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Numerical Simulation of Flow and Upstream Fish Movement inside a Pool-and-Weir Fishway

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ABSTRACT: Analysis of the fish movements in real situations is a good way to understand the dependence of fish behavior on the hydraulic conditions. This paper presents a numerical model to study the path of fish movements at different hydraulic conditions. The commercial computational fluid dynamic code FLOW-3D was used to simulate the fish ladder flow. Based on the results of the flow simulation,a numerical model for fish movement was developed by combining a low energy concept and random movements in which the effects of turbulence and fish memory are taken into account. The model was validated using experimental data of flow and fish movement inside a pool-and-weir fishway archived from a previous study (Atsushi, 2009). The simulated results of the flow velocity and the fish path are in good agreement with the experimental data.

KEYWORDS: Fish passage, Individual based model, Pool and weir fishway.

1 INTRODUCTION

One approach to study the fish movement through fish passage is to track its behavior against the change of hydraulic conditions. This approach may help to assess the efficiencies of fishways and will provide information about the proportions of the migrating populations that actually move upstream. Additionally, this approach can help us to better understand the mentality of the fish for traversing a velocity barrier.

Monitoring the fish inside the fish passage can be used for calibration and validation of numerical model for fish movement in relation to different hydraulic conditions. Abdelaziz et al. (2011) developed a model based on the concept of energy expenditure with random movements and turbulence effects to simulate the fish upstream movement inside the culvert, where the main flow direction was almost the same. This technique is not valid for the case when the flow direction changes point by point, e.g. in a pool-and-weir fishway. In this case, based on the maximumvelocitydirection, the fish recognizes the direction of the fishway. At the same time, the fish tries to minimize the energy expenditure by travelling against the lower velocities. Power et al. (1985) suggested that the fishway entrance should be as close as possible to the source of the competing flow from the turbine. Another strategy suggested by Castro-Santos and Haro (2008) is to supplement the flow at the fishway entrance by additional tube. This increases the ratio of flow at the fishway entrance to turbine flow without increasing the total flow passed through fishway itself.

In this study, a numerical model for fish passage through a pool and weir fishway is developed and verified with an experimental data. Numerical modeling will be carried out to investigate the effects of changing the hydraulic conditions in a pool and weir fishway. The FLOW-3D computer program is applied to simulate the flow.

2NUMERICAL APPROACH

In FLOW-3D, the hydrodynamic module is based on the solution of the three-dimensional Navier-Stokes equations and the continuity equation for incompressible flows. The governing equations can be written in a tensor form as follows (Flow Science Inc., 2008):

$$\frac{\partial (U_i A_i)}{\partial X_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + \frac{1}{V_f}\left(U_j A_j \frac{\partial U_i}{\partial X_j} \right) = -\frac{1}{\rho}\frac{\partial P}{\partial X_i} + f_i \tag{2}$$

where:

$$\rho V_f f_i = \tau_{b,i} - \left[\frac{\partial}{\partial X_j}\left(A_j S_{ij} \right) \right]; \quad S_{ij} = -\mu_{tot}\left[\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right] \tag{3}$$

where U_i (1, 2, 3) = the velocity components in X_i directions; P = pressure; A_i = fractional area open to flow in the i-direction; V_f = fractional volume open to flow; f_i = the gravity force per unit volume; S_{ij} = strain rate tensor; $\tau_{b,i}$ = wall shear stress; ρ = density of water; μ_{tot} = total dynamic viscosity, which includes the effects of turbulence ($\mu_{tot} = \mu + \mu_T$); μ = dynamic viscosity; and μ_T = eddy viscosity. Different turbulence models are available in the code.

The second part of our model employs a discrete and particle-based representation of individual fish migrating through the fishway. The model releases a number of simulated fish and tracks their movements using a concept of minimum energy expenditure with a discrete random-walk method and other special fish behaviors. Additionally, the fish recognizes the direction of the upstream flow inside the fishway by moving against the high water flow. Figure 1 shows the flowchart that summarizes the structure of the proposed model.

