Development of a visualization platform oriented to Lake water quality targets management - A case study of Lake Taihu

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Abstract

Lake Taihu is well known for its severe environmental degradation. In previous studies of lake quality target management, the water quality targets were poorly correlated with watershed pollutant reduction, and most studies lacked visualized management platform that covered all elements including lakes, in-lake estuaries, rivers and watershed regions. In this study, a browser/server-based visualization platform for lake quality target management was developed. Five models that covered both the watershed and lake scales were integrated based on two critical functions. First, the proposed method can be used to determine watershed pollutant reduction amounts based on certain lake quality target parameters, such as those for TN, TP, NH3N and COD. Second, the method can simulate the lake quality trends associated with different watershed adjustment plans. The platform was deployed by the Taihu Basin Authority (TBA) of the Ministry of Water Resources. Overall, this platform is a useful tool for watershed-lake environmental management.

1. Introduction

In recent decades, Lake Taihu in China has become seriously polluted due to excessive land exploitation and anthropogenic disturbances in the watershed. Lake eutrophication has been widely reported and has become a serious environmental problem (Duan et al., 2015). Therefore, the control of pollutant discharge in the watershed is a primary focus of the management of water quality targets by environmental administrators (Quinn et al., 2010; Wang, 2002; Zhang et al., 2015).

Various studies and applications of water quality target management have been developed in many countries since the 1980s, including the Rhine total control management program of the European Union (EU), the Japan Tokyo Bay total control program, and the total maximum daily load (TMDL) plan in the United States (U.S.) (USEPA, 2002). Currently, the TMDL plan is widely used worldwide. The TMDL represents the maximum daily load of a certain pollutant that meets a given water quality standard. This approach consists of three critical modules: the pollution load access module, the safety margin module and the emission distribution module (Castronova and Goodall, 2010; Goodall et al., 2011; Kim et al., 2012). Previous studies have suggested that water quality target management should include different factors, such as land use, catchment area, emission reduction units, water quality indicators and reduction measures (H.J. Zhang et al., 2013; S. Zhang et al., 2013). All these factors are linked and require an all-encompassing approach to water quality target management, which is combined at the lake and watershed scales.

In China, the research regarding water quality target management began later than equivalent studies in European countries and the U.S. (USEPA, 2002; Wang et al., 2014). Since 2006, under the impetus of the “11th Five-Year” and “12th Five-Year” plans, many studies have been conducted on the water quality target management of severely polluted large rivers and lakes, including Lake Taihu, Lake Chaohu, the Ganjiang River Basin and the Yellow River Delta (Huang et al., 2010). The studies and applications largely followed the basic framework of the TMDL, and watershed-level scenarios were considered. Recently, water quality target management has been improved from the control of pollutant concentrations in lake water to the control of the amount of pollutant discharge from the watershed (Lei et al., 2013; Meng et al., 2008; Shan et al., 2015). However, some limitations to such studies must be addressed. First, models must be integrated efficiently. A complete approach to water quality target management consists of many factors, including lake pollution concentrations, allowable pollutant discharge amounts, channel transport amounts and watershed output amounts. Mechanistic models that covered all process nodes in the entire watershed and lake region are also necessary (Hu, 2016; Tanentzap et al., 2007). Researchers from developed countries (the U.S., Germany, etc.) have recognized that many complex environmental problems can
benefit from multi-disciplinary analysis using integrated modeling methods (Laniak et al., 2013; Whelan et al., 2014). However, the existing models are relatively independent and lack integration in China, resulted in that the studies of lake quality target management had systematic deficiencies. Second, a visualization platform that includes all the essential factors in watershed-lake management must be developed. Although several computational software platforms have been designed and implemented based on model calculations (e.g., BASINS, HydroModeler, SWAT, etc.) (Castronova et al., 2013; US EPA, 2015; Whelan et al., 2009), none of them includes all the critical factors related to lake quality and watershed environmental management (Whelan et al., 2014). Therefore, a visualization platform that can integrate various models and massive data intelligently is urgently required so that water quality target management can be more conveniently and intuitively used by environmental protection departments (H.J. Zhang et al., 2013; S. Zhang et al., 2013).

