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Applying Numerical Models for Water Environments in Watersheds – Case Studies of Tai Lake, Middle and Lower Han River and East Lake in China

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Additional information is available at the end of the chapter

1. Introduction

The overall status of the global water environment has entered into a new stage exhibiting serious ecological degradation and complex environmental pollution. China is confronting critical water environmental problems, such as increasing pollutant loads and aggravated surface and ground water contamination. Based on the mechanisms of water environment evolution and contaminant transport, as well as theories of the watershed non-point source pollution model, the hydrodynamic model and water-quality model, this study built a comprehensive social-economic-hydrology-water environment model system for investigating water environments in watersheds. This model system can simulate the water cycle of watersheds and water environment quality changing processes, and analyse the utilization of water resources, pollutant discharges and the relationship between quantitative couplings and response connections, as well as reveal the formation mechanism of watershed pollutants and the laws of water environment revolution. This model system has successfully supported the comprehensive watersheds managements in Tai Lake, the middle and lower Han River and East Lake in China.

1.1. Research background

The load of pollutants entering the water environment has rapidly increased in China since the implementation of open and reform policies in China, while minor progress has been achieved in the mitigation of pollution. Among China's seven major river systems, the Songhua River and Huai River are slightly polluted, the Yellow River and the Liao River are moderately polluted and the Hai River is highly polluted. Eutrophication of lakes and reservoirs has

become serious and is high in nitrogen and phosphorus. Drinking water may have been polluted with conventional contaminants and new types of toxic pollution, which threatens to health of urban and rural people.

The watersheds water environment model can be used in the simulation and evaluation of water environments, the forecasting and prediction of water quality, and can supplement the establishment of the standardization of pollutant discharges and water quality management. It is an important tool for the water planning, management and scientific research of water-sheds. An established watersheds water environment model can describe the pollutant migration and transformation rules over time and in terms of space scale. We can make reasonable predictions about the development of the water environment based on the study of variables and fixed scientific parameters. Therefore, the study of watersheds water envi-ronment system simulation technology and especially the integration of other factors such as physical environment and ecology into the model system is one of the core technologies in watersheds water planning and environmental management.

Lake Tai is located in the Yangtze River Delta and is one of the five largest fresh water lakes in China. In China's lake district, many sub-lakes form extensive water networks. The Tai Lake basin is China's fastest changing and developing region. In recent years, due to the continuous degradation of water quality, eutrophication in Lake Tai has worsened and has had negative impacts on regional socio-economic development.

The total length of the Han River is 1532 kilometres, making it the largest tributary of the Yangtze River. Danjiangkou Reservoir, located in the middle and upper reaches of the Han River, acts as the water source of the South-To-North Water Transfer Project, which channels water from the Danjiangkou Reservoir through Henan and Hebei Province to the serious water shortage district in Beijing-Tianjin, China. It provides water to more than 100 million people along its main canal. The water transfer project reduced the reservoir's water level, substituting water resources supply and the demand balance of the middle and upper reaches of Han watersheds.

East Lake, located in Wuhan, is the second largest downtown lake in China; however, the lake has become atrophied. Due to a rapidly increasing urban population and intensification of the industrial and agricultural sectors, the lake has received excessive amounts of nitrogen and phosphorus, sourced from surrounding point- and non-point sources. The local authorities have made good progress on point-source pollution control. In order to achieve the overall ecological health of East Lake, the next step is to strengthen the control of non-point source pollution and establish a water management network for East Lake.

In summary, this study presents an adaptable watershed aquatic environment model that can be applied to Lake Tai, middle and lower of Han River, and East Lake. The study will establish: (1) an complex model of a river-lake network to achieve dynamic modelling of the Lake Tai water environment; (2) establish a comprehensive water quality model for a systematic water control project to quantitatively estimate the impact of water transfer; (3) a project for control-ling the water quality of middle and downstream Han River; (4) build a non-point, dynami-cally-sourced 3D mathematically-coupled water quality model according to the characteristics

of the received water and boundaries across watersheds, as well as the geography of East Lake. This approach will assist in answering how water contamination developed in each watershed, as well as the evolution patterns of the aquatic environment. The findings will help to improve control of the pollution of watersheds in order to maintain the sustainability of their environmental, social and economic development.

1.2. Research progresses

1.2.1. Non-point source model

The source of non-point pollution primarily derives from the application of fertilizers, pesticides, effluent irrigation and runoff from urban surfaces. Due to the complexity of these sources, the indetermination of the mechanism, it can be challenging to quantify the formation and load of non-point source pollution. In this instance, establishing models that stimulate watershed environments from time and space perspectives can be the most effective and direct measures. Usery et al. [1] coupled GIS and the distributed non-point source model to stimulate and evaluate watershed contaminants. Bryan [2] suggested a multi-standard evaluation measure in the study of non-point agricultural source pollution in Western Australia. Chowdary et al. [3] applied remote sensing and GIS to stimulate non-point agricultural pollutants and sediments on 2700 ha of land in Jharkhand State. Gikas et al. [4] utilized a SWAT model suitable for non-point source pollution in the Mediterranean region. Wang et al. [5] adapted LEAM, which was designated for modelling land use changes, to non-point source pollution and water quality modelling for the determination of the long-term effect of urbanization on water quality.

Recently, the intensification of non-point source pollution has drawn the increasing attention of the science community. Zhang [6-7] built a model of distributed urban-precipitation-runoff source pollution according to the properties of urban-sourced pollution and its transformation processes for the Project of Urban Water Environment Remediation Wuhan, which analysed pollution patterns resulting from different precipitations and land uses. Qiao et al. [8] coupled river network development DEM grid vector data to supply an alternative means for analysing basic terrain data in a non-point source model. Liu et al. [9] combined RS and GIS technology to construct a watershed non-point source pollution model to calculate pollution loads of various types of pollution sources. Tang et al. [10] applied a SWAT watershed non-point source pollution model to evaluate the effect of measures on water quality improvement in Wenyu River.

1.2.2. Water dynamics and quality model

Contaminants produced from lands are discharged as a single point source into rivers and lakes. The quantification of the migration and transformation of pollutants requires a dynamic water quality model. In light of the different properties of watersheds, such models study river network water dynamics and quality, including that of lakes and reservoirs.

1.2.2.1. Dynamic river network water and quality model

Many dynamic river network water and quality models have already undergone real-world applications. [11] Mikell [12] scattered the water level of watercourses and the flow of water into calculation points. Arega [13] established a simple two-dimensional waterflow-salinity model and applied obvious TVD limited volumetric calculus to solve the calculation of waterflow-salinity. Peng et al. [14] constructed the model for establishing the Han River's water quality ecology numerically, which took into account the effect of the top support action of the water level of the Yangtze River. They then numerically stimulated the migration and transformation of water dynamics, total phosphorus, dissolved oxygen and phytoplankton of the Han River.

1.2.2.2. Lakes and reservoirs: water dynamics and quality model

The common lake and reservoir water dynamics and quality models are grouped into zero-, one-, two- and three-dimensional modelling and according to specific resolutions. Vejzak [15] tested the effect of eutrophication on phytoplankton dynamic, built an eutrophication model and predicted the effect of different nutritional changes. Asaeda [16] stimulated the effect of large aquatic vegetation degradation on nutrient budget in shallow lakes. Kurup [17] applied the finite difference scheme, where TISAT and CE-QUAL-W2 were coupled and tested in a swan lake estuary. Angelini [18] utilized the ELLOBO model to illustrate three status varieties on reservoirs. AyseMuhammetoglu [19] suggested a three-dimensional model on the effect of advantageous large aquatic vegetation on the quality of water of shallow lakes. Wang et al. [20] applied sourced convection diffusion equation and the water ecology dynamic model, based on the two-dimensional watershed water flow-quality model, and as a result built the shallow water ecological restoration model, which they applied to the study of reservoir restoration in Shenzhen.

2. Non-point source model

2.1. Runoff-yield model

The sub-basin was considered as a nonlinear reservoir. We combined the Manning Continuity equation and established the nonlinear hysteresis of surface runoff storage. The Manning Continuity equation can be presented as:

$$\frac{dV}{dt} = A_{s1} \cdot \frac{dh}{dt} = A_{s1}P - Q_{W1} \tag{1}$$

where $A_{s}1$ is the basin area (m²), V is sub-basin water rate (m³), T is time (s), H is the water depth (m), $Q_{W}1$ is the sub-basin for the flow of traffic and P is net rain (m/s).

$$Q_{W1} = Q'_{pl} + Q'_{gl} \tag{2}$$

where Q_{p1}' is the surface of the slope flow (m³/s) and Q_{g1}' is the flow into the ditch (m³/s).

The flow equation for the sub-valley can be presented as:

$$Q_{W1} = W \cdot \frac{1}{n} \left(h\text{-}h_p\right)^{5/3} S^{1/2} \tag{3}$$

where W is the width of the sub-basin type (m), S is sub-basin slope, N is the Manning roughness surface and H_P is the hollow lag of storage water depth (mm).

The Von Hoyningen-Hune formula was applied for formulating canopy interception of rainfall:

$$P_i = aLAI \left[1 - \frac{1}{1 + \dfrac{bp_{gross}}{aLAI}} \right] \tag{4}$$

where Pi is the quantity of rainfall interception (mm), a is the empirical coefficient (cmd-1), pgross is rainfall (mm), LAI is the leaf area index (m²m⁻²) and b is soil coverage, b=LAI/3. With an increase in rainfall, the rainfall interception amount will gradually approached to the saturation value $aLAI$.

Fill the depression, in the form of incremental is:

$$\Delta V = \Delta P_e e^{-P_e/S_d} \tag{5}$$

where Pe is net rainfall (mm) and Sd is maximum filling depression (mm).

For infiltration, the Green-Ampt equation can be applied when initial rainfall is stronger than the infiltration amount, as well as when the initial rainfall is less than the infiltration amount. The surface infiltration capacity can be defined as:

when F < F$_s$:

$$f = i$$

$$F_s = \frac{S \cdot M}{i/K_s - 1}$$

$$(i > K_s) \tag{6}$$

$$F_s = 0(i \le K_s),$$

when $F \ge F_s$:

$$f = f_p$$

$$f_p = K_s \left(1 + \frac{S \cdot M}{F} \right) \tag{7}$$

where f is infiltration rate (mm/s), F_p is stable infiltration rate (mm/s), M is the initial saturation (mm/mm), I is the rainfall intensity (mm/s), F is the cumulative infiltration amount (mm), K_s is soil saturated hydraulic conductivity (mm/s), S is the wetting front of capillary suction (mm) and F_s is saturated with the cumulative infiltration amount (mm).

2.2. The pollution-generation model

1.   Pollutant accumulation

The cumulative equation can be represented as:

$$\frac{dL_{si}}{dt} = k_i - k_{2i} L_{si} \tag{8}$$

where i is the first type of surface coverage, K_i is dust sedimentation rate (g/m^2 day), L_{si} is the surface dust (g/m^2), K_{2i} is the consumption rate of dust fall (d^{-1}) and T is time (d).

The accumulated amount of dust, where *Lsi* is proportional to the accumulated amount of pollutants *Lij* can be presented as:

$$L_{si} = f_{ij} \cdot L_{ij} \tag{9}$$

where *fij* is the *i* kind of surface coverage on the characteristics of the j proportion coefficient of pollutants (mg/g).

2.   Pollutant washing

The pollutant washing index equation can be represented as:

$$\Delta L_{ij} = L_{ij} \left[1 - \exp\left(-k_{3i} R \right) \right] \tag{10}$$

where ΔLij is the j type of pollutants (g/m²) devided from the i cover characteristics of catchment units wash, Lij is the amount of pollutants accumulated at the start of rain in the j catchment units by covering i characteristics (g/m²), $k3i$ is the scouring coefficient of the water unit by covering i characteristics set of (mm⁻¹) and R is rainfall (mm).

3. River network water dynamics and water quality model

We applied the Saint Venant equations to describe the process of river water dynamics; the fundamental equations can be presented as follows:

Continuity equation is,

$$\frac{\partial A_j}{\partial t} + \frac{\partial Q_j}{\partial x} = q_j \tag{11}$$

The momentum equation is,

$$\frac{\partial Q_j}{\partial t} + \frac{\partial u_j Q_j}{\partial x} + g A_j \frac{\partial z_j}{\partial x} + \frac{g n^2 |u_j| Q_j}{R^{4/3}} = 0 \tag{12}$$

where uj is the j river channel section's average flow velocity, Qj is the flow of river channel j, A is the crossing water area of river j, T is time, Qj is the river flow Q of lateral flow bus j, G is acceleration of gravity, zj is the j river channel water level, N is the river roughness and R is hydraulic radius.

