Forecasting Yangtze finless porpoise movement behavior using an Eulerian–Eulerian-diffusion method (EEDM)

Hongwei Fang, Dongchen Dai, Songheng Li, Guojian He, Lei Huang

A The State Key Laboratory of Hydro Science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, PR China
b Alden Research Laboratory, Inc., 30 Shrewsbury Street, Holden, MA 01520–1843, USA

A R T I C L E   I N F O
Article history:
Received 14 March 2015
Received in revised form 26 October 2015
Accepted 2 December 2015
Available online 23 December 2015

Keywords:
Fish passage
Eulerian Eulerian diffusion model
Kinetic theory
Eulerian
Velocity preference
Yangtze finless porpoise

A B S T R A C T
It has been observed in recent years that the water level of Poyang Lake, the largest freshwater lake in China, is decreasing gradually in the dry seasons, resulting in some serious environmental and ecological issues, such as vegetation and prey decreasing. The local government has proposed a dam downstream of the lake to control the declining trend. The construction of the lake level control structure could affect the migration of some aquatic animals, including this endangered porpoise species. A two dimensional (2D) diffusion model was developed to assess the movements of porpoises in Poyang Lake with the dam in place. This 2D model was coupled with a hydrodynamic model to evaluate the passage efficiency of the proposed bypass system of the planned dam. The diffusion model was based on the Boltzmann equation of kinetic theory. In this model porpoises were treated as particles which have flow velocity preference, share similar modes of mechanics with porpoises. The model was built on the Eulerian framework so that it can be well coupled with the general hydrodynamic model. The porpoise’s distribution and movements are represented by particle diffusion. What’s more, this model is suitable for modeling distributions of other aquatic species, such as fish, due to its sophisticated theoretical principles. The results indicated that the passage efficiency of the bypass system is acceptable whether in the dry or wet seasons. We also applied the model to the entire Poyang Lake to predict the possible habitats for the porpoises. The control equation of the model will be complemented with other source terms, i.e., water temperature, water quality, and water depth to consider their future impacts from this development.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Being the largest freshwater lake, Poyang Lake is located in the South-Central of China. It is connected with the Yangtze River in the north. The observation data by the lake’s hydrological stations indicate that the lake water level keeps decreasing, especially in the dry seasons (Lai et al., 2014a,b; Ye et al., 2014). As a result, the area of Poyang Lake decreased from the normal value of 4125 km² to only 54 km² (Zhang et al., 2014) in 2011. Therefore, the local government has proposed to build a control structure at the connection channel between the Yangtze River and the Poyang Lake (Fig. 1) to maintain the water level. It has been demonstrated that human intervention has caused adverse effect to the aquatic animals (Castro et al., 2013; Eekema et al., 2012; Lai et al., 2014a), especially to the Yangtze finless porpoise in this region. Yangtze finless porpoises are one of the endangered species in China. They migrate between the Yangtze River and the Poyang Lake periodically (Kimura et al., 2012; Zhao et al., 2013). The negative impact was due to direct blockage of the migration routines and relocation of the habitat sites (Ban and Xiao, 2014; Bui et al., 2013; Shaffer et al., 2009; Wang et al., 2013). Therefore, the passage efficiency of the proposed bypass system becomes the critical issue before the scheme is approved (Johnson et al., 2005; Wertheimer, 2007). In view of the limited and variable success achieved by existing bypass systems worldwide (Noonan et al., 2012), it is useful to develop numerical models to evaluate the performance of such systems (Katopodis and Williams, 2012).

In order to figure out the inner mechanism of fish movements, a lot of investigations have been conducted. Fish tend to react conditionally according to different surrounding environment, especially to hydrodynamic changes (Jian et al., 2015; Weibel and Peter, 2013; Zhong et al., 2013). Different species were tested in multiple circumstances and some characteristics and trends have been found. Many observations and studies on fish movements have been performed in the laboratories (Crossman et al., 2013; Lee, 2013; Olsen et al., 2013). Fortunately, those reactions can be studied separately based on behavioral theories which could contribute to the
computational simulation of fish diffusion models. For several decades, many models based on the Lagrangian approach have been developed from the perspective of either individual-based model such as Baetens (2013), Scheibe and Richmond (2002), and Tu et al. (2012) or collective motion. Vicsek et al. (1999) defined interaction activities between the members of a group, following certain rules, called self-propelled particle model. Tunstrom et al. (2013) managed to demonstrate the collective behavior is related to the number of group members. Some of the models prove to be quite accurate when operating in the small scale region and have been widely adopted to evaluate the performance of certain bypass systems (Goodwin et al., 2006).

