

Effect of water diversion from the Yangtze River to Chang Lake on hydrodynamic characteristics and water quality of Chang Lake

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Abstract: A 2-D hydrodynamic and water quality model was developed and employed to analyze the effect of water diversion from the Yangtze River to Chang Lake. Three levels of water diversion volume were assumed. Hydrodynamic characteristics and water quality of the lake before and after the water diversion projects were modelled using the developed model. The results shown that water diversion has effect on part of the lake area, and the pollution in the west area of the lake was taken to the west and finally the main area of the lake because of the slow current caused by water diversion, which indicated that the water diversion project expanded the polluted area. However, the balance concentration of water quality index decreased as the quantity of water diversion increased from 50 m³/s to 150m³/s.

1. Introduction

Hubei Province is known as a province of thousand lakes, which provide important support for the social and economic development of Hubei Province. However, the water environment of those lakes have been polluted seriously during the last decades.

Water quality of lakes were not improved previously just through controlling point source pollution, and river-lake connection project has been an important ecological construction to achieve the goal. However, there were some key issues to be answered before connection projects were constructed, such as the effect of connection project on water quality, new pollutions caused by the connection project, the specific and effective scheme for connection project, etc., and also these questions need to be answered through researches on connection projects of rivers and lakes.

Chang Lake in Hubei province in the middle of China was chosen as the research object to discuss effects of river-lake connection project on lake water quality, and to research and make more specific and effective schemes of water diversion in the connection project, which can also provide certain support for water environmental management of Chang Lake basin.

2. Research Area

Chang Lake is the third large lake in Hubei Province in the northeast of Jinzhou City and the southwest of Shayang City, it's an important lake for flood regulation and storage in Chang Lake catchment supplying 6.97*10⁸ m³ storage volume for the catchment of 3240km² scale. Moreover,



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Chang Lake supplies fresh water to millions of people in the bordering areas, and provides important support for the economic development of the Four-Lake area.

Chang Lake was connected to Yangtze River and Han River in history, but it was separated from rivers gradually by human activity, which caused a series of water environmental problems, such as decrease of lake area, water pollution, reduction of biodiversity, et.al. Therefore, water connection projects between lakes and rivers has been an argent construction for Chang Lake basin to recover the river-lake ecological system.

3. Method

3.1 Governing equations

2-D Saint-Venant equations were employed as governing equations for lake hydrodynamic modelling, which were shown as follows[1] (equation 1),

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}^{\text{adv}}}{\partial x} + \frac{\partial \mathbf{G}^{\text{adv}}}{\partial y} = \frac{\partial \mathbf{E}^{\text{diff}}}{\partial x} + \frac{\partial \mathbf{G}^{\text{diff}}}{\partial y} + \mathbf{S} \quad (1)$$

where t indicates the time; x and y are Cartesian coordinates; \mathbf{U} , \mathbf{E} , \mathbf{G} and \mathbf{S} are vectors of the conserved flow variables, fluxes in the x and y -directions, and source terms, respectively; in which

$$\mathbf{U} = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \quad \mathbf{S} = \mathbf{S}_0 + \mathbf{S}_f = \begin{bmatrix} 0 \\ ghS_{0x} \\ ghS_{0y} \end{bmatrix} + \begin{bmatrix} 0 \\ -ghS_{fx} \\ -ghS_{fy} \end{bmatrix},$$

$$\mathbf{E}^{\text{adv}} = \begin{bmatrix} hu \\ hu^2 + gh^2/2 \\ huv \end{bmatrix}, \quad \mathbf{G}^{\text{adv}} = \begin{bmatrix} hv \\ huv \\ hv^2 + gh^2/2 \end{bmatrix},$$

$$\mathbf{E}^{\text{diff}} = \begin{bmatrix} 0 \\ 2hv_t \frac{\partial u}{\partial x} \\ hv_t (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}) \end{bmatrix}, \quad \mathbf{G}^{\text{diff}} = \begin{bmatrix} 0 \\ hv_t (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}) \\ 2hv_t \frac{\partial v}{\partial y} \end{bmatrix} \quad (2)$$

where h is the water depth; u and v are the depth-averaged velocity components in the x - and y -directions, respectively; $g = 9.81 \text{ m/s}^2$ is the gravity acceleration; S_{0x} and S_{0y} are bed slopes in the x - and y directions, respectively; S_{fx} and S_{fy} are friction slopes in the x - and y directions, respectively.

