Ecological Engineering 141 (2019) 105597

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Quantitative assessment of fish passage efficiency at a vertical-slot fishway on the Daduhe River in Southwest China

Jianghui Bao[a,b], Weiwei Li[a,b], Chaoshuo Zhang[a,b], Xiangyuan Mi[a,b], Hongtao Li[a], Xiujiang Zhao[c], Na Cao[d], William M. Twardek[e], Steven J. Cooke[e], Ming Duan[a,*]

[a] State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, Hubei, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] China Three Gorges Corporation, Beijing 100038, China
[d] Appraisal Center for Environment and Engineering, Ministry of Environmental Protection, Beijing 100012, China
[e] Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel by Dr., Ottawa, ON K1S 5B6, Canada

ARTICLE INFO

Keywords:
Fishway
Passage efficiency
Monitoring
Fish migration
PIT tags

ABSTRACT

Fish passage facilities are constructed to enable fish to pass anthropogenic barriers such as dams though their efficiency varies across species and location. There are a number of studies that assess the efficiency of fish passage facilities, yet rarely have such assessments been conducted in Asia. We conducted one of the first quantitative assessments of the efficiency of a vertical-slot fishway in Asia on the Daduhe River in Southwest China. Quantitative assessment of fish passage efficiency was conducted using a combination of methods, including fish sampling, video recordings and a Passive Integrated Transponder (PIT) system for tracking individually-tagged fish ($N = 69$ of 6 species). Fish sampling revealed 40 species assembled downstream of the dam. Fish captured closer to the fishway tended to be larger than fish caught more distant from the fishway. Half of the fish species observed downstream of the fishway were also observed at the entrance to the fishway (i.e. 153 individuals across 20 species). Video records revealed that overall passage rates were 71.2% based on the number of fish observed at the exit of the viewing chamber relative to that observed passing the entrance viewing chamber. Most fish passed the fishway at night with peak passage occurring in June. PIT technology results revealed that passage efficiency among the six tagged species ranged from 0% to 60% (four species successfully ascended the fishway). Transit time from the fishway entrance to exit was variable both among and within species that successfully ascended the fishway (i.e. 17.9–20.3 h for *Schizothorax davidi,* 6.4–88.8 h for *Schizothorax preuanti,* 46.4 h for *Silurus meridionalis,* 22.1–53.9 h *Semilabeo prochilus*). Fishway performance varied by species such that there is evidence that the fishway may be useful for maintaining river connectivity for some species. However, passage was often restricted during periods when there was sufficient flow in the fishway. Additional research is needed to put these findings in an ecological context given the overall low number of fish that passed the dam.

1. Introduction

Anthropogenic infrastructure installed on rivers for the purpose of generating electricity, irrigation, flood control, and low flow augmentation is common around the globe. However, the facilities often involve dams which have the potential to fragment rivers and thus interrupt river connectivity (Park et al. 2008; Doehring et al. 2011; Hall et al. 2011). Dams are well known as barriers to both upstream and downstream movement of fish which is problematic as many species are obligatory migrants and need to reach spawning, rearing or overwinter habitats to complete their life cycle (Baras and Lucas 2001; Zhuang et al. 2016). There are many examples of how dam fragmentation has isolated habitats leading to reductions in population abundance, persistence and genetic diversity and therefore contributed to imperilment or extirpation (e.g. Dunham et al. 1997; Vaughn and Taylor 1999; Khan and Colbo 2008). Researchers and habitat restoration practitioners have devoted great efforts to the development of strategies to mitigate or restore river connectivity at dams (Tummers and Hudson 2016; Dodd

* Corresponding author at: State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, Hubei, China.
E-mail address: duanming@ihb.ac.cn (M. Duan).

https://doi.org/10.1016/j.ecoleng.2019.105597

Available online 24 October 2019

et al., 2017; Pennock et al. 2017). Although habitat connectivity can be re-established through dam removal, a more common approach is the use of fish passage facilities to allow fish to move beyond the obstacle (e.g. fishway, ladders, nature-like bypass) (Mckay et al. 2013).

Fish passage structures, including nature-like bypass, pool and weir pass, culvert and vertical slot fishways (VSFs), have been universally used for alleviating habitat fragmentation and restoring longitudinal connectivity (Clay 1995). VSFs are among the most commonly used device (Stuart and Cooper, 1999; Roscoe and Hinch 2010) given that they offer some advantages relative to other fishway configurations. For example, they remain operational across a greater range of water depth changes and different species can navigate through the slots at their preferred depth according to their swimming behavior (Larinier 2001; FAO/DVWK. 2002; Romão et al., 2017). For these reasons, VSFs are regarded as being able to pass a wide range of fish species (White et al. 2010; Thiem et al. 2013; Sanz-Ronda et al. 2016; Romão et al. 2017). In China, VSFs account for 76% (28 of 40) of the total number of fishways (Mao 2018), yet to date there have been very few assessments of such devices for species in China or more broadly across Asia.

Several recent reviews (e.g. Roscoe and Hinch 2010; Bunt et al. 2012; Silva et al. 2018) have identified that the majority of published fishway assessments emanate from a few regions (e.g. North America, Europe, Australia) and that there is a need to understand fishway performance in other regions with diverse freshwater fish communities. Moreover, according to Roscoe and Hinch (2010), 45% of all fishway studies were exclusively focused on salmonids emphasizing that we know much about one family of fish and very little about thousands of other species that reside in rivers that have been fragmented. Roscoe and Hinch (2010) also noted that only 30% of fish passage studies focused on the whole local fish community. Passage efficiency can vary greatly across and within species due to differences in swimming ability (Haro et al. 2004), physiological state (Pon et al. 2009), motivation (Bunt et al. 2012) and body size (Mallen-Cooper and Brand 2007). Selective passage may lead to rapid life-history trait evolution within populations (Haugen et al. 2008; Maynard and Zydlewski 2017) and shifts in fish community structure. In the Yangtze River Basin of China, there are over 400 freshwater fish species, including 124 endemic species to the upper Yangtze River (He et al. 2011). These species vary widely in their basic ecology from the demersal cold-water fish *Euchiloglanis davidi* to the hole-gap fishes *Liobagrus marginatus* and *Paracobitis variegatus* (Table 1). As passage rates differ greatly across species (Bunt et al. 2012), it is necessary to develop a holistic method to assess passage efficiency of a broad range of species at VSFs in China.

Sampling in the vicinity downstream of a dam can reveal information on local fish assemblage and the species that could potentially use the fishways (Aparicio et al. 2012). Customized traps are often used due to their advantages in identifying species and sizes of individuals, and their ability to inform the spatial distribution of individuals when multiple locations are sampled. Video recordings at the entrance and exit of fishways have been used to quantify patterns of fishway use (e.g., Aparicio et al. 2012) and can provide information on both daily and seasonal trends (Santos et al. 2005). Further, the species passing the fishway can be identified without any need to capture or handle the fish. The shortcoming of video technology is that it can only record behaviour on a small spatial scale as fish move through a fishway (Struthers et al. 2015). PIT technology is an important tagging method to deliver detailed information on fish behaviour during passage, such as quantifying transition time and identifying when and where fallback occurs (Baras and Lucas 2001). In addition, this method can be used to quantify individual passage success and overall passage efficiency through a passage structure. These tools are often implemented on fish during migratory periods as most river-resident species require access to different habitats for spawning and other life cycle activities (Baras and Lucas 2001; Dodd et al. 2017). Additionally, fish tend to be physiologically motivated to through fishways during the spawning period, making this an ideal period to evaluate the influence of the fishway at restoring ecological connectivity (Winemiller et al. 2016).

Since 2002, 10 fishways have been built in China and an additional 30 fishways are planned or under construction (Shi et al. 2015). However, little is known about the biological performance of these structures. We conducted a passage study at the ZTB fishway, the first VSF on the Daduhe River in Southwest China. The study was completed from June to August in 2017 during the breeding season for the majority of the economically-valuable and imperiled species in the Daduhe River (Yang et al. 2010; Luan et al. 2016; Yu et al. 2018). We used a variety of methods including routine fish sampling, video recordings, and a PIT system (to track individually tagged fish) to assess the performance of the ZTB fishway across various species and sizes of fish. This multi-method approach was used to quantify the suite of species below the fishway and those that entered, to ascertain detailed aspects of passage behaviour, and to generate passage efficiency estimates. The information presented here will inform fish passage design and also serve as a model for conducting fish passage assessments in other fishways in China and more broadly across Asia.

2. Material and methods

2.1. Study area

This study was conducted from June to August in 2017 during the migratory season (Yang et al. 2010; Luan et al. 2016; Yu et al. 2018) for the majority of economically-valuable and imperiled fish species on the Daduhe River (Fig. 1), located in Sichuan province, Southwest China. It is the largest tributary of the Minjiang River, and a secondary tributary of the upper Yangtze River. Total length of the Daduhe River is about 1062 km, with a basin area of 77, 400 km^2. The Daduhe River and its tributaries are teeming with fish, and about 100 species of fish have been recorded in this river including endemic species (five species), state protected species (2 species), provincially protected species (11 species) and economically-valuable species (63) (Xu et al. 2013). However, 15 dams have been built on this river (with another 14 planned), which is believed to be a main factor disrupting the

Table 1
The status (assessed by Sichuan Province and RLCV, 2016) and ecological type of target and tagged species. EN: endangered, VU: vulnerable, NT: near threatened, LC: least concern, DD: data deficient, EC: economical.