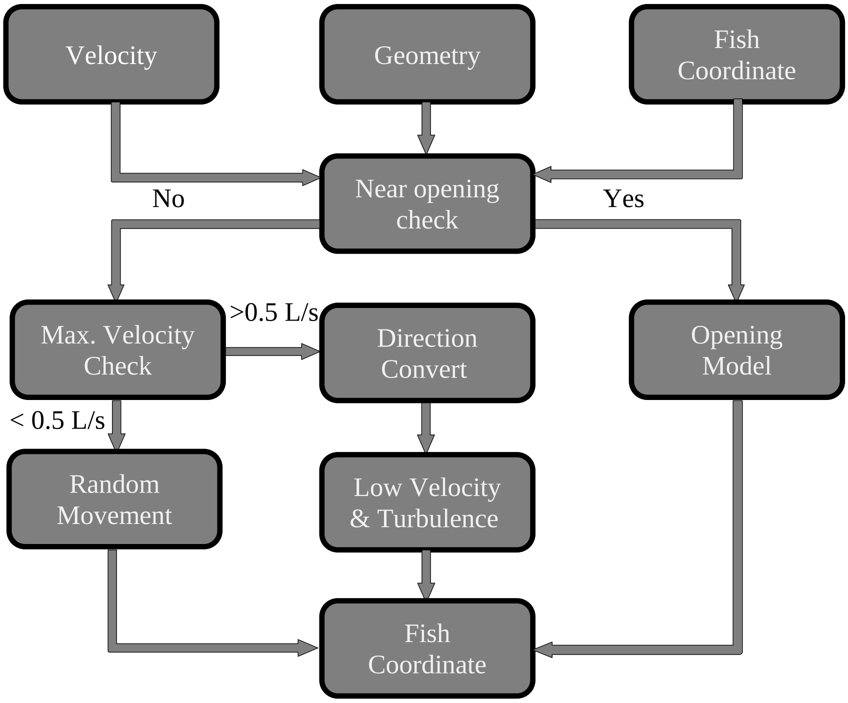

Figure 1 The structure of the proposed two dimensions fish model

According to this flowchart, the main steps of the model can be summarized as follow:

1. To start the model, the data related to the fishway geometry, the measured or simulated velocity and the coordinates of the fish at the entrance of thefishway are required.
2. Based on these data, the model checks whether there is an opening within a distance around the fish in the upstream direction or not (see figure 2).

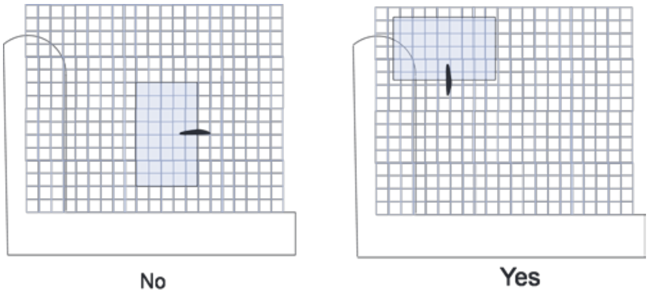

Figure 2 Near-opening check.

3. In case of the presence of the opening, the fish will go directly toward the opening.
4. Otherwise, the model checks the maximum velocity within a distance around the fish in the upstream direction.
5. If the maximum velocity around the fish is less than a special value which can be determined during model calibrations (e.g. 0.5 fish length/s), the fish could not recognize the flow direction and the random movement will be selected. Pearson et al. (2006) noticed in his study of Juvenile coho that the fish exhibited more exploratory behavior in flow lower than 1.5 ft^3/s.
6. On the other hand, if the velocity is high enough for the fish to recognize the upstream direction, the fish will go in a direction against the direction of the high flow.
7. In this case, the direction conversion model will be done to allow the low energy and turbulent model to be applied (figure 3).

