Potential impact of Poyang Lake Hydraulic Project on hydrodynamic environment and fish habitat

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Abstract. The problem of dry water in Poyang Lake has been deteriorating, and the ecological function is declining. Hence, the construction of Poyang Lake Hydraulic Project (PLHP) was proposed. In this study, the potential impact of PLHP on fish was explored by establishing a research framework among hydrodynamics, biological behaviours, spatial distribution and abundance of aquatic organisms. Two scenarios of the current dry water situation and PLHP regulation scheme were simulated, and the variables of water depth, velocity, riverbed surface morphology, habitat area, food resources, movement ability and biological connectivity were discussed. Results show that the effect of PLHP on fish habitat has both positive and negative aspects. For the whole area, the hydraulic project improves the habitat suitability area and food resources of fish, but weakens the migration ability and connectivity with the Yangtze River. The degree of dual influence depends on the dispatching water level. These results could provide guidance for the reasonable operation of PLHP and the protection working of fish in Poyang Lake.

1. Introduction
Poyang Lake is the largest freshwater lake in China, which is directly connected with the main stream of the Yangtze River. It is rich in biodiversity, especially an important habitat for many kinds of fish species[1]. However, with the operation of a large number of reservoirs on the main stream of the upper reaches of the Yangtze River[2], the water level of Poyang Lake is declining[3,4], which leads to the deterioration of the ecological environment in Poyang Lake. Therefore, the construction plan of Poyang Lake Hydraulic Project (PLHP) was proposed to restore the function of Poyang Lake by regulating and storing the water quantity in the lake area[5]. When constructing a water conservancy project, it is necessary to clearly evaluate its potential impact on aquatic environment and ecology[6,7]. Previous studies have focused on the hydrodynamic and water quality changes that may be caused by PLHP[8,9]. However, the analysis and prediction of the impact on aquatic organisms and ecological habitats are relatively scarce.

The investigations of fish habitat are usually based on its ecological behaviours, such as feeding, reproduction, overwintering and migration[10]. These behaviours are influenced by water temperature, depth, flow velocity, sediment concentration, riverbed surface morphology and food resources. More than 100 kinds of fishes live in Poyang Lake, mainly Cyprinidae[1,11]. These fish mainly feed on benthic invertebrates, phytoplankton and aquatic plants. According to migration characteristics, the fish in Poyang Lake can be divided into lake settlement type, lake-river migration type and lake-river-sea migration type[12]. The main species of settled fish are Cyprinus carpio and Carassius auratus, whose abundance and spatial pattern are only affected by the water environment in the lake area[12].

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The typical species of migratory fish are the four major Chinese carps, which migrate between the main stream of the Yangtze River and Poyang Lake. And their density and distribution are also affected by the connectivity characteristics between the river and lake [13].

Suitability area, food resources, movement ability and biological connectivity are the key indicators of the health status of fish habitat. The goal of this research is to use fish as a representative of aquatic organisms, to establish a framework for ecological habitat response to the operation of PLHP. The hydrodynamic and bed surface morphological differences directly brought by the project under the regulation and current dry situations will be simulated. Furthermore, the influence on fish habitat characteristics will be quantitatively evaluated. The findings will be helpful to explore the most beneficial operation scheme of PLHP for aquatic organisms.

2. Mathematical models
A research framework for the impact of hydraulic project on hydrodynamics, fish behaviours, habitat features and fish abundance is proposed (figure 1).

2.1 Simulation of hydrodynamics and sediment
The hydrodynamic module is dominated by the two-dimensional Reynolds averaged Navier-Stokes theory, including continuity and momentum equations [14,15].

\[
\frac{\partial Z}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0
\]  \hspace{1cm} (1)

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial Z}{\partial x} + g \sqrt{u^2 + v^2} = & \ n \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial Z}{\partial y} + g \sqrt{u^2 + v^2} = & \ n \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)
\end{align*}
\]  \hspace{1cm} (2)

where \( Z \) is the water level; \( H \) is the water depth; \( u \) and \( v \) are the vertically averaged velocities in the \( x \)- and \( y \)- directions, respectively; \( g \) is the gravitational acceleration; and \( C \) is the Chezy resistance coefficient; \( n \) is the turbulent viscosity coefficient.

