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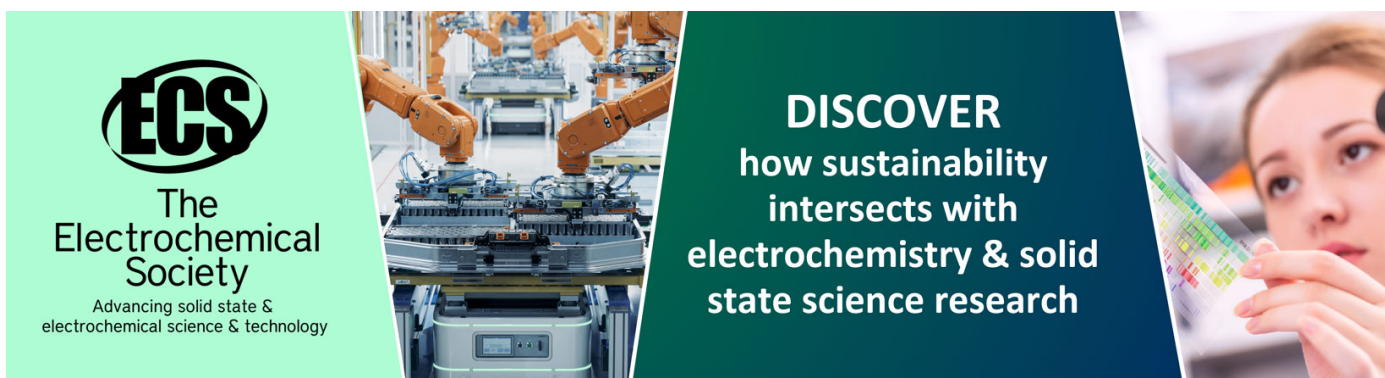
## Numerical simulation of effects of inlet water depth of ecological fishway on the suitability of passing fish

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# Numerical simulation of effects of inlet water depth of ecological fishway on the suitability of passing fish

B Ma<sup>1</sup>, F Dong<sup>1,2</sup>, W Q Peng<sup>1</sup>, X B Liu<sup>1</sup>, A P Huang<sup>1</sup>, X K Chen<sup>1</sup>, L Hou<sup>1</sup>, W J Wang<sup>1</sup>, Y Si<sup>1</sup>, and J W Yao<sup>1</sup>

<sup>1</sup>State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

E-mail: dongfei@iwhr.com

**Abstract.** Ecological fishways can not only restore the free passages of migratory organisms, but also play the role of ecological corridor. Currently, the behavior and ecology of the target fish were not fully taken into account in the design of fishways. So this paper takes the swimming ability of *Hueho taimen*, *Brachymystax lenok* and *Thymallus arcticus* in Buhe River as indicators, presents a systematic numerical investigation on effects of different inlet water depth in ecological fishway using a three-dimensional hydrodynamic model (EFDC). The numerical results indicate that the inlet water depth is a key factor in the ability to pass fish. It is shown that the two schemes with different slopes and roughness have significant differences in the flow field distribution under the same inlet water depth; the differences are the location where the maximum velocity occurs and the range beyond the upper limit of the velocity. In addition, when the inlet water depth increases to 0.8m, the flow field distribution of both designs are more suitable for fish passage. The outcomes of this study will be helpful to improve the design of the entrance of Buhe River fishway and make the target species more suitable for passing through.

## 1. Introduction

The construction of dams and other hydraulic structures in rivers has rapidly increased due to the development of water conservancy and the increasing demands for flood control, irrigation, and the generation of power [1]. However, these projects have blocked the connectivity and damaged the ecological integrity of the river, resulting in a series of changes in the material circulation, energy flow and information transmission of the river ecosystem, thus blocking the upstream and downstream migration channels, which has a great impact on the characteristics of migratory fish. The construction of fishways has been an effective tool used to restore fish migration passages. The purpose of a fishway is to assist fish in smoothly bypassing an obstacle and alleviate the negative effects of the hydraulic structure. More importantly, fishways prevent fish from extinction, by protecting river connectivity and biodiversity [2].