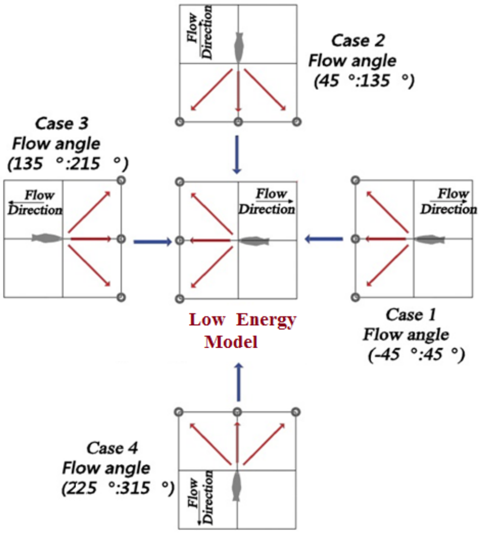

Figure 3 Coordinate conversion from the current coordinate to the local coordinate suitable to the low energy model.

8. The steps mentioned above are repeated until the fish reaches to the most upstream part of the fishway.
9. Finally the path is smoothed using the moving average filter method.

Low Velocity and Turbulence Concepts

Combining a low energy concept with random movements, the effects of turbulence and fish memory are taken into account in the model. Figure4 shows the flowchart that summarizes the steps applied for low velocity and turbulence concepts.

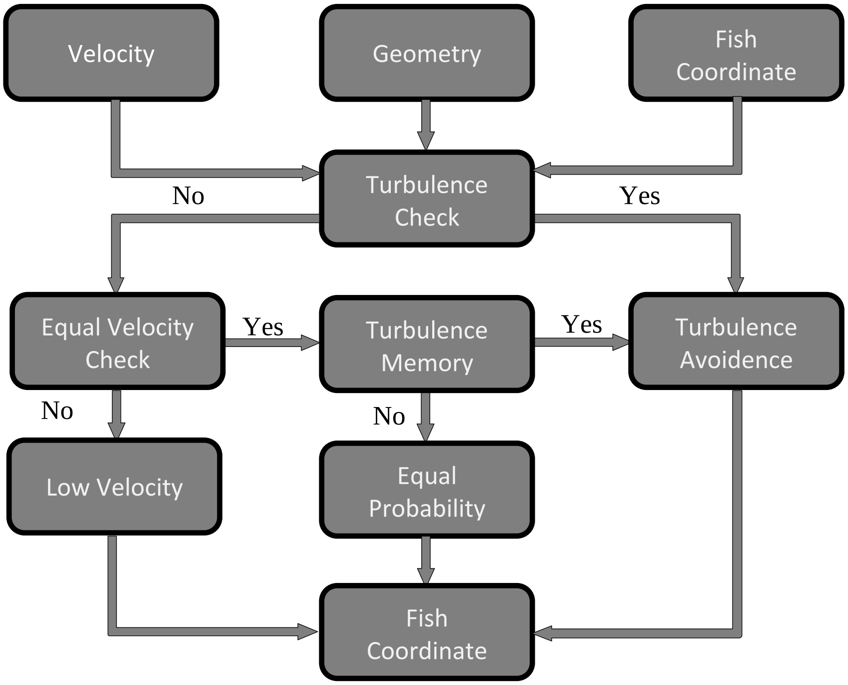

Figure 4 The structure of the proposed low energy and turbulent model

The model processes can be summarized as follow

1. The geometrical data, the measured or simulated velocity and the coordinates of the fish at the time step are converted to the local coordinates and considered.
2. The model checks whether there is turbulence or not based on the velocity gradient. The larger is the velocity gradient, the higher is the turbulence. The critical velocity gradient is the maximum one, where the fish can pass the flow without taking the effect of turbulence avoidance into account. This value should be adjusted during the model calibration. The turbulence avoidance behavior was found previously by Olla and Davis (1990) while Mackenzie et al. (1994)found that increasing the turbulence intensity decreased the fish's critical velocity, i.e., the maximum velocity at which a fish can sustain itself in a stream.
3. If the velocity gradient is greater than the critical velocity gradient, the turbulence avoidance model will be applied.
    - The values P_1, P_2 and P_3 are the probabilities of the fish to move upstream to the direction away from the turbulence domain, the forward direction, and into the turbulence domain respectively. They are selected in a way that $P_1 + P_2 + P_3 = 1.0$ and $P_1> P_2> P_3$. These values are problem-dependent and should, in general, be adjusted to the flow domain and the fish observed path during the model calibration.
    - A pseudo random value between 0.0 and 1.0 will be calculated using Wichmann-Hill's random number generator (Wichmann and Hill, 1982).
    - If the random value falls between 0.0 and P_1, the fish will go away from the turbulence.If the random value falls between P_1 and P_1+P_2, the forward direction will be selected. Otherwise, the direction into turbulence domain will be selected (see figure 5)

