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Development and Application of A Coupled Modeling System in A Shallow Lake*

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Abstract: *Growing developments in lake basins in China, have adversely affected the water quality of lake, in particular, the water bodies of many famous shallow lake are seriously polluted in recent years. Some projects have been built up to improve the water quality, for example, the sewage interception project (i.e. Xiyuan tunnel project) and four sewage treatment plants etc. have been built up in Dianchi Lake. In order to predict and evaluate the effects of projects on the water quality, it is necessary to develop a coupled model system, which should mainly include wind, circulation and water quality parameters. This paper describes the development and application of a coupled modeling system in a shallow lake, which include a 3D micro-meteorology model (3DMM), a 2D hydrodynamic model (2DHM) and a 2D water quality model(2DWM).The coupled modeling system has been applied to predict the effects of environmental protection projects on water quality in Dianchi Lake.*

Keywords: *Shallow lake, Coupled modeling system, 3DMM, 2DHM, 2DWM*

1. Introduction

Although hydrodynamics and water quality models have been significantly advanced in recent years, and have been used to assist the management of lake or reservoir resources. But earlier models often used coarse grid and contained loosely coupled or uncoupled models between the hydrodynamic and water quality.

To illustrate situations where coupled models are needed, we first present a few typical problems for shallow lake system.

① In recent years, many of shallow lake systems (e.g., Dianchi Lake, Taihu Lake, Chaohu Lake, etc.), that are very important fresh water resources in China, are subjected to heavy pressure from water quality increasingly worsening. In these shallow lakes, the main water quality problems are of organic pollution and eutrophication.

② It has become increasingly evident that physical mixing processes in lakes and reservoirs have significant effects on water quality, in particular, wind-induced water movements are

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responsible for the transport of nutrients and the dispersion of effluents in a shallow lake (George, 1981).

③ Wind is the most major force that induces water movement in a shallow lake, when wind-induced currents were simulated with numerical models the approximations of a spatially uniform and timely constant wind field over the simulated area were normally made in past 2-3 decades. However, many evidences have shown that these simplifications are not valid in most case, and can lead to serious error in the computed flow field (J.Józsa, *et al.*, 1990; Li Jinxiu, *et al.*, 1996).

④ In fact, when wind flows across a lake, in particular, flows across a large lake, there must be a non-uniform wind field over lake because of the effects of complex topography around lake and the surface roughness difference between water and land (Pang Yong, *et al.*, 1995).

⑤ In order to precisely quantify the wind-induced circulation and water quality distribution, we can't rely on the generally limited field data to give us some comprehensive story, the field data can give us some quantitative understanding of a lake system, but there are always data gaps (both in space and time) that must be filled. Modeling is a good tool to synthesize all the field data to put a comprehensive story, and then modeling can be used to predict the further conditions of a lake system.

Recognizing the intimate relationships among the various ecological components (including wind, hydrodynamics, water quality, etc.) and the important role of model in understanding of a lake system. A comprehensive modeling system is therefore required to answer the questions of a lake system. The modeling system should include a micro-meteorology model, a hydro-dynamic model and a water quality model.

This paper describes the development and application of a coupled modeling system in Dianchi Lake. It includes a 3D micro-meteorology model used to simulate the complex wind field over lake, a 2D hydrodynamic model used to simulate the wind-driven currents and a 2D COD (chemical oxygen demand) water quality model used to simulate the COD concentrations distributions. The details of the eutrophication model (include the indices: nitrogen, phosphorus, chlorophyll and temperature etc.) will be given by Yu Xuezhong soon.

2. Description of Dianchi Lake

Dianchi Lake is a famous fresh lake in the plateau in China, it is located in the southern suburbs from Kunming city in Yunnan province, with a surface of 298 km^2, and a average depth of 3 m-5 m. The length of lake from south to north is about 40km and the maximum width from east to west is 12.5km, the lake is in the shape of a bow-from north to south. In the western side of the lake there are hills, which are 100 m-500 m high from the water surface and form a wind-sheltered zone close to the west side. The sketch map of Dianchi Lake is shown in fig. 1.

A natural dike in the northern part of the lake separates the lake into two water zones, which are connected by navigating channel opened in the dike. The northern zone is named Caohai with a surface area 11 km^2 and the southern water zone is the main body of Dianchi Lake, named Waihai with a surface area 287 km^2.

