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Flooding Events Assessment Using Mike Flood Model, Dongting Lake, China

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***Abstract* – Dongting Lake Basin is composed of a complex flow regime of rivers network, in recent years a large number of floods occurred in the Dongting Lake Basin, Lake water level crisis, flood prevention and control have become a focus in the middle Yangtze River. However Numerical modelling of flood events often requires a simultaneous description of the flow through relatively narrow channel networks and across extended plains. MIKE FLOOD integrates the one-dimensional models, MIKE 11 for rivers system and the two-dimensional model MIKE21 for lake into a single, dynamically coupled modelling system. Using a coupled approach enables the best features of both the one - dimensional and the two dimensional models to be utilised, whilst at the same time avoiding many of the limitations of resolution and accuracy encountered when using MIKE 11 or MIKE 21 separately. Further, it is a key to describe flooding across plains that the hydrodynamic model can represent flow across dry land or drying of flooded areas. A method based on a point to point approach to dynamically linked 1-D and 2-D hydrodynamic models is described. It uses an explicit predictor type implementation of the link and it is demonstrated using a simple example that the method provides a numerically sound approach. The ability of a 2-D model to describe critical flows, by using a local Froude number dependent upwinding scheme, is demonstrated by comparison of simulated and with observed data. The results indicated that the numerical simulation analysis carried out over a period of 2011 to 2014 in the Dongting Lake Basin clarify the water exchange ability of Dongting Lake including the flood evolution process, different flow fields, water level variation. We found that for each station water level variation in Dongting Lake is approximately 10m for maximum, increasing in summer and reducing in winter.**

***Keywords* – Coupled Modelling, Dongting Lake, Flow Fields, Froude Number, Mike Flood, Numerical Simulation.**

I. INTRODUCTION

Today flood plain modelling may involve dynamic prediction of inundation areas within complex topographic areas comprising channels networks, estuaries, bays, lakes or coastal areas in addition to the natural marshland and plains, which may be determining for flow paths and flood wave propagation. This puts strict requirements to spatial resolution and accuracy. Therefore dynamic modelling of surges and flooding events in an economically feasible way is a rather delicate task. It simultaneously requires an accurate representation of narrow cross sections, in order to obtain an accurate description of the discharges, and a representation of the rather complex flow on extended flood plains.

This study has been conducted on the Dongting Lake Basin located in and is located in the northeastern part of Hunan Province, China. Dongting Lake is a large, shallow and covers a water surface area of 2,625 km^2. It is a flood basin of the Yangtze River. Hence the lake's size depends on the season. In the July–September period, flood water from the Yangtze flows into the lake, enlarging it greatly, when the Yangtze River rises as a result its headwaters and summer rains along its length. The lake's area, which normally is 2,625 km², may increase to 20,000 km² in flood season, when vast amounts of water and sediment flow into the lake. As a result flood and waterlogged disaster is frequent and serious [1]. Dongting Lake has been reported as a lake in crisis because of dropping water levels due Mud and sand keep silting up in the south of the lake. Therefore the storing capacity is becoming smaller [2]. The silted mud becomes new land, which becomes islands and beaches, which people then live on. Dongting Lake was China's largest lake (6300 km²) 150 years ago. Nowadays, it is the second-largest flesh water, its size having been reduced by rapid sedimentation and reclamation for farmland [3]. The One-dimensional and two-dimensional hydrodynamic is required for flooding events, The advantage of 1-D network model is that they provide a very accurate description of the cross sections and only need to resolve the downstream gradient. The model therefore consists of linked 1-D sections, enabling very efficient solution methods. In addition, the 1-D model can naturally be combined with hydraulic theories for flow through culverts or gates, enabling a reasonable description of highly regulated areas. The drawback is that the flow path must be defined beforehand, a description that is not always realistic for example on flat areas with large variations in water levels. Moreover, the flow from the 1-D cross sections into the floodplains is not based on its physical behavior.

The advantage of the 2-D models is that they describe the spatial distribution of the flow and also provide a more general description of the flow. Thus, the models attempt to actually resolve the spatial variations and thus require a smooth bathymetry. It is therefore difficult to represent very small features accurately, as it requires a large number of computational points. The use of unstructured meshes has improved the possibilities but in realistic

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setups it may still be prohibitive to provide a sufficient resolution[4];[5].

