The optimization of flow conditions in the spawning grounds of the Chinese sturgeon (*Acipenser sinensis*) through Gezhouba Dam units

Abstract:

The waters downstream from the Gezhouba Dam are the only spawning grounds of the Chinese sturgeon. To optimize the flow conditions in the spawning grounds by controlling the opening mode of the Gezhouba Dam generator units, a mathematical model of the three-dimensional hydrodynamics of the Chinese sturgeon spawning grounds was established in FLOW-3D. The model was verified with velocity measurements, and the results were in good agreement. Additionally, the model was used to invert the flow field of monitoring results from 2016-2019, and it was concluded that the preferred velocity range for the Chinese sturgeon was 0.6-1.5 m/s. The flow fields of different opening modes of the generator units were simulated with the same flow rate, and the results showed that the suitable velocity area was the largest when all units of the Dajiang Plant of the Gezhouba Dam were open and that conditions were especially favourable on the left side. Comparison of the suitable velocity area with different flow rates showed that when the flow rate was less than 12000 m^3/s, more than 90% of the area was suitable and that when the flow rate was greater than 12000 m^3/s, the suitable area decreased rapidly with increasing flow rate. Moreover, the suitable areas under different opening modes under high-flow conditions were compared, and the results showed that at flow rates of 12000 ~ 15000 m^3/s, opening 11~13 units on the left side was best. When the flow rate reached 15000 m^3/s, it was best to open all of the units. In this paper, the optimal opening scheme at different flow rates was analysed, and the results provide new ideas for Chinese sturgeon protection and ecosystem protection.

Keywords:

Chinese sturgeon; Spawning ground; 3D simulation; Suitable velocity; Gezhouba Dam; Opening mode of units

1 INTRODUCTION

The Chinese sturgeon is a large anadromous fish and is a national first-class protection animal and a critically endangered species (Wang, Tao, & Chang, 2019). Before the construction of Gezhouba Dam, the spawning grounds of the Chinese sturgeon were mainly in the lower reaches of the Jinsha River and the upper reaches of the Yangtze River (Chang & Cao,1999; Wei, 2003). After the closure of Gezhouba Dam, a new spawning ground formed in the waters downstream of the Gezhouba Dam and now represents the only Chinese sturgeon spawning ground (Hu, Ke, Zhang, Luo, & Gong, 1992). According to the results of continuous monitoring in recent years, the breeding scale of Chinese sturgeon has decreased (Chang & Cao, 1999; Wang et al., 2019).

After the sexual maturity of the Chinese sturgeon, its reproductive behaviour is affected by the environment and hydrological conditions of the spawning ground. Threshold ranges exist for numerous conditions, and the Chinese sturgeon can reproduce normally only within these threshold ranges. One crucial factor is the flow velocity. A study has shown that the Chinese sturgeon will actively choose hydraulic conditions that are beneficial to its habitat and reproduction (Ban, Gao, Diplas, Xiao, & Shi, 2018), and flow velocities exceeding the maximum tolerable velocity of fish will affect the normal habitat (Booker, 2003). The study of spawning grounds has great significance for improving spawning conditions and protecting the Chinese sturgeon. Research on the spawning ground of the Chinese sturgeon has mainly focused on three aspects. First, the spawning ground of the Chinese sturgeon has been studied by means of historical data and field measurements (Ban, 2009; Chen, 2007; Wei, 2003; Yang et al., 2007; Zhang et al., 2007). Second, the characteristics of the spawning ground of the Chinese sturgeon have been inverted by numerical simulation (Tao, Chen, & Wang, 2017; Wang & Xia. 2010; Wang, Xia, &Wang, 2012; Wu & Fu, 2007). Third, the influence of dam operation on the characteristics of water flow in the spawning grounds has been studied (Bi, Tian, Yang, 2016; Huang, Guo, Xing, Jiang, Yang, 2013; & Mao, Li, Dai, & Ke, 2014). Because the spawning ground of the Chinese sturgeon is mainly distributed in the waters downstream of the Gezhouba Dam, differences in the flow rate and operation mode of the Gezhouba Dam units will change the water flow conditions, so it is necessary to thoroughly study these effects.

To effectively model the actual situation, the method of numerical simulation and field monitoring was used in this paper. A mathematical model of the 3D hydrodynamics of the spawning ground of the Chinese sturgeon was established, the flow field based on sonar monitoring results of the Chinese sturgeon from 2016 to 2019 was simulated by the model, and we obtained the preferred velocity range of the Chinese sturgeon. Furthermore, the optimal scheme of different units of the Gezhouba Dam was simulated and analysed, and methods for improving the flow conditions in spawning ground are proposed. Therefore, the results provide new ideas for

Chinese sturgeon protection and ecosystem protection.

2 MATERIALS AND METHODS

2.1 Study area

The Gezhouba Dam Project is the first large hydropower station on the Yangtze River, with a total installed capacity of 2.7 million kilowatts. There are 21 generator units; 14 units with a capacity of 125,000 kilowatts are installed in the Dajiang Plant, and 2 units with a capacity of 170,000 kilowatts and 5 units with a capacity of 125,000 kilowatts are installed in the Erjiang Plant (Zhao, 1991). The units are numbered from the left bank to the right bank sequentially. The numbers of the Erjiang Plant units are #1~#7, and the numbers of the Dajiang Plant units are #8~#21.

