Diverting Changjiang river water to control eutrophication in Lake Donghu

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ABSTRACT The characteristics of Lake Donghu in Wuhan China are expected to be beneficial to use the method of the diversion of the Changjiang River to control its water quality. After discussing the mixing mechanisms of two diversion ways as "discharging while diverting" (DWD) and "discharging before diverting" (DBD), and establishing a model to forecast the diversion effects, and lastly considering the impacts of the project to wash Lake Donghu in this way on environment and society etc., the diversion way as "DBD" and the diversion times as from January to May and from October to December are recommended. So what is shown is that the project should be done and can be done.

INTRODUCTION

Study Background

Since 1965, Lake Donghu, a famous lake in Wuhan city, in the Hubei province, China, has been suffering eutrophication. The Alga productivity has become higher and higher, while the strains have radically decreased and blue-green alga becomes dominant species. It has been characterized by a low Secchi-disk transparence, high value of chlorophyll-a. The main reasons are that people are taking to many water weeds out of the lake, excessive breeding of herbivorous fishes is undertaken and wastewater and sewage from industry, hospital and domesticity is delivered into the lake.

As to its salient comprehensive functions, such as the source of potable water, a productive fishing water and a splendid aquatic sports field, Hubei Province Government and many local organizations have begun to save Lake Donghu since 1978. Many means have been tried, but no final solution could be found yet.

Controlling eutrophication is nothing more than three aspects. They are control of the external phosphorus and
nitrogen load, in-lake eutrophication control and control of non-point source nutrients in the drainage basin. Among these, one method in the second aspect will be discussed in this paper, i.e. diverting the Changjiang River water into Lake Donghu, based on that flushing rate can be expected to reduce the opportunity for biomass accumulation while the replaced river water volume to decline the in-lake nutrient level.

Study objectives

The overall study aim is to design, to assess and to predict the water diversion project. The project is important for its widespread influences, and only when a reliable feasibility report has been given the project can be considered to begin.

The initial study objectives are:
a) to find the possibility of the water diversion project;
b) to design the water diversion project;
c) to simulate the water diversion project.

This paper focuses on part of the feasibility research. Other areas such as physical simulation study, economic analysis are still continued and will be reported separately.

STUDY INVESTIGATION

Brief description of study area

Lake Donghu is one of the well-known shallow lakes in the Changjiang River basin. It consists of Lake Guozheng, Lake Xiaoji, Lake Tangline, Lake Miao, Lake Tuan, Lake Xiantan, Lake Hou, Lake Yujia, as shown in Fig. 1. Its water surface is about 32.0 km². 13.25 km² is the water surface of Lake Guozhen and Lake Xiaoji, which is the so-called main district of Lake Donghu. The average depth of the main district is 2.69 m and the volume is 35.64 x 10⁶m³.

It is easy to find from Fig. 1 that Lake Donghu is of an elegant characteristic that if the Changjiang River flowing around the lake is looked as an arc, then the location of Lake Donghu is in a string of the arc. The length of the reach of the Changjiang River from Wuhan Great Bridge to Gate Beihu downstream is 47 km, but the length of the straight line between the two points is only 28 km. Lake Donghu is on the straight line. There are many pumping gates, sluice gates and channels. The largest subproject for making river-lake-river water circulation is to open the watershed between Lake Tuan and Lake Yanxi.
Phosphorous and nitrogen balances in Lake Donghu

According to the surveying data and reports from Lake Donghu Environmental Quality Assessment Research Union (1980), Environment Protection Agency of Hubei Province and Institute of Hydrobiology of Academia Sinica in Wuhan, the total nitrogen (T-N) and total phosphorous (T-P) residing in Lake Donghu are 71.0% and 55.4% respectively, as shown in Table 1, which is the most important fact that leads to the eutrophication of Lake Donghu.