However, when dealing with large areas, such as the Poyang Lake, the Lagrangian approach models could be not effective and efficient because of the requirements for small computational intervals, massive memory and data storage. Meanwhile, all of the behavior models need to be coupled with the computational fluid dynamics (CFD) models which are built on a Eulerian framework. Therefore, a new Eulerian approach suitable for large areas was developed and presented in this paper. The Eulerian model was based on the Boltzmann equation of kinetic theory, which was developed to predict the distribution of molecules at an equilibrium state (Chapman and Cowling, 1970). Beverton and Holt (2004) discussed kinetic theory of gas and fish dispersion in great detail including an analysis of plaice. More detailed treatment of the kinetic theory of gasses related to fish schooling was introduced by Carrillo et al. (2009). Wang and Ning (1990) first applied the Boltzmann equation to solve the sediment concentration distribution. Likewise, compared with the grid size for a large area, aquatic animals can be treated as particles with specific constraints, so that the Boltzmann equation becomes suitable for the model. In this paper porpoise were considered as particles that follow velocity preferences and regular migrations trends. Rather than the individuals, the movement of porpoises in groups in this model is simulated as the particles are diffusing between each divided area in the lake. Thus, the model in this paper is called the Eulerian Eul- rian diffusion model (EEDM) and was used to evaluate the impact of hydraulic conditions on the Yangtze finless porpoise, utilizing available field data.

2. Model overview

2.1. Describing hydrodynamic flow patterns with the Eulerian framework

The area of Poyang Lake is 4125 km² under normal lake WS El. 20 m. The 2.8 km long dam will be located at the Pingfeng–Changling cross section of the lake outlet channel as shown in Fig. 1. We considered the whole area of Poyang Lake as object region. The hydrodynamic flow patterns in this area were calculated in an orthogonal planar coordinate system. The model solved the Navier–Stokes equations of fluid motion at discrete points in an Eulerian mesh with average mesh size of 500 m × 500 m.

The continuity equation of the model is:

\[
\frac{\partial h}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial h}{\partial y} = 0
\]  
(1)

The momentum equation of the model is:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial h}{\partial x} + \frac{\partial h}{\partial t} \frac{\sqrt{u^2 + v^2}}{C^2} = v_1 \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)
\]

(2)

where \(u, v\) are the flow velocity at the x and y directions, respectively, \(h\) is the water depth, \(g\) is the gravitational acceleration, \(C\) is the Chezy coefficient and \(v_1\) is the turbulent viscosity coefficient.

2.2. Describing moving characteristics of the Yangtze finless porpoise with the Eulerian framework

Rather than focusing on the individual movement behavior, the Yangtze River finless porpoise is treated as a group of many individuals in the EEDM model. This approach can deal with a much larger domain (like the whole lake area in this study) than that of the traditional Lagrangian framework. Since the Yangtze River porpoises were considered as a group of plenty of individuals, we assumed them as particles which control their own movements. Wang and Ning (1990) applied the kinetic theory to predict the concentration distribution of sediment particles. The key equation of
their model is the Boltzmann equation which is developed to figure out the procedure of the distribution of molecules transition from non-equilibrium state to equilibrium state based on continuity and mechanics theory. Fish movement is a kind of transition procedure from non-equilibrium to equilibrium, which can be described by the Boltzmann equation as well, as long as certain terms of the equation are altered appropriately. The equation of the model is based on Boltzmann equation as the following:

\[
\frac{\partial f}{\partial t} + v_i \frac{\partial f}{\partial x_i} + \frac{\partial f}{\partial t} = \left( \frac{\partial f}{\partial t} \right)_c
\]  

(3)

where \( f = f(v_i, x_i, t) \) is the velocity distribution function of porpoise, which describes the number of the porpoise group within a unit volume with the velocity of \( v_i \) at the coordinates of \( (x_i, y_i, z_i) \) at time \( t \). \( v_i \) is the porpoise velocity, \( x_i \) is the horizontal or vertical coordinate, \( t \) is time and \( F_i \) is the resultant of all forces exerted on the porpoise per unit volume. The left hand side (LHS) of Eq. (3) contains both continuity and momentum terms, while the right hand side (RHS) represents additional parameters caused by collisions between molecules in kinetic theory, or 0 in this model, as collisions between porpoises are reasonably considered to not occur.

