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Integrated Hydraulic and Biological Monitoring Reveals Stage-Specific Passage Performance in a Vertical-Slot Fishway in the Upper Yangtze River

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Abstract

Dams fragment river networks, but post-construction evaluations of fishways often treat hydraulic suitability and biological performance separately. We assessed a 1486-m-long vertical-slot fishway comprising 326 pools at the Jinsha Hydropower Station in the upper Yangtze River during its first operating season. The assessment integrated upstream and downstream fish-assemblage surveys, as-built geometric inspection, field hydraulic measurements, diagnostic three-dimensional computational fluid dynamics (CFD), underwater video, block-net sampling, and passive integrated transponder (PIT) telemetry of 95 fish representing 12 species. Pre-commissioning inspection revealed substantial deviations in vertical-slot width, which were corrected before operation. Mean measured entrance velocity was approximately 0.40 m/s and representative slot velocities were 0.90–1.08 m/s; diagnostic CFD reproduced slot-jet velocity magnitudes of approximately 0.9–1.1 m/s and indicated localized flow-acceleration magnitudes of approximately 1.9 m/s^2 near slot transitions. PIT detections declined from 57 fish at the downstream monitoring checkpoint (T1) to 34 at an intermediate dam-site checkpoint (T2) and 12 at the upstream-exit checkpoint (T3). Accordingly, 60.0% of released fish were detected at T1, 21.1% of fish detected at T1 subsequently reached T3, and 12.6% of all released fish reached T3 from the release location within the monitoring period. The combination of broadly acceptable representative velocities with a low observed route-completion proportion within the PIT-tagged experimental group indicates that compliance with nominal hydraulic criteria alone is insufficient for evaluating long fishways. The progressive decline in PIT detections, local hydraulic heterogeneity, as-built geometric variability, and unoptimized operation emerged as priority hypotheses for adaptive testing. Post-construction evaluation should therefore couple structural quality control and stage-specific biological monitoring with controlled operational trials of attraction flow, gate settings, and water levels.

Keywords: river connectivity; vertical-slot fishway; PIT telemetry; passage success; hydraulic heterogeneity; adaptive operation

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1. Introduction

Dams provide renewable-energy and water-management benefits, but they also disrupt longitudinal river connectivity and can restrict migration, gene flow, and access to spawning,

feeding, nursery, and refuge habitats. Fish-passage structures are therefore a core ecological-engineering intervention for restoring movement pathways in regulated rivers [1–3]. Their ecological value, however, depends on realized biological performance rather than on structural completion or nominal hydraulic compliance alone.

Vertical-slot fishways are widely used because they can accommodate fluctuations in water level while maintaining a continuous water column through successive pools [4]. Passage nevertheless depends on a sequence of behavioral and hydraulic processes: fish must approach and locate the entrance, enter the structure, traverse hydraulically challenging sections, use low-velocity recovery zones when needed, and ultimately exit upstream. Consequently, mean pool velocity or compliance with a single design threshold cannot, by itself, demonstrate restored connectivity. Standardized, stage-specific metrics are needed to distinguish limitations in approach and entry from bottlenecks that occur within the fishway [5–8].

This distinction is especially important for long fishways, in which modest losses at successive sections can accumulate into poor whole-facility performance. Studies from southwestern China have shown that passage success can vary substantially among species, seasons, hydraulic conditions, and fishway sections [9,10]. At the national scale, vertical-slot fishways are now among the most widely implemented fish-passage structures in China, whereas systematic post-construction monitoring remains limited relative to the number of facilities built [11]. Robust post-construction evaluation is therefore needed not only to verify design assumptions, but also to identify structural and operational adjustments that can improve ecological outcomes.

In China, fish passage is increasingly embedded in environmental regulation and project-level ecological management. The Fisheries Law requires fish-passage facilities or other remedial measures where dams or sluices on migration routes seriously affect fishery resources. More recently, NB/T 11179-2023 formalized environmental monitoring throughout hydropower-project construction and operation, while NB/T 11181-2023 established procedures for environmental-protection acceptance at project completion [12,13]. Yet a national review identified 211 fish-passage facilities but operational records for only 18, showing that standardized effectiveness monitoring still lags behind construction [11]. This regulatory–implementation gap highlights the need for biologically explicit post-construction assessment to guide adaptive operation and structural refinement.