Despite these methods present different advantages like computational efficiency and the ease of parameterization [6], and not necessarily perform less than the two-dimensional modeling methods, it will only give a partial and limited representation of the complex processes between the channel and the floodplains [7]. Although, common problems regarding two-dimensional approach are data requirements and significant computational time. Due to these difficulties, a new method was developed; Mike Flood which coupled one and two-dimensional unsteady hydraulic. The possible use of cross sections within the channel and high-resolution digital elevation model to describe complex floodplains topography, has made this method an increasingly practical flood analysis tool[8].

Any future sustainable utilization of the water resources of the Basin and proper mitigations measures of the existing problems related to the lake level fluctuation and flooding events demands the establishment of a proper conceptual hydrodynamic model of the Basin. This paper basically has focused on the water dynamics for the Lake Basin and the Lake Dongting; describe the concept of MIKE Flood, which is a dynamically coupled 1-D and 2-D model system. The features of the numerical method to flooding applications are described and validation of the method with supporting evidences from observed and measured hydrological data.

II. The Study Area

Dongting Lake Fig. **1**, the second largest freshwater lake in China, lies in the middle reaches of the Yangtze River, located at longitude 111 ° 14 '~ 113 ° 10', latitude 28 ° 30 '~ 30 ° 23', namely the south bank of Jingjiang River, north of Hunan Province. Dongting Lake drains into the Yangtze River through unique outlet at the Chenglingji and is fed by the Yangtze River via three small channels: Songzi, Ouchi, and Hudu. These channels are connected to the Yangtze River and to four tributaries the Xiang, Zi, Yuan, Li River. This network plays important role of Yangtze River flood diversion Storage function and Dongting region flood control. Water levels in Dongting Lake vary seasonally according to the water levels of the Yangtze River. During peak flood period, surface water is extensive. While during the low water period, the water is constrained to the lakebed and river channels. Dongting Lake terrain, from West to East, is divided into the East Dongting Lake, South Lake, West, from West to East to form an inclined surface[9]. Numerous branches and multiple indefinite flows connecting with each other import the East, South Dongting Lake; constitute a complicated river network system. The flood simulation condition is therefore complex and is of great importance for the floods of the Yangtze River with different characteristics, the storage and discharge of Dongting Lake to Chenglingji outlet.

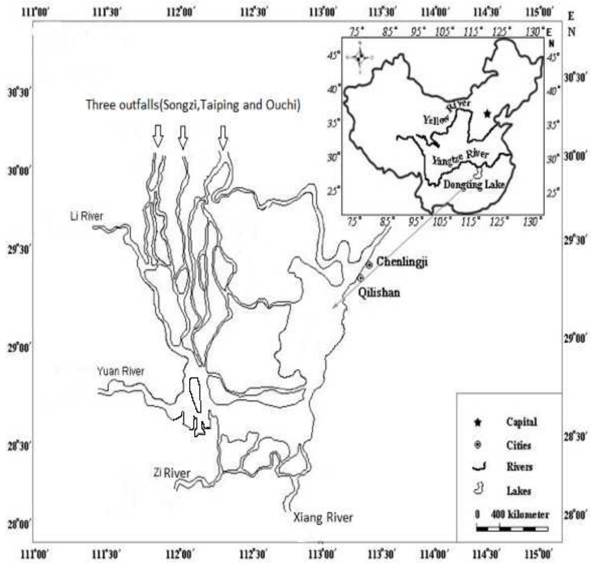

Fig. 1. Dongting Lake Basin Water Network

III. Methodology

The mathematical equations and numerical formulation have been developed. This section details the Hydrodynamic modeling and parameters taken into account to achieve model.

The One-Dimensional Model

The one-dimensional model is based on the cross-sectional averaged Saint-Venant equations, describing the development of the water dept h and the discharge Q or the mean flow speed U. These can be written for the continuity equation as shown below:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=F_s \quad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\alpha Q^2}{A}\right)+gA\frac{\partial}{\partial x}h+\frac{gQ|Q|}{C^2 AR}=0 \quad (2)$$

Where $A=f(h)$ is the area of wet cross-section, which depends on the water depth and $R=A/P$ is the hydraulic radius with $P=g(h)$ being the wet perimeter. h is the water depth, Q is the discharge, α is a velocity distribution coefficient, x is the distance between chainage, t is time, F_s is a source term, g is gravitational acceleration, C is the Chezy number.

