Study on the Dynamic Correlation between Water-level and Reservoir Capacity of Poyang Lake Based on EFDC

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Abstract

Reservoir capacity is a key parameter for lakes and reservoirs. To facilitate the quick and accurate calculation of the reservoir capacity of lakes, especially those with large area and complicated floor topography, a two-dimensional hydrodynamic model based on the Environmental Fluid Dynamics Code (EFDC), was developed for Poyang Lake. This model, based on the lake topography data of Poyang Lake collected in 2010, can accurately simulate the reservoir capacity of Poyang Lake. The simulation results revealed that, the water level at Xingzi, Duchang, Tangyin and Kangshan Station and the reservoir capacity of Poyang Lake exhibited relatively good correlation (with $R^2 > 0.90$), except for Tangyin Station in normal and dry years. The variation in reservoir capacity, which is very significant from rising stage to recession stage of each typical hydrological year, was relatively minor for Tangyin Station. The correlation equation between water level and reservoir capacity of Poyang Lake was established respectively for wet, normal and dry year ($R^2 > 0.95$) by means of fitting, to minimize the influence of factors like lake surface gradient. This model enables more accurate and quicker calculation of the reservoir capacity as well as the dynamic reservoir capacity of Poyang Lake at present and in the future (after Poyang lake water conservancy hub project is completed). In addition, the method provided a theoretical reference for accurate, dynamic and quick calculation of the reservoir capacity for other lakes and reservoirs.

Key Words: Poyang Lake, EFDC Model, Dynamic Reservoir Capacity, Water Level

1. Introduction

Poyang Lake is the largest freshwater lake in China and one branch of the Yangtze River system. It has special biological functionality including flood control and maintaining biological diversity. Poyang Lake plays an important role in safeguarding the regional and national ecological safety. Dynamic reservoir capacity was an important parameter for agriculture irrigation, water supply, aquatic ecological environment, wetland ecological environment, etc. The highly dynamic characteristics of water level in Poyang Lake lead to the unique lake-wetland landscape and biological structure [1]. Since 2003, influenced by reduced inflows and changes of water resources along Yangtze River, Poyang Lake has experienced early occurrence and prolonged dry season, low water level, etc. [2], which will affect the reservoir capacity of Poyang Lake unavoidably.

Poyang Lake has a vast area of water surface with a unique morphology of “calabash”, which varies significantly with water level at rising and recession stage. Poyang Lake is 50~60 km from east to west, 110 km...
from south to north whistle only 5~15 km as narrowest at the north. As an open lake, the rise/drop of water level at Poyang Lake is subject to the inflows from the five rivers and the jacking effect of the Yangtze River, which vary dramatically at different time of the year and from year after year. In particular, as the water level drops, the difference of water levels at the four hydrologic stations increases. Under different inflow conditions, the same water level corresponds to different surface area and reservoir capacity. With the increase of the hydraulic head of Poyang Lake and the complexity of the lake floor topography, it is more difficult to simulate the water level-reservoir capacity correlation. All of these present challenges in the estimate of lake reservoir capacity, an important parameter describing the special biological functionality of the lake.

In recent years, extensive research has been conducted on the calculation of the reservoir capacity of lakes. Sheng et al. [3] estimated water volume changes in lakes and reservoirs from the four satellite altimetry database (i) global reservoir and lake monitoring (GRLM); (ii) river lake hydrology (RLH); (iii) hydroweb and (iv) ICESat-GLAS level 2 global land surface altimetry data (ICESat-GLAS) in combination with Landsat TM/ETM + imagery data. Rodrigues et al. [4] developed a simple method to estimate reservoir storage volumes based on remotely sensed reservoir surface area measured with LANDSAT. Yao et al. [5] deduced an empirical equation of the lake volume-area relationship based on multi-source remote-sensing images from Landsat MSS, Landsat TM/ETM + and Terra ASTER and a topographic map, which were digitized to delineate the outlines of the lake between 1977 and 2009. Sattari et al. [6] calculated the minimum reservoir volume of Keyserk reservoir by GAMS (general algebraic modeling system) software model. Tan et al. [7] used Thiessen polygon to divide Poyang Lake into several subzones based on the water level differences resulting from variations of hydrologic regimes, and calculated the surface area and volume of each subzone, which were used to develop the elevation (at the lake basin) - surface area - reservoir capacity correlation as well as the water level-reservoir capacity correlation of Poyang Lake under dynamic hydrologic conditions.

Poyang Lake is a highly dynamic lake, which acts as lake at high water levels and river at low water levels. The hydrologic regimes lead to various water gradients, and the gradients during the water level rise and recession are significantly different. Moreover, the monitoring sites in the lake area are rare and uniformly distributed, which all lead to great uncertainty when calculating the capacity of the lake using DEM (digital elevation model) and water level documentary. Based on the definition of lake characteristics and reservoir capacity [8], the capacity in this study is the total water quantity from the lake inlets to the seven inlets of the remotest backwater cross-section. The precision and work burden involved in the calculation of the reservoir capacity of Poyang Lake still require further improvement and reduction. Hydrodynamic model, a critical tool for quantitative analysis on flow regimes [9], which minimizes the influence of water level differences and complicated floor topography by means of high resolution simulation, is capable of quick simulation of the variations in flow regimes of river and lake system. In this study, based on the previous study by Lai et al. [10] and Hu et al. [11] calculated that Poyang Lake was a shallow lake. Few studies reported about the reservoir capacity calculated by EFDC. Therefore, a two-dimensional hydrodynamic model based on EFDC was developed to calculate the reservoir capacity and establish the dynamic correlation between varying water level and reservoir capacity of Poyang Lake. This study will provide theoretical basis for further quantitative analysis on water resources and aquatic ecological environment of Poyang Lake.