Species	Target/tagged species	Status	Ecological type in inhabitation
Schizothorax davidi	target and tagged	EN	demersal and cold-water fish
Schizothorax prenanti	target and tagged	VU and EC	demersal and cold-water fish
Euchiloglanis davidi	target	EN	demersal and cold-water fish
Onychostoma sima	target	EN	demersal
Gobiobotia nudicorpa	target	DD	demersal
Beaufortia szechuanensis	target	NT	demersal
Liobagrus marginatus	tagged	VU	demersal and hole-gap fish
Paracobitis variegatus	tagged	DD	demersal and hole-gap fish
Pseudogyrincheilus prochilus	tagged	LC and EC	demersal and hole-gap fish
Silurus meridionalis	tagged	LC and EC	demersal

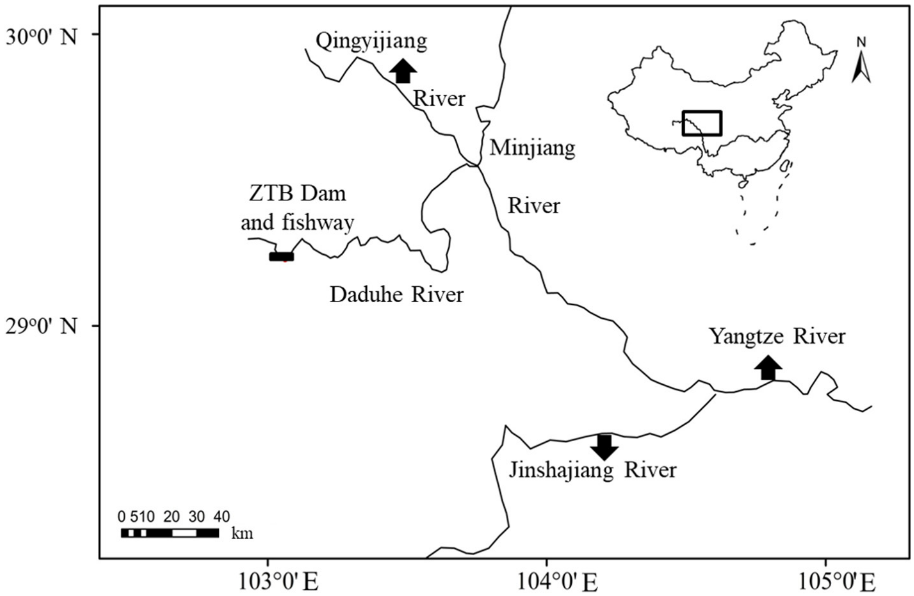

Fig. 1. Study area (ZTB Dam and Fishway) on the Daduhe River, Southwest China.

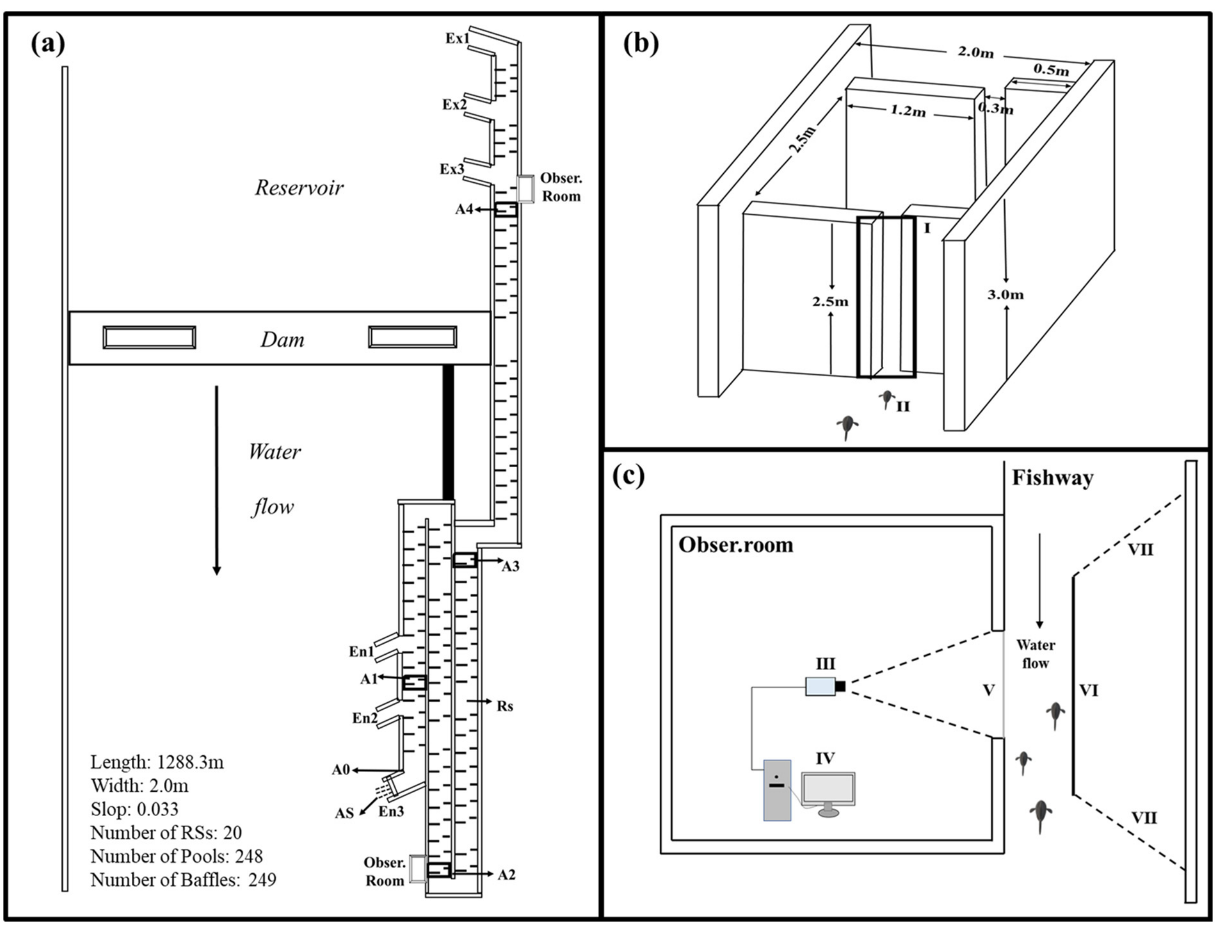

Fig. 2. Schematic of the ZTB vertical-slot fishway on the Daduhe River, Southwest China. (a) Plan view of the fishway, location of observation room. En1, En2, En3, Ex1, Ex2 and Ex3 indicate locations of three entrances and exits; A0 indicate location of releasing tagged fish; A1, A2, A3, A4 indicate locations of PIT antennas; Rs (Rest room); As (Attraction system); (b) Structure of vertical slot and PIT antennas. I: antennas; II: tagged fish (c) Structure of video monitor system in the obser. Room. III: camera; IV: video system; V: glass window; VI: bounce card; VII: wire mesh.

connectivity of the river for fish migration. The first VSF (29°14′N, 103°03′E) was constructed to improve longitudinal connectivity when the ZTB Dam was built on the Daduhe River in 2015 approximately 120 km from the mouth of Minjiang River. It is 1228.3 m long with an average slope of 0.033, height of 30 m, designed water velocities of 1.1–1.25 m/s (based on known or expected critical swimming speeds; Hou et al. 2018), and is located on the left bank of the river (Fig. 2). The fishway comprises three entrances, an attraction system (φ50 mm PVC), two observation rooms (4 m × 5 m, width × length), 249 baffles, 248 pools (2 m × 2.5 m, width × length), three exits and subsidiary facilities (Fig. 2). The head drop between consecutive pools (Δh) is 0.09 m. This corresponds to a potential velocity (Vmax) of 1.34 m.s-1 based on the calculation from the equation: $Vmax= \sqrt{2g\Delta h}$, where g is the acceleration due to gravity (9.8 m/s^2). The mean volumetric dissipated power (Pv) in a pool was 52.92 w/m^3 given by the equation: $Pv = \frac{pgQ\Delta h}{LBhm}$, where p is the water specific mass (1000 kg/m^3), Q is the discharge, hm is the mean water depth in the pools, L is the pool length and B is the pool width. The altitude at the bottom of the fishway exit is 620 m, the water depth of the fishway was designed to range from 1 m to 2.5 m. This VSF was designed and built for the targeted passage of economically-valuable species (assessed by Sichuan Province) and imperiled species (RLCV, Red List of China's Vertebrates, 2016) including *Schizothorax davidi*, *Schizothorax pregnanti*, *E. davidi*, *Onychostoma sima*, *Gobiobotia nudicorpa*and *Beaufortia szechuanensis* (Table 1). Additionally, this ladder was built to increase genetic diversity of all species both upstream and downstream of the ladder through increased passage.

2.2. Downstream fish community

Sampling was conducted at three sites near the VSF downstream of the ZTB Dam to identify the number and species of upstream fish present during the spawning period and thus presumably attempting to access upstream areas. The first site (S1) was sampled approximately 2.0 km away from the entrance of the fishway; the second site (S2) was located about 1.0 km from the entrance of the fishway; the third site (S3) was located 0.5 km from the entrance of the fishway. Three gill nets (4 m × 1.5 m length × height; mesh size: 1 cm) were used to capture fish at each sampling site. Nets were placed for 12 h on six different days of each month from June to August in 2017. Collected fish were identified to species based on morphological characteristics (Ding 1994). Total length (TL), standard length (SL) and wet body weight (BW) were measured to the nearest 0.1 cm and 0.1 g, respectively, after which the fish was dissected to determine sex and maturation status (an indication of migratory motivation) via examination of the gonads. Biomass was expressed in terms of catch per unit of effort (CPUE): catch (in grams) per each net set every hour.