Field surveys have shown that the only stable spawning ground of the Chinese sturgeon is located in the section between the Gezhouba Dam and Miaozui, approximately 4 km downstream of Gezhouba Dam (Chang, 1999; Tan, 2002; Wei, 2003; Wei, Yang, Ke, Kynard, & Micah, 1998). Therefore, the area between Gezhouba Dam and Miaozui was selected for investigation in this study, as shown in Figure 1. This area was divided into several cross-sections (Figure 1c), and the velocity of the cross-section was measured with a 300 kHz acoustic Doppler velocity profiler (ADCP). In addition, sonar monitoring was also performed in this area. According to the monitoring results from 2016 to 2019, most of the Chinese sturgeon signals appeared within 1 km below the Dajiang Plant units of the Gezhouba Dam, as shown in the red box in Figure 1c. However, according to the field investigation, the area of the spawning ground has decreased further in recent years because most of the spawning behaviour of Chinese sturgeon has occurred in the red box in Figure 1c since 2008 (Du at el. 2015; Wu et al. 2017). Hence, the range of 700 m downstream of the Dajiang Plant units was the key simulation area in this study. This stretch is shown in Figure 1d, which shows an underwater topographic map of this area, and the colour shading and contours represent the water depth when the water level behind the dam was 41.2 m. The units on the right side are #8~#15, and the corresponding water area under the units was shallow, mostly 7-10 m. There is a deep pit 200 metres from the Gezhouba Dam with a water depth of approximately 13 m. Units #16~#21 are on the left side, and the corresponding water area is deeper, i.e., 12~15 m within 300 m of the dam, and then the water depth becomes shallower to approximately 10 m.

2.2 Numerical model

2.2.1 Governing equations

FLOW-3D is an advanced commercial CFD package based on the finite volume method (FVM) that solves the Reynolds-averaged Navier-Stokes equations, and it can effectively estimate the flow structure and velocity distribution in different water layers (Chen & Tfwala, 2018). Based on the assumption that the water body is an incompressible viscous fluid, the governing equations include the continuity equation and momentum equations (Flow Science 2012).

Continuity equation

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}\left(\rho u A_x\right) + \frac{\partial}{\partial y}\left(\rho v A_y\right) + \frac{\partial}{\partial z}\left(\rho w A_z\right) = 0 \qquad (1)$$

Momentum equations:

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\left\{u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} + w A_z \frac{\partial u}{\partial z}\right\} = \frac{-1}{\rho}\frac{\partial p}{\partial x} + G_x + F_x \qquad (2)$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F}\left\{u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z}\right\} = \frac{-1}{\rho}\frac{\partial p}{\partial y} + G_y + F_y \qquad (3)$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F}\left\{u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z}\right\} = \frac{-1}{\rho}\frac{\partial p}{\partial z} + G_z + F_z \qquad (4)$$

where V_F is the cell fractional volume; ρ is fluid density; u, v, and w are the fluid velocity components in the x, y, and z directions; A_x, A_y, and A_z are the fluid fractional area in the x, y, and z directions; p is pressure; G_x, G_y, and G_z are gravitational components in the x, y, and z directions; and F_x, F_y, and F_z are viscous accelerations in the x, y, and z directions.

The program uses the volume of fluid (VOF) method based on Euler's method to help it accurately determine the boundary of the free surface (Hirt & Nichols, 1981), and it has a powerful capability to deal with free surface flows. FAVOR is applied to model complex geometries (Hirt & Sicilian, 1985), making the code more versatile and applicable to most CFD applications. The complex change in the free surface in the VOF method can be described as:

$$\frac{\partial F}{\partial t} + \frac{1}{V_F}\left[\frac{\partial\left(F A_x u\right)}{\partial x} + \frac{\partial\left(F A_y v\right)}{\partial y} + \frac{\partial\left(F A_z w\right)}{\partial z}\right] = 0 \qquad (5)$$

where F is the fluid volume function and the other terms are as defined in Equation (1).

2.2.2 Turbulence closure model

The $k-\varepsilon$ turbulence closure models include the turbulent kinetic energy equation and turbulent energy dissipation equation rate. The expression is as follows:

Turbulent kinetic energy equation:

$$\frac{\partial k_T}{\partial t} + \frac{1}{V_F}\left\{u A_x \frac{\partial k_T}{\partial x} + v A_y \frac{\partial k_T}{\partial y} + w A_z \frac{\partial k_T}{\partial z}\right\} = P_T + \varepsilon_T \qquad (6)$$

where k_T is the turbulent kinetic energy; ε_T is the turbulent energy dissipation rate; and P_T is the turbulent kinetic energy generation term, which is determined as follows:

$$P_T = \frac{\mu}{\rho V_F}\left\{2 A_x \left(\frac{\partial u}{\partial x}\right)^2 + 2 A_y \left(\frac{\partial v}{\partial y}\right)^2 + 2 A_z \left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\left(A_x \frac{\partial v}{\partial x} + A_y \frac{\partial u}{\partial y}\right) + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\left(A_z \frac{\partial u}{\partial z} + A_x \right.\right.$$

(7)

where μ is the dynamic viscosity coefficient.

Turbulent kinetic energy dissipation rate equation:

$$\frac{\partial \varepsilon_T}{\partial t}+\frac{1}{V_F}\left\{u_x A_x \frac{\partial \varepsilon_T}{\partial x}+u_y A_y \frac{\partial \varepsilon_T}{\partial y}+u_z A_z \frac{\partial \varepsilon_T}{\partial z}\right\}=C_{\varepsilon 1}\frac{\varepsilon_T}{k_T}P_T-C_{\varepsilon 2}\frac{\varepsilon_T^{\,2}}{k_T} \qquad (8)$$

where $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are empirical constants, and the default values in the model are 1.44 and 1.92, respectively (Su, 2017).

2.2.3 Boundary and initial conditions

The inlet boundary used the flow rate boundary, and the flow rate was determined based on the location and the scheduling of the Gezhouba Dam units. The pressure boundary was used for the outlet boundary and was set to the water level. The water surface was a free surface, using a pressure boundary, given standard atmospheric pressure. The wall boundary was used for the solid boundary of the bottom and both sides. The initial condition was the water level, and the initial velocity was 0.

2.2.4 Mesh construction

A hexahedral orthogonal grid was used to mesh the model, which can iteratively define a base mesh to fit surface geometries. The finite volume method was used to discretize the governing equation, and the GMRES algorithm was used to solve the equation (Flow3D, 2012; Moukalled, Mangani, & Darwish, 2015). Mesh sizes were chosen to respect the requirements of the grid convergence index (GCI) method for testing spatial convergence (Celik et al., 2008). The X-axis direction and Y-axis direction mesh sizes were 3-8 m, and the Z-axis direction mesh sizes were 1-2 m.