The sediment module is based on a non-equilibrium suspended sediment transport equation and a semi-empirical formula for ripple height of bed surface morphology [16,17,18].

\[
\frac{\partial (HS)}{\partial t} + \frac{\partial (HSu)}{\partial x} + \frac{\partial (HSv)}{\partial y} = \frac{\partial}{\partial x} \left( E_x H \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y} \left( E_y H \frac{\partial S}{\partial y} \right) - \alpha \omega (S - S_m)
\]  \hspace{1cm} (3)

\[
h_r = 0.086 H \frac{U_m}{\sqrt{g H \frac{H}{d_{50}}}}^{\frac{3}{4}}
\]  \hspace{1cm} (4)

where \( S \) and \( S_m \) are the depth-average suspended sediment content and sediment carrying capacity, respectively; \( E_x \) and \( E_y \) are the diffusion coefficients in the \( x \)- and \( y \)- directions; \( \alpha \) is the recovery coefficient of the suspended sediment; \( h_r \) is the ripple height; \( \omega \) is the settling velocity; \( U_m \) is the depth-averaged velocity; \( d_{50} \) is the median particle size.
2.2 Evaluation of fish habitat

(a) Habitat suitability area

Most of fish species in Poyang Lake are carps, whose distribution is mainly affected by water depth, flow velocity and water temperature, and has a relatively well-defined suitability index[19].

\[
HSI = \left[ f(H) f(V) f(T) \right]^{1/3}
\]  
\[
HSA = \sum_n HSI_n \times A_n
\]

where HSI is the habitat suitability index; \( f(H) \), \( f(V) \) and \( f(T) \) are suitability functions for water depth, flow velocity and water temperature, respectively; HSA is the habitat suitability area of the whole area; \( A_n \) is the area of computational grid.

(b) Food resources

The fish living in the bottom water layer of Poyang Lake mainly feed on benthic invertebrates[20]. Thus, this research takes it as a representative to explore the change of food resources of fish. The abundance of benthic invertebrates can be calculated by a biomass dynamic equation, and the key influence parameter is the bed surface morphology[18].

\[
\frac{dBI}{dt} = \left( G_{max} \frac{N}{N + k_{inv,N}} \frac{1}{1 + k_{inv,B} BI} f_{bsm} f_{ton} - \text{Exc} - \text{Pre} \right) BI
\]

\[
f_{bsm} = \alpha_{bsm} h^3 \exp\left( \beta_{bsm} h^2 \right) + \gamma_{bsm}
\]

where BI is benthic invertebrate biomass; \( G_{max} \) is the maximum growth rate; \( N \) is the nutrient content; \( k_{inv,N} \) and \( k_{inv,B} \) are the inverse half saturation coefficients for nutrient and space; \( f_{bsm} \) is the bed surface morphology parameter; \( f_{ton} \) is the water temperature parameter; Exc and Pre are excretion and predation rates; \( G_{max}, \text{Exc} \) and Pre are usually defined as constant; \( \alpha_{bsm}, \beta_{bsm}, \) and \( \gamma_{bsm} \) are calculation parameters for \( f_{bsm} \).

(c) Motion activity

The movement of fish has strong following characteristics of the water flow, and the swimming speed depends on the flow velocity. Thus, in this study, fish is regarded as particle with mass, and the diffusion equation of tracer is adopted to describe the swimming time of fish[21]. The reciprocal of the duration when the particles are founded at the monitor section is used to describe the motion activity.

\[
\frac{\partial C(t, \bar{x})}{\partial t} + \nabla \cdot \left[ \text{K} \nabla C(t, \bar{x}) \right] = 0
\]

where \( C(t, \bar{x}) \) is the tracer concentration at time \( t \) and location \( \bar{x} \); \( \text{K} \) is the diffusivity tensor.