2.3. Patterns of fishway use

Video systems set in the two observation rooms (at the entrance and exit) were used to obtain continuous (24 h/d) video footage of fish that passed in front of a rectangular glass window (1.17 m × 0.65 m, length × high) with small window lights. A constriction device ensured that the fish swam near the window so fish could be readily identified from the video (Fig. 2). Every week, the recordings were manually analyzed to generate time-stamped records of each detection event. The species and size (estimated TL by image) were recorded, and any individuals that fell back were removed to prevent duplicate counting. All observations were conducted by two experienced researchers and then compared and corrected (average adoption). The video was clear enough to count and identity fish given that the water in the fishway came from a deep reservoir and turbidity was low. Video was not analyzed during days with high turbidity (three days) nor when there was insufficient discharge in the ladder to allow passage (thirty-three days). As a result, a total of 55 days of video were analyzed of the three months the third entrance and exit were operating.

Environmental variables were measured every month from June to August in 2017. Water temperature (°C), dissolved oxygen (mg/l) and pH were recorded from the river using a portable water quality instrument Thermo Orion Star A329 (Thermo Fisher Scientific Inc., Waltham, MA USA) at the time of sampling. Flow velocities (minimum; mean; maximum) in the fishway (slots, rest rooms and observation room) were measured on five different days each month and three different pools each day with an electromagnetic water velocity meter (FP111, Global Water, TX, USA). Daily water level in the reservoir and quantity of water for power generation were acquired from the website of the Daduhe River Hydropower Development Company, Ltd. (http://www.spddr.com/).

2.4. Passage behaviour and efficiency

PIT technology was used to estimate the passage efficiency and characterize behaviour within the fishway. Fishes including *S. davidi, S. prenanti*, *Silurus meridionalis, Pseudogyrincheilus prochilus, L. marginatus* and *P. variegates* were captured downstream of the fishway (approximately 50 m from the entrance of En3) with gill nets (checked every hour). Only sixty-nine individuals were tagged (selected bigger and mature individuals) for this aspect of the study due to low abundance of target species downstream of the dam, resulting in low CPUE. These six species were selected as they are economically-valuable or imperiled species in China (Table 1).

Individuals were tagged with full duplex PIT tags (8.3 mm × 1.4 mm; 0.02 g in air; 134.2 KHZ) using a needle injector through a small (0.4 cm long) incision in the body cavity along the ventral midline (Castro-Santos et al. 2017). Prior to tagging in the field, fish were anaesthetized with eugenol (0.02 g/l), weighed (BW, g) and measured (TL, SL, cm). To minimize impacts of stress from handling, fish were handled quickly and all procedures were completed within one minute. After the surgery, fish were transferred into a well aerated tank of fresh river water for recovery. Over 12 h later, the tagged fish were released back into the entrance of the fishway (A0). Fish were released into the fishway as a means to increase the number of fish attempting passage (Wagner et al. 2012; Steffensen et al. 2013).

Four fixed location, cross-channel, swim-through full-duplex PIT antennas (0.5 m × 2 m, width × height) were installed during the study (Fig. 2); Antenna 1 (A1) was located approximately 100 m upstream of the fishway entrance within the fishway, Antenna 2 (A2), Antenna 3 (A3) and Antenna 4 (A4) were approximately 380 m, 680 m and 1000 m upstream of the first antenna, respectively (Fig. 2). When the tagged fish passed the antenna, the date, time, detection period, and unique tag ID number were recorded and stored on a SD card in the data logger. Logging equipment ran continuously from August 21st to September 21st, 2017 on the basis that we downloaded the PIT data once a week and stopped the machine only once there were no additional detections for a week. Given that PIT-tagging was conducted near the end of the migratory season, when individuals may be less motivated to move upstream (influencing fishway efficiency measures), we minimized this impact by tagging larger and more mature individuals. PIT data were used to evaluate the efficiency of the fishway, transit time, migration speed, fallback frequency and fallback rate.

2.5. Statistical analyses

A number of calculations were completed to analyze the data from both the video and PIT tag data that we outline below;

2.5.1. Video data

Actual estimated length of the fish (F_a) was calculated as $F_a = G_a \times F_v/G_v$, where G_v and F_v were virtual lengths of the rectangle glass and fish in the video, G_a was the actual length of rectangle glass.

Video-determined passage rate (R_V) was calculated as the number of fish that were observed by video in the entrance viewing chamber divided by those observed at the exit viewing chamber.

2.5.2. PIT tag data

For PIT tagged fish, passage efficiency (E_p) was calculated as the percentage of fish that were detected in A1, A2, A3, and A4 divided by those released in A0, respectively, per species. Among them, A0 to A4 represents the overall passage efficiency, while others represent the partial passage efficiency.

Transit time (T_t): time between the release time in A0 and first detection time in A1, A2, A3, and A4, respectively, per species.

Transit speeds (S_t): transit distance (A0-A1, A0-A2, A0-A3, A0-A4) divided by corresponding transit time, respectively, per species (expressed as fish speed/m of fishway).

Fishway delay time (T_d): time between the release time in A0 and last detection time at A4.

Fallback (I_f): detection of a fish at a downstream antenna after detection at an upstream antenna.

Fallback frequency (F_f): the number of fallback events for each individual.

Fallback rate (R_f): percentage of individuals that fell back from an antenna relative to the total number of individuals reaching that antenna.

Overlap rate (R_o): percentage of numbers of passing designed target species divided by numbers of designed target species.

Data were examined for normality and homogeneity of variance prior to determining suitability of parametric or non-parametric statistical approaches. One-way ANOVAs (Multiple Comparison-Tukey Method) were used to test size (TL, cm) differences among fish collected in three sites downstream of the fishway and in the entrance of the fishway. A two sample Kolmogorov-Smirnov test was used to test for differences in size distribution between fish in the three sample sites and fishway. Kruskal-Wallis tests were used to compare the difference of fish counts (refers to the counts at the ladder entrance and exit by video) over three months as well as differences in transition time, transition speed and fallback times between sections of the fishway (A0-A1, A0-A2, A0-A3, A0-A4, Fig. 2). Mann-Whitney tests were used to test whether the passage counts were different between day and night based on the video recordings and PIT tag data. In order to estimate whether swimming distance was related to body size, body size (SL, cm) of tagged *S. preuanti* among four monitoring sites was compared with the Spearman's rank-order correlations test. Index of relative importance (IRI) (Pinkas et al. 1970), Shannon-Weiner diversity index (H′) (Shannon and Weaver, 1949), Margalef's species richness index (Margalef 1957) and Pielou's evenness index (J') (Pielou 1975) were calculated to evaluate the fish species diversity among gill net sampled fish downstream of the fishway. All the data analyses and plots were performed using R version 3.3.5 (ggplot2 package) and significance was considered at an α level of 0.05.

3. Results

Surface water temperature (°C) downstream of the dam ranged from 16.5 to 19.5 °C; dissolved oxygen: 8.1–11.6 mg/l; pH: 5.5–8.9; TDS: 175.0–246.5 mg/l. The mean water velocity was 0.3 m/s (min: 0, max: 1.1) in the slot, 0.1 m/s (min: 0, max: 0.3) in the rest room; 0.2 m/s (min: 0, max: 0.5) in the observation room; the water level in the fishway varied from 0 m (i.e. no water) to 1.5 m (Table 2). Minimal flows were not provided to the fishway for thirty-three days, rendering passage impossible through the fishway during these periods.

3.1. Downstream fish community

A total of 743 individuals from 40 species belonging to 9 families were collected near the fishway in the Daduhe River (Table 3). The

Table 2
Environmental factors (Water temperature, Dissolved oxygen, pH, TDS, Water Velocity) within ZTB Fishway from June to August 2017.

Month	DO (mg/L)	pH	Water temperature (°C)	Water level (m)	TDS (mg/L)	Water velocity in vertical slot (m/s)	Water velocity in rest room (m/s)	Water velocity outside of obser. Room (m/s)
	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)
June	10.1 ± 1.0 (8.8–11.6)	5.8 ± 0.2 (5.5–5.9)	16.6 ± 0.2 (16.5–16.9)	1.0 ± 0.3 (0–1.2)	201.0 ± 26.0 (182.1–246.5)	0.3 ± 0.1 (0.0–0.8)	0.1 ± 0.1 (0.0–0.2)	0.2 ± 0.1 (0.0–0.4)
July	8.7 ± 0.8 (8.1–9.4)	7.7 ± 0.5 (6.3–8.0)	18.0 ± 0.5 (17.2–18.8)	0.7 ± 0.7 (0–1.5)	183.9 ± 21.4 (175.0–205.4)	0.3 ± 0.2 (0.0–1.1)	0.1 ± 0.1 (0.0–0.3)	0.2 ± 0.1 (0.0–0.4)
August	8.6 ± 0.4 (8.3–10.2)	9.1 ± 0.4 (7.5–8.9)	18.8 ± 0.5 (18.2–19.5)	0.8 ± 0.5 (0–1.3)	203.4 ± 5.6 (196.2–210.7)	0.3 ± 0.1 (0.0–0.7)	0.1 ± 0.1 (0.0–0.2)	0.2 ± 0.2 (0.0–0.5)

Table 3
List of fish species captured downstream of the ZTB Fishway from June to August 2017 (Hou, 2018; Noonan, 2012; Stuart, 1999; Bold: Order and Family).