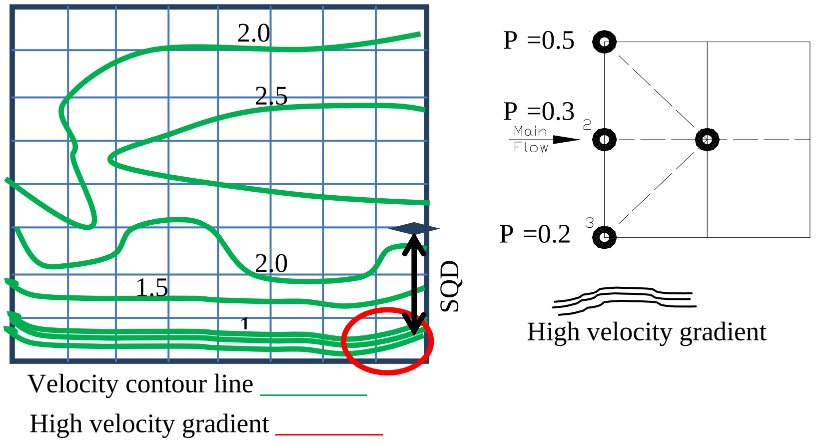

Figure 5: Effect of turbulence on fish movement

4. Otherwise, the model checks the velocity at the next three points in the upstream direction searching for the lowest velocity. In this case the minimum energy expenditure model with random probability will be applied.Many investigators showed that the fish seeks to minimize their energy expenditure by travelling against the lower velocities (see for example Kane et al., 2000; Pearson et al., 2005).
    - The velocities in the nearby grid cells, namely upstream U_p, upstream left U_l, and upstream right $U_r$are compared with each other. The path with the lowest velocity takes higher probability P_1, while the middle velocity has the probability P_2 and the highest velocity takes probability P_3.
    - A pseudo random value between 0.0 and 1.0 will be calculated. If the random value falls between 0.0 and P_1, the fish will go to the lowest point.If the random value falls between P_1 and P_1+P_2, the middle velocity will be selected. Otherwise, the highest velocity will be selected.
5. In case that the three points have the same velocity, the fish will search in its memory if there was turbulence in one side within the specific number of previous movements, then the turbulence avoidance technique will be applied.
6. Otherwise, the fish will have equal probabilities to the three directions.

3 EXPERIMENTAL STUDY

Atsushi et al, (2008) and Atsushi (2009) studied the relationship between the flow structure and the swimming behavior of Japanese daces (Leuciscus hakonensis) in multiple pool-and-weir type fishway by changing the length of each pool, the number of pools and the different in height between two successive weirs. For each of these experiments, the discharge is varied from 0.021 to 0.19 m^3/s. Figure 6 shows a typical geometry shape of the experiments. In this paper Experiments of type A will be studied which consist of a three pool tank (N=3) with length (L) = 80 cm, downstream weir height (H) is 40 cm, the thickness of each weir (D) is 20 cm, and the different in height between two successive weirs (D_Y) is 10 cm. Three different experiments have beendone. Table1 summarizes the flow and the water head over the weir for these cases.