Various methods are applied to solve the equation along with some simplifications (with only hydrodynamic factors considered, regardless of temperature, predation and mortality, etc.). The obtained velocity distribution is:

\[
f = \exp \left( \lambda + b \cdot v - \frac{1}{2} m \beta v^2 \right)
\]  

(4)

where \( \lambda, b \) and \( b \) are coefficients which need to be determined. Together with Eq. (3) we conclude that:

\[
\lambda = \int m \beta F \cdot dx
\]  

(5)

It is clear that \( \lambda \) is related with the external forces. Therefore, Eq. (4) can be rewritten as:

\[
f = A \exp \left( \lambda - \frac{1}{2} \beta m v^2 \right)
\]  

(6)

where \( A \) is a new coefficient to be determined and \( V \) is the average velocity of porpoise. Therefore, the simulated number of porpoise per unit volume is:

\[
n = \int f dv_i = \int A \exp \left( \lambda - \frac{1}{2} \beta m v^2 \right) dv_i
\]  

(7)

\[
= A \left( \frac{2\pi}{m \beta} \right)^{3/2} e^{\lambda}
\]

Since the average kinetic energy of porpoise per unit volume can be expressed as:

\[
\frac{1}{2} m v^2 = \frac{m}{2n} \left( \frac{1}{2} \right) \int f dv_i = \frac{\alpha}{2\beta}
\]  

(8)

where \( \alpha \) is a constant number, \( \beta \) thus is solved. Eq. (5) can be extended as:

\[
\lambda = m \beta \int (F_x dx + F_y dy + F_z dz)
\]  

(9)

Blake (1996) defined five external resistant forces in his book: friction drag, profile drag, pressure drag, interference drag, lift and induced drag. We include the first two in the model, as other three forces are relatively smaller and can be neglected.

Friction drag alters with the flow velocity of the region surrounding the porpoise’s body and can be expressed as:

\[
D = 0.5 \rho \bar{U}^2 S_D C_f
\]  

(10)

where \( \bar{U} = \bar{U}_w - \bar{U}_f \) is the relative velocity between porpoise and flow, \( \rho \) is the water density, \( S_D \) is the wetted area of porpoise and \( C_f \) is the friction coefficient with the value of 0.01. \( S_D \) is a specie-dependent parameter, that is to say, for a porpoise, \( S_D \) may be 0.05 m², but for a Chinese sturgeon or carp, \( S_D \) would be much less due to their relatively smaller bodies. For different species, \( C_f \) basically maintains the same for different species.

Profile drag is introduced by the pressure difference between the front and back region of porpoise when an angle \( \theta \) exists between fish body and flow direction. It can be expressed as the same form of friction drag as:

\[
P = 0.5 \rho \bar{U}^2 S_m C_P
\]  

(11)

where \( C_P \) is defined as:

\[
C_P = C_P(\bar{U} - C_P)^2
\]  

(12)

where \( C_P = 0.1227 \), according to Blake (1996). The unit for \( \bar{U} \) in Eq. (12) should be in radians. We assume \( C_P \) as a species related coefficient which will be discussed in detail later.

In addition to the resistant forces, we defined thrust force as:

\[
T = 0.5 \rho \bar{U}^2 S_a C_T
\]  

(13)

where \( C_T \) is the thrust coefficient and is assumed as another species related coefficient to be discussed later as well, and \( U_f \) is the porpoise velocity.

With Eqs. (10), (11) and (13), therefore, the expression of \( \lambda \) now is:

\[
\lambda = m \beta \int \left[ 0.5 \rho \bar{U}^2 S_D C_f - 0.5 \rho \bar{U}^2 S_m (C_T + C_P) \right] dx
\]

\[
+ \int \left[ 0.5 \rho \bar{U}^2 S_a C_T - 0.5 \rho \bar{U}^2 S_m (C_T + C_P) \right] dy
\]

(14)

\[
= m \beta \left[ 0.5 \rho \bar{U}^2 S_D C_f - 0.5 \rho \bar{U}^2 S_m (C_T + C_P) \right] x
\]

\[
+ m \beta \left[ 0.5 \rho \bar{U}^2 S_a C_T - 0.5 \rho \bar{U}^2 S_m (C_T + C_P) \right] y
\]

Once the coefficient \( A \) in Eq. (6) is determined, the porpoise number per unit volume is settled:

\[
n = A \left( \frac{2\pi}{m \beta} \right)^{3/2} e^{\lambda}
\]

(15)

where \( C_{ps}, C_f \) and \( S_m \) are the species related coefficients, \( V \) is the porpoise velocity. It is found that the fish velocity of certain amount of species is linear with flow velocity (Blake et al., 2007; Jan et al., 2007; Sepulveda et al., 2007), so we replaced the porpoise velocity with flow velocity in the model for its accessibility. \( S_m \) is the wetted area of specific subject, which is a particular parameter of the given specie. It is fixed once specie is confirmed. \( C_{ps} \) and \( C_f \) can be estimated in validation procedure to match the preference curve of the give specie, as presented in Fig. 2, \( C_{ps} \) is a real term coefficient while \( C_f \), as discussed before with an unknown form, can be expressed as the exponential value of the flow velocity \( V \). By assigning the appropriate values to \( C_{ps} \) and \( C_f \), the curve of simulated porpoise numbers could be matched with different aquatic species.