Species	Species	Species
Cypriniformes	*Abbottina rivularis*	**Siluridae**
Cyprinidae	*Saurogobio dabryi*	*Silurus asotus*
Cyprinus carpio var.specularis	*Rhinogobio typus*	*Silurus meridionalis*
Carassius auratus	**Cobitidae**	**Bagridae**
Hypophthalmichthyinae molitrix	*Leptobotia fasciata*	*Pelteobagrus eupogon*
Schizothorax wangchiachii	*Leptobotia elongata*	*Pelteobagrus nitidus*
Schizothorax prenanti	*Leptobotia taeniops*	*Paracobitis variegates*
Schizothorax davidi	*Misgurnus anguillicaudatus*	*Leiocassis longirostris*
Pseudogyrincheilus prochilus	**Homalopteridae**	*Leiocassis crassilabris*
Garra pingi pingi	*Beaufortia szechuanensis*	**Amblycipitidae**
Sinilabeo rendahli rendahli	*Lepturichthys fimbriata*	*Liobagrus marginatus*
Onychostoma sima	*Paracobitis potanini*	**Sisoridae**
Percocypris pingi pingi	*Paracobitis variegates*	*Euchiloglanis davidi*
Zacco platypus	*Triplophysa orientalis*	*Glyptothoraxfukiensis fukiensis*
Hemiculter leucisculus	*Hemimyzon sinensis*	**Perciformes**
Parabrarnis pekinensis	*Hemimyzon abbreviata*	**Eleotridae**
Pseudorasbora parva	**Suluriformes**	*Ctenogobius giurinus*

most diverse family was Cyprinidae (18 species), followed by Homalopteridae (7 species), Bagridae (5 species), Cobitidae (4 species), Siluridae and Sisoridae (2 species each), Amblycipitidae and Eleotridae (1 species each). The dominant species were *S. prenanti*, *P. prochilus*, *Hemiculter leucisculus*, *Misgurnus anguillicaudatus*, *L. marginatus*, and *E. davidi*. The CPUE of fish was lowest in June (0.62 g/h/net), highest in July (0.82 g/h/net), and intermediate in August (0.69 g/h/net) (Fig. 3). Examination of dissected gonads showed that a greater proportion of *H. leucisculus* were females in June, July and August (55.6%, 52.9%, 100%) while *L. marginatus* had a smaller proportion of females in June (39.0%) but greater proportion in July and August (64.3%, 100.0%); whereas *P. prochilus* had higher proportions of male fish in June, July and August (92.3%, 80.6% and 100.0%, Fig. 4), *E. davidi* had higher proportions of male fish in June and August but not in July (60.0%, 47.1% and 50.0%, Fig. 4). The proportion of females observed increased monthly for all species except *P. prochilus.* Fish sampled closer to the fishway entrance tended to be much larger (TL) than in areas further downstream and were greatest within the fishway entrance; S1 (11.6 ± 3.9 cm, Mean ± SD) < S2 (15.6 ± 6.1 cm) < S3 (17.3 ± 4.5 cm) (One-way ANOVA, all $P < .05$), F (19.6 ± 11.5 cm) (Fig. 5).

3.2. Patterns of fishway use

153 individuals were counted by video at the observation room viewing window at the fishway entrance, whereas 109 fish were counted at the exit between June 1st and August 31st, 2017 yielding a 71.2% passage rate. These fish were classified into 20 species (five species could be identified in the fishway, nine species could be identified to genus, but six species were unidentified). The most abundant species within the fishway were *L. marginatus*, *E. davidi*, *Hemiculter* sp., *Saurogobio* sp., and *Silurus* sp. In total, 50% (20 species) of the fish species observed downstream of the fishway in gill nets were also

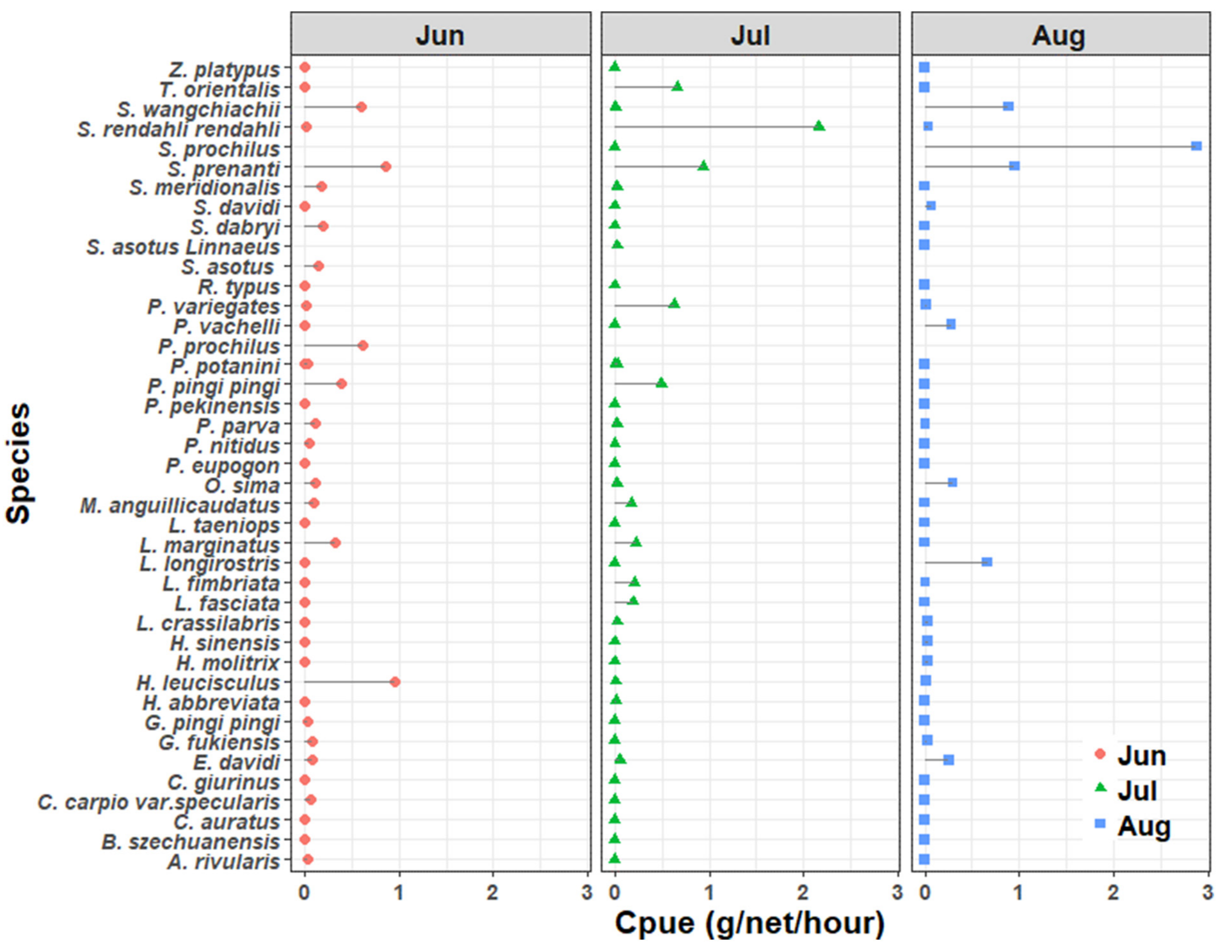

Fig. 3. The CPUE (g/nets/h) of different species captured in downstream of the ZTB Fishway from June to August 2017.

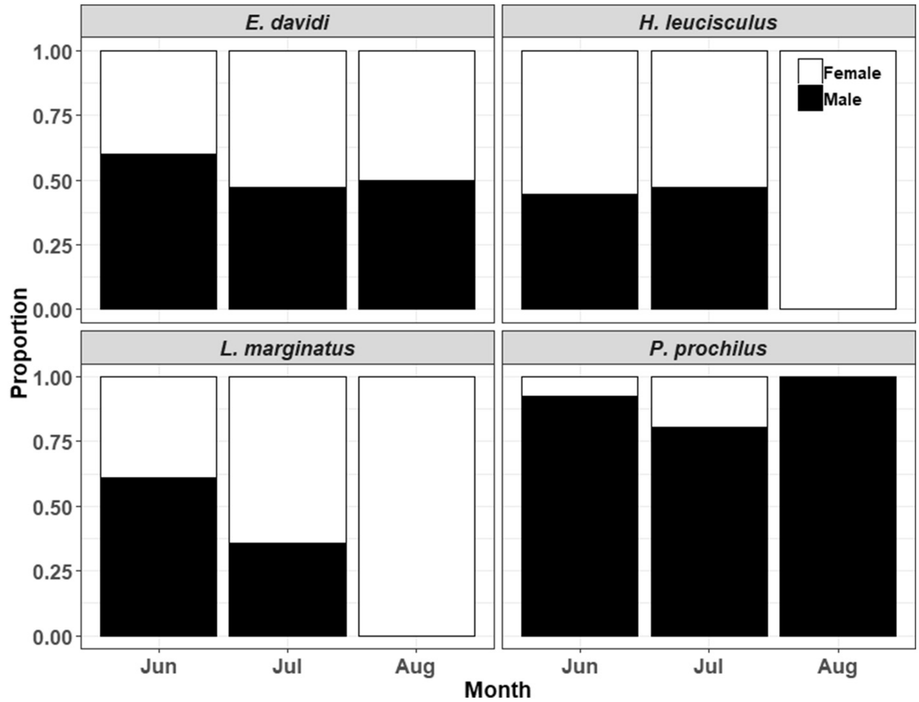

Fig. 4. Proportion of female and male of four dominate species captured in downstream of the ZTB Fishway from June to August 2017.