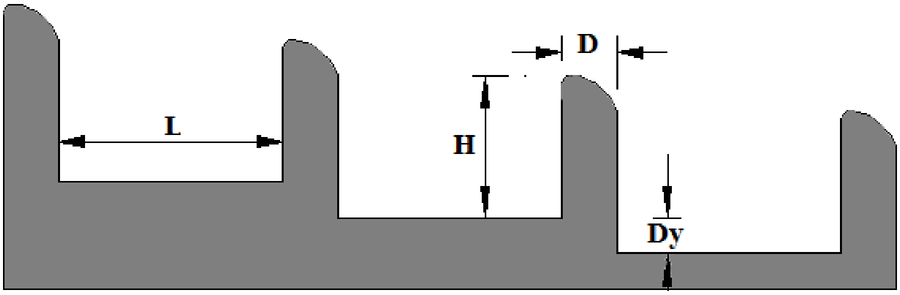

Figure 6: Typical shape of the hydraulic model

Table 1 Discharge conditions (after Atsushi, 2009)

	Weir Overflow depth Δh (m)	Flow unit width q ($m^3/s/m$)
Case 1	0.05	0.021
Case 2	0.10	0.064
Case 3	0.20	0.200

The fish length varied from 9.0 – 12.0 cm and its weight varied from 10 – 20 g. The maximum burst speed was 10 times the fish length (0.9 – 1.2 m/s). The fish movement was extracted using digital video camera and combined with the water velocity in order to determine the relation between hydraulic conditions and fish movement.

4 MODEL CALIBRATION

The model was calibrated using the data for experiment Type A- case1 provided by Atsushi (2009). As shown in Figure 7, the measured water elevation was used as initial condition and the water elevations at the upstream and downstream boundary conditions were specified as 84.52 cm and 44.00 cm respectively. The RNG turbulence model was used. All the simulations were two dimensions. A uniform 1.0 cm rectangular grid is used in x and z directions to mesh the domain.

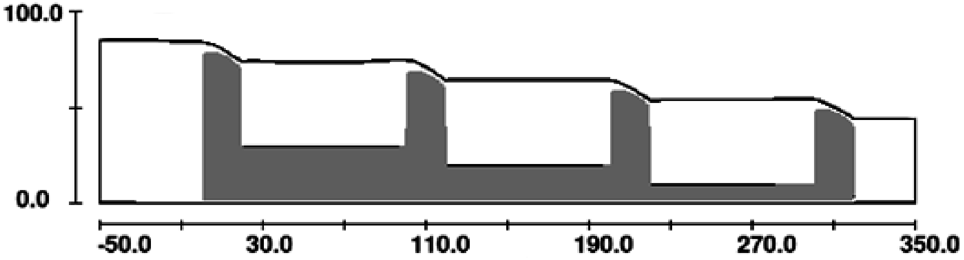

Figure 7 Model set up

In Figure 8, the simulated results were compared with the measurements of mean velocity in the domain. In general, the velocity directions were non-uniform, and a large area was occupied by low velocities. It can be seen that, in the experiment as well as in the numerical model, the main flow was located in the domain near the wall and bed. The middle flow area was characterized by a circulated weak flow. On the other hand, the flow near the water surface was reversed due to the backwater effect. The measured velocity over the weir is smaller than the simulated one for the three weirs since the vertical direction component could not be measured due to very shallow water depth. Figure 9 shows a comparison between the measured and simulated maximum velocity near the walls and the beds. The numerical model could simulate the water surface elevation while some difference can be seen in the maximum velocity path. The measured velocity in the middle pool is smaller than in the first and the third one. There is no clear reason for this difference which not appears in the simulated result. The measured maximum velocity near the bed in the middle pool is almost half the simulated results.

