Optimization and Effect of Inner Water Diversion and Distribution in the West Lake of Hangzhou

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Abstract: West Lake is a world-famous landscape in Hangzhou, listed on the World Heritage list. In 2003, Hangzhou municipal government implemented the project of water diversion project, which diverted 400,000t/d water from Qiantang River into West Lake, thus, improved the overall water quality of West Lake significantly. However, due to the zigzag lakeshore line and the in lake embankment separation, the diverted water could not fully exchange among different regions of the lake, therefore, high concentration region of nutrient and cyanobacteria outbreak risk still existed in some lake bays. On the basis of spatial water quality analysis, this study put forward the internal water diversion and distribution scheme of the West Lake. Total phosphorus (TP) model with Environmental Fluid Dynamic Code (EFDC) was built to study the optimum water diversion quantity and distribution layout. According to the numerical result, the recommended water diversion scale was 70,000t/d, the layout of diversion and distribution recommended was "2 in 3 out". The internal water diversion and distribution project was complemented in October 2015. According to the comparison of water quality before and after the project construction, the improvement rates of TP, TN and Chlorophyll A were 26.0%, 8.9% and 25.9% respectively, and the dead water area was reduced from 35% to 13%, which greatly improved the water environment of the water diversion area.

1. Introduction

Since the G20 summit was successfully held in 2016, as a famous tourist city, Hangzhou became more famous around the world. West Lake is a golden card of Hangzhou, which occupies an important position in Chinese historical, cultural and scenic spots. It has been listed on the World Heritage list since 2011. Due to the development of industrial society, the water quality of the West Lake was deteriorating, and the lake body has been deposited seriously since 1950. Later on, it experienced many dredging and remediation work for decades. From 2000 to 2003, the Hangzhou Municipal Government launched the West Lake Comprehensive Protection Project, measures such as water area expansion, ecological water diversion, pollution sources remediation, non-point pollution treatment and the water ecological system restoration were carried out, thus, the area and volume of West Lake have been restored, the pollution degree of the West Lake has been relieved, and the trend of water environment deterioration in West Lake has been fundamentally reversed[1-2].

The West Lake received tens of millions of tourists every year, therefore it suffered large amount of emissions from motor vehicles exhaust. Moreover, agricultural activities such as tea planting and farming activities in the river basin, as well as commercial activities such as farmhouse and hotels, affected the quality of the lake's water. Thus, the lake was still facing a great risk of environment deterioration.
On the other hand, due to the uneven diverted water distribution, zigzag lakeshore line, and the
inlake embankment separation, the diverted water could not fully exchanged among different regions
of the lake. As a result, high concentration region of nutrient and cyanobacteria outbreak risk still
existed in some lake bays.

Based on the measured water quality data, this study analyzed the temporal and spatial distribution
of nutrients in the West Lake, furthermore, optimal scheme of inner water diversion and distribution in
the West Lake was studied by EFDC hydrodynamic and water quality model. The effect of the water
diversion and distribution project was verified by the comparison of the water quality monitored before
and after the project construction.

2. General situation of West Lake
The area of West Lake basin is 27.25 km², and the annual average runoff is about 14 million m³. The
lake is close to the urban area on one side, surrounded by mountains on the other three sides, and it is
divided into several sub lakes by Sudi, Baidi and Yanggongdi embankments, connected by bridge
holes. See figure1. Its area east to Yanggongdi embankment is 5.66 km², with an average water depth
of 2.27m.

![Figure 1. General situation of West Lake and its Watershed](image)

Since 2003, large quantity of water has been pumped from the Qiantang River with the flow rate
400000t/d, which was injected into the West Lake after coagulation and precipitation. The water
injected into the West Lake from 6 inlets in the southwest and west, and then discharged into the
downstream channel by 9 outlets in the north and east. The water distribution and entrance size of
inlets and outlets are not uniform, in which Xiaonanhu is the largest inlet with 270,000t/d, while
Shengtang sluice is the largest outlet, the output flow rate is about 250,000t/d, Yue Lake pumping
station is the second largest, and the output flow rate is 100,000 t/d.

