water.

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