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Evaluation of streams and weather contribution on Dongting Lake water budget: a key driving tool for wetland management and protection

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Abstract

With the considerable fluctuation of China's second freshwater lake, Dongting Lake has changed its water budget. Over the last few years, many floods and water level depletion occurred; thus, the research on Dongting Lake flood prevention and control, and understanding the hydrological processes has great importance in the middle Yangtze River. In this study, MIKE FLOOD Modeling coupling one-dimensional and two-dimensional Mike hydrodynamic (1D-2D MHD) is used for simulating hydrodynamic behavior of Dontgting Lake controlled by Yangtze River and its basin. The model was employed to simulate the lake storage capacity and water budget in dry and wet seasons over the period 2011-2014. A large amount of inflow was observed in 2012, whereas in 2011 was less compare to all four years. The findings revealed that runoff from rivers(Xiang, Zi, Yuan, and Li) is dominating the lake water variation. During the dry season, the flow characteristics in the East Lake and South Lake have an obvious counter-clockwise circulation because of the influence of wind and terrain conditions. Besides, lake surface temperature is mainly affected by the air above the lake. This study results provide a comprehensive tool for lake water fluctuation and wetland management.

Keywords: Modeling; Dongting Lake Basin; Storage capacity; Numerical simulation; Water budget; Wetland management

Introduction

The recent Dongting Lake water monitoring and investigations show that the situation has dramatically water shrinkage trends, particularly water level diminution issues; there is a big difference in water level during dry and wet seasons. Water shortage and flooding have an impact on Dongting Lake, regional socio-economic development. Thus, it is necessary for the formation mechanism of the Dongting Lake hydrodynamics study; through the establishment of water dynamics – seasonal variation model and simulation of water fluctuations in the lake.

The lake water generally is coming from Yangtze, Xiang, Zi, Yuan, and Li River systems. They form complex networks and bring sand and mud to the lake during the rainy season [1]. In recent years, the lake has greatly reduced, giving a rise to the researchers to investigate the reasons and effects of these changes of Chinese most important lake [2].

The previous studies indicated that sediment and runoff changes in Dongting Lake [3, 4]were due to the Three Gorges Dam(TGD) construction in the middle of Yangtze River, affecting the lake area and volume [5]. As a flood control study is concerned, the Dongting water dynamic was controlled by the TGD through the Yangtze River [6, 7]. However, other tributaries (such as Xiang, Zi, Yuan, and Li River) might have contributed to the lake inflow. The use of flood model by generating a class polygon containing elevation, depth, and speed of flood current provided the flood characteristics [8], but the flooded field still in the personal Geo-database. The polders restoration for Dongting Lake flood event conditions, the quantification of flood limitation effects indicated that the flood responses may due to the choice of management option [9]. However, the suitable approaches of lake rehabilitation are determined due to various flood responses [10, 11]. There were remarkable geomorphological changes on Yangtze River and its diversion canals system and reduction of Dongting Lake area as well as storage capacity [12].

For the wetlands study domain, on flooding events (during wet and dry season) in the lowlands of Dongting Lake suggested that during the dry season, water remained in canals, huge portions of lowlands are subjected to the water shortage and reach the annual minimum water level; during the flood season, the entire lake is completely flooded and reaches the maximum water level [13]. Based on investigations carried out by Xiao et al.,(2010) [14] on the East Dongting Lake flood control function analysis and evaluation; it was due to the flood and silting problems that the lake wetland area has been divided into different parts. However, despite previous studies of Dongting Lake water management, sediment concentration, and flood disaster issues; there are some gaps because of lake deterioration and environmental hazards still existing. The actual main problems facing Dongting Lake are water shrinkage, biodiversity losses, and structures due to the flooding. The main reason for this situation is mainly affected by changes in hydrological regime, climate conditions, and a variety of human activities [15, 16]. The current study aims to evaluate the contribution of rivers inlet and weather conditions to the lake water budget through the establishment of a hydrological model coupling one dimensional

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model of the river and two dimensional model of the lake; the results may provide a compressive tool for Dongting Lake water fluctuation and wetland management.

Methods

Study area description

The Chinese second-largest freshwater, Dongting Lake located at 111 ° 14 '- 113 ° 10' longitude, 28 ° 30 '- 30 ° 23' latitude; and fed by the Yangze River though (Songzi, Taiping and Ouchi) small canals; and Xiang, Zi, Yuan, and Li Rivers in lets with single outflow at Chenglingji (Figure 1). These connexions contribute to Dongting Lake flood control especially during the Yangtze River flood diversion during heavy rain season. The lake area refers to the south of the Jingjiang River, Xiang, Zi, Yuan, Li River tail controllers below elevation in the 50m following cross Hunan, Hubei provinces vast plains, with about 2625km2 surface area. Dongting Lake terrain, from West to East, is split into East Lake, South Lake, West Lake; from West to East the lake forms an inclined surface [17]. The lake had the largest level fluctuation amplitude, yearly average water level ranging between 24.0m-31.0m, annual precipitation varies between 1200mm-1450 mm, and the terrain elevation varies between 0-15m.