The water quality of West Lake has been significantly improved after the implementation of the
water diversion project. Recent studies[2] showed that TP and Chlorophyll A concentration in west
inner lake decreased by 60.2%, 75% respectively, and TP and Chlorophyll A concentration in outer
west lake decreased by 35.2%, 63.0%, respectively. Thus, the eutrophication degree was greatly
alleviated.

However, the water quality of the whole lake was not identical. Figure 2 showed the results of TP
concentration in three typical areas, namely, Maojiabu, west inner lake and outer west lake. It could be seen from the figure that the concentration of TP in different area were related to the diverted water distribution, therefore, the concentration and variation were the lowest in west inner lake and the highest in the outer west lake. Besides, the river basin runoff was the periodic factor which caused superposition effect especially in the upper lake area in rainy season, such as for Maojiabu.

![Graph](image)

**Figure 2.** TP concentration in three monitoring sites of West Lake in 2011

In order to further analyze the spatial differences of water quality in the outer west lake, temporary and intensive monitoring of water quality in the area was carried out for 5 times in 2015, the monitoring points were shown in figure 3. The results showed that the water quality of the outer west lake, showed highly spatial characteristics, as indicated in figure 3. Zone A was the main channel from inlet to outlet, and the water quality was relatively good, the water quality of zone B was relatively poor and the water quality of zone C was the worst. The lake shore line in zone C is close to the city, where attracted the most amount of tourists, and the demand for water quality improvement is the most urgent. According to the investigation, further improvement of water quality in zone C by increasing external water diversion did not meet the engineering conditions. Therefore, it was a more realistic choice to divert water from the area west of the Su dike to zone C by laying pipelines at the bottom of the lake. This paper focused on the analysis of the diversion water scale and its layout.

![Map](image)

**Figure 3.** A schematic diagram of water quality zoning in Waixihu Lake
3. Research methodology

3.1. Model setup

The hydrodynamic water quality model of West Lake was developed by the environmental hydrodynamic model EFDC (Environmental Fluid Dynamic Code)[3]. In order to accurately simulate the hydrodynamic process, curved orthogonal grid was adopted. The whole lake was divided into 18578 grids with a distance of 2-30m, encrypted at each bridge hole, see figure 4.

According to the field monitoring, vertical stratification was observed in the West Lake[4]. In order to simulate the topography of the lake bottom, σ coordinate was introduced to simulate the vertical direction, which was divided into three layers on average. The height of vertical grid was defined by the thickness of lake bottom and surface water body.

The simulation period of the model was from June 17 to August 12, 2013 (During this period, TP concentration in West Lake increased gradually), using the measured data as the initial and boundary conditions.

3.2. Model verification and parameters validation

This paper mainly analyzed the effect of water quality improvement in zone C of the main lake with internal water diversion and distribution. The flow in and out of the six bridges of Sudi embankment had a direct effect on the spatial distribution of water quality in the main lake, therefore, the discharge of the six bridges in the Sudi dike was verified. According to the field observation of West Lake in 2013, the discharge in and out of the bridge holes of the Sudi embankment was basically stable when there has no rainfall. The comparison between the calculated flow rate of each bridge and the measured values was listed in Table 1.

Table 4. Computing grids, main inlets and outlets, and monitoring points in West Lake

According to the field monitoring, vertical stratification was observed in the West Lake[4]. In order to simulate the topography of the lake bottom, σ coordinate was introduced to simulate the vertical direction, which was divided into three layers on average. The height of vertical grid was defined by the thickness of lake bottom and surface water body.

The simulation period of the model was from June 17 to August 12, 2013 (During this period, TP concentration in West Lake increased gradually), using the measured data as the initial and boundary conditions.

Table 1 Comparison between measured and calculated quantity across 6 bridge openings under Sudi

| bridge opening | 1   | 2   | 3   | 4   | 5   | 6   |
|----------------|-----|-----|-----|-----|-----|-----|
| measured value | 1.65| 0.19| 0.16| 0.18| -0.14| -0.26|
| calculated value | 1.68| 0.19| 0.20| 0.22| -0.13| -0.22|

*Positive value indicates entering into the Waixihu area from Xilihu lake; negative value opposite.