A COMPARISON BETWEEN THE TWO DIVERSION WAYS AS "DISCHARGING WHILE DIVERTING" AND "DISCHARGING BEFORE DIVERTING"

In order to maintain the static state of Lake Donghu as possible as we can during water diversion, we must consider both discharging and diverting. There are two ways. One is "discharging while diverting" (DWD) which means that lake volume is kept unchangeably while diverting and discharging. Another is "discharging before diverting" (DBD) which means that before diverting the Changjiang River water to Lake Donghu, a part of lake water which volume is just as the
same as diverting river water per time has been discharged from lake and the cycle, if any, can repeat successively. These two ways are compared in this paper.

TABLE 1 The balance of T-N and T-P in Lake Donghu.

<table>
<thead>
<tr>
<th>Component</th>
<th>Input (T/μ)</th>
<th>Output (T/μ)</th>
<th>Residue-in Lake (T/μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste and sewage</td>
<td>From</td>
<td>From</td>
<td>From</td>
</tr>
<tr>
<td>Surface Runoff</td>
<td>From</td>
<td>From</td>
<td>From</td>
</tr>
<tr>
<td>Precipitation</td>
<td>From</td>
<td>Sum</td>
<td>To</td>
</tr>
<tr>
<td>Natural</td>
<td></td>
<td>Water Works</td>
<td>Irrigation System</td>
</tr>
<tr>
<td>Irrigation System</td>
<td>To</td>
<td>To</td>
<td>To</td>
</tr>
<tr>
<td>Seized Fisheries</td>
<td>To</td>
<td>Changjiang River</td>
<td>To</td>
</tr>
<tr>
<td>Changjiang River</td>
<td></td>
<td></td>
<td>Sum</td>
</tr>
</tbody>
</table>

T-N 598.89 98.79 42.0 30.46 770.14 105.85 34.8 29.52 53.35 223.72 546.4
T-P 52.76 13.02 1.2 6.38 72.86 9.13 3.0 15.73 4.62 32.49 40.4

In "DBD", it is acceptable to simplify the lake as plug-flow reactor. That it may be visualized as containing a series of isolated volumes of liquid which are contiguous with their adjacent volumes but do not mix with them, is rather like a series of carriages in a train.

If the permitted changeable level is Ah, then the permitted changeable volume, also the volume of water needed in diversion is ΔhA, where A is the lake area. When flush water flow is qr, water discharge is Eqi, where i=1,...,I indicates waste discharge gates, then the permitted water diversion time T is:

\[ T = \frac{\Delta hA}{(\Sigma q_i + qr)} \]  (1)

So when the water diversion time is T, then the waters of the lake include waste water (T Σq i), flush water (Tqr) and old lake water (v-T(qr + Eqi)). The mean concentration of water quality component in lake at water diversion time T is:

\[ c = \frac{(\Sigma c_i q_i + qcr) + (v - T(qr + Eq_i))c_l}{v} \]  (2)

in which c_i,cr,cl are the concentration of water quality component from the gate i, in the Changjiang River water and in the lake respectively. v is the lake volume.

In "DWD", the lake is considered as completely mixed reactor. That is, the concentration of outflow is equal the concentration in the lake. The mass balance model can be written as:

\[ \Sigma q_i c_i + qcr = (\Sigma q_i + qr)c + vdc/dt \]  (3)
where \( t \) is time and \( c \) is the concentration of outflow in the lake.

Considering:

\[
c/t = \alpha = c_1
\]

we obtain a solution:

\[
c = \frac{(c_1 - (\sum q_i c_i + q r c_r)/(\sum q_i + q r))}{\exp(- (\sum q_i + q r) t/v)}
\]  

For sake of convenience to compare, let \( t \) be equal to \( T \). Given the value of \( c_1, q_1, c_i, v \), we can calculate \( c_T \) under "DBD" and \( c_t \) under "DWD".

As shown in Table 2, "DBD" gains an advantage over "DWD". Henceforth the water diversion way should adopt "DBD".