2.2.5 Model validation

The measured velocity data from downstream of the Gezhouba Dam were used to verify the model. The discharge of the Gezhouba Dam was 12000 m^3/s, and the water level was 41.2 m. The comparisons between the measured and model values for cross-sections 1~6 are presented in Figure 2. According to the comparison results, the model values with a roughness of 0.02 was closest to the measured values, so the calibrated roughness of the model was set to 0.02. From Figure 2, the distribution flow velocity of each cross-section was in good agreement, especially in the Dajiang River area where the spawning ground of the Chinese sturgeon was located. The error of the model and measured values were generally less than 0.2 m/s, and the maximum error was 0.43 m/s, which appeared next to the dividing dike in cross-section 3. The two-tailed t-test permutation of the model and measured values showed no significant difference, $P=0.45>0.05$. Therefore, the model simulation was reasonable and acceptably simulated the water flow characteristics of the spawning ground of the Chinese sturgeon.

2.3 Acoustic monitoring

Acoustic monitoring is a fast and effective method to study Chinese sturgeon because it can study the number and distribution of fish without approaching and harming the fish (Tao, Qiao, Tan, & Chang, 2009). For acoustic monitoring, this paper used a DIDSON dual-frequency video sonar system, which is currently the only imaging sonar using an acoustic system. This system has been widely used in fishery management, structural detection, pipeline leakage identification, underwater monitoring, underwater searching, underwater security inspection and so on (Belcher, Hanot, & Burch, 2002).

The main monitoring area was approximately 4 km long between the Gezhouba Dam and Miaozui, which represents the only spawning ground of the Chinese sturgeon. When investigating, the sonar transmitter was fixed to the side of the survey vessel through a specific support and was located 0.3 m below the water surface. The shooting angle was 45° downward relative to the horizontal plane. A GPS device produced by the Garmin company was used for navigation and positioning. We performed monitoring continuously every day from November to January of the following year for 3~4 hours, with a zigzag survey pattern to ensure full coverage of the spawning ground. The monitoring results were saved in the form of video images, and the images were judged and analysed directly. Chinese sturgeon signals were confirmed by measuring the full length, swimming behaviour, body shape, etc. To reduce the error of judgement and obtain high-accuracy Chinese sturgeon signals, each monitoring signal was confirmed by at least two different researchers.

3 RESULTS

3.1 Flow velocity threshold

There were 47 Chinese sturgeon signals in 2016, 14 Chinese sturgeon signals in 2017, 20 Chinese sturgeon signals in 2018, and 11 Chinese sturgeon signals in 2019, which were identified with the DIDSON dual-frequency video sonar system. The flow field of each sturgeon signal was simulated by the model, and the velocity value of each signal location was obtained. According to the statistical analysis of the flow velocity values, the frequency of the sturgeon signal at different flow velocity values is shown in Figure 3. The results showed that most of the signals were concentrated in areas with flow velocities of 0.6~1.5 m/s, accounting for 88.1% of the signals; areas with flow velocities below 0.6 m/s accounted for 4.3% of the signals, and areas with flow velocities above 1.5 m/s accounted for 7.6%. Therefore, 0.6~1.5 m/s was chosen as the preferred flow velocity range of the Chinese sturgeon.

3.2 Different opening modes with the same flow rate

The flow rate of the spawning day on November 24, 2016, was used to study the flow velocity distribution with different opening modes, and the specific opening mode cases are shown in Table 1. Case 1 was the actual situation on the day of spawning, and the flow rate was 6150 m^3/

s. The Dajiang Plant featured 7 open units, namely, #8, #11, #13, #14, #16, #19, #21. According to the amounts of electricity generated by the Dajiang Plant and Erjiang Plant on that day, the proportion of the Dajiang River flow was 58.8%, and the average flow rate of each unit was 516.6 m^3/s. Case 2 and case 3 also featured 7 open units with the same flow rate, but in case 2, units #15~#21 were open continuously on the right side, and in case 3, units #8~#14 were open continuously near the left side. Case 4 and case 5 were the most concentrated conditions with the flow rate of 6150 m^3/s because the maximum throughflow rate for each unit in the Dajiang Plant is 825 m^3/s (Jie & Xu, 2009). In these cases, at least 5 units were open, with an average flow rate of 723 m^3/s per unit. Case 4 involved opening units #8~#12 continuously on the left side, and case 5 involved opening units #17~#21 continuously on the right side. Case 6 involved opening 14 units on the Dajiang River at the same time, and the average flow rate of each unit was 258.3 m^3/s.

Figure 4 shows the flow fields of the spawning ground under different opening modes with the same flow rate, and the studied area is shown in Figure 1d. By comparing the areas with a velocity threshold range of 0.6-1.5 m/s under different cases, the most favourable opening mode was determined. In case 1, the proportion of suitable area was 86.2%. The velocity at the outlet of the units was higher than the flow threshold, but the flow rate of each unit was only 516.6 m^3/s, so the high-velocity range was limited, and most areas were suitable. In case 2 and case 3, there was a large difference in the proportions of suitable area, 90.6% and 63%, respectively. Because the left side was deeper than the right side, the flow velocity on the right side was higher under the same flow rate, and case 3 more easily exceeded the flow threshold, resulting in a larger unsuitable range. Case 2 was more suitable than case 1, which also demonstrated that opening the left-side units was more favourable. In case 4 and case 5, the proportions of suitable area were small, 61% and 72.5%, respectively. Because the units were concentrated, the flow rate of each unit was too high, and the outlet velocity was more than 2 m/s, so a large area of high velocity appears downstream of the units, with obvious backflow under the shut-down units. The proportion of suitable area in case 5 was larger than that in case 4 and case 3, further indicating that opening the left-side units was more favourable than opening the right-side units. Case 6, in which all units were open, has suitable velocity area proportion of 95.9%, greater than that in any other case. Because the flow rate of each unit was only 258.3 m^3/s, the velocity of the unit outlet was less than 1.5 m/s, and almost all areas were suitable except for the small areas on both sides. The suitable velocity area was the largest when all units of the Dajiang Plant of the Gezhouba Dam were open; therefore, for a given flow rate, it is best to open all of the units.