2. Methodology

The Environmental Fluid Dynamics Code (EFDC), a modeling package developed by John Hamrick at Virginia Institute of Marine Science (VIMS) at the college of William and Mary [12], is a hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions [13]. It has evolved over the past two decades to become one of the most widely used hydrodynamic models in the world [14–16]. EFDC uses stretched or sigma vertical coordinates and Cartesian or curvilinear, orthogonal horizontal coordinates to represent the physical characteristics of a water body. The EFDC model allows for drying and wetting in shallow
areas by a mass conservation scheme. EFDC was developed by FORTRAN language with an open source, thus it can be modified properly and already has been widely applied [17]. In addition, the model is a highly recommended hydrodynamic model by the US Environmental Protection Agency [18].

Based on simulation results, the daily hydrological station monitoring level corresponding to dynamic capacity was calculated based on the equation below:

$$V_i = \sum_{j=1}^{k} D_{dry,ij} \times S_j$$  \hspace{1cm} (1)

where, $V_i$ = the lake storage capacity on day $i$; $D_{dry,ij}$ = the water depth of grid cell; $S_j$ = the area of grid cell No. $j$.

### 2.1 The Governing Equations for EFDC Hydrodynamic Model

EFDC model includes a set of equations based on three-dimensional incompressible, variable density liquid with turbulent boundary layer. Boussinesq hypotheses are utilized to deal with the momentum resulting from the variable density. After these two coordinate transformations, the momentum equation and continuity equations are as follows:

The momentum equations are:

$$\frac{\partial (m_Hu)}{\partial t} + \frac{\partial (m_HHu)}{\partial x} + \frac{\partial (m_HHv)}{\partial y} + \frac{\partial (mvw)}{\partial z}$$
$$- (mvw) \frac{\partial m}{\partial x} - u \frac{\partial m}{\partial y} = -m_s H \frac{\partial (g_{\rho 0} + p)}{\partial x} - m_l (\frac{\partial h}{\partial x} - z \frac{\partial H}{\partial x}) + \frac{\partial}{\partial z} (m \frac{1}{H} A_r \frac{\partial y}{\partial z}) + Q_v$$  \hspace{1cm} (2)

$$\frac{\partial (m_HHv)}{\partial t} + \frac{\partial (m_HHu)}{\partial x} + \frac{\partial (m_HHv)}{\partial y} + \frac{\partial (mvw)}{\partial z}$$
$$+ (mvw) \frac{\partial m}{\partial x} - u \frac{\partial m}{\partial y} = -m_s H \frac{\partial (g_{\rho 0} + p)}{\partial y} - m_l (\frac{\partial h}{\partial y} - z \frac{\partial H}{\partial y}) + \frac{\partial}{\partial z} (m \frac{1}{H} A_r \frac{\partial x}{\partial z}) + Q_v$$  \hspace{1cm} (3)

$$\frac{\partial p}{\partial z} = -gH \frac{\partial \rho_0}{\partial z} = -gHb$$  \hspace{1cm} (4)

The continuity equations are:

$$\frac{\partial (m_H)}{\partial t} + \frac{\partial (m_Hu)}{\partial x} + \frac{\partial (m_HHv)}{\partial y} + \frac{\partial (mvw)}{\partial z} = 0$$  \hspace{1cm} (5)

$$\frac{\partial (m_HHv)}{\partial t} + \frac{\partial (m_HHu)}{\partial x} + \frac{\partial (m_HHv)}{\partial y} + \frac{\partial (mvw)}{\partial z} = 0$$  \hspace{1cm} (6)

$$\rho = \rho(p, S, T)$$  \hspace{1cm} (7)

where, $u$, $v$, $w$ are horizontal velocity components in the boundary-fitted orthogonal curvilinear coordinate, $x$-, $y$- and $z$-directions respectively; $m_s$ and $m_l$ are the horizontal curvilinear coordinate scale factors; $m = m_s m_l$ is the square roots of the diagonal components of the metric tensor; $A_r$ is the vertical turbulent diffusivity; $f$ is the Coriolis parameter; $P$ is pressure; $\rho$ is the water density; $\rho_0$ is the reference density; $S$ is salinity; $T$ is temperature; $Q_v$ and $Q_v$ are momentum source-sink terms.

### 2.2 Two-dimensional Hydrodynamic Model for Poyang Lake

A two-dimensional model was also used in this study for simplification and computational efficiency. The Mellor-Yamada level 2.5 turbulence closure schemes were employed in the model [19]. Based on the remote sensing images obtained at flooding stage in 1998 and the GIS data of the embankment of Poyang Lake, the maximum surface area of Poyang Lake was calculated. Poyang Lake was therefore divided into 96,004 grid cells using orthogonal curvilinear grid, with grid cell resolution ranging between 178 m-205 m, and the orthogonality parameter of the grid cell being less than 0.2 (Figure 1). The flow boundary in the model was set up using daily inflow data (m$^3$/s) recorded at hydrological stations on the five tributaries of Poyang Lake (Figure 1). Those hydrological stations included respectively Hukou, Xingzi, Duchang, Tangyin, Kangshan, and Wucheng, Hukou is the lake’s only outlet. Little groundwater data is accessible in study area. Furthermore, groundwater only accounts for 1.3% of the total water balance in Poyang Lake [20], therefore groundwater is neglected in the model. The open boundary was set up using the daily water level records (using meter units and the elevation of the Yellow Sea) at Hukou station. The other boundary conditions were expressed by time-related...
meteorological conditions, including daily precipitation, wind speed and direction, air temperature, air pressure, relative humidity, and cloud cover collected at the seven hydrologic stations mentioned above.

