Analysis of Affirming the Height of Weir Based on Fish Swimming Performance in Mountain River

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Abstract: The weir group has been great negative impact on fish migration, and there is no corresponding construction standard for the height of weir which may destroy fish migration. In this study, the discharge in extreme velocity of the local fish and submerged conditions of the weir was taken as a limitation of the height of the weir group in mountain area. Taking Majin River as an example, the height of weir was analyzed aiming for the local fish to get over the weir in migration period with one-dimensional hydrodynamics model. The results showed that the fish cannot pass through all weirs at a specific discharge with current weir height, by reducing the height of the weir, the discharge met to fish migration can be reduced, and different weirs required different heights to be reduced. The fish can pass through all weirs at a limited discharge with the weir heights reduced. This method provides a calculation method for determining the height of weir in mountain river.

1. Introduction

The discharges of mountain river vary greatly in wet season and dry season, there are many weirs built in mountain rivers for irrigation, and the height of weir is designed based on the irrigation demand [1]. In recent years, the construction of weirs is more concentrated in landscape effect with the improvement of people’s demand for landscape. Since the cognize of designers is limited in affirming the height of weir, which was built too high to connect the river in vertical, the fish migration was interrupted and the fish habitat was broken into pieces [2]. These changes have a negative impact on the whole river eco-system [3, 4].

In this paper, taking Majin River as an example, the proper height of weir was analyzed aiming for the local fish to get over the weir within migration period. It could be used for reference to affirm the height of weir in mountain river.

2. Study method

The practical profile weir is dominant in kinds of weir in mountain river. With small water quantity, the flow over the weir is free flow, and the water level under the weir is lower than the height of weir, this type of overflow is favored by the leaping fish. While other fish could not jump up to upstream of the weir, which has some impact on fish migration. As the water quantity increases, the type of overflow changes from free flow to submerged flow, and the water level under the weir is higher than the height of weir, the upstream and downstream is connected, most kinds of fish could migrate from downstream to upstream. In hydraulics, the water level of downstream higher than the height of weir and submerged hydraulic jump are the conditions of submerged flow of practical profile weir.
According to the different swimming time, the swimming types of fish can be roughly divided into burst swimming, sustained swimming and prolonged swimming. Burst swimming (or sprint swimming, darting swimming) [5, 6] is an important way for fish to escape capture and from predators [7, 8], it has an important effect on the survival of the fish and is the maximum speed that the fish can reach. When the flow over the weir changes from free flow to submerged flow gradually, the location of maximum velocity is near the crest of the weir. The fish can swim across the weir only if the velocity of burst swimming is greater than that near the weir crest. In flood period, the flow velocity near the weir crest is tremendous, the fish cannot swim across the weir even the weir is submerged. So, it’s proposed that the flow for fish migration should be satisfied when the practical profile weir is submerged and the maximum velocity across the weir is less than that of burst swimming of the fish, and the flow is taken as a limitation of the height of the weir group in mountain area.

3. Study area
The study area is located at Majin River from Shizhu Country to Majin Country in Kaihua County, Zhejiang Province. Majin River is one of tributaries of Qiantang River, with the length of 102.2km and watershed area of 1011.3km$^2$. The length of study river section is 9.5km, and the average slope is 2.6‰, and the watershed area of Majin River above Shizhu country is 233 km$^2$. In this area, there are 3 hydropower stations and 6 weirs (seen figure 1).

Opsariichthys bidens is taken for the research object of this study, which is an important economic fish with a small body size, and widely exists in the Yangtze River Basin and also in Majin River. Meanwhile the fish is used for the design of fishpass. According to the study, the critical swimming speed value of Opsariichthys bidens is distributed in 61.07-120.03 cm/s, and the range of sprint swimming speed is 65.03-155.07 cm/s. Therefore, the value of 1.55m/s is used as the burst swimming
speed that Opsariichthys bidens can swim across the weir, it’s proposed that if Opsariichthys bidens can make it possible for swimming across the weir crest, the extreme velocity of the weir crest should be less than 1.55m/s.