For a given \( A \) value, we are able to obtain the pattern of relative simulated numbers of porpoise by assigning different value to \( C_{ps} \) and \( C_f \) as shown in Fig. 2, which agrees well with the fact that fish has flow velocity preference (Ban et al., 2013; Holm et al., 2001; Webb, 1998). The relative simulated number is introduced by normalizing the results of Eq. (15) to compare the relative value
Fig. 2. The relationship of relative simulated number of porpoises and flow velocity with different $C_t$ (a) and $C_{ps}$ (b).

Fig. 3. The relationship of relative simulated porpoise number and $\theta$ (in radians).

Fig. 4. Instruction of mesh division procedure. + means water level, dot means water depth, − means flow velocity at $u$ direction and $|$ means flow velocity at $v$ direction.

of number of porpoises under different water velocity or $\theta$. $C_{ps}$ is a real term coefficient while $C_t$, as discussed before with an unknown form, can be expressed as the exponential value of the flow velocity $V$. By assigning the appropriate values to $C_{ps}$ and $C_t$, the curve of simulated number of porpoises could be matched with different aquatic species. The form of $C_t$ corresponds to the subject’s sensitivity to flow velocity, that is to say that sharper curve represents more sensible specie. And the value of $C_{ps}$ corresponds to the subject’s adaptability to flow velocity, which means higher $C_{ps}$ represents the specie with larger size.

Table 1
Comparison of the CFD velocity and measured velocity.

<table>
<thead>
<tr>
<th>Point</th>
<th>Distance to the left bank (m)</th>
<th>CFD velocity (m/s)</th>
<th>Measured velocity (m/s)</th>
<th>Offset by %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>643</td>
<td>0.2798</td>
<td>0.2908</td>
<td>−3.78</td>
</tr>
<tr>
<td>2</td>
<td>1603</td>
<td>0.1516</td>
<td>0.1402</td>
<td>8.13</td>
</tr>
<tr>
<td>3</td>
<td>2311</td>
<td>0.2995</td>
<td>0.3012</td>
<td>−0.56</td>
</tr>
<tr>
<td>4</td>
<td>2730</td>
<td>0.5268</td>
<td>0.5369</td>
<td>−1.88</td>
</tr>
</tbody>
</table>
Fig. 3 shows the relationship between the predicted porpoise number and the angle of the orientation. This relationship curve explains well the trend of porpoise behavior when entering the Poyang Lake. Porpoises enter the Poyang Lake mostly against the lake current, exhibiting upstream fish passage characteristics. Therefore, the predicted relative numbers increased when \( \theta \) increased (\( \theta = 0^\circ \) when fish following the flow and \( \theta = 180^\circ \) when fish against flow). The predicted relative number of porpoises reached the maximum at the angle of 180\(^\circ\), because profile drag is the dominant resistant force and from the perspective of mechanics, the profile drag balances when \( \theta \) is either 0\(^\circ\) or 180\(^\circ\).

### 3. Numerical solution procedures

#### 3.1. CFD numerical method

The velocity and water elevation were obtained by adopting the alternating direction implicit (ADI) method to solve Eqs. (1) and (2). The time step was separated into two parts to solve for water level and flow, flow velocity at \( u \) and \( v \) direction, as shown in Fig. 4.

### Table 2

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Nominal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>Flow density</td>
<td>1000 (kg/m(^3))</td>
</tr>
<tr>
<td>( S_w )</td>
<td>Wetted area of fish</td>
<td>0.05 (m(^2))</td>
</tr>
<tr>
<td>( C_g )</td>
<td>Drag coefficient</td>
<td>0.01</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Profile coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td>( C_{ps} )</td>
<td>Species related profile coefficient</td>
<td>0.0165</td>
</tr>
<tr>
<td>( C_{df} )</td>
<td>Profile coefficient</td>
<td>0.1227</td>
</tr>
<tr>
<td>( C_t )</td>
<td>Thrust coefficient</td>
<td>0.1</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Kinetic energy coefficient</td>
<td>3</td>
</tr>
</tbody>
</table>

Pursuant method was applied as the next step after Eqs. (1) and (2) are discretized. The main procedure of the pursuant method at the first and second half time step is:

\[
\frac{U^{i+1/2} - U^i}{\Delta t/2} + \frac{1}{2} A_x U^{i+1/2} + \frac{1}{2} A_y U^i = 0
\]

\[
\frac{U^{i+1} - U^{i+1/2}}{\Delta t/2} + \frac{1}{2} A_x U^{i+1/2} + \frac{1}{2} A_y U^{i+1} = 0
\]

where

\[
A_x = \begin{bmatrix}
\frac{\partial}{\partial x} & f & g \\
0 & \frac{\partial}{\partial x} & 0 \\
h & 0 & \frac{\partial}{\partial x}
\end{bmatrix}
\]

\[
A_y = \begin{bmatrix}
v & \frac{\partial}{\partial y} & 0 \\
0 & v & \frac{\partial}{\partial y} \\
h & 0 & \frac{\partial}{\partial y}
\end{bmatrix}
\]

By running the pursuant method starting from the grid \((1, 1)\) to \((m, n)\), it is available to obtain the hydrodynamic parameters such as average velocity, water depth and water level in each grid at the given time \( t \).