Currently, the research of fishway mainly focuses on the hydraulic design parameters of traditional fishway [3-6] and the selection of model types [7,8]. Maria Bermudez *et al* [9] simulated sixteen different designs of vertical slot fishways with two different slopes. Wu *et al* [10] studied the hydraulic characteristics of vertical slot fishway with different bottom slopes. Liu *et al* [11] made a more detailed study on the hydraulic and turbulent characteristics of two turbulent structures in vertical slot fishway. In fact, the efficiency of passing fish not only depends on the flow pattern and hydraulics of the fishway, but also depends on the coordination between the target fish and the flow. Take this for





consideration, a new fishway emerged. Katopodis [12] first proposed the concept of ecological fishway, which is a multi-functional bypass channel very similar to the tributaries of ecological rivers. The research of ecological fishway is mainly based on the flow characteristics and layout [13-15]. Larinier [2] pointed out that in order to ensure all types aquatic organisms can go through, the slope of ecological fishway is generally limited to 1%-5%.

Based on the above analysis, there are few studies on the ecological fishway. In this paper, a three-dimensional Environmental Fluid Dynamics Code (EFDC) model was used to study the relationship between the inlet elevation of fishway and the crossing ability of target species. To accomplish this, the flow field distributions of the two fishway design schemes under 8 different inlet depths (0.55 m, 0.6 m, 0.65 m, 0.7 m, 0.75 m, 0.8 m, 0.85 m, 0.9 m) were simulated. And based on the swimming ability of the target fish species, the influence of the flow field on the fish crossing ability under various scenarios was analyzed.

## 2. Materials and methods

### 2.1. Study area

The ecological fishway is located on the right bank of the Buhe River, which is the tributary of the Irtysh River. After investigation, the total number of fish species in the Buhe River are 18. The main passing fishes of the project are *Hueho taimen*, *Brachymystax lenok*, *Thymallus arcticus*, consideration of the fishes are the *Acerina cernua*, *Leuciscus leuciscus baicalensis*, *Leuciscus idus*, *Barbatula nuda*, *Cobitis granoei*.

According to *Study Report on Swimming Ability Test of Fish Crossing Facilities in Buhe River*, the selection of “continuous swimming time” and “burst swimming speed” is extremely important as test indexes; the reason is that these two indicators represent the minimum and maximum speed that can be achieved by fish, respectively. For the burst swimming speed, the 95% confidence interval of the *Hueho taimen* is 1.49-1.60 m/s, the mean is 1.54 m/s and the median is 1.57 m/s. The 95% confidence interval of the *Brachymystax lenok* is 0.93-1.26 m/s, the mean is 1.10 m/s and the median is 1.54 m/s. The 95% confidence interval of the *Thymallus arcticus* is 1.16-1.37 m/s, the mean is 1.27 m/s and the median is 1.26 m/s. For the continuous swimming speed, when the duration of swimming is longer than 200 minutes, the upper limit of the sustained swimming speed of *Hueho taimen* is about 0.67 m/s, *Brachymystax lenok* is about 0.7 m/s, *Thymallus arcticus* is about 0.61 m/s.

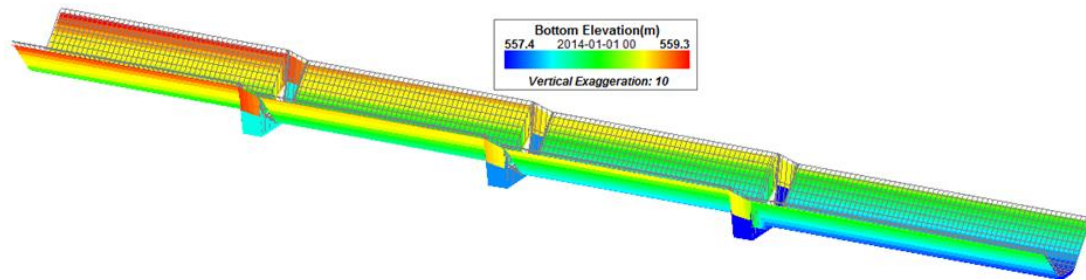
### 2.2. Model description

The EFDC is an open source surface water modelling system that can simulate hydrodynamics and water age, sediment, and water quality levels in one, two, and three dimensions [16]. Governing equations of hydrodynamics include three-dimensional equations of turbulent currents with a second moment turbulence closure scheme. The numerical solution of the EFDC adopts finite difference method, space and time are two order accuracy, in which time contains 3 time layers. A detailed introduction of theoretical and computational features of the model can be found in materials written by the author of Hamrick [17].