$$S_{0x} = -\frac{\partial b(x, y)}{\partial x}, \quad S_{0y} = -\frac{\partial b(x, y)}{\partial y} \quad (3)$$

3.2 Finite volume discretization

The integral form of (1) is

$$\frac{\partial}{\partial t} \int_{\Omega} \mathbf{U} d\Omega + \int_{\Omega} \left(\frac{\partial \mathbf{E}^{\text{adv}}}{\partial x} + \frac{\partial \mathbf{G}^{\text{adv}}}{\partial y} \right) d\Omega = \int_{\Omega} \left(\frac{\partial \mathbf{E}^{\text{diff}}}{\partial x} + \frac{\partial \mathbf{G}^{\text{diff}}}{\partial y} \right) d\Omega + \int_{\Omega} \mathbf{S} d\Omega \quad (4)$$

Applying Green's theorem, Eq. (4) becomes

$$\frac{\partial}{\partial t} \int_{\Omega} \mathbf{U} d\Omega + \oint_{\partial\Omega} \mathbf{F}^{\text{adv}} \cdot \mathbf{n} dl = \oint_{\partial\Omega} \mathbf{F}^{\text{diff}} \cdot \mathbf{n} dl + \int_{\Omega} \mathbf{S} d\Omega \quad (5)$$

in which Ω is the control volume; $\partial\Omega$ denotes the boundary of the volume; \mathbf{n} is the unit outward vector normal to the boundary; $d\Omega$ and dl are the area and arc elements, respectively.

$$\mathbf{F}^{\text{adv}} = [\mathbf{E}^{\text{adv}}, \mathbf{G}^{\text{adv}}]^T; \quad \mathbf{F}^{\text{diff}} = [\mathbf{E}^{\text{diff}}, \mathbf{G}^{\text{diff}}]^T.$$

3.3 Computational grid

Considering the advantages of the triangular mesh such as strong fitting ability of complex boundary,

convenient in mesh generation and local encryption, the unstructured triangular element was employed in the study[1-5]. A grid is characterized by three vertices, three edges, and three or less immediate neighbor grids. The vertices of each cell C_i have to be numbered in the counter-clockwise direction, as vertices 1–2–3 shown in Figure 1. The edge of each cell are also numbered counter-clockwise, as edge $\Gamma_{i,1} - \Gamma_{i,2} - \Gamma_{i,3}$ shown in Figure 1. Each edge has a start node, an end node, and a unit outward normal vector. The neighbor cells of each cell should be numbered the same as edges.

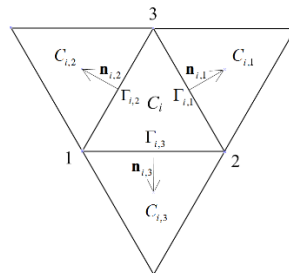


Figure 1 schematic diagram of the unstructured triangular grid

4. Feasibility analysis of water diversion project from the Yangtze River to Chang Lake

A routine water quality monitoring station was set up near the port where water was transferred from the Yangtze River to the Hanjiang River. Monitoring data of COD_{Mn} , ammonia and total phosphorus from year 2006 to 2015 were employed and analyzed. The results shown water quality of Yangtze River measured up to the third level of Environmental quality standards for surface water (GB3838-2002), which was superior to the water quality of Chang Lake, which indicated that water connection between the Yangtze River and Chang Lake can improve the hydrodynamic characteristics, furthermore, it can also improve the water quality of Chang Lake.