With a water surface area of 2338 km² and an average water depth of 1.9 m, Lake Taihu is the third largest freshwater lake in China. Additionally, the basin area of the lake is 36,895 km², and it is located in Jiangsu, Zhejiang, and Anhui Provinces and Shanghai Municipality (Sun and Huang, 1993). The Taihu Basin is one of the most developed regions in China, and it plays a critical role in the national economy. The Taihu Basin is the drinking water source of 59.2 Million people. The per capita GDP reached $112 thousands in 2015, which was 2.3 times than that of the average value in China. However, rapid urbanization and industrialization in recent decades have resulted in the discharge of high nutrient loads and organic wastewater into the river network around the lake. As a result, Lake Taihu has become the most seriously polluted area in China (Kong et al., 2009). Thus, the lake environment management and recovery must start at the watershed scale.

In this study, a browser/server-based visualization platform for water quality target management in Lake Taihu is developed. Both watershed-scale and aquatic-scale models are integrated in the platform. Ultimately, the platform attempts to address the following two tasks: i) determining the reduction amounts of different pollutants in the watershed under certain lake water quality targets and ii) simulating trends in lake water quality based on different watershed pollution sources and channel flow adjustment strategies.

2. Description of the software

2.1. Software framework design

Developing a service operation and visualization platform for Lake Taihu water quality target management (TLWT) was the fundamental objective of this study; the coupling and integration of multiple models are the core methods of TLWT. TLWT aimed at producing an intelligent decision-making platform for watershed-lake pollutant reduction and regulation. The TLWT method was deployed by the Taihu Basin Authority (TBA) of the Ministry of Water Resources, which is the customer organization of the platform. The TLWT method adopts a prevailing browser/server (B/S) structure, and a diagram of the general structure design is shown in Fig. 1.

The platform was designed in accordance with a three-layer architecture, which includes a database layer, an operation layer and a presentation layer (ESRI, 2007). The data layer is used to develop multiple databases using data acquisition, data pre-processing, and data standardization processes. The model layer is the central part of the platform. Six models, including the water quality target model, the inflowing river pollutant transport and transformation model, and the pollutant reduction spatial distribution model, were integrated into this layer. Two complete functional processes were formed by the service standard. One process determines the spatial distribution of the pollutant reduction amount based on a certain lake water quality target (backward estimation), and the other process simulates the changes in lake water quality under different watershed pollution source adjustment plans (forward simulation). These two functions can directly provide decision-making services for the TBA. In the presentation layer, the model integration and calculation results are presented to the platform users. A variety of visual presentation forms, including a geographic information system (GIS) spatial rendering form, statistical charts and tables, and dynamic animations, can be viewed based on the selection of each user.

2.2. Overview of the individual models

Five models were introduced into the platform. And the overview description of each model was represented as following (Table 1):

Model 1: Water quality response to lake ecosystem: The structural dynamic model was developed in order to analyze the temporal tendency of lake quality indicators (TP, TN, CODmn etc), as well as the scale and frequency of algae bloom. The input parameters were the measured aquatic phytoplankton parameters and water quality indices, including phytoplankton respiration rate, nitrogen and phosphorus uptake rate, plant body size and leaf area index. Finally, the change tendency of algae and phytoplankton species can be simulated under different scenes of pollutants' concentration status, which is the premise of divisional lake quality targets determination (Hu et al., 2006; Li et al., 2016).

Model 2: Lake water quality target capacity: The relationship between the revenue, transformation and retention rates of lake pollutants and the lake quality targets under various hydrological and meteorological conditions were analyzed based on Model 2. The atmospheric deposition flux, the meteorological observation data and sediment pollution release were input into the model framework. Finally, the divisional and monthly lake water quality target capacities were calculated for different lake quality indicators and threshold values (Han et al., 2015).

Model 3: Transport and distribution of pollutant flux into the lake: The model was developed based on the Lagrange algorithm, which was used to analyze the transport, diffusion and degradation process for pollutants delivered from estuary into the lake, and then the allowed amounts of pollutants' flux discharged into Lake, as well as the controlled pollutants' concentration in estuary were assigned. The input parameters included the spatial locations of rivers flowing into the lake, lake surface wind field, and pollutants loads in different inflow river sections (Hu and Qin, 2002; Wu et al., 2013).