4. Calculate method

One-dimensional hydrodynamics model was built with Saint Venant equations, which contain equation of motion and of flow continuity. The equations can be written as follows.

\begin{align}
\frac{\partial Q}{\partial t} + \frac{\partial (QA)}{\partial x} &= 0 \\
\frac{\partial Q}{\partial t} + \left(\alpha \frac{Q^2}{A}\right) + gA \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} &= 0
\end{align}

Where \( x \) is the distance, \( t \) is time, \( A \) is discharge section area, \( Q \) is the discharge, \( h \) is water depth, \( C \) is Chezy resistance coefficient, \( R \) is hydraulic radius, \( \alpha \) is momentum coefficient.

The discharge and velocity across the weir were calculated by weir flow formula, which is showed as follows.

\[ Q = \varepsilon \sigma m b \sqrt{2gH_0^2} \]

Where \( \varepsilon \) is side shrinkage factor, \( m \) is flow coefficient, \( \sigma_s \) is submerged coefficient, \( H_0 \) is the weir head, \( b \) is the river width.

The data of river sections, morphological characteristics of weirs and hydropower stations were provided by Kaihua County Water Resources Bureau. The discharge was set in the upstream boundary of the model, and simulated period lasted 100 days with the discharge ranged gradually from 0 to 200m³/s in upstream. Water level was set in the downstream boundary, due to the dense weirs and hydropower stations, the water level of the downstream has little impact on that above the weir, and was calculated by Chezy-Manning Formula.

5. Results

5.1 Discharge in extreme velocity and submerged conditions

According to the model results, the statistical discharge while the velocity of the weir crest was 1.55m/s was showed respectively in table 1.

| No. | Name                | Discharges in extreme velocity | Critical discharges in submerged condition |
|-----|---------------------|-------------------------------|-------------------------------------------|
| 1   | Jiutang Weir        | 50                            | 174.9                                     |
| 2   | Xiashan Weir        | 66                            | 69.9                                      |
| 3   | Taiyang Island Weir | 87                            | 80.9                                      |
| 4   | Bajia Weir          | 67                            | 114.8                                     |
| 5   | Baocun Weir         | 66                            | 53.5                                      |
| 6   | Xutang Weir         | 85                            | 41                                        |

The heights of the 3 hydropower stations are generally above 3m, which are hard for fish to migrate. Nevertheless, the heights of the 6 weirs are relatively low for fish to migrate while the weirs are submerged and the velocities across the weir crest are less than 1.55m/s. Since the discharge of the 6 weirs were different while the velocity across the weir crest was 1.55m/s, the minimum water quantity 50 m³/s can be used as confined quantity, if the water quantity was more than 50m³/s, the fish could not swim across some weir.

The water level above and under the weirs was calculated in the model, combined the condition of submerged flow, the critical discharge in submerged flow were showed in table 1. The results
indicated that the critical discharge of each weir varied greatly, it means that different weirs have different ecological flow requirements for fish migration. The ecological flow had to reach 174.9 m$^3$/s while the 2 weirs between Qixi Third and Xiashan Hydropower Station meet the fish migration, and that was 114.8 m$^3$/s while the 4 weirs between Xiashan and Majin Hydropower Station met the fish migration.

Otherwise, the Critical discharges in submerged condition of the weirs were larger than that in extreme velocity except Baocun Weir and Xutang Weir, it means that there were still some distances from the weir crest to the water level in downstream when the velocities of the 4 weirs reached the extreme velocity, it’s hard for fish to migrate.

The height and spatial relation of 6 weirs involved in the simulation were showed in figure 2, and the relation of discharge per unit width in submerged flow and the height difference between the weir and the next downstream weir were showed in figure 3, it’s obviously that the critical discharge in submerged flow is related to the elevation of weir crest and the river slope, the higher the crest, the greater the river slope, the larger the critical discharge needed.