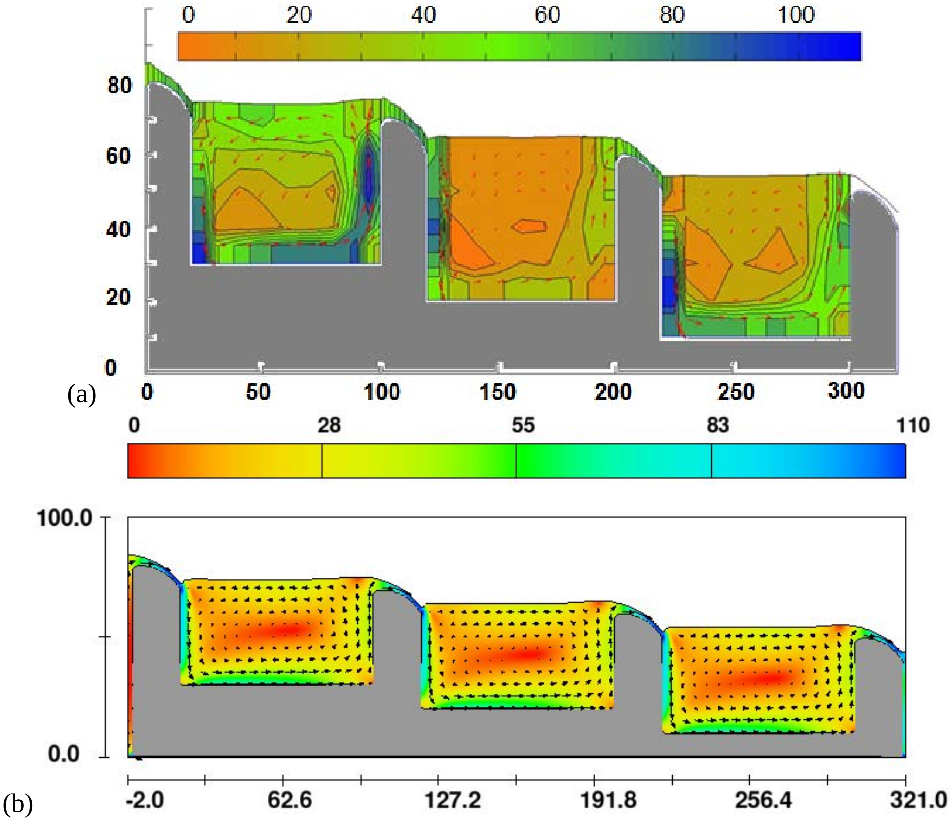

Figure 8 Measured velocity distribution (a) (after Atsushi, 2009) and simulated velocity distribution (b)

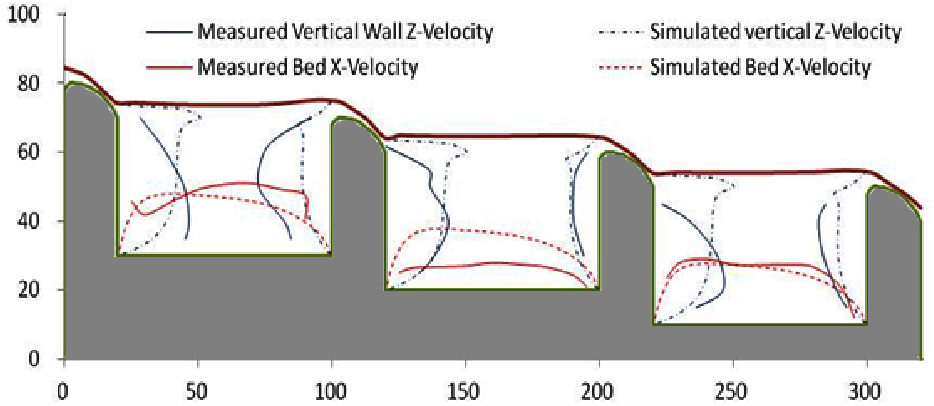

Figure 9 Maximum velocity near the bed and walls.

5 MODEL APPLICATION

To study the effect of changing the flow on the velocity distribution and fish movements, the model was setup according to Type - A experiments. The flow as well as the water depth varied from one experiment to the other as indicated in table 1. Figure 10 represents the fish movement in the low flow conditions (0.021 $m^3/s/m$), while the velocity distribution of this case is previously represented in figure 8.b. The fish follow the flow direction and move in the neighborhood of the bed and walls. The simulation is in a good agreement with the measured fish path. The only difference can be seen in the middle pool where the simulated velocity is higher than the measured velocity.