(d) Biological connectivity

The gates of dam have different opening pattern under the regulation scheme[22]. The opening time and area directly determine the connectivity of aquatic organisms inside and outside the lake. That depends on the flow discharge and the water level upstream and downstream the dam.

\[
be = \frac{Q}{\sigma_n e \varphi \sqrt{2 g H_0}} \left( 1 - \frac{h_c}{H_0} \right)^{-1/2}
\]

where \( be \) is the opening area of gates; \( Q \) is the discharge; \( \sigma_n, e \) and \( \varphi \) are flow coefficients; \( h_c \) is the water depth downstream the dam; \( H_0 \) is the water head upstream the dam.

3. Research area

Poyang Lake is located in the middle and lower reaches of the Yangtze River (figure 2), with a drainage area of 162,000 km² and a maximum water surface area of about 3,000 km²[9]. Influenced by monsoon climate, the runoff of Poyang Lake shows obvious seasonality, and the water level and
surface area fluctuate greatly. Autumn and winter are the dry seasons of Poyang Lake, when the inflowing flow is between 800 m\(^3\)/s and 4,000 m\(^3\)/s in the dry water year. Only the channel area can maintain a certain water depth, and the lake area shows the characteristics of river.

**Figure 2.** Sketch map of Poyang Lake in the Yangtze River basin.

PLHP is planned to be constructed at Pingfeng. This study calculates the lake area to the south of PLHP. The upper boundary adopts the discharge condition of the inflowing rivers from 2006 to 2007, and the lower boundary adopts the water level condition at the dam. Two water level conditions are simulated (figure 3), i.e., the regulation scheme of the PLHP, and the current situation of a dry water year from 2006 to 2007, respectively. The simulation period is from 1\(^{st}\) September to 28\(^{th}\) February of the next year. During this period, the same time series of water temperature is used for the whole lake area, varying between 28.7 \(^{\circ}\)C and 9.8\(^{\circ}\)C. The model adopts orthogonal structured grids. The study area is divided into 305 rows \(\times\) 295 columns, with the cell grid size of 300 m \(\times\) 300 m.

**Figure 3.** Two water level boundary scenarios.

### 4. Results

Hydrodynamic simulation results were verified by the field water level at Xingzi, Duchang, Tangyin and Kangshan stations. The simulation results show good agreement with the observed data. The parameters used for the fish habitat evaluation were derived from the literatures, which have been mentioned in the model description.

#### 4.1 Hydrodynamic environment

Fish needs the minimum water depth of 0.25 m to meet the survival requirement, and 2.0m is a critical water depth for fish to be possibly affected by human activities. Thus, these two water depth values
were selected to describe the impact of PLHP on water depth and surface area. Under current dry scenario, the water depth in Poyang Lake is shallow. From September, Poyang Lake gradually enters a low water level period. The water surface area with water depth greater than 0.25 m is around 1,000 km², fluctuating with the change of inflowing discharge (figure 4a). The area of water surface with water depth greater than 2.0m is about 200 km², which does not change much in autumn and winter. The operation of PLHP has a significant impact on the improvement of water depth and surface area. In September and October, the water surface area with water depth greater than 0.25 m increases to about 2,500 km², an increase of 1.5 times. The water surface area with water depth greater than 2.0 m increases to 1,500-2,000 km², a maximum increase of nearly 10 times. However, from December to February of next year, due to the small upstream discharge, even the water level in the lake area is regulated by the project, it can only meet the water depth in the main channels, and the effect of water surface improvement in the whole lake area is not obvious.

The changes of water depth and flow velocity are negatively correlated. As the water depth increases in lake area, the flow velocity will decrease correspondingly. 0.2 m/s is the most suitable velocity for fish habitat. Under current dry water scenario, the water surface area of less than 0.2 m/s is around 800 km² (figure 4b), corresponding to the water depth of nearly 0.25 m. The area of water surface with flow velocity greater than 0.2 m/s fluctuates greatly. When the inflowing discharge is large, that area is around 500 km², and when the discharge is small, that area is only around 150 km². PLHP weakens the water flow in Poyang Lake, especially in September and October. In autumn, almost all the areas with velocity greater than 0.2 m/s no longer exist. From December to February, PLHP has slight effect on flow velocity.

