Spawning flow velocity demand for representative fish species in the upper Yangtze River

Lisi Xu¹,², and Zhengjie Yin¹,²*
¹Changjiang River Scientific Research Institute, 430010, Wuhan, Hubei, China
²Hubei key Laboratory of Water Resources & Eco-Environmental Sciences, 430010, Wuhan, Hubei, China
* Corresponding author: yinzj@mail.crsri.cn

Abstract. To mitigate possible negative impacts of cascade dams on spawning of rare and endemic fish species in the national nature reserve downstream of these dams, spawning flow velocity demand for fish need to be considered in the cascade dams operation. Based on the cascade dams constructed in the upper Yangtze River, Coreius Heterodon was selected as the representative fish species. According to the drifting distance of fish eggs, the flow velocity characteristics at the spawning location of Coreius Heterodon were analysed with the unsteady flow mathematical model. The results show that a large flow velocity increase process is good for Coreius Heterodon spawning, and the process of velocity fluctuation is similar before spawning. The cumulative velocity amplitude, the cumulative number of fluctuations and the maximum velocity amplitude are closely correlation with the spawning number. The velocity in spawning period is affected by the dams operation, and the suitable range of velocity is changed from [0.8m/s, 1.2m/s] to [1.1m/s, 1.4m/s]. The results can provide the basis for future ecological operation based on flow velocity index of the cascade dams.

1. Introduction
There are four large cascade hydropower dams in the downstream Jinshajiang River, which are Wudongde, Baihetan, luoxidu and Xiangjiaba. At present, Xiluodu and Xiangjiaba hydropower dams have been completed and put into operation, and Wudongde and Baihetan projects are under construction. There is a national nature reserve for rare and endemic fish species in the upper Yangtze River in their downstream. The reserve mainstream starts from Xiangjiaba and extends down to Songji River in Chongqing (Sun et al., 2014). The study area of this paper is shown in figure 1.

Coreius Heterodon is a typical fish that produces pelagic eggs, which is an important economic fish in the upper reaches of the Yangtze River. It once accounted for a high proportion of the fish catches (Gao et al., 2015), and it has a certain representativeness, but the Coreius Heterodon number shows a decreasing trend (Gao et al., 2013). Impounding and operation of Xiangjiaba and Xiluodu cascade dams has caused the alteration of hydrologic regimes in the downstream of the dams to some extent, thus affecting the spawning and breeding activities of fish in the reserve (Chen et al., 2016), especially those that produce drifting eggs (Duan et al., 2015). Exploring the hydraulic conditions suitable for fish spawning is the basis of accurately calculating the ecological flow process of target species (Yi et al., 2017), which can contribute to reducing the negative impact of dams operation on river ecosystem.

The stimulation of hydrodynamic process of water level, discharge and flow velocity increase are the important conditions to promote fish spawning (Liu and He, 1992). Huang (2018) analyzed the threshold ranges of high flow pulse related indexes during spawning period of Coreius Heterodon. Han
et al. (2016) proposed the appropriate ranges of velocity and water depth to the spawning of Schizothorax lantsangensis and Schizothorax lissolabiatus. The increase of discharge and water level are all reflected in the change of flow velocity in hydrodynamic process. Sempeski and Gaudin (1995) found that in the Pollon and Suran rivers of France, the flow velocity at trout spawning field is similar every year, which indicates that the velocity is an important parameter to describe trout spawning field. Zhang (2017) studied the range of trigger velocity, spawning appropriate velocity and spawning appropriate velocity rise rate for spawning.

At present, the research on the suitability of hydraulic factors for fish spawning mainly analyzes the hydraulic characteristics at a typical cross section of the spawning field, but the spawning location is distributed in the whole spawning field. Therefore, the hydraulic conditions of representative cross sections can not accurately reflect the hydrodynamic demand for spawning behavior. According to the development data of eggs captured in Jiangjin cross section (see figure 1) from 2011 to 2016, the drifting distance of fish eggs and the location where Coreius Heterodon spawning could be deduced. Using the unsteady flow mathematical model, the velocity fluctuation characteristics before spawning and appropriate ranges of flow velocity in the spawning period were analyzed, and the velocity demand for spawning behavior was obtained. The results will help to define the threshold of the hydrologic regiem indicators that need to be guaranteed for the fish protection.