One-Two hydrodynamic coupling model

Model description

The water dynamics may be estimated based on numerical approaches. The fluid flows equations are established under continuity and mass conservation theories. The Navier-Stokes equations could be employed to solve three dimensions fluid dynamics [18, 19]. The simple form of one-dimensional (1-D) and two-dimensional (2-D) relationships use the Saint Venant equations are employed to the various complex fluid flow where the specification of flow unnecessary. 1-D Saint Venant equations have computational restrictions, could not perfectly model complex topography. Recent studies suggested 2D more appropriate to solve the above issue.

A 2-D could model complex topography effectively; however, the combination of both 1D and 2-D could give accurate model results. During the hydrological model development, errors should be taken into considerations. Errors could be coming from various sources [20]. Uncertainty resulting from data collection, assumptions made while developing a model and calibration techniques as well as mesh resolution choice [21].

Lake water dynamics is fundamental research for lake water environment, so the establishment of water and ecosystem dynamics coupled-mode combines type, in this study, is essential for better understanding the movement of fluid within the lake, lakes and rivers and the lakes water budget. Furthermore, the findings will have an important contribution to decision-making for lake water management and wetland protection.

One dimensional (1-D) model of the river system

The model is consist of the Saint-Venant cross-sectional averaged equations [22, 23], expressing the water depth h and the discharge Q or the mean flow speed U. The following equations express continuity and the 1-D section-averaged Navier-Stokes Equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (2.1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(uQ) + gA\left(\frac{\partial h}{\partial x} - s_0\right) + gAs_f = 0 \qquad (2.2)$$

Where A is the cross-sectional area (m2);Q is the discharge (m3/s); S_0 is the bed slope(%); and S_f is the friction slope(%).

Both continuity and conservation of momentum equations are obtained upon the following hypothesis [24]. The density of water negligible due to its incompressibility and homogeneity; the bed slope is small and the cosine of its angle is assumed to be 1; the flow moves in a direction parallel to the bottom; the flow is subcritical; supercritical flow conditions are computed with a reduced momentum equation, that neglects the nonlinear terms.

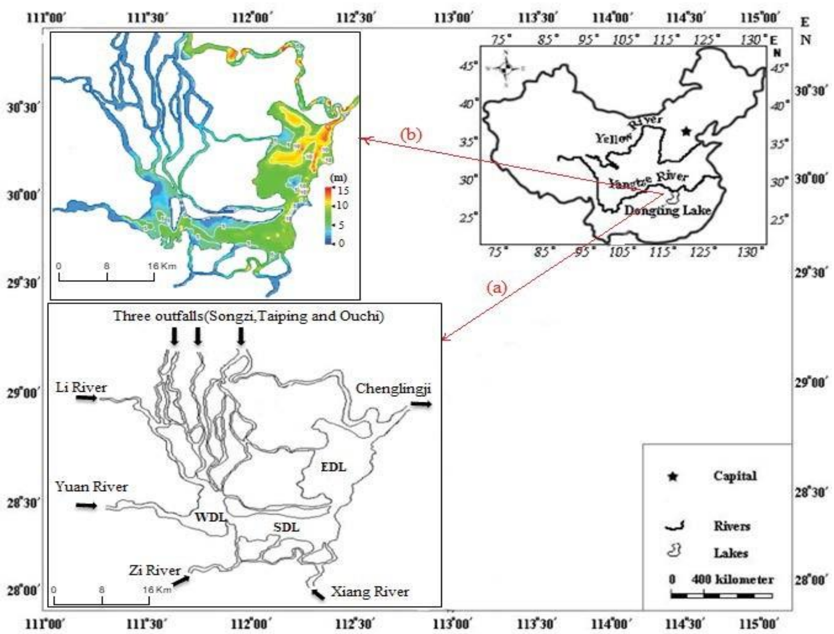

Figure 1: (a) Dongting Lake Rivers inlet and outlet including (WDL: West Dongting Lake, SDL: South Dongting Lake, EDL: East Dongting Lake); (b) Dongting Lake topography.

Based on the above assumptions, the equations used in MIKE11 numerical hydraulic solver are as follow: Continuity equation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_{lat} \quad (2.3)$$

Momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\alpha Q^2/A\right)}{\partial x}+gA\frac{\partial h}{\partial x}+\frac{gQ|Q|}{C^2AR}=0 \quad (2.4)$$

Where q_{lat} is the lateral discharge per unit length [m²/s]; α is momentum distribution coefficient; xis the distance [m]; g the gravity acceleration [m/s^2]; his the water level [m]; Cis the Chezy coefficient[m$^{1/2}$/s]; R is the hydraulic radius [m] [25]

Two-dimensional model of lake

The 2-D model is consisting of the Saint-Venant equations depth-averaged, the derivation of 2D Saint -Venant equations are expressed as follow:

$$\frac{\partial h}{\partial t}+\frac{\partial (hU)}{\partial x}+\frac{\partial (hV)}{\partial y}=0 \quad (2.5)$$

$$\frac{\partial (hU)}{\partial t}+\frac{\partial (hUU)}{\partial x}+\frac{\partial (hVU)}{\partial y}=\frac{\partial (hT_{xx})}{\partial x}+\frac{\partial (hT_{xy})}{\partial y}-gh\frac{\partial z}{\partial x}-\frac{\tau h_x}{\rho} \quad (2.6)$$

$$\frac{\partial (hV)}{\partial t}+\frac{\partial (hUV)}{\partial x}+\frac{\partial (hVV)}{\partial y}=\frac{\partial (hxy)}{\partial x}+\frac{\partial (hT_{yy})}{\partial y}-gh\frac{\partial z}{\partial x}-\frac{\tau h_y}{\rho} \quad (2.7)$$

Where U and V are the depth-averaged velocity components in the x and y directions, respectively; h is the water depth; T_{xx}, T_{xy}, and T_{yy}, are depth-averaged turbulent stresses; τh_x, τh_y are the bed friction shear stresses, and z is the water surface elevation.