The lake floor topography adopted the data measured in field in 2010 (with scale of 1:25000). The upper boundary conditions of the model adopted the daily flow measurements (m^3/s) at 7 lake inlets including Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, Duhangfeng from the five rivers. The lower boundary adopted the daily water level measurements at the lake outlet (m, based on Yellow Sea elevation). According to the EFDC of the cell dry and wet transformation threshold judgment, for the wetting and drying feature of the model, the calibrated main parameters of the model are shown in Table 1. Parameters not shown in Table 1 include the dry depth of 0.10 m and the dry step of 16 s. An adaptive time step was used in the simulation, and its basic time step was 1s.

2.3 Model Calibration and Validation

To improve the simulation performance of the model at high water and low water level as well as the efficiency for calibration of model parameters, a period of 8 months starting from November 1, 1999 to July 31, 2000, which covers both wet year and dry year, was selected as the model parameter calibration period. The model validation period was from January 1, 1999 to December 31, 2003 (5 years). Model validation was performed by comparing the simulated water level with the data observed at Xingzhi, Duchang, Tangyin, and Kangshan Station, which are located respectively in the south and the north of Poyang Lake (Figure 1). The standard deviation, relative deviation, RMS deviation and Nash-Stucliffe efficiency factor are summarized in Table 2 [21].

In order to validate the calibrated parameters of the model, the five years from 1 January 1999 to 31 December 2003 were selected as the model verification duration. The model was verified by using continuously measured daily water levels at four hydrological stations Xingzi, Duchang, Tangyin, and Kangshan. Figure 2 provides the comparison of measured water levels and simulated water levels at the four verification sites during the verification period of the model. Ten variables were included in a subsequent error analysis and the results are shown in Table 2. Mean absolute error in Table 2 is the average value of the difference between daily measured water level and simulated water level.

The daily measured flow velocity and flow direction datasets were not available for the study area. Two datasets of flow velocity and flow direction at eight sites (see

Table 1. Calibrated parameters and optimal values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial value</th>
<th>Bounds</th>
<th>Calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom roughness height (m)</td>
<td>0.2</td>
<td>0.01–0.4</td>
<td>0.2 for lake bed; 0.25 for floodplain</td>
</tr>
<tr>
<td>Horizontal eddy viscosity (m²/s)</td>
<td>0.1</td>
<td>0.01–0.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Wet depth (m)</td>
<td>0.1</td>
<td>0.01–0.2</td>
<td>0.06</td>
</tr>
</tbody>
</table>
V1–V8 in Figure 1) were used to validate the simulated results. This data was collected by the Water Resources Department of Jiangxi Province during a low water level period (28–29 December 2010) and a high water level period (9–11 October 2010). The position, observation date, flow velocity, flow direction, and related validation information at the 8 sites are shown in Table 3. The two values in the bracket in column 4 of Table 3 refer to the two simulated velocity components in the x and y directions, respectively.

From Figure 2 and Table 2 it can be seen that the mean error at the four sites varied from 0.234 m to 0.393 m, the relative error ranged from 2.062% to 3.353%, the RMS error ranged from 0.303 to 0.513, and the Nash-Stucliffe efficiency coefficient ranged from 0.950 to 0.989. The errors of Xingzi site and Duchang site were proximate to each other. The errors of Tangyin and Kangshan exhibited a large difference, which might be related to a mismatch between the grid size and topographic variability in Tangyin and Kangshan. Compared with the bed topography of other sites, the bed topographies of Tangyin and Kangshan were more complex with greater elevation variability (Figure 1). Furthermore, the grids of the model had coarser resolution in Kangshan as compared with those of other sites (Figure 3(b)), thus the resolution of the grids in Tangyin and Kangshan did not properly reflect the elevation variability of the actual topography. In addition, the measured water levels of Kangshan from November 1999 to May 2000, from December 2000 to May 2001, from December 2001 to May 2002, and from December 2002 to April 2003 were highly variable (Figure 2), while the simulated water levels of were generally stable. This might be because the terrain was flattened after interpolation. A combination of the two causes above resulted in significant error between the measured value and simulated value at the Kangshan site.