The pollutants diffusion equation can be presented as:

$$\frac{\partial (h_j c_i)}{\partial t} + \frac{\partial (u_j h_j c_i)}{\partial x} = \frac{\partial^2 (E h_j c_i)}{\partial x^2} - h_j k_d c_i + h_j S_m \tag{13}$$

where Ci is pollutant concentration, Hj is j river channel water level, uj is j river channel, E is the diffusion coefficient, Sm is pollutant source items, Kd is the pollutant degradation coefficient, $Kd = K0\theta^{T-20}$, T is the water temperature, θ is coefficient of 1 ~ 1.08 and $K0$ is the degradation coefficient of the normal temperature.

The river network node equation can be presented as:

$$z_{j_1} = z_{j_2} = \cdots = z_{j_n} \tag{14}$$

$$A_j \frac{\Delta z_{j_i}}{\Delta t} = \sum Q_{j_i} \tag{15}$$

$$c_s = \frac{\sum\limits_{i_{in}} c_{i_{in}} Q_{i_{in}}}{\sum\limits_{i_{out}} Q_{i_{out}}} \tag{16}$$

where zj is for the node j water level, Aj is the node j cross-sectional area, cs is the water concentration of node j, $ciin$ is the water concentration of inflow and $Qiin$ is the inflow flow.

4. Lake water dynamics and water quality model

We described the natural water body movement control equation using the continuity equation and momentum equation. Under the rectangular coordinate system, this can be expressed as follows:

Continuous equation is:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \tag{17}$$

X direction momentum equation is:

$$\frac{\partial hu}{\partial t} + \frac{\partial huu}{\partial x} + \frac{\partial hvu}{\partial y} + gh\frac{\partial z}{\partial x} + \frac{gn^2 h\sqrt{u^2 + v^2} u}{h^{4/3}} =$$
$$= hfv + \frac{\rho_a f_w \left(w_x^2 + w_y^2\right) w_x}{\rho_w} + \frac{\partial}{\partial x}(h\gamma_t \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(h\gamma_t \frac{\partial u}{\partial y}) \tag{18}$$

Y direction momentum equation is:

$$\frac{\partial hv}{\partial t} + \frac{\partial huv}{\partial x} + \frac{\partial hvv}{\partial y} + gh\frac{\partial z}{\partial y} + \frac{gn^2 h\sqrt{u^2 + v^2} v}{h^{4/3}} =$$
$$= -hfu + \frac{\rho_a f_w \left(w_x^2 + w_y^2\right) w_y}{\rho_w} + \frac{\partial}{\partial x}(h\gamma_t \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(h\gamma_t \frac{\partial v}{\partial y}) \tag{19}$$

where u and v are the vertical average velocities on x and y direction, Z is the surface elevation, H is the depth of the water, F is Coriolis force coefficient $F = 2\Omega\sin\theta$, to which Ω is suitable for

the earth's rotation angular frequency, θ is local latitude, γ_i is turbulence viscosity coefficient, ρa, ρw is the density of air and water, fw is wind stress coefficient and Wx and Wy are the wind speeds on x and y direction.

The pollutants diffusion equation can be presented as:

$$\frac{\partial hC_i}{\partial t} + \frac{\partial huC_i}{\partial x} + \frac{\partial hvC_i}{\partial y} = \frac{\partial}{\partial x}(hK_x \frac{\partial C_i}{\partial x}) + \frac{\partial}{\partial y}(hK_y \frac{\partial C_i}{\partial y}) - hS_i \tag{20}$$

where C_i is the concentration of contaminant i and K_x and K_y are the diffusion coefficients on the x and y directions. The pollutants diffusion equation fully considered that water convection and diffusion can potentially degrade pollutants.

5. One-dimensional and two-dimensional model coupling method

On the interface section of the one-dimensional and two-dimensional models, we used the one-dimensional model to simulate the river water level and change of flow rate, and took the data as an implicit variable of the two-dimensional lake model. At the same time, water level, flow and concentration showed equivalent conditions for both models, so that the coupling of one-dimensional and two-dimensional models was achieved. Transitional elements were the connecting units between the one-dimensional model and two-dimensional models. The transitional unit grid layout is shown in Figure 1.
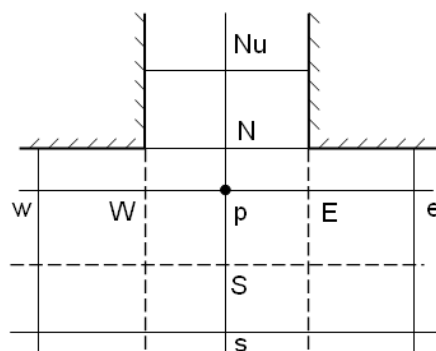

Figure 1. One-dimensional and two-dimensional models of connection.

Water connection condition:

$$Z_1 = Z_2 \tag{21}$$

Traffic connection conditions:

$$Q_1 = \int U_\varepsilon h_\varepsilon d\varepsilon \tag{22}$$

Water connection conditions:

$$C_1 = C_2 \tag{23}$$

where $Z1$, $Z2$ is the water level on the connection section of one- and two-dimensional models, $C1$, $C2$ is water quality concentration on the connection section of one- and two-dimensional models, $Q1$ is flow on the connection section of one- and two-dimensional models, Us is velocity on the connection section of one- and two-dimensional models, uj is the coordinate on the connection section of one- and two-dimensional models and H is the water depth.

6. Numerical dispersion and solving

Adapting the hydrodynamic and water quality model equation to a unified form can be presented as:

$$\left(\varphi\right)_t + \left(u\varphi\right)_x + \left(v\varphi\right)_y = \left(\varepsilon_s \varphi_x\right)_x + \left(\varepsilon_s \varphi_y\right)_y + S_\varphi \tag{24}$$

We used non-orthogonal and non-staggered grids to adopt the processing of the wind convection format within the control body, to integral and discrete on the formula(24), and to obtain the discrete equation of convection diffusion as follows:

$$a_p \varphi_p = \sum_{nb} a_{nb} \varphi_{nb} + S_p^\varphi \tag{25}$$

where ap and anb are the relevant coefficients, respectively.

We used the SIMPLE orthogonal algorithm to establish the η free surface correction equation and velocity correction equation. The η correction equation can be presented as:

$$d_p \eta_p' = \sum_{nb} d_{nb} \eta_{nb}' + S_p^\eta \tag{26}$$

The velocity correction equation can be presented as:

$$u_p' = u_p^* + b_p^u \left(\eta_p' - \eta_e'\right); v_p' = v_p^* + b_p^v \left(\eta_p' - \eta_n'\right) \tag{27}$$

where b_p^u, b_p^v, d_p and d_{np} are the discrete coefficients and u_p^*, v_p^* and η'_p are guesses.

The surface and velocity equations both belong to diagonal algebraic equations, where the SIMPLE algorithm can be applied for finding a rapid solution.

7. Examples of application

7.1. The survey of experimental research and the typical environmental processes in Lake Tai

7.1.1. The Lake Tai basin overview

Lake Tai basin is located in the delta plain area of Yangtze River and its watershed area is 36 500 km^2 [21]. Lake Tai basin is China's fastest changing and development region and its serious water pollution is a top concern. In investigating the complexity of the Lake Tai watershed, this study only selected Ge Lake, which is in the west of Lake Tai.

7.1.1.1. Natural environment conditions

The study area is located in upstream Lake Tai and is a major pollutant source of Lake Tai (as shown in Figure 2).The local climate is subtropical and experiences moist marine monsoons. It has abundant rainfall and sunlight hours annually. [22]

Figure 2. Location map of the Ge Lake river network of the Lake Tai Basin.

7.1.1.2. Social and economic situation

The local economy of the studied area is quite well-developed, with steady agronomy and rapidly increasing industrial economy. The local GDP per capita was 15,900 CNY in 2000 and 63 000 CNY in 2008, which was three times higher than the national average. [23]

7.1.2. Analysis and evaluation of water quality of Ge Lake

7.1.2.1. Water quality at Ge Lake

The results of water quality evaluation are shown in Table 1, where TP, TN and COD exceed largely when compared with the normal standard. The properties of organic pollution are highlighted.

Period	NH$_3$-N	COD	TN	TP	Water quality category
Dry season	Grade II	Grade V	Worse than Grade V	Grade III	Worse than Grade V
Normal season	Grade IV	Grade IV	Worse than Grade V	Grade IV	Worse than Grade V
Wet season	Grade II	Grade V	Worse than Grade V	Grade IV	Worse than Grade V

Table 1. Water quality evaluation results for Ge Lake in 2010.

7.1.2.2. The analysis of varying water quality in Ge Lake

The water quality is worse than Grade V at Ge Lake, with atrophied nutrition and the major pollution indicators of COD and NH3-N, as well as TN and TP. The lake water quality has declined from Grade III in the early 1990s to the poorer Grade V class and the lake's pollution index has risen 10% per year on average. Presently, algal species have become dominant and the lake has changed from being a grass-type lake into an algae-type lake.

7.1.3. Ge Lake water quality model

Combined with the features of the study area, in view of the mixture of pollutants present, a one-dimensional and two-dimensional mathematical model, respectively, were chosen to describe the hydrodynamic processes of the river and the transformation processes of pollutant migration. The finite control volume method was applied to solve the control equation of the two-dimensional hydrodynamic- and water-quality model (see Section 2). To generalize the research area, typical Ge-Lake watershed hydrology and water quality data were applied, which assisted in calibrating and verifying the model.

7.1.3.1. Drainage generalization

The river network in the study area was divided into different calculation sections, including 110 river sections, 91 calculation nodes and 519 calculation sections. The river network generalization results are shown in Figure 3.
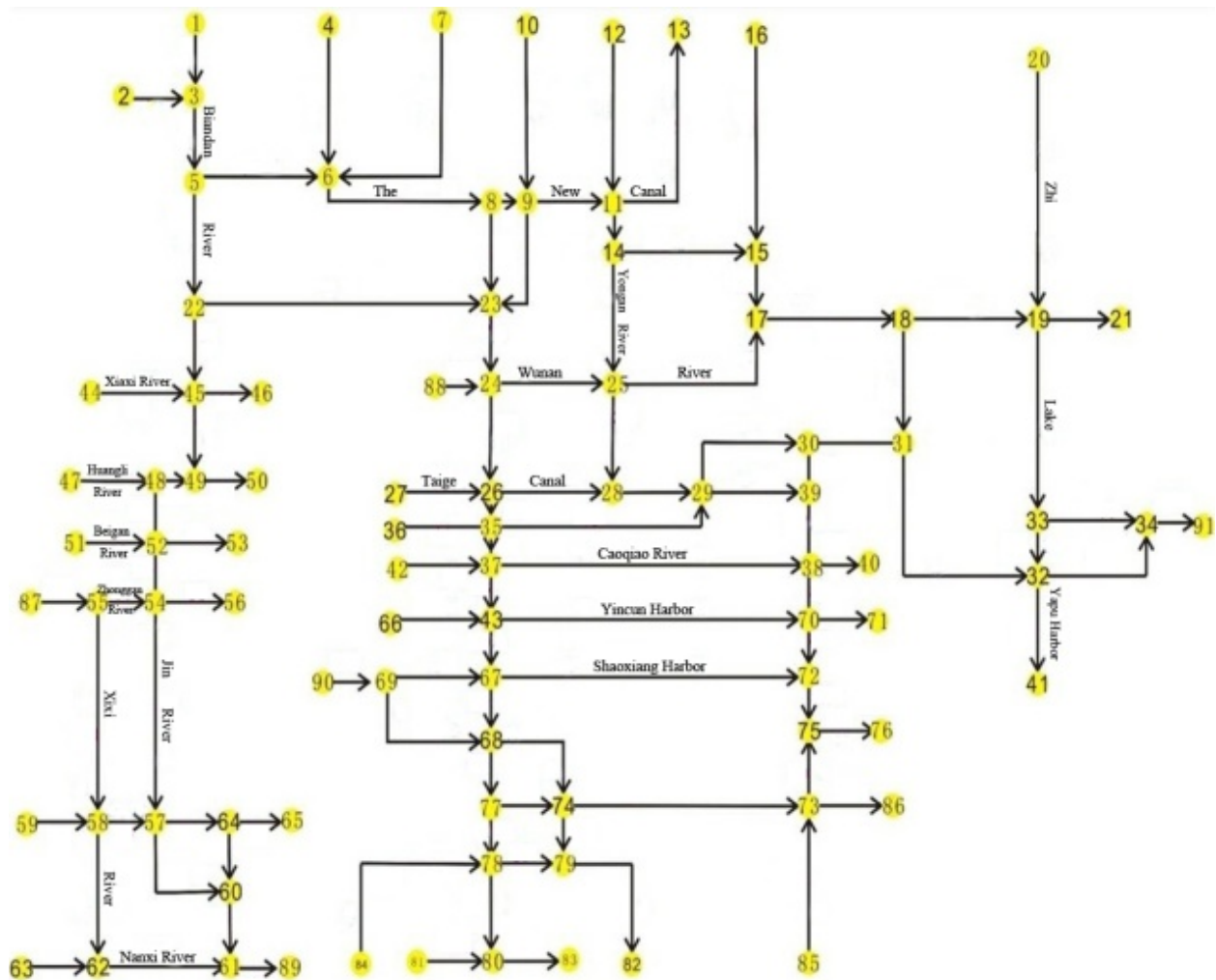
Figure 3. The typical river network profile in Ge-Lake.