The Two-Dimensional Model

The two-dimensional model is based on the depth averaged Saint-Venant equations, describing the evolution of the water level s and two Cartesian velocity components U and V. This can be given in simplified form for the continuity equation and are expressed as follow:

$$\frac{\partial S}{\partial t}+\frac{\partial}{\partial x}Uh+\frac{\partial}{\partial y}Vh=F_s \quad (3)$$

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$$\frac{\partial S}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+g\frac{\partial S}{\partial x}+\frac{g}{c^2 d}U\sqrt{U^2+V^2}$$
$$+\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial U}{\partial y}\right)=F_sU_s \qquad (4)$$

$$\frac{\partial S}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+g\frac{\partial S}{\partial x}+\frac{g}{c^2 d}V\sqrt{U^2+V^2}$$
$$+\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial V}{\partial y}\right)=F_sV_s \qquad (5)$$

Where U and V are depth averaged Cartesian velocity components, C is the Chezy number, S is the elevation, h is the total water depth, K_{xx} and K_{yy} are eddy viscosities, F_s is a source term, U_s and V_s are the velocities at the source.

Coupled Model

The concept of One-dimensional and Two-dimensional coupling is that both models are stepped forward independently, such that the numerical solution methods that are optimized for each type of equations can be retained. The linkage to the 1-D model consists of the elevation in the link point in the 2-D domain or the average in the link area, which enters the equation as a boundary condition. The 2-D model receives the discharge from the link point in the 1-D model through the source term F_s. For maintaining a correct time centering of the two models relative to each other, the discharge is extrapolated from time step n to time step $n+\frac{1}{2}$ by alternating Q and h points as it is indicated Fig. 2, by using a simplified predictor equation, containing the gravity and friction terms such that:

$$F_s=Q^n+\frac{\Delta t}{2}\left(gA\frac{\Delta h^n}{\Delta x}+g\frac{Q^n\left|Q^n\right|}{C^2AR}\right) \qquad (6)$$

Where F_s the time is centered source term and $\Delta h/\Delta x$ is the surface slope in the 1-D model.

Numerical Formulation

The formulation of numerical solution is obtained from a finite difference form of the equations using a staggered C grid and a semi-implicit ADI two-step algorithm, where the centering of the gravity wave terms.

By rewriting the convective and friction terms a robust and accurate solution can be obtained [10]. This enables an efficient solution consisting basically of consecutive line sweeps across the domain. Two extensions to the numerical solution method are important for the present applications to flood plain flows, namely the ability to describe flooding and drying of computational nodes and to describe propagation of flood waves across initially dried or very shallow areas. But the problem is that with dried out cells, like cells where the water level drops to or below the bed level produce a zero or negative total water depth, is to develop methods that provide stable and physical solutions and that conserve mass. Several methods have been suggested such as clipping of the water depth to a small positive value, artificially increased friction for small water depths or implementation of slots where the cell area diminishes when the water level falls below the bed level. Utilization of an up winded discretisation of the water depth, combined with a positive and monotone scheme for the water depth Fig. **3**, provides an attractive solution:

$$\frac{\partial}{\partial x}\left(\frac{pp}{h}\right)\cong\left[\left(\frac{p_{j+1}+p_j}{2}\right)^{n+1}\cdot\left(\frac{p_{j+1}+p_j}{2}\right)^{n}\cdot\frac{1}{h_{j+1}^n}-\left(\frac{p_j+p_{j-1}}{2}\right)^{n+1}\cdot\left(\frac{p_j+p_{j-1}}{2}\right)^{n}\cdot\frac{1}{h_{j-1}^n}\right]_k\cdot\frac{1}{\Delta x} \qquad (7)$$

$$\bar{u}^2\Delta t\frac{\partial^2 p}{\partial^2 x}=$$
$$\Delta t\left(\frac{p_{j,k}^n}{h^*}\right)^2\cdot\left(\frac{p_{j+1,k}-2p_j+p_{j-1}}{\Delta x^2}\right)_k^{n+1} \qquad (8)$$

Where

$$h^*=\frac{1}{2}\left(h_{j+1}+h_j\right)_k^n \qquad (9)$$

The difference form in (7) is used for flow at low Froude Numbers and in (8) we approximate, the average velocity over the interval from $t_1=n\cdot\Delta t$ to $t_2=(n+1)\cdot\Delta t$ by $p_{j,k}/h^*$. For flow at high Froude Numbers, a scheme as described below is used. In this scheme selective introduction of numerical dissipation has been used to improve the robustness of the numerical solution in areas of high velocity gradients, and to provide MIKE 21 with the capability to simulate locally super-critical flows.