Table 1 showed that the flow rate in and out of the bridge holes of the Sudi embankment basically agreed well with the actual situation, and the absolute error was within 0.04 m³/s.

The simulated and the measured flow value in different sites of the West Lake were listed in Table
2 (see figure 4 for monitoring points), the magnitude of the simulated velocity was basically consistent with the measured one. However, due to the large randomness of wind field and cruise ship influences, the simulation result of flow direction was quite different from the measured one.

| Calculation point | A | B | C | D | E |
|-------------------|---|---|---|---|---|
| **Surface layer** | measured | 0.9 | 0.8 | 1.5 | 1.3 | 0.6 |
| calculated       | 1.25 | 0.57 | 1.49 | 0.94 | 0.84 |
| **Bottom layer** | measured | 1.1 | 1 | 1 | 0.7 | 0.4 |
| calculated       | 0.96 | 0.83 | 1.76 | 0.56 | 0.49 |

The model was validated with TP concentration at the West Lake intensive observation sites on June 24 and August 12. Two main coefficients of TP model validated were TP degradation coefficient and sediment release coefficient, and the former one was 0.14d$^{-1}$ while the latter one was 3.3mg/m$^2$/d, which were within the coefficient range calculated by Han Zengxi et al. [5-6]. Besides, the error of TP concentration in each monitoring point was within ±0.01mg/l, and the relative error was within ±20%, see figure 5.

**Figure 5.** Verification of TP concentration in West Lake: a, June 24th; b, August 12th

4. **Internal Water diversion and distribution scheme**

The general idea of internal diversion and distribution of water in West Lake was to pump water from inner west lake, which would provide best water quality to zone C of outer west lake, lead to a reduction of both the concentration of nutrients and the risk of eutrophication. Therefore, reasonable water diversion scale and rational distribution of water outlets were the main factors to determine in the scheme study phase.

4.1. **Water diversion scale**

On the basis of EFDC model, TP concentration, water age and velocity of the water receiving region were chosen to measure the water diversion benefit under the scale of 50,000t/d, 70,000t/d, 80,000t/d, 100,000t/d. The results were shown in Table 3.

From Table 3, the larger was the water diversion scale, the better was the water quality in the
receiving area for water age and velocity. However, for TP concentration, the efficiency of water diversion decreased with the increasing of the amount of diverted water. The results showed that the concentration of unilateral water decreased by 3.2% at 50,000t/d, which were 2%, 1% and 0.5% at 70,000t/d, 80,000t/d and 10,000t/d, respectively. Hence, it was anticipated that 70,000 t/d water diversion quantity was the most cost-optimal scale.

Table 3. Effect under different water diversion scale

| item                | index                        | Present status | 50,000t/d | 70,000t/d | 80,000t/d | 10,000t/d |
|---------------------|------------------------------|----------------|-----------|-----------|-----------|-----------|
| TP concentration    | regional average(mg/L)       | 0.085          | 0.071     | 0.068     | 0.067     | 0.066     |
|                     | improvement rate (%)         | -              | 16%       | 20%       | 21%       | 22%       |
| Water age           | regional average(mg/L)       | 28.1           | 22.4      | 20.8      | 20.3      | 19.1      |
|                     | improvement rate (%)         | -              | 20%       | 26%       | 28%       | 32%       |
| Flow rate           | regional average(mg/L)       | 0.08           | 0.13      | 0.14      | 0.15      | 0.18      |
|                     | improvement rate (%)         | -              | 63%       | 75%       | 88%       | 125%      |
| Dead water area     | (%)                          | 35             | 21        | 13        | 9         | 5         |

4.2. Outlet distribution

On the premise of determining the total water diversion scale was 70,000t/d, the number of water outlets and its distribution were studied. Six indices, including TP concentration, graded TP concentration, water age, graded water age, flow velocity and graded flow rate were compared under the 3 outlets, 6 outlets and 9 outlets scheme. The outlets distribution was showed in figure 6; the corresponding distribution of water outputs was shown in Table 4; the calculated results were listed in Table 5 and Table 6.