7.1.3.2. Rate of model and validation

The distribution map of verification monitoring points in Ge Lake is shown in Figure 4.

Using daily water flow data from Xiaxi bridge station (Xiaxi River), Huangli station (Huangli River) and Dong'an bridge station (Beigang River) in 2007, we were able to calculate water outflow and input at every river sections. This was then applied to the verification of hydro-dynamics at the upper-boundary conditions. Using daily water level data from Dukou station, Dapukou station and Yixing station at Lake Tai in 2007, we were able to calculate water output level at every river sections.This was then applied for the verification of hydrodynamics at lower-boundary conditions. We used pollution discharge load data in 2007 for the verification of the water quality model.
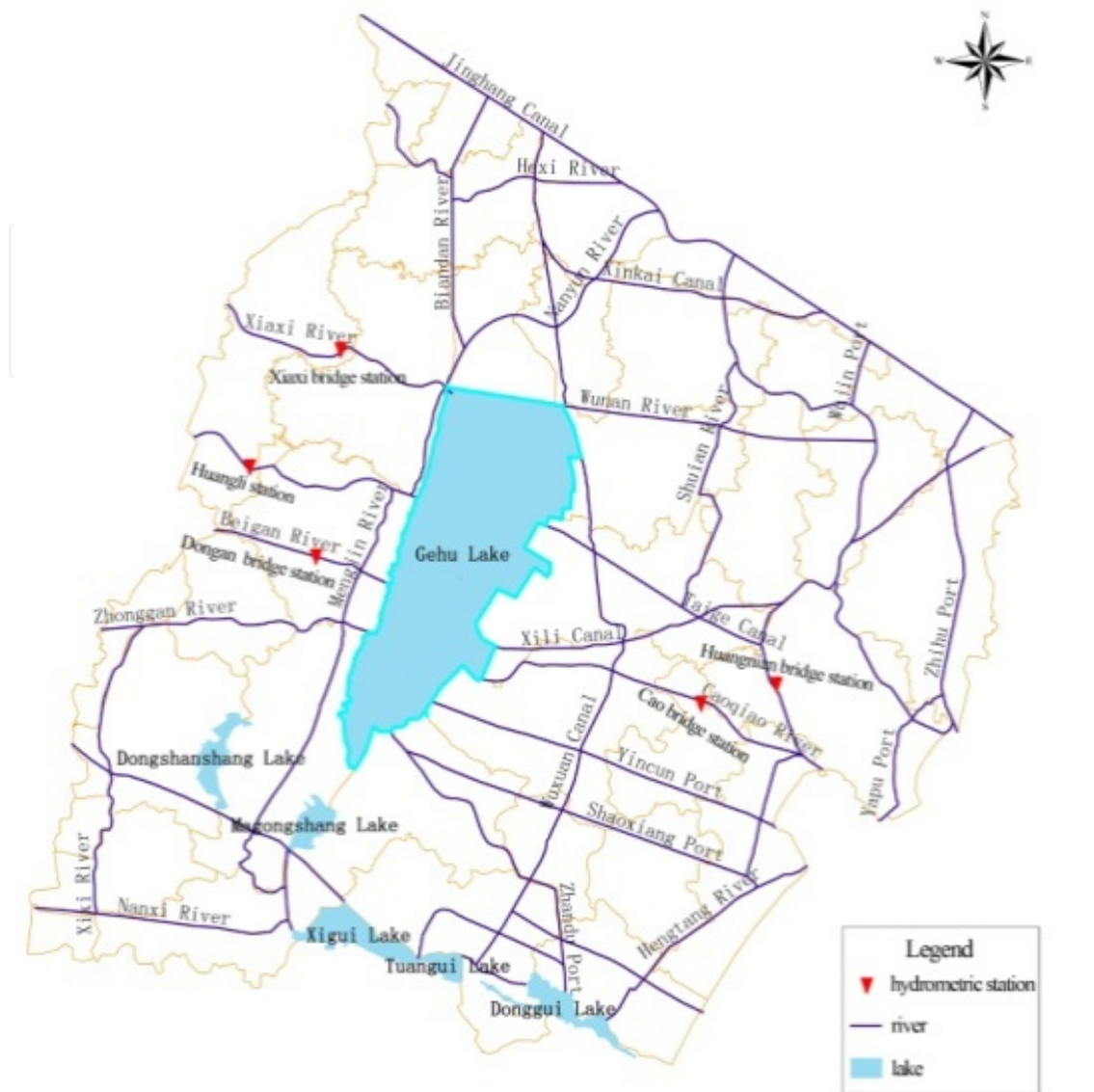
Figure 4. Distribution map of verification monitoring points in Ge Lake.

Correlation parameters

1.   Roughness coefficient

The empirical formula and the result of the model parameter calibration determined the roughness coefficient n. River roughness was 0.02 ~ 0.025 and Ge-Lake had roughness of approximately 0.022.

2.   Diffusion coefficient

The diffusion coefficient of the body of water in the study area (Ex) was obtained using an empirical formula according to Lagrange turbulence length and the intensity of turbulence length concept. The Ex values can be expressed as:

$$E_x = \alpha h u_*$$ (28)

$$u_* = \sqrt{ghI}$$ (29)

where α is the dimensionless coefficient, (0. 1-0.2); u_* is the friction velocity (m/s), I is the water surface slope and h is the water level (m).

3. Degradation coefficient

The degradation coefficient (K_0) of NH$_3$-N, COD, TN and TP are shown in Table 2.

Parameter	NH$_3$-N	COD	TN	TP
K_0 (d^{-1})	0.03-0.15	0.02-0.13	0.05-0.08	0.05

Table 2. Degradation coefficient (K_0) of NH$_3$-N, COD, TN and TP.

Model validation

1. Hydrodynamic model validation

Daily water flow and water level data (2007) from Huangnianqiao station (Taige Canal) and Caoqiao station (Caoqiao River) was used to verify the water dynamics of the model.

1. flow verification

The results of flow verification are shown in Figures 5 and 6. Overall, changes in flow calculation were consistent with changes in the measured data.
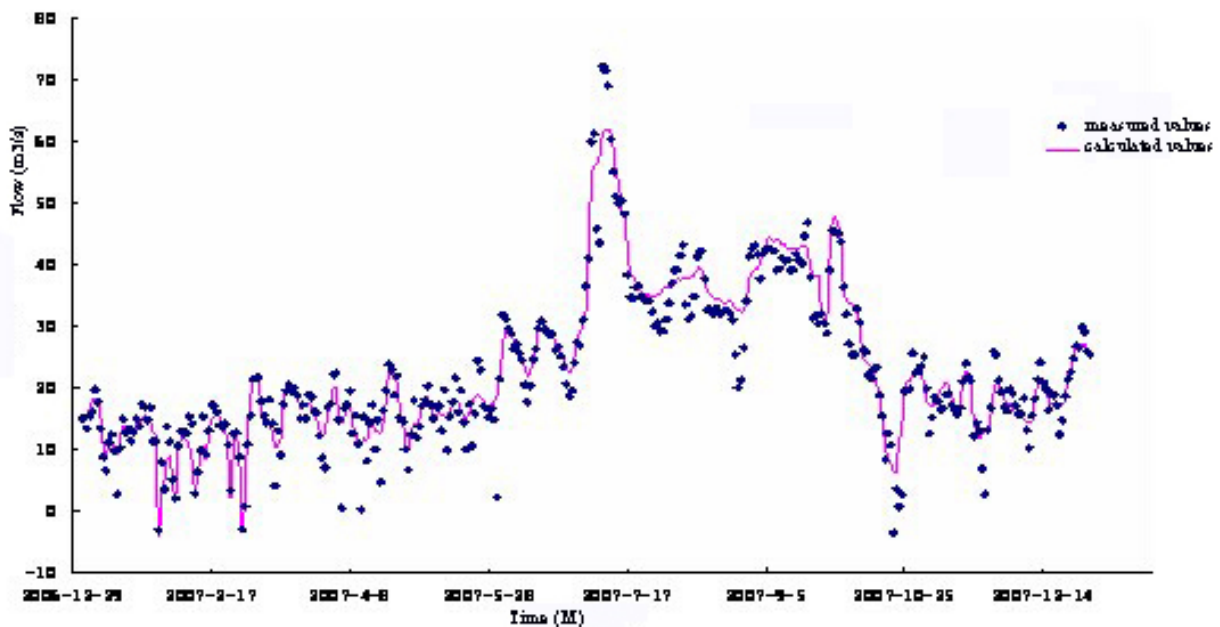
Figure 5. Flow verification of Huangnianqiao section.
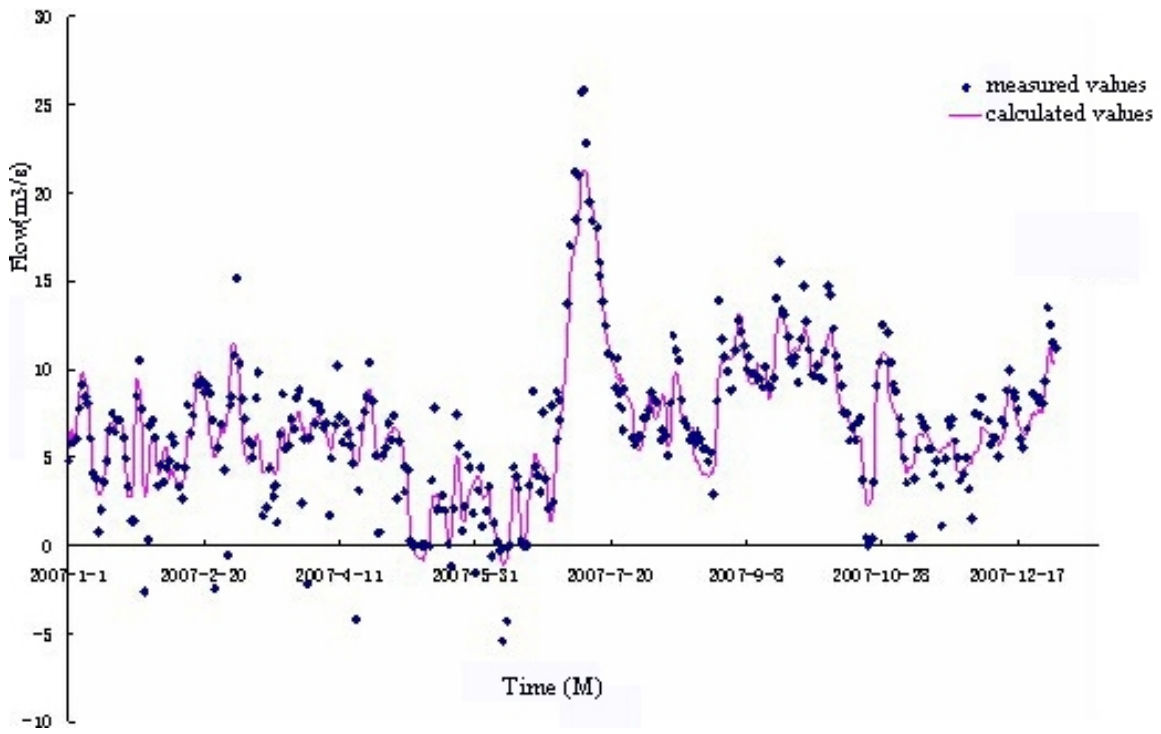
Figure 6. Flow verification of Caoqiao section.