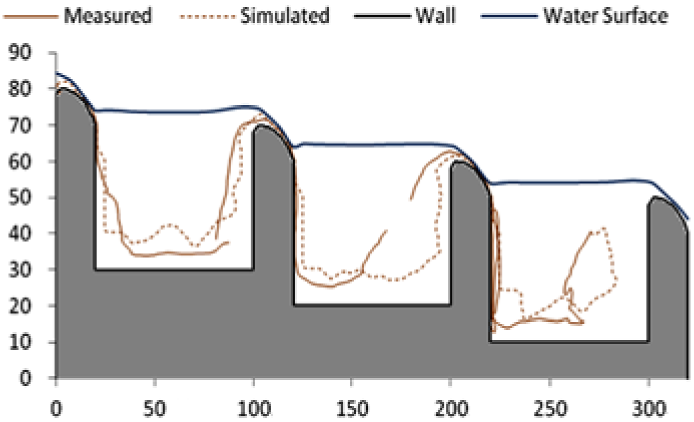

Figure 10 Simulated and observed fish movement inside the pool tank for type A – case1

By increasing the specific dischargeupto 0.064 m^3/s/m, the flow is redistributed over higher distance from the bed and the wall as can be seen in figure 11.a. Additionally, the maximum velocity inside the pool as well as over the weir becomes higher. In this case, the fish move in the middle of the bottom layer where the velocity is constant and the direction of flow is clear. Figure 11.b shows a comparison between the measured and simulated fish path against simulated flow. In this case, the measured path cuts the circulation zone in the middle of the pool especially in the middle and the most downstream pools. The maximum difference between the simulation and measured path can be seen in the middle pool. The fish may use this area as a resting zone. In our model fish resting is not yet considered.

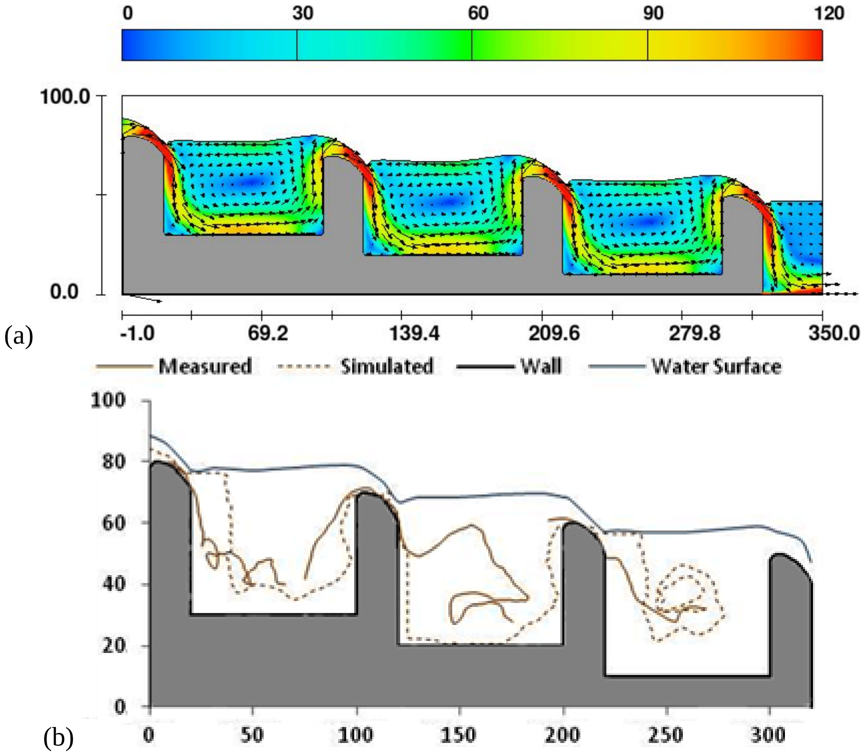

Figure 11 Simulated velocity distribution (a) and fish movement path inside the pool tank (b) for Type A- case2

Further increase of the specific dischargeupto 0.2 m3/s/m has a great effect on the distribution of velocity inside the pool. Figure 12.a shows the simulated velocity distribution for case 3. In this case, the main flow direction moves up near the surface while the big circulation zone inside the pool is vanished and replaced with three small circulating zones around the main flow. The fish move in the neighborhood of the main flow where the velocity is constant and the direction is clear (figure 12.b). The fish exit this flow domain to the circulation zone during the resting time.