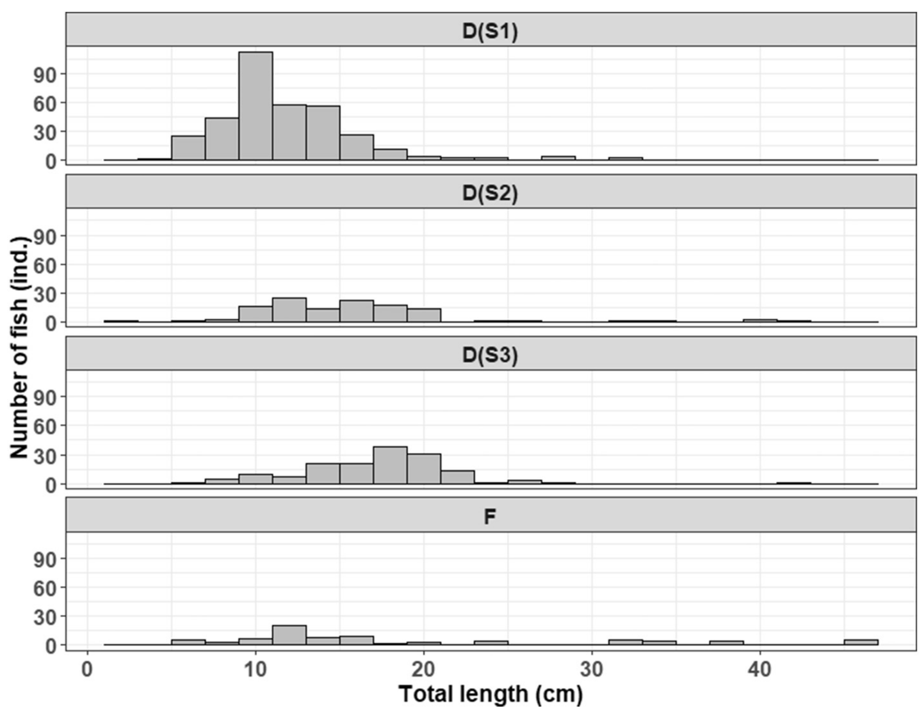

Fig. 5. Length-Frequency distribution at three sites from downstream of dam and in the fishway; S1, S2 and S3 represented 2.0 km (the first sample site), 1.0 km (the second sample site) and 0.5 km (the third sample site) away from the fishway, F: in the downstream of dam, respectively.

observed at the entrance to the fishway and the overlap rate (percentage of numbers of passing designed target species divided by numbers of designed target species) was 33%. The Margalef richness index and Shannon diversity index downstream of the dam were higher than in the fishway but these differences were not significantly different (*Mann-Whitney test, P* = .1). In contrast, the Pielou evenness index was lower downstream than in the fishway (Table 4). Additionally, the number of migrating fish was significantly different between months at the entrance (*Kruskal-Wallis tests, p* = .02; Fig. 6), with minimal differences (*Kruskal-Wallis tests*, *p* = .59) between June and July but significantly lower counts in August (*Kruskal-Wallis tests*, Jun-Aug (*p* = .04), Jul-Aug (*p* = .04)). Fish tended to enter and exit the fishway at a greater rate during nighttime (19:00–07:00) (*Mann-Whitney test*, *P* < .001). The peak rate of fish passage was during 20:00–04:00 (Fig. 6).

3.3. Passage behaviour and efficiency

Sixty-nine individuals were PIT-tagged in the experiment, 55 of

Table 4
Temporal and spatial variation in species diversity of the fish assemblages in ZTB Fishway from June to August 2017 in the Daduhe River.

Sites	Month	Margalef's richness index	Shannon-Weiner diversity index	Pielou's evenness index
Downstream of dam	June	4.58	2.31	0.68
	July	4.50	2.28	0.73
	August	3.94	2.18	0.74
Fishway	June	2.14	1.81	0.82
	July	2.23	2.00	0.91
	August	1.93	1.49	0.68

which were detected at the fishway entrance (Table 5). The remaining 14 fish fell back from the entrance of the fishway and were not recorded during the 30 days monitoring period. The lowest passage efficiencies observed were that of *P. variegates* (0%) and *L. marginatus* (0%), two species that are data deficient and vulnerable respectively, and are species that increase genetic diversity for passage. The highest passage efficiency was for *P. prochilus* (60%) which is an economically-valuable fish species. The details of tagged fish and passing rate at four different monitoring sites are presented in Tables 5 and 6. There was no significant difference in body size for *S. davidi* (the fish tagged most often) among four different sites within the fishway (*Kruskal-Wallis test, all P* > .05), indicating that progression through the fishway was not affected by length of fish for this species (26.9–35.9 cm).

Transit time and speed from A0 to A4 varied substantially among

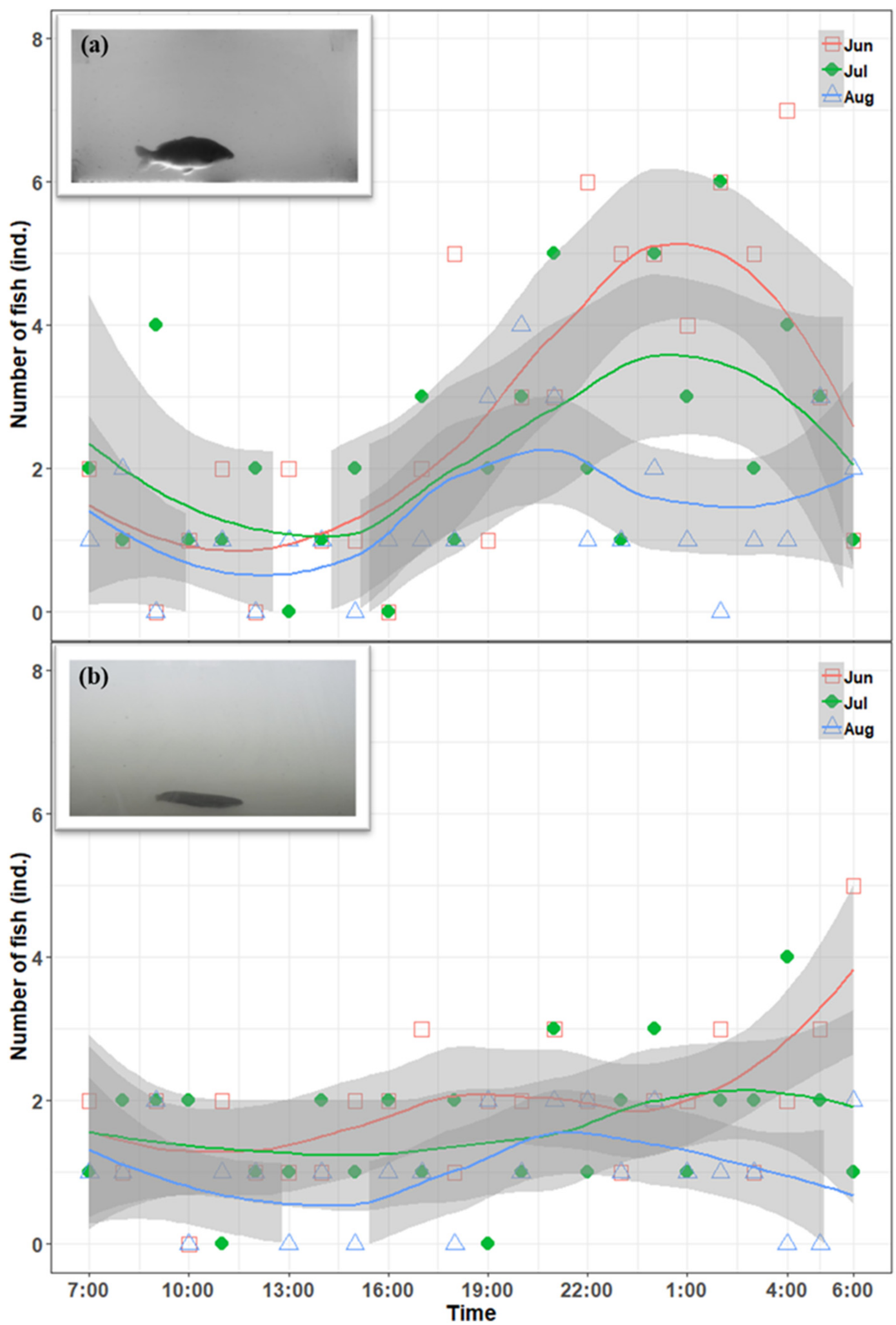

Fig. 6. Monthly (June to August) and Diurnal Rhythm (24 h) variations of the fish numbers at (a) the entrance of fishway, and (b) the exit of fishway in the ZTB fishway on the Daduhe River, Southwest China.

Table 5
Number, body length, body weight of the tagged fish and percentage of passing number in four fishway sections on the Daduhe River in Southwest China.

Species	Number tagged	Standard Length(cm)	Body Weight (g)	Percentage of passing (P) and fallback (F) numbers in four fishway sections (N)							
		Mean ± SD (range)	Mean ± SD (range)	A0-A1 (P)	A0-A1 (F)	A0-A2 (P)	A0-A2 (F)	A0-A3 (P)	A0-A3 (F)	A0-A4 (P)	A0-A4 (F)
Schizothorax davidi	7	29.5 ± 9.7 (16.7–37.1)	480.3 ± 216.7 (71.3–703.5)	85.0 (6)	66.7 (4)	71.0 (5)	100 (5)	57.0 (4)	50 (2)	28.6 (2)	100 (2)
Schizothorax preuanti	45	29.6 ± 7.7 (15.5–35.9)	444.7 ± 202.4 (57.6–675.0)	80.0 (36)	63.8 (23)	51.0 (23)	78.2 (18)	36.0 (16)	87.5 (14)	17.8 (8)	100 (8)
Silurus meridionalis	5	29.0 ± 5.2 (14.0–42.5)	261.5 ± 141.7 (29.0–602.0)	80.0 (4)	50 (2)	60.0 (3)	66.7 (2)	40.0 (2)	100 (2)	20.0 (1)	100 (1)
Pseudogyrincheilus prochilus	5	13.6 ± 5.7 (9.7–15.2)	54.3 ± 165.7 (18.2–109.2)	60 (3)	100 (3)	60.0 (3)	66.7 (2)	60.0 (3)	66.7 (2)	60.0 (3)	100 (3)
Liobagrus marginatus	5	12.2 ± 6.3 (10.4–13.9)	21.9 ± 193.3 (13.1–33.5)	100.0 (5)	100 (5)	60.0 (3)	66.7 (2)	20.0 (1)	100 (1)	0	0
Paracobitis variegates	2	16.1	15.5 ± 0.1 (15.5–15.6)	50.0 (1)	100 (1)	0	0	0	0	0	0
Total	69	26.3 ± 8.7(9.7–42.5)	357.0 ± 220.7 (13.1–703.5)	79.7 (55)	69.1 (38)	53.6 (37)	78.3 (29)	37.6 (26)	80.7 (21)	20.3 (14)	100 (14)

Table 6
Transit time and speed of the tagged fish when passing four fishway sections on the Daduhe River in Southwest China. NA: no data available.