In 1994, the average COD concentration reached 10.7 $mg \cdot L^{-1}$ in Dianchi Lake, a total of 28 218 ton of COD loading which mainly came from north point sources (Kunming city) entered the lake, and at least 85 % of COD was accumulated in Dianchi Lake because of the reasons as following:

① There is only one outflow in the south-western bank of lake, the pollutant sources are largely distributed in the northern of lake. These disadvantage conditions result in that the water quality of outflow is relatively better than that of inflows.

② Because of the effect of lower velocity and long distance movement of effluent from inflows to outflow, it is very not benefit to drainage of pollutant away from lake, and so many pollutants are accumulated in lake.

Recently, some projects have been built up to improve the water quality, which mainly include the project of Xiyuan tunnel (see figure1) and four sewage treatment plants. The Xiyuan tunnel is used to change the water flow condition in Dianchi Lake. The seriously polluted water in Caohai is drained directly to Xiyuan tunnel and may shorten the movement distance of effluent from inflows to outflow may be shorted, Caohai and Waihai are really separated by ship lock. The four sewage treatment plants are used to treat the sewage from Kunming city, and according to the design standard, the total COD loading is expected to decrease by 40 %.

To asses the effect of these projects on the water quality of Dianchi Lake, we used the coupled modeling system described below to simulate the circulation and the COD concentration distribution.

3. A Coupled Modeling System in Shallow Lake

3.1. A 3D micro-meteorology model (3DMM)

To meet complex topography surrounding Dianchi Lake, we develop a terrain-following (x, y, $\bar{z}$) coordinate three dimensional micro-meteorology model, define $\bar{z}$ as follow:

$$\bar{Z} = H(Z - Z_g)/(H - Z_g)$$

where, H is the top height of initial model, Z_g is the terrain height.

Based on assumption of dry and incompressible in the modeled atmosphere, the motion of atmosphere in (x, y, $\bar{z}$) coordinate system can be described as follow:

$$\frac{du}{dt} = -\theta \frac{\partial \pi}{\partial x} + g \frac{\bar{z} - H}{H} \cdot \frac{\partial Z_g}{\partial x} + f \cdot v + F_u$$

$$\frac{dv}{dt} = -\theta \frac{\partial \pi}{\partial y} + g \frac{\bar{z} - H}{H} \frac{\partial Z_g}{\partial y} - f \cdot u + F_v$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \bar{\omega}}{\partial \bar{z}} - \frac{u}{H - Zg} \cdot \frac{\partial Z_g}{\partial x} - \frac{v}{H - Z_g} \cdot \frac{\partial Z_g}{\partial y} = 0$$

$$\frac{d\theta}{dt} = F_\theta,$$

$$\frac{\partial \pi}{\partial \bar{z}} = -\frac{H - Z_g}{H} \cdot \frac{g}{\theta}$$

where,

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + \bar{\omega}\frac{\partial}{\partial \bar{z}}$$

$$\bar{\omega} = \omega\frac{H}{H - Z_g} + \frac{\bar{z} - H}{H - Z_g} \cdot u \cdot \frac{\partial Z_g}{\partial x} + \frac{\bar{z} - H}{H - Z_g} \cdot v \cdot \frac{\partial Z_g}{\partial y}$$

u, v, ω are the wind velocities in x, y, z directions respectively, $\bar{\omega}$ is wind velocity in $\bar{z}$ direction, f is the coriolis parameter, θ is the potential temperature.

$\pi = C_p\left(P/P_0\right)^{R/C_p}$ is Exner function representing atmosphere pressure,

P_0=1 000 hPa.

F_u, F_v, F_θ are turbulent eddy term representing the u, v, θ respectively. Where:

$$F_\phi = K_H \cdot (\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2}) + \left(\frac{H}{H - Zg}\right)^2 \cdot \frac{\partial}{\partial \bar{z}}\left(K_V \cdot \frac{\partial \phi}{\partial \bar{z}}\right)$$

where, K_H, K_V are turbulent eddy coefficients in horizontal and vertical directions respectively.