This numerical dissipation has been introduced through selective up-winding of the convective momentum terms, as *Fr* increases. The rationale behind this approach is that the introduction of numerical dissipation at high Froude Numbers can be tuned to be roughly analogous to the physical dissipation caused by increased levels of turbulence in high velocity flows.

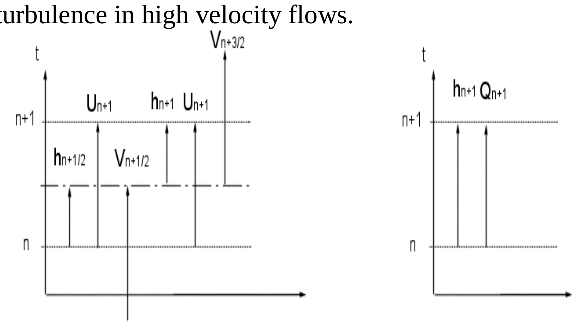

Fig. 2. Time Centering of the ADI Algorithm in the 2-D Model (left) and in the 1-D Model (right)

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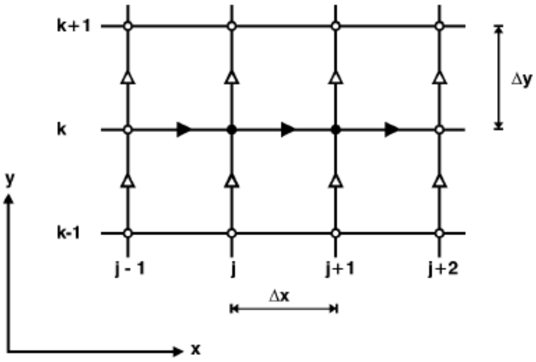

Fig. 3. Grid Notation: x-Momentum Equation

Effects of up-winding

The fully space centered description of the convective momentum term considered is approximated by:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_j \approx \frac{1}{\Delta x}\left[\left(\frac{p^2}{h}\right)_{j+\frac{1}{2}} - \left(\frac{p^2}{h}\right)_{j-\frac{1}{2}}\right] \qquad (10)$$

For positive flow in the x-direction, the up-winded form of the convective momentum term can be approximated by:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j-\frac{1}{2}} \approx \frac{1}{\Delta x}\left[\left(\frac{p^2}{h}\right)_{j} - \left(\frac{p^2}{h}\right)_{j-1}\right] \qquad (11)$$

Allowing for the back-centering in space, the up-winded term can be shown to be equivalent to the original space-centered term, plus an additional second order term, as follows:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j-\frac{1}{2}} \approx \frac{1}{\partial x}\cdot\frac{p^2}{h_j} - \frac{\Delta x}{2}\cdot\frac{\partial^2}{\partial x^2}\left(\frac{p^2}{h}\right)_j \qquad (12)$$

This second order term is highly dissipative for high frequency oscillations, but has little effect on lower frequencies. That is, it will tend to damp out high frequency numerical instabilities, while having little effect on the overall computation.

Selective up-winding

This comes to ensure that the dissipative effects of up-winding are only included when necessary, a Froude Number dependent weighting factor α has been introduced and is applied to the convective momentum terms, as follow:

$$\begin{aligned} &\alpha = 0,\ Fr \le 0.25; \\ &\alpha = \frac{3}{4}(Fr - 0.25), 0.25 \le Fr \le 1; \qquad (13) \\ &\alpha = 1, Fr \ge 1 \end{aligned}$$

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_j \approx (1-\alpha)\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_j + \alpha\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j-\frac{1}{2}} \qquad (14)$$

However, this brings the effects of up-winding in gradually as the Froude Number increases from 0.25 to 1. For Froude Numbers of Fr = 1 or more, the convective momentum term is fully up-winded.