Species	Number tagged	A0-A1		A0-A2		A0-A3		A0-A4	
		Transit time (h)	Transit speed (h/m)	Transit time (h)	Transit speed (h/m)	Transit time (h)	Transit speed (h/m)	Transit time (h)	Transit speed (h/m)
		Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)
Schizothorax davidi	7	4.1 ± 4.8 (0.2–10.2)	121.7 ± 132.4 (9.8–299.2) ()(9.7–500.0)	13.0 ± 5.6 (6.4–22.0)	33.9 ± 15.3 (17.3–59.0)	21.4 ± 6.3 (16.2–29.3)	33.9 ± 9.4 (23.2–42.11)	19.1 ± 1.7 (17.9–20.3)	57.7 ± 5.2 (54.1–61.4)
Schizothorax preuanti	45	8.5 ± 8.4 (0.3–33.6)	13.4 ± 66.9 (3.0–333.3)	16.3 ± 17.6 (6.4–22.0)	23.3 ± 51.4 (5.3–177.6)	16.6 ± 12.5 (6.4–22.0)	40.9 ± 26.7 (12.7–127.4)	28.3 ± 26.5 (6.4–88.8)	64.9 ± 37.3 (12.4–165.4)
Silurus meridionalis	5	5.4 ± 5.7 (0.2–11.1)	102.5 ± 119.7 (9.0–500.0)	25.2 ± 8.4 (13.5–33.6)	5.7 ± 8.2 (0.6–15.1)	26.6 ± 7.9 (22.4–33.6)	13.4 ± 17.2 (1.2–25.5)	46.4	23.7
Pseudogyrincheilus prochilus	5	7.8 ± 13.1 (0.3–23.6)	197.7 ± 171.9 (4.3–333.3)	18.0 ± 14.9 (2.3–31.9)	65.4 ± 86.3 (11.9–165.0)	21.0 ± 4.5 (15.8–23.6)	33.6 ± 8.1 (28.8–43.0)	35.2 ± 16.6 (22.1–53.9)	35.8 ± 14.7 (20.4–49.8)
Liobagrus marginatus	5	19.2 ± 17.4 (0.2–42.9)	105.3 ± 220.7 (2.3–500.0)	117.4 ± 95.2 (53.4–226.9)	4.7 ± 2.8 (1.7–7.1)	82.4	8.2	NA	NA
Paracobitis variegates	2	6.4	15.6	NA	NA	NA	NA	NA	NA
Total	69	4.1 ± 4.8 (0.2–10.2)	67.4 ± 87.5 (2.3–500.0)	19.0 ± 18.9 (6.4–226.9)	46.7 ± 49.6 (0.6–165.0)	20.9 ± 16.6 (6.4–33.6)	44.3 ± 26.2 (1.2–127.4)	29.7 ± 21.6 (6.4–88.8)	54.7 ± 37.3 (12.4–165.4)

species and among individuals (Table 6). *S. preuanti* and *S. davidi* moved through the fishway relatively quickly (28.3 ± 26.5 h and 19.1 ± 1.7 h), while *S. meridionalis* spent considerably longer passing the fishway (46.4 h). However, there was no significant difference in migratory speed among different parts (A0-A1, A0-A2, A0-A3, A0-A4) of the fishway (*Kruskal-Wallis test, all* $P > .05$). However, most of the fish that passed each antenna experienced fallback. The species of *S. davidi, S. preuanti* and *L. marginatus* fell back more times than *S. meridionalis, P. prochilus* and *P. variegates,* and a final fallback rate of 100% was observed. Fallback rate through different sections were A1 (69.1%), A2 (78.3%), A3 (80.7%), and A4 (100%), respectively (Table 5). The average number of fallbacks for tagged individuals through different sections were A1 (8), A2 (10), A3 (4) and A4 (23), respectively. We found that tagged fish were detected most frequently at A4 (near the fishway exit). In addition, observations from videos below the fishway exit indicated that fish were delayed in the exit of the fishway before reaching the upstream reservoir.

4. Discussion

We conducted one of the first biological assessments of a VSF in China and more broadly within Asia. Using multiple methods (e.g. routine fish sampling, videography and PIT technology) we generated data on the movement of fish through the ZTB fishway over the spawning period from June to August. Overall, it was found that 50% of the 40 species found within close proximity of the fishway used the fish pass but that passage rates and speeds differed between species. Passage was clearly impeded during periods that the fishway did not provide minimum flows for passage (~1/3rd of the study period). Data derived from this study will be used to inform future fish passage development, operation, and assessment in the region.

Despite a small sample size of tagged fish, more fish should be tagged in future study for a better understanding of fishway efficiency, a measure of tagged fish passage efficiency was provided for the ladder at 20.3%. This proportion of fish passed was lower than pool and weir fishways (about 40%) or same type of vertical-slot fishways efficiency (about 30%) for non-salmonids, close to natural fishways (about 23%), whereas higher than Denil fishways (about 15%) and fish lock/elevators (about 10%) according to the statistical results described in a review (Noonan et al. 2012). Unfortunately, we cannot find a similar length and type fishway efficiency to compare more accurately. There are several possible explanations for the low passage efficiency of vertical-slot fishway observed in this study. Relative to semelparous species, not all fish tagged or counted within this study may have been motivated to migrate upstream despite sampling larger fish during the end of spawning period (Cooke and Hinch 2013). It is also possible that in some instances, PIT receivers were unable to detect multiple tags at once if fish passed concurrently. Both of these factors would result in an underestimation of fishway efficiency. A number of environmental factors may have influenced pssage rates. The maximum water velocities in the slots ranged from 0.7 m/s to 1.1 m/s lower than the designed values of 1.1–1.25 m/s, and were therefore lower than the optimal ranges for the targeted species for this fishway. High water velocity can prevent some fish with weak swimming ability from passing through a fishway, whereas low water velocity may not provide sufficient stimulus to encourage fish movement upstream (Kemp et al. 2011; Maynard and Zydlewski 2017; Ovidio et al. 2017). Appropriate water levels are critical to ensuring effective fish passage (Tao et al. 2015), though these levels were often not provided to the ZTB fishway. In the present study, the level of water downstream of the dam was higher than the lowest-bottom entrance of the fishway most of the time. Further, the water level upstream of the dam (ranged from 619 to 623 m) was also lower than the lowest-bottom exit of fishway (620 m) approximately 1/3rd of the time. As a result, the water flows in the fishway were disrupted due to the low water levels in the reservoir, which had an undesirable effect on the ascending fish (i.e. in the present study some individuals spent several hours or even several days waiting for sufficient water to complete their movement through the fishway). It is important to note that the water levels in this system fluctuate hourly unlike many other systems where VSF have been used. Most inflow water was used for power generation with insufficient water allocated to fish passage, and thus the fishway required regular inspection and maintenance. Results from this study suggest the bottom of the fishway exit should be modified lower than 618 m according to the water level in the reservoir to ensure sufficient water for the fish to successfully pass the fishway.

Species-specific differences in fish passage existed at the ZTB fishway which appear to be partly related to fish size. The size of river-resident fish captured in gill nets tended to increase nearer to the fishway and was greatest in the fishway entrance. This may be a result of increasing flows as fish approach the fishway and the weaker swimming performance of smaller individuals (Silva et al. 2011; Bunt et al. 2012). Previous work found that larger Iberian barbel (*Luciobarbus bocagei*) had a higher passage success than smaller size-individuals during their upstream movements across various discharge levels (0.039 to 0.077 m^3/s) (White et al. 2010; Sanz-Ronda et al. 2016). Larger fish might also be more sexually mature and motivated to move upstream than their smaller counterparts (Pennock et al. 2017). However, once fish entered the ZTB fishway, body size had little influence on passage success of *S. davidi*.

Moving beyond a single-species approach has been identified as an important future direction for the design and monitoring of fish passage facilities (Roscoe and Hinch 2010; Silva et al. 2018). Based on the number of fish observed at the exit of the viewing chamber relative to that observed passing the entrance viewing chamber the ZTB fishway had a community passage rate of 71.2%, which is greater than the 33.9% passage rate of fish through the Changzhou fishway in China (Chen et al. 2014). It should be noted however, that turbidity was high occasionally and video observations likely underestimated the abundance of fish and potentially the presence of some fish species (especially more cryptic ones).

This study generated relevant information on movement ecology to inform and improve fish passage for these species. Fish abundance and movement tended to decrease as the season progressed from June to August, which is consistent with the general understanding that June is the peak of the fish breeding season on the Daduhe River. Further, fish movement through the ladder was considerably greater at night, providing insight on diurnal movement of these fishes. Additional information on the ecology and migration biology of the fish community would assist in determining the extent to which fish passage is needed for various species/life-stages as well as the timing and purpose (e.g. spawning, feeding, etc) of migrations.