3.3 Different flow rates under the same opening mode

The velocity distribution of the spawning field is affected not only by the opening mode of the units but also by the flow rate of the Gezhouba Dam. To study the influence of different flow rates, the following 14 cases were simulated, as shown in Table 2. All units of the Dajiang Plant were considered open because the proportion of suitable area was expected to be the largest under such circumstances. From 1982 to the present, the flow rate on the natural spawning day of Chinese sturgeon under the Gezhouba Dam has a wide range, with the highest flow rate of 27290 m^3/s in 1990 and the lowest flow rate of 5590 m^3/s in 2012. However, the highest design flow rate of the Gezhouba Dam units is 17930 m^3/s (Zhao, 1991). Once the design flow rate is exceeded, the sluice on the Erjiang River discharges water, and the velocity distribution of the study area is not affected. Therefore, case 1 represented the lowest flow rate of 5590 m^3/s, and case 2 represented a flow rate of 6000 m^3/s. For each subsequent case, the flow rate was increased by 1000 m^3/s to case 13 with the highest flow of 17930 m^3/s. In case 14, all units reached the design flow rate, and the flow rate of each unit was 825 m^3/s (Jie & Xu, 2009).

Figure 5 shows the proportion of suitable velocity area with all units open under different flow rates. According to the calculation results, the proportion of suitable area fluctuated slightly at approximately 96.2% for flow rates from 5590 m^3/s to 11000 m^3/s, with the lowest value being 94.6% for a flow rate of 10000 m^3/s and the highest value being 98% for a flow rate of 8000 m^3/s. Because the flow rate of each unit was lower than 504 m^3/s, the velocity of the unit outlet was low, and most areas were within the velocity threshold. Therefore, it is advantageous to open all units when the flow rate is low. After the flow rate reaches 12000 m^3/s, the proportion of suitable area rapidly decreased to 70.7% and gradually decreased with increases in the flow rate to 20.2% at a flow rate of 17930 m^3/s. Because the flow rate of each unit was higher than 504 m^3/s, on the right side of the Dajiang River, the velocity of the unit outlet exceeded the velocity threshold and increased with increases in the flow rate, and the range of influence gradually increased. In the last case, the proportion of suitable area was only 6% when the units reached the designed flow rate of 825 m^3/s. Because the flow rate of each unit was too high, almost all areas exceeded the velocity threshold except for small areas on both sides. Therefore, at flow rates less than 12,000 m^3/s, opening all the units is favourable, and at flow rate greater than 12000 m^3/s, the higher the flow rate is, the more unfavourable the conditions are.

3.4 The optimal scheme under high-flow conditions

The critical value of the Gezhouba Dam flow rate is 12000 m^3/s, and the proportion of suitable area exhibits a large turning point at this critical value, so high-flow conditions are considered flow rates greater than 12000 m^3/s. Because opening the units on the left side of the Dajiang Plant is more favourable, to increase the suitable area under high-flow conditions, 20 cases with a left-side opening mode under different flow rates were simulated, as shown in Table 3. Because the highest flow rate of each unit in the Dajiang Plant is 825 m^3/s (Jie & Xu, 2009), at least 9 units need to be open when the flow rate is 12000 m^3/s. Case 1 was designed to open 9 units on the left, namely, units #13~#21, and the flow rate of each unit was 784 m^3/s. Case 2-5 increase by 1 unit from left to right, until 13 units were opened . For flow rates of 13000 m^3/s, 14000 m^3/s, 15000 m^3/s, and 16000 m^3/s, the lowest numbers of open units were 10, 10, 11, and 12. When the flow rate was 17000 m^3/s and 17930 m^3/s, the lowest number of open units was at least 13.

Figure 6 shows the proportions of suitable area for different opening modes under high-flow conditions, where the 12000-09 on the x-axis means that the flow rate is 12000 m^3/s and 9 units are open on the left. The calculation results showed that when the flow rate was 12000 m^3/s, 13000 m^3/s, and 14000 m^3/s, the proportion of suitable area showed a parabolic trend with the increase in the number of units. When the flow rate was 12000 m^3/s, the proportion of suitable area with 11 open units on the left was the largest, 79.4%, which was 8.7% larger than the value for all units open and 15% larger than the value for the lowest number of units open. Opening the 12 units on the left yield values approximately the same as opening 11 units, with a difference of only 0.1%. When the flow rate was 13000 m^3/s, 12 open units on the left had the largest proportion of suitable flow velocity area, reaching 73.2%, which was 6.3% larger than the value for all units open and 10% larger than the value for the lowest number of units open. Opening the 11 units on the left was approximately the same as opening 12 units, with a difference of only 0.7%. When the flow rate was 14000 m^3/s, the proportions of suitable area produced by opening 12 units and 13 units on the left were the same, 67.3%, which was 2.1% larger than the value for all units open and 11.5% larger than the value for the lowest number of units open. The proportion of suitable area of the lowest number of units open was usually the lowest because the flow rate of each unit was too high, resulting in a large area of high velocity under the unit's outlet, and the influence distance was far, which was not suitable for Chinese sturgeon habitat. For a flow rate of 15000 m^3/s, with the increase in the number of units, the proportion of suitable area increased, and there was no parabolic trend because the flow rate of each unit was over 678 m^3/s; thus, on the left side, there was a large area of high velocity, and the influence extended very far, which was not suitable for Chinese sturgeon.