**TABLE 2 The concentration of COD at diverting time \( t \) under "DBD" and "DWD".**

<table>
<thead>
<tr>
<th>( t ) (day)</th>
<th>0</th>
<th>1</th>
<th>3.5</th>
<th>5</th>
<th>7</th>
<th>14</th>
<th>19</th>
<th>( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c ) under &quot;DBD&quot; (mg/l)</td>
<td>5.00</td>
<td>4.87</td>
<td>4.55</td>
<td>4.36</td>
<td>4.103</td>
<td>3.207</td>
<td>2.59</td>
<td>2.59</td>
</tr>
<tr>
<td>( c ) under &quot;DWD&quot; (mg/l)</td>
<td>5.00</td>
<td>4.88</td>
<td>4.59</td>
<td>4.42</td>
<td>4.26</td>
<td>3.84</td>
<td>3.48</td>
<td>2.59</td>
</tr>
</tbody>
</table>

**NOTE:** \( c_T = 2.59, c_\infty = 2.59 \) means that the initial basin water has totally been discharged when diverting the Changjiang River, the concentration of which is written as

\[
c_{\text{mix}} = \frac{\sum c_i q_i c_r r}{\sum q_i + q_r}
\]

The purpose to calculate the extreme occasion is only for comparison.

**SIMULATING THE EFFECT OF WATER DIVERSION**

Actually, the lake can not be simply considered as plug-flow reactor. The effect of water replacement calculated by Equation (2) or (5) is almost unbelievable. The mixing concentration should theoretically be calculated at least by a two-dimensional continuity equation and water quality model, which obiously needs a large amount of field data and work. As a feasibility study, a kind of simple but practical calculation tool to forecast the effect of water diversion is more necessary. Hence the practicable model to calculate the effect of water replacement or water diversion.

In the model, the lake is divided into a number of units \( \Delta A_i = 1...,J \). The concept of "line of equal flow" has been used and the analysis will be shown:

We assume that the rate of inflow at the first day is only laid on the first unit \( A_1 \) and the water diversion way is "DBD".
In the first day, inside the unit, the rate of inflow in \((\Sigma q_i + qr)T/J\) (we hold the daily rate of inflow is \((\Sigma q_i + qr)T/J\)) is fully mixing with a part of old water \((v - \Delta v)/J\). \(\Delta v\) is the permitted changeable volume, the value which is equal to \(\Delta hA\) is equal to \((\Sigma q_i + q_r)T\), as mentioned above. At the end of the day, the mixing concentration of the unit is \(c_{11}\):

\[
c_{11} = J((\Sigma q_i c_i + qrcr)T/J + (v - \Delta v)c_{l-1,1}/J/v
\]

and in other area of the lake still \(c_l\).

At the second day, the rate of inflow is also maintained as \(T(\Sigma q_i + qr)/J\). Since the external water from the rate of inflow at the first day has moved over to the second unit, the first unit can receive the inflow continuously. So the concentration \(c_{tj}\) of the \(j\)th unit at the \(t\)th day is calculated as:

\[
c_{ti} = J((\Sigma q_i c_i + qrcr)T/J + (v - \Delta v)c_{t-1,1}/J/v \quad t = 2, \ldots, T
\]

\[
c_{tj} = c_l \quad t < j, \ j = 2, \ldots, J
\]

\[
c_{tj} = J((\Sigma q_i + qr)c_{t-1,j-1}T/J + (v - \Delta v)c_{t-1,j}/J/v \quad t > j, \ j = 2, \ldots, J
\]

the mean concentration all the lake at the \(t\)th day can be written as:

\[
\text{AVER}(t) = (\Sigma c_{tj})/J
\]

where \(J\) is the parameter of the model. How to divide lake into units will decide the calculation reliability in real case. The factors such as the kind of lake, mixing conditions, can help us to determine \(J\).

In this paper, the value of \(J\) is approximately held the value of the time when diverting water mass moves over to the discharging gate along the main flow line, indicated by \(m\).