### Table 2. Deviation analysis for model validation

<table>
<thead>
<tr>
<th>Item</th>
<th>Average water level measurements (m)</th>
<th>Average water level simulated (m)</th>
<th>Standard deviation</th>
<th>Relative deviation</th>
<th>RMS deviation</th>
<th>Nash-Stucliffe efficiency factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xingzi</td>
<td>11.182</td>
<td>11.412</td>
<td>0.233</td>
<td>2.592</td>
<td>0.334</td>
<td>0.984</td>
</tr>
<tr>
<td>Duchang</td>
<td>11.887</td>
<td>11.958</td>
<td>0.160</td>
<td>1.523</td>
<td>0.229</td>
<td>0.988</td>
</tr>
<tr>
<td>Tangyin</td>
<td>12.550</td>
<td>12.316</td>
<td>0.284</td>
<td>2.369</td>
<td>0.366</td>
<td>0.950</td>
</tr>
<tr>
<td>Kangshan</td>
<td>13.165</td>
<td>13.229</td>
<td>0.351</td>
<td>2.792</td>
<td>0.459</td>
<td>0.852</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Simulated highest water level (m)</th>
<th>Average absolute error (m)</th>
<th>Average relative error (%)</th>
<th>RMS error</th>
<th>Nash-Stucliffe efficiency coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xingzi</td>
<td>20.046</td>
<td>0.234</td>
<td>2.478</td>
<td>0.351</td>
<td>0.989</td>
</tr>
<tr>
<td>Duchang</td>
<td>20.070</td>
<td>0.221</td>
<td>2.062</td>
<td>0.303</td>
<td>0.988</td>
</tr>
<tr>
<td>Tangyin</td>
<td>20.070</td>
<td>0.393</td>
<td>3.353</td>
<td>0.513</td>
<td>0.950</td>
</tr>
<tr>
<td>Kangshan</td>
<td>20.070</td>
<td>0.321</td>
<td>2.481</td>
<td>0.412</td>
<td>0.951</td>
</tr>
</tbody>
</table>

![Figure 2. Observed and simulated daily water level for model validation.](image)
According to Table 3, the site with the maximum error was V8 (December 29). The V8 error and relative error were 0.403 m/s and 30.3%, respectively. The site with the minimum error was V3 (October 11), and its error and relative error was -0.017 m/s and -3.8%, respectively. For flow direction, the site with the maximum error (37.3°) was V8 (December 29) and the site with the minimum error (0.9°) was V2 (December 28). The mean error of velocities at the eight sites was 0.106 m/s, the mean relative error was 13.3%, and the mean error of flow direction was 7.8°. According to further analysis, the mean error of the velocity in the high water level period was 0.054 m/s, the mean relative error was 12.9%, and the mean error of flow direction was 5.8°. In the low water level period (December), the mean error of the velocity was 0.158 m/s, the relative error was 13.8%, and the mean error of flow direction was 9.9°. This indicates that the velocity and flow direction errors for the simulation

Table 3. Verification of current velocity and direction

<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
<th>Measured flow velocity (m/s)</th>
<th>Simulated flow velocity (m/s) (x, y)</th>
<th>Error</th>
<th>Relative error (%)</th>
<th>Measured flow direction (degree)</th>
<th>Simulated flow direction (degree)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 10</td>
<td>V1</td>
<td>0.104</td>
<td>0.131 (0.064, 0.114)</td>
<td>-0.027</td>
<td>-26.0</td>
<td>37.7</td>
<td>29.3</td>
<td>8.4</td>
</tr>
<tr>
<td>Oct. 9</td>
<td>V2</td>
<td>0.537</td>
<td>0.419 (-0.210, 0.363)</td>
<td>0.118</td>
<td>22.0</td>
<td>338.9</td>
<td>330.0</td>
<td>8.9</td>
</tr>
<tr>
<td>Oct. 11</td>
<td>V3</td>
<td>0.445</td>
<td>0.462 (-0.178, 0.426)</td>
<td>-0.017</td>
<td>-3.8</td>
<td>325.9</td>
<td>337.3</td>
<td>-11.4</td>
</tr>
<tr>
<td>Oct. 10</td>
<td>V4</td>
<td>0.387</td>
<td>0.332 (-0.208, 0.259)</td>
<td>0.055</td>
<td>14.2</td>
<td>323.2</td>
<td>321.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Oct. 9</td>
<td>V5</td>
<td>0.397</td>
<td>0.373 (0.345, 0.338)</td>
<td>0.024</td>
<td>6.0</td>
<td>39.7</td>
<td>45.6</td>
<td>-5.9</td>
</tr>
<tr>
<td>Oct. 10</td>
<td>V6</td>
<td>0.744</td>
<td>0.692 (-0.662, 0.201)</td>
<td>0.052</td>
<td>7.0</td>
<td>294.6</td>
<td>286.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Oct. 11</td>
<td>V7</td>
<td>0.600</td>
<td>0.480 (-0.308, 0.368)</td>
<td>0.120</td>
<td>20.0</td>
<td>321.5</td>
<td>320.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Oct. 11</td>
<td>V8</td>
<td>0.500</td>
<td>0.479 (-0.063, 0.475)</td>
<td>0.021</td>
<td>4.2</td>
<td>353.7</td>
<td>352.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Measured flow velocity (m/s)</th>
<th>Simulated flow velocity (m/s) (x, y)</th>
<th>Error</th>
<th>Relative error (%)</th>
<th>Measured flow direction (degree)</th>
<th>Simulated flow direction (degree)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 28</td>
<td>V1</td>
<td>0.515</td>
<td>0.473 (0.244, 0.407)</td>
<td>0.042</td>
<td>8.2</td>
<td>37.3</td>
<td>30.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Dec. 28</td>
<td>V2</td>
<td>0.791</td>
<td>0.728 (0.098, 0.701)</td>
<td>0.063</td>
<td>8.0</td>
<td>8.9</td>
<td>8.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Dec. 28</td>
<td>V3</td>
<td>1.060</td>
<td>1.10 (-0.222, 1.079)</td>
<td>-0.040</td>
<td>-3.8</td>
<td>341.4</td>
<td>348.4</td>
<td>-7.0</td>
</tr>
<tr>
<td>Dec. 29</td>
<td>V4</td>
<td>1.050</td>
<td>0.941 (-0.559, 0.757)</td>
<td>0.109</td>
<td>10.4</td>
<td>321.3</td>
<td>323.6</td>
<td>-2.3</td>
</tr>
<tr>
<td>Dec. 29</td>
<td>V5</td>
<td>1.190</td>
<td>1.05 (0.722, 0.768)</td>
<td>0.140</td>
<td>11.8</td>
<td>43.3</td>
<td>46.33</td>
<td>3.0</td>
</tr>
<tr>
<td>Dec. 29</td>
<td>V6</td>
<td>1.040</td>
<td>0.942 (-0.559, 0.757)</td>
<td>0.098</td>
<td>9.4</td>
<td>326.5</td>
<td>323.6</td>
<td>2.9</td>
</tr>
<tr>
<td>Dec. 28</td>
<td>V7</td>
<td>1.290</td>
<td>0.923 (-0.564, 0.731)</td>
<td>0.367</td>
<td>28.4</td>
<td>341.4</td>
<td>322.4</td>
<td>19.0</td>
</tr>
<tr>
<td>Dec. 29</td>
<td>V8</td>
<td>1.330</td>
<td>0.927 (-0.572, 0.731)</td>
<td>0.403</td>
<td>30.3</td>
<td>359.4</td>
<td>322.1</td>
<td>37.3</td>
</tr>
</tbody>
</table>