2.   Water level validation

The results of water level verification are shown in Figures 7 and 8. The precision of the model was good and it was able to meet the needs of the calculation.
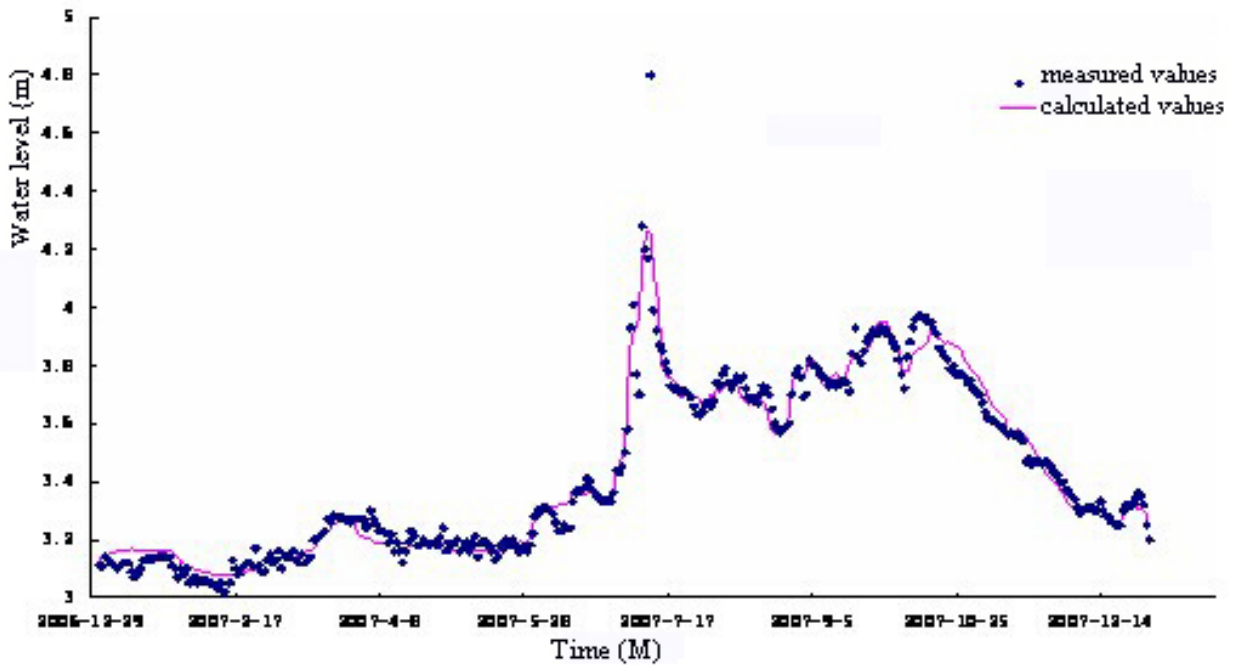
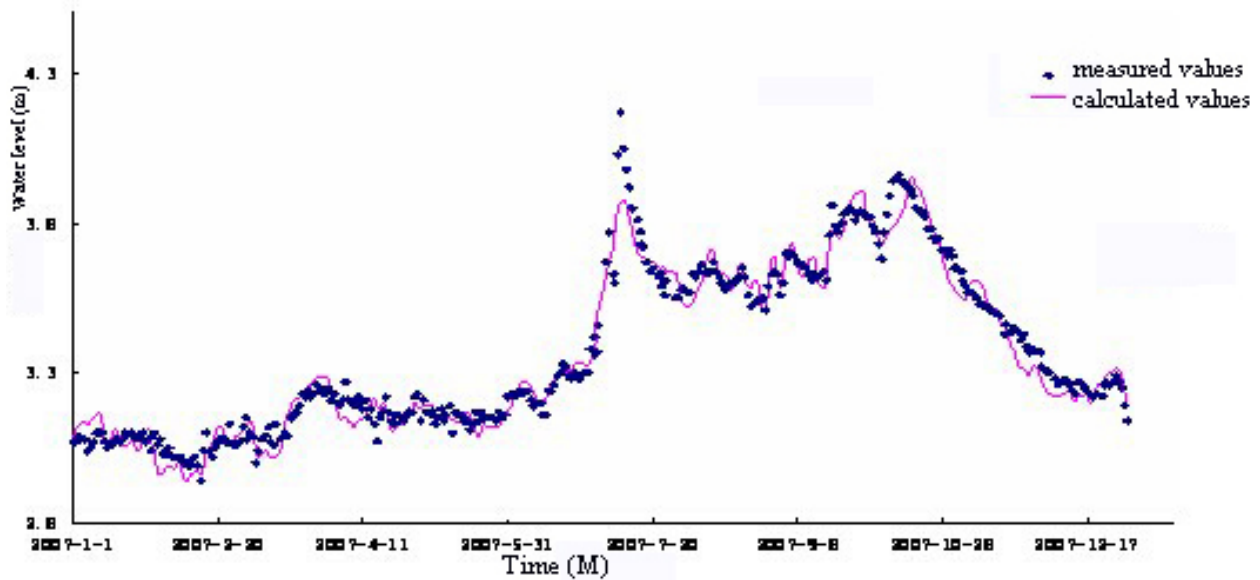**Figure 7.** Water level verification of Huangnianhe section.

Figure 8. Water level verification of Caoqiao section.

The two-dimensional hydrodynamic model used daily water level data from Fangqian station (Ge Lake) for verification. It showed that the rule of calculated values and measured values had good consistency. Validation results are shown in Figure 9.
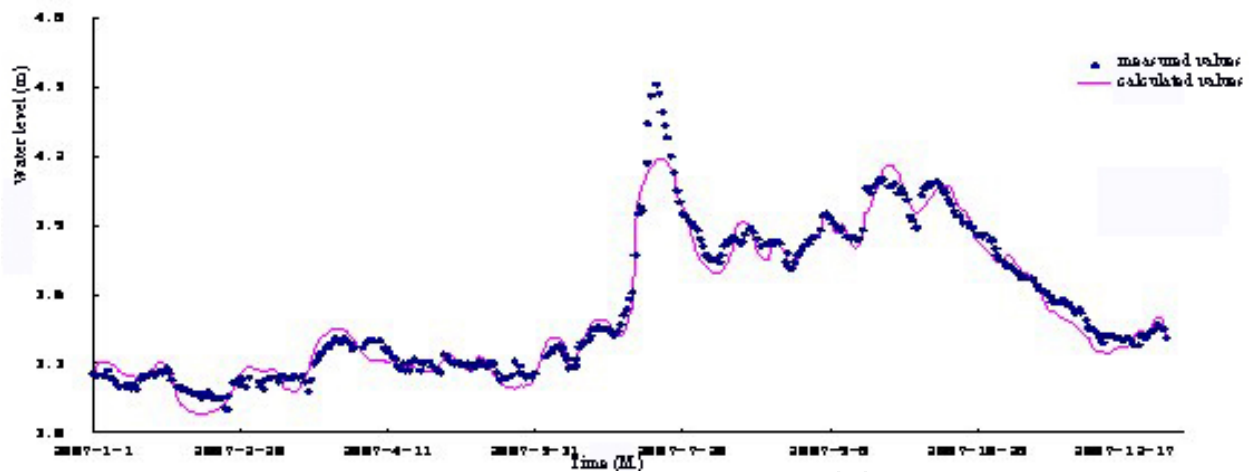
Figure 9. Water level verification of Ge-Lake.

3.   Water quality model validation

Choosing three section stations within the scope of the study area, i.e., Huangnianqiao, Xuenianqiao and Cao Qiao, we used monthly-measured water quality data in 2007 to validate the river network model. The calculated results were compared with the measured values. Model simulated values and measured values were consistent, matching the requirements for the river's one-dimensional water quality simulation.

Sections	Relative Error			
	NH₃-N	COD	TN	TP
Huangnianqiao Section	23.98	18.92	23.49	21.56
Xuenianqiao Section	34.56	31.6	26.28	30.54
Caoqiao Section	20.5	16.68	22.65	23.56

Table 3. Average error of all section indexes (%).

We selected north Ge Lake as a regular water quality monitoring site. We validated the two-dimensional lake water quality model results by using measured data from January, April, July and October, 2007. As shown in Table 4, by comparing the simulated values and measured values, NH_3-N, COD, TN and TP in Ge Lake indicated that the relative errors were mostly less than 30% and the average error was roughly 24%.

Time	Relative Error			
	NH₃-N	COD	TN	TP
2007-1	18.92	20.11	14.66	17.39
2007-4	28.23	20.45	26.12	11.54
2007-7	29.03	21.55	13.24	24.48
2007-10	36.11	37.08	22	34.51

Table 4. Relative error of all indexes (%).

7.1.4. Conclusion

This study established a complex lake-river network coupled with a one- and two-dimensional water quality model under human interference. The research was based on socio-economic, demographical, climatic and hydrological data from 2007 at Ge Lake (Lake Tai region). Chemical oxygen demand, ammonium-N, total nitrogen and total phosphorus were selected as water quality indicators. The study analysed the water environment evolution rules as affected by human activities and interference. The results showed that ammonium-N and COD were mainly derived from domestic waste and industrial point sources; TN was primarily sourced from domestic waste and agricultural non-point sources; TP was largely derived from domestic and aquaculture pollution.

In view of the lakes in the region that were included in the river network, this study established a water environment holding capacity calculation model; the research findings are fairly adaptive to wider application in terms of water resource conservation and environmental management. The study also introduced a new angle for dynamic water-holding capacity modelling research. This approach can be integrated into pollutant control and environmental monitoring technologies in order to achieve the overall health of the water environment.

7.2. Modelling water quality and quantity according to the influence of cascade reservoirs and inter-basin water diversion projects on the middle and lower Han River [24]

7.2.1. Overview: the middle and lower Han River watersheds

At a length of 1531 km, the Han River is the largest tributary of the Yangtze River. The middle- and lower-Han rivers begin at the downstream end of the Danjiangkou Reservoir and flows for about 650 km before joining the Yangtze River at Wuhan City (see Figure 10). The total area of the drainage basin is about 63 800 km2. The river's reaches have been extensively dammed since the 1950s and its course has been highly regulated by a series of coupled reservoirs, among which Danjiangkou Reservoir is the largest; also contributing to this is the water source for the Middle Route Project (MRP) for the South-to-North Water Diversion (SNWD) Project, about 9.5 billion m^3 of water will be extracted from the Danjiangkou Reservoir and supplied to northern China annually, amounting to about 30% of the current annual downstream discharge. In order to mitigate the project's effects, the Yangtze-Hanjiang Water Diversion Project (YHWD) is supposed to transfer water from the upstream of the Yangtze River to the downstream of the Hanjiang River near Qianjiang City with a maximum capacity of 500 m^3/s.

The cascade reservoirs and the inter-basin water diversion projects, i.e. the MRP and the YHWD, lead to profound and complex effects in the middle and lower Hanjiang River
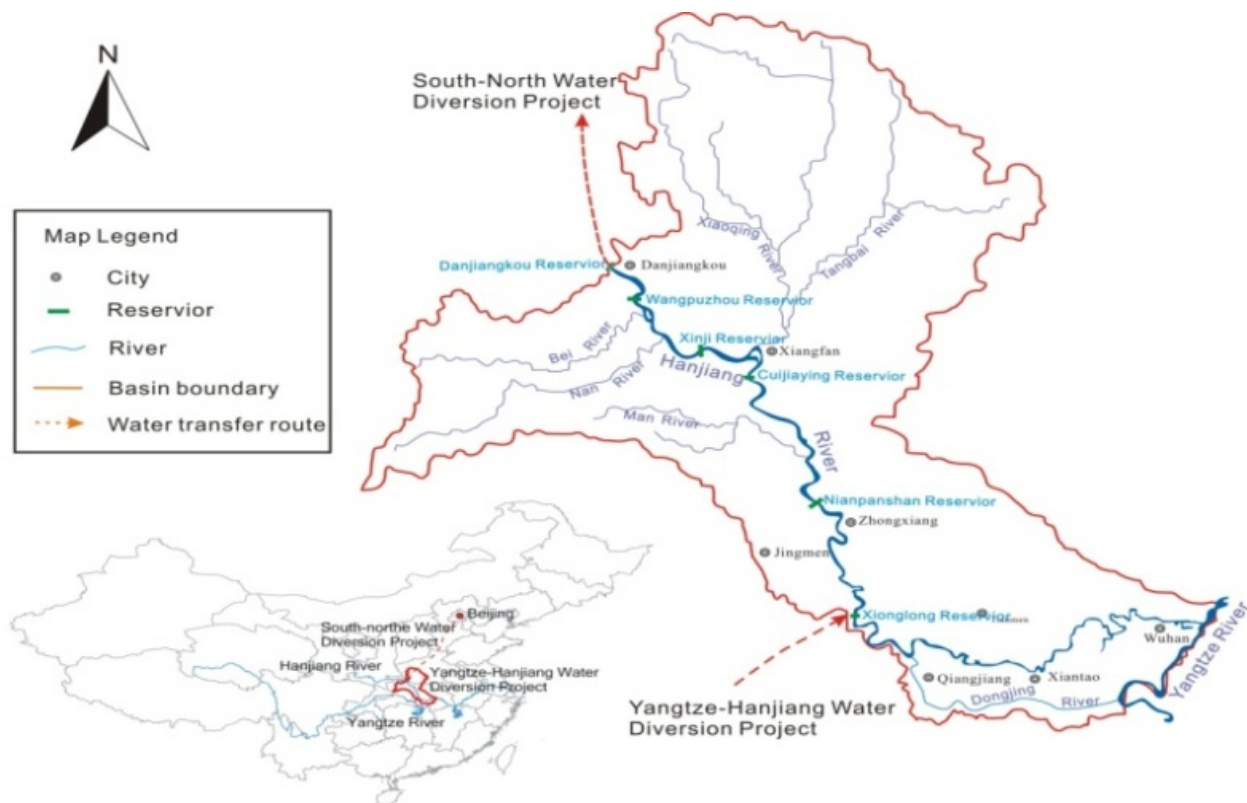

Figure 10. Location map for the middle and lower Han River Basin.