Model 4: River network pollutant transport and flux tracing: The numerical simulation optimization method and back stepping method were introduced into this model, which was developed to acquire the monthly pollutants self-purification coefficients, and then the attenuation process of pollutants in the river networks can be captured. In order to acquire the parameters including pollutants flux amount and retention & conversion coefficient, the continuous field observation of pollutants' decay retention and pollutants' flux amounts were necessary to launched in typical sections (Lai et al., 2013).

Model 5: Watershed pollutant reduction spatial distribution and optimization: The constrained conditions of controlling indicators were proposed for watershed pollutant reduction allocation, which were used to analyze the water quality and emission reduction cost in constrained watershed ecological function regions. And then the objective function of watershed pollutants' flux and reduction can be operated quantitatively. The watershed massive data support included the watershed socioeconomic development, the aquatic environment observation and water resource supply level were essential in the model and equation framework (Hao et al., 2016a, 2016b).

For all the above, the basic information regarding the model parameters is shown in Table 1. The five models covered the entire watershed region of Lake Taihu, including the upstream watershed region. Specially, three models focused on lake quality, two models focused on the estuary and the river network, as well as the fifth model focused on...
the watershed.

2.3. Overview of model integration

Model integration is the critical driving force of the purpose and function of the platform. The logical and functional relationships among the different models are shown in Fig. 2. Two complete functional processes of the platform are shown: determining the spatial distribution of pollutant reduction amounts based on certain lake water quality targets (backward estimation) and simulating changes in the lake water quality under different watershed pollution source adjustment plans (forward simulation).

In the backward estimation process, five models were interconnected. Specifically, the lake water targets of four selected indicators (total phosphorous (TP), total nitrogen (TN), ammoniacal nitrogen (NH₃N), and chemical oxygen demand (CODMn)) among the
different lake divisions were calculated dynamically based on the “water quality response of the lake ecosystem”, and the four indicator targets were passed to the second model of the “lake water quality target capacity”. Then, the environmental capacities based on different lake water targets were calculated and passed to the subsequent two models, which focus on river networks. Then, the allowable pollutant levels in the main inflow rivers and the necessary pollutant reductions can be obtained from these two models. Finally, the reduction amounts can be assigned to different watershed units. The forward simulation process is simpler than backward estimation, in which two models were integrated. Specifically, the pollution source adjustment plans in the watershed consisted of the river flow amount, the number of inflowing rivers, the pollution source locations and the pollutant discharge amounts. These indicators are used as inputs into the river network pollutant transport and flux tracing models, which are used to calculate the pollutant loads that enter the lake via different tributaries. The results are passed to the lake ecosystem model of the water quality response, which is the first model in the backward estimation process. Finally, the changes in lake indicators are determined using this model.

According to the functional relationships, massive amounts of data were required by the platform and used to run the models. The data can be classified into several types. First, the fundamental geographic data, which include the watershed boundary, transport and upstream elements, the spatial distributions of different lake divisions and the watershed ecological function divisions. Second, monitoring data, which include lake quality data, inflowing river quality data, flow quantity data, sediment data and meteorological data. Third, business data that are in consist of the calculation results of the different models, including the lake quality targets calculation results, the lake quality target capacity results, the River network pollutant transport and flux tracing results, and the watershed pollutant reduction spatial distribution results.

The local plug-in integration method was used in the platform (Fig. 3). Dynamic link library (DLL) files were generated by each model and then integrated in the platform. Additionally, the “standards and specifications of platform files” control was developed by the platform developer. Standards for model input/output data, the interface and method of model integration, and model storage routes were qualified and defined using this control. Firstly, the model output/input interface: The data used in different models included the meteorological data, lake quality data based on a Lake Taihu grid, flow amount data and pollutant concentration data based on different inflowing rivers. Therefore, the multiple data sources required a complex design of the output/input interface. The design allows for the definition of data objects, the reading and writing of data files, and the selection of data visualization forms, which are standardized simultaneously. The designs of input and output interfaces were showed in Table 2, the defined interfaces were including the model start-up interface, the running status interface, and the temporal order interface. These interfaces covered all the elements within the entire calculation process from model pretreatment to results representation. Secondly, the method of model and platform integration: The seamless integration of different models and the TLWT platform relied on several defined and standardized methods, which encompassed the processes of model initialization, execution and calculation (Table 3).

