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The influence of cascade hydropower development on the hydrodynamic conditions impacting the reproductive process of fish with semi-buoyant eggs

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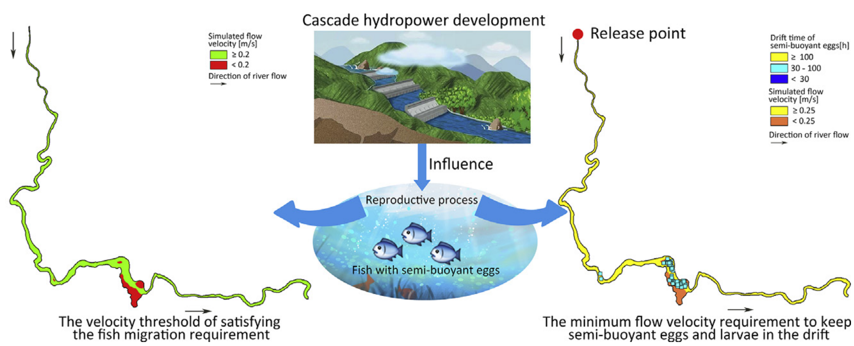
HIGHLIGHTS

- It is difficult to form a fish migration passage in the reservoir in all potential scenarios.
- Semi-buoyant eggs and larvae sank to the bottom and perished before they hatched and were old enough to survive.
- It is possible that fish with semi-buoyant eggs can reproduce successfully after the protection of the tributary.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydropower projects have changed the physical habitat of rivers, which has a serious impact on the survival of local fish. The reproduction of fish producing semi-buoyant eggs requires a specific hydrodynamic condition. To predict the influence of cascade hydropower development on the reproductive process of fish with semi-buoyant eggs, a MIKE 21 Flow Model was applied. Lagrangian particle tracking was used to simulate the movement of semi-buoyant eggs and larvae using the Agent-based Modeling (ABM) lab module. The calibrated model showed good agreement between the simulated and observed data for the hydrodynamic process in the reservoir. Twelve scenarios were defined to fully understand whether fish with semi-buoyant eggs can reproduce naturally. The results showed the following: (1) It is difficult to form a fish migration passage in the reservoir in all potential scenarios. (2) Semi-buoyant eggs and larvae sank to the bottom and perished before they hatched and were old enough to survive, since the hydrodynamic conditions could not meet the minimum flow velocity required to keep them in the drift. (3) Even if the hydrodynamic conditions can keep them in the drift in impossible high-discharge conditions, there was not enough drifting time and distance in the reservoir. The results implied that fishes with semi-buoyant eggs cannot reproduce naturally in the main stream, but it is possible that they can reproduce successfully after the protection of the tributary. The method is transferrable to other locations via establishment of models with relevant data to a particular area.

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1. Introduction

Lack of fish habitat protection is one of the most prominent problems in river hydropower development. Construction of cascaded hydropower stations disrupt the connectivity among river channels and changes the natural flood pulse pattern [Barros and Rosman, 2018; Tiemann et al., 2004; Yi et al., 2010]. Changes in the hydraulics have a serious impact on the survival and reproduction of local fish, especially for fish with semi-buoyant eggs, whose survival and reproduction require a specific hydrodynamic condition [Cheng et al., 2015; Fu et al., 2003; Liu et al., 2012; Tan et al., 2016]. To prevent such significant problems, it is necessary to thoroughly assess the potential impacts of cascade hydropower development on the reproductive process of fish with semi-buoyant eggs.

Fish populations are highly dependent on the characteristics of the aquatic habitat, which supports all their biological functions [Larinier, 2001]. In the early 1940s, it was gradually realized that the construction of water conservancy facilities would lead to the reduction of fishing grounds, and extensive research has been carried out concerning the relationship between the environmental flow and water demand of fish [Larinier, 2001; Murchie et al., 2008; Nilsson and Svedmark, 2002; Petts, 1984; Porcher and Travade, 1992; Tharme, 2003]. With a deepening study on the ecological impact of the hydropower project on aquatic organisms, the influence of the change in river flow conditions on fish survival has been paid increasing attention [Qin et al., 2014; Wilde, 2006]. It has been proven that high flowrate in the reproduction period is one of the main factors that promote the migration of migratory fish upstream to spawn [Bonner and Wilde, 2000; Durham and Wilde, 2009; Hoagstrom et al., 2008; Wilde and Durham, 2008]. Numerous studies have demonstrated that the water current provides the primary orientation cue for fluvial fish migration [Aldven et al., 2015; Baigún et al., 2007; Xu et al., 2017]. When the flow velocities were lower than the fish requirement and could not offer orientation cues for migration, migratory fish failed to complete their migration [Hinch and Rand, 2000; Smith et al., 2005; Tao et al., 2015; Xu et al., 2016]. Furthermore, maintaining the larval drift process is fundamental for the conservation of a great number of migratory fish [Barros and Rosman, 2018; Barthem et al., 2014]. The eggs and very young larvae of fish with semi-buoyant eggs are slightly heavier than water. To survive, semi-buoyant eggs must remain suspended in the water, supported by the turbulence of the flow, until they hatch and develop the ability to swim [Kocovsky et al., 2012; Kolar et al., 2007; Murphy and Jackson, 2013; Tatiana et al., 2015; Workgroup, 2010]. In addition, fish eggs need enough drifting distance in the reservoir; otherwise, the hatching rate of eggs will reduce and the early mortality of larvae will increase. However, the drifting distance of semi-buoyant eggs used to be determined by empirical formulas; quantitative computation by mathematical models should be a more accurate method for forecasting the trajectories of semi-buoyant eggs with travel time.

Construction of dams on rivers change natural flood regimes, patterns of biological production and distribution of organisms in space and time [Marques et al., 2018]. A considerable percentage of migratory fishes can seek out alternative migration routes in the tributaries downstream on encountering dams, especially in the rivers close by [Antonio et al., 2007]. Thus, the conservation of non-regulated tributaries is important as an alternative route for reproductive migration because these watercourses have not had their hydrological regime and physical and chemical conditions of the water changed [Freitas et al., 2013; Pelicice and Agostinho, 2008; Sato et al., 2005; Weber et al., 2013]. In addition, nearby tributaries can function as source areas, minimizing the ecological impact of damming on the fish assemblages [Marques et al., 2018]. Therefore, the preservation of the tributaries is imperative since they contribute to diversity maintenance and should be considered in further impoundment projects [Marques et al., 2018].