7.2.2. Application

7.2.2.1. Model set-up

A coupled one-dimensional hydrodynamic- and water-quality model was developed in a bid to assess water quality and quantity in the middle- and lower-Han rivers as a result of the impact of the operation of the cascade reservoirs and inter-basin water diversion projects. The systematic model includes numerical descriptions of the hydrodynamic and pollutant transport processes, the loads of different water users, stream-aquifer interactions, as well as the operations of cascade reservoirs and inter-basin water transfer projects (see Chapter 2).

7.2.2.2. Division of the study basin

The middle and lower Han rivers were divided into five reaches with 157 sections and the area outside the river was divided into 18 sub-hydrological units. A schematic illustration of the watershed is shown in Figure 11.
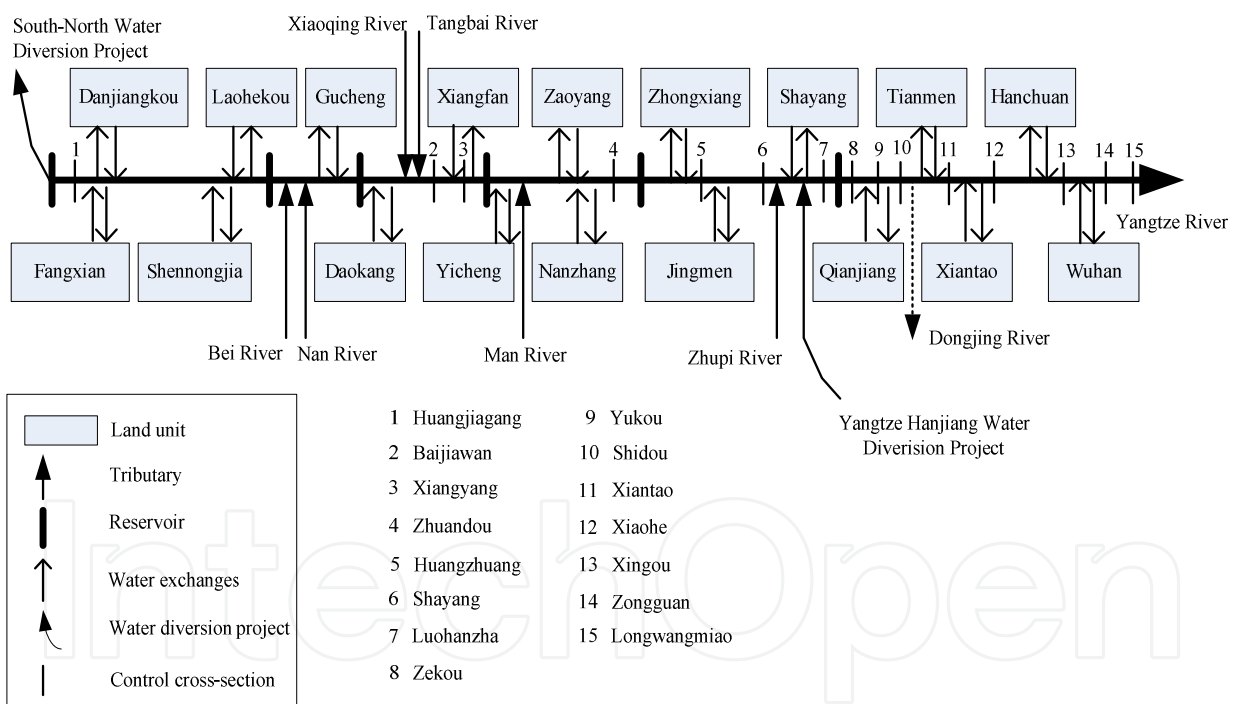
Figure 11. Schematic illustration of the basin.

7.2.2.3. Model calibration and validation

1. Parameters

Manning's roughness coefficient n1d took on the values of 0.03 to 0.055 according to a hydrological report from the Department of Water Resources of Hubei Province.

The value of the longitudinal dispersion coefficient ranged from 0.05 to 1 m^2/s, according to the national standard of the Technical Guide and Standard of Environmental Impact Assessment issued by China's Ministry of Environmental Protection. The degradation coefficients of pollutants are shown in Table 5.

Pollutant	COD_{Mn}	NH_3-N	TP
Degradation coefficient	0.25-0.3	0.33-0.35	0.06-0.09

Table 5. Degradation coefficients of different pollutants (d^{-1}).

2. Calibration and validation

The monitoring data of hydrodynamics and water quality from 2005 were used for calibrating the model. COD_{Mn}, NH_3-N and TP were chosen as water-quality indexes. The hydrodynamics and water quality were simulated along five monitoring sections using data from 2006 to 2007 to validate the model. The average relative deviations of the water levels between the simulated values and the measured values were within 1% of each other. The average relative deviations of the computed COD_{Mn}, NH_3-N and TP concentrations vs. the measured values were less than 20%. The model could therefore accurately simulate hydrodynamic conditions and water quality.
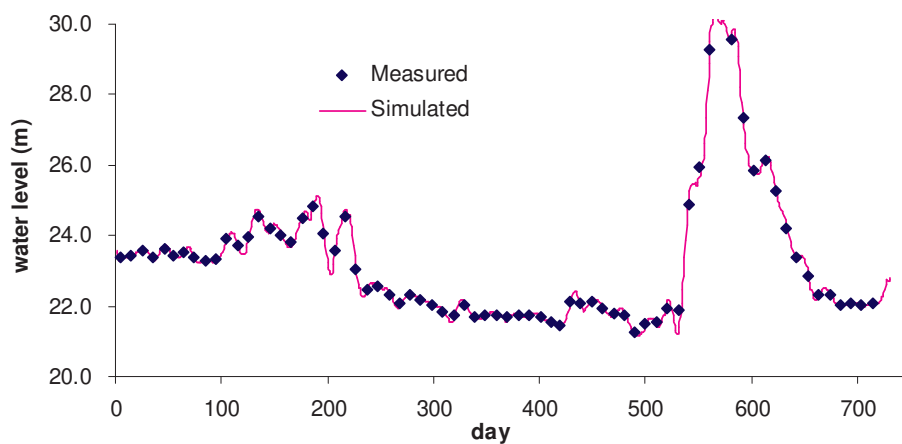
Figure 12. Hydrodynamic validation results of typical control cross-section 3.

7.2.3. Results

The long-term series of hydrological data from 1956 to 1998 were analysed to evaluate the long-standing trends in water quantity and quality of the middle and lower Han rivers. Two hydrological conditions were involved: the existing hydrological conditions prior to starting inter-basin water division projects and future hydrological-hydrodynamic conditions considering the cascade reservoirs and inter-basin water diversion projects (after initiating the projects).
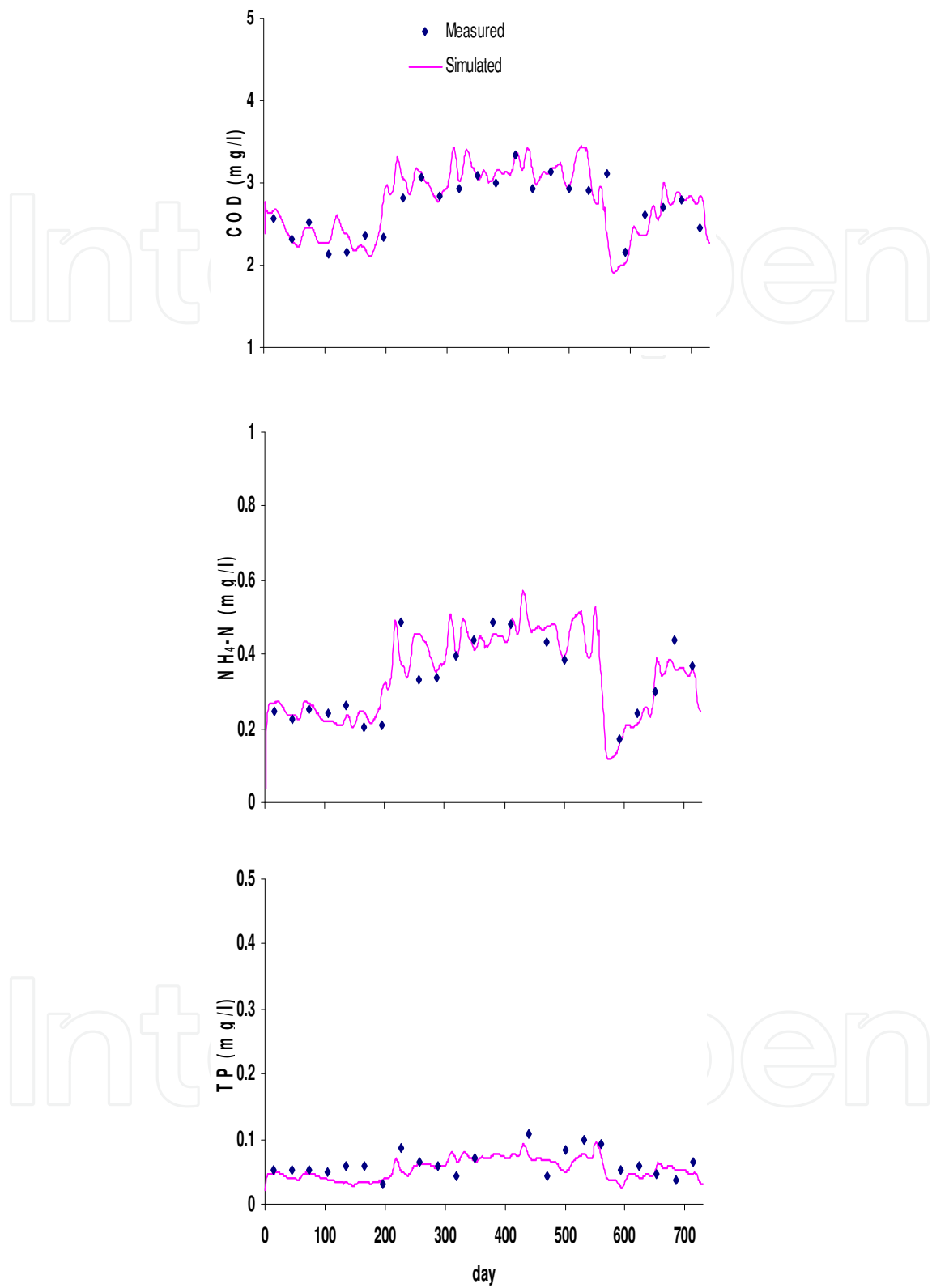
Figure 13. Water-quality validation results of typical control cross-section 3 (calculated and measured concentration of COD$_{Mn}$, NH$_3$-N and TP).

7.2.3.1. Analysis of water quantity

Based on the daily water demand/supply balance calculation, the discharge volume along the stream of the middle and lower Han rivers was analysed. Six sections in the middle and lower reaches were selected as control sections for six major cities along the river. Sections 1, 3, 5, 6, 8 and 13 respectively, represented the conditions of Danjiangkou, Xiangfan, Jingmen, Shayang, Qianjiang and Wuhan reaches.

Table 6 shows the average annual discharges of the six control sections prior to and following the projects. According to the calculated results, the problem of water deficiency will be serious for the middle reaches of the Han river in the future, as the operation of the MRP will significantly decrease stream discharge. As shown in Tables 7 and 8, operation of the cascade reservoirs and the MRP will significantly impact the hydrological/hydrodynamic conditions of the middle and lower Han rivers. The average water level will be decreased by 0.23 to 0.39 m in the river reaches downstream of Danjiangkou Reservoir, except for section 3 and section 6, which are controlled by the operation of Cuijiaying Reservoir and Xinglong Reservoir.