Computational Form

From (7), the actual representation of the convective momentum equation for positive flow in the x-direction can be expressed as follows:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j,k}^{n+\frac{1}{2}} \approx$$

$$\left[\begin{array}{l} \frac{\left[(1-\alpha)p_{j+1}+(1+\alpha)p_j\right]^{n+1}}{2}\cdot \\ \frac{\left[(1-\alpha)p_{j+1}+(1+\alpha)p_j\right]^{n}}{2}\cdot \\ \frac{1}{\left[(1-\alpha)h_{j+1}+\alpha h_j\right]^{n}} \\ -\frac{\left[(1-\alpha)p_{j}+(1+\alpha)p_{j-1}\right]^{n+1}}{2}\cdot \\ \frac{\left[(1-\alpha)p_{j}+(1+\alpha)p_{j-1}\right]^{n}}{2}\cdot \\ \frac{1}{\left[(1-\alpha)h_{j}+\alpha h_{j-1}\right]^{n}} \end{array}\right]_k \cdot\frac{1}{\Delta x} \qquad (15)$$

The weighting factor α for each grid point is calculated every time step, immediately prior to the calculation of the momentum equation coefficients. This causes that numerical dissipation is only introduced at grid points where high Froude Number flow is occurring, and that the normal high accuracy solution of MIKE 21 is obtained throughout the rest of the model domain [11].

Selective up-winding is only included on the convective momentum terms and not the cross momentum terms. With the introduction of selective up-winding of the convective momentum terms, it has been possible to virtually eliminate the unrealistic oscillations and local instabilities that occurred previously when modeling high Froude Number flows. This has improved significantly the robustness of MIKE 21's solution procedure at high Froude Numbers, and has enhanced significantly MIKE 21's capability to locally super-critical flows; Selective up-winding also ensures that the high accuracy of solutions in other remaining unaffected areas.

The model Sum up

The use of spatially centered discretization of the convective terms provides a high accuracy of the numerical solution but for stability reasons restricts the flows to the sub-critical regime, therefore; the Froude number $Fr = U\sqrt{gh}$ must be less than 1 ,where U , g and h are flow speed, cross sectional of the flow and gravity

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respectively. For coastal applications this is usually not a serious restriction, but for flood waves propagating over dried or very shallow areas, critical or super critical conditions often arise. Therefore we need to introduce extra dissipation of short wave energy locally, either by introducing an artificial eddy viscosity or through the numerical scheme. By using an upwind weighting of the convective terms proved that the present solution method can be stable, even for super critical flows, and it avoids artificial wiggling of both velocities and water levels. The weighting is selected based on the local Froude number such that for $Fr < 0.25$ a centered scheme is used and a gradually increasing up winding until $Fr>1.0$ where a fully up winded scheme is used.

IV. Numerical Results and Discussions

The water Monitoring stations were undertaken within Dongting Lake Basin throughout the period from January 2011 to December 2014. For hydrodynamic module, the computation continued for four years within a time step of 20 second from an initial stationary until the fully developed simulated water level and flow fields are obtained as shown in the final results.

Selected Water Monitoring Stations

The data from eleven water monitoring stations have been selected to be used in the model include inlets from Yangtze river and four river system in Western, Southern Dongting Lake as well as some stations in Eastern Dongting Lake as shows the Fig. **4**.