Based on water balance, considering the shape of the lake, the topographic angle \(\theta\) in diverting gate, \(m\) is presented by:

\[
m = 0 (h - \Delta h) R^2/qr
\]

where \(R\) is the distance from the water diversion gate to discharging gate along the main flow line (is 5.6 km in main parts of the lake), \(h\) is the depth of the main basin of the lake and \(\theta = \pi/3\) in this case. Others have been shown above.

Because the model is only under the "DBD", so at the end of the \(T\)th day, the lake volume again arrives at \(v\), the same
as that before discharging and the water diversion should stop.

According to this, we limit the application of the model only within $t < T$.

WATER DIVERSION DESIGN

Water diversion scheme

Lake Donghu is connected to the Changjiang River by several channels and gates, as it is shown in Fig.1 and there are many possibilities for water diversion. One of them is to bring the Changjiang River water from Gate Wufeng by the Channel Qingshanggang. After enlarging the ability to bring water across the watershed Wudong between Lake Donghu and Lake Yanxi, which is 1400 meters long, the water can pass though Lake Donghu and Lake Yanxi and will flow through the Gate Beihu into the Changjiang River again. Another possibility is to use the gate Wufeng for water inflow and outflow. The water diversion way can only be "DBD".

However, when it is the main interest to have the dilution effect on the most seriously polluted district of Lake Donghu and to limit the influence area of the diversion as small as possible, than we recommend an other diversion scheme. The water diversion gate, in this scheme, should be in Luojia. A channel has to be built to diverting the water into Lake Shuiguo, one the most seriously polluted parts of Lake Donghu. The water flows to Lake Guozheng and Lake Xiaoji northwards and will be discharged from Gate Wufeng of Channel Qingshangaang into the Changjiang River again. The shortcoming of this scheme is that the channel has to be built in the flourishing area which has large population and many work units. The project is not as easy to construct as the above mentioned schemes.

Water diversion time

As shown in Fig. 2 the range of level change in Lake Donghu is only about 0,5 meter, while in the Changjiang River (at station of Pump Jiangxin near Wuhan Iron and Steel Company) 14 meters. There are about 100 days (from May to October) when the level of the Changjiang River is higher than that of Lake Donghu. In these days, the Changjiang River water can flow itself into Lake Donghu, while in the other time, drawing projects must be used for diversion. From the water balancing of Lake Donghu, however, the selection of water diversion time should avoid June, July, August and September, at which months the lake surface receives most of annual precipitation and waste discharge. Because the rate of inflow is higher than the rate for outflow, therefore diverting river water to Lake Donghu in these months is not suitable.
Therefore in this paper we suggest that the water diversion should be from October to May.

We assume 5 days per water diversion time and 2 times per month, according to the analysis. So the annual diversion time is 16 days.

Water diversion effect

From the investigation, the amounts of COD, T-N, T-P in waste discharge (\(\Sigma c_i q_i\)) are \(30.29 \times 10^3\), \(12.48 \times 10^3\), \(0.92 \times 10^3\) mg/day respectively. The concentrations of COD, T-N, T-P in the Changjiang River are 1.3, 0.816, 0.055 mg/l respectively. Waste discharge (\(\Sigma q_i\)) is 1.74 m\(^3\)/s. So, if we assume \(q_r\) is 20 m\(^3\)/s and \(\Delta h\) 0.81 m (the largest changeable level for Donghu Waterworks), then the concentration of COD in lake can be calculated by the model above to decrease by 28 %, while T-N 18 % and T-P 27 % respectively after the water volume diverted is 3.88 times as much as normal basin volume. The effect as such is, any how, attractive.

