Habitat succession of the Yangtze finless porpoise in Poyang Lake under the changing hydrodynamic and feeding environment

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\begin{abstract}

Poyang Lake, located in the middle and lower reaches of the Yangtze River, is the largest freshwater lake in China and the most important habitat for the Yangtze finless porpoise. With the operation of the Three Gorges Dam, the water ecosystem functions of Poyang Lake are deteriorating, which has negatively influenced the habitat of Yangtze finless porpoise. In this research, quantitative functions of the three environmental factors, flow velocity, water depth and food availability, which have the greatest impact on the abundance of Yangtze finless porpoise were constructed, and then a habitat model of the Yangtze finless porpoise was established based on hydrodynamic model. The model results are in good agreement with the observed data, and the simulation well reproduces the spatial position distribution and abundance of the Yangtze finless porpoise in Poyang Lake. Then, the proposed model is applied to compare three scenarios before and after the operation of Three Gorges Dam, and simulate the evolution of hydrodynamics, feeding environment and Yangtze finless porpoise habitat in Poyang Lake. Two typical parts of river-lake connection channel and the main lake area were analyzed separately. Results show that the water depth, surface area and food availability in Poyang Lake are gradually decreasing, which lead to the weakening and plaque-like fragmentation of the Yangtze finless porpoise habitat. The findings in this study could help to understand how changes in aquatic conditions affect the ecological habitat, and provide scientific guidance for the future protection of Yangtze finless porpoise.
\end{abstract}

1. Background

The construction of hydraulic engineering projects is of great significance to the development and safety of human economy and society, but it can also cause a series of ecological problems (Santucci et al., 2005; Ban et al., 2019). As the largest freshwater lake of China, Poyang Lake is one of the only two lakes that are directly connected with Yangtze River mainstream. It is located 900 km downstream of the Three Gorges Dam, connecting to the Balijiang section of the Yangtze River at Hukou station (see Fig. 1). Poyang Lake is an important habitat for a variety of aquatic animals and plants, with rich biodiversity and habitat suitability (Lai et al., 2014). In recent years, with the operation of the Three Gorges Dam, the sediment carried from the upper reaches of Yangtze River has been intercepted by the dam, resulting in aggravation of riverbed erosion in the middle and lower reaches of the riverbed (Huang et al., 2019). The water level at Hukou station has been continuously reduced (Lai et al., 2014; Fang et al., 2014), resulting in the increase of discharge from Poyang Lake towards the Yangtze River (Gao et al., 2014). The water surface area of Poyang Lake continues to shrink (Wang et al., 2019). The low flow condition occurs earlier than before and the duration of the low flow in Poyang Lake becomes longer. Such trend becomes worse. However, with the deterioration of water environment conditions, the ecological habitat of Poyang Lake is weakening, and the biological diversity and abundance of benthic animals and fish are declining (Li et al., 2019; Liu et al., 2019; Zhang et al., 2011).

Yangtze finless porpoise is the only freshwater dolphins in the world. It is a kind of migratory aquatic organism in the rivers and lakes, and only exists in the mainstream of the middle and lower reaches of the Yangtze River and two large connecting lakes (Huang et al., 2017). Yangtze finless porpoise enters the Poyang Lake from the Balijiang river section through the Hukou station. Due to the deterioration of water ecological habitat function, the number of Yangtze finless porpoise in the mainstream of the Yangtze River has decreased from around 2500 in 1990 to around 500 in 2012 (Mei et al., 2014). According to previous survey data in November of each year (see Fig. 2), the number of

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Yangtze finless porpoise in Balijiang river section has decreased by about half from 1996 to 2008, with a significant reduction trend (Wei et al., 2002; Zhao et al., 2011). At present, the Yangtze River finless porpoise has been included in the IUCN Red List of threatened species (Kimura et al., 2010; Wang et al., 2013). According to the current population decline trend, the finless porpoise is expected to disappear within 100 years (Mei et al., 2012). The in-depth investigation and protection work is very necessary and urgent to conduct.