Similarly, MIKE 21 two-dimensional hydrodynamic model equations to solve 2-D flows are given below:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=\frac{\partial d}{\partial t} \quad (2.8)$$

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{C^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})\right]=0 \quad (2.9)$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gp\sqrt{p^2+q^2}}{C^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{\partial}{\partial x}(h\tau_{xy})\right]=0 \quad (2.10)$$

Where p and q are flux densities in the x and y directions, respectively (m3/s/m); ζ is the water surface elevation (m); d is water depth variation over time (m); ρw is the density of water (kg/m3) [26].

To reduce the limits of the 1-D hydraulic model, the 2-D model gives a suitable method of flood modeling with MIKE 21 by predicting the interchange between canal and floodplains but it requires a long computation time [27]. To overcome those difficulties the new approach MIKE FLOOD that coupling 1-D and 2-D was established [28]. This approach has become progressively more practical for flood studies and river- lake complex systems because of its features for describing floodplain's complex topography [29].

One/Two Dimensional coupling model

The dynamic linkage of the 1-D and 2-D models consists of a point coupling; such that the river endpoints could be linked to the meeting point or an area in the 2-D model, For example, a river inflow or out flow to the lake. 1- D and 2-D models coupling approach benefiting both methods, MIKE FLOOD linked the MIKE11 and MIKE21 software with various choice of coupling. We applied lateral coupling of MIKE11 to MIKE21 by sideward modeling of water coming into the floodplain from the river canal [26]. We modeled the river canal flow to the floodplain with a simplified weir equation. The conservation of momentum was neglected for lateral linkage because the 1-D model cannot simulate cross channel flow [25].

Boundary and initial conditions

Dongting Lake watershed is inland lake; thus, the boundary conditions are not included in the numerical simulation of open borders. Computing the actual average value used in the Dongting Lake in January each site counted as initial input conditions.

Horizontal rigid boundary

For Lakeshore these rigid boundaries, because the water cannot pass through, so the horizontal component of velocity becomes 0.

$$(\vec{v}_k)_n=0 \qquad (1\le k\le K) \quad (2.11)$$

Among them, vk is the horizontal speed direction, k represents the kth layer (Table 1). On the other hand, the tangential velocity is treated as a no-slip boundary, since the horizontal direction of grid scale is usually too rough.

$$\frac{\partial}{\partial \vec{n}}(\vec{v}_k)_t=0 \qquad (1\le k\le K \quad (2.12)$$

Rigid boundary diffusion fluxes of temperature (especially through runoff) is set to 0.

$$K_H*\frac{\partial}{\partial \vec{n}}(T)=0 \qquad (1\le k\le K \quad (2.13)$$

Where K_H represents vortex divergence unit of cm^2 · s-^{2}.

Water surface

Usually, water shear surface is estimated by the following equations:

$$\begin{cases}\frac{1}{\rho}\tau_x=\frac{\rho_a}{\rho_1}\gamma_a^2*W_x\sqrt{W_x^2+W_y^2}\\ \frac{1}{\rho}\tau_y=\frac{\rho_a}{\rho_1}\gamma_a^2*W_y\sqrt{W_x^2+W_y^2}\end{cases} \quad (2.14)$$

Among them, Wx, Wy, are respectively, above the surface of the water at 10m x, y-direction wind speed, ρa represents the density of air,

Layer number	Water depth range(m)	Thickness (m)	Representative water depth(m)
1	S-2.0	S-2.0	1.00
2	2-4.5	2.5	3.25
3	4.5-7.0	2.5	5.75
4	7.0-9.5	2.5	8.25
5	9.5-12.0	2.5	10.75
6	12.0-14.5	2.5	13.25
7	14.5-16.5	2.0	15.50
8	16.5-B	B-6.0	19.50

Table1: Dongting vertical stratification numerical model, S and B represent the surface and bottom of the lake, respectively.

ρ represents the density of water, γ_a^2 indicates drag coefficient, τ_x and τ_y denote shear stress in x and y directions.

The lake surface water temperature Qs by exchanging heat flux and the atmosphere can be determined by:

$$-K_H * \frac{\partial T}{\partial \vec{n}} = \frac{Q_s}{\rho * c_v} \quad (2.15)$$

Among them, Cv under fixed volume represents the specific heat capacity of the lake.