Control section	Before the projects (m³/s)	After the projects (m³/s)	Reduction
1	1161.6	811.3	-350.3
3	1292.7	912.7	-380.0
5	1518.0	1157.2	-360.8
6	1497.8	1139.3	-358.5
8	1341.5	1195.2	-146.3
13	1277.0	1140.0	-137.0

Table 6. Comparison of the average annual discharge of the control sections before/after the SNWD and YHWD projects.
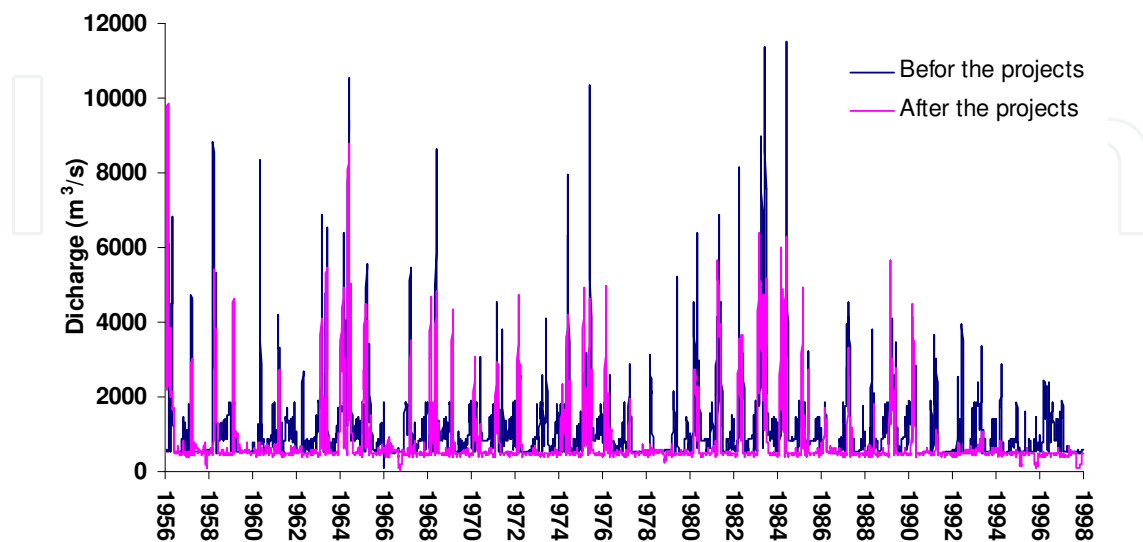

Figure 14. Calculated daily discharge of section 1 before/after the projects.
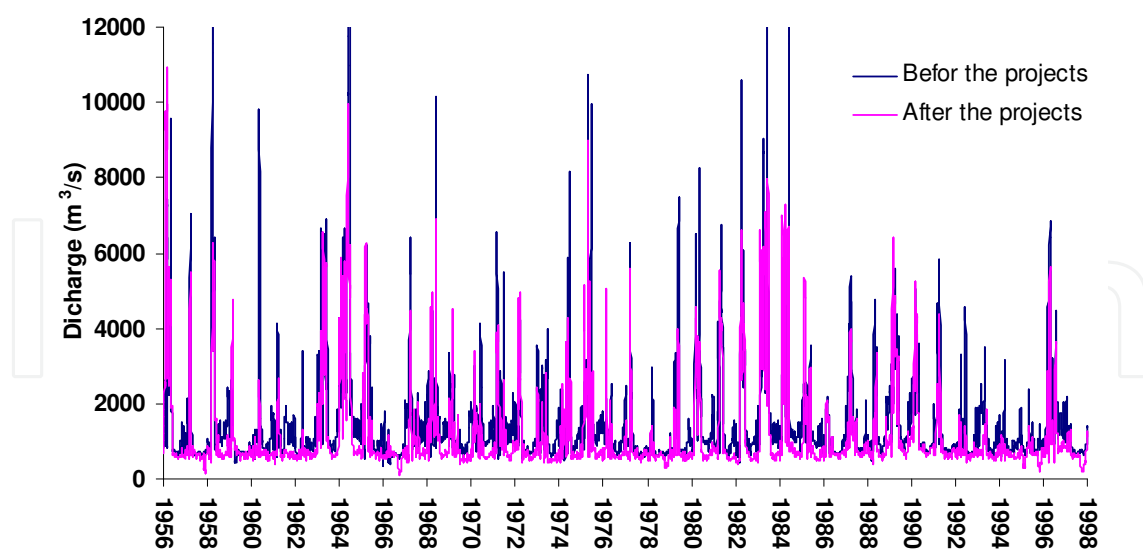
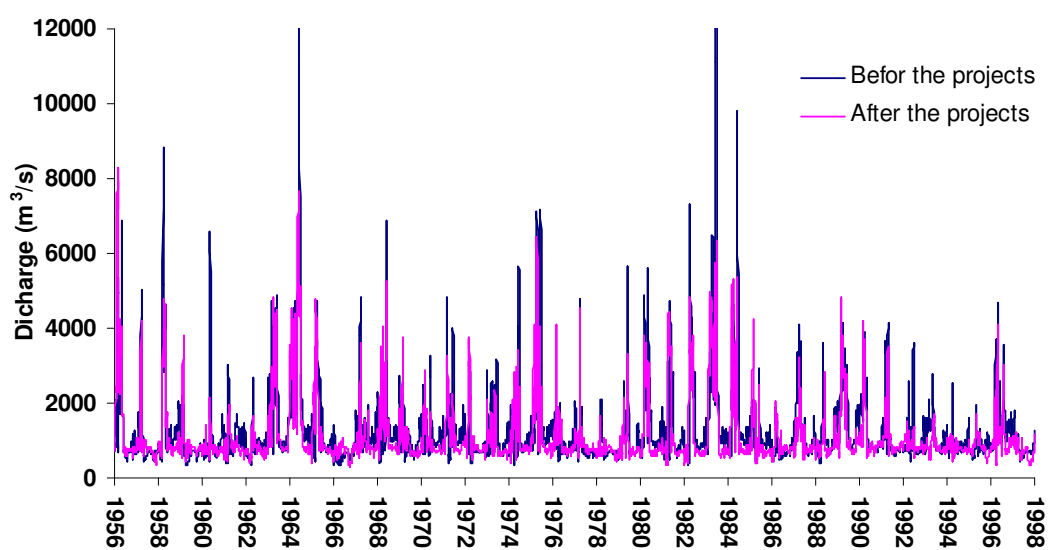**Figure 15.** Calculated daily discharge of section 3 before/after the projects.

Figure 16. Calculated daily discharge of section 13 before/after the projects.

Control section	Before the projects (m)	After the projects (m)	Reduction
1	87.23	86.85	-0.38
3	58.67	62.78	4.11
5	40.04	39.65	-0.39
6	33.47	36.35	2.88
8	29.5	29.27	-0.23
11	24.29	24.03	-0.26

Table 7. Comparison of the average annual water level of the control sections before/after the SNWD and YHWD projects.

Control section	Before the projects (m/s)	After the projects (m/s)	Reduction
1	0.73	0.59	-0.14
3	0.9	0.31	-0.59
5	1.11	0.97	-0.14
6	0.69	0.32	-0.37
8	0.74	0.72	-0.02
11	0.67	0.64	-0.03

Table 8. Comparison of the average annual flow velocity of the control sections before/after the SNWD and YHWD projects.

7.2.3.2. Analysis of water quality

The results showed that the middle-lower reaches of the Han river will have similar trends of water-quality degradation. The average concentration of COD_{Mn} in the river was 2.61 mg/L, NH3-N 0.52 mg/L and TP 0.16 mg/L with existing hydrological-hydrodynamic conditions; with future operation of the cascade reservoirs and inter-basin water diversion projects, the average concentration of COD_{Mn} will increase by 55% to 4.04 mg/L, NH_3-N by 48% to 0.78 mg/L and TP by 46% to 0.24 mg/L.

Following the completion of the projects, the water quality will be degraded to Class IV. This result indicates that the operation of the YHWD project will be unable to mitigate water-quality deterioration in the lower Han River. The model simulations indicated that the dual effects of the projects, i.e., increasing the nutrient concentration and decreasing the flow velocity, could induce an environment favourable for algal growth. Thus, large-scale blooms likely occurred, even if only in the middle reaches of the river.

Sections	COD_{Mn}		NH_3-N		TP	
	Before the projects	After the projects	Before the projects	After the projects	Before the projects	After the projects
1	2.08	3.09	0.14	0.22	0.03	0.04
2	3.18	4.67	0.75	1.09	0.14	0.20
4	3.04	4.47	0.68	1.00	0.15	0.22
5	2.97	4.38	0.61	0.91	0.16	0.23
6	2.65	3.99	0.54	0.82	0.16	0.23
7	2.62	3.95	0.53	0.81	0.16	0.23
8	2.38	4.04	0.47	0.73	0.16	0.24
9	2.30	3.89	0.45	0.70	0.15	0.24
10	2.17	3.65	0.42	0.65	0.17	0.24
11	2.47	3.94	0.48	0.71	0.17	0.25
12	2.51	3.86	0.48	0.68	0.17	0.25
13	2.49	3.83	0.47	0.68	0.17	0.25
14	2.66	3.92	0.47	0.67	0.18	0.26
15	2.47	3.98	0.47	0.67	0.18	0.26

Table 9. Comparison of the simulated water quality of the main sections before/after the SNWD and YHWD projects.
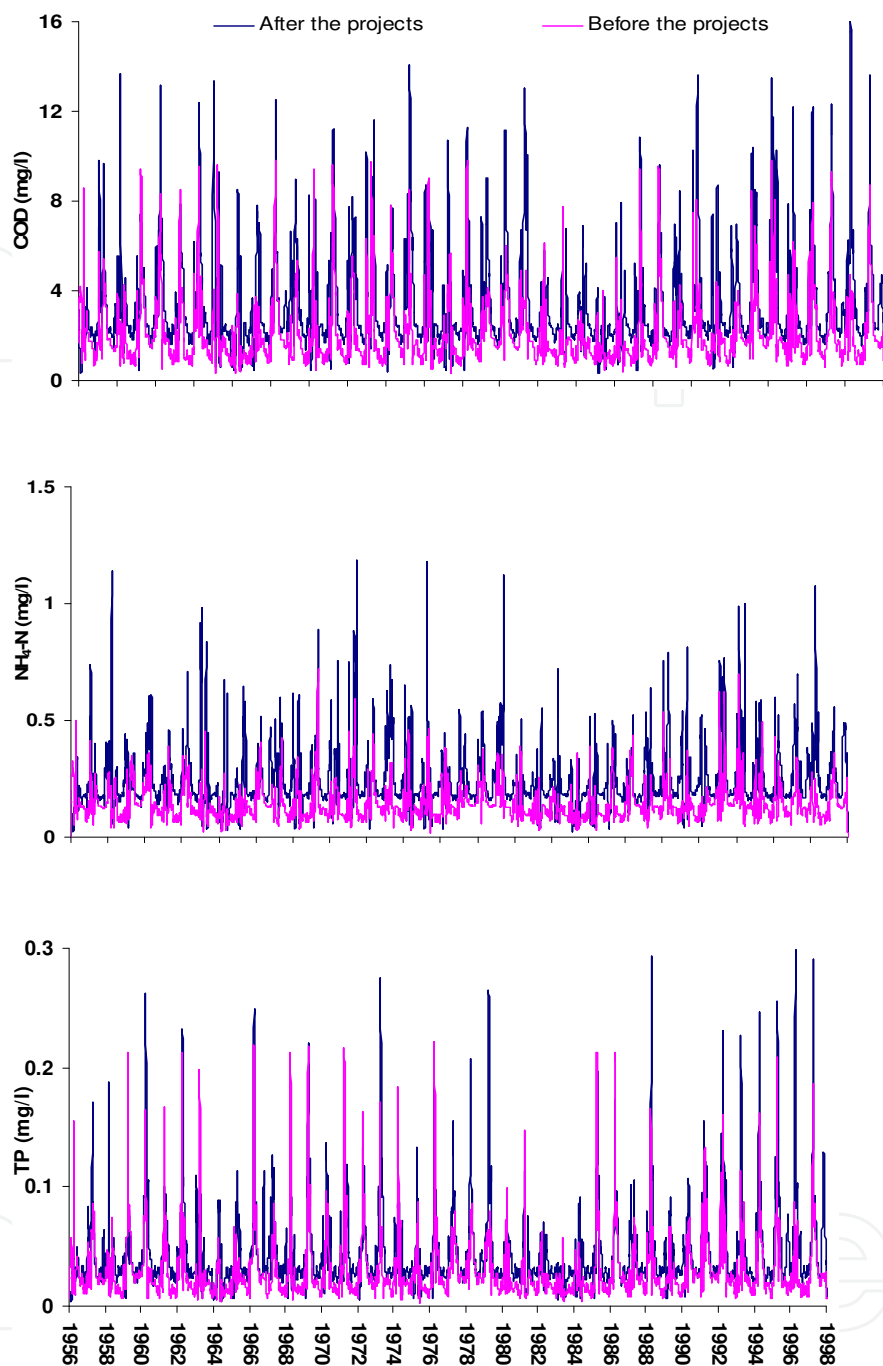
Figure 17. Calculated daily concentrations of COD, NH$_3$-N and TP of section 4 before/after the projects

7.2.4. Conclusions

A combined water-quantity-quality model was applied to simulate the current and future characteristics of water quantity and water quality in the middle and lower Han rivers. The simulation results showed that the implementation of the MRP and the operation of cascade reservoirs will exacerbate the problems of water pollution and water deficiency in the middle

and lower reaches of the river. This model can assist water resource managers to make the right decisions about water improvement measures.