5.2 Analysis of proper weir height

According to table 1, using the minimum discharge satisfying the extreme velocity in each weir as the limiting condition, the discharge should be less than 50 m$^3$/s when the extreme velocities of each weir is less than 1.55 m/s. However, the critical discharges of Jiutang Weir, Xiashan Weir, Bajia Weir, Taiyang Island Weir and Baocun Weir were larger than 50 m$^3$/s in submerged flow, the fish can only swim across the Xutang Weir while the discharge was less than 50 m$^3$/s. It is unrealistic to reduce the height of the hydropower station, thus, taking Jiutang Weir and Xiashan Weir, the 2 weirs between Qixi Third Hydropower Station and Xiashan Hydropower Station as the research objects, the discharges of each weir in submerged flow were anglicized when the height of weir was reduced to different height. Because the decreasing height of the downstream weir would affect the discharge of the upstream weir in submerged flow, the corresponding discharges of Xiashan Weir in submerged flow were analyzed firstly when it’s reduced to different heights (seen figure 4).
With the decrease of the height of Xiashan Weir, the discharge of the weir in submerged flow decreased gradually, and the discharge of adjacent Jiutang Weir in submerged flow increased gradually oppositely. This is due to the decrease of the downstream weir, the height difference between the weir and the upstream weir increased, resulting in the increase of discharge of the upstream weir in submerged flow. When the discharge across Xiashan Weir was lower than 50m³/s, the corresponding weir height was 1.35m, which needed to be reduced by 0.15m. After the height of Xiashan Weir fell to 1.35m, the corresponding discharges of Jiutang Weir in submerged were showed in figure 5 with different heights.

With the decrease of the height of Jiutang Weir, the discharge of the weir in submerged flow decreased gradually, and the discharge across Jiutang Weir was lower than 50m³/s, the corresponding weir height was 0.88m, which needed to be reduced by 0.62m.

By the same method, the heights of the 3 weirs these needed to be reduced were calculated between Xiashan and Majin Hydropower Station. To sum up, when all weirs met the requirements of submerged flow and the flow velocities through weirs were less than 1.55m/s, the corresponding elevation of each weir as shown in table 2.

| No. | Name               | Current weir height | Conditional height | Height need to reduce |
|-----|--------------------|---------------------|--------------------|----------------------|
| 1   | Jiutang Weir       | 1.5                 | 0.88               | 0.62                 |
| 2   | Xiashan Weir       | 1.5                 | 1.35               | 0.15                 |
| 3   | Taiyang Island Weir| 2.1                 | 1.58               | 0.52                 |
| 4   | Bajia Weir         | 1.1                 | 0.79               | 0.31                 |
| 5   | Baocun Weir        | 1                   | 0.98               | 0.02                 |
| 6   | Xutang Weir        | 1.9                 | 1.9                | 0                    |

5.3 Discussion
The distribution of the dense weirs changed the nature of the river, and the original river between the weirs would appear the character of a lake. Taking Taiyang Island Weir and Bajia Weir as an example, the heights of the 2 weirs are 2.1 m and 1.1m respectively, because of the relatively short distance between the 2 weirs, the elevation of Bajia Weir is higher than the river bottom elevation of Taiyang Island Weir. The pond-like river segment between the 2 weirs would destroy the structure of longitudinal shoal-deep pool of mountain river, the living environment of mountain river fishes is destroyed, which has a negative influence on the survival of fishes. The problem can be solved by reducing the height of the weir or widening the distance between the weirs, but reducing the height of the weir would create better conditions for fish migration. So during the restoration process of fish habitat in river with high density weirs, it is a good method to adjust the height of weir by fish demand, which can also be used as a condition to limit the height of dam in the process of dam construction.

6. Conclusion
In this paper, taking Majin River as an example, the discharge in extreme velocity of the local fish and submerged conditions of the weir was taken as a limitation of the height of the weir group in mountain area. The height of weir was analyzed aiming for the local fish across the weir in migration period. This paper studied the following conclusions.

1) The discharge of the 6 weirs were different while the velocity across the weir crest was 1.55m/s or in submerged flow. Fish cannot pass through all weirs at a specific discharge.

2) Using the minimum discharge satisfying the extreme velocity in each weir as the limiting condition, the critical discharges of 5 weirs were larger than 50m³/s in submerged flow, the fish can only swim across the Xutang Weir with the limited discharge.

3) By reducing the height of the weir, the discharge met to fish migration can be reduced, and different weirs required different heights to be reduced.
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