Lake bottom

Similarly, the bottom flow of the lake can be expressed as the shear force:

$$\begin{cases} \frac{1}{\rho}\tau_x = \gamma_b^2 * u_B\sqrt{u_B^2 + v_B^2} \\ \frac{1}{\rho}\tau_y = \gamma_b^2 * v_B\sqrt{u_B^2 + v_B^2} \end{cases} \quad \textbf{(2.16)}$$

Among them, u_B, v_B is the lake bottom flow rate in x, y-direction, respectively, γ_b^2 is the coefficient of friction. (Table 1)

Data source and processing

The Dongting lake wind speed, Solar radiation, the relative humidity radiation, and cloud cover. These weather conditions on the hydrodynamic characteristics of the Dongting Lake Basin have a very important influence on Dongting Lake Basin hydrodynamic model among other parameters. 2014 has been chosen as the hydrodynamic Dongting Lake Basin Numerical simulation of the year. For data accessibility issues, the weather data has been downloaded from the National Oceanic and Atmospheric Administration (NOAA) web (http://www.esrl.noaa.gov/psd/data/). The field data have been provided by Dongting Lake Conservancy bureau.

Model calibration

The model is calibrated using observed data. Several parameters could be modified to cope with the actual results [30]. Some parameters, that could be modified during model calibration, include the stream of floodplain surface roughness, mesh resolution, and eddy viscosity. The most important parameter for one-dimensional model is canal roughness [31]. However, 2-D models are comparatively not sensitive to variation in floodplain roughness [32], current velocity, and changes in mesh density, for the linked 1D-2D models, the control parameter could be the canal roughness. [33]studies indicated flood plain and canal roughness calibration may change according to the modeled flow. The Probabilities estimation is related to the conditioning predictions of realizations of a distributed quasi-2-D flood routing model based on known levels at the field alongside the reach. The Manning's "n" roughness coefficient was adjusted by using the rating curve by fitting the monitored data.

Results and Discussions

Dongting Lake Meteorological condition

The Dongting lake wind speed: In the wind speed data, the time interval of data is 6 hours, space, and time while using geographic information system commonly used inverse distance weighting interpolation method [34] to obtain computing grid area wind year Speed and direction changes. When computing grid nodes given the right to a particular data point weight with a specific party time, grid computing to the reciprocal distance between the observation point is proportional to. For each grid, all right within a given region weight is a known point M number of not more than 1, and the sum of the weights equals 1. When a known point coincides with the grid nodes, which have been known points are given a weight of 1.0 for the actual, indicates that the value of the grid is completely observed values of the observation points by Representative [35]. As it is shown in (Figure 2), the 2014 average wind speed in January, April, July, and October is represented; it can be seen that the wind speed varies according to the seasons and its effects on the lake flows is significant, the lake basin is the strongest winter wind, the average wind speed of about 2 ~ 3m / s, whereas the spring and summer wind is weak, the average wind speed is about 0.5 ~ 0.7m / s.

Dongting Lake average rainfall distribution: Similarly, average rainfall interpolation results shown in (Figure 3). Using the inverse distance weighting interpolation method for the entire calculation area interpolating the grid, all the grid points were obtained during precipitation changes in January, April, July, and October. The lowest average rainfall distribution was observed in January, while the highest average rainfall was observed in October. The rainfall distribution reduces from Northern to the East and gradually increases from the South to West part of the lake. Annual rainfall varies greatly; on seasonal distribution, spring and summer are high, autumn and winter are slightly less.

Dongting Lake maximum amount of solar radiation and water temperature: Dongting Lake is located in the subtropical atmosphere season with abundant sunshine, intense solar radiation, the maximum amount of change throughout the day shooting range is 400 to 800 cal.cm-2.day-1, the actual amount of the average annual radiation 418.6 cal.cm-2.day-1 as shown (Figure 4). Similarly, the temperature variation is shown in (Figure 5), the maximum average temperature is about 30 ° C, the lowest temperature of about 1°C. Due to the large shallow in Dongting Lake, the lake's water exchange frequent convective turbulence action is strong [36], so the lake is relatively uniform heat distribution, the vertical temperature difference between the temperature along the depth is unlikely.

Dongting Lake evaporation and relative humidity: The annual average relative humidity of Dongting Lake is about 80%, such that from July to October is a rainy season and humidity is maximum as it can be seen in (Figure 6a). similarly, the 2014 annual evaporation also is shown in (Figure 6b). the highest is in summer especially in July, due to the lake subtropical pressure control, more sunny days, thus, evaporation is highest during this month; in January, due to the winter low temperature, steam fat is not strong, hence, the minimum amount of evaporation is observed during this month.

Simulated and measured water level comparison: To verify the performance of the hydrodynamic model, the average water level of Dongting Lake in 2014 was simulated and compared with the measured ones (Figure 7), the measured water level data were obtained from the Dongting Lake water conservancy bureau in Hunan province. Although the simulation results and the measured values, there are some gaps, such as in summer (June, July, August), the average simulated water level values is lower than the measured values, which may be due to the flood Dongting current value which is large [37], and it is not included in the calculation of the inflow which caused large differences. Overall, the lake hydrodynamic model Water level simulated values in 2014 indicated similar trends with the measured values, the model fitness degree is better, it can be used to further research in the Dongting Lake water body flow characteristics, water quality, and ecological characteristics.