The 3DMM was compared with analytical solutions for three idealized airflow before being calibrated and verified with field data from Dianchi Lake (Li Shujun, 1996).The turbulent eddy coefficients in horizontal and vertical directions respectively were given,

K_H =50m^2·s^{-1}

$K_V(z) = K_V(z_1)\frac{z}{z_1}\exp\left[-\rho(z - z_1)/h\right]$ K_v was taken by Shir and Shieh empirical relationship (Shir, C. & C., Shieh, L. J.),where z_1=10m which represents the height of wind station, ρ is the stability coefficient of atmosphere, and was given ρ=2.0, h is the height of mixing layer.

3.2 A 2D Hydrodynamic Model (2DHM)

In the majority of shallow lakes, the horizontal spatial patterns of water quality is more important than the vertical spatial patterns, the water body can be treated as a two-components system which is of practicality. Therefore, the depth-integrated 2D plane non-steady flow equations are applied for describing the water movement of lake.

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}(u\cdot M)+\frac{\partial}{\partial y}(v\cdot M)=-g\cdot H\frac{\partial H}{\partial x}+f\cdot N+\frac{1}{\rho}(\tau_{x(s)}-\tau_{x(b)})$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(u\cdot N)+\frac{\partial}{\partial y}(v\cdot N)=-g\cdot H\frac{\partial H}{\partial y}-f\cdot M+\frac{1}{\rho}(\tau_{y(s)}-\tau_{y(b)})$$

where, Z is the water surface elevation, h is the water depth, $h=Z-Z_b$, Z_b is the bed elevation. u, v are the velocity components in x, y directions, M,N are the discharges per unit width in x, y directions, f is the Coriolis parameter, $\tau_{x(b)},\tau_{y(b)}$ are the bottom friction stresses in x, y directions, $\tau_{x(s)}$ $\tau_{y(s)}$ are the wind stresses at surface in x, y directions.

$$\tau_{x(s)}=\rho_a C_D\cdot w\cdot w_x \qquad \tau_{y(s)}=\rho_a C_D\cdot w\cdot w_y$$

where, ρ_a is air density, w_x, w_y are the wind velocity components in x, y direction respectively, and w is wind speed at an elevation of 10 m above the lake surface, C_D is a surface drag coefficient. According to Bendtsson, the drag coefficient is about 1.0×10^{-3} in most fresh water, and the most convenient wind drag coefficient was set at about 1.3×10^{-3} in a shallow lake. $\tau_{x(b)},\tau_{y(b)}$ are the bottom friction stresses in x, y directions respectively.

$$\tau_{x(b)}=c_b\cdot\rho\cdot u\cdot\sqrt{u^2+v^2}\ \ \tau_{y(b)}=c_b\cdot\rho\cdot v\cdot\sqrt{u^2+v^2}$$

c_b is the bottom friction coefficient, and is given by Chezy formula as $c_b=\frac{1}{n}\cdot h^{\frac{1}{6}}$, n is the bed roughness of lake.

Numerical tests with 2DHM indicated that the bed roughness has little effect on the flow patterns in Dianchi Lake, and may be given by empirical value about 0.02.

3.3 A 2D COD Water Quality Model (2DWM)

In early water quality models were often used coarse grid spacing and large time step, even used a few boxes to resolve a lake. The reasons of that are: (i) the computation is more efficient, and (ii) it has been argued that water quality variations are of much larger spatial and temporal scales than that of hydraulic variations, they do not properly incorporate the effect of hydrodynamics. Although these simplifications of computation may work sometimes, such an approach in general has many deficiencies. Primarily, due to the poorer representation of the hydrodynamics, typical water quality models contain greater uncertainty, which limits its predictability.

In this study, we develop a COD water quality model, which is solved with the same time step and spatial grid as the hydrodynamic model. The fundamental equations of motion used as

$$\frac{\partial(hC)}{\partial t}+\frac{\partial(UC)}{\partial x}+\frac{\partial(VC)}{\partial y}=\frac{\partial}{\partial x}\left(K_x h\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y h\frac{\partial C}{\partial y}\right)+S+\lambda\cdot h\cdot C$$

where, C is the COD concentration, K_x, K_y is the turbulent diffusion coefficient x, y directions respectively, s is the term of sources (or sinks), λ is the COD comprehensive decay coefficient.

The K_x, K_y were taken by empirical formulation by Lam *et al.* (Bowie, *et al*, 1985)

$K_x = K_y = 0.0056L^{1.3}$, where L is the length of computed grid (cm).In 2DWM of Dianchi Lake, the space grid with L=50 000 cm,and $K_x = K_y$ =0.8 $m^2 \cdot s^{-1}$.