Figure 3. Parameters of the Poyang Lake hydrodynamic model (a) Orthogonality; (b) resolution (m).
results in the high water level period (October) were lower than those in the low water level period. To better verify the reliability of the simulation results, it is necessary to contrast the spatial distribution of water, i.e., the simulated water surface in contrast to the actual water surface.

Figure 4 shows the comparison between two groups of simulated lake water depth distributions and lake water surfaces from remote sensing images taken during low/high water level periods. Figure 4(a) and (b) illustrate the simulated water depth distribution on 10 December 1999 and the lake water surface from the remote sensing image taken on the same date, respectively. Figure 4(c) and (d) refer to the simulated water depth distribution of the lake on 23 September 2000 and the remote sensing image of the water surface on the same date, respectively. According to the comparisons of Figure 4(a) with (b) and (c) with (d), the simulated water surfaces and the actual water surfaces exhibit a high level of correspondence.

Reference to the middle reaches of the Yangtze River lake river lake relationship evolution process and mechanism (2012CB417001) typical year selected Research Report, Based on the measured hydrological data of the main control station, combined with the selection of typical year requirements, the hydrological year classification for Poyang Lake (including wet, normal and dry year) in the recent 10 years as defined by hydrological sector in Jiangxi Province, year 2005, 2006 and 2010 were selected respectively as typical wet, normal and dry year for simulation. By high-resolution simulation of the reservoir capacity based on EFDC model, the relationship between the water level and the reservoir capacity in typical hydrological years was simulated, and the dynamic correlation equation for water level-reservoir capacity of Poyang Lake was established.

3. Simulation Results and Analysis

3.1 Analysis on the Correlation of Monitoring Water Level of Each Hydrologic Station and the Simulated Reservoir Capacity of Poyang Lake

Correlation analysis was conducted on the water level of each hydrologic station and the reservoir capacity calculated based on EFDC model for each typical hydrologic year. The correlation equations and correlation coefficient (which were established based on EFDC model) for the each station respectively in dry, normal and wet year are summarized in Table 4. The correlation between water level at each hydrologic station and the reservoir capacity of Poyang Lake for each typical hydrologic year is presented in Figure 1.

As can be seen in Table 4 and Figure 5 in dry year, water level-reservoir capacity correlation coefficient for Xingzhi, Duchang, Tangyin and Kangshan Station is respectively at 0.94, 0.95, 0.95 and 0.79, with the highest correlation coefficient occurring at Duchang and Tangyin station. In normal year, the correlation coefficient is respectively at 0.93, 0.92, 0.93 and 0.70, with the highest correlation coefficient occurring in Xingzi and Tangyin station; whereas in wet year, the correlation coefficient is respectively at 0.96, 0.97, 0.96 and 0.92, with the highest correlation coefficient occurring in Duchang Station. The correlation coefficient decreases in turn from wet year, dry year to normal year.

Figure 4. Comparison between simulated lake surface and water surface in satellite image (a) Simulated water surface of Dec. 10, 1999; (b) satellite image of water surface on Dec. 10, 1999; (c) Simulated water surface of Sep. 23, 2000; (d) satellite image water surface on Sep. 23, 2000.
At different hydrologic years, the water levels of the hydrologic stations in the middle of Poyang Lake have the best correlations with their capacity, while water levels of Kangshan station located in the upstream of Poyang Lake has a low correlation with the water level and capacity of the outlet hydrologic station named Xingzi. Therefore, quick and accurate calculation of reservoir capacity of Poyang Lake can be achieved by selecting corresponding water level-reservoir capacity correlation equation, depending on the hydrologic year classification.