A three-dimensional EFDC model is established to simulate the ecological fishway lounge section. The study zone is divided into 4,740 rectangular grid elements in horizontal direction, and local refinement method is carried out between the rest pool and the upstream and downstream parts of the channel. Longitudinal spacing  $\Delta x = 1\text{ m}$ , transverse spacing  $\Delta y = 0.2\text{ m}$ , grid spacing between the rest pool and the upstream and downstream connections of the channel is from 0.03 to 0.1 m. Sigma coordinates grid is adopted vertically, and is divided into 5 layers in equal proportions (figure 1). Design flow  $Q = 1.48\text{ m}^3/\text{s}$  as upstream boundary condition. According to different Computational Scenarios, the depth of downstream boundary is from 0.55m to 0.9m and the design water depth is 0.7 m. Initial water level is 558.5 m. In order to accurately simulate the internal flow field of fishway, the eddy viscosity is calculated using the Smagorinsky subgrid scale scheme in Large Eddy Simulation (LES). At the same time, in order to ensure calculation stability, the time step is set as 0.02s, and the



computation time is 0.5 h.



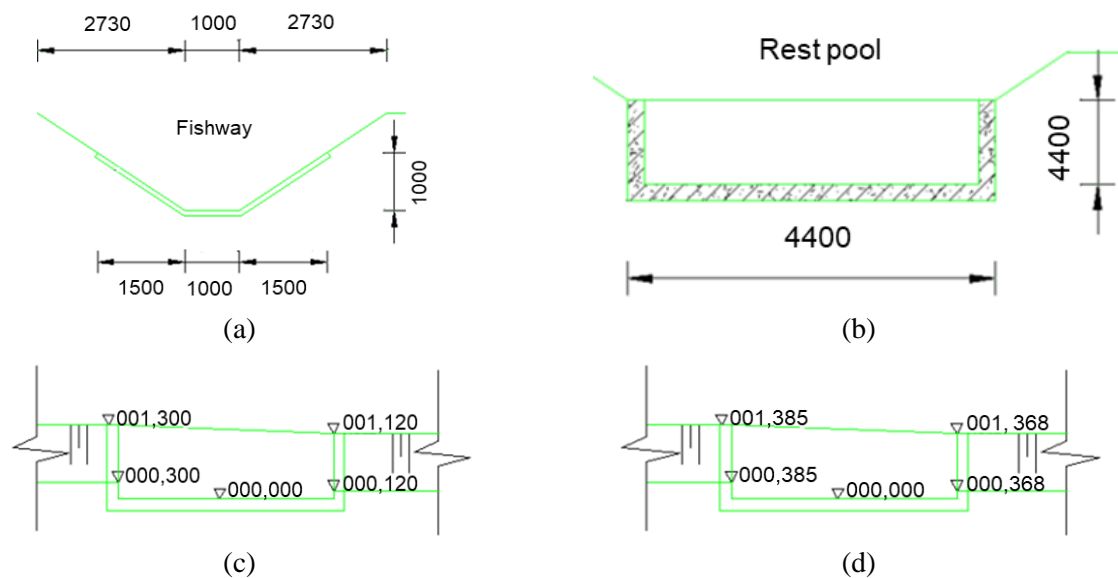
**Figure 1.** Fishway grid. The vertical x and horizontal y display ratios are 1:5.

### 2.3. Setting of computational scenarios

In order to compare the effects of two different fishway designs on the ability to pass the fish, the EFDC model is used to simulate different conditions. The two designs are as follows:

Case 1: The fishway consists of regular trapezoidal open channel and regular rectangular rest pools. The bottom width and deep of trapezoidal open channel are 1.0 m and 1.0 m respectively, the slope is 0.42%, side slope is 1:1.5 and roughness coefficient is 0.035. Fishway has 8 rest pools, and the bottom of each rest pool is a square with a length of 4 m and deep is 1 m, level difference between fishway inlet and outlet is 0.18m. The fishway cross-sectional and the longitudinal section are shown in figure 2.

Case 2: The differences between case 2 and case 1 are: (1) the bottom slope of fishway is changed to 1.82%. (2) There are 10 resting pools and the level difference between inlet and outlet is 0.017 m. (3) The coefficient of roughness is 0.032. The typical longitudinal section of lounge is shown in figure 2.