2.4. Software function design

The platform functions were designed according to the actual business requirements of the TBA. Two sub-systems, the pre-processing system and the model operation and decision support system, were developed (Fig. 4). The pre-processing system is for the platform and network administrator. The authority assignment and the user definitions can be edited in this sub-system; in addition, the model configuration and data management are included in this sub-system. The model operation and decision support system is for business users. The core function of this sub-system is the operation and visualization of two complete functional processes. Moreover, program comparison and decision report generation are designed as the responsibilities of business users. The reports are generated based on the report template, which is predetermined in the platform, and specific details can be provided according to the calculation results of the models. From the decision reports, the optimum watershed adjustment measures can be evaluated and determined by the department leadership of the TBA directly.

3. Software application

Based on the data management of the pre-processing system, two complete functional processes are established in the operation and decision support system of the model.
3.1. Backward estimation

The backward estimation pre-initialization interface is shown in Fig. 5. Three different methods of lake quality target determination, namely, those based on national control targets, custom defined targets and model calculation targets, are provided in the platform. As shown in Fig. 5, the custom defined targets were selected, and a normal water year was selected as the model operation scenario. Then, the hydrological and meteorological conditions that were pre-set in the platform can be used directly as input data for model #1.

The modeling results of the lake quality targets for different lake divisions from January 2014 to June 2014 are shown in Fig. 6. The upper middle portion of the figure represents the dynamic evolution trend of a certain water quality target within the temporal periods defined in the model (the TP target was selected in the application example and is shown in Fig. 6), and the data lists containing lake quality targets based on different indicators, different lake divisions and specific dates are displayed in full in the lower part of Fig. 5. The TP targets were concentrated in grade III and grade IV under the flat water level scenario, and the TP concentrations in the central lake region were determined to range from 0.05–0.1 mg/L (Grade IV). This level was much higher than that in the western lake region, which exhibited a baseline range of 0.025–0.05 mg/L (Grade III). This interval is consistent with the national control target for Lake Taihu in 2020 (0.05 mg/L).

According to the modeling results of the water quality response of the lake ecosystem (model #1) and the default temporal interval, the models can be sequentially operated automatically in the background. Specifically, the TP reduction amounts in the 33 inflowing rivers and the watershed pollutant reduction amounts in different administrative divisions, which represent the crucial intermediate process of backward estimation and the final results of all the models, respectively, are displayed in Fig. 7 and Fig. 8. With respect to the inflowing rivers, the TP reduction amounts were highest in the western region of the watershed. Specifically, the reduction amounts in Changxing Port and Hexi New Port, which are located in the southwestern region of the watershed, were 1056 t and 1205 t, respectively. These values were much higher than those of the other inflowing rivers (Fig. 7). With respect to different watershed units, the administrative divisions, topography, landform divisions and water functional divisions can be selected, and the administrative divisions were considered in the application (Fig. 8). Wujin City and Yixing City, which are located in the southwestern part of the region and close to the Lake Taihu boundary, required high reduction amounts.

3.2. Forward simulation

Two functions were developed according to the business requirements of the TBA. The first function was to simulate the changes in lake water quality based on the flow rate management of the inflowing rivers. This function is consistent with the business requirements of the dispatch supervision department of the TBA. The second function was to simulate the changes in inflowing rivers and the lake quality based on the emission amount and location adjustment. This function is consistent with the business requirements of the programming and planning department of the TBA.

In this section, the first function is used as an example. The monthly discharge amounts of the rivers that flow into Lake Taihu are shown in the center of Fig. 9. Based on these results, information was extracted from the background database. Second, the selected rivers that required adjustments were identified. Specifically, the Dapu River and Guating Port were identified based on monthly discharge values of 58.3 m³/s and 17.2 m³/s, respectively, and the corresponding split ratio was 3.4:1 by default. In this application, the split ratio was changed to 2:1. Therefore, the discharge at Guating Port was adjusted from 17.2 m³/s to 29.2 m³/s, which is half of the default discharge amount of the Dapu River. Finally, the model was operated based on the adjusted input.