Mathematical models are valuable tools for better understanding various physical, chemical, and biological interactions in the aquatic system [Li et al., 2016; Paliwal and Patra, 2011]. MIKE 21 is a comprehensive modeling system for the simulation of hydraulics and hydraulic-related phenomena in water environments, such as rivers, reservoirs, estuaries, bays, coastal areas and seas [Warren and Bach, 1992]. Furthermore, the Lagrangian particle tracking method can be coupled with hydrodynamic models to simulate the transport of fish eggs, but the minimum flow velocity required to keep semi-buoyant eggs in the drift, the settling speed of eggs and the time required for eggs to hatch were rarely considered in previous research.

The Jinsha River is found in China and it is the upper reach of the Yangtze River. It is known as an important spawning ground and hatchery for fish, and its natural flow condition is the basis for the survival and reproduction of fish with semi-buoyant eggs. The species of fish with semi-buoyant eggs in the study area was shown in Table 1 [Duan et al., 2015]. In recent decades, comprehensive large-scale cascade hydropower stations have been rapidly developed and utilized in China [X Tang and Zhou, 2012]. The Jinsha River will become the world's largest reservoir group, with the length of cascade reservoirs averaging <100 km in the near future. The rate of expansion and scale of construction in Jinsha River are quite rare in world history, and the influence of hydrodynamic condition changes on the reproductive process of fish with semi-buoyant eggs after the completion of the cascade reservoir has drawn great attention.

The purpose of this study was to predict the influence of cascade hydropower development on the reproductive process of fish with semi-buoyant eggs. We hypothesized that fishes with semi-buoyant eggs cannot reproduce naturally in the reservoir under all of the potential operating schemes of the hydropower stations. 12 different operating scenarios were developed based on the MIKE 21 FM model that aided in testing the hypotheses. Lagrangian particle tracking technology based on agent-based models was used to help analyze the trajectories of eggs and larvae based on the travel times. Furthermore, whether fish with semi-buoyant eggs can reproduce successfully after the protection of tributary was discussed. The results of the model-based analysis provide useful information for decision makers regarding the construction and operation of hydrodynamic stations.

Table 1
Species of fish with semi-buoyant eggs in the study area.

Order	Family	Subfamily	Species
Cypriniformes	Cyprinidae	Gobioninae	*Squalidus argentatus*
			Rhinogobio cylindricus
			Rhinogobio ventralis
			Rhinogobio typus
			Coreius heterodon
			Saurogobio dabryi
		Gobiobotinae	*Gobiobotia boulengeri*
			Gobiobotia filifer
		Leuciscinae	*Ctenopharyngodon idellus*
			Mylopharyngodon piceus
			Elopichthys bambusa
		Culterinae	*Pseudolaubuca engraulis*
			Pseudolaubuca sinensis
		Hypophthalmichthyinae	*Hypophthalmichthys molitrix*
			Hypophthalmichthys nobilis
	Homalopteridae		*Lepturichthys fimbriata*
			Jinshaia sinensis
	Cobitidae	Botiinae	*Leptobotia rubrilabris*
			Leptobotia elongata
			Leptobotia taeniops
			Botia superciliaris
			Parabotia fasciata

2. Methods and materials

2.1. Study area

The Jinsha River is approximately 3481 km long and has a vertical drop of approximately 5100 m. It is divided into upper, middle and lower reaches. The range of the middle reach of the Jinsha River is from Shigu town in Yunnan Province to Panzhihua city in Sichuan Province. It is approximately 564 km long and has a vertical drop of 838 m. The Jinsha River has abundant water flow and a large vertical drop, which contains abundant hydroelectric power. Eight hydropower stations are planned in the middle reach of Jinsha River: Longpan, Liangjiaren, Liyuan, Ahai, Jinanqiao, Longkaihou, Ludila and Guanyinyan. So far, except for Longpan hydropower station and Liangjiaren hydropower station, the construction of the other six hydropower stations has been completed (Fig. 1).

The Ludila Reservoir (from Longkaikou hydropower station to Ludila hydropower station) was chosen to predict the influence of cascade hydropower development on the reproductive process of fish with semi-buoyant eggs. The length of Ludila Reservoir is 99 km, and its total storage capacity is 1.78×10^8 m^3. The normal water level for Ludila Reservoir is 1223 m, and the corresponding surface area is 51.7 km^2.

2.2. Hydrodynamic condition required of fish with semi-buoyant eggs

The hydrodynamic condition required of fish with semi-buoyant eggs mainly involves the following two aspects: the velocity threshold of satisfying the fish migration requirement and the minimum flow velocity requirement to keep semi-buoyant eggs and larvae in the drift [Murphy and Jackson, 2013; Tatiana et al., 2015; Xu et al., 2017; Yi et al., 2010].

On the one hand, according to China's national standard on fishway design, the basic flow velocities (rheotactic speeds) of major migration fishes are 0.2 m/s [MWPRPC, 2013]. Therefore, the velocity threshold of satisfying fish migration requirement was defined as 0.2 m/s in this study [Xu et al., 2017]. On the other hand, previous studies suggested that the lower limit to the velocity in spawning rivers was 0.25 m/s, and eggs and larvae will sink to the bottom and perish if the velocity is less than this value [Kolar et al., 2007; Murphy and Jackson, 2013; M Tang et al., 1989; Yi et al., 2010]. Furthermore, according to USGS data, the eggs hatch in approximately 30 h depending on temperature, and the larvae need an additional 70 h before they develop the ability to swim [Workgroup, 2010]. Over all, the flow velocities are required to keep semi-buoyant eggs and larvae in the drift (≥0.25 m/s) for at least 100 h. This estimates of hatching time and time needed to develop the ability to swim were almost the shortest based on limited data in many of the studies, and the accuracy of estimates of times was sufficient for the purposes of this study [Chong et al., 2008; Murphy and Jackson, 2013; Wei et al., 2010].

2.3. Numerical model description

The MIKE 21 modeling system is a two-dimensional mathematical model that was developed for complex applications with oceanographic, coastal, estuarine environments, and inland surface water (e.g., overland flooding and lakes or reservoirs). Agent-based modeling (ABM) is a relatively recent development. It can be used for advanced simulations of behavior and states of individuals or particles in water environments. Detailed information of Mike 21 modeling system and ABM is described in supplementary materials.