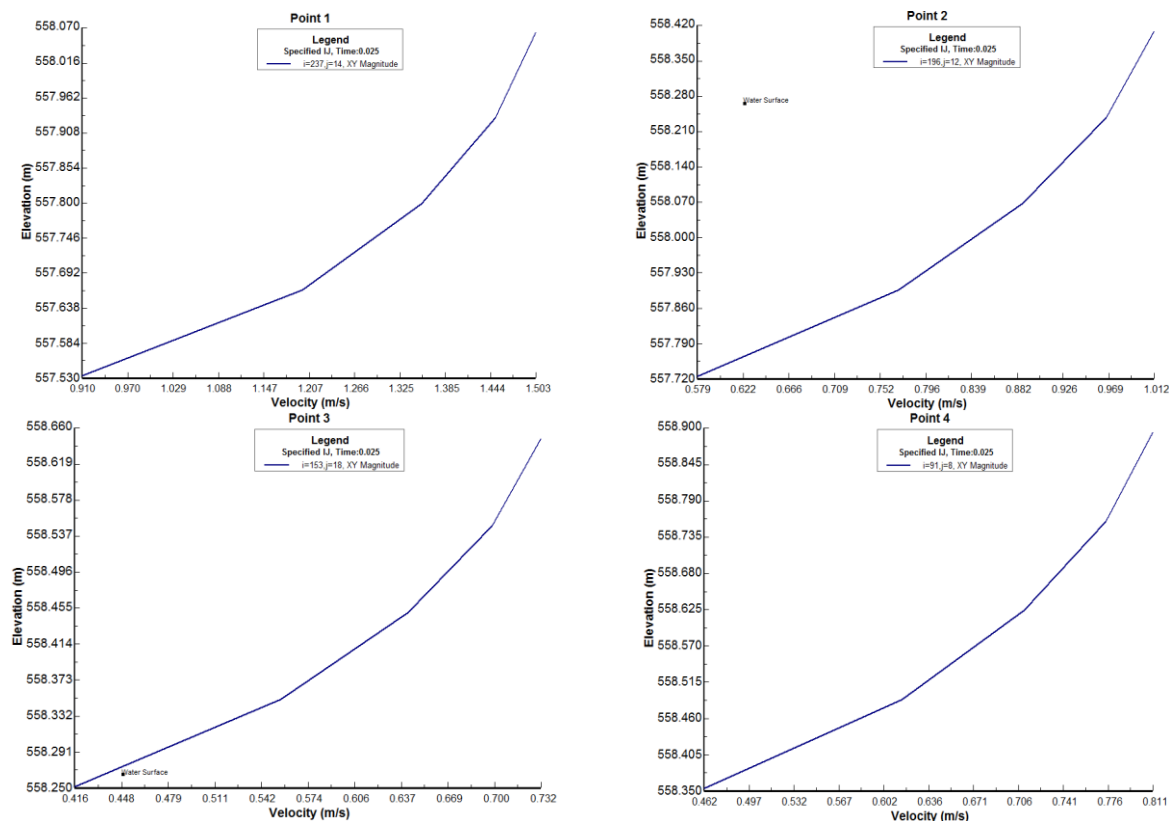
**Figure 2.** (a) Fishway cross section, (b) Rest pool cross section, (c) Longitudinal profile of rest pool at case 1 and (d) Longitudinal profile of rest pool at case 2.

In each case, various sub-conditions are simulated, that is, the downstream boundary condition of each water depth correspond to one sub-condition, which is 0.55 m, 0.60 m, 0.65 m, 0.70 m, 0.75 m, 0.80 m, 0.85 m and 0.90 m, respectively.



## 2.4. Model verification

The calculation results of the model with boundary water depth of 0.60 m in scenarios 2 are compared with the empirical distribution. And select 4 locations along the fishway to analyze the vertical velocity distribution (figure 3). Figure 3 shows that the simulated velocity is logarithmic curve distribution in the vertical direction, which is consistent with the general rules of hydraulics.



**Figure 3.** Vertical velocity distribution at different locations.

## 3. Results and discussion

### 3.1. Results

The relationship between the depth of the inlet and the distribution of the flow field was simulated. And considering the burst swimming speed of the three indicator species are 1.54 m/s, 1.10 m/s and 1.27 m/s, respectively, and the upper limit values of continuous swimming speed are 0.67 m/s, 0.7 m/s and 0.61 m/s respectively. Therefore, the upper limit of the graph display is set as 1.10 m/s, and the lower limit is set as 0.61 m/s. so as to conveniently observe the suitability of the two fishway design schemes for passing fish under various inlet water.