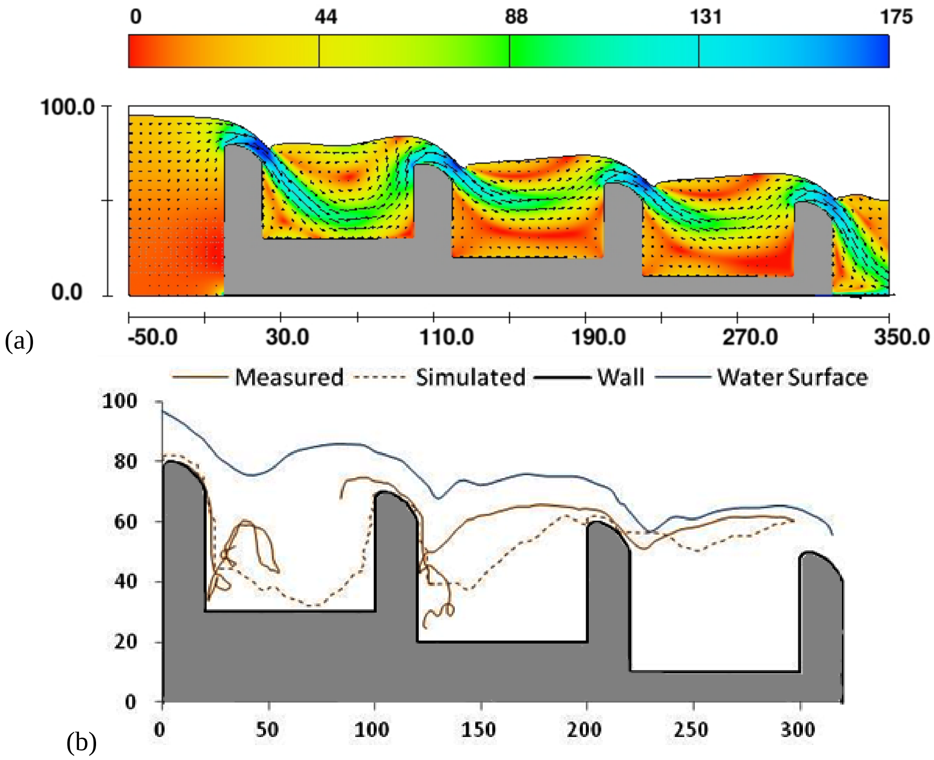

Figure 12 Simulated velocity distribution (a) and fish movement path inside the pool tank (b) for Type A - case3

6 CONCLUSIONS

A numerical model for fish movement inside a pool and weir fishway was developed and applied to experimental cases in the labs. The model wasbased on a low energy concept and random movements. The effects of turbulence and fish memory were also taken into account. In the model, the fish used the maximum velocity to recognize the upstream direction. The flow was predicted using an existing numerical model (FLOW-3D). The model provided good results of flow pattern and fish movement compared to the experimental data provided by Atsushi (2009). The simulated results showed that the flow inside the pool was highly non-uniform and a large area was occupied by a low velocity current. The flow characteristic upstream of the fishway has a great effect on the distribution of velocity inside the fishway. In Low flow condition, the main flow was located in the domain near the wall and bed. The middle flow area is characterized by a circulated weak flow. On the other hand, the flow near the water surface is reversed due to the backwater effect. By increasing the flow, the main flow direction move gradually from the bottom near the bed to the top of the pool near the water surface. Accordingly, the velocity distributions as well as the position of the circulated weak flow are changed. The fish move against the main flow direction and use the circulating zones as a rest zones. The numbers of the resting areas as well as the fish resting period are increased by increasing the flow discharge. These issues were not yet considered in the present model.

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