The habitat of Yangtze finless porpoise is influenced by both abiotic and biological factors. Recent studies have shown that water depth, flow velocity, substrate type, distance from the shore, water quality and availability of food all affect the abundance of Yangtze finless porpoise (Wei et al., 2003; Zhang et al., 2015). The number of dead Yangtze finless porpoise discovered from 2008 to 2014 was 176, of which 61.4 were identified as the cause of abnormal aging death (Xu et al., 2015). The main factors of abnormal deaths include shipping disturbances, small water depth leading to stranding and hunger due to food deprivation (Zhao et al., 2008; Zhang et al., 2013; Xu et al., 2015). Heavy ship traffic increases the physical consumption of Yangtze finless porpoise, interferes with the swimming routes, and the huge noise is also an unfavorable physiological stimulus (Nabi et al., 2018). The ship’s navigation route mainly depends on the water depth. When the water level is too shallow, the available water surface will be narrowed, which will reduce the safety distance between ship traffic and the Yangtze finless porpoise habitat (Wang et al., 2015). For the swimming aquatic animals with strong current-tropism characterizes, water flow has an important impact on habitat selection (Goodwin et al., 2006; Fang et al., 2016a, b). Yangtze finless porpoise often occur in areas where water flows confluence, and this area is also rich in fish resources (Wei et al., 2003; Zhang et al., 2015). In order to get enough food intake, Yangtze finless porpoise often chooses to enter the port area with great influence on human activities at dusk and night, which further shows that the lack of food resources has very adverse effects on the finless porpoise (Wang et al., 2015).

Previous research has mainly used field surveys to record the population number and habitat environment changes of Yangtze finless porpoise, but field observations tend to be limited in both time and space scale. Establishing habitat models for studying the abundance and spatial distribution of aquatic animals is a necessary step for prediction and protection (Habit et al., 2007; Torres et al., 2013). Yangtze Lake is the most important habitat for feeding and activities of Yangtze finless porpoise. However, the research on the habitat model for Yangtze finless porpoise in Poyang Lake area has not been conducted. This study will analyze the quantitative effects of water depth, flow velocity and food availability on the abundance of Yangtze finless porpoise, and then develop a habitat model for Yangtze finless porpoise based on the survey data. The developed model will be applied to simulate scenarios to quantitatively calculate the potential changes of hydrodynamics, food resources and Yangtze finless porpoise habitat in Poyang Lake. Finally, the scenario results will be compared with each other to analyze the reasons for the decrease of Yangtze finless porpoise abundance in different regions of Poyang Lake, which will provide scientific evidences for the future protection work.

2. Study area

Poyang Lake is located on the south bank of the middle and lower reaches of the Yangtze River, with a drainage area of 162,000 km², accounting for 9% of the Yangtze River drainage area (Gao et al., 2014). The inflowing rivers including Xiu River, Gan River, Fu River, Xin River and Rao River (Lai et al., 2014), enter the lake from Qijin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan and Dufengkeng stations, and then flow towards the mainstream of Yangtze River through Hukou station (see Fig. 3a). The topography of Poyang Lake is complex and undulating, including many narrow river channels and butterfly lakes, showing an overall trend of higher in the South and lower in the north. The topographic map uses the elevation of the Yellow Sea Base Level (the water level involved in the following adopts the same base level), which changes between 3.0 m and 14.0 m (see Fig. 3b). The whole Poyang Lake can be divided into two typical parts, one is the main lake area with wide surface and shallow water depth south of Xingzi station, and the other is river-lake connection channel area with small width and large water depth north of Xingzi station.

Influenced by the precipitation of monsoon climate, the flow discharge into Poyang Lake appears obviously seasonal characteristics. From June to August, the flow discharge of rivers entering the lake is relatively large, which is the wet season of Poyang Lake. From November to February, the upstream flow discharge is relatively low, which is the drought season of Poyang Lake. Most areas are exposed to shoals. Other times are the normal seasons. The maximum water level difference of wet and drought period in the lake area is around 8.8 m (Zhang and Werner, 2015). With the change of the inflow discharge, Poyang Lake presents the transformation of the lake and river phases, and the water surface area also varies between approximately 100 and 3000 km² (Lai et al., 2014).