#### 3.2. EEDM model numerical method

The distribution coefficient of each grid point is calculated to obtain the number of porpoises within each mesh. If the number of porpoises within \( n_{ij} \) at grid point \((i, j)\) at time \( t \) is known then the undetermined coefficient \( A \) is obtained by Eq. (19), as the other coefficients are settled with the hydrodynamic patterns from the CFD model.

Fig. 7. Porpoise distribution observed by Kimura. The data of (a) was collected in May, 2008 and the data of (b) was collected in August, 2010.
Fig. 8. Porpoise distribution results calculated by the EEDM model. (a) Was modeled with the hydrodynamic pattern in May, 2008 and (b) in August, 2010.

\[ n_{i,j} = A \left( \frac{2\pi V^2}{\alpha} \right)^{3/2} e^{\lambda} \]  \hspace{1cm} \text{(19)}

Therefore, when the porpoises move toward the four surrounding grid points from point \((i,j)\), the relative simulated number \(r_{i-1,j}^t\), \(r_{i,j-1}^t\), \(r_{i+1,j}^t\), and \(r_{i,j+1}^t\) in each direction will be solved by the following equation:

\[ r_{i-1,j}^t = A \left( \frac{2\pi V^2}{\alpha} \right)^{3/2} e^{\lambda} \]  \hspace{1cm} \text{(20)}
Fig. 10. Comparison of the predicted and observed data in August, 2010: (a) in channel 5, (b) in channel 6 and (c) in channel 7. Columns are the observed number of porpoises; solid lines are the simulated numbers.

With the relative value of each grid point, the actual number of porpoises at the four grid points at time $t+1$ should be available:

$$r_{i+1,j}^t = A \left( \frac{2\pi V^2_{i+1}}{\alpha} \right)^{3/2} e^{x_{i+1,j}^t}$$  \hspace{1cm} (21)

$$r_{i,j-1}^t = A \left( \frac{2\pi V^2_j}{\alpha} \right)^{3/2} e^{x_{i,j-1}^t}$$ \hspace{1cm} (22)

$$r_{i,j+1}^t = A \left( \frac{2\pi V^2_j}{\alpha} \right)^{3/2} e^{x_{i,j+1}^t}$$ \hspace{1cm} (23)

With the relative value of each grid point, the actual number of porpoises at the four grid points at time $t+1$ should be available:

$$n_{i-1,j}^{t+1} = \frac{r_{i-1,j+1}^t + r_{i-1,j}^t + r_{i-1,j-1}^t + r_{i-1,j+1}^t}{n_{i,j}^t}$$ \hspace{1cm} (24)

$$n_{i+1,j}^{t+1} = \frac{r_{i+1,j+1}^t + r_{i+1,j}^t + r_{i+1,j-1}^t + r_{i+1,j+1}^t}{n_{i,j}^t}$$ \hspace{1cm} (25)

$$n_{i,j-1}^{t+1} = \frac{r_{i,j-1}^t + r_{i,j+1}^t + r_{i,j-1}^t + r_{i,j+1}^t}{n_{i,j}^t}$$ \hspace{1cm} (26)

$$n_{i,j+1}^{t+1} = \frac{r_{i,j+1}^t + r_{i,j-1}^t + r_{i,j+1}^t + r_{i,j+1}^t}{n_{i,j}^t}$$ \hspace{1cm} (27)

Fig. 11. Statistical result of the predicted number of porpoises. The solid line means predicted numbers equal the observed data.

With the running of the method through the entire set of grid points and the given boundaries of actual number of porpoises at the specific grid points, porpoise number of the entire region at any time interval can be obtained.
3.3. Boundary conditions

The boundary conditions of the CFD model were collected from the field data of the hydrological stations both at the entrance and inside the Poyang Lake from 2000 to 2008. The lake inlet discharge is given at three channels which are connected with the Poyang Lake in the south. The lake outlet water level is given at Hukou, which is at the entrance of the lake. Specific details of the data are laid in the corresponding sections of the paper.

The boundary conditions of the EEDM model were collected by Kimura et al. (2010) at the area where the Yangtze River and the Poyang Lake is connected. For the validation and calibration models, the virtual porpoises are released at Pengze, downstream the Yangtze River. For the application model, the virtual porpoises are released at Hukou as well. Specific details of the data are laid in the corresponding sections of the paper.

4. Validation and calibration

4.1. CFD model validation

The boundary conditions of the CFD model were collected on October 12th, 2010 when the lake’s average discharge was 5100 m$^3$/s and the water level at the entrance was 13.81 m. The flow field and water depth of the lake is shown in Fig. 5.