2.4. Model configuration

2.4.1. Grid generation

A high-resolution triangle mesh was developed for the Ludila Reservoir (from Longkaikou hydropower station to Ludila hydropower station), as shown in Fig. S1 (Supplementary materials). An unstructured mesh containing a total of 11,491 triangular elements and 6837 nodes is used. Fig. 2 shows the boundary and corresponding underwater terrain of the Ludila Reservoir. The model simulation was implemented with a dynamic time step interval of 240 s, which has been proven to be appropriate to guarantee both the precision and stability of the model.

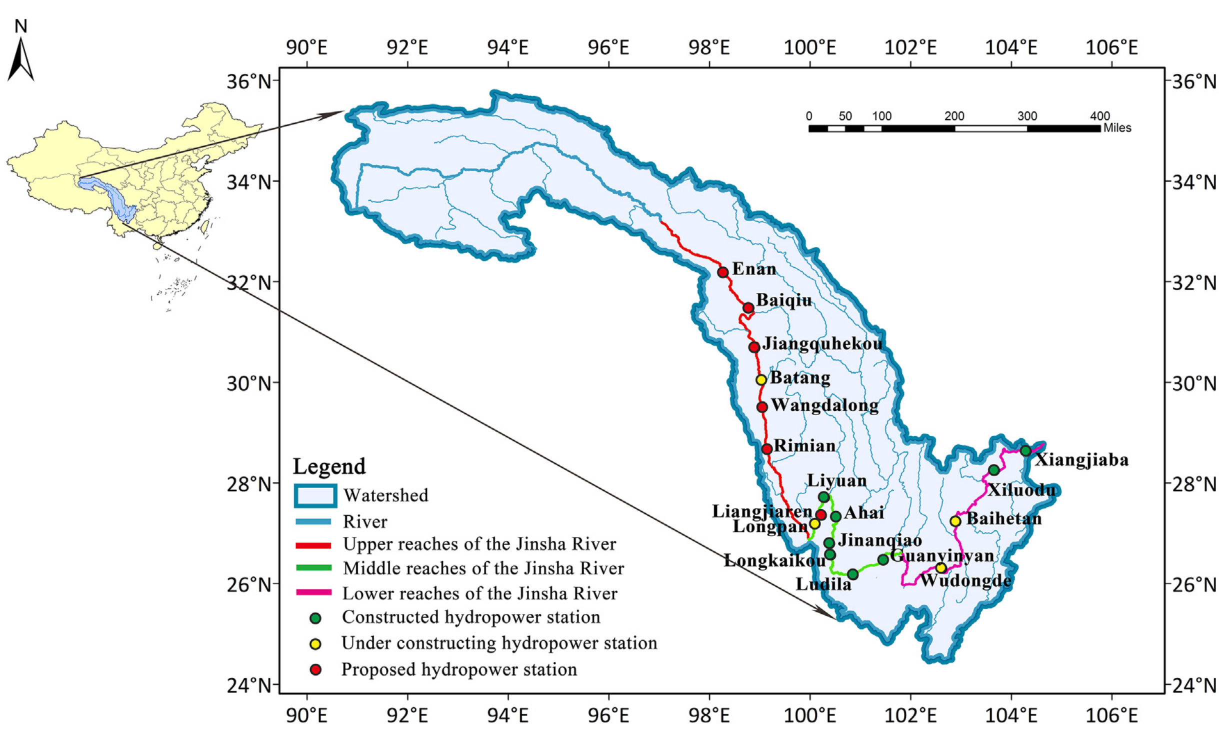

Fig. 1. Location of Jinsha River watershed and the situation of cascade hydropower development.

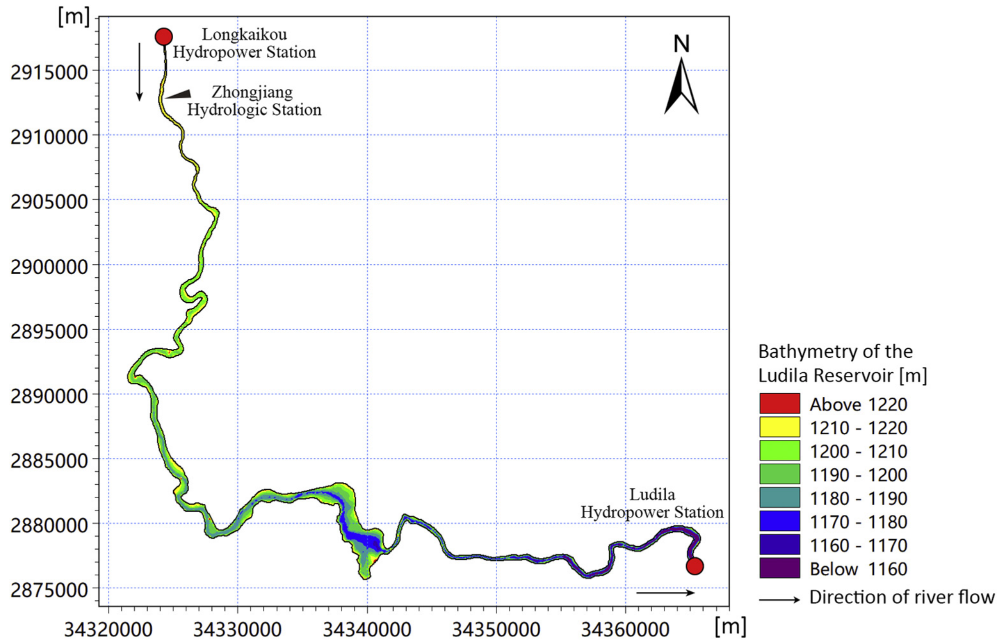

Fig. 2. Bathymetry of the Ludila Reservoir.

2.4.2. Model calibration and validation

In this study, the first half of 2015 was chosen to calibrate the model, and the second half of 2015 was chosen to validate the model with the same calibrated parameters. The models were run for a warm-start period of one month until reaching the steady-state solutions, and then the steady-state solutions were used to represent the initial conditions for the hydrodynamics model. The boundary conditions included the discharge of Longkaikou hydropower station and the water level (WL) of Ludila hydropower station. Time series data for the daily discharge and water level were obtained from the Annual Hydrological Report of the People's Republic of China (Jinsha River Basin). Meteorological data were downloaded from the China Meteorological Data Sharing Service System. Sequential trials have been performed to modify the hydrodynamic parameters until the model error was acceptable.