The study area includes the main lake area and the river-lake connection channel of Poyang Lake. The model adopts orthogonal structured grids, dividing the calculation area into 305 rows and 375 columns, with the grid size of 300 × 300 m. The partial grid is shown in Fig. 3a. The calculation of hydrodynamic model in Poyang Lake generally begins with the high water level period and simulates a complete hydrological year. In this study, the upper boundary condition of the hydrodynamic model uses the inflow discharge of the five rivers, and the lower boundary condition uses the water level of Hukou station (Fig. 4).

3. Model configuration

3.1. Hydrodynamic model

The hydrodynamic calculations are controlled by two-dimensional Reynolds Average Navier–Stokes theory integrated along the vertical direction (Fang et al., 2006), including continuity and two momentum equations.
The continuous equation of hydrodynamic model is
\[
\frac{\partial Z}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0
\] (1)

The momentum equations of hydrodynamic model are
\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial Z}{\partial x} + g \frac{u^2 + v^2}{C^2 H} = \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)
\] (2)
\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial Z}{\partial y} + g \frac{u^2 + v^2}{C^2 H} = \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)
\] (3)

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; \( \nu \) is the horizontal eddy viscosity coefficient of turbulent, using 2.0 m\(^2\)/s at the beginning of the calculation; and \( C \) is the Chezy resistance coefficient, which is usually calculated through the Manning formula
\[
C = \frac{1}{n} H^{1/6}
\] (4)

where \( n \) is the Manning's roughness coefficient of riverbed, using 0.025 as the initial value of the calculation.

3.2. Yangtze finless porpoise model

Swimming behavior is the most important feature of aquatic animals such as finless porpoise. Through swimming, aquatic animals can search for food resources, seek benefits and avoid harm, and actively select suitable areas of habitat (Goodwin et al., 2006; Fang et al., 2016a, 2016b). Boltzmann equation is based on the theory of continuity and momentum, which is the most classical equation used to describe the relationship between particle velocity, spatial position and external force. In the large spatial scale, aquatic animals can be regarded as moving particles. Fang et al. (2016a, 2016b) has adopted Boltzmann theory to establish a motion model for aquatic animals under the Euler framework. The basic form of the Boltzmann equation for aquatic animals is
\[
\frac{\partial f_i}{\partial t} + u \frac{\partial f_i}{\partial x} + v \frac{\partial f_i}{\partial y} = \frac{\partial F_i}{\partial t}
\] (5)

where \( i \) represents two dimensions, \( f_i = f_i(u, x, t) \), is the distribution function of aquatic animals within a unit volume with velocity \( v_i \), at the coordinates \( x_i \), at the time \( t \); \( F_i \) is the resultant of external forces on aquatic animals; the right-hand side term is the molecule collision parameter.

Due to the small size and low concentration of aquatic animals in space, the collision term of Eq. (5) can be negligible, that is, and the right-hand term can be assumed as zero. When the motion reaches a stable equilibrium state, the distribution function \( f \) belongs to a time independent form. Using the variational method to solve the number of aquatic animals per unit volume (Fang et al., 2016a, 2016b)
\[
N_f(v) = A \left( \frac{2\pi v^3}{\alpha} \right)^{1/2} e^{-\lambda}
\] (6)
\[
\lambda = \beta [0.5u^2 S_{f} C_f - 0.5u^2 S_{f} (C_f + C_p)]
+ \beta [0.5u^2 S_{f} C_f - 0.5u^2 S_{f} (C_f + C_p)]
\] (7)
\[
C_p = C_{pf}(\theta - C_{pf})^2
\] (8)
where $N_f(v)$ is the number of aquatic animal integrated for different velocities per unit volume; $V$ is scalar swimming velocity of aquatic animal, which is related to flow velocity; $\alpha$ and $\beta$ are kinetic energy coefficients; $A$ is a parameter to be calibrated with certain field data; $\rho$ is the water density; $u_x$ and $u_y$ are swimming velocities of aquatic animal in x- and y-directions, respectively; $u_z$ is the relative velocity between aquatic animal and water flow in x- and y-directions, respectively; $S_a$ is the wetted surface area of aquatic animal; $C_p$, $C_w$, and $C_r$ are thrusting drag coefficient, profile drag coefficient, and friction drag coefficient, respectively; $\theta$ is the angle between aquatic animal and flow direction; $C_{ps}$ is used to adjust the range of flow velocity for different aquatic animals.