As shown in tables 1 and 2, the biggest difference between the two schemes is that the largest velocity of Scheme 1 only occurs at the entrance of the fishway, while the largest velocity of Scheme 2 is scattered at the entrance of the fishway and the upper end of each rest pool. In addition, when the water depth at the entrance of the fishway exceeds 0.8 m, the flow field of case 1 is suitable for fish to pass, while the flow field of condition 2 is still not suitable for fish to pass in the upstream of the rest pool no. 8, and the range is large. Superficially, the case 1 is more suitable for fish to pass, and the higher the water depth at the inlet of the fishway, the more beneficial it is for fish to migrate. Further analyses of some aspects of the simulated results are presented in the Discussion.



**Table 1.** Flow field distribution of case 1.

Sub-condition	Inlet water level(m)	Inlet depth(m)	Maximum velocity(m/s)	Location of maximum velocity	Length exceeding 1.1m/s(m)
1-1	558.01	0.55	1.77	Fishway entrance	24
1-2	558.06	0.60	1.58	Fishway entrance	22
1-3	558.11	0.65	1.17	Fishway entrance	3
1-4	558.16	0.70	1.41	Fishway entrance	45
1-5	558.21	0.75	1.17	Fishway entrance	3
1-6	558.26	0.80	1.08	Fishway entrance	0
1-7	558.31	0.85	0.98	Fishway entrance	0
1-8	558.36	0.90	0.91	Fishway entrance	0

**Table 2.** Flow field distribution of case 2.

Sub-condition	Inlet water level (m)	Inlet depth(m)	Maximum velocity(m/s)	Location of maximum velocity	Length exceeding 1.1m/s(m)
2-1	557.98	0.55	1.60	Fishway entrance	46
2-2	558.03	0.60	1.43	Fishway entrance	44
2-3	558.08	0.65	1.19	Fishway entrance	47
2-4	558.13	0.70	1.41	Fishway entrance	37
2-5	558.18	0.75	1.25	Upper section of 8# Lounge	15
2-6	558.23	0.80	1.25	Upper section of 8# Lounge	15
2-7	558.28	0.85	1.25	Upper section of 8# Lounge	11
2-8	558.33	0.90	1.17	Upper section of 8# Lounge	9

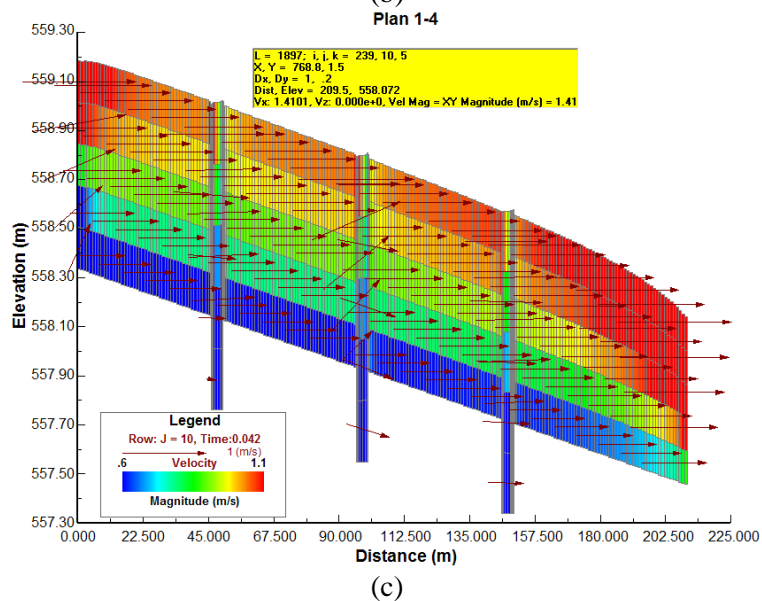
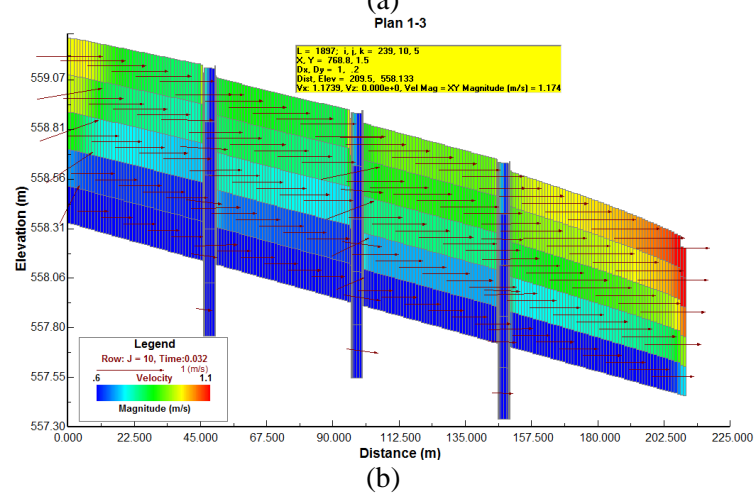
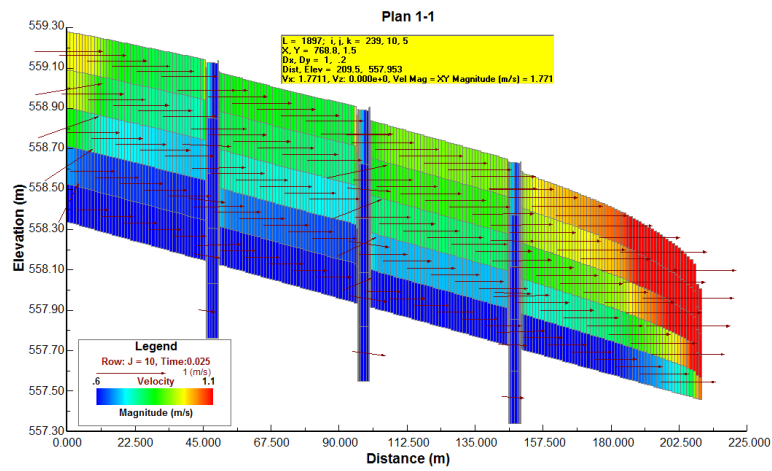
### 3.2. Discussion