2.4.3. Lagrangian particle tracking

In this study, the trajectories of the semi-buoyant eggs and larvae were identified using hydrodynamics coupled to a Lagrangian particle movement modeling based on the MIKE 21 Flow Model FM-ABM Lab. We released 100 particles at Longkaikou hydropower station at a time after the flow field reached a stable state. In this case, the horizontal direction of particles was the same as the horizontal current direction, and the horizontal speed of particles was the same as the horizontal current speed. The movement of the agent particles are given as the sum of a displacement determined by the hydrodynamic flow field and a dispersive component as a result of random processes (e.g. turbulence in the water). In addition to the horizontal movement, there is a setting velocity definition that specifies the vertical movement [DHI, 2014]. Since very young larvae have weak swimming abilities, they can be considered to be particles like semi-buoyant eggs [Barros and Rosman, 2018]. According to the minimum flow velocity requirement to keep semi-buoyant eggs and larvae in the drift, the vertical movement of particles was defined as follows: (1) If the flow velocity was ≥0.25 m/s, the particles would drift in the water; (2) If the flow velocity was <0.25 m/s, the settling speed of particles was 0.75 cm/s [Murphy and Jackson, 2013]. The semi-buoyant eggs and very young larvae are thought to die if they settle to the bottom, which allows us to determine their destination in the reservoir [Chapman and George, 2011; Kolar et al., 2007]. We estimated the drifting time of semi-buoyant eggs and larvae based on the total moving time of particles to see if there was enough drifting time for the semi-buoyant eggs to hatch and to develop the ability to swim.

2.5. Scenario definitions

After the two-dimensional hydrodynamic model for Ludila Reservoir was calibrated, it was used to analyze how the hydrodynamic condition would respond to a series of potential operating scenarios of the hydropower stations. Furthermore, the influence of different hydrodynamic conditions on the reproductive process of fish with semi-buoyant eggs was studied.

Two basic scenarios were designed to explore whether fishes with semi-buoyant eggs can reproduce naturally under the conditions of (a) different water discharges of Longkaikou hydropower station; and (b) different operating water levels of the reservoir. The historical mean daily water level and discharge at Zhongjiang Station from 2014 to 2016 are shown in Fig. S2 (Supplementary materials). The normal water level for Ludila hydropower station is 1223 m, and the flood control water level during the flood season is 1212 m. Based on the situations that occur mostly during the operation of the hydropower stations, 12 scenarios are listed in Table 2. For all of the scenarios, the model configurations and parameters, except for the different

Table 2
Potential operating scenarios of the Ludila Reservoir.

Scenarios	Operating water levels of the Ludila Reservoir (m)	Water discharges of Longkaikou hydropower station (m^3/s)
A01	1212	500
A02	1212	2000
A03	1212	4000
A04	1212	6000
B01	1218	500
B02	1218	2000
B03	1218	4000
B04	1218	6000
C01	1223	500
C02	1223	2000
C03	1223	4000
C04	1223	6000

discharges and water levels shown in Table 2, stayed the same for the validated model.

3. Results

3.1. Hydrodynamic calibration

The calibrated hydrodynamic model showed good agreement between the simulated and observed data for the water surface elevation (Fig. 3). The mean absolute errors of the water level simulation were 0.252 m and 0.297 m, and the mean relative errors were 0.021% and 0.024% for the first half and the second half of the year, respectively. This indicated that the model accurately simulated real life systems, and the parameter selection was reasonable.

3.2. Scenario analysis

3.2.1. The impact on migration of fish

Fig. 4 shows the simulated horizontal velocity magnitude in the reservoir in different scenarios. The zone where the simulated flow velocity was ≥0.2 m/s was labeled with a green color (suitable zone for migration), and the zone where the simulated flow velocity was <0.2 m/s was labeled with red color (unsuitable zone for migration). When the water level was 1212 m, the proportion of the suitable migration area increased from 7.67% to 72.82% as the water discharge of Longkaikou hydropower station increased from 500 m^3/s to 6000 m^3/s (Fig. 4a). When the water level was 1218 m, the proportion of the suitable migration area increased from 6.11% to 72.38% as the water discharge of Longkaikou hydropower station increased from 500 m^3/s to 6000 m^3/s (Fig. 4b). When the water level was 1223 m, the proportion of suitable migration area increased from 3.70% to 70.60% as the water discharge of Longkaikou hydropower station increased from 500 m^3/s to 6000 m^3/s (Fig. 4c). However, there was always an unsuitable area (approximately 30% of the total area) in which the flow velocity was lower than 0.2 m/s in all cases. The fish would lose their hydrodynamic orientation cues for migration in this area [Xu et al., 2017]. The results indicated that cascade hydropower development would have an influence on the migration of fish. Fish in the upstream of the unsuitable area were able to migrate to the upstream to spawn successfully, while fish in the downstream of this area may not be able to get through this area for migration in spite of the reservoir operation.

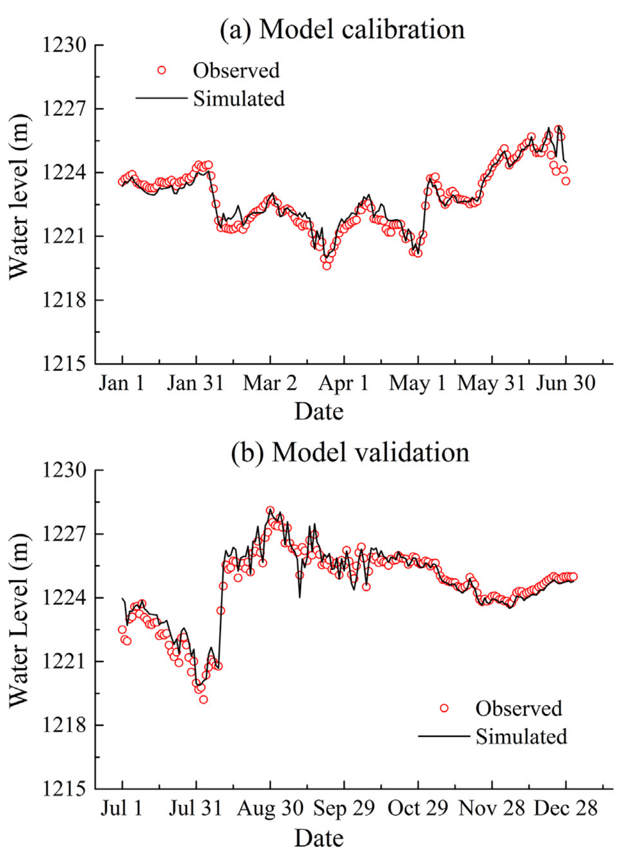

Fig. 3. Simulated and observed water levels at Zhongjiang station (2015).