5. Results and Discussion

5.1 calculation cells

All the lake area of 134km² was divided into 9745 triangle cells, 5743 nodes with 13750m² per cell.

5.2 Hydrodynamic modelling and analysis of Chang Lake without water diversion project

The hydrodynamic model was employed for modelling the hydrodynamic characteristics of the Chang Lake. Considering that water level of the lake had little changes in a year, the water level of Chang Lake for calculation was considered as 29.5m according to filed hydrological data, and the corresponding flow field of the lake in water level 29.5m was shown in Fig.2.

The results shown that the flow velocity in the whole lake is very small in current case without water diversion project. Main lake area of Miao Lake and Haizi Lake has weak circumfluence by the drainage of sewage outfalls. However, considering the effect of wind and sewage drainage, the water level of the lake has little change less than 0.005m.

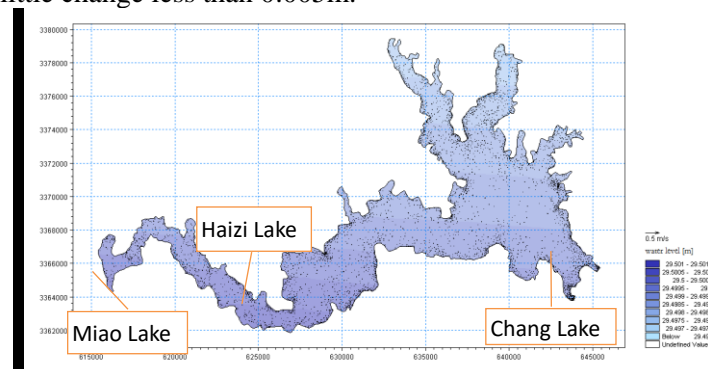


Figure 2 Flow field of Chang Lake at the level of 29.5m without water diversion project

5.3 Hydrodynamic characteristics analysis of Chang Lake with water diversion project from the Yangtze River to Chang Lake

Three different water discharge were designed for water diversion from Yangtze River to Chang Lake, such as $50\text{m}^3/\text{s}$ 、 $100\text{m}^3/\text{s}$ 、 $150\text{m}^3/\text{s}$. Simulated water flow fields of the lake in the three cases with different water diversion flow were shown in Fig. 2 to Fig.4, respectively.

The results shown that flow velocity near the area of Miao Lake, and Haizi Lake and the west of Chang Lake, where water flow into Chang Lake from Yangtze River, was distinctive and the flow velocity became slow quickly after water flowing into the main area of Chang Lake. Flow velocity near Gate Liuling and Xijiakou, the outlet of Chang Lake, were relatively fast but weak in the northern bay of Chang Lake. In all, water exchange in Miao Lake, and Haizi Lake and west Chang Lake were distinct, while capacity of water exchanges in the northern bay and main area of Chang Lake were weak.

Flow velocity in Miao Lake, and Haizi Lake and the west area of Chang Lake increased obviously along with the increase of water diversion from the Yangtze River, however, flow velocity in the main area of Chang Lake, and the northern bay has little change with the increase of water diversion.

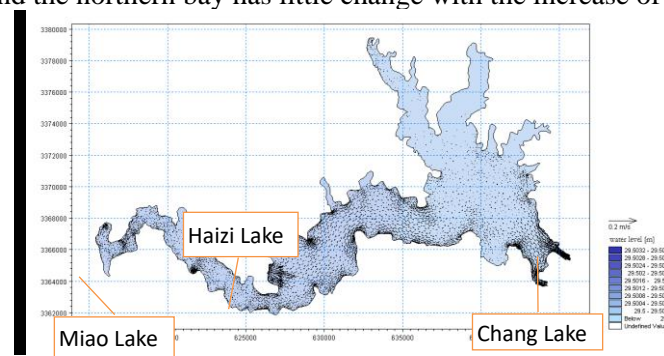


Figure 3 Flow field of Chang Lake with water diversion of $50\text{m}^3/\text{s}$ from the Yangtze River