THE EFFECT OF SILT ON DIVERSION

Based on the equation:

\[
W = \sum_{i=1}^{16} p_i q_r T
\]

where \(p_i\) is the mean silt content in water diversion period, calculated in the light of a typical year (1986 in this paper), \(T\) being 5 day, \(q_r\) 20 m\(^3\)/s as above, then the annual silt discharge is 3101 ton. The value will be less if a silt chamber is constructed. Therefore we can see that the effect of silt on diversion is very small.
DISCUSSION

The selection of diversion flow

If diversion flow is too large, then the investment will be increased too radically to be afforded. On the other hand, if diversion flow is too small, then the effect of water replacement will be hardly obvious and the initial objectives will not be achieved. How to select a suitable diversion flow is very important. One of the regulation rules is that $q_r$ cannot be less than $(\sum c_i q_{i})/c_r$. The upper limit of $q_r$ is determined by the water diversion facility which is now available and the finances to be provided.

The replacement coefficient

Because of free way of flow within the lake in real case, if the diversion period is short, there certainly exists part of districts which cannot be influenced. In the recommended scheme, the diverting area is limited as such by controlling the relevant sluice gates when project starts. Since the flushing rate is limited, it is hard to produce full mixing within the lake.

If we underline the diverting direction and discharging direction, we obtain an angle $\beta$. If the coefficient of water replacement is 1 under $\beta = 180^\circ$, then when $\beta = 0^\circ$, the coefficient is 0. This is one of the factors which determines the value of overall coefficient, indicating $r_\beta = \beta/180^\circ$. On the other category, the shape of the lake is also very decisive, indicating $r_l = L/(2\pi A/\pi)$, $L$ is the real perimeter of the lake. Another factor is the attitude of diversion flow, indicating $r_q = \sum c_i q_{i}/c_r Q_r$, $Q_r$ is the real diversion flow. According to these, we can calculate the replacement coefficient $r$ by:

$$r = f(r_\beta, r_l, r_q) \quad (11)$$

The social impacts of diversion

In a discussion if the diversion strategy has been scientifically and technically proved and if it is possible and necessary for in-Lake Donghu eutrophication or of other measure may also be proved to be possible and necessary, we must decide which method should be first applied in Lake Donghu under technical expertise, financial resources and manpower at present. It depends on cost-benefit analysis and distinguishing the social impacts of the measures. There are about four categories of social impact, as described in S.O. Ryding & W. Rast (1989):

(1) Economical impact -- includes efficiency, i.e. the most efficient use of scarce resources is required to
maximize their impact, as well as such fiscal and social factors as national and/or district distribution of wealth, balance-of-trade, the increased fish field due to enough fish food organisms from advance eutrophication and the decrease owing to diversion.

(2) Demographic impact -- involves population distribution characteristics such as shift from distant Lake Donghu to (whether self-sufficient or dependent on government agencies), change in health parameters and also the possible spreading of schistosomiasis due to the blood fluke with the river water after diversion.

(3) Environmental impact -- involves both natural (e.g. aesthetic appreciation of a pristine lake) and "created" concerns (e.g. the change of sense of sight, although this effect is small, as what was discussed above; crowding and increased noise as the result of a tourist influx to aesthetically again pleasing Lake Donghu due to diversion)

(4) Cultural impact -- involves the way that population perceive and react to environmental changes. An example is a cultural attitude regarding the sanctity of the pristine Lake Donghu, as contrasted with a spartan work ethic supporting the notion that maximum use of a lake for economic productivity is critical. The detail assessment on these will be done in other report.

CONCLUSIONS

Usually, the eutrophication control programs can be directed either toward treating the basic causes or the symptoms (e.g. flush augmentation, as was mentioned above). A combination of the two will be most useful. Since the cost of treating the basic cause (excessive nutrient inputs) is too high, moreover, to Lake Donghu, additional treatment is necessary, treating the specific symptoms of eutrophication is the logical and perhaps only option. Although the measure is less effective over long term than external nutrient control programs, it does offer an effective means of combating, at least temporarily, the negative impacts of eutrophication. What also should be noticed is that the final control must cooperate treating the basic causes, which are perhaps the Achilles's heel of the measure: diversion.

REFERENCES