4. Discussion

4.1 Spawning time and the preferred flow rate of Chinese sturgeon

Figure 7 shows the spawning date of the Chinese sturgeon downstream of the Gezhouba Dam. According to statistics, Chinese sturgeon spawning activity occurs 1~2 times every year. From 1982 to 2002, two spawning events per year was common, occurring in 76.2% of the years. Since 2003, most years have featured only one spawning event, with a second spawning event occurring only once on December 2, 2012. The spawning date was mainly from mid-October to November. The first spawn was concentrated in late October before 2003, in mid-November in 2003-2006 an in late November since 2007. Therefore, the spawning date has become gradually delayed (Shen, Wang, Wang, & Yu, 2017). The second spawning was concentrated between late October and mid-November, generally occurring 2~27 days after the first spawning, with an average of 15 days later. To date, the last spawning of Chinese sturgeon occurred on November 24, 2016, and no natural reproduction of Chinese sturgeon was observed downstream of the Gezhouba Dam from 2017 to 2019 (Wang LH, & Huang ZL, 2020).

Figure 8 shows the daily flow rate of the Chinese sturgeon during the spawning day downstream of the Gezhouba Dam. The highest flow rate of the first spawning was 27290 m^3/s on October 15, 1990, and the lowest flow rate was 5810 m^3/s on November 23, 2009. The highest flow rate of the second spawning was 18170 m^3/s on November 1, 2000, and the lowest flow rate was 5590 m^3/s on December 2, 2012. As the spawning date gradually became delayed, the flow rate of the first spawning showed a downward trend overall. The spawning flow rate was less than 12000 m^3/s after 2002. Most spawning dates featured flow rates higher than 12000 m^3/s before 2002, accounting for 75%, with flow rates higher than 15000 m^3/s accounting for 55% and flow rates higher than the design flow rate of 17930 m^3/s accounting for 25%. The flow rate of the second spawning was lower than that of the first spawning, and flow rates higher than 12000 m^3/s accounted for 52.9%, those higher than 15000 m^3/s accounted for 17.6%, and a flow rate higher than 179300 m^3/s occurred only once, on November 1, 2000.

4.2 Changes in the spawning grounds of Chinese sturgeon

Before the closure of the Gezhouba Dam Water Conservancy Project, the spawning grounds of the Chinese sturgeon extended from the lower reaches of the Jinsha River to the upper reaches of the Yangtze River, and the main spawning grounds, including 19 different spawning grounds, were concentrated from Pingshan to Hejiang (YARSG,1988).

After the closure of the Gezhouba Dam, the Chinese sturgeon formed a new spawning ground downstream of the Gezhouba Dam. Many scholars have studied the distribution of the new spawning ground of Chinese sturgeon by means of the anatomy of egg-eating fish, ultrasonic telemetering and tracing, and egg harvesting at the bottom of the river (Wei et al., 1997; Wei et al., 2009; Yang et al., 2006). During 1983-1995, the range of the spawning ground of the Chinese sturgeon extended from the Gezhouba Dam to Xiaoting, with a length of approximately 30 km, with spawning mainly concentrated in the approximately 12-km reach between the Gezhouba Dam and Yanzhiba Islet (Hu et al., 1992; Yu, Xu, & Deng, 1986).

Over the period 1996-2007, the spawning ground was the main channel of the Yangtze River from the Gezhouba Dam to approximately 2 km upstream of Yanzhiba Islet, and the main spawning site was within the approximately 4-km reach from the Gezhouba Dam to Miaozui (Yang et al., 2006; Zhang et al., 2011). The spawning area could be divided into two parts, the upstream spawning area and downstream spawning area, and the spawning times and scale of the downstream spawning area were obviously larger than those of the upstream spawning area (Wei, 2003; Zhang et al., 2011). Because the spawning date was mainly concentrated in October, the spawning flow rate was high, the suitable area of the upstream spawning area was small, and the upstream spawning area did not feature favourable locations for the Chinese sturgeon to perch; thus, the Chinese sturgeon primarily chose to spawn in the downstream spawning area.

All the natural reproduction of Chinese sturgeon has occurred in the upstream spawning area since 2008 (Du at el., 2015; Wu et al., 2017), which was also the main research area of this paper. Since 2008, the natural reproduction date of Chinese sturgeon has been postponed to middle and late November, or even early December, when the flow rates were less than 10000 m^3/s. The suitable area of the upstream spawning ground was large. Thus, because the Chinese sturgeon migrates upstream for reproduction, the Chinese sturgeon chose to reproduce in the upstream spawning ground.

4.3 Factors affecting spawning of Chinese sturgeon

According to current research, the riverbed topography, bottom substrate, velocity, water temperature, water level, flow rate, sediment content and other factors are thought to affect the spawning of Chinese sturgeon. Some researchers emphasize the important role of water level (YARSG,1988). Other researchers suggest that the changes in riverbed bottom substrate may have caused positional changes in the critical spawning ground of Chinese sturgeon (Du et al., 2011; Du et al., 2015). Some researchers believe that the delay in the decrease in water temperature caused by the Three Gorges Reservoir and the low numbers of reproductively mature individuals have contributed to the failure in natural breeding (Chang, Lin, Gao, Liu, Duan, & Liu, 2017; Tao, Wang, Wang, Wu, & Ni. 2018).

This study focused on flow velocity because the natural reproduction of Chinese sturgeon requires suitable flow conditions in the spawning ground, and the fish can directly feel the velocity. In addition, the flow velocity can be optimized through changes in reservoir operation and the opening mode of dam units. In contrast, other factors are difficult for humans to change. To protect the Chinese sturgeon, we identified an operational mode that can improve the flow conditions of the spawning ground. However, other factors should also be studied in the future because these factors may work together.

4.4 Suitable water flow conditions for Chinese sturgeon

To determine the suitable flow velocity of Chinese sturgeon, many scholars have chosen different methods. Some researcher, through field measurements and historical data, concluded that the Chinese sturgeon chose an area with a flow velocity of 0.62~1.16 m/s when spawning (Chen, 2007). The hydrological data and the measured data of the spawning grounds of the Chinese sturgeon downstream of the Gezhouba Dam were analysed, and the Tennant method was used to calculate the velocity range of 1.0~2.0 m/s (Ban, 2009). Some scholars measured the spawning days of the Chinese sturgeon on site and concluded that the suitable flow rate range for Chinese sturgeon was 1.07~1.65 m/s (Wei, 2003). Some researchers measured the velocity in the spawning ground by ADCP and found that the average velocity of the spawning ground was 0.73~1.75 m/s (Zhang et al., 2007). Some researchers used a numerical model to retrieve the flow field of historical detection days and concluded that the suitable velocity range of Chinese sturgeon was 1.1~1.7 m/s (Yang, Tan, Chang, & Yan, 2007). Some researchers simulated the spawning ground of Chinese sturgeon and concluded that the most suitable velocity range was 0.97~1.48 m/s (Wang, Dai, & Dai, 2013). Other researchers thought a velocity of 1.06–1.56 m/s was highly suitable ranges for spawning of the Chinese sturgeon (Yi, Sun, & Zhang, 2016). These results confirmed the preference of the Chinese sturgeon for a certain flow velocity while spawning, but the obtained suitable ranges differ due to differences in research precision and methods.