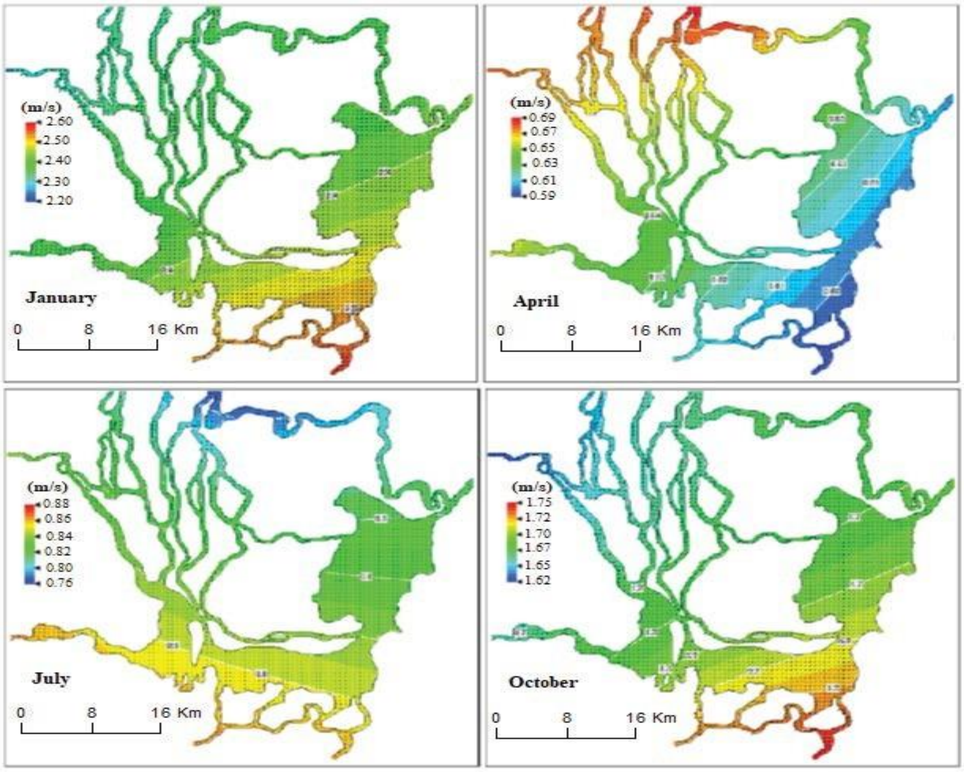

Figure 2: Dongting Lake average wind in 2014.

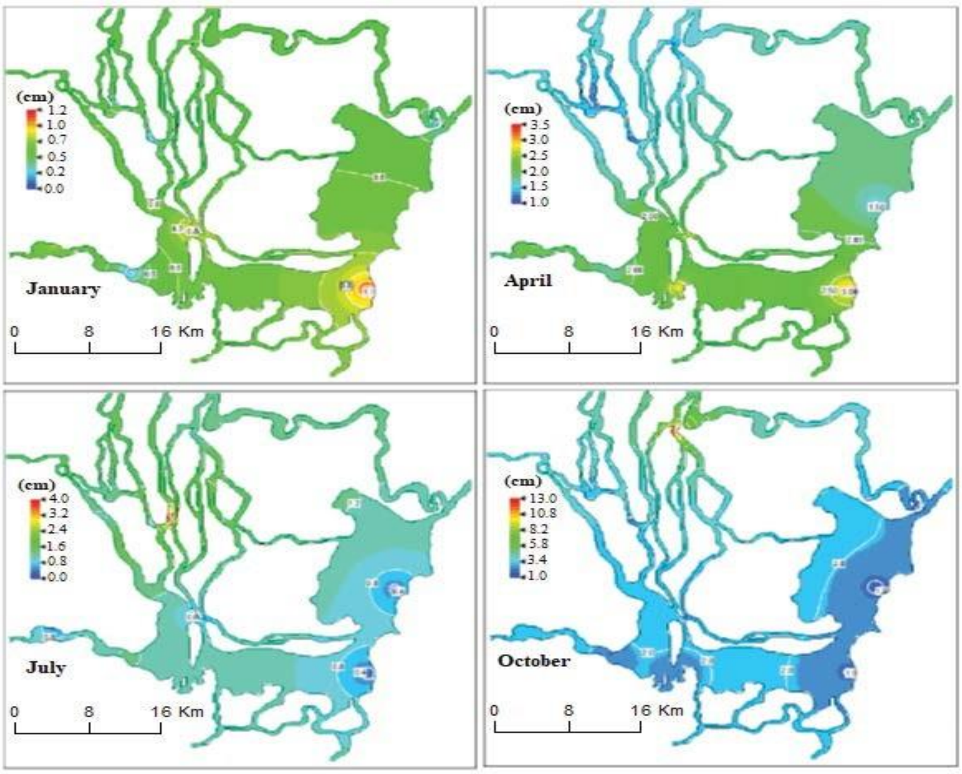

Figure 3: Dongting Lake average rainfall distribution in 2014.