3.2.2. The impact on the incubation of semi-buoyant eggs

Simulation results of the final state of particles in different scenarios are shown in Fig. 5. Semi-buoyant eggs were represented by particles, and different colors were used to differentiate the evolution times of the fish eggs and larvae. Dark blue particles represented eggs drifting in the reservoir for <30 h. Cyan particles represented eggs drifting in the reservoir ≥30 h but <100 h, which means that the semi-buoyant eggs hatched successfully but the larvae did not develop the ability to swim. Yellow particles represented eggs drifting in the reservoir ≥100 h, and they were old enough to survive without the support of the turbulence of the flow.

As shown in Fig. 5, under the same water level condition of the reservoir, the greater the flow, the longer the semi-buoyant eggs drifted and the farther away they drifted. When the water level was 1212 m, all of the semi-buoyant eggs sank to the bottom after 11 h, 19 h and 29 h when the discharge of Longkaikou hydropower station was 500 m^3/s, 2000 m^3/s and 4000 m^3/s, respectively (Fig. 5a). The drifting time was not enough for the eggs to hatch in these three scenarios. If the flow increased to 6000 m^3/s, the eggs hatched successfully, but the larvae did not develop the ability to swim. The simulated final states of semi-buoyant eggs of water level 1218 m were similar with that of water level 1212 m (Fig. 5b). For water level 1223 m, there was not enough time for eggs to hatch even when the discharge increased to 6000 m^3/s (Fig. 5c).

4. Discussion

4.1. Limiting cases

According to the results of the scenario analysis, even when the discharge of Longkaikou hydropower station increased to 6000 m^3/s, there still existed an area where the velocity was not satisfactory for fish migration and could not keep semi-buoyant eggs and larvae in the drift. Taking the normal water level (1223 m) as an example, we tried to increase the discharge further to explore whether any scenarios exist that meet the requirement of fishes via “trial and error”.

As shown in Fig. 6a, when the discharge increased to 15,000 m^3/s, the reservoir hydrodynamic conditions met the requirements for fish migration. However, there still existed an area in which the hydrodynamic conditions could not keep semi-buoyant eggs and larvae in the drift (the orange area in Fig. 6b). When the discharge increased to 20,000 m^3/s, the reservoir formed a passage in which the hydrodynamic conditions met the requirements for fish migration and could keep semi-buoyant eggs and larvae in the drift. Nevertheless, it took as short as 33 h when the semi-buoyant eggs drifted downstream and began arriving at Ludila hydropower station (Fig. 7a). All of the eggs arrived at Ludila hydropower station within 56 h, with the exception of several eggs that sank to the bottom and perished (Fig. 7b). In conclusion, even if the reservoir hydrodynamic conditions can keep semi-buoyant eggs in the drift in this limiting case, there was not enough drifting time and drifting distance for the semi-buoyant eggs to hatch and develop the ability to swim in the reservoir, let alone the actual discharge of Longkaikou hydropower station could not reach such a high value.