![Figure 4. Water surface area of the different water depth and flow velocity.](image)

**4.2 Fish habitat evaluation**

Habitat suitability area reflects the living space of fish, which has an influence on fish abundance and biodiversity. The most suitable flow velocity is between 0.05 m/s and 0.5 m/s, and the most suitable water depth is from 0.5 m to 1.5 m. Meanwhile, the most suitable temperature for fish is around 25 °C. In autumn and winter, the water temperature in the lake area gradually decreases, and the temperature suitability of fish decreases accordingly. With the decrease of inflowing discharge, the water surface area greatly reduces. Thus, in the current dry water scenario, the largest suitability area occurs in September, around 550 km² (figure 5a). The suitability area in January appears the smallest, around 300 km². Due to the increase of water depth in the lake area by PLHP, the habitat suitability area of fish increases to about 1,000 km² in September and October, which has three times larger. From December to February, the suitability area also slightly increases by about 10%.

Benthic invertebrates live in the surface sediment of riverbed, where exchange of nutrient and dissolved oxygen is abundant. With the variation of hydrodynamic conditions, the height of ripple morphology changes accordingly. The biomass of benthic invertebrates reaches its maximum in autumn, and gradually decreases later, due to the influence of water temperature variation [18]. Based
on the bed surface morphology parameters, different biomass values of initial field were set for simulation. The result demonstrates the average biomass of the whole lake area (figure 5b). The niche of benthic invertebrates to the ripple height shows a form of single peak, thus, there are differences in the increase of biomass in different regions. However, from the perspective of the whole lake, PLHP is beneficial to the growth of benthic invertebrates, and improves the food resources of fish.

Figure 5. Comparison of suitability area, food resources, motion ability and biological connectivity.

In the study, tracer particles were released near the entrance of the northern branch of the Gan River, where the inflowing discharge is relatively large and can reflect the water flow characteristics in the lake area. Monitoring points were set at the section of PLHP to calculate the time required for tracer particles to be transmitted. In the current dry water scenario, the transport duration of tracer particles is around 5 days, and the difference among months is relatively small. The month with the smallest transport duration appears in December, which needs 3.8 days. As PLHP weakens the flow characteristics, under the regulation scheme, the transmission period is between 4.5 days and 14 days. The minimum transmission period also occurs in December, and the largest transport duration appears in September. The reciprocal of the transmission period was used to describe the swimming ability of fish (figure 5c). Obviously, PLHP declines the motion ability of fish, which changes the most in September, reducing by 65%. In other months, the swimming ability of fish also decreases by around 20% to 50%. The influence of PLHP on the biological connectivity is very significant (figure 5d). It was assumed that the connectivity under the current dry water year scenario is 1.0. Correspondingly, under the regulation scheme, the connectivity calculated from the gate opening area is only about 0.05, with a reduction of more than 90%. The decrease of biological connectivity will affect the life process of most migratory fish species. The impact of dam barriers need to be eliminated as much as possible by rationally laying out fish passages.
5. Summary and conclusion
In order to study the potential influence of PLHP on fish habitat in Poyang Lake, this paper selected water depth, flow velocity, suitability area, food resources, motion ability and biological connectivity as indicators, and simulated the current situation and project regulation scheme. The main findings are as follows. The operation of PLHP increases the suitability area and food resources of fish, which are more beneficial for the settled type fish. However, because the dam weakens the flow characteristics of the water in Poyang Lake and directly blocks the upstream and downstream, it is harmful for the swimming capacity and biological connectivity of the migratory fish.

From September to December, the hydraulic project has the greatest influence on hydrodynamic environment and fish habitat in the lake area. This period also is a relatively important stage for fish migration. When the upstream flow and precipitation are suitable, the dispatching water level can be properly adjusted to ensure the movement of fish. Fishway should be optimized to increase the lake-river connectivity. In addition, the operation of PLHP will also affect aquatic plants and water quality, leading to the variation of fish spawning and reproduction, which needs further studied.

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