7.3. East Lake experimental research survey and typical environmental processes

7.3.1. The natural environment

East Lake is constituted by Guozheng Lake, Hou Lake, Miao Lake, Shuiguo Lake, Tangling Lake and others. Its geological structure is complex; the length of East Lake is 11.5 km and its average width 2.9 km. East Lake is connected to the Yangtze River via the Castle Peak port.

East Lake lies in Wuchang, which is the political, cultural and information centre of Hubei Province.

7.3.2. The non-point source water quality model

We built the non-point source model based on the digital elevation map (DEM). On the basis of hydraulics and the water quality model, we established the East Lake three-dimensional hydrodynamic and water quality model equation (see Chapter 2).This scenario was based on 2006 calibration results. After removing the point sources, we used the non-point source data to simulate the water quality status of East Lake from 2007 to 2010.

7.3.2.1. Division of the study basin

East Lake was divided into five reaches and the quantity of grid measured as 47 x 62; a schematic illustration of the watershed is shown in Figure 18.

Figure 18. The division map for East Lake.

7.3.2.2. Correlation parameters

According to the measured data of East Lake from 2000 to 2005, we calibrated parameters, such as roughness coefficient, nitrogen degradation coefficient, organophosphate degradation coefficient in this study.

7.3.2.3. Computational conditions and pollution load input values

Using the measured results of water level and water quality from 2006 as initial conditions for control within the model, we calculated the changing process of flow, water level, water temperature, as well as the water quality of TP, TN, NH_4, DO.

Through a survey about the pollution circumstances of East Lake, we confirmed 22 outlets surrounding the main point source and 61 non-point source outlets. Their positions are shown in Figure 19.
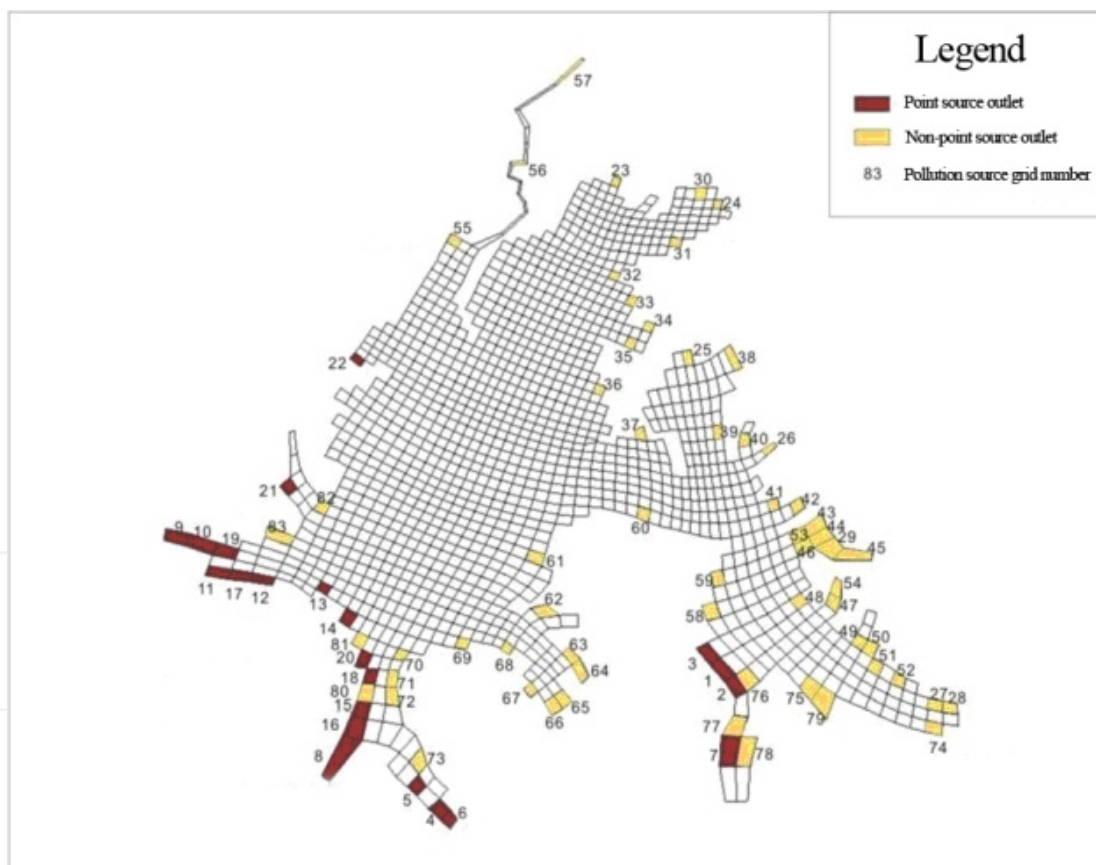
Figure 19. The source of pollutants map for East Lake.

7.3.2.4. Model validation

In this research, we used measured data of East Lake from 2006 to verify the model.
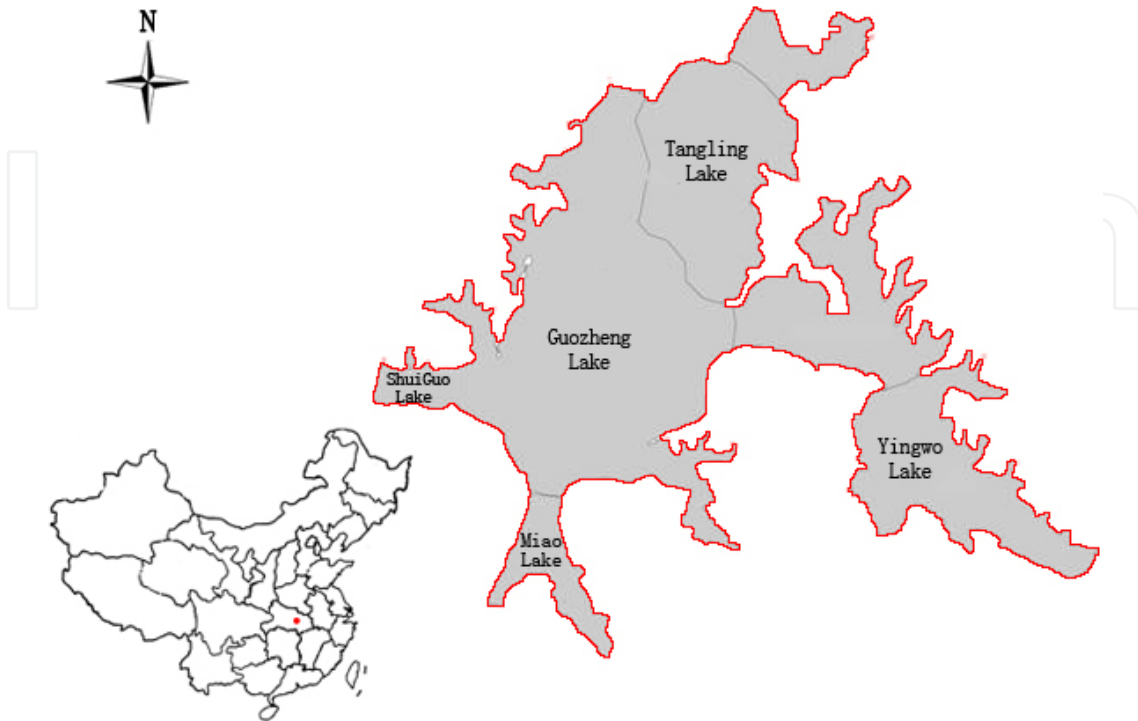
Figure 20. Location map of East Lake.

The model was verified as follows:

1.   Results for Miao Lake verification are shown in Figures 21 to 24 below:
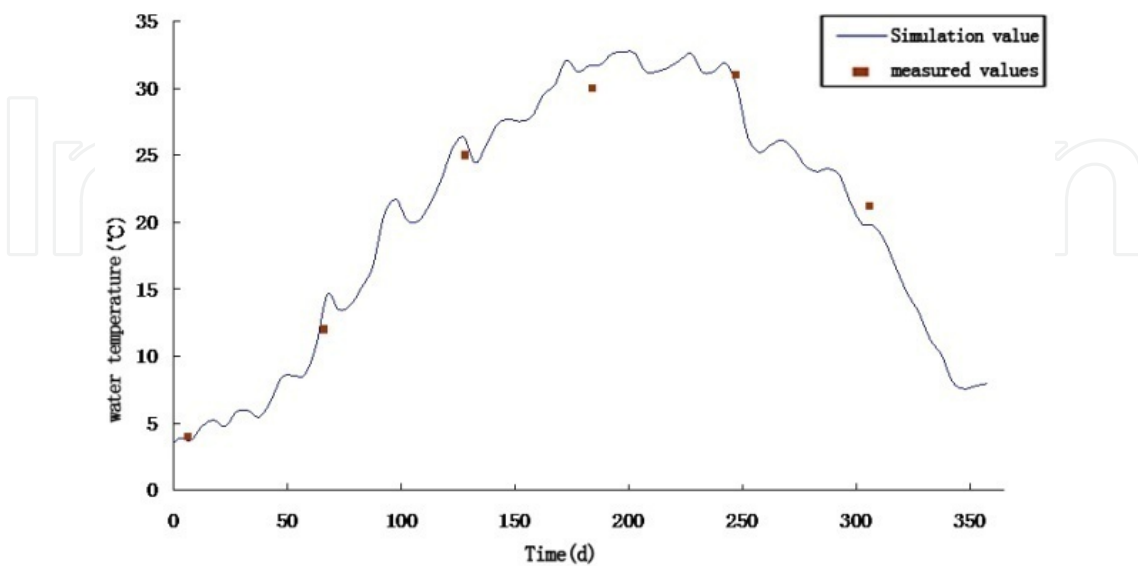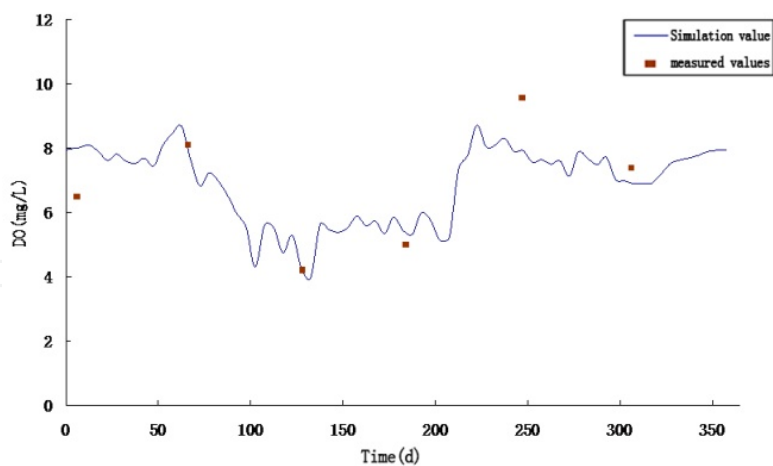

Figure 21. Verification chart for Miao Lake temperature.
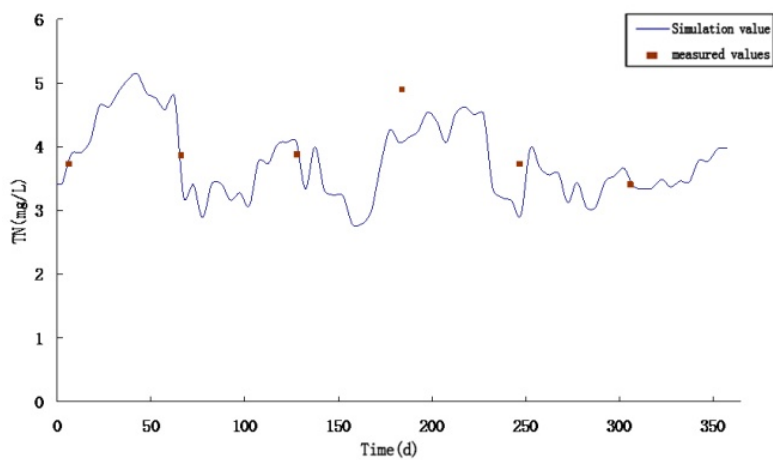
Figure 22. Verification chart for Miao Lake DO.
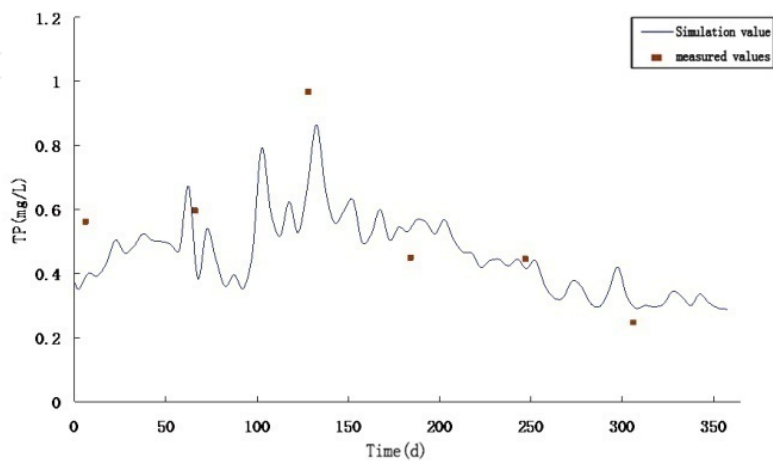

Figure 23. Verification chart for Miao Lake TN.