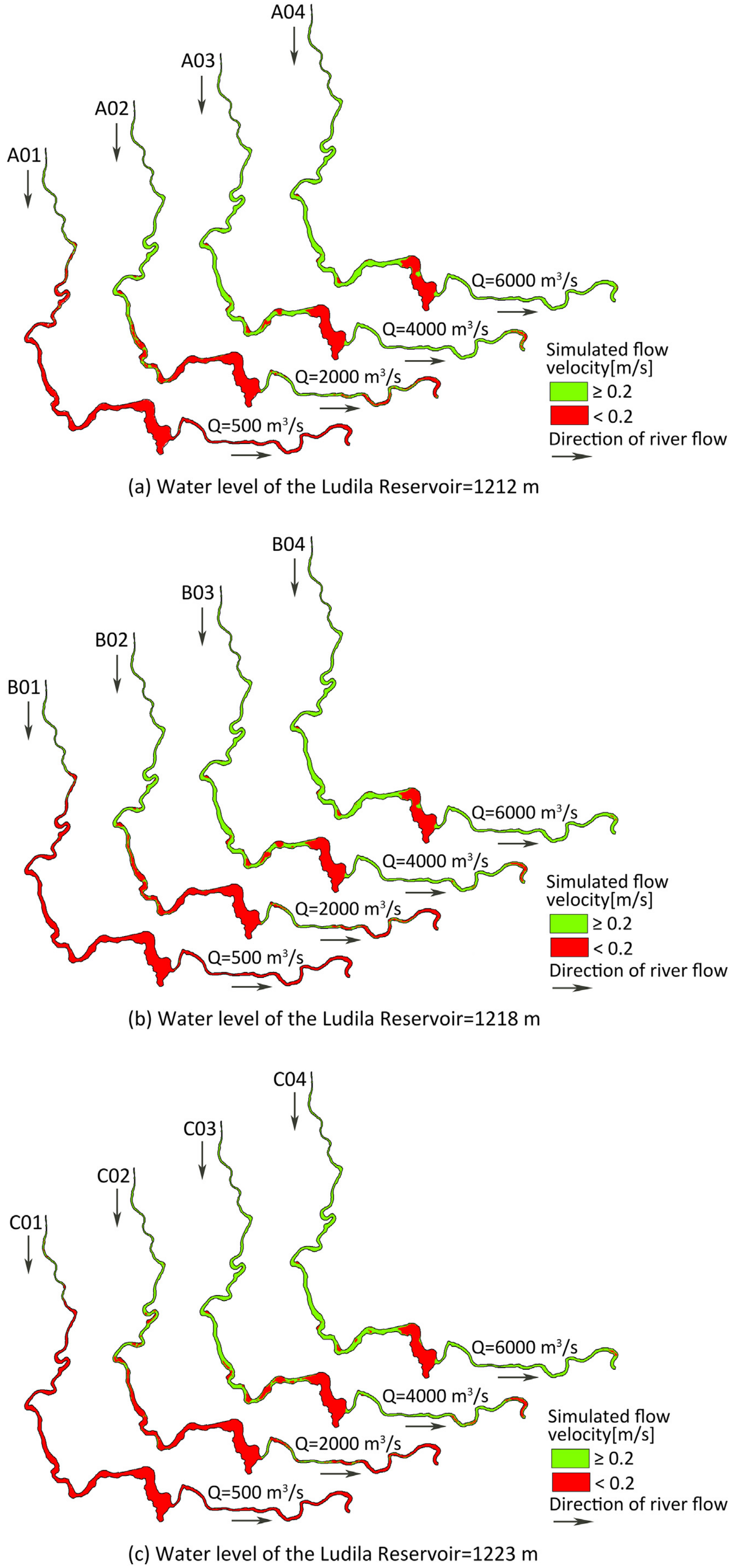

Fig. 4. Hydrodynamic simulation results in the reservoir in different scenarios. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

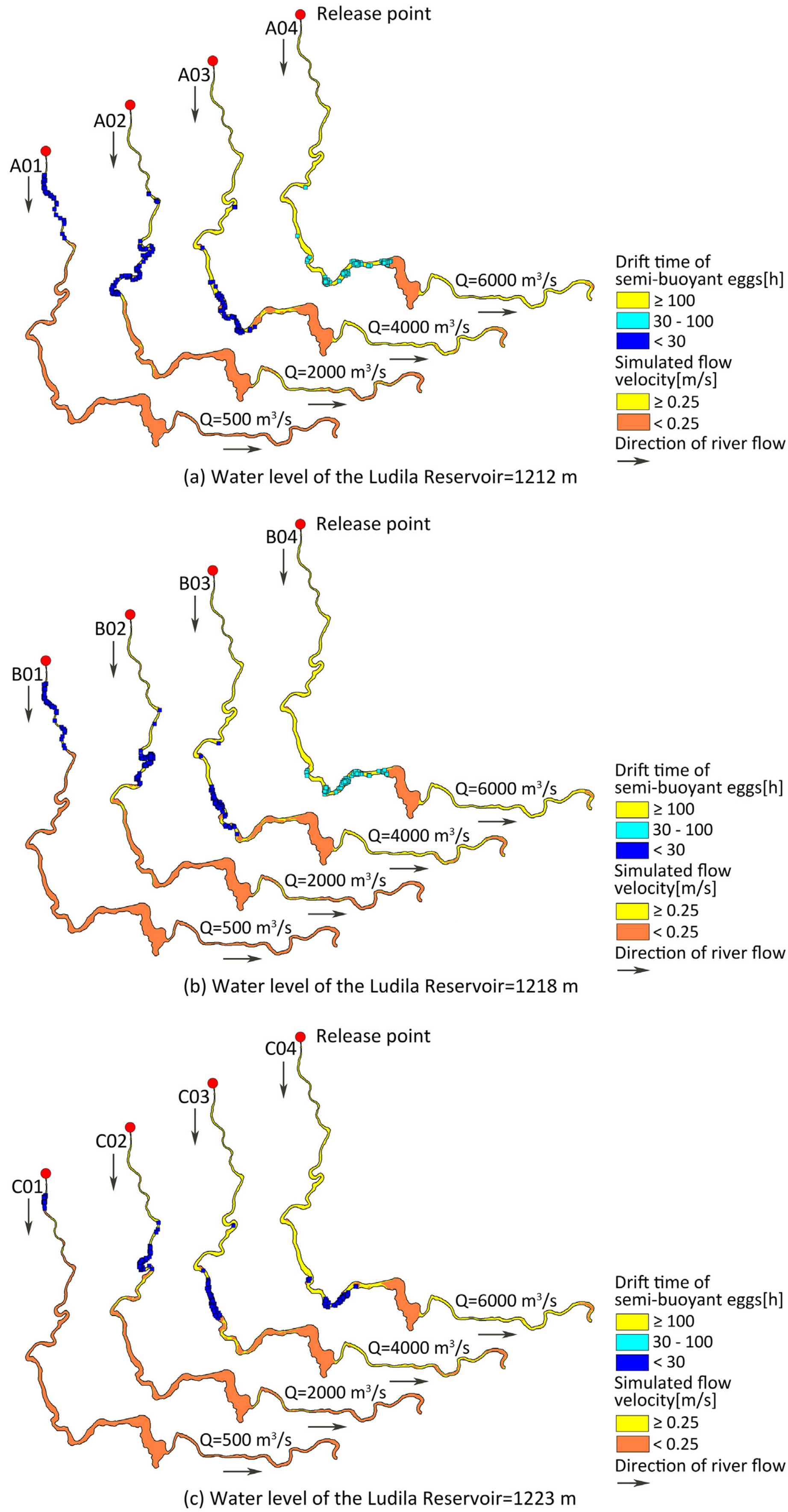

Fig. 5. Final states of semi-buoyant eggs in different scenarios. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