### 3.2 Analysis on Correlation of Water Level and Reservoir Capacity Respectively for Rising and Recession Stage

Due to the significant water level fluctuations and complicated floor topography, Poyang Lake is characterized by two hydrologic stages, including rising and recession stage. The correlation between water level and

<table>
<thead>
<tr>
<th>Typical hydrologic year</th>
<th>Hydrologic station</th>
<th>Water level - reservoir capacity correlation equation (Unit: storage $10^8$m$^3$, level m)</th>
<th>Correlation coefficient ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry year</td>
<td>Xingzhi</td>
<td>$y = 12.92e^{0.13x}$</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Duchang</td>
<td>$y = 9.93e^{0.15x}$</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Tangyin</td>
<td>$y = 1.03e^{0.31x}$</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Kangshan</td>
<td>$y = 0.16e^{0.41x}$</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Xingzhi</td>
<td>$y = 10.21e^{0.15x}$</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Duchang</td>
<td>$y = 15.17x - 126.84$</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Tangyin</td>
<td>$y = 1.03 e^{0.20x}$</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Kangshan</td>
<td>$y = 26.50x - 316$</td>
<td>0.70</td>
</tr>
<tr>
<td>Normal year</td>
<td>Xingzhi</td>
<td>$y = 10.21 e^{0.1567x}$</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Duchang</td>
<td>$y = 7.17 e^{0.18x}$</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Tangyin</td>
<td>$y = 1.44 e^{0.28x}$</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Kangshan</td>
<td>$y = 32.35x - 399.92$</td>
<td>0.92</td>
</tr>
<tr>
<td>Wet year</td>
<td>Xingzhi</td>
<td>$y = 32.35x - 399.92$</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Duchang</td>
<td>$y = 7.17 e^{0.18x}$</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Tangyin</td>
<td>$y = 1.44 e^{0.28x}$</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Kangshan</td>
<td>$y = 32.35x - 399.92$</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Figure 5. Correlation of water level at each hydrologic station and the reservoir capacity of Poyang Lake in different hydrologic years.
the reservoir capacity respectively at rising and recession stage of each typical hydrologic year for the four hydrologic stations is presented in the figure below.

3.2.1 Correlation of Water Level at Each Hydrologic Station and the Reservoir Capacity of Poyang Lake Respectively at Rising and Recession Stage in Dry Year

As can be observed from Figure 6, the water level and the reservoir capacity exhibit relatively good correlation ($R^2 > 0.90$) at both rising and recession stage for Xingzi, Duchang, Tangyin Station, whereas the correlation for Kangshan station is relatively poor ($0.90 > R^2 > 0.80$). The reservoir capacity of Poyang Lake varies from rising stage to recession stage in dry year. Based on the water level-reservoir capacity correlation for Xingzi and Duchang Station, the storage capacity corresponding to the same water level at rising stage is higher than at recession stage.

For Tangyin Station, the reservoir capacity respectively at rising and recession stage have a point of intersection (corresponding to water level of 14 m), above which the reservoir capacity at rising stage is higher than at recession stage, below which the result is opposite. Based on the water level-reservoir capacity correlation for Kangshan Station, the reservoir capacity at rising stage is lower than at recession stage when the water level is lower than 16.2 m, and the result is opposite when the water level is higher than 16.2 m.

3.2.2 Correlation of Water Level at Each Hydrologic Station and the Reservoir Capacity of Poyang Lake in Normal Year

As can be observed from Figure 7, water level at Xingzi, Duchang, and Tangyin Station and the reservoir capacity of Poyang Lake exhibit a good correlation ($R^2 > 0.9$) both at rising and recession stage, whereas the water level at Kangshan Station and the reservoir capacity of Poyang Lake exhibit a poorer correlation ($0.9 > R^2 > 0.75$). For Xingzi Station, when the water level is lower than 13.3 m, the reservoir capacity corresponding to the same water level at rising stage is higher than at recession stage, and the result is opposite when the water level is higher than 13.3 m. The difference between reservoir capacity at rising and recession stage is not significant for Xingzi, Duchang, and Tangyin Station. Based on the correlation equation for Kangshan Station, the reservoir capacity corresponding to the same water level at rising stage is lower than at recession stage when the water level is lower than 15.8 m, and the result

![Figure 6. Correlation of water level at each hydrologic station and the reservoir capacity of Poyang Lake respectively at rising and recession stage in dry year.](image-url)
is opposite when the water level is higher than 15.8 m.

3.2.3 Correlation of Water Level at each Hydrologic Station and the Reservoir Capacity of Poyang Lake in Wet Year

It can be observed from Figure 8, the water level and the reservoir capacity exhibited a relatively good correlation ($R^2 > 0.95$) both at rising and recession stage for Xingzi, Duchang, Tangyin Station. For Xingzi, Duchang and Tangyin Station, the reservoir capacity corresponding to the same water level at rising stage appeared above that at recession stage, suggesting the reservoir capacity

Figure 7. Correlation between water level and reservoir capacity at rising and recession stage in normal year.

Figure 8. Correlation between water level and reservoir capacity at rising and recession stage in wet year.
at rising stage is higher than at recession stage. Based on water level-reservoir capacity correlation equations for Kangshan Station, the reservoir capacity at rising stage is lower than at recession stage when the water level is lower than 16.6 m, and the result is opposite when the water level is higher than 16.6 m.

According to analysis on the correlation of water level at each hydrologic station and the reservoir capacity of Poyang Lake respectively at rising and recession stage of each typical hydrologic year, the water level and reservoir capacity correlation coefficient at both rising and recession stage decreases in turn from wet, normal to dry year. The difference of reservoir capacity at rising and recession stage is larger in dry year, but smaller in normal year and wet year. For Xingzi, Duchang, Tangyin and Kangshan Station, the water level-reservoir capacity correlation curves respectively at rising and recession stage intersect in a counter-clockwise manner, with the intersection for Tangyin or Kangshan Station occurring at water level of 15–17 m, probably due to the influence by the topography and lake floor orographical characteristics of Poyang Lake. This suggests that both the volume and the characteristics of inflows have influence over the calculation of the reservoir capacity of Poyang Lake.