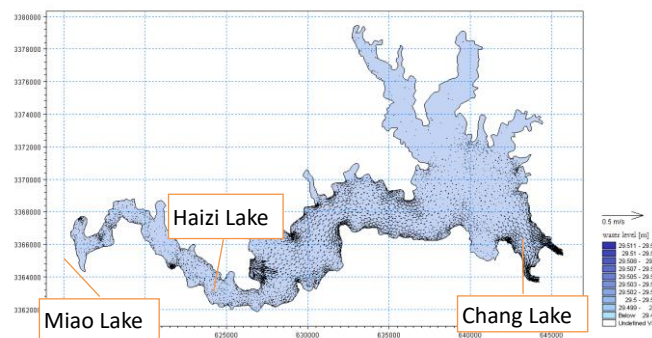


Figure 4 Flow field of Chang Lake with water diversion of $100\text{m}^3/\text{s}$ from the Yangtze River

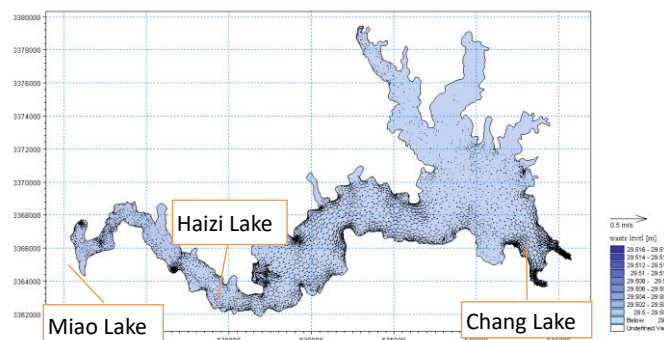


Figure 5 Flow field of Chang Lake with water diversion of $150\text{m}^3/\text{s}$ from the Yangtze River

5.4 Effect analysis of water quality improvement in different water diversion project

(1) water quality modelling of the lake without water diversion project

According to the surface shape and hydrodynamic characteristics of the lake, some typical points were chosen to analyze changes of water quality along with the water diversion process in different design condition. Changes of the concentrations of COD and TP at these typical points along with water diversion process were analyzed. The location of these typical points were shown in Fig. 6.

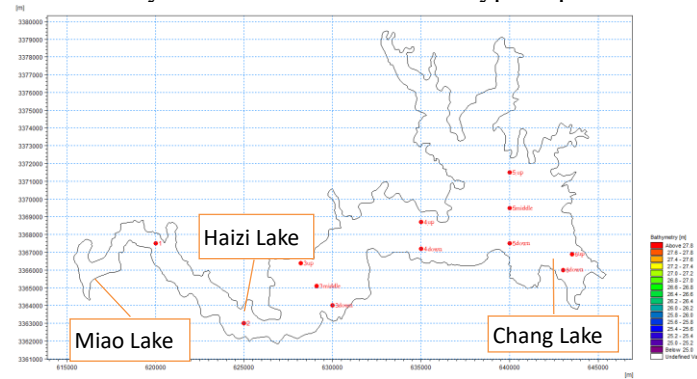


Figure 6 Location of typical points for water quality analysis

In current scheme without water diversion project, modelled concentration changes of COD in the typical points were shown in Fig.6. The results shown that the concentrations of COD in the lake will increase along with the sewage drainage and come to dynamic balance and tended to be stable, as shown in Fig.7.