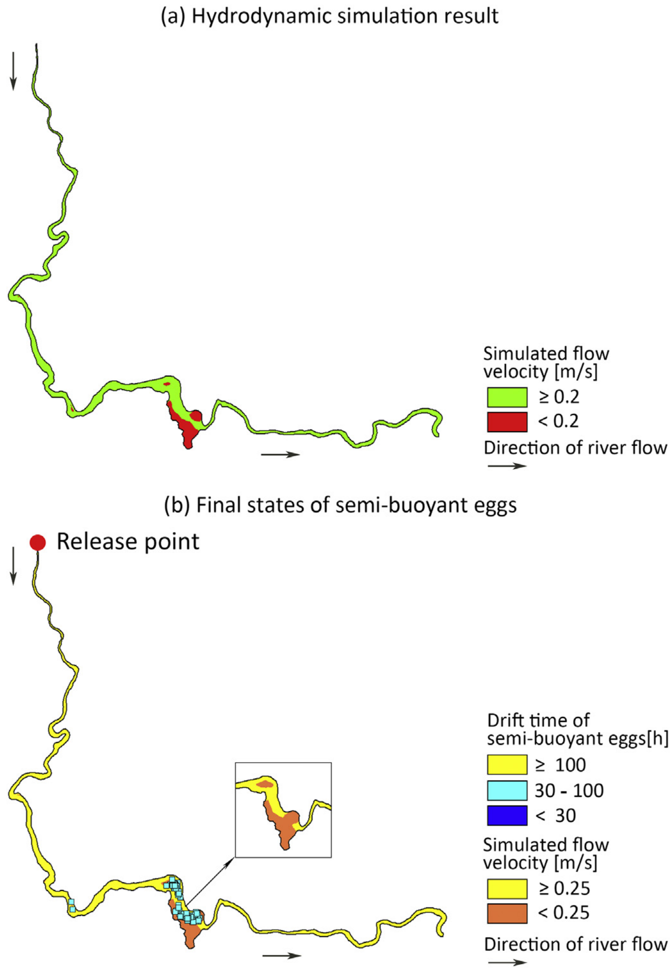

Fig. 6. Hydrodynamic simulation results and final states of semi-buoyant eggs. (WL = 1223 m, Q = 15,000 m^3/s).

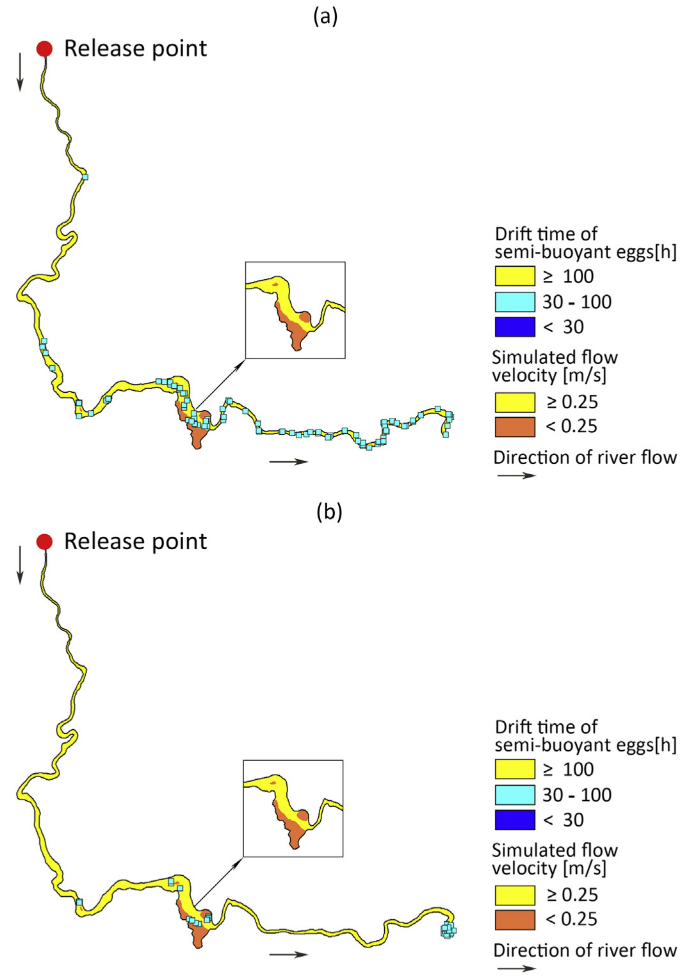

Fig. 7. The states of semi-buoyant eggs. (WL = 1223 m, Q = 20,000 m^3/s). (a) The midway state when the first egg reached Ludila hydropower station, (b) The final state.

4.2. Operation suggestions

Based on the existing scenarios in Table 2, we increased the water discharge further to investigate the relationship between the maximum drifting time of semi-buoyant eggs and the different water discharges. As shown in Fig. 8, when water discharges were ≤6000 m^3/s, the greater the flow, the longer the semi-buoyant eggs drifted under the same water level condition of the reservoir. However, as the discharge increased further, the maximum drifting time of semi-buoyant eggs no longer increased substantially. This was mainly because the area where the flow velocity met the requirement of floating eggs increased as water discharge increased from 500 m^3/s to 6000 m^3/s (As shown in Fig. 5). Nevertheless, there was a relatively wide area in the middle and lower parts of the reservoir, in which the flow velocity could not meet the minimum requirement to keep semi-buoyant eggs and larvae in the drift. In addition, the area where eggs sank changed little as the water discharge became greater than 6000 m^3/s, and this area did not disappear, even when the water discharge increased to an impossibly high value of 15,000 m^3/s (Fig. 6b). Therefore, the maximum drifting time of semi-buoyant eggs remained nearly constant or declined slightly when water discharge further increased.

Except for the issues discussed above, previous research have showed that five days represents maximum time that eggs and larvae passively drift before larvae develop air bladders and actively seek suitable nursery habitat, and it is estimated that eggs can be transported up to 216–359 km downstream during 3–5 d of passive drift [Widmer et al., 2012]. Barros and Rosman studied the average drift time of the fish eggs and larvae along almost 130 km of Jirau Reservoir, and the results showed that there are variations between of 1 and 6 days during the months of a typical hydrological year: from 1 to 2 days in March and January, from 2 to 3 days in November, and from 5 to 6 days in September

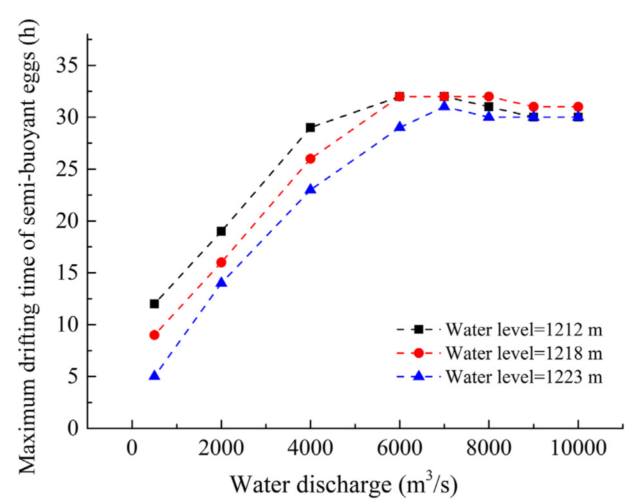

Fig. 8. Maximum drifting time of semi-buoyant eggs for different water levels and discharges.