Figure 24. Verification chart for Miao Lake TP.

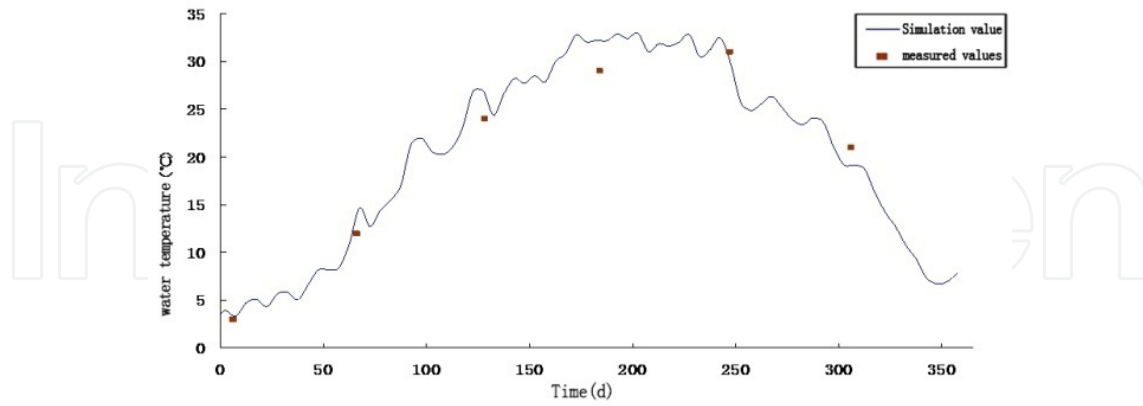**2.**   The verification results for Tangling Lake are shown in Figures 25 and 26 below:

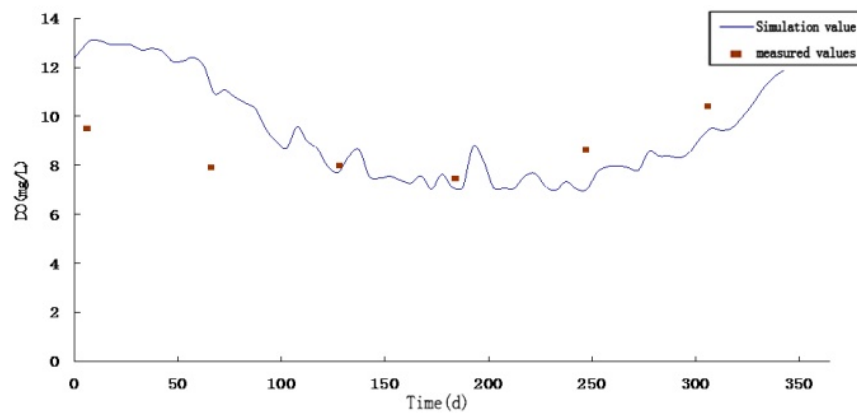**Figure 25.** Verification chart for Tangling Lake temperature.

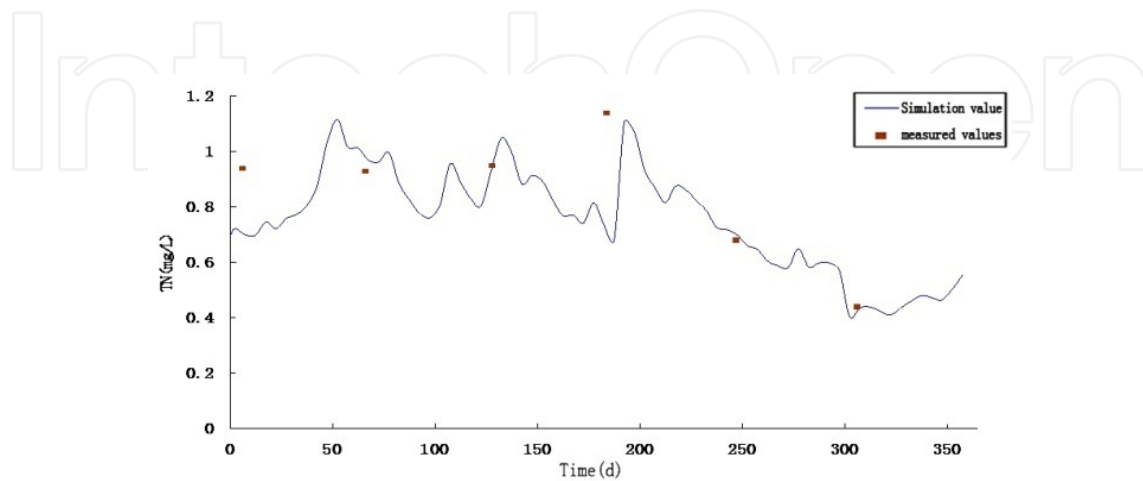**Figure 26.** The verification chart for Tangling Lake DO.

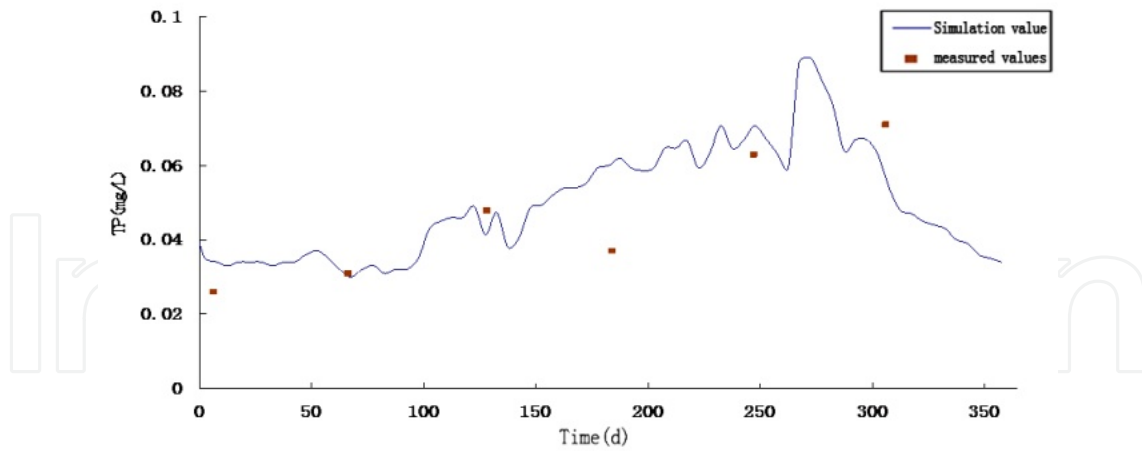**Figure 27.** The verification chart for Tangling Lake TN.

Figure 28. Verification chart for Tangling Lake TP.

The verification charts show that the maximum error of simulated calculation was less than 20% when compared to the measured concentration. The relative error in about 96% of samples was less than 10%. Results showed that the model was able to meet the requirements of simulation research.

7.3.2.5. Model application

The simulation results showed that the management of point sources will improve the water quality of East Lake, but that the effect will not be obvious in the short-term. The management of non-point source pollution should also be strengthened.

We conducted our research by including two study lakes. The results showed that the water quality of Miao Lake improved significantly, while Tang Ling Lake's did not.
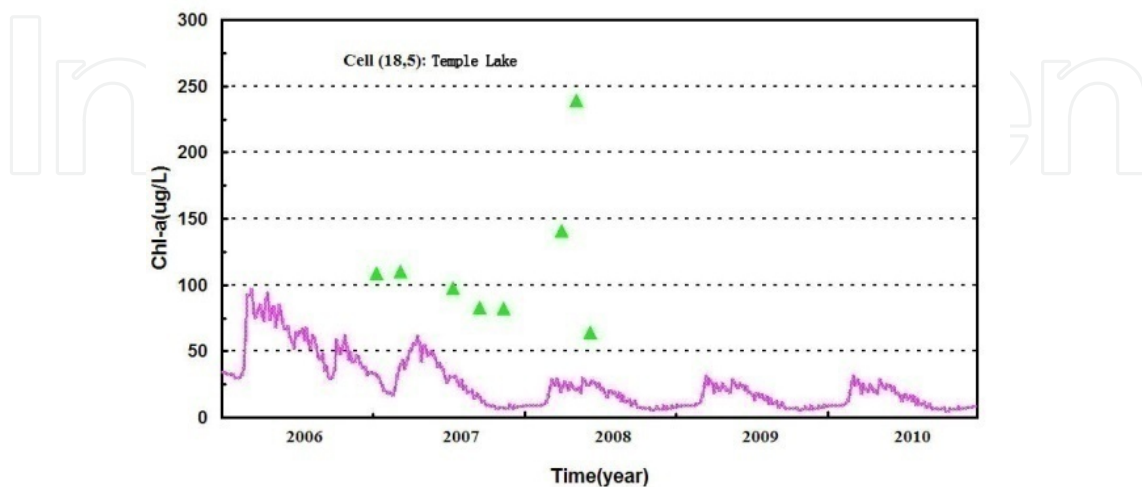

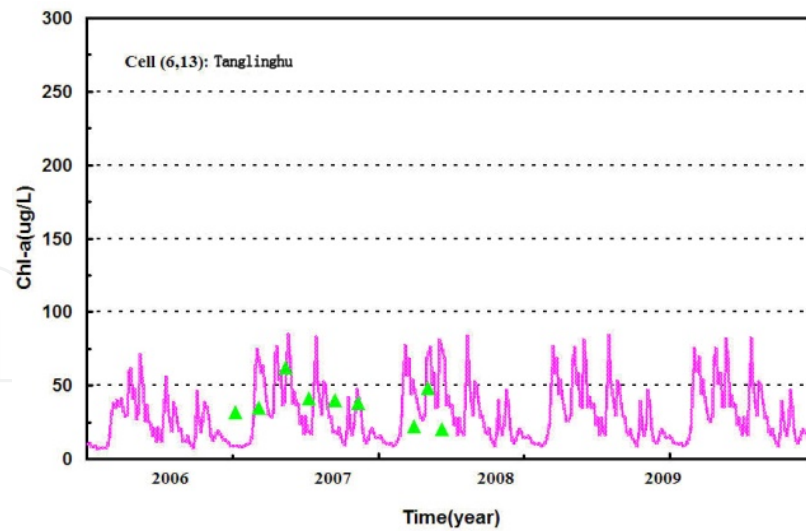**Figure 29.** Water quality simulation of Miao Lake.

Figure 30. Water quality simulation of Tangling Lake.

7.3.3. Conclusion

The present research established a three-dimensional layered water hydrodynamic numerical model of East Lake. Using the measured data of hydrology and water quality from 2006, we completed the model parameters for calibration and validation. Then, we analysed the water quality and drew the following conclusion: the water quality of East Lake region must be improved. Factors such as non-point source and sediment need to be considered in the overall consideration.

8. Conclusion

The watersheds water environment system model established in this study has a solid theoretical basis and was successfully applied in the water environment response and simulation analysis of Tai Lake, the middle and lower Han rivers and East Lake.

1. We established a two-dimensional interfaced complex model of the river-lake network coupled with water quality, which was applied to the river network of Lake Tai using a series of conditions related to social economy, population, meteorological and hydrological factors measured in 2007. The research findings are fairly adaptive to wider application in terms of water resource conservation and environmental management.

2. We used the coupled water-quantity-quality model to simulate the current and future characteristics of water quantity and water quality for the middle and lower Han rivers. The model can assist administrators decision-making concerning water improvement measures.

3. Based on the hydraulic and water quality models, we created a three dimensional hydrodynamic and water quality model that can be successfully applied to the simulation of non-point source pollution, thereby providing a scientific tool for water environment management work.

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