Table 2
The information of output/input interfaces design.

<table>
<thead>
<tr>
<th>Input/output interface</th>
<th>Interface</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>StartModel RunCompute</td>
<td>model calculation start</td>
</tr>
<tr>
<td></td>
<td>GetBasinModelRunState</td>
<td>current model running status</td>
</tr>
<tr>
<td></td>
<td>GetComputeDateTimeOrder</td>
<td>model running time order</td>
</tr>
<tr>
<td></td>
<td>GetProcessData</td>
<td>output features process</td>
</tr>
<tr>
<td></td>
<td>GetWaterQualityResult</td>
<td>lake quality calculation results</td>
</tr>
<tr>
<td></td>
<td>SetStatisticsPredictRunCompute</td>
<td>results statistics</td>
</tr>
</tbody>
</table>

![Fig. 3. The models integration standard of the platform.](image-url)
conditions, and the daily variations in Lake Taihu quality are displayed in Fig. 10 (the indicator of TN was selected and is presented). The TN concentrations followed a spatially decreasing tendency from northwest to southeast. Specifically, the highest TN concentrations were found in Zhushan Bay and Meiliang Bay, which are displayed in orange and red, respectively. At these locations, the TN concentrations exceeded 6.0 mg/L. By contrast, the TN concentration remained lower than 0.5 mg/L in East Taihu because the accumulation of nutrients is prevented by large amounts of aquatic plant cover (Luo et al., 2016). With respect to the simulation trends over ten months, Zhushan Bay and

Table 3
The description of model and platform integration method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Function</th>
<th>Description</th>
<th>Instance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialize(String schemaName)</td>
<td>models initialization</td>
<td>1. Provide the schemaName in string type, and the input/output file and log file path can be generated based on the schemaName 2. Find out the location of Initialize file. 3. Upload the Initialize file. 4. Validate the Initialize file. 5. Write the execution status into the log file based on the method of Log(). 6. Return value as the method closed.</td>
<td>1. The example of lake quality indicators file Date TP TN COD 2014-10-12 20 15 0.7 2014-10-13 18 15 null</td>
</tr>
<tr>
<td>Execute()</td>
<td>models integration and calculation</td>
<td>1. File description 2. File path 3. Write the execution status into the log file based on the method of Log(). 4. Return value as the method closed.</td>
<td>1. File path of model execution root: ---config/</td>
</tr>
</tbody>
</table>
Meiliang Bay, which exhibited the highest TN concentrations, displayed minimal variations, and the TN concentrations at the center of Lake Taihu and the western coastal region decreased to some extent over the full temporal scale.

Platform performance testing was conducted by the Nanjing Hoperun Software Company, and the data exchange performance within the model integration process was specifically evaluated (Table 4). The platform can support large-scale data calculation, especially data inquiry and digital map rendering operations. In addition, when the temporal scale of model calculations was < 8 years and the data exchange amount was lower than 20.3 GB, the response time of the platform server was approximately 10–20 s. However, the response time of the platform server can be increased significantly as the data calculation amount expanded continuously.

4. Discussion

4.1. The special features focused on model integration

The two complete functional processes, including backward estimation and forward simulation, are the core of the platform. These functions were established based on multi-model integration. In this case, some special technologies related to model configuration and model initialization were required.

(i) The visual and custom configuration of the model template.

The complicated initial conditions, boundary conditions, calculation
conditions, control parameters and output parameters of the different models increased the difficulty of model integration and business user operation. Specifically, substantial efforts are required for model adaptation and pre-processing if the boundary condition and input parameters are adjusted.

To reduce unnecessary background preparation and the model configuration time prior to the running of each model, this platform implements model template customization and visualization technology to simplify model pre-processing and ensure data consistency among the different models. The model template was developed based on the integrated database, in which the spatial data and attribute data of model are managed. Then, the data dictionary, which defines the data fields, data sources, data formats, data types and involved models, was formulated. Finally, the model template was customized. The initial conditions, boundary conditions, control parameters and output parameters that refer to each model were displayed

Fig. 6. Modeling results of lake quality targets for different lake divisions. (From Jan 2014 to Jun 2014).