PIT-tag data provided fine-scale information on the movement of sixty-nine individuals within the fishway. Movement of PIT-tagged fish revealed that individuals spent long periods (several hours or days) to successfully pass through the fishway. Information on the mechanisms behind delays can be used to inform future design refinementsto minimize delays (Castro-Santos and Haro 2003; Castro-Santos and Perry 2012). Although delays were similar between sections, delays differed between species. *L. marginatus* and *P. variegates* belonged to the hole gap type species and had smaller body sizes and longer durations of passage in the fishway, while *P. prochilus* had a relatively higher speed and the highest passage efficiency.

In the present study, our results indicated that the probability of fallback was positively correlated with the distance swam in the fishway. Fallback was greatest for fish passing A2 and A4 than A1 and A3. A2 was close to the observation room and the water velocity in the observation room was high (Table 2). A4 was close to the exit of the fishway where water velocity was high and resulted in a high proportion of fish stranding/holding near the exit and falling back frequently. This fallback may be related to exhaustion from burst swimming (Burnett et al. 2014) and depth variations near the fishway exit yet it is important to note that we lack information on normal “fallback” rates and behaviour (see Frank et al. 2009) for the species studied here. Fallback may lead to injury or death, and depletes energy reserves as fish must re-ascend the fishway (Thiem et al. 2016). These challenges could reduce the likelihood of an individual completing its migration, spawning, and surviving post-breeding (Roscoe and Hinch, 2011).

5. Conclusions

This study was the first to estimate fishway efficiency in China using an integrative multi-method assessment approach using gill net sampling, video monitoring, and PIT tagging. This study addressed a number of critical questions including which species are located near the fishway, which species pass the fishway, and the behaviour of fish as they pass the fishway. The fishway was found to pass 50% of the species observed downstream with varying rates of passage. Based on the gill net sampling, it appears larger sized individuals are more likely to approach and enter the ladder, but body size for *S. davidi* did not influence passage rates within the fishway. Based on the findings of this study, the ZTB fishway has the capacity to restore connectivity to upstream habitats but it is unclear whether it has restored functional connectivity (i.e. allowing fish to complete critical lifecycle stages upstream) (McLaughlin et al. 2013). Additional research is also needed to put these findings in an ecological context given the overall low number of fish that passed the dam. Moreover, nothing is known about post-passage consequences or fishway attraction efficiency which is required to fully assess the ability of this fishway to restore functional connectivity. Further research should also investigate the swimming performance of unpassed species to evaluate potential hydrodynamic conditions that may facilitate passage of a greater proportion of the fish community. Given that upstream reservoir levels can result in the exit being “perched” some modifications to the facility or changes in operations to increase flow through the fishway could benefit migratory fish.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to express our thanks to two anonymous reviewers. In this work, M.D. was financially supported by the National Key R & D Program of China (Nos. 2018YFD 0901701, 2018YFD 0900605), the Special Research Fund for Public Interest of MWR of China (No. 201201028-02), the Open Fund of State Key Laboratory of Freshwater Ecology and Biotechnology (No. 2018FB03), the Key Laboratory of Algal Biology, Institute of Hydrobiology, Chinese Academy of Sciences (No. 2018-004) , the Hubei Key Laboratory of Three Gorges Project for Conservation of Fishes (No. 201902), and the Special Research Fund for Behavioural Ecology in the Daduhe River of Wuhan Sino-Eco Ecological Science & Technology Corporation Limited (Nos. 2017SE01, 2018SE02).

Data deposited in the Dryad Digital Repository 0000-0002-0721-6053.

References

Aparicio, E., Pintor, C., Duran, C., Carmona-Catot, G., 2012. Fish passage assessment at the most downstream barrier of the Ebro River (NE Iberian Peninsula). Limnetica. 29, 37–46.

Baras, E., Lucas, M.C., 2001. Impacts of man's modification of river hydrology on freshwater fish migration: a mechanistic perspective. Ecohydrol. Hydrobiol. 1, 291–304.

Bunt, C.M., Castro-Santos, T., Haro, A., 2012. Performance of fish passage structures at upstream barriers to migration. River Res. Appl. 28, 457–478. https://doi.org/10.1002/rra.1565.

Burnett, N.J., Hinch, S.G., Braun, D.C., Casselman, M.T., Middleton, C.T., Wilson, S.M., Cooke, S.J., 2014. Burst swimming in areas of high flow: delayed consequences of anaerobiosis in wild adult sockeye salmon. Physiol. Biochem. Zool. 87, 587–598. https://doi.org/10.1086/677219.

Castro-Santos, T., Haro, A., 2003. Quantifying migratory delay: a new application of survival analysis methods. Can. J. Fish. Aquat. Sci. 60, 986–996. https://doi.org/10.1139/f03-086.

Castro-Santos, T., Perry, R., 2012. Time-to-event analysis as a framework for quantifying fish passage performance. In: Adams, N.S., Beeman, J.W., Eiler, J.H. (Eds.), Telemetry Techniques: A User Guide for Fisheries Research. Trans. Am. Fish. Soc, Bethesda, Md, pp. 427–452. https://doi.org/10.1139/cjfas-2016-0089.

Castro-Santos, T., Shi, X.T., Haro, A., 2017. Migratory behaviour of adult sea lamprey and cumulative passage performance through four fishways. Can. J. Fish. Aquat. Sci. 74, 790–800. https://doi.org/10.1139/cjfas-2016-0089.

Chen, K.Q., Tao, J., Chang, Z.N., Cao, X.H., Ge, H.F., 2014. Difficulties and prospects of fishways in China: an overview of the construction status and operation practice since 2000. Ecol. Eng. 70, 82–91. https://doi.org/10.1016/j.ecoleng.2014.04.012.

Clay, C.H., 1995. Design of Fishways and Other Fish Facilities, 2nd ed. Lewis Publishers, Boca Raton, FL, pp. 248.

Cooke, S.J., Hinch, S.G., 2013. Improving the reliability of fishway attraction and passage efficiency estimates to inform fishway engineering, science, and practice. Ecol. Eng. 58, 123–132. https://doi.org/10.1016/j.ecoleng.2013.06.005.

Ding, R.H., 1994. The Fishes of Sichuan, China. Sichuan Publishing House of Science and Technology, Chengdu.

Dodd, J.R., Gowx, I.G., Bolland, J.D., 2017. Efficiency of a nature-like bypass channel for restoring longitudinal connectivity for a river-resident population of brown trout. J. Environ. Manag. 204, 318–326. https://doi.org/10.1016/j.jenvman.2017.09.004.

Doehring, K., Young, R.G., McIntosh, A.R., 2011. Factors affecting juvenile galaxiid fish passage at culverts. Mar. Freshw. Res. 62, 38–45. https://doi.org/10.1071/mf10101.

Dunham, J.B., Vinyard, G.L., Rieman, B.E., 1997. Habitat fragmentation and extinction risk of Lahontan cutthroat trout. North Am. J. Fish Manage. 17, 1126–1133. https://doi.org/10.1577/1548-8675 (1997)017 < 1126:HFAERO > 2.3.CO;2.

FAO/DVWK, 2002. Fish Passes - Design, Dimensions and Monitoring. FAO, Rome.

Frank, H.J., Mather, M.E., Smith, J.M., Muth, R.M., Finn, J.T., McCormick, S.D., 2009. What is “fallback”?: metrics needed to assess telemetry tag effects on anadromous fish behavior. Hydrobiologia. 635, 237–249. https://doi.org/10.1007/s10750-009-9917-3.

Hall, C.J., Jordaan, A., Frisk, M.G., 2011. The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. Landsc. Ecol. 26, 95–107. https://doi.org/10.1007/s10980-010-9539-1.

Haro, A., Castro-Santos, T., Noreika, J., Odeh, M., 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Can. J. Fish. Aquat. Sci. 61, 1590–1601. https://doi.org/10.1139/f04-093.

Haugen, T.O., Aass, P., Stenseth, N.C., Vollestad, L.A., 2008. Changes in selection and evolutionary responses in migratory brown trout following the construction of a fish ladder: human induced evolution of brown trout vital rates. Evol. Appl. 1, 319–335. https://doi.org/10.1111/j.1752-4571. 2008.00031.x.

He, Y.F., Wang, J.W., Lek, S., Cao, W.X., Lek-Ang, S., 2011. Structure of endemic fish assemblages in the upper Yangtze River Basin. River Res. Appl. 27, 59–75. https://doi.org/10.1002/rra.1339.

Hou, Y., Cai, L., Wang, X., Chen, X., Zhu, D., Johnson, D., Shi, X., 2018. Swimming performance of 12 Schizothoracinae species from five rivers. J. Fish Biol. 92, 2022–2028. https://doi.org/10.1111/jfb.13632.

Kemp, P.S., Russon, I.J., Vowles, A.S., Lucas, M.C., 2011. The influence of discharge and temperature on the ability of upstream migrant adult river lamprey (*Lampetra fluviatilis*) to pass experimental overshot and undershot weirs. River Res. Appl. 27, 488–498. https://doi.org/10.1002/rra.1364.

Khan, B., Colbo, M.H., 2008. The impact of physical disturbance on stream communities: lessons from road culverts. Hydrobiologia. 600, 229–235. https://doi.org/10.1007/s10750-007-9236- 5.

Larinier, M., 2001. Environmental issues, dams and fish migration. In: Marmulla, G. (Ed.), Dams, Fish and Fisheries: Opportunities, Challenges and Conflict Resolution. FAO, Rome, Italy, pp. 45–90.

Luan, L., Jiang, Y.L., Liu, Y., He, Y.P., Yang, J.X., 2016. Variation of fish composition after impoundment of Pubugou Reservoir and proposed protection strategy. J. Hydroecology. 37, 62–69. (in Chinese with English abstract). 10.15928/j.1674-3075.2016.03.009.

Mallen-Cooper, M., Brand, D.A., 2007. Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? Fisheries Manag. Ecol. 14, 319–332. https://doi.org/10.1111/j.1365-2400.2007.00557.x.