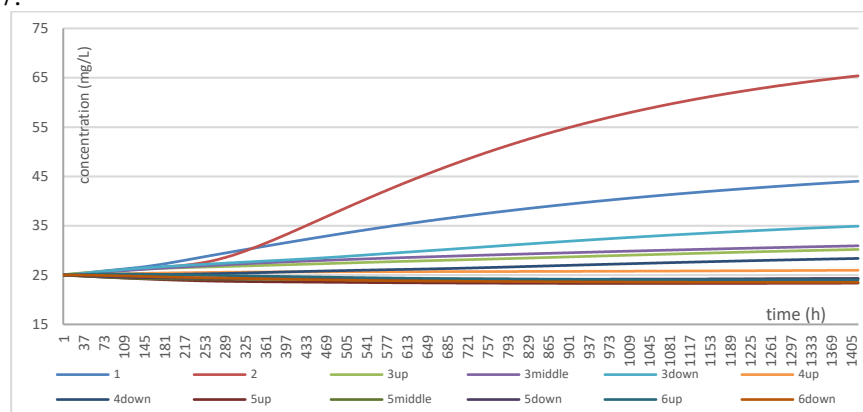


Figure 7 Changes of COD concentration in the typical points without water diversion project

(2) Changes of COD concentration in the typical points in different water diversion process

Changes of water quality were modelled in different water diversion project. The results shown that the concentration of different water index had similar changes in one water diversion project. Therefore, modelled results of COD changes were list as follows while results of other water quality indexes were not list in this paper as space was limited. Changes of COD concentration at the typical points in different water diversion project were shown in Fig.8 to Figure. 10.

The results shown that concentration of COD increased firstly and then decreased to balance concentration during the water diversion process. The reason was that pollutants in the west of the lake were transferred to the east of the lake, and entered the main lake area by small current from the south bay caused water diversion, which resulted in larger polluted area and more replace time of water in the lake. And the balance concentration of COD decreased as the increase of water diversion flux

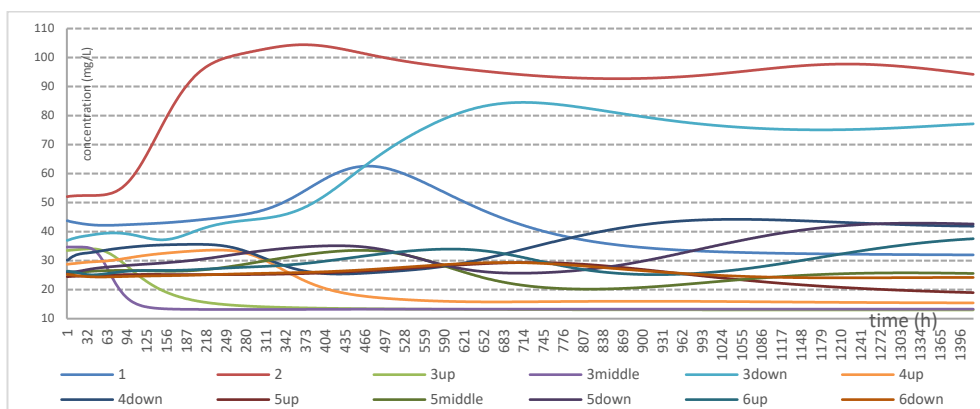


Figure 8 Chages of COD concentration at the typical points with water diversion of 50 m³/s from the Yangtze River

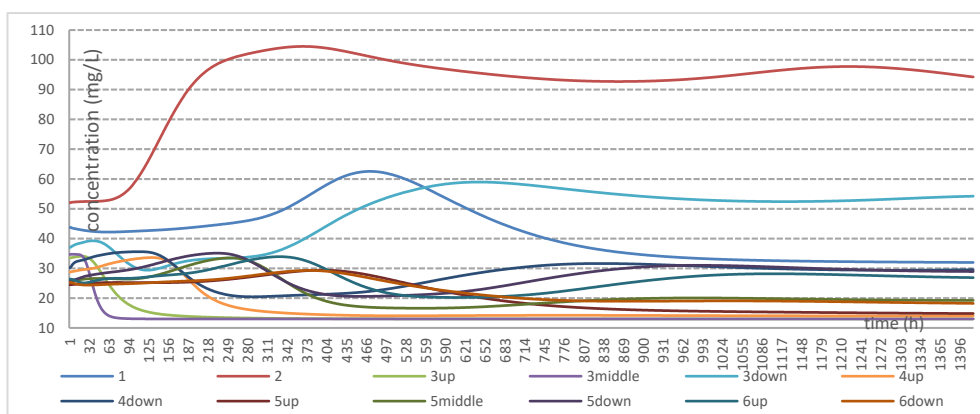


Figure 9 Chages of COD concentration at the typical points with water diversion of 100 m³/s from the Yangtze River