This study established a three-dimensional numerical model of the spawning ground of the Chinese sturgeon downstream of the Gezhouba Dam. The opening mode of the dam units was considered in detail, and the model was used to simulate the flow field of the Chinese sturgeon monitored in the field. The results showed that most of the sturgeon signals appeared in the velocity range of 0.6~1.5 m/s. Therefore, this range was treated as the velocity threshold of the Chinese sturgeon, and it had a certain degree of agreement with the ranges proposed by most other researchers .

5 CONCLUSIONS

Based on monitoring results from 2016-2019, the FLOW-3D model was used to simulate the flow field of monitored sturgeon signals, and it was concluded that the preferred velocity range for the Chinese sturgeon was 0.6-1.5 m/s. Under a given flow rate, the suitable velocity area was the largest when all units of the Dajiang Plant of the Gezhouba Dam were open, and conditions were more favourable when units on the left side were open. Under different flow rates, when the flow rate was less than 12000 m^3/s, the proportion of suitable area fluctuated slightly at approximately 96.2%, and when the flow rate reached 12000 m^3/s, the suitable area decreased rapidly with increasing flow rate. Moreover, for different opening modes at high flows, at flow rates of 12000 ~ 13000 m^3/s, opening 11~12 units on the left side was best; at a flow rate of 14000 m^3/s, opening 12~13 units on the left side was best; and when the flow rate reached 15000 m^3/s, opening 14 units was best. The optimal scheme for the opening mode of the units at different flow rates was analysed, and the results provide new ideas for Chinese sturgeon protection and ecosystem protection.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

REFERENCES

Ban, X. (2009). Study on Physical Habitat Model and Ecological Water Requirement of Chinese Sturgeon Spawning Ground (in Chinese with English abstract). Wuhan University:Wuhan, China.

Ban, X., Gao, X., Diplas, P., Xiao, F., & Shi, X. T. (2018). Suitability analysis of three-dimensional hydraulic factors for spawning habitat of Chinese sturgeon. *Advances in Water Science*, 29(1),80-88 (in Chinese with English abstract).

Belcher, E., Hanot, W., & Burch, J. (2002). Dual-Frequency Identification Sonar (DIDSON) Proceedings of the 2002 International Symposium on Underwater Technology.

Bi X, Tian ZF, & Yang MF. (2016). Influence of different operation modes of Gezhouba Hydropower Station on flow conditions of Chinese sturgeon's spawning ground(in Chinese with English abstract). *Yangtze River*, 47(17), 25-29.

Booker, D. J. (2003). Hydraulic modelling of fish habitat in urban rivers during high flows. *Hydrological Processes*, 17(3), 577-599.

Celik, I. B., Ghia, U., Roache, P. J., Freitas, C. J., Coleman, H., & Raad, P. E. (2008). Procedurefor estimation and reporting of uncertainty due to discretization in CFD applications. *J. Fluids Eng. Trans.* ASME 130(7), 0780011–0780014.

Chang, J. B. (1999). Change trend of composition characteristic and number of Chinese Sturgeon propagation colony (in Chinese with English abstract). Institute of hydrobiology Chineseacademy of sciences: Wuhan, China.

Chang, J. B., &Cao, W. X. (1999). History and prospect of conservation on the Chinese Sturgeon in the Yangtze River (In Chinese). *Acta Hydrobiologica Sinica*, 23, 713–720.

Chang, T., Lin, P. C., Gao X., Liu F., Duan Z. H., & Liu H. Z. (2017). Using adaptive resolution imaging sonar to investigate Chinese sturgeon (Acipenser sinensis Gray, 1835) behavior on its only spawning ground in the Yangtze River. *Journal of Applied Ichthyology Volume*: 33, Issue, 4, 681-688.

Chen, S. C., & Tfwala S. S. (2018) Performance Assessment of FLOW-3D and XFlow in the Numerical Modelling of Fish-Bone Type Fishway Hydraulics, 7th International Symposium on Hydraulic Structures.

Chen, Y. B. (2007). Study on Ecological Hydrological Mechanism and Protection Countermeasures of Three Gorges Reservoir Affecting the Breeding of Chinese Sturgeon (in Chinese with English abstract). Institute of Aquatic Biology, Chinese Academy of Sciences: Wuhan, China.

Du, H., Wei, Q. W., Zhang, H., Wang, C. Y., Wu, J. M., &Shen, L. (2015). Changes of bottom substrate characteristics in spawning ground of Chinese sturgeon downstream the Gezhouba Dam from impounding of three gorge reservoir (in Chinese with English abstract). *Acta Ecologica Sinica*, 35(9), 3124-3131.

Du, H., Wei, Q. W., Zhang, H., Liu, Z. G., Wang, C. Y., & Li, Y. H. (2011). Bottom substrate attributes relative to bedform morphologyof spawning site of Chinese sturgeon (Acipenser sinensis) below the Gezhouba dam. *J. Appl. Ichthyol.* 27, 257–262.

Flow Science (2012). *Flow-3D User Manual: v10.1*, Flow Science, Inc.

Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics*, 39(1), 201-225.

Hirt, C. W., & Sicilian, J. M. (1985). A porosity technique for the definition of obstacles in rectangular cell meshes. Proceeding 4th International Conference on Numerical Ship Hydrodynamics.