3.3 Difference of the Reservoir Capacity at Rising and Recession Stage in Each Typical Hydrologic Year

The annual variation of the reservoir capacity of Poyang Lake was simulated to analyze its correlation with the water level at Xingzi, Duchang, Tangyin and Kangshan respectively at rising and recession stage of each typical hydrologic year. The correlation is presented in Figure 9–11.

As can be observed in Figure 9, in wet year, four obvious rising-recession cycles were observed at Poyang Lake, during which, the reservoir capacity and water level at each hydrologic station exhibited a similar variation pattern: i.e., the reservoir capacity at rising stage is higher than at recession stage, with the difference of reservoir capacity decreasing in turn from Xingzi, Duchang, Tangyin to Kangshan Station. In wet year, the influence on water level-reservoir capacity correlation due to inflows from the five rivers and the jacking effect due to backwater from Yangtze River was not significant, no matter at rising stage or recession stage. In wet year, as the difference of reservoir capacity about 3-30 \times 10^8 \text{ m}^3, at rising and recession stage is relatively significant for Kangshan and Duchang Station, it is more rational to calculate the reservoir capacity based on the...
water level at Tangyin and Xingzi Station.

As shown in Figure 10, three obvious rising-recession cycles were observed at Poyang Lake in normal year. For Xingzi and Duchang Station, the reservoir capacity corresponding to the same water level at rising stage is higher than at recession stage, with the difference of reservoir capacity decreasing with the increase of water level, with a difference of $25 \times 10^8$ m$^3$. For Tangyin Station, the difference of reservoir capacity at rising and recession stage is relatively small. Whereas for Kangshan
Station, the reservoir capacity at rising stage is lower than at recession stage, and the difference of reservoir capacity caused by the inflows from five rivers (depending on the type and duration of rising and recession stage) is relatively large. In normal year, the reservoir capacity of Poyang Lake can be better simulated by using the water level-reservoir capacity correlation equation for Tangyin Station.

As can be observed in Figure 11, in dry year, three obvious rising-recession cycles were observed at Poyang Lake. For Xingzi, Duchang and Tangyin Station, the reservoir capacity corresponding to the same water level at rising stage is higher than at recession stage, with the difference decreasing in turn from Xingzi, Duchang to Tangyin station. For Kangshan Station, the reservoir capacity corresponding to the same water level at rising stage is lower than that at recession stage, with a difference of \(28 \times 10^8 \text{ m}^3\). The difference of reservoir capacity at rising and recession stage caused by the jacking effect of backwater of Yangtze river is not significant, whereas that caused by inflows from five rivers is relatively significant. In dry year, the reservoir capacity of Poyang Lake can be better simulated by using the water level-reservoir capacity correlation equation for Tangyin Station.

By quantitative analysis on the rising and recession stage of Poyang Lake in typical wet, normal and dry years, and the establishment of the water level-reservoir capacity correlation at different hydrologic monitoring points, the variation of reservoir capacity of Poyang Lake under different lake morphologies was determined. The impact of rising and recession stage on the reservoir capacity of Poyang Lake is more significant in normal and dry year, but less significant in wet year. When calculating the reservoir capacity of Poyang Lake, the impact of rising and recession stage on reservoir capacity shall be taken into account. In wet, normal and dry years, the difference of reservoir capacity at rising and recession stage for Tangyin Station is minor.

3.4 Multiple Linear Regression Analysis on the Water Level and the Reservoir Capacity of Poyang Lake

Multiple linear regression method was used to establish the multiple linear regression equation for the reservoir capacity and the water levels at all the four hydrologic stations. The multiple linear regression equation for each typical year is given as below:

\[
V = L_1 \times 4.72 - L_2 \times 7.32 + L_3 \times 27.94 - L_4 \times 9.07 - 142.94 \quad (8)
\]

\[
V = L_1 \times 0.68 - L_2 \times 8.34 + L_3 \times 5.17 - L_4 \times 6.48 - 210.66 \quad (9)
\]

\[
V = L_1 \times 18.25 - L_2 \times 26.73 + L_3 \times 31.41 + L_4 \times 3.37 - 290 \quad (10)
\]

where \(V\) is the lake reservoir capacity (\(10^8 \text{ cubic meters}\)); \(L_1, L_2, L_3\) and \(L_4\) are the water level respectively at Xingzi, Duchang, Tangyin and Kangshan Station (meters).

As shown Equations 8, 9 and 10, the multiple linear regression equations respectively for typical wet, normal and dry year, which were established based on the water levels at all the four hydrologic stations and the reservoir capacity simulated, exhibit good correlation (\(R^2 > 0.90\)), with \(R^2\) decreasing in turn from normal year, wet year to dry year. In dry year, the water levels at Tangyin and Kangshan Station have most significant impact in calculation of the reservoir capacity. In normal year, the water levels at Duchang and Kangshan Station have most significant impact in calculation of the reservoir capacity. Whereas in wet year, the water levels at Duchang and Tangyin have most significant impact in calculation of the reservoir capacity. The reservoir capacity-water level multiple linear correlation equations respectively for typical wet, normal and dry year were established based on EFDC model (Equations 8, 9 and 10) for quick and accurate calculation of the reservoir capacity of Poyang Lake.