Mao, 2018. Review of fishway research in China. Ecol. Eng. 115, 91–95. https://doi.org/10.1016/j.ecoleng.2018.01.010.

Margalef, D.R., 1957. Information theory in ecology. Int. J. Gen. Syst. 3, 36–71.

Maynard, G.A., Zydlewski, J.D., 2017. Size selection from fishways and potential evolutionary responses in a threatened Atlantic salmon population. River Res. Appl. 33https://doi.org/10.1002/rra.3155. 1104–1015.

Mckay, S.K., Schramski, J.R., Conyngham, J.N., Fischenich, J.C., 2013. Assessing upstream fish passage connectivity with network analysis. Ecol. Appl. 23, 1396–1409. https://doi.org/10.1890/12-1564.1.

McLaughlin, R.L., Smyth, E.R.B., Castro-Santos, T., Jones, M.L., Koops, M.A., Pratt, T.C., Velez-Espino, L.A., 2013. Unintended consequences and trade-offs of fish passage. Fish Fish. 14, 580–604. https://doi.org/10.1111/faf.12003.

Noonan, M.J., Grant, J.W.A., Jackson, C.D., 2012. A qualitative assessment of fish passage efficiency. Fish & Fisheries 13, 450–464. https://doi.org/10.1111/j.1467-2979.2011.

00445.x.
Ovidio, M., Sonny, D., Dierckx, A., Watthez, Q., Bourguignon, S., de le Court, B., Detrait, O., Benitea, J.P., 2017. The use of behavioural metrics to evaluate fishway efficiency. River Res. Appl. 33, 1484–1493. https://doi.org/10.1002/rra.3217.
Park, D., Sullivan, M., Bayne, E., Scrimgeour, G., 2008. Landscape-level stream fragmentation caused by hanging culverts along roads in Alberta's boreal forest. Can. J. For. Res. 38, 566–575. https://doi.org/10.1139/X07-179.
Pennock, C.A., Bender, D., Hofmeier, J., Mounts, J.A., Waters, R., Weaver, V.D., Gido, K.B., 2017. Can fishways mitigate fragmentation effects on great plains fish communities? Can. J. Fish. Aquat. Sci. 75, 121–130. https://doi.org/10.1139/cjfas-2016-0466.
Pielou, E.C., 1975. Ecological Diversity. John Wiley and Sons, New York.
Pinkas, L., Oliphant, M.S., Iverson, I.L.K., 1970. Food habits of Albacore, bluefin tuna, and bonito in California waters. Fish Bull Calif. 152, 1–105.
Pon, L.B., Hinch, S.G., Cooke, S.J., Patterson, D.A., Farrell, A.P., 2009. Physiological, energetic and behavioural correlates of successful fishway passage of adult sockeye salmon Oncorhynchus nerka in the Seton River, British Columbia. J. Fish Biol. 74, 1323–1336. https://doi.org/10.1111/j.1095-8649.2009.02213.x.
Romão, F., Quaresma, A.L., Branco, P., Santos, J.M., Amaral, S., Ferreira, M.T., Katopodis, C., Pinheiro, A.N., 2017. Passage performance of two cyprinids with different ecological traits in a fishway with distinct vertical slot configurations. Ecol. Eng. 108, 180–188. https://doi.org/10.1016/j.ecoleng.2017.04.031.
Roscoe, D.W., Hinch, S.G., 2010. Efficiency monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish Fish. 11, 12–33. https://doi.org/10.1111/j.1467 -2979.2009.00333.x.
Santos, J.M., Ferreira, M.T., Godinho, F.N., Bochechas, J., 2005. Efficacy of a nature-like bypass channel in a Portuguese lowland river. J. Appl. Ichthyol. 21, 381–388. https://doi.org/10.1111/i.1439-0426.2005.00616.x.
Sanz-Ronda, F.J., Bravo-Córdoba, F.J., Fuentes-Pérez, J.F., Castro-Santos, T., 2016. Ascent ability of brown trout, Salmo trutta, and two Iberian cyprinids - Iberian barbel, Luciobarbus bocagei, and northern straight-mouth nase, Pseudochondrostoma duriense - in a vertical slot fishway. Knowl. Manag. Aquat. Ecosyst. 417, 1–9. https://doi.org/10.1051/kmae/2015043.
Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana. https://doi.org/10.1002/j.1538-7305.1948.tb00917.x.
Shi, X.T., Kynard, B., Liu, D.F., Qiao, Y., Chen, Q.W., 2015. Development of fish passage in China. Fisheries 40, 161–169. https://doi.org/10.1080/03632415.2015.1017634.
Silva, A.T., Santos, J.M., Ferreira, M.T., Pinheiro, A.N., Katopodis, C., 2011. Effects of water velocity and turbulence on the behaviour of lberian barbel (*Luciobarbus bocagei*, Steindachner 1864) in an experimental pool-type fishway. River Res. Appl. 27, 360–373. https://doi.org/10.1002/rra.1363.
Silva, A.T., Lucas, M.C., Castro-Santos, T., Katopodis, C., Baumgartner, L.J., Thiem, J.D., Aarestrup, K., Pompeu, P.S., O'Brien, G.C., Braun, D.C., Burnett, N.J., Zhu, D.Z., Fjeldstad, H.-P., Forseth, T., Rajaratnam, N., Williams, J.G., Cooke, S.J., 2018. The future of fish passage science, engineering, and practice. Fish Fish. 19, 340–362. https://doi.org/10.1111/faf.12258.
Steffensen, S.M., Thiem, J.D., Stamplecoskie, K.M., Binder, T.R., Hatry, C., Langlois-Andersom, N., Cooke, S.J., 2013. Biological effectiveness of an inexpensive nature-like fishway for passage of warmwater fish in a small Ontario stream. Ecol. Freshw. Fish 22, 374–383. https://doi.org/10.1111/eff.12032.
Struthers, D.P., Danylchuk, A.J., Wilson, A.D.M., Cooke, S.J., 2015. Action cameras: Bringing aquatic and fisheries research into view. Fisheries 40, 502–512. https://doi.org/10.1080/03632415.2015.1082472.
Stuart, I.G., Mallen-Cooper, M., 1999. An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical subtropical river. Regula. Riv-Res. Manage 15, 575–590.
Tao, J.P., Tan, X.C., Yang, Z., Wang, X., Cai, Y.P., Qiao, Y., Chang, J.B., 2015. Fish migration through a fish passage associated with water velocities at the Changzhou fishway. J. Appl. Ichthyol. 31, 72–76. https://doi.org/10.1111/jai.12634.
Thiem, J.D., Binder, T.R., Dumont, P., Hatin, D., Hatry, C., Katopodis, C., Stamplecoskie, K.M., Cooke, S.J., 2013. Multi-species fish passage behaviour in a vertical slot fishway on the Richelieu River, Quebec, Canada. River Res. Appl. 29, 582–592. https://doi.org/10.1002/rra.2553.
Thiem, J.D., Dawson, J.W., Hatin, D., Danylchuk, A.J., Dumont, P., Gleiss, A.C., Wilson, R.P., Cooke, S.J., 2016. Swimming activity and energetic costs of adult lake sturgeon during fishway passage. J. Exp. Biol. 219, 2534–2544. https://doi.org/10.1242/jeb.140087.
Tummers, J.S., Hudson, S., 2016. Evaluating the efficiency of restoring longitudinal connectivity for stream fish communities: towards a more holistic approach. Sci. Total Environ. 569, 850–860. https://doi.org/10.1016/j.scitotenv.2016.06.207.
Vaughn, C.C., Taylor, C.M., 1999. Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. Conserv. Biol. 13, 912–920. https://doi.org/10.1046/j.1523- 1739. 1999.97343.x.
Wagner, R.L., Makrakis, S., Castro-Santos, T., Makrakis, M.S., Dias, J.H.P., Belmont, R.F., 2012. Passage performance of long-distance upstream migrants at a large dam on the Parana River and the compounding effects of entry and ascent. Neotrop. Ichthyol. 10, 785–795. https://doi.org/10.1590/S1679-622520120004000 11.
White, L.J., Harris, J.H., Keller, R.J., 2010. Movement of three non-salmonid fish species through a low-gradient vertical-slot fishway. River Res. Appl. 27, 499–510. https://doi.org/10.1002/rra.1371.
Winemiller, K.O., McIntyre, P.B., Castello, L., et al., 2016. Balancing hydropower and biodiversity in the Amazon, Congo and Mekong. Science 351, 128–129. https://doi.org/10.1126/science. aac7082.
Xu, H.Y., Wei, L., Zhao, Z.X., Sun, X.C., Zhao, Y., 2013. Study on design of fishway for Zhentouba I Hydropower Station in Dadu River. Water. Pow. 39, 5–7. (in Chinese with English abstract). https://doi.org/10.3969/j.issn.0559-9342.2013.10.002.
Yang, Y.L., Wen, Y.L., Li, C.P., Tan, Y., Deng, H.J., 2010. Impact of power station of Dadu River on fishes and solution. Sichuan. Environ. 06, 65–70. (in Chinese with English abstract). 10.14034/j.cnki.schj.2010.06.032.
Yu, X.Y., Tan, D.Q., Dan, S.G., Wang, J.W., 2018. Reproductive biology of *Liobagrus marginatus* (Günther) in Panzhihua reach of the Jinsha River. Sichuan J. of Zoology 37, 291–297. (in Chinese with English abstract). 10.11984/j.issn.1000-7083.20170288.
Zhuang, P., Zhao, F., Zhang, T., Chen, Y., Liu, J.Y., Zhang, L.Z., Kynard, B., 2016. New evidence may support the persistence and adaptability of the near-extinct Chinese sturgeon. Biol. Conserv. 193, 66–69. https://doi.org/10.1016/j.biocon.2015.11.006.