Hu, D. G., Ke, F. E., Zhang, G. L., Luo, J. D., & Gong, M. H. (1992). Investigation and Study on Spawning Ground of Chinese Sturgeon under Gezhouba Dam (in Chinese with English abstract). *Freshwater Fisheries*, 5, 6-10.

Huang, M. H., Guo, H., Xing, L. H., Jiang, W., & Yang, W. (2013). Influence of Gezhouba Project Dispatching on the Flow Condition of Chinese Sturgeon's Spawning Ground (in Chinese with English abstract). *Journal of Yangtze River Scientific Research Institute*, 30(8),102-107.

Mao, J. Q., Li, Z., Dai, H. C., & Ke, Y. (2014). Short-term Hydrodynamic feature of Chinese sturgeon spawning ground under reservoir regulation conditions (in Chinese with English abstract). *Journal of Drainage and Irrigation Machinery Engineering*, 32(5), 399-403.

Moukalled, F., Mangani, L., & Darwish, M. (2015). The Finite Volume Method in Computational Fluid Dynamics. Springer International Publishing.

Shen, Y. X., Wang, P. F., Wang, C., & Yang, Y. (2017). Potential causes of habitat degradation and spawning time delay of the Chinese sturgeon (Acipenser sinensis). *Ecological Informatics Volume*, 43, 96-105.

Su W. (2017). Numerical Simulation of Hydrodynamic Interaction between Head-on Ship-ship Based on FLOW3D (in Chinese with English abstract). Wuhan University of Technology, Wuhan, China.

Tan, X. C. (2002). Hydroacoustic surveys on spawning stock of Acipenser sinensis in the Yangtze River and planktivorous carps in the East Lake (in Chinese with English abstract). Institute of hydrobiology Chinese academy of sciences: Wuhan, China.

Tao, Y. W., Wang Y. K., Wang D., Wu J. C., & Ni L. L. (2018). Changes of water temperature under dam of Three Gorges Reservoir and its effect on fish spawning. *Journal of Hydroelectric Power*, 37(10), 48-55.

Tao, J. P., Qiao, Y., Tan, X. C., & Chang, J. B. (2009). Species identification of Chinese sturgeon using acoustic descriptors and ascertaining their spatial distribution in the spawning ground of Gezhouba Dam (in Chinese). *Chinese Sci Bull*, 54(19), 2975-2982.

Tao, J., Chen, K. Y., & Wang, D. S. (2017). Three-dimensional flow characteristics of spawning ground of Chinese sturgeon (in Chinese with English abstract). *Journal of Hydraulic Engineering*, 48(10), 1250-1259.

Wang, Y. K. & Xia, Z. Q. (2010). Three-dimensional Hydraulics Characteristics of Chinese Sturgeon Spawning Site in the Yangtze River (in Chinese with English abstract). *Journal of Sichuan University: Engineering Science Edition*, 42(1), 14-19.

Wang, H. Z., Tao, J. P., & Chang, J. B. (2019). Endangered Levels and Conservation Options Evaluations for Chinese Sturgeon, Acipenser sinensis Gary (in Chinese with English abstract). *Resources and Environment in the Yangtze Basin*, 28(09), 2100-2108.

Wang, L. H., & Huang, Z. L. (2020). What is actually the main cause for the survival crisis of Chinese sturgeon (in Chinese with English abstract)? *Journal of lake sciences*, 32(4), 924-940.

Wang, Y. K., Xia, Z. Q., & Wang, D. (2012) Characterization of hydraulic suitability of Chinese sturgeon (Academensor sinensis) spawning habitat in the Yangtze River. *Hydrological Processes*, 26(23), 3489-3498.

Wang, Y., Dai, H. C., & Dai, L.Q. (2013). Hydrodynamic characteristics of spawning ground of Chinese sturgeon after impoundment operation of the Three Gorges Reservoir (in Chinese with English abstract). *Journal of Hydroelectric Engineering*, 32(6), 122-126.

Wei, Q. W. (2003). Assessment of reproductive behavior ecology and resources of Chinese sturgeon (in Chinese with English abstract). Institute of Hydrobiology, Chinese Academy of Sciences: Wuhan, China.

Wei, Q. W., Ke, F. E., Zhang, J. M., Zhuang, P., Luo, J. D., Zhou, R.Q., & Yang, W. H. (1997). Biology, fisheries, and conservation of sturgeons and paddlefish in China. *Environment Biology Fish*, 48, 241–255.

Wei, Q. W., Yang, D. G., Ke, F. E., Kynard, B., & Micah, K. (1998). Technique of ultrasonic telemetry for Chinese Sturgeon, Acipenser sinensis, in Yangtze River (in Chinese with English abstract). *Journal of Fisheries of China*, 22, 211–217.

Wei, Q. W., Kynard, B., Yang, D. G., Chen, X. H., Du, H., Shen, L., & Zhang, H. (2009). Using drift nets to capture early life stages andmonitor spawning of the Yangtze River Chinese sturgeon(Acipenser sinensis). *J. Appl. Ichthyol*. 25(Suppl. 2), 100–106.

Wu, F. Y., & Fu, X. L. (2007). The 3-D flow field numerical simulation of Acipenser Sinensis' spawning sites in Gezhouba downstream (in Chinese with English abstract). *Journal of Hydroelectric engineering*, 26(2), 114-118.

Wu, J. M., Wang, C. Y., Zhang, S. H., Zhang, H., Du, H., Liu, Z. G., & Wei, Q. W. (2017). From continuous to occasional: Small-scale natural reproduction of Chinese sturgeon occured in the Gezhouba spawning ground (in Chinese with English abstract). *Journal of Fishery Sciences of China,* 24(3), 425-431.

Xie, H. B., & Xu, H. Q. (2009), Operation Stability of Gezhouba Hydropower Station after its Capacity Increasing (In Chinese). *Large Electric Machine and Hydraulic Turbine*, 6(5), 39-43.