![Fig. 1. Sketch map of study area.](image)

2. mathematical model

2.1 Basic equation of the model

The control equations of this model are the Saint-Venant equations, the Abbott six-point implicit format is used for discretization, and the traditional Thomas algorithm is used in the numerical calculation. The control equations is as follows:

\[
\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \tag{1}
\]

\[
\frac{\partial Q}{\partial t} + \left(\alpha Q^2 A^{-1}\right) \frac{\partial h}{\partial x} + gA \frac{\partial |Q|}{\partial x} + g|Q| \frac{C^2 AR}{Q} = 0 \tag{2}
\]

Where: \(Q\) is the discharge (m\(^3\)/s); \(A\) is the discharge section area (m\(^2\)); \(q\) is the local inflow or partial flow (m\(^2\)/s); \(\alpha\) is the momentum distribution coefficient; \(h\) is the water level; \(C\) is the Chézy coefficient; \(R\) is Hydraulic radius.
2.2 Modeling and calibration

According to the topographic data of the river in the reserve in 2005, a one-dimensional hydrodynamic model of the Yangtze River mainstream from Yibin station to Cuntan station was established. Minjiang River, Tuojiang River, Chishuihe River and Jialing River and other tributaries were regarded as point sources. The upstream discharge boundary could be approximated by the sum of Xiangjiaba station discharge near the upstream mainstream and the discharge of Hengjiang tributary. The downstream water level boundary adopted the water level record data of Cuntan station. The water level of Yibin station, the water level of Zhutuo station, the water level of Luzhou Station and the discharge of Cuntan station were verified. By adjusting the roughness of river bed along water depth and river reach, the daily water level and discharge process of hydrodynamic model from 2011 to 2016 were calibrated.

The roughness of each cross section is set along the direction of water depth, and the mathematical model of the river channel in the reserve is calibrated by segment. After calibration, the water level error is less than 0.5m. Taking the calculated results in 2015 as an example, shown in figure 2. On the whole, the simulation value is in good agreement with the measured data. The calculated results of this model can be used for the subsequent analysis in this paper.

3. Analysis of flow velocity characteristics at spawning location

3.1 Hydrodynamic process before spawning

Analysing the hydrodynamic process at the spawning location of seven fish eggs, where Coreius Heterodon spawned every year from 2011 to 2015. Figure 3 and table 1 show the hydrodynamic process of each fish egg before spawning. Each egg used in the analysis represents a spawning behavior with a certain spawning number. The characteristics of hydrodynamic process are mainly the number of fluctuations and the velocity amplitude. It is defined that the number of fluctuations is the times of monotonic changes of velocity process line, the velocity amplitude is the velocity difference at the time of two successive monotonic changes of the line.

The flow velocity can rise or fall in a short time for spawning. Generally, there is an obvious process of velocity increase before spawning. The velocity process before spawning is similar, and the spawning...
velocity is close, which shows that the velocity for Coreius Heterodon spawning in the same spawning location is relatively fixed (figure 3).

![Fig. 3. Velocity process before Coreius Heterodon spawning.](image)

The cumulative fluctuations of the flow velocity before these 7 spawnings are shown in table 1. The spawning of Coreius Heterodon is in the process of the overall upward trend of the flow velocity. The cumulative velocity amplitude is greater than 0.28 m/s. The cumulative number of fluctuations is more than 51 times. According to the weighted average of spawning number, the flow velocity fluctuates about 62 times. The maximum amplitude is greater than 0.19 m/s, and the velocity change process with amplitude greater than 0.1 m/s should be experienced more than 4 times before spawning (table 1).

| Egg number | Spawning number (10^7ind.) | Cumulative velocity amplitude (m/s) | Number of fluctuations | Maximum amplitude (m/s) | Times of amplitude greater than 0.05 m/s | Times of amplitude greater than 0.1 m/s |
|------------|----------------------------|------------------------------------|------------------------|-------------------------|------------------------------------------|----------------------------------------|
|            |                            | Fall | Rise | Fall | Rise | Fall | Rise | Fall | Rise | Fall | Rise | Fall | Rise | Fall | Rise | Fall | Rise |
| 1          | 0.143                      | 0.28 | 51   | 0.19 | 8    | 14   | 4    | 5    |
| 2          | 0.562                      | 0.47 | 63   | 0.20 | 9    | 12   | 0    | 5    |
| 3          | 0.223                      | 0.83 | 69   | 0.48 | 12   | 16   | 7    | 11   |
| 4          | 0.223                      | 0.83 | 69   | 0.48 | 12   | 16   | 7    | 11   |
| 5          | 0.143                      | 0.34 | 71   | 0.47 | 15   | 11   | 10   | 5    |
| 6          | 0.333                      | 0.35 | 67   | 0.47 | 13   | 9    | 8    | 4    |
| 7          | 0.809                      | 0.37 | 55   | 0.26 | 12   | 13   | 6    | 6    |

From table 1, it is easy to get the response relationship between spawning number and cumulative velocity amplitude, cumulative number of fluctuations and maximum amplitude. When the cumulative velocity amplitude, the cumulative number of fluctuations and the maximum amplitude are 0.37 m/s, 55 times and 0.26 m/s respectively, the largest spawning number appears in the analytical section in these six years. When the three indexes are far away from 0.37 m/s, 55 times and 0.26 m/s, the spawning number tends to decrease. It shows that the stimulation of velocity fluctuation is imperative for spawning, and the closer the indexes of cumulative velocity amplitude, cumulative number of fluctuations and maximum amplitude are to the appropriate ranges of spawning, the larger the spawning number is.