Fig. 7. Spatial rendered graph of the NH3N reduction amounts for the 33 in-flowing rivers (results of Model #3).
in the visual interface. This interface provides the default template for the models, and the template can be edited by the system administrator. The customization interface is shown in Fig. 11. The tree view list in the left column of the figure shows the data sources of the models, and the boundary conditions and input data can be dragged into the data items list, which is displayed in the right column of Fig. 11. Specifically, the default configuration of the data items in model #1 is presented. These items include the lake quality, lake grids, meteorological indicators and aquatic vegetation indicators. The default configuration can be edited in the simplified model calculation process or by changing the model objectives.

(ii) The initial conditions for model integration and operation can be selected flexibly.

The lake water quality targets are essential to model integration. Estuarine pollutant loads, transformation coefficients, and optimization plans of watershed pollutant reduction are calculated based on the

![Fig. 8. Spatial rendered graph of the watershed pollutant reduction amounts (COD) within different administrative divisions (results of Model #5).](image)

![Fig. 9. The in-flowing river discharge adjustment interface.](image)
output data of model #1.

In the platform, three different methods of lake quality target determination are provided (Table 5). The diversified determination modes were designed to make the platform more convenient and efficient for users. Specifically, information about the lake water quality in different lake divisions can be assessed monthly based on the modeling of complex indicators, such as lake hydrological and meteorological conditions, aquatic vegetation species and bloom frequency. Such modeling was performed in model #1. Therefore, the model can be utilized by platform users to determine the lake water quality targets in a scientific and dynamic manner. Additionally, users can determine the lake water quality targets directly based on their subjective judgments, and the temporal and spatial scales can be selected by the users. This mode reduces the run time of model #1, in which the water quality targets can be imported directly without the model calculations. Moreover, the national control targets are provided to the users. The targets for the four restricted lake water indicators in the entire lake region in 2020 and 2030 are displayed intuitively in the platform (CAEP, 2015). These targets can be used as guidance for watershed pollutant reduction optimization planning based on certain lake quality targets, and they enable managers to perform comparisons between the model calculation results and actual monitoring data.

4.2. The advantage of TLWT

The important issues that must be solved in research regarding environmental models and platform frameworks were discussed by Whelan et al. (2014), who showed that model timeliness, availability, and integration, as well as data transmission among different models, are the key factors in environmental management platforms (Moore and Tindall, 2005). Furthermore, the coverage region of the existing platforms is limited. For instance, the BASINS model proposed by the U.S. Environmental Protection Agency (EPA) is acknowledged as the most comprehensive watershed environment framework. The model focuses on non-point and point source pollution and river pollutant transportation in a watershed based on several mature models; however, the lake algae and nutrients response are not thoroughly considered (US EPA, 2015).

Table 4
The description of platform data performance testing.

<table>
<thead>
<tr>
<th>Evaluation no.</th>
<th>Data process</th>
<th>Time series</th>
<th>Data amount produced</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDBOMT1</td>
<td>Data inquiry</td>
<td>Jan,2000–Jan,2010</td>
<td>131161 items</td>
<td>&lt; 4 s</td>
</tr>
<tr>
<td>GDBOMT2</td>
<td>Single model calculation</td>
<td>Jan,2000–Jan,2010</td>
<td>98.4 MB</td>
<td>&lt; 2 s</td>
</tr>
<tr>
<td>GDBOMT3</td>
<td>Model integration and calculation</td>
<td>One year(Jan, 2009–Jan,2010)</td>
<td>1.3G</td>
<td>&lt; 5 s</td>
</tr>
<tr>
<td>GDBOMT4</td>
<td>Model integration and calculation</td>
<td>Five year(Jan, 2006–Jan,2010)</td>
<td>7.3G</td>
<td>13.1 s</td>
</tr>
<tr>
<td>GDBOMT5</td>
<td>Model integration and calculation</td>
<td>Eight years(Jan, 2003–Jan,2010)</td>
<td>20.3G</td>
<td>32 min</td>
</tr>
</tbody>
</table>
Several watershed management platforms have been developed in China based on TMDLs. The platforms play important roles in typical watershed management areas, including the Taihu, Heihe, and Chaohu basins and the Yellow River Delta (Ge et al., 2013; Guo et al., 2012). However, these platforms mainly focus on the data management stage and are limited in their decision-making roles for pollutant control, which is of genuine concern to governments and civilians in severely polluted watersheds (Meng et al., 2008; Hu, 2016).