In order to further analyze the fish crossing ability of each scenarios, the flow field corresponding to the water depth of the downstream boundary of 0.55, 0.65, 0.7, and 0.8 m are selected. The flow field characteristics of fishway are demonstrated by combining 2d and 3d. Figure 4 shows the simulation results of various sub-conditions under case1. When the water level at the entrance of the fishway is 558.01 m, the length exceeding the maximum swimming speed of 1.1 m/s is 24 m, and the maximum velocity appears at the entrance of the fishway, which is 1.77 m/s. This indicates that the water depth at fishway entrance makes it difficult for fish to enter. When the inlet water depth of the fishway increases to 0.65 m, the length of velocity greater than 1.1 m/s is decreases to 3 m and the maximum velocity decreases to 1.174 m/s. When the water depth at the entrance of the fishway is 0.7 m, the surface velocity of the whole fishway is greater than 1.1 m/s, and the velocity increases obviously at upstream of the rest pool, compared with the working condition with the downstream boundary water depth of 0.55 m, the maximum velocity decreased to 1.41 m/s. When the inlet water depth increases to 0.85 m, the velocity of the whole fishway is suitable for fish to pass through, and the maximum velocity is 0.98 m/s, which is within the appropriate velocity range. It is concluded that at case 1, with the increase of water depth at the downstream boundary, the velocity approaching a suitable range for fish migration. However, as the water depth increases, the velocity has no obvious regularity. It is therefore possible to take that engineer measures in the scheme to increase the water depth of the fishway entrance so that the target fishes can be easily passed.

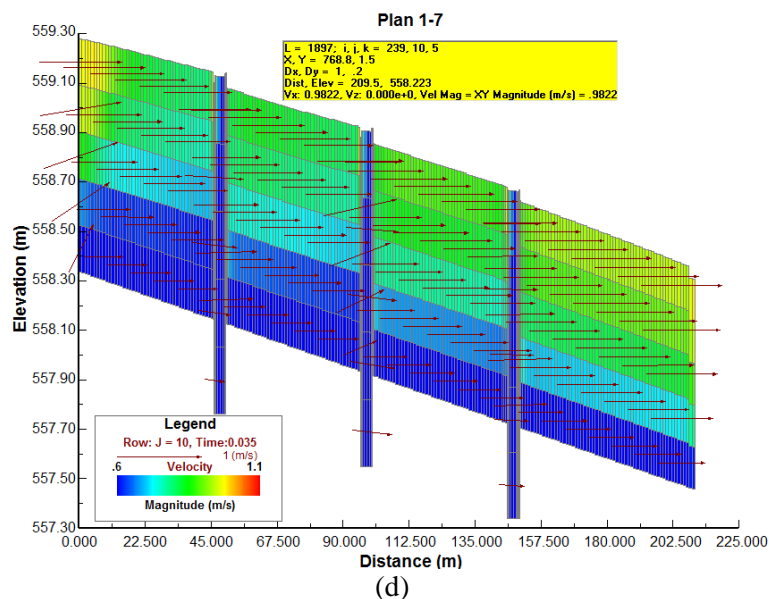
Figure 5 shows that the flow field distribution of each sub-condition under the case 2. When the water depth at the entrance of the fishway is 0.55 m, the maximum velocity at the entrance of the fishway and upstream of the NO.8, 9 and 10 rest pools, and the total length exceeding 1.1 m/s are 6 m, 6 m, 8 m and 26 m, respectively. The maximum velocity is 1.60 m/s at the inlet of the fishway. Compared with the inlet depth of 0.55 m, the length exceeding the maximum swimming speed under water depth of 0.65 m is increased to 47 m. However, the velocity decreased significantly. When the water depth is 0.7 m, the length exceeding 1.1 m/s at the fishway entrance and upstream of the NO. 8, 9 and 10 rest pools are 6 m, 6 m, 6 m and 19 m, the total length is 37 m, which is obviously less than sub-condition 2-3, but the maximum velocity is greater than sub-condition 2-3. As the inlet water