Figure 6. Layout of outlets in Water diversion and Distribution area

Table 4. Water distribution under different number of outlets (unit:10,000t/d)

| schemes         | 3 outlets | 6 outlets | 9 outlets |
|-----------------|-----------|-----------|-----------|
| Outlet points   | 1#、2#    | 3#        | 1#、2#、4#、5# | 3#、4#、5#、7#、8# | 3#、6#、9# |
| water allocation| 2.5       | 2.0       | 1.25      | 1.0       | 0.83      | 0.67      |
| Total amount    | 7.0       | 7.0       | 7.0       |           |           |           |
Table 5. TP concentration, water age, flow rate and dead water area improvement in demonstration area under different effluent layout

|                        | present situation | 3 outlets | 6 outlets | 9 outlets |
|------------------------|-------------------|-----------|-----------|-----------|
| **TP concentration**   | regional average(mg/L) | 0.085 | 0.068 | 0.069 | 0.071 |
|                        | improvement rate (%) | - | 20% | 19% | 17% |
| **Water age**          | regional average(mg/L) | 28.1 | 20.8 | 20.7 | 21.5 |
|                        | improvement rate (%) | - | 26% | 26% | 23% |
| **Flow rate**          | regional average(mg/L) | 0.08 | 0.14 | 0.13 | 0.12 |
|                        | improvement rate (%) | - | 75% | 63% | 50% |
| **Dead water area**    | (%)                | 35 | 13 | 15 | 16 |

Table 6. Graded TP concentration, water age and flow rate in demonstration area under different effluent layout

| Graded TP area percentage | present situation | 3 outlets | 6 outlets | 9 outlets |
|---------------------------|-------------------|-----------|-----------|-----------|
| **TP classification(mg/L)** | ≥0.06 | 100% | 99% | 92% | 92% |
|                          | ≥0.07 | 74% | 37% | 41% | 47% |
|                          | ≥0.08 | 51% | 1% | 4% | 9% |
|                          | ≥0.09 | 33% | 1% | 1% | 2% |
|                          | ≥0.1  | 20% | 1% | 1% | 0% |

| Water age area percentage | present situation | 3 outlets | 6 outlets | 9 outlets |
|---------------------------|-------------------|-----------|-----------|-----------|
| **Water age classification(d)** | ≥20 | 79% | 51% | 49% | 54% |
|                          | ≥30 | 30% | 7% | 8% | 13% |
|                          | ≥40 | 14% | 1% | 1% | 1% |
|                          | ≥60 | 1% | 0% | 0% | 0% |

| Stepwise velocity area percentage | present situation | 3 outlets | 6 outlets | 9 outlets |
|-----------------------------------|-------------------|-----------|-----------|-----------|
| **Velocity classification(cm/s)** | ≤0.05 | 29% | 2% | 4% | 5% |
|                                   | ≤0.1 | 72% | 25% | 27% | 34% |
|                                   | ≤0.15 | 93% | 62% | 69% | 70% |
|                                   | ≤0.2 | 97% | 87% | 89% | 91% |

It could be seen from Table 5 that since the water diversion quantity did not increased while the water outlets were increased, differences between the three schemes were not significant. On the whole, because of the relative concentration of outlet flow, the improvement of water quality under three outlets (3 outlets) scheme was the best one. The outcomes showed that, under the "3 outlets" scheme, the mean TP concentration in the demonstration area was reduced by 20 percent, the water age was reduced by 26%, the flow rate was increased by 75%, the area of the dead water area was reduced to 13%.

It could be seen from Table 6 that the improvements of TP concentration, water age and flow rate in the water receiving area were also optimized by "3 outlets" scheme. The area of TP concentration ≥ 0.08mg/L decreased from 51% to 1%, the area of water age≥30 days decreased from 30% to 7%, and the area of velocity ≤ 0.5m/s decreased from 29% to 2%.

4.3. Scheme determination
According to the above analysis, it was determined that the best water source of internal water diversion was west inner lake, the efficient scale of water diversion was 70,000 t/d, and the diverted water distributed with 3 outlets. After the implementation of the diversion and distribution project, the
renewal rate of the water body in the receiving area had been greatly improved, and the water quality concentration would also be improved obviously according to model prediction.