Fang et al. (2016a, 2016b) used the above model to simulate the distribution of river chub in the laboratory flume under different velocity conditions (Webb, 1998) and the spatial distribution of Yangtze finless porpoise observed in 2008 and 2010 at Balijiang river section (Kimura et al., 2010). The rationality and validity of the model were verified, and a set of parameters which are applicable to Yangtze finless porpoise were calibrated (see Table 1).

Considering that Yangtze finless porpoise can perch in static water, this study assumes the relative number to be 0.2 under the most unfavorable flow condition. Then the relationship between the relative number of Yangtze finless porpoise and flow velocity can be obtained as shown as the black solid curve in Fig. 5. The other two curves show that the model can be applied to more aquatic animals with different adaptation range by adjusting $C_{ps}$.

Eqs. (8)–(10) reflect the suitability requirement of Yangtze finless porpoise for the flow velocity. In the above applications, the spatial scale of simulation area is relatively small, so other environment variables can be considered to have less spatially variability. Water depth and food availability are both important factors affecting the distribution of finless porpoise in the Yangtze River and Poyang Lake. To simulate the Yangtze finless porpoise habitat in a large water area such as Poyang Lake, the model needs to investigate the influences of water depth and food availability (Kimura et al., 2012; Mei et al., 2017). Then, the Yangtze finless porpoise model is improved as follows.

$$C_{n_f} = f(h) f(F_a) N_f(v)$$

where $C_{n_f}$ is the number of Yangtze finless porpoise after combining various factors; $f(h)$ is the function of water depth influence; $f(F_a)$ is the function of food availability influence.

The quantitative effect of water depth on Yangtze finless porpoise can be directly obtained from the survey data (Wei et al., 2003). Fig. 6 shows the relative relationship between the observation times of Yangtze finless porpoise and water depth. Yangtze finless porpoise mainly exists in waters between 2.0 m and 9.0 m deep. When the water depth is more than 3.0 m, the number of Yangtze finless porpoise decreases exponentially.

In the present study, it is assumed that the optimal water depth of Yangtze finless porpoise is 3.0 m. When the water depth is greater than or less than 3.0 m, the exponential function and linear function are used to fit the relative relationship (see Fig. 6).

$$f(h) = \begin{cases} 0.333h, & h \leq 3.0m \\ 1.393e^{-0.111h}, & h > 3.0m \end{cases}$$

Investigation results at Balijiang river section indicate that the observation probability of Yangtze finless porpoise in the water areas with fish distribution is more than 40%, and that in the areas without fish distribution is less than 20% (Kimura et al., 2009). However, the quantitative relationship between the Yangtze finless porpoise abundance and its food availability lacks more detailed data. Tableau et al. (2016) summarized the measured data, and divided the impact of food availability on predator abundance into two categories. One is that food availability is the necessary limiting factor for predator distribution, shown as a positive correlation (Fig. 7a). The other is that food availability is not the limiting factor for predator distribution, and there is no significant relationship between them (Fig. 7b).

For Yangtze finless porpoise, food availability is undoubtedly an important limiting factor. Based on the actual situation of food utilization by predators, this study assumes that when the food availability is low, the abundance of Yangtze finless porpoise positively increases with the increment of food availability, and when the food availability reaches the sufficient state, Yangtze finless porpoise is no longer affected. This assumption is similar to the definition of logistic equation (Thornley et al., 2007), so the same form is adopted to describe the quantitative relationship between Yangtze finless porpoise abundance and food availability.

$$f(F_a) = \frac{K_e F_a e^{-F_a}}{K_0 + e^{F_a e^{-F_a}} - 1}$$

where $F_a$ is the food availability; $f(F_a)$ is the influence function of food availability; $K$ is used to define the relative maximum predator abundance. In the present study, $K$ is set to 1.0. $K_0$ represents the tolerance ability of predator when the food availability is 0. A larger $K_0$ represents a greater tolerance ability. When $K_0$ is equal to 1.0, the abundance of predator is not affected by food. $r$ is a control parameter that is used to
adjust the critical value as food availability increases to the sufficient state. The larger value of $r$, and then the smaller food availability required for the sufficient state.