depth increases to 0.8 m, the maximum velocity position changes from the inlet to the upstream of the No. 8 rest pool. The range of velocity suitable for fish migration also gradually decreases, but it still exists.

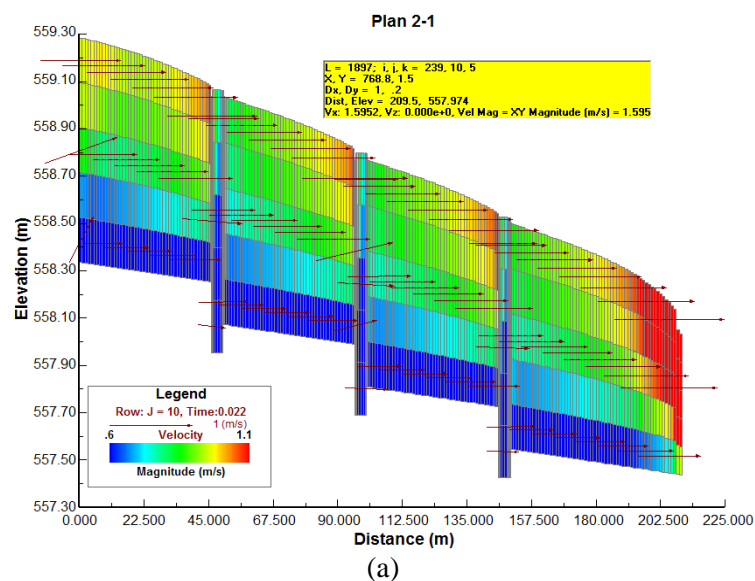




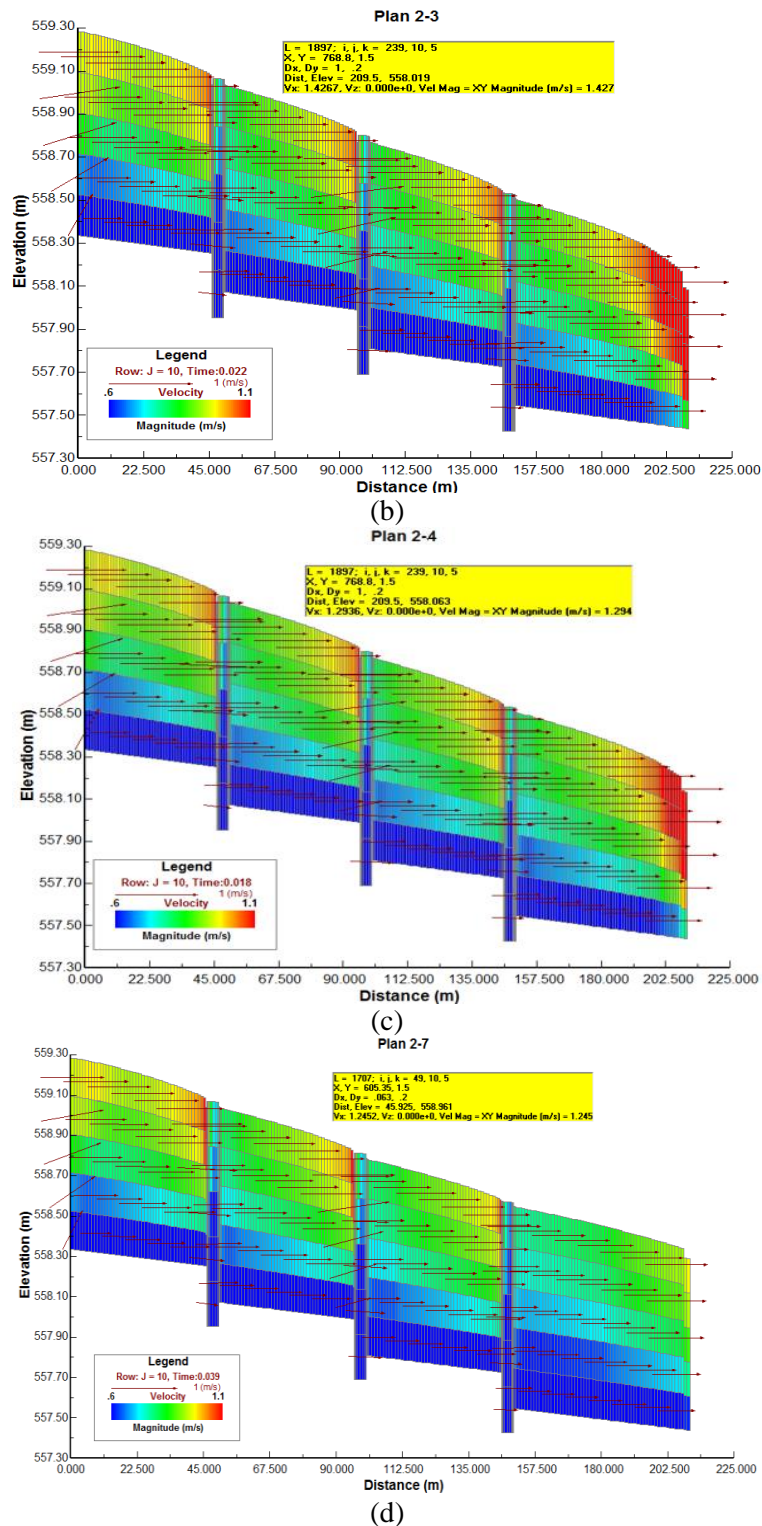


**Figure 4.** Flow field distribution (two-dimensional) of different downstream boundary conditions under case 1. (a) The entrance depth of the fishway is 0.55 m. (b) The entrance depth of the fishway is 0.65 m. (c) The entrance depth of the fishway is 0.7 m. (d) The entrance depth of the fishway is 0.85 m.

Case 1 differs from Case 2 in the following points. The first point is that the maximum velocity of case 1 is near the entrance of the fishway, while the maximum velocity of case 2 is not only at the fishway entrance, but also at the upstream of the 8th, 9th and 10th rest pools, which increases the difficulty of crossing the fish. Secondly, for the maximum velocity and the range of more than maximum swimming speed, there is no obvious regularity with the increase of the inlet water depth between the two plans. Finally, when the water depth at the inlet of the fishway is greater than 0.8 m, the flow field of the entire fishway in scenario 1 is all suitable for fish passing, while under various working conditions, the inlet of fishway of scenario 2 and the upstream of the 8th, 9th and 10th rest pools are not suitable for fish migration.