The fishway at Jinsha Hydropower Station provides an informative case because it is unusually long (approximately 1.5 km), contains 326 pools, and was designed to serve a multispecies assemblage that includes endemic and rheophilic fishes. We integrated as-built inspection, field hydraulics, diagnostic CFD, fish-community sampling, video and block-net observations, and PIT telemetry to address three questions: (1) Did the constructed geometry and hydraulic conditions remain within the intended design envelope? (2) At which monitored stage was the greatest decline in PIT detections observed? (3) Which operational or engineering actions are most strongly supported by the observed patterns? By explicitly separating release-to-T1 arrival, intermediate-route progression, and T1-to-T3 passage metrics, we sought to develop a post-construction diagnostic framework that is transferable to other long fishways used to restore longitudinal river connectivity.

2. Materials and Methods

2.1. Study Area and Fishway Configuration

Jinsha Hydropower Station is located on the Panzhihua reach of the middle Jinsha River in southwestern Sichuan Province, China [14]. The Jinsha River forms the upper course of the Yangtze River and is approximately 3481 km long, with a drainage area of 458,800 km^2 [15]. The fishway was completed in March 2021 on the left bank, adjacent

to the powerhouse. It is a composite vertical-slot system comprising three entrances, two exits, a fish-collection channel, and a supplemental-flow system. The main fishway extends approximately 1486 m and contains 326 pools. It consists primarily of standard vertical-slot pools ("normal pools") approximately 3.0 m wide and 3.5 m long, with a bed slope of 1:50. Longer, lower-gradient rest pools were inserted periodically, generally after approximately every 10 normal pools; these pools were approximately 7.0 m long with a bed slope of 1:100 and were intended to provide lower-velocity recovery areas during upstream passage. Both pool types used the same general single-sided vertical-slot configuration with a design slot width of 0.40 m. The standard-pool geometry corresponds to a nominal bed-elevation drop of 0.070 m between successive pools. Design-stage hydraulic-model information indicated an inter-pool water-surface difference of approximately 0.06 m (design value 6.2 cm) when the water depth along the fishway was approximately 2.5 m; these values are design/physical-model results rather than prototype measurements obtained in the present study. U-shaped entrance and exit reaches are fitted with vertical-lift gates operated in response to upstream and downstream water levels (Figure 1). The prototype operating conditions evaluated in this study are characterized separately by measured upstream water levels of 1020.32 and 1021.21 m (Section 3.2.2) and should not be interpreted as design inlet levels.