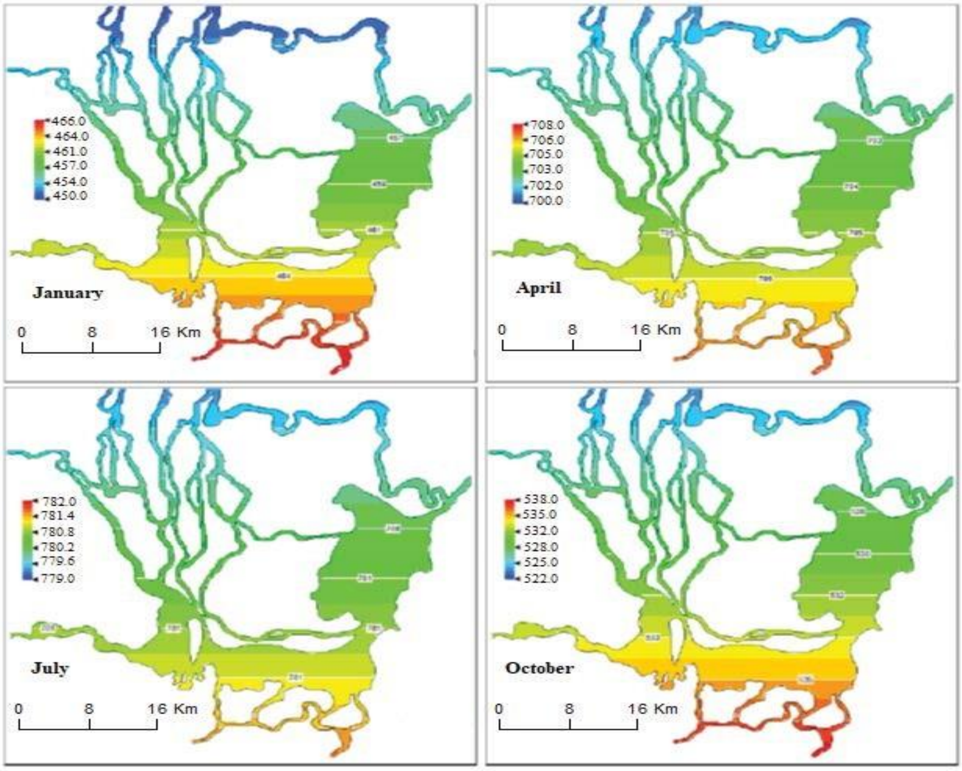

Figure 4: Dongting Lake maximum amount of solar radiationin 2014.

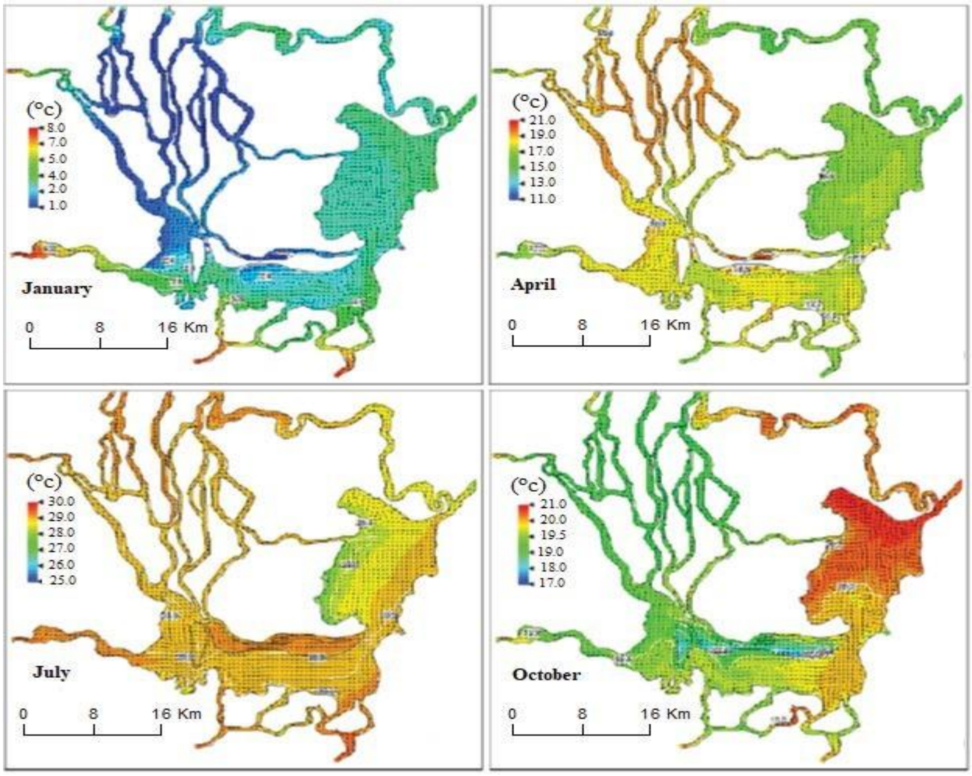

Figure 5: Dongting Lake water flow and temperature distribution in 2014.