Compared with the platforms and frameworks developed in recent decades, the advantages of the TLWT approach can be summarized as follows:

(1) The intelligence and comprehensiveness meet the dynamic environmental management objectives of the TBA.

This platform has been developed to provide optimization plans for watershed pollutant reduction in different ecological function zones for the TBA, and model integration was the basis of the functional design. In this case, the model template configuration and selection of initial conditions, which were discussed in the previous section, were designed to meet the dynamic management requirements of the TBA. Moreover, some critical environmental information, including lake quality targets, the lake environmental capacity and allowable pollutant levels in inflowing rivers, can be captured during the backward estimation and forward simulation functional processes, and these procedural data were exported for several specific TBA tasks. Additionally, the information covers the entire region of the Lake Taihu watershed, which involved all critical elements within the Lake Taihu watershed, i.e., lakes, in-lake estuaries, river networks and watershed regions (Fig. 12). Five models were designed oriented to different elements, in which the model #1 and #2 were corresponds to the lake water, the model #3 was corresponds to in-lake estuaries, and model #4 and model #5 were correspond to river networks and watershed units, respectively. For all the above, the comprehensiveness of the TLWT method is a highlight of this approach.

(2) The functional flexibility.

The TBA website provides the open interface for the platform, and the present platform version focuses on two functional processes. These functions can be updated and extended in future versions, and new functional modules can be integrated into the TLWT. For instance, the algal bloom monitoring and warning function, which was also developed independently by the research and development group of the TLWT, could provide a monitoring service for the algae protection requirements of the TBA. Currently, the TLWT and algal bloom monitoring and warning function module are not integrated; however, they should be integrated in TLWT V2.0 due to the module designs and use requirements.

(3) The data transmission efficiency.

Dissimilar data sources and types, as well as the inefficiency and redundancy of data transmission, were acknowledged as the most critical technical bottlenecks for model integration. With respect to data transmission, the allopatry database was used for storage and management in the TLWT approach. Large amounts of hydrological and water quality data are used as model initial conditions and parameters. The data were derived from hydrological monitoring data from the TBA, and the original data were collected at hourly or daily scales. In this case, the slowness and redundancy associated with data processing can be mitigated if all the monitoring data are managed in the TLWT database directly and used in model calculations. Conversely, the local TLWT database was linked to the TBA monitoring database in this

Table. 5
The information of three lake quality target determination methods.

<table>
<thead>
<tr>
<th>No</th>
<th>Methods</th>
<th>Data sources</th>
<th>Spatial units</th>
<th>Temporal units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>National control targets</td>
<td>The planning scheme for Taihu basin environment governance and management</td>
<td>The entire lake region</td>
<td>2020 and 2030</td>
</tr>
<tr>
<td>2</td>
<td>Custom defined targets</td>
<td>Defined by the platform users</td>
<td>The entire lake region; different lake divisions</td>
<td>The temporal units can be defined by the users; both yearly units and monthly units can be accepted monthly unit, and the yearly result can be assessed by a monthly averaging algorithm</td>
</tr>
<tr>
<td>3</td>
<td>Model calculation targets</td>
<td>Calculated by Model #1</td>
<td>different lake divisions</td>
<td></td>
</tr>
</tbody>
</table>
study; therefore, the massive amount of monitoring data did not need to be stored in the local TLWT database. This method allowed the calculation efficiency of the model and the platform integration procedure to be elevated.

(4) Multi-source data unification and standardization.

Different models require massive data sets and multiple data sources developed independently by different parties. The data pre-processing workload is considerably increased when different data sources, data formats, data organization schemes and calculations are used. Thus, multi-source data unification and standardization is of utmost importance.