Combined with Table 4, correlations of the multiple linear regressions between water level and capacity at the four hydrologic stations are respectively lower in dry year than that in Duchang and Tangyin, higher at normal year than that in Tangyin and similar with that in

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Duchang. Different calculations of capacity can be done based on the hydrologic years, especially for that in dry and normal year. The correlation between water levels and capacity in each hydrologic stations at wet and normal year are lower the multiple linear regression equation, which reveals that, estimating the reservoir capacity of Poyang Lake based on the water level of any individual hydrologic station is inaccurate, mainly because of the complicated floor topography of the lake.

Lu et al. [22] calculated the capacity of the Three Gorges Reservoir based on the topography DEM dataset by means of GIS and hydraulics. Chen et al. [23] put forward new approaches to calculate dynamic capacity based on the three-dimensional pixel surface via remote sensing, GIS and spatial information technology. Tan et al. [7] also got the reservoir capacity of Poyang Lake via differentiation analysis based on differential and integral calculus and Thiessen polygon theory. However, all the methods cannot get the real time capacity. Based on the correlation between the water level of each individual hydrologic station and the reservoir capacity of Poyang Lake in each typical hydrologic year (as shown in Table 4), and the correlation equations between water levels of all the four hydrologic stations and the reservoir capacity of Poyang Lake in each typical hydrologic year (as shown in Equations 7, 8 and 9), the correlation coefficient for water level and the reservoir capacity of Poyang Lake based on all the four hydrologic stations is all higher than that based on each individual station. In another word, it is very hard to accurately estimate the reservoir capacity of Poyang Lake based on the water level of any individual hydrologic station, mainly because of the complicated floor topography of Poyang lake (which leans towards Poyang Lake from east, south and west). In recent years, sand, cofferdam and other factors also affect the relationship between hydrological station and storage capacity of the lake. The present study calculated the capacity of Poyang Lake based EFDC model simulations, which may also have uncertainties due to settings of the model boundary and wet-dry interface. It was also found that capacity of Xingzi and Duchang stations were highly influenced by water level fluctuations, especially in dry years. Therefore, the calculation should consider the impact of water level changes in the Poyang Lake.

In addition, such factors as sand mining, construction of cofferdam, etc. may also influence the correlation of water level at each hydrological station and the reservoir capacity. The reservoir capacity of Poyang Lake is simulated based on EFDC model, which is subject to boundary and dry-wet interface setup. Tan Guoliang et al. (2013) established the correlation between the reservoir capacity of Poyang Lake with the water levels at Xingzi and Sheshan Station (within the border of Duchang) by means of differentiation analysis based on differential and integral calculus and Thiessen polygon theory, without taking into account the influence of rising and recession stage on the reservoir capacity. According to simulation results in this study, the water level-reservoir capacity correlation for Xingzi and Duchang Station are subject to significant influence by rising and recession stage especially in normal year and dry years from Figures 9, 10 and 11, the reservoir storage capacity have significance difference in process of rising and recession, Poyang Lake reservoir storage capacity were affected by the typical year, rising and recession process. Therefore, the influence of rising and recession stage shall be taken into account in simulation of the reservoir capacity of Poyang Lake.

This is probably due to floor topography characteristics of Poyang Lake. Poyang Lake entirely slopes from the east, south and west sides to the lake, constituting a huge basin with opening north. Meanwhile, in recent years, sand, cofferdam and other factors also affect the relationship between hydrological station and storage capacity of the lake. The present study calculated the capacity of Poyang Lake based EFDC model simulations, which may also have uncertainties due to settings of the model boundary and wet-dry interface. It was also found that capacity of Xingzi and Duchang stations were highly influenced by water level fluctuations, especially in dry years. Therefore, the calculation should consider the impact of water level changes in the Poyang Lake.

Based on the hydrologic regimes and lake floor topography characteristics of Poyang Lake, EFDC model was established for high precision simulation of the water level-reservoir capacity correlation. The equation for calculation of the reservoir capacity of Poyang Lake respectively in typical wet, normal and dry years was established, and quantitative analysis was conducted on the influence of rising and recession stage on the reservoir capacity of Poyang Lake.

4. Conclusions

(1) The two-dimensional hydrodynamic model built from EFDC model can highly correlate with the dynamic change of water levels, calculate capacity of Poyang Lake with complex dynamics, as well as built the re-
gression between capacity and water levels in Xingzi, Duchang, Tangyin and Kangshan stations. It was found that relationship between water level and capacity are pretty good and related to the hydrologic years.

(2) High resolution calculation of the reservoir capacity of Poyang Lake was conducted using EFDC model, the influence of rising and recession process was quantified, and the correlation between water level at hydrologic station and lake reservoir capacity was established. The results showed that water level at the four hydrologic stations had a close correlation with the reservoir capacity of Poyang Lake both at rising and recession stage. The difference of reservoir capacity at rising and recession stage is minor in high and normal year, but large in dry year. The irregular roping phenomenon was first observed.

(3) Considering the lake surface gradient of Poyang lake, the regression model between water level at the four hydrologic stations and the reservoir capacity of Poyang lake was established. It helped to quickly and accurately calculate the real time reservoir capacity of Poyang Lake in different typical hydrologic years. Moreover, the model can be used in capacity calculation after the Poyang Lake Hub is built, which is fast and accurate as well as provides theoretical basis for the integrated management of water resources of the lakes and reservoirs.

References


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