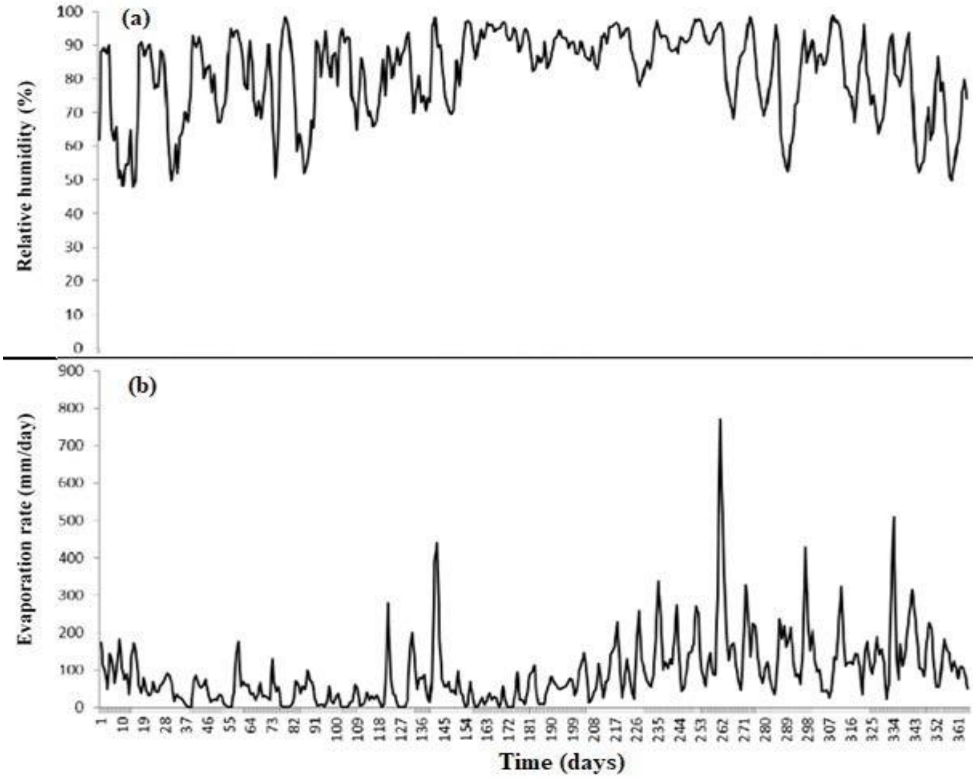

Figure 6: Dongting Lake annual relative humidity(a) and evaporationrate (b) in 2014.

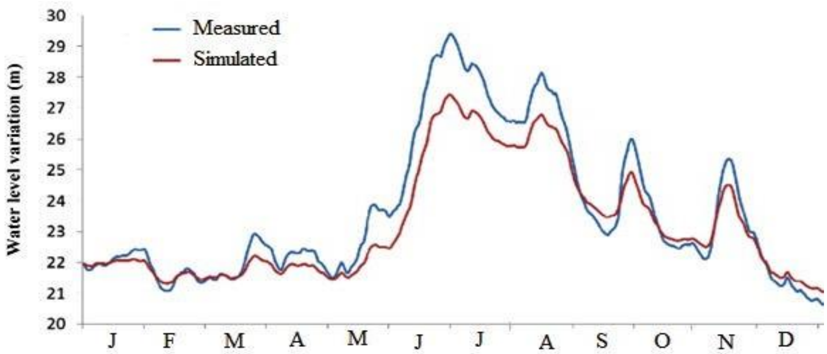

Figure 7: Lake water level simulated and measured values.

Dongting Lake water budget: The precipitation and the river's inflow are contributing to increase the lake water budget while the outflow and evaporation reduce the water of the lake. Dongting Lake's water budget from 2011 to 2014 is tabulated and summarized in (Table 2). The result indicated that the average inflow of Dongting Lake for the four years is 2666.1x108m3, the four rivers (Xiang, Zi, Yuan, and Li) are dominating the lake inflow, with 60% of the annual major rivers inflow contributing to the lake [38]. Similarly, the average outflow of Dongting Lake is 2650.6x108m3 (Table 2). In addition, the sum of inflow and precipitation is almost balanced with that of the outflow through Chenglingji (outlet) and lake surface evaporation. Inflow and outflow are larger than precipitation and evaporation, that`s why they become the dominant factor of the Dongting Lake water balance. Moreover, 2012 was the year with larger rainfall, whereas in 2011 was less (Figure 8) and (Table 2).

Conclusions

The present study evaluates Dongting Lake water dynamics through the establishment of MIKEFOOD which is a 1D-2D Hydrodynamic coupling model and based on Dongting Lake watershed hydrology and meteorology simultaneous monitoring, flow fields, and data based on information on water level variation status, were used for Dongting Lake basin hydrodynamic simulation analysis. However, the main conclusions are as follows:

(1) In this study, the model was selected and the data obtained, provided a suitable test of linking 1-D and 2-D floodplain flow modeling for the area. A method for the model setup was structured in this study, according to the standardized calibration and validation of various interpolation methods, and monitoring of model responses for several model parameters.

	2014	2013	2012	2011	Average
Inflow	2923.5	2443.2	3428.4	1869.3	2666.1
Outflow	2914.4	2478.3	3403.5	1806.1	2650.6
Evaporation	36.2	37.4	37.1	30.4	35.3
Precipitation	34.9	34.1	45.3	23.9	34.6

Table 2: Dongting Lake water budget from 2011 up to 2014 (10^8 m^3).