The COD comprehensive decay coefficient λ is calibrated by measured data from Dianchi Lake, the constant value of 0.025 $1 \cdot d^{-1}$ was given.

These three models described above make a modeling system,

3DMM → 2DHM → 2DWM

Modeling System in Dianchi Lake

A regular explicit finite difference method is used to solve the modeling system, with a grid spacing of 500m×500m for 2DHM and 2DWM. In the 3DMM, the horizontal grid spacing was 1000m×1000m, in the vertical direction, was represented by layers with non-uniform thickness.

4. Modeling System Application in Dianchi Lake

In this paper, we use the modeling system to characterize the hydrodynamic phenomena, and predict the COD concentration distributions of Dianchi Lake under six conditions, and to asses the effect of these projects (e.g. Xiyuan tunnel and four sewage treatment plants) on the water quality of Dianchi Lake.

4.1 The main flow pattern in Dianchi Lake

The river inflows and outflow entering the lake with low quantity have relatively low effect on the generally circulation pattern. The water system in Dianchi Lake is shown in Fig. 1. The water movements of lake are therefore greatly induced by wind over lake. Dianchi Lake is located in the southwest monsoon climate zone, the south-west wind is the annual prevailing wind direction.

With a coupled of 3DMM and 2DHM, computed wind field over lake and flow field are shown in Fig. 2, 3. The wind field is really non-uniform because of the effect of hills shelter, and the computed flow field under non-uniform is fitting better the measured lake flows (Fig. 4) than the computed flow field with uniform wind field (Li Jinxiu, *et al.*, 1996).

4.2 The Water quality predicting

To examine the effect of the Xiyuan tunnel and four sewage treatment plants on the water quality, we compare the results of six model-runs: (1) present condition, the two water bodies of Caohai and Waihai are connected by navigating channel; (2) the future condition, the Xiyuan tunnel and four sewage treatment plant will run, the water in Caohai will be drained directly to Xiyuan tunnel, Caohai and Waihai will be really separated by ship lock; (3) the condition(1) and

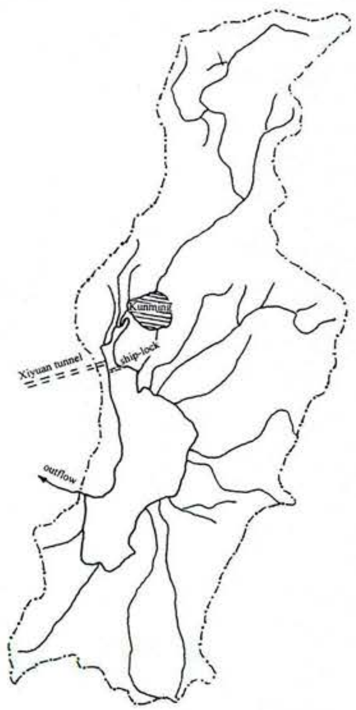

Fig. 1 Sktch map of water system in Dianchi Lake

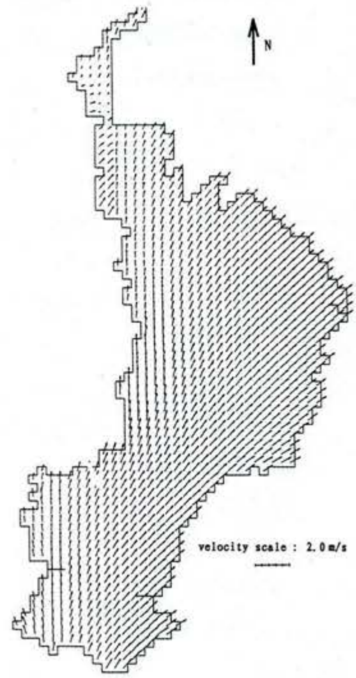

Fig. 2 Simulated horizontal wind field (SW wind: 4.2 $m \cdot s^{-1}$) at 10 m height from the surface of Dianchi Lake