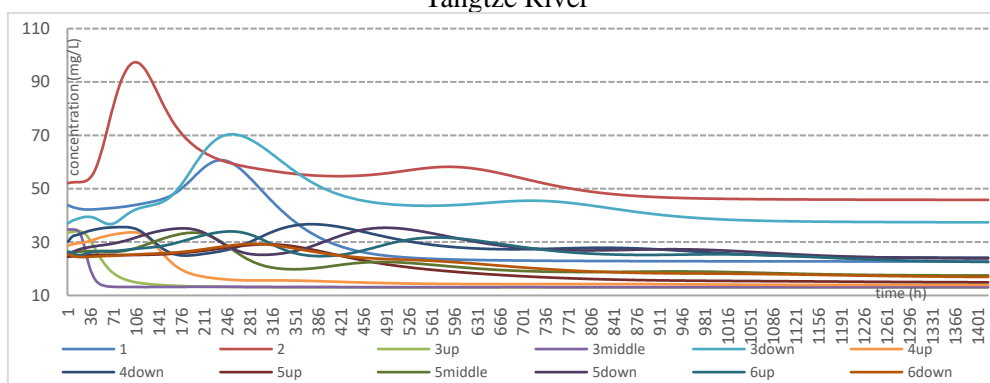


Figure 10 Chages of COD concentration at the typical points with water diversion of 150m³/s from the Yangtze River

In different water diversion process (50 m³/s, 100 m³/s, 150 m³/s) from the Yangtze River, the balanced concentration field of COD of the whole lake were shown in Fig.11 to Fig.13.

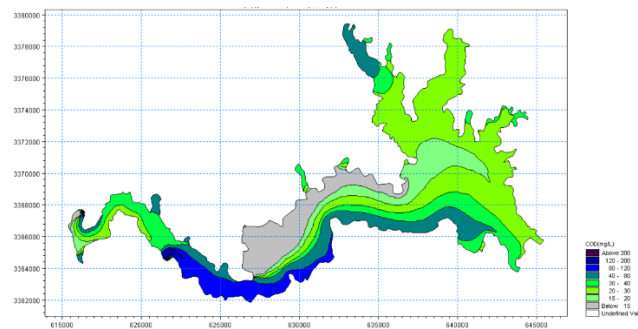


Figure 11 Balance concentration field of COD with water diversion of 50m³/s from the Yangtze River

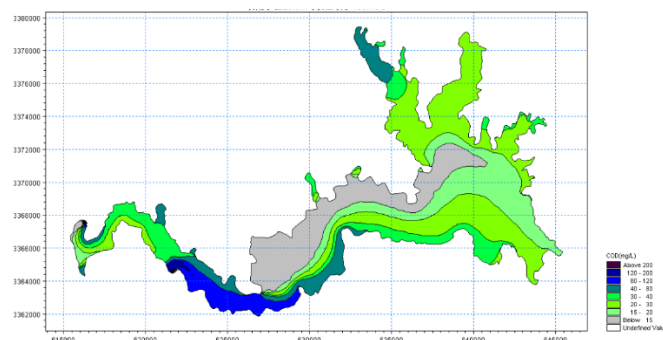


Figure 12 Balance concentration field of COD with water diversion of 100m³/s from the Yangtze River