Yangtze finless porpoise mainly feeds on small fish located on the surface of water bodies (Wei et al., 2003; Zhang et al., 2013). The main kinds of fish in Poyang Lake are carps (Zhang et al., 2011), whose distribution is mainly affected by flow velocity, water depth and temperature (Wang and Lin, 2013; Yi et al., 2014). These environmental variables have a relatively clear suitability index for carps (Fig. 8).

The abundance of small fish assemblages is the indicator of the food availability, can be determined by the habitat suitability index equation (Yi et al., 2014).

$$F_A = (g(v)g(h)g(T))^{1/3}$$

where $g(v)$, $g(h)$ and $g(T)$ are the influence of flow velocity, water depth and temperature on the carps, respectively.

To facilitate a more intuitive understanding of the theoretical model, Fig. 10 shows a conceptual diagram of the whole model.

4. Model calibration results

4.1. Hydrodynamic calibration

Firstly, the current scenario of the period from 2006 to 2007 was calculated. The Manning coefficient and horizontal eddy viscosity coefficient were mainly adjusted, and the parameters were calibrated through the measured water level data of four hydrological stations at Xingzi, Duchang, Tangyin and Kangshan (see Fig. 11). The Nash-Sutcliffe efficiency coefficient (NSE) and Pearson correlation coefficient (Pearson R) are used to characterize the difference between measured and simulated water level. When the best simulation effect is eventually determined, Manning coefficient and horizontal viscosity coefficient are 0.02 and 2.0 m$^2$/s, respectively. The four hydrological stations are evenly distributed in space, which can reflect the simulation effectiveness of the whole lake. From the overall perspective of the whole year, the simulation results can successfully reproduce the observed flow field with higher accuracy. Due to the existence of certain sand-dredging working in Poyang Lake, which cannot be considered in the model calculation, the simulated value in the low water level period is higher than the measured value, but it does not affect the supporting foundation of the hydrodynamic simulation results for the subsequent calculation.

Fig. 12a is the hydrodynamic calculation result on June 26th 2006, when the inflow discharge of the five rivers is 7088.50 m$^3$/s, and the outflow’s water level at Hukou station is 14.22 m. Poyang Lake is in the high water level season, presenting a lake’s pattern, with the water surface area greater than 0.25 m of 2806.24 m$^2$, and the water surface area greater than 2.0 m of 2371.83 m$^2$. The water depth of the river-lake connection channel is mainly over 8.0 m, and the flow velocity is around 0.3 m/s; while the water depth of the main lake area is mainly less than 6.0 m, and the flow velocity is around 0.2 m/s.

Fig. 12b is the hydrodynamic calculation result on February 11st 2007, when the inflow discharge of the five rivers is 893.06 m$^3$/s, and the outflow’s water level at Hukou station is 5.45 m. Poyang Lake is in the low water level drought season, presenting a river’s pattern, with the water surface area of more than 0.25 m is only 791.98 m$^2$, about 1/3 of that of the wet season, and the water surface area of over 2.0 m is only 173.43 m$^2$. At this time, only the main channel area of river-lake connection area can maintain a water depth of more than 2.0 m, and the flow velocity is around 0.15 m/s.