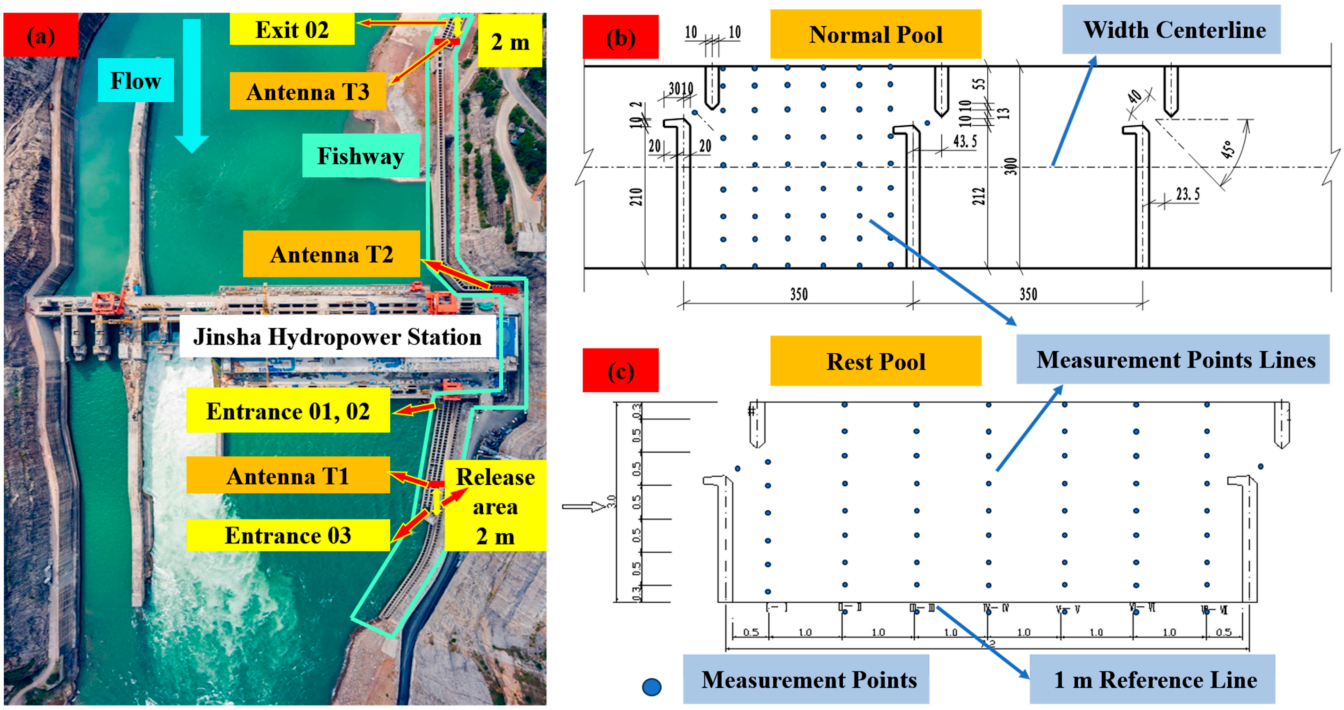


Figure 1. Layout of the Jinsha Hydropower Station fishway and PIT telemetry system, with representative pool configurations: (**a**) fishway layout, antenna locations, and fish release area; (**b**) normal pool; and (**c**) rest pool. Dimensions are expressed in meters (m) in panels (**a**,**c**), and in centimeters (cm) in panel (**b**).

2.2. Fish Resource Assemblage Survey

Fish assemblages were surveyed upstream and downstream of the dam in accordance with the Yangtze River Fish Monitoring Manual [16], the Handbook for Surveys of Natural Fishery Resources in Inland Waters [17], and the Technical Code for Investigation and Assessment of Aquatic Ecosystem for Hydropower Projects (NB/T 10079-2018) [18]. Specifically, the upstream survey reach extended from downstream of the Guanyinyan Dam to immediately upstream of the Jinsha Dam, whereas the downstream survey reach extended

from immediately downstream of the Jinsha Dam to the Yuzha reach. These survey reaches were selected to characterize fish assemblages upstream and downstream of the dam and to provide ecological context for potential fishway users. Within each designated survey reach, four set cage nets (mouth opening 30 × 40 cm; length 10 m) and one gill net (1.5 m deep, 50 m long, 2-cm mesh) were deployed during fixed-duration daily sampling. Field surveys were conducted in April and September 2021 by contracted local fishers, with supplementary sampling by the project team. These periods were selected based on multi-year fish-resource monitoring in the middle Jinsha River and published information on the seasonal movements of regional fishes [19]. The fish assemblage relevant to the fishway is dominated by freshwater resident and potamodromous species rather than diadromous fishes. April overlaps with the spring–early summer reproductive-migration period of several target fishes, including *Coreius guichenoti*, whereas September represents another period of pronounced seasonal movement observed in long-term regional surveys. Accordingly, the April and September surveys were intended to characterize fish assemblages during two biologically active movement periods, rather than to encompass the complete migratory period of every species. Fish were identified to species in the field and measured individually for total length, standard length, and body mass (to the nearest 1 mm and 1 g, respectively). Healthy individuals showing normal swimming behavior and no visible external injury were selected for subsequent PIT-tagging trials and transferred to the Jinsha Hydropower Station fish propagation station. Fish were transported in water-filled containers supplied with continuous aeration/oxygenation, with transport water maintained as close as possible to the temperature and water-quality conditions of the source river. Handling and transfer times were minimized, and fish were visually monitored during transport for abnormal behavior or loss of equilibrium. Upon arrival, fish were transferred to holding tanks and allowed to acclimate before tagging.