5. Improvement effect of water quality and flow rate

The internal water diversion and distribution project was completed and operational in October 2015. Third-party organizations were commissioned to monitor the water quality and flow rate of the demonstration areas before and after the project. Four monitoring points were set as shown in figure 7.

![Figure 7. Layout of monitoring points](image)

5.1. The effect of water quality improvement

Because of the seasonal variation of water quality in the West Lake, the monitoring data from January to June 2014 were selected as the pre-construction conditions, and the monitoring data from January to June 2016 as the after construction conditions. A comparative analysis of monitoring data over the same period was carried out, the results of which were shown in table 7.

It could be seen from the table that the improvement rates of total Phosphorus, total Nitrogen and Chlorophyll A after the construction of the demonstration area were 30.6% 29.7% and 23.6% respectively. The improvement was greater than the prediction values. On the one hand, the water quality of the demonstration area had been improved significantly after the implementation of the diversion project, on the other hand, the overall environment of West Lake had also been continuously improved from 2014 to 2016.

|                | Pre - construction | After construction |
|----------------|--------------------|--------------------|
|                | TP (mg/L) | TN (mg/L) | Chlorophyll A (mg/m$^3$) | TP (mg/L) | TN (mg/L) | Chlorophyll A (mg/m$^3$) |
| January 2014   | 0.034     | 2.4       | 5.72                   | January 2016 | 0.012 | 1.74       | 8.81  |
| February 2014  | 0.031     | 2.63      | 5.8                    | February 2016 | 0.019 | 1.89       | 9.28  |
| March 2014     | 0.034     | 2.63      | 3.4                    | March 2016   | 0.039 | 2.09       | 7.81  |
| April 2014     | 0.038     | 2.77      | 18.3                   | April 2016   | 0.025 | 1.58       | 21.4  |
| May 2014       | 0.031     | 2.23      | 119                    | May 2016     | 0.023 | 1.54       | 37.1  |
| June 2014      | 0.044     | 1.57      | 18.6                   | June 2016    | 0.031 | 1.15       | 24.4  |
| mean value     | 0.036     | 2.36      | 23.7                   | mean value   | 0.025 | 1.66       | 18.1  |

Improvement 30.6% 29.7% 23.6%
5.2. The effect of flow rate improvement

The velocity of the water receiving area was monitored by ADCP velocity meter, and the velocity was monitored 12 times before and after the project construction. Based on the results of the monitoring, the improvement of the average velocity of the four monitoring points in the demonstration area was shown in Table 8.

|          | 1#     | 2#     | 3#     | 4#     | Averaged value |
|----------|--------|--------|--------|--------|----------------|
| Pre - construction (m/s) | 0.016  | 0.014  | 0.010  | 0.012  | 0.013          |
| After construction (m/s)  | 0.017  | 0.017  | 0.019  | 0.019  | 0.018          |
| Improvement                | 5%     | 23%    | 90%    | 63%    | 40%            |

It could be seen from the table that after the construction of the internal water diversion and distribution project, the velocity of all the monitoring points in the demonstration area were improved to varying degrees, the average improvement effect of the velocity at the four points was 40%. Among them, 3# and 4# points were located near the outlets, lead to the biggest improvement rate.

6. Conclusions

In this study, the effects of water quality improvement as well as the temporal and spatial variation characteristics of water quality in West Lake since 2003 were analyzed. It was pointed out that there was a high nutrient concentration area in the outer west Lake. The internal water diversion and distribution project on the purpose of transferring high quality water to the high concentration area through the pipeline under the lake has been proposed in this study.

The TP model of West Lake was developed using EFDC model. The model was adopted to select the optimal scheme of the internal water diversion and distribution project, to forecast the effect of the project.

According to the comparative analysis of water quality and velocity of water before and after the implementation of the project, it was shown that the water quality and dynamic conditions of the demonstration area were improved obviously. TP, TN and Chlorophyll A decreased by 30.6% 29.7% and 23.6% respectively, while velocity increased by 40%. It proved that the project really made the lake water mixing more uniformly, thus had a good effect on preventing eutrophication in high concentration areas.

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