4.2. Yangtze finless porpoise calibration

The simulation results of Yangtze finless porpoise model are presented at the normal water period that is more representative in the hydrological year. The selected date is May 1st 2007, when the
The simulated water level of Xingzi station is 9.62 m. The water surface area greater than 0.25 m is 1808.66 m², and that greater than 2.0 m is 376.37 m², which is between the wet and drought season. The average flow velocity in the lake area is 0.30 m/s to 0.40 m/s (see Fig. 13a). When calculating the fish abundance, the same water temperature is used in the whole lake. The water temperature on May 1st is 21.4 °C, and the corresponding g(T) is 1.0. The most abundant area of fish is the main lake area between Duchang and Kangshan, which is also the spawning place and protection area for carps (see Fig. 13b). The water depth in this area mainly varies from 0.5 m to 1.5 m, and the flow velocity is between 0.3 m/s and 0.5 m/s, which is the most suitable niche for carps. The distribution of fish in the river-lake connection channel between Hukou and Xingzi is relatively average, especially the east beach side is more suitable for fish distribution, while the difference in density of fish in the main lake between Xingzi and Kangshan is larger.

Then, the spatial distribution pattern of Yangtze finless porpoise was simulated under the comprehensive hydrodynamic food availability conditions (see Fig. 13c). Fig. 13d is the main occurrence locations of Yangtze finless porpoise over the years in Poyang Lake recorded by Liu et al. (2016). The two gray circles mark the Yangtze finless porpoise Nature Reserve, one is near the south of Xingzi station, and the other is located in the main area between Tangyin and Kangshan. The value of fish abundance was directly used as the food availability parameter for Yangtze finless porpoise, and the parameter r in Eq. (11) was calibrated to make the simulation result best to reproduce the observed spatial distribution pattern. Finally, 10.0 was chosen as the value of r, and the influence curve of food availability on Yangtze finless porpoise was determined as the black solid line in Fig. 8b. It can be seen that the simulation results of Yangtze finless porpoise are in good agreement with the observed data.
Fig. 12. Maps of water depth and flow field at (a) high water level period and (b) low water level period.

Fig. 13. Maps of (a) water depth and flow field, (b) fish abundance (food availability), (c) simulated Yangtze finless porpoise distribution at the normal water level, and (d) observed locations of Yangtze finless porpoise.
agreement with the measured results, and it successfully reproduce the dense distribution of finless porpoise in the nature reserve. The total number of Yangtze finless porpoise in Poyang Lake can be computed by Eq. (13). Combined with the observation record (Ministry of Agriculture and Rural Affairs of China, 2016), the value of $A$ in Eq. (6) is determined to be 50.

$$TS_n = \sum_{i=1}^{M} A_i (Sn_f)$$

where $TS_n$ is the total number of Yangtze finless porpoise; $A_i$ is the area of the computing grid.

5. Model application results

5.1. Computing scenarios setting

The primary purpose of this study is to analyze the changes in hydrodynamics and feeding environment brought about by the construction of Three Gorges Dam using the developed habitat model. Three different scenarios are designed in the model application. The flow discharge condition at the upper boundary only refers to seasonal variation, with the same flow time process for three scenarios. In contrast, the lower boundary adopts different water level time process at Hukou station (see Fig. 14). Among the three scenarios, the “1959–2002 Average” scenario describes the historically averaged flow conditions. This scenario uses the averaged water levels from 1959 to 2002, which represents the flow conditions before the construction of Three Gorges Dam. The “2030–2031” scenario describes the future forecasting situation. This scenario uses the water level conditions at around 30 years later after the construction of the Three Georges Dam. The change of water levels is mainly caused by the riverbed erosion of the Yangtze River mainstream (Fang et al., 2014). The “2006–2007” scenario is the current situation after the beginning of the operation of Three Gorges Dam. This scenario is a baseline situation, where the same conditions are used in the model calibration. In order to facilitate the comparison of the differences among the three scenarios, “2006–2007” scenario is still shown in Fig. 14.

5.2. Hydrodynamic evolution

The water level in Poyang Lake area is generally characterized by the value at Xingzi station. Fig. 15a shows the monthly water level decrease between the “2006–2007” and “1959–2002 Average” scenario. Results indicate that the largest alternation in water levels occurs during the normal water level period including September, October and May, with a decline of about 5.5 m. The water level change does not change dramatically in the wet and drought seasons, and water level does not change during the driest season between the two scenarios.