[Barros and Rosman, 2018]. Garcia et al. presented the FluEgg (Fluvial Egg Drift Simulator) model to predict the drifting behavior of eggs based on the physical properties of the eggs and the hydrodynamic characteristics of the stream. The model predicted that successful transport of Asian carp eggs to the point of hatching is possible in the lower Sandusky River [Garcia et al., 2013]. In addition, a related study showed that when Three Gorges Dam (TGD) regulation scheme with 156 m water level is carried out, hydraulic process in three of four spawning sites is not suitable for spawning of Asian carps. If TGD regulation scheme with 175 m water level is carried out, there will be no enough time and distance for spawn growth before the mid of June, while there will be enough time and distance for spawn growth after the mid of June [Chong et al., 2008].

In this study, semi-buoyant eggs either sank to the bottom and perished before they reached the minimum incubation time, or they did not have time to develop the ability to swim. None of them were old enough to survive in all cases, mainly because there was a relatively wide area in the middle and lower part of the reservoir in which the hydrodynamic conditions could not meet the minimum flow velocity required to keep semi-buoyant eggs and larvae in the drift. The result indicated that the reservoir did not have sufficient hydraulic characteristics to support the successful recruitment of fish with semi-buoyant eggs in all of the potential operating conditions. Even so, the optimum operation suggestion to promote the migration of fish and the incubation of semi-buoyant eggs in the main stream is to reduce the water level and to increase the discharge of the Longkaikou hydropower station in all of the potential operating conditions during fish migration periods, which can help to obtain the maximum migration area for fish and the maximum drifting time of semi-buoyant eggs.

4.3. The need for tributary protection

The massive development of water energy resources in Jinsha River has affected the survival and reproduction of local fish [Cheng et al., 2015; Fu et al., 2003]. In the upper Yangtze River, the construction of the Three Gorges Reservoir alone was thought to threaten 20 endemic species and to cause high extinction risk for six fish species, and cascade hydropower development in Jinsha River may be expected to cause even more-severe effects on fish fauna and biodiversity [Cheng et al., 2015]. For instance, the migratory routes of *C. guichenoti* and *R. ventralis* were blocked with the operation of the Xiangjiaba hydropower project in 2008, whose spawning grounds are distributed exclusively in the Jinsha River and Yalong River [Liu et al., 2012; Tan et al., 2016]. In addition, previous studies have suggested that more than 40 fish species, including 19 endemic to the upper Yangtze River, will be adversely affected by the Three Gorges Dam, Gezhouba, and Jinsha River Cascades Reservoir [Fu et al., 2003; Tan et al., 2016]. It is unlikely that the construction of water conservancy projects are prohibited for the purpose of fish protection, but it is possible that one or two tributaries could be selected to establish nature reserves so that fish can resume a normal life in it [Cao, 2008].

A large number of studies have shown the importance of tributaries downstream from dams to mitigate the impact of dams in migratory fish species [Antonio et al., 2007; Freitas et al., 2013; Marques et al., 2018; Nunes et al., 2015; Pereira Arantes et al., 2011; Weber et al., 2013]. On the one hand, tributaries can act as source habitats in reservoirs, since they harbor spawning and early development grounds for native fish species [Marques et al., 2018]. The ecological impact of dams may be mitigated when there are major tributaries with breeding sites upstream from the reservoirs to serve as nursery habitats for fingerling development [Baumgartner et al., 2004; Pereira Arantes et al., 2011]. On the other hand, tributaries downstream from dams can act as alternative routes for migratory fishes in the eventuality that they do not travel up the reservoir [Antonio et al., 2007; Freitas et al., 2013; Weber et al., 2013]. Recaptures downstream from dam indicated that a considerable percentage of migratory fishes tended to move toward nearby tributaries on encountering obstacles [Antonio et al., 2007]. Some studies have supported this trend, and reported that migratory fishes can successfully use tributaries downstream from dam for spawning [Godinho and Kynard, 2006; Sato et al., 2005]. This behavior can assure the reproduction of populations even when principal migration routes are lost [Antonio et al., 2007]. Thus, keeping tributaries non regulated and conserved is an important tool for diversity maintenance in areas that are already impacted by damming [Marques et al., 2018].

After investigation and comparison, we suggest that the Yanggong River be the preferred tributary for the establishment of a nature reserve. The location of Yanggong River is shown in Fig. S3 (Supplementary materials). Yanggong River is 124 km long, and the natural drop is approximately 1610 m. We recommended that a nature reserve should be established on the whole Yanggong River. In the meantime, clean up the waterway and restoration of the natural flow pattern of the river should be completed. Furthermore, artificial proliferation and releasing can be carried out properly. In this case, if we reduce the water level and increase the discharge of Longkaikou hydropower station in the main stream during fish migration periods, it is possible that fish with semi-buoyant eggs can reproduce successfully after the protection of the tributary.

5. Conclusions

The results of this study showed that cascade hydropower development will have a serious impact on the reproduction of fish producing semi-buoyant eggs. On the one hand, the principal migration routes of fish with semi-buoyant eggs are lost in the reservoir in all potential scenarios. There was an unsuitable area (approximately 30% of the total area) in which the flow velocity could not meet the requirements for fish migration. Fish in the upstream of this area can migrate to the upstream to spawn successfully, while fish in the downstream of this area may not be able to get through this area despite reservoir operation. On the other hand, semi-buoyant eggs and larvae sank to the bottom and perished before they hatched and were old enough to survive. Moreover, even if the hydrodynamic conditions could keep them in the drift in impossible high discharge conditions, there was not enough drifting time and distance for the semi-buoyant eggs to hatch and to develop the ability to swim in the reservoir. The results indicated that the reservoir on the main stream did not have sufficient hydraulic characteristics to support the successful recruitment of fish with semi-buoyant eggs. However, if we select one or two tributaries to protect fish habitats and eliminate the small hydropower projects on them, it is possible that fish with semi-buoyant eggs can reproduce successfully in the tributary together with the main stream. In this case, the suggested optimum operation in the main stream to satisfy the fish requirement is relatively low water level of the reservoir and relatively high discharge of Longkaikou hydropower station during fish migration periods.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.06.411.

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