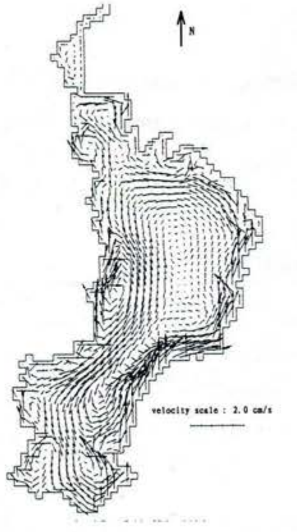

Fig. 3 Simulated flow field in Dianchi Lake under simulated wind field

Fig. 4 Measured flow direction at 0.1 h of relative water depth

(2) will run under SW wind condition and different hydrological years which include the wet year, dry year and the mean water year. Simulated COD concentration value with coupled modeling system under three hydrological years and two project measure conditions as tab.1, fig. 5 and figure6 (other cases omitted).

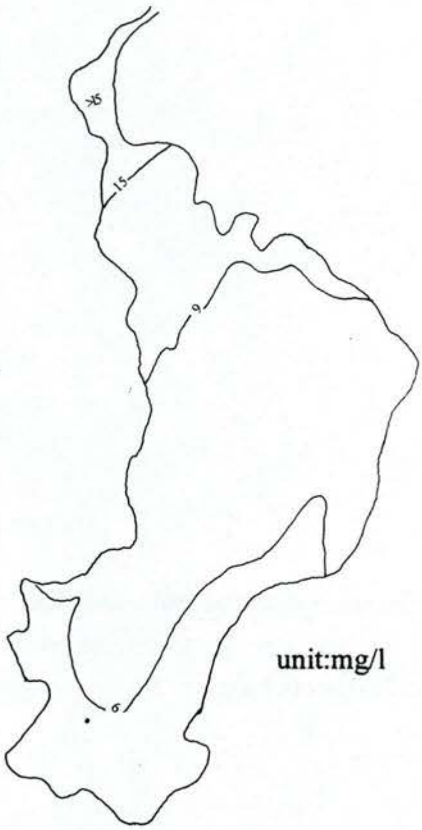

Fig. 5 Simulated COD concentration distribution in Dianchi Lake under conditions of present, dry year and SW wind

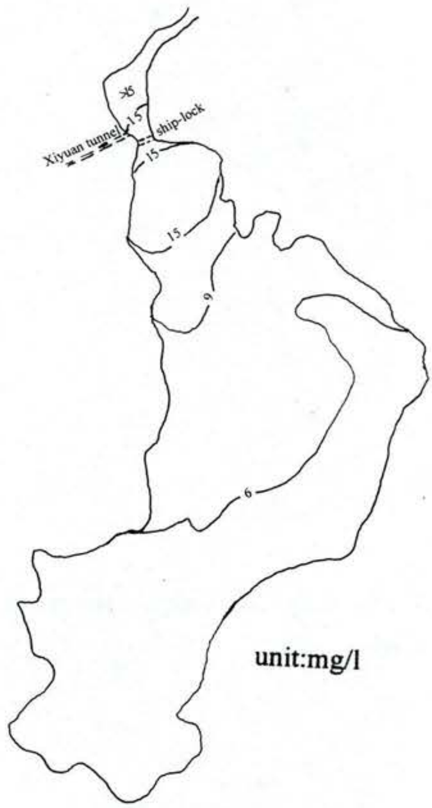

Fig. 6 Simulated COD concentration distribution in Dianchi Lake under conditions of future, dry year and SW wind

Tab.1 Simulated COD concentration under six conditions (unit: $mg \cdot L^{-1}$)

		Wet year	Dry year	mean year
Average concentration	Present condition	20.04	22.14	18.27
In Caohai($mg \cdot L^{-1}$)	Future condition	16.24	20.34	19.35
Average concentration	Present condition	8.69	12.85	10.08
In Waihai($mg \cdot L^{-1}$)	Future condition	5.34	7.88	7.26

The above results indicate, the water quality of Dianchi Lake will be obviously improved after the Xiyuan tunnel and four sewage treatment plants run.

5. Conclusions and recommendations

It is believed that the coupled modeling system is required to answer the problems in a shallow lake. A coupled modeling system described herein was used successfully to simulate the general pattern of the wind-induced circulation and to predict the COD concentration value under six conditions in Dianchi Lake.

Continued effort is needed to develop robust coupled models of aerodynamics, hydrodynamics and water quality dynamics for larger shallow lakes. The water quality dynamics should include the interactions among vegetation, nutrients, etc.

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