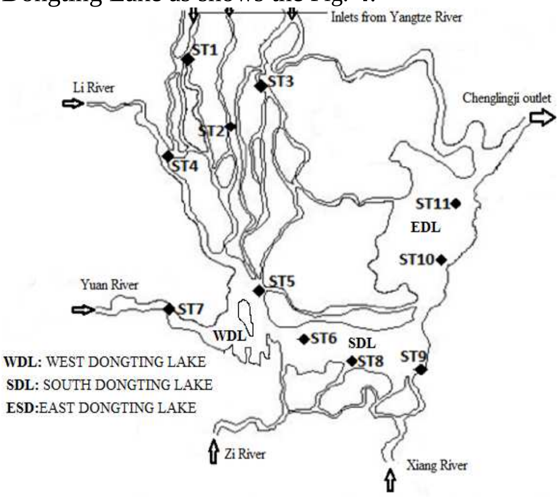
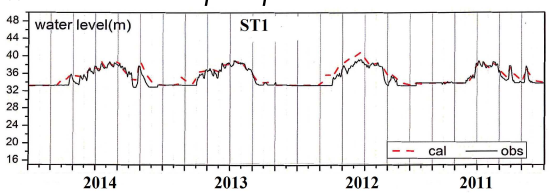
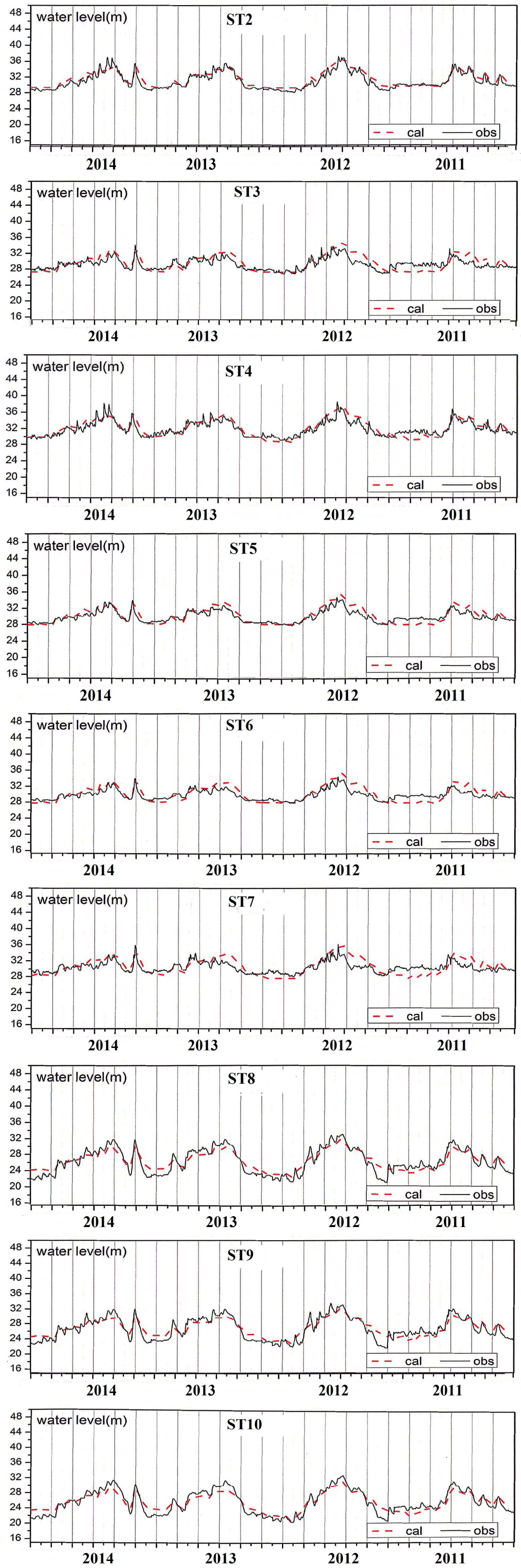


Fig. 4. Location of Water Monitoring Stations in Dongting Lake

Water Level and flow fields Simulation





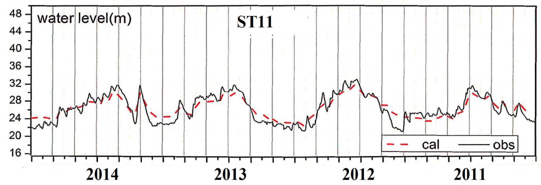


Fig. 5. Simulated and Observed Water Level Comparison at ST1 to ST11 from January 2011 to December 2014

The data from 2011 up to 2014 were simulated, for hydrodynamic model the computation continued for the whole four years with a time step of 20s from initial stationary until the full-developed field is obtained. The results of simulated water level were used to compare with the observed data as shown in Fig. **5**, we observed clear that for each station water level variation in Dongting Lake is approximately 10m for maximum, increasing in summer and reducing in winter.

The 2014 average water level was simulated in order to verify the Dongting Lake hydrodynamic model was apparently reasonable. However, the simulated average water results were compared with the observed value of the measured value of the data from the Dongting Lake water conservancy bureau as shown in Fig. **6** and we noticed that for the simulated results and the actual value, there are some difference especially during the summer in June, September and August, such that the average simulated water level is lower than the observed value; This may be caused by the flood Dongting Current value which is large. Hence, the Dongting Lake hydrodynamic model water level simulation values in 2014 indicated similar tendency with the observed value, As a result fitting the model.