**Figure 5.** Flow field distribution (two-dimensional) of different downstream boundary conditions under case 2. (a) The entrance depth of the fishway is 0.55 m. (b) The entrance depth of the fishway is 0.65 m. (c) The entrance depth of the fishway is 0.7 m. (d) The entrance depth of the fishway is 0.85 m.



#### 4. Conclusion

Through a quantitative analysis of flow field distribution at different inlet depths of fishway based on the EFDC model, the water depth conditions of fishway entrance suitable for fish passage are obtained. The specific research results are as follows: (1) When the inlet water depth of the fishway increases to 0.8m, the portion of the inlet and the upstream of rest pools that exceeds the upper limit of 1.1 m/s will eventually decrease, at this point, in scenario 1 with slope of 0.42% and roughness of 0.035, the velocity of the entire fishway is less than 1.1m/s, which is beneficial to fish migration; in scenario 2 with slope of 1.82% and roughness of 0.032, only the upstream of individual resting pools is not suitable for fish to pass. (2) In case 2, with the increase of water depth at the inlet of the fishway, the position of the maximum velocity changes and is transferred from the inlet to the upstream of the rest pool, which is conducive to fish entering the fishway. In summary, for the two design schemes of the fishway in Buhe River, the suitable depth at the entrance boundary of the fishway is 0.8-0.9m, which provides a theoretical basis for the design of fishway entrance.

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