Fig. 15b shows the monthly water level decrease of “2030–2031” scenario compared with the “2006–2007” scenario. The water level in the wet season and drought season will decrease significantly in the future. With the continuous operation of the Three Gorges Dam, the riverbed of Yangtze River mainstream has been eroding, and then the water level of the Poyang Lake continues to decrease.

Fig. 16 shows the shallow water areas and deep water areas. The shallow water areas are less than 0.25 m deep, and the water surface area with water deeper than 0.25 m (a shallow water depth) and greater than 2.0 m (a deep water depth) under three scenarios, respectively. It is obviously that in the past average scenario, the period to maintain a

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Fig. 14. Water level at Hukou station of the past average, current and future forecasting scenarios.

Fig. 15. Decline of the water level at Xingzi station.

Fig. 16. Water surfaces area of three different scenarios.
low water depth exists much longer than that in the current scenario, especially in September, October and May. After the operation of Three Gorges Dam, the water surface area of Poyang Lake has a significant shrinking trend. For the high water depth, even in the wet season from June to August, the current scenario is still 30% less than the past average scenario, and will further decrease in the future forecasting scenario. During drought season, the area of the larger water depth is around 200 km², accounting for only 8% of the whole lake area. The

Fig. 17. Maps at normal water level period of past average and future forecasting scenarios: (a,b) water depth and flow field; (c,d) fish abundance (food availability); (e,f) simulated finless porpoise.
decline of water level and the narrowing of water surface in the lake area will inevitably have an adverse impact on the ecological function of Poyang Lake.

5.3. Yangtze finless porpoise habitat decline

Fig. 17 shows the calculation results of hydrodynamic model and Yangtze finless porpoise abundance model under “1959–2002 Average” and “2030–2031” scenarios. In the “1959–2002 Average” scenario, the simulated water level of Xingzi station is 3 m, and the water area greater than 0.25 m in the lake area is 2101.84 m², and the water area greater than 2.0 m is 629.30 m². The river-lake connection channel is full of water, and only a few areas in the main lake cannot maintain a certain depth of water. The average flow velocity in the lake area is 0.3 m/s (Fig. 17a). In the “2030–2031” scenario, the simulated water level of Xingzi station is 9.24 m, and the water area greater than 0.25 m in the lake area is 1761.96 m², and the water area greater than 2.0 m is 357.92 m². The water area in the river-lake connection channel area also has obvious decreased. The flow velocity in the lake area is usually over 0.5 m/s (Fig. 17b).

In the “1959–2002 Average” scenario, the spatial distribution of carp in the river-lake connection channel is relatively uniform, and the fish abundance in most areas is around 0.6. The largest abundance occurs between Duchang and Kangshan, and the maximum abundance reaches 1.0 (Fig. 17c). In the “2030–2031” scenario, the fish distribution area in the river-lake connection channel shows obvious horizontal contraction, and more areas are not suitable for fish distribution due to the shallow water depth (Fig. 17d). Comparison of results shows that the distribution area of fish in the main lake area is also further narrowed with a trend of patching, and the fish abundance near Duchang has decreased significantly.

Finally, the abundance and spatial distribution of Yangtze finless porpoise were simulated. The simulated number of Yangtze finless porpoise of three scenarios are 711, 536 and 513, respectively, implying an apparent downward trend. In the “1959–2002 Average” scenario, the habitats of Yangtze finless porpoise in Poyang Lake are highly dense. And Yangtze finless porpoise is densely distributed and rich in abundance in the two nature reserve areas, (Fig. 17c). In the “2030–2031” scenario, the abundance of Yangtze finless porpoise in both the river-lake connection channel and main lake area decreases significantly with patches. Yangtze finless porpoise does not show obviously dominant distributions in the two nature reserves (Fig. 17d).