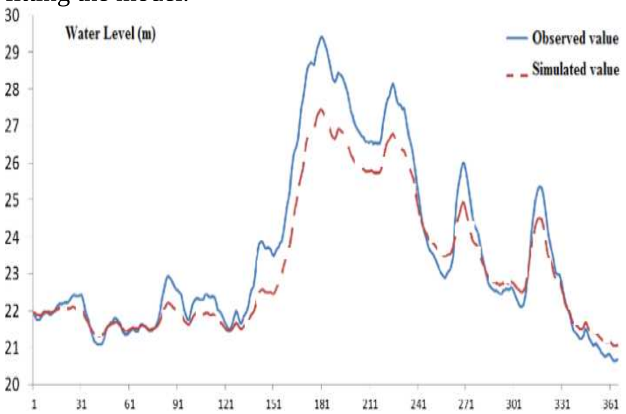
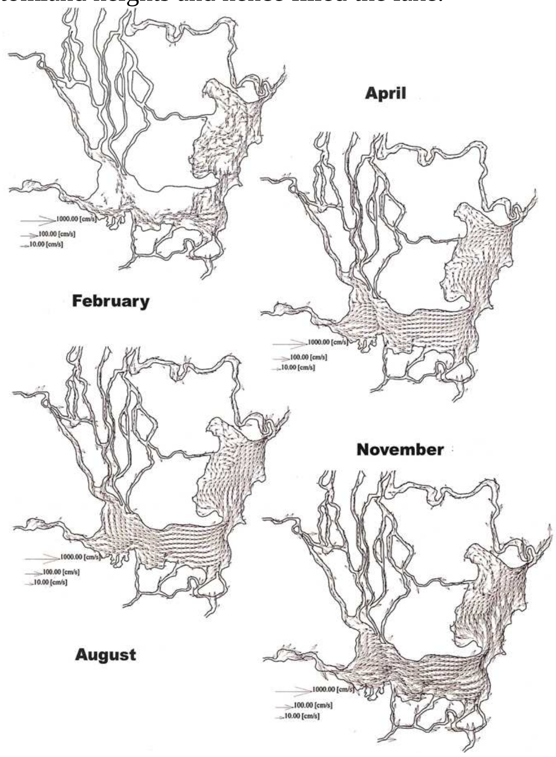


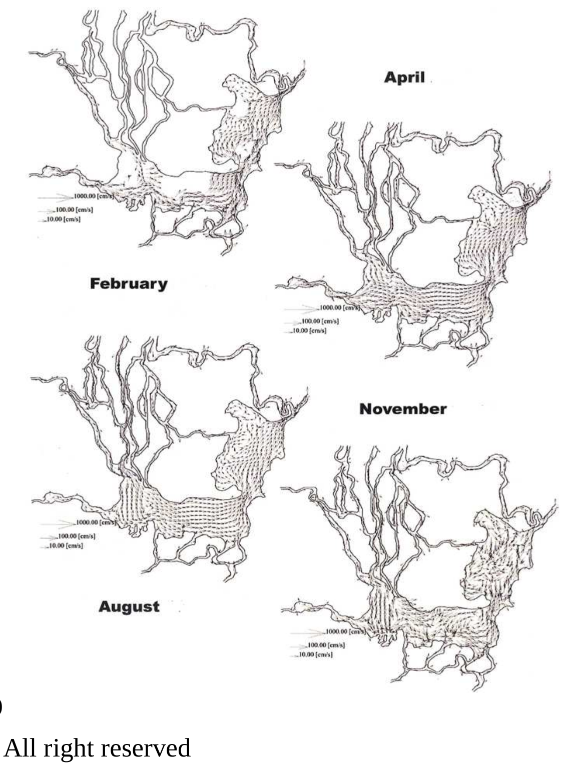
Fig. 6. Dongting Lake Average Water Level Simulated and Observed Values in 2014

The yearly flow fields from 2011 to 2014 as shown the

Fig. **7** are composed by water from the Yangtze River and four major rivers connected to the lake through West Dongting Lake(WDL), South Dongting Lake (SDL) and flow out through East Dongting Lake (EDL) and join again the Yangtze River through the Chenglingji outlet. Although because of lower resolution of computational grid, it is difficult to distinguish very small thalweg, but still accurately describes the simulation results of major flow path and main lake blocks. Due to a large amount of sediment deposition from Yangtze River floods, river beach developed rapidly and lake size is reduced. During February, the lake bottomland is divided because of low water level, the lake surface distribution is still fragmented and incomplete, large water body is often connected by narrow channel. As long as water level is gradually rise, separate lake surface polymerized when expanding to bottomland heights and hence filled the lake.