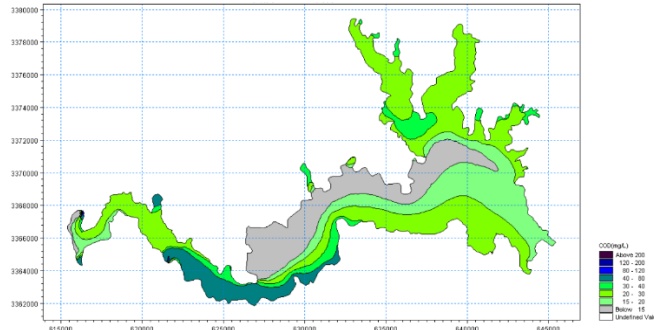


Figure 13 Balance concentration field of COD with water diversion of 150m³/s from the Yangtze River

As shown in Fig.11 to Fig.13, when the diversion water flow increased from 50 m³/s to 150 m³/s, water quality were improved gradually with shorter polluted zone, lower concentration of COD, and the increase of water area with good quality.

When the diversion water flow was 50 m³/s, the polluted zone were shaped with the length of 25km nearby the south bay, where the COD concentration exceeded 40 mg/L which was the limited concentration of the fifth level in the national surface standard (GB3838-2002). And the area where the COD concentration exceeded the fourth level was 30km long, expanded to the southeast of the lake.

when the diversion water flow was 100m³/s, the polluted zone were shaped with the length of 17km nearby the southern bay, where the COD concentration exceeded 40 mg/L which was the limited concentration of the fifth level in the national surface standard (GB3838-2002). And the area where the COD concentration exceeded the fourth level was 28km long shorter than that in the scheme of 50 m³ water diversion.

When the diversion water flow was 150 m³/s, the polluted zone were shaped with the length of

15km nearby the southern bay, where the COD concentration exceeded 40 mg/L which was the limited concentration of the fifth level in the national surface standard (GB3838-2002). And the area where the COD concentration exceeded the fourth level was 18km long much shorter than that in the scheme of 50 m³/s water diversion.

According to the modelled results, water areas with different quality and the corresponding percent over the whole lake were summarized in different water diversion scheme, shown in Tab. 1.

Table 1 water area with different level of water quality in different water diversion						
LEVEL OF WATER QUALITY	WATER DIVERSION(M ³ /S)			AREA (KM ²)		
	50	100	150	50	100	150
2 (<15MG/L)	17.27	27.13	28.67	13	20	21
3 (<20MG/L)	15.09	24.39	28.79	11	18	22
4(<30MG/L)	49.36	44.96	55.05	37	34	41
5(<40MG/L)	21.93	17.31	9.91	16	13	7
LESS 5(>40MG/L)	29.68	19.49	10.95	22	15	8

As shown in Tab.1, in different water diversion scheme, the water area where COD concentration were lower than the third level of the national surface standard, were 24%, 38% and 43% of the lake area, while the water area where COD concentration exceeded the fifth level of the national surface standard, were 38%, 28% and 15%.

6. Conclusion and discussion

A 2-D hydrodynamic and water quality model was developed and employed to analyze the effect of water diversion from the Yangtze River to Chang Lake. Hydrodynamic and water quality before and after the water diversion projects were modelled using the developed model.

The results shown that the flow velocity in the whole lake is very slow in current case without water diversion project. Main lake area of Miao Lake and Haizi Lake has weak circumfluence by the drainage of sewage outfalls. Water diversion had obvious effect on the flow velocity near the water-inlet of the water diversion project, and had little effect on the northern bay and the main water area of the lake.

Results of modelled water quality shown that concentration of COD increased firstly and then decreased during the water diversion process, especially in the south of the lake. The reason was that pollutants in the west of the lake were transferred to the east of the lake, and entered the main lake area by slow current from the southern bay caused water diversion, which resulted in larger polluted area and more replace time of water in the lake. When the diversion water flux increased from 50 m³/s to 150 m³/s, water quality were improved gradually with shorter polluted zone, lower concentration of COD, and the increase of water area with good quality.

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