To further quantitatively analyze the changes of hydrodynamics and Yangtze finless porpoise habitat in Poyang Lake area under the three different scenarios, the water surface area, average food availability and Yangtze finless porpoise abundance of the two parts of river-lake connection channel and main lake area were counted separately (Table 2). The average food availability is defined as follows

\[ \overline{F_a} = \frac{1}{M} \sum_{i=1}^{M} (F_{ai}) \]  

(14)

Comparison between “2006–2007” scenario and “1959–2002 Average” scenario (see Fig. 18): the water surface area of the low water depth in the river-lake connection channel decreases more significantly, down by 20%, while the water surface area of the high water depth in the main lake area decreases more significantly, down by 36%. Because the hydrodynamic conditions for fish are suitable in both circumstances, the average availability of fish remains stable, merely increases by 3%. However, the main lake area has a significant variation of hydrodynamics, and the average availability of fish has dropped by 15%. The total abundances of Yangtze finless porpoise in the river-lake connection channel and main lake area decrease by 31% and 23%, respectively. Compared with the past average scenario, the reduction of Yangtze porpoise abundance in the river-lake connection channel is mainly due to the decline of water area, while the reduction in the main lake area is mainly due to the decline of food availability. In addition, the proposed model does not directly quantify the impact of shipping, and its interference will further intensify as the large water depth of the main lake area decrease.

Comparison between the “2030–2031” and “2006–2007” scenarios (see Fig. 18) shows that the water surface area of shallow water depth, deep water depth, average food availability and Yangtze finless porpoise in the river-lake connection channel have still greatly changed, by 12%, 46%, 24% and 23%, respectively. Because of the further decline of the water level, the water depth in the river-lake connection channel has also become too shallow, leading to further narrowing of the water surface area. The river-lake connection channel is the only waterway for Yangtze finless porpoise to enter and exit Poyang Lake. The narrowing of its water surface will reduce the habitat space and increase the impact of shipping, which will be unfavorable for the swimming routes of Yangtze finless porpoise. On the contrary, in the main lake area, the changes of water surface area, average food availability and Yangtze finless porpoise abundance tend to be gentle, decreasing by around 2% respectively. However, the fragmentation of habitat patches in the main lake area is still increasing. Overall, the abundance of finless porpoise in the whole lake still decreased to a large extent.

6. Conclusions

To investigate how the changes of aquatic environment in Poyang Lake affect the Yangtze finless porpoise, three key variables, flow velocity, water depth and food availability were selected. And their
impacts on the abundance of Yangtze finless porpoise were determined. Then a habitat model of Yangtze finless porpoise was established. The model results have successfully reproduced the hydrodynamic characteristics and the spatial distribution pattern of Yangtze finless porpoise in Poyang Lake, and the simulation results show good agreement with the field observation data. The main findings of this study are as follows:

(1) After the operation of Three Gorges Dam, the hydrodynamic conditions in Poyang Lake has deteriorated, with decreasing water level and water surface area. The existence period of the high water depth are becoming shorter. Moreover, the declining trend of water level will continue in the future.

(2) With the changes of hydrodynamics, the habitat suitability of small fish in Poyang Lake has been declined. The reduction of water area and food availability have resulted in a decrease in the number of Yangtze finless porpoise populations, a shrinking spatial distribution area, and fragmentation of habitat.

(3) In the future forecasting scenario, as the habitat suitability of river-lake connecting part is still declining, the possibility of Yangtze finless porpoise swimming from the Yangtze River mainstream into Poyang Lake will be greatly reduced. Although the habitat environment changes in the main lake area tend to be stable, the abundance of Yangtze finless porpoise in Poyang Lake still remains pessimistic.

(4) The impact of human activities on the Yangtze finless porpoise, such as shipping traffic and fishing, is closely related to water depth and surface area. Improving the hydrodynamic conditions of Poyang Lake is the key point to protecting the Yangtze finless porpoise.

This research provides a model tool to explore the habitat of Yangtze finless porpoise. Moreover, the findings could provide guidance for the protection and habitat restoration works in the future. Due to the scarcity of field investigation data of Yangtze finless porpoise, the model calibration in this study is still weak. The follow-up study will continue to focus on the increase of field data and further optimize model parameters.

CRediT authorship contribution statement

**Yong Han:** Methodology, Writing - original draft. **Zhiyu Sun:** Supervision. **Hongwei Fang:** Conceptualization, Funding acquisition. **Sen Bai:** Writing - review & editing. **Lei Huang:** Resources. **Guojian He:** Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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