(a)



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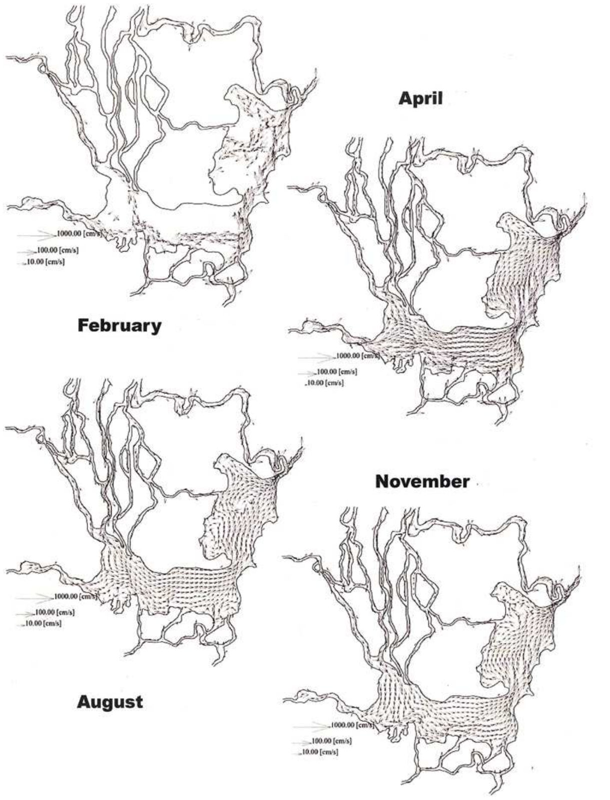
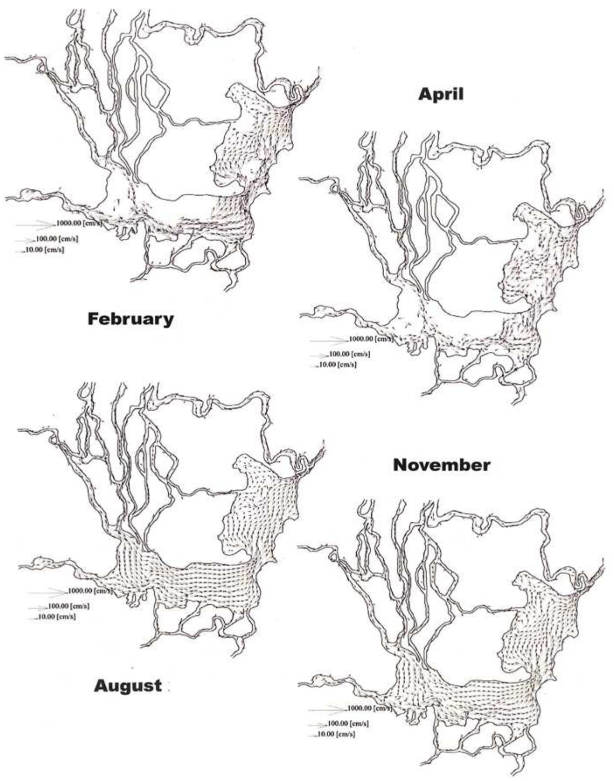


(c)



(d)

Fig. 7. Dongting Lake Simulated Flow fields in February, April, August and November for 2014(a), 2013(b), 2012(c) and 2011(d)

V. Conclusions

Water dynamics simulation is one of the most important works for water resources protection and is an important part of digital river system and water body, while digital river system is the future trend of water resources and management. With the help of MIKE Flood model of water dynamics platform, water level and flow fields in Dongting Lake was simulated. This paper aims to analyze the water dynamics that will probably occur along Dongting Lake. This research could be used as a reference in decision making for the development and protection of Dongting Lake watershed. The following conclusions can be drawn.

The water level simulation results in the Dongting Lake from 2011 to 2014 show that the water level simulated at selected different control water stations are significant and were used to compare with the observed data, which show that for each station water level variation in Dongting Lake is approximately 10m for maximum, increasing in summer when vast amounts of water and sediment flow into the lake. Which may resulting in flood and waterlogged disaster in the lake region and reducing due to the mud and sand keep silting up in the south of the lake which may cause water crisis because of dropping water levels. Therefore, the storing capacity is becoming smaller because of flood diversion from Yangtze River. Hence, the modal is significant in decision making for the development and protection of Dongting Lake watershed.

On the basis of the flow field distribution results generated by the MIKE 21 hydrodynamics model, the 2014 data in February, April, August and November were used for model calibration and validation. The results revealed that the coupled lake model could reasonably reflect changes in key state variables. The simulation results indicate that the model is a useful tool because it helps to reflect on effects in lake restoration and management. Meanwhile, the coupled model increases understanding of processes and interactions between components in Lake Ecosystem and external conditions.

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