Yang, D. G., Kynard, B., Wei, Q. W., Chen, X. H., Zheng, W. D., & Du, H. (2006). Distribution and movement of Chinese sturgeon, Acipenser sinensis, in spawning ground located below the Gezhouba Dam during spawning seasons. *J. Appl. Ichthyol*. 22(Suppl. 1), 145–151.

Yang, D. G., Wei, Q. W., Chen, X. H., Liu, J. Y., Zhu, Y. J. & Wang, K. (2007). Hydrology status on the spawning ground of Acipenser sinensis below the Gezhouba Dam and its relation to the spawning run (in Chinese with English abstract). *Acta Ecologica Sinica*, 27, 862–869.

Yangtze Aquatic Resources Survey Group (YARSG). (1988) The biology of the sturgeons and paddlefish in the Yangtze River and their artificial propagation (in Chinese) . Sichuan Scientific and Technical Publishing House, Chengdu, China.

Yi, Y. J., Sun, J., & Zhang, S. H. (2016). A habitat suitability model for Chinese sturgeon determined using the generalized additive method. *Journal of Hydrology Volume*: *5*34, pp 11-18

Yu, Z. T., Xu, W. X., & Deng, Z. L. (1986). Study on reproductive ecology of Chinese sturgeon (Acipenser sinensis) in the downstream of Gezhouba hydroelectric project (in Chinese). Transactions of the Chinese Ichthyologic Society, the Chinese Ichthyological Society (Ed.). Science Press, Beijing, 1–14.

Zhang, H., Wei, Q. W., Kynard, B., Du, H., Yang, D. G., & Chen, X.H. (2011). Spatial structure and bottom characteristics of theonly remaining spawning area of Chinese sturgeon in the Yangtze River. *J. Appl. Ichthyol*. 27, 251–256.

Zhang, H., Wei, Q. W., Yang, D. G., Du, H., Zhang, H. J., & Chen, X. H. (2007), Preliminary observation of natural propagation velocity field of Chinese sturgeon under Gezhouba dam (in Chinese with English abstract). *Chinese Fisheries Science*, 14(2), 183-191.

Zhao, R. H. (1991). Reservoir Regulation of Gezhouba Water Control Project (in Chinese). *Central China Electric Powe*r, 2, 24-29.

Tables

Table 1 Calculation cases with different opening modes of units under the same flow rate

Case No.	Opening mode of units	Flow rate of each unit (m^3/s)
1	Open 7 units according to the actual situation, #8, #11, #13, #14, #16, #19, #21	516.6
2	Open 7 units on the left, #15~21	516.6
3	Open 7 units on the right, #8~14	516.6
4	Open 5 units on the right, #8~12	723
5	Open 5 units on the left, #17~21	723
6	Open 14 units, #8~21	258.3

Table 2 Calculation cases with the same opening mode under different flow rates

Case No.	Flow rate (m^3/s)	Opening mode of units	Flow rate of each unit (m^3/s)
1	5590	Open 14 units, #8~21	243.2
2	6000	Open 14 units, #8~21	252
3	7000	Open 14 units, #8~21	294
4	8000	Open 14 units, #8~21	336
5	9000	Open 14 units, #8~21	378
6	10000	Open 14 units, #8~21	420
7	11000	Open 14 units, #8~21	462
8	12000	Open 14 units, #8~21	504
9	13000	Open 14 units, #8~21	546
10	14000	Open 14 units, #8~21	588
11	15000	Open 14 units, #8~21	630
11	16000	Open 14 units, #8~21	672
12	17000	Open 14 units, #8~21	714
13	17930	Open 14 units, #8~21	753
14	>17930	Open 14 units, #8~21	825

Table 3 Calculation cases with different opening modes under high-flow conditions

Case No.	Flow rate (m^3/s)	Opening mode of units	Flow rate of each unit (m^3/s)
1	12000	Open 9 units on the left, #13~21	784.0
2	12000	Open 10 units on the left, #12~21	705.6
3	12000	Open 11 units on the left, #11~21	641.5
4	12000	Open 12units on the left, #10~21	588.0
5	12000	Open 13 units on the left, #9~21	542.8
6	13000	Open 10 units on the left, #12~21	764.4
7	13000	Open 11 units on the left, #11~21	694.9
8	13000	Open 12 units on the left, #10~21	637.0
9	13000	Open 13 units on the left, #9~21	588.0
10	14000	Open 10 units on the left, #12~21	823.2
11	14000	Open 11 units on the left, #11~21	748.4
12	14000	Open 12 units on the left, #10~21	686.0
13	14000	Open 13 units on the left, #9~21	633.2
14	15000	Open 11 units on the left, #11~21	801.8
15	15000	Open 12 units on the left, #10~21	735.0
16	15000	Open 13 units on the left, #9~21	678.5
17	16000	Open 12 units on the left, #10~21	784.0
18	16000	Open 13 units on the left, #9~21	723.7
19	17000	Open 13 units on the left, #9~21	768.9
20	17930	Open 13 units on the left, #9~21	811.0

Figure legends

Figure 1 Location of the study area. (a) Location of Yangtze River and Hubei Province in China; (b) Location of the Gezhuba Dam in Hubei Province, where is shown in red; (c) General condition of the field survey and location of the cross-sections (CS1~CS6); (d) Location of the units of the Dajiang Plant and the underwater topographic map of study area.

Figure 2 Plots of the measured and model values for cross-sections 1~6 (Figure 1c)

Figure 3 Plots of frequency for the different flow velocity ranges of Chinese sturgeon signals.

Figure 4 The flow field of the spawning ground under different opening modes with the same flow rate, where the numbers at the top of each picture are the number of the unit to open, and the arrows indicate the direction of water flow.

Figure 5 The proportions of suitable velocity area with all units opened under different flow rates.

Figure 6 The proportions of suitable area for different opening modes under high-flow conditions, where the 12000-09 on the x-axis means that the flow rate is 12000 m^3/s and 9 units are open on the left.

Figure 7 Spawning date of the Chinese Sturgeon downstream of the Gezhouba Dam

Figure 8 The daily flow rate of the Chinese sturgeon during the spawning day downstream of the Gezhouba Dam.