2.3. As-Built Geometry and Hydraulics

2.3.1. As-Built Geometry Survey

From 8 to 15 March 2021, before water was introduced into the fishway, pool length, width, depth, baffle configuration, and vertical-slot width were surveyed using a GLM 100-25 C laser distance meter (Robert Bosch GmbH, Gerlingen, Germany) and a Trimble DiNi digital level (Trimble Inc., Westminster, CO, USA), with a steel square used for supplementary verification of local structural dimensions. The fishway employs a single-slot, baffle-type vertical-slot configuration, with a nominal slot width of 0.40 m and a baffle thickness of 0.20 m. Each slot is formed by an asymmetric arrangement consisting of a main lateral baffle and a shorter opposing deflector, producing a concentrated jet through the slot and recirculation zones within the pool. Similar baffle-controlled vertical-slot configurations have been widely investigated in previous hydraulic studies [8,20]. Measurements were compared with the geometric criteria specified in the original fishway design. Deviations in slot width, baffle geometry, and structural completeness were recorded for all 326 pools. Where slot dimensions deviated substantially from the design, baffle edges and associated structural elements were adjusted or reconstructed to restore the intended slot geometry. Missing structural components were reinstalled according to the design drawings, and the corrected geometry was rechecked before the fishway entered operation.

2.3.2. Field Hydraulic Measurements

Flow velocity was measured at the fishway entrance, a representative standard pool, a representative rest pool, and the upstream exit. Within the standard and rest pools, measurements were taken at four characteristic locations corresponding to the vertical slot, pool center, left side, and right side (Figure 1). These measurement-point labels correspond

directly to the locations reported in the hydraulic results. Because precise point coordinates were not available in the original field records, their positions in the schematic are shown as functional measurement locations rather than exact surveyed coordinates. Flow velocity was measured at the fishway entrance, representative normal pools, rest pools, and the upstream exit using a surface-velocity radar (HZ-SVR-35VH, Hangzheng Technology, Shanghai, China), with particular attention to the vertical-slot region. Measurements were interpreted in relation to the swimming-performance envelope of regional target fishes, while recognizing that successful passage depends on both a detectable attraction signal and the availability of lower-velocity recovery areas [21–23]. Tailrace velocities were additionally measured with an ultrasonic current meter (FlowTracker, SonTek, San Diego, CA, USA) to characterize the hydraulic context into which the fishway entrance discharged.

2.3.3. Diagnostic CFD Modelling

Representative pools were simulated in ANSYS Fluent 2024 R2 using a three-dimensional Reynolds-averaged Navier–Stokes (RANS) formulation. The modeled reach was selected from the repeated main section of the fishway and represented the standard vertical-slot pool configuration rather than the full 1486-m fishway. Entrance and exit reaches, rest pools, and other structurally distinct sections were outside the intended scope of the CFD analysis. The computational geometry was based on measured pool and slot dimensions, and field hydraulic information from the monitored operating conditions was used to parameterize the simulations. Accordingly, the CFD analysis was intended to characterize the local spatial flow structure of the standard-pool configuration rather than to predict hydraulic conditions throughout all 326 pools. Turbulence was closed with the renormalization-group (RNG) k–ε model, and the air–water interface was represented using the Volume of Fluid (VOF) method. The numerical analysis was used to resolve spatial features that could not be characterized by point measurements alone, including jet trajectory, shear-layer development, recirculation, and localized acceleration near slot transitions. In the source CFD output, acceleration is a distinct hydraulic variable with units of m/s^2 and is not equivalent to velocity magnitude (m/s). Model plausibility was assessed by comparing simulated velocity magnitudes and flow-pattern structure with available field observations at representative locations. Because the field measurements and CFD outputs were not obtained at strictly co-located points under identical boundary conditions, this comparison was treated as a field-scale consistency/plausibility check rather than formal point-by-point validation. For visualization of the in-pool velocity field, velocity magnitude was extracted on a horizontal plane located 0.2H below the free surface (