3.2 Hydrodynamic conditions in spawning period
According to the spawning location of each captured egg seedlings, the daily velocity at the location in the spawning period were analyzed.
3.2.1 Distribution of spawning velocity
Based on the analysis of the number of captured egg seedlings of Coreius Heterodon in 2011-2016, the distribution of spawning velocity in six years is shown in figure 4. The velocity range of Coreius Heterodon spawning is [0.3, 2.4] (flow velocity unit m/s, the same below). The velocity ranges for peak spawning number is [0.9,1.1] U [1.6,1.7], and the proportion of spawning number in this range to the total spawning number in six years is about 28% and 11.5%, about 40% in total. The spawning number in the velocity range [0.8,1.4] accounts for 58% of the six-year spawning number; the spawning number in the velocity range [0.8,1.9] accounts for 84%.

![Fig. 4. Distribution of spawning velocity of Coreius Heterodon.](image)

3.2.2 Distribution of spawning velocity in each year
See figure 5 for the statistics of spawning velocity of Coreius Heterodon in each year from 2011 to 2016. The velocity range of Coreius Heterodon spawning every year is [1.1,1.4], which is also an important velocity range for Coreius Heterodon spawning. The cumulative six-year spawning number in this interval accounts for 23.4% of the total number. There is a certain difference in the range of spawning velocity and the spatial distribution of spawning number in each year.

![Fig. 5. Distribution of spawning velocity of Coreius Heterodon in each year.](image)
3.2.3. Comparison of spawning velocity before and after impounding

According to the impounding time of Xiluodu-Xiangjiaba cascade reservoir, the period from 2011 to 2016 was divided into three stages, namely before impounding (2011-2012), impounding period (2013-2014) and trial operation period (2015-2016). Figure 6 shows the distribution of spawning number in the velocity range at each stage.

![Fig. 6. Comparison of spawning velocity of Coreius Heterodon before and after impounding.](image)

After the operation of the upstream dams, the range of velocity for Coreius Heterodon spawning has been reduced from [0.3, 2.4] to [1.0, 2.1], and the reduction ratio is about 48%. On the one hand, the different hydraulic characteristics of the two stages can couple the biological characteristics for Coreius Heterodon spawning; on the other hand, the alteration of hydrologic regimes caused by the cascade dams may have an impact on Coreius Heterodon spawning.

At the same time, it is found that the main velocity range for spawning in the trial operation period is [1.1, 1.4], and the proportion of spawning number in this range before impounding and during the trial operation period is 16% and 49%, respectively. The main velocity range for Coreius Heterodon spawning before impounding is [0.8, 1.2], and the proportion of spawning number is about 49%. It can be seen that the main spawning velocity increases to a certain extent after impounding, which may be related to the delay in spawning caused by the decrease of water temperature. It also shows that after the cascade dams is operated, the velocity of spawning location in reserve can still meet the demand to Coreius Heterodon spawning, and the velocity range is slightly adjusted.

4. Conclusion

In this paper, the velocity characteristics at spawning location of Coreius Heterodon were analyzed with the unsteady flow mathematical model. The conclusions are as follows:

(1) Based on the spawning location, this paper studied the spawning velocity demand, which can more contribute to direct ecological operation.

(2) The process of velocity rising is beneficial to Coreius Heterodon spawning. The velocity process before spawning is similar, and the spawning velocity is close. In the process of velocity fluctuation before spawning, the indexes of cumulative velocity amplitude, cumulative number of fluctuations and maximum amplitude can be used to predict and estimate spawning number.

(3) The main velocity range for Coreius Heterodon spawning is [0.8 m/s, 1.4 m/s]. After the reservoir impounding, the spawning velocity range decreases by 48%. The main spawning velocity range also changes from [0.8 m/s, 1.2 m/s] to [1.1 m/s, 1.4 m/s], with overlap and fine adjustment.
(4) In order to protect the rare and endemic fish in the upper Yangtze River, ecological operation based on flow velocity index can be carried out to promote the ecological environment protection of hydropower development.

(5) Due to the limited hydrological data and spawning number data of Coreius Heterodon, the similarity of flow velocity fluctuation process before spawning in the same spawning location was preliminarily analyzed. The samples need to be increased for further study to determine the appropriate threshold range of hydrodynamic indexes. At the same time, the contrast samples before and after impounding can be increased to show the influence of dams operation on the spawning ability of Coreius Heterodon.

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