First, lake grids and inflowing river data must be unified. The inflow and outflow rivers are required for calculations of the transport and distribution of the pollutant flux in the lake model (model #3) and the river network pollutant transport and flux tracing model (model #4). In model #3, 33 inflowing rivers were established by the model developers. However, the generalized river network data were produced by the corresponding developer of model #4, and 61 rivers were created. Thus, model #3 references model #4 in the platform, and the long-term field monitoring data from the 61 rivers were managed in the platform database. These data were used by model #3 and model #4 simultaneously. In addition, Lake Taihu was divided into 69*69 grids according to the model requirements, and the water quality responses of the lake ecosystem model (model #1) and the lake water quality target capacity model (model #2) were calculated based on different grids. However, model #1 was started from (0, 0), with corresponding coordinates of (119.895158, 30.935322), and model #2 was started from (1, 1), with corresponding coordinates of (119.89606, 30.93277). The differences were unified in the platform to provide a reference for the grid format of model #1.

4.3. The transferability of the TLWT

The open interface was developed in TLWT, which improved the likelihood of platform framework transferred into other typical lake and watersheds. And some issues were needed to be emphasized and solved during the transplant process. Firstly, the model parameters need to be re-rated. The lake and watershed scales, as well as the hydrological and meteorological conditions, changed obviously in lakes like Lake Chaohu, Dianchi, and other international lakes. Therefore, the model boundary condition, the parameter initialization and the required massive data are needed to be re-rated and re-pretreated. For instance, the lake grid in Lake Taihu were divided into 69*69 grids, and the selected typical hydrologic years (high flow year, normal flow year and dry year) were 1998, 2006 and 2013 based on the monitoring data. However, these conditions would be remarkable different in Lake Chaohu. For this case, the standardized and automatic massive data processing system that covered “data acquisition - data reorganization - data storage - data representation” is necessary to design into the platform transplant process.

Secondly, the framework of model integration is needed to be optimized. In the existing platform, the coupling and integration of the model is based on the distributed integration of DLL or EXE files. This is a loosely coupled form. Moreover, the individual models were developed independently, as then the input/output file, storage directory and data item format are unified through repeated investigation and communication. This existed integration method is not effective in the standardized management and the integration efficiency of the models. Therefore, it is necessary to form a set of highly operable and universal integration criterion in the process of transplant, which can covered the following aspects of standardized interface of mining data, model interface setting and integration method.
4.4. The limitations of the TLWT approach

The platform was designed based on the actual business requirements of the TBA. The integration of several independent models and the ability to dynamically visualize modeling results were two of the core focuses of the platform. However, the method has some limitations. First, error propagation exists in the involved models. As shown above, although the accuracy of a specific model can be verified, errors will accumulate in the integration process involving different models because the models were developed independently. Therefore, the input parameters and output results of each model must be more consistent. Additionally, parameter calibration must be improved during platform updating and maintenance. Second, the platform server and network transport mechanism must be more advanced. In the formulated platform, the output data for the lake is calculated based on 69*69 grids, and the temporal resolution is designated as monthly. However, the amount of data would increase exponentially if the platform were applied extensively by the TBA. Therefore, the management of massive data elements is a critical challenge faced by the platform, and data security and efficiency issues are key issues in platform implementation.

5. Conclusions

From the management perspective, the link between watershed pollutant discharge control and lake water quality target management is important to watershed administrators in China. The integration of models that include all critical factors at the watershed-lake scale, as well as a comprehensive and logical platform for lake water quality management, represent the most important and urgent tasks.

TLWT was developed by integrating five models that cover different parts of the Lake Taihu watershed. Moreover, the B/S structure and GIS visualization engine ensure that the TLWT platform can successfully describe the spatial and temporal dynamics of lake water quality targets, the lake environmental capacity, inflowing river fluxes, river network pollutant transport and watershed pollutant reduction driven by model integration and calculations. Most importantly, two complete functional processes, backward estimation and forward simulation, can be established and implemented by the TBA directly. Thus, TLWT is a helpful tool for watershed-lake environmental management. However, the error propagation among models, data inconsistencies and the network transport mechanisms of the platform must be improved in future work.

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