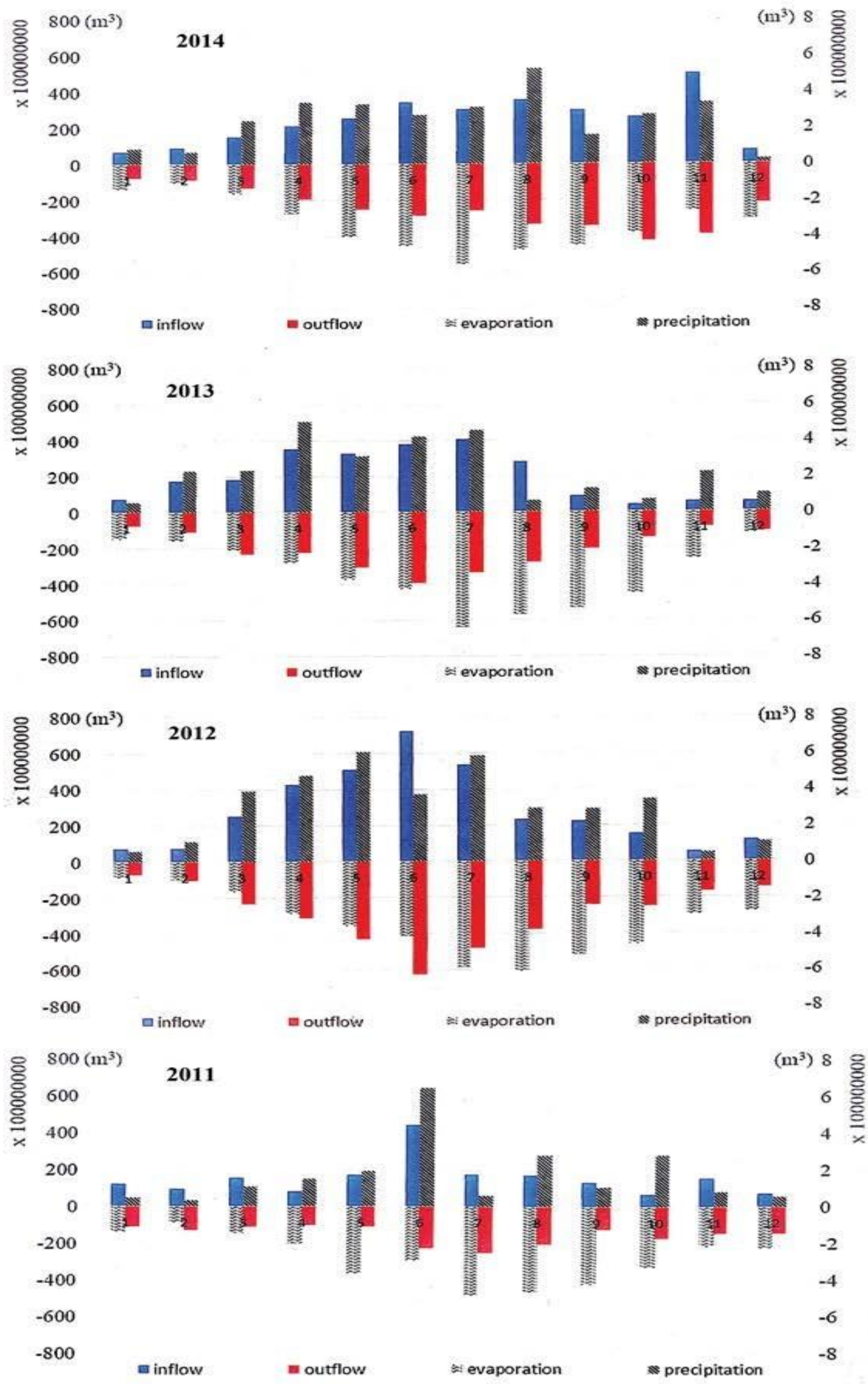

Figure 8: Dongting Lake water budget simulation from 2011 up to 2014.

(2) Hydrodynamic characteristics of the Dongting Lake basin: runoff flows into the lake is a major component that affects the lake hydrodynamic. Four rivers system inflow containsthe significant contributions of runoff into the lake. The overall situation in the Dongting Lake water flow each month, is flowing from the southwest to northeast of the lake towards Chenglingji outlet. During dry season in South Dongting Lake, the flow characteristics of the East Dongting Lake have an obvious counter-clockwise rotation of the wind. Surface water temperature is also the main factor for lake water variation. During the summer when vast amounts of water and sediment flow into the lake, may resulting in flood accompanied by erosion and reducing the storage capacity 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 the Yangtze River. Hence, the model is significant in decision-making for the development and protection of Dongting Lake watershed.

(3) The results of the water budget in Dongting Lake indicated that the sum of inflow and precipitation is almost balanced with that of the outflow through Chenglingji outlet and lake surface evaporation. Inflow and outflow are larger than precipitation and evaporation, that`s why they become the dominant factor of the Dongting Lake water balance.

The current issues of global warming, climate change due to human activities, the lake is controlled by the upstream of the Yangtze River Water Conservancy Hub especially the Three Gorges reservoir, producing a change of rivers inflow to the lake. There were changesin the Dongting Lake water dynamic and variation. Therefore, further research on Dongting Lake water and ecosystem has great significance.

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