For validation, we compared the calculated velocity of Poyang Lake with the flow velocity that was monitored at the same cross section at the field station on the same day as presented in Table 1 and Fig. 6. It is concluded that the CFD model was validated and it can be used for other flow conditions.

4.2. EEDM model calibration

The first set of calibration data of porpoise distribution were collected in May, 2008. The validation region is located at the north of Poyang Lake, where the Yangtze River and Poyang Lake join, as shown in Fig. 7. We first obtained the hydrodynamic patterns of that region by CFD model. Then all the coefficients listed in Table 2 of the EEDM model were adjusted until the results qualitatively resemble porpoise distribution from the calibration data.

As shown in Fig. 7(a), the entire region was divided into four zones, with serial numbers assigned during the calibration. The value of every coefficient is listed in Table 2. The comparisons of model result and observed data are shown in Fig. 8(a), and quantitatively compared in Fig. 9. Fig. 8(a) matches well with Fig. 7(a). The numbers of porpoise distributed in channel 4 are obviously less than that in the other three channels, while the numbers of the other three channels are distributed averagely. The similar distribution pattern is shown in Fig. 9 by comparing the actual numbers of porpoises. The same value of each coefficient in Table 1 is used in the following procedure.

4.3. EEDM model validation

The set of validation data for validation was collected in August, 2010 as shown in Fig. 7(b). Simulated results are presented in
Fig. 13. (a) Water depth of the Poyang Lake and (b) water depth, flow and porpoise distribution of downstream dam.

Fig. 8(b). In similar approach, the entire region is divided into three zones since the last channel (Zone 4 in Fig. 7(a)) had no observed porpoises. It is obvious that the simulated number of porpoises in the last channel is zero, which matches with the observed situation quite well.

The distribution of the porpoise varies greatly in different month is mostly due to that normally it is dry season during May while wet season during August. Flow velocity in the Poyang Lake during the wet season lies within the relative low value range of the velocity preference curve, which negatively affects porpoise’s entry behavior. Therefore, the relative number of porpoise that enter into the Poyang Lake would be less than that in the Yangtze River.

However, due to its limitation, the hydrodynamic module eventually provides the relatively continuous hydrodynamic conditions, which would impact the results of the EEDM model in the same way. Therefore, no huge differences about the number of porpoise would occur between the adjacent grid cells. The EEDM model then may be inaccurate to simulate the abnormal sudden increase or decrease between the adjacent cells, exactly as what appears from the observed data in Channel 6 where 10 porpoises were observed at one location while less than 3 porpoises were observed at other locations. It is not a unique limitation since discrepancies also exist when a Lagrangian behavior model is coupled with the Eulerian hydrodynamic model. In reality the porpoise distribution may be affected by other factors besides hydrodynamic patterns, such as water temperature, predation, dissolved gas and pollutant, etc. It is found that the rate of Yangtze finless porpoise detection was significantly higher in areas where fishes were present than in areas of their absence (Zhang et al., 2013). Boat avoidance behavior may also cause local discrepancies (Li et al., 2008). One or coupled of those factors may cause a sudden increase of the number of porpoises to one location in the channel, which could not be captured simply by the hydrodynamic module. Other than that, the EEDM model matches with the observed data quite well, as compared in Fig. 10.

Fig. 11 shows the statistical result of the EEDM model. The \( r^2 = 0.6548 \) in Fig. 11 indicates a weak regression. One of the reasons that cause such huge variation has been discussed before that the EEDM is not able to simulate mutations by only coupling with the hydrodynamic module. The other reason is that observed error may exist in the validation data, as found by Kimura et al. (2009). Without that spot considered, \( r^2 \) becomes 0.98, which proves to be quite accurate. Although the EEDM model performs less accurate when simulating the distribution decided by multiple factors other than hydrodynamic conditions, when applying the EEDM model on their specific behavior such as mitigating through the dams, the result can be matched and satisfied. Therefore, it is concluded that this model calibration is reasonable and the EEDM model may be used in practical engineering projects, recognizing its limitations.

5. Model application

The purpose of setting up the dam (see Fig. 1) is to maintain water level at an appropriate value in dry years during the migration period of porpoises. The most extreme case during dry year corresponds to flow discharge of 2700 m\(^3\)/s and water level of 8.5 m. From Eq. (28) it was decided that only four gates need to be opened to maintain the water level above 10 m.
Table 3
The porpoise passage efficiency in three cases.

<table>
<thead>
<tr>
<th></th>
<th>Dry year (%)</th>
<th>Normal year (%)</th>
<th>Wet year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passage before the dam</td>
<td>69.34</td>
<td>98.23</td>
<td>88.82</td>
</tr>
<tr>
<td>Passage after the dam</td>
<td>67.26</td>
<td>96.90</td>
<td>81.38</td>
</tr>
</tbody>
</table>

Fig. 14. The observed distribution locations (yellow stars) and calculated migration routines of porpoise. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 16. Comparison of passage efficiency before and after the dam.

Fig. 15. The movement routines and colonies of porpoises: (a) flow discharge of 2500 m³/s and water level of 8.5 m at the entrance; (b) flow discharge of 7500 m³/s and water level of 13.9 m at the entrance; (c) flow discharge of 16500 m³/s and water level of 17.3 m at the entrance. The black solid lines are the routines that porpoise choose to move, the red circles represent the colonies and the sizes of the circles represent the relative amount of porpoises. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
\[ Q = \varepsilon \sigma_m n b \sqrt{2gH_0^{3/2}} \]  

where \( Q \) is the total discharge, \( \varepsilon \) is the contraction coefficient, \( m \) is the discharge coefficient, \( \sigma_m \) is the submergence coefficient, \( n \) is the numbers of the opening gates and \( H_0 \) is the water level inside the lake.

A total of 5000 virtual porpoises were released at the entrance of the Poyang Lake. After 10 h and 20 h the porpoise distribution in Poyang Lake is shown in Fig. 12(a) and (b), respectively. The detailed bypass design was not considered in the EEDM model. In the EEDM model, only when porpoises are reaching at the entrance of the passage tunnel, they are considered to be able to pass through the tunnel. Otherwise, they are considered failing to pass through. It is clearly that some porpoises successfully passed through the bypass system and continued their migration to the upstream area while the rest stayed in the downstream region of the dam. One of the reasons that some porpoises stayed in downstream of the dam can be explained from Fig. 13. There is a big eddy/recirculation zone right downstream the dam. Porpoises prefer to stay in this type of recirculation region where there may be adequate food and a good place for reproduction (Wei et al., 2003). The long term behavior of porpoises is impacted by many factors, such as water depth, substrate, flow velocity and water temperature. The model aiming at habitat location prediction is under research, with all the factors considered. In order to improve the effectiveness of the passage, porpoises can be attracted and enticed by certain human factors to the entrance of the passage system, along with reasonable inner construction of the passage tunnel (Katopodis and Williams, 2012).

The move routines and habitat locations are very similar to the field data collected in by Xiao and Zhang (2002), as presented in Fig. 14. The total 9 observed porpoise distribution sites are located exactly along the calculated routines of EEDM model.
When boundaries of hydrodynamic patterns changed, the porpoise movement would vary, as shown in Fig. 15. This case was set with 7500 m$^3$/s discharge and 13.9 m water level at the entrance of the lake. A total of 5000 virtual porpoises were released at the entrance. After 50 h the porpoise distribution is shown in Fig. 15(b). Since the water level rose, the flow recirculation zone formed as in Fig. 13(b) disappeared and was no longer a habitat region for porpoises. After adopting the model, it can be concluded that most of the porpoises successfully passed through the bypass system and chose their own habitat afterwards. The sizes of the red dots indicate that there are three relative large porpoise groups after 50 h: one is in the area close to the upstream of dam, and the other two are located in the middle area of the lake. Along with rising water level, porpoises no longer move simply in the main channel of the lake.

In summary, the porpoise EEDM model along with CFD model has been validated and calibrated with available field data in a limited way. The model has been applied to the practical real-world project to evaluate the porpoise distribution in the bypass system and porpoise habitat in a large lake region. However, the EEDM model includes some assumptions and limitations that make the prediction reasonable but rather crude. Improvements that include the impacts of water depth, substrate and temperature into the equations will be considered in the future model.

6. Discussion

As mentioned in the previous section, the porpoise EEDM model was applied to two different flows of 2500 m$^3$/s and 7500 m$^3$/s at the lake entrance, which represents dry and normal year conditions, respectively. The model was further applied to the third condition of 16,500 m$^3$/s flow discharge at the lake entrance as a wet year condition for comparison. The movement routines and colonies of 5000 virtual porpoise are shown in Fig. 15. Certain amounts of porpoise stayed upstream of the dam in all three cases. Porpoises can only move forward following the main channel of the lake in dry year with low water level, while they tended to move along the lakeside region in normal and wet years.

Compared to the cases without dam under the same conditions, small differences existed, as shown in Fig. 17. Most of the porpoises passed the bypass system of the dam. The dam may delay the passage of the porpoises. The percentages of porpoises that passed the dam are listed in Table 3. The comparison of passage efficiency before and after the dam is presented in Fig. 16. The passage efficiency in normal year is the highest, followed by the wet year and dry year. The lower passage efficiency in dry year is not caused by the bypass system, since almost the same amount of porpoises stayed at the same location when there is no dam, as shown in Fig. 17(a).

From the previous discussion it is concluded that within the limitation of the EEDM model, the dam is not expected to have significant impacts on the movement. The passage efficiency of the dam is estimated to be within 90% of the situation without the dam, therefore it is deemed acceptable. In addition, in order to analyze what difference would occur when the structure of the dam is altered since the local hydrodynamic condition in the nearby region of dam varies, we designed 3 cases for the discussion. Fig. 18 shows the distribution of the 5000 virtual porpoises under three conditions: (1) four sluice gates at the left section of the dam are opened while the rest are closed; (2) four sluice gates at the middle section of the dam are opened while the rest are closed, and (3) four sluice gates at the right section of the dam are opened while the rest are closed. The results indicated that the distribution of porpoises merely changed when different sluice gates are opened. That’s because in the EEDM model most of the porpoises tended to move along the right bank of the lake where the bypass system is to be constructed. The flow distribution near the bypass system was relatively stable when the flow distribution in the left area changed with different sluice gates opened, which had not significant impact on the general fish passage efficiency. In all three cases, porpoises are set that only by approaching to the entrance of the bypass tunnel, can they pass through the bypass system, and otherwise they will fail to pass. The structure of the bypass system is not considered as well.

The EEDM model in this paper is dedicated to model and predict the fish movement and evaluate the passage efficiency of
bypass systems and to minimize the adverse effects on fish by the alteration of hydrodynamic patterns. Although with significant limitations, several fish behavior models have been developed based on various theoretical systems and aiming at the fish responses to hydrodynamic. Nevertheless, there are other factors that affect fish movement behavior besides hydrodynamic patterns, e.g., mortality (Christie and Regier, 1988), water temperature (He, 2003), predation and predator avoidance (Petersen and DeAngelis, 2000) and dissolved gas (Matthews and Berg, 1997), etc. It is expected that the model would provide more insights on fish behavior when more of these factors are appropriately incorporated into the model.

Despite its limitations, the model which was developed is now capable of evaluating the fish passage efficiency of an existing or new fish bypass system. If the predicted fish passage efficiency is lower than the prescribed criteria, improvement of the passage system needs to be improved. Then the model will be used again to evaluate the new system with improvements. This procedure is repeated until the fish passage efficiency of the bypass system meets the requirements. The biggest advantage of the computational model is that it can be used to optimize the design from a wide range of design concepts in an effective, economic, and efficient way. Combined with physical modeling, the numerical model can assist in arriving at more optimized solutions to problems which occur in real cases.

7. Conclusion

An Eulerian model based on the Boltzmann equation of kinetic theory is developed in this paper. In this model porpoises are treated as a group of plenty particles which have a tendency for rheotropism. Compared with other models, the advantages lie in: (1) being capable of modeling any region no matter what scale it has, of which the general Lagrangian model is incapable, (2) being better coupled with the general CFD models since both of them are built on the Eulerian framework, (3) being easily altered to be suitable for different species, due to the flexibility of the theoretical parameters $C_p$ and $C_t$, and (4) being able to forecast the potential habitat of the aquatic animals. What's more, the results of the model agreed reasonably well with the observed data.

The modeling indicates that the Yangtze finless porpoises prefer to move along the left bank during the upstream migration period, where the dam is located. Porpoises which move upstream and end-up in the ship or spillway channels could be at least delayed there and only those that move to the bypass channel may find the bypass entrance. Despite these limitations, modeling results indicate small impacts on the porpoise migration behavior. The passage efficiency is relatively lower in the dry season, whereas the main benefit for the porpoises is the formation of appropriate habitat upstream of the dam during low water levels. However, the EEDM model assumes that porpoises approaching the bypass system will be successfully guided to us it. This may not reflect reality as porpoises may not be attracted or resist the artificial structure and turn around instead. In order to minimize the adverse effect of the dam, further analysis should be conducted and some guiding measures may be introduced when porpoises are approaching to the dam, such as attraction flow (Katopodis and Williams, 2012) or other measures which may be effective.

For future developments, and since fish seem to respond to turbulence (Enders et al., 2003), improved models such as the large eddy simulation (LES) model (Fang et al., 2014) would be introduced, so that the hydrodynamic patterns become diversified and closer to reality. As for the coefficients defined in the EEDM model, a more reasonable method may be adopted, such as the genetic algorithm, to obtain better simulating results. The movement behavior of aquatic animals is affected by a few other signatures such as water temperature, water depth, pollution and substrate besides hydrodynamic patterns, the corresponding source terms will be added in the basic equations. Meanwhile, more modules which are applied to simulate sediment concentration (Honglu et al., 2015; Hosseinjanzadeh et al., 2015), pollution distribution (Palley et al., 2015; Zhao et al., 2015) would be coupled with the EEDM model. Once the two modules are coupled with the CFD and EEDM models, it is believed that results will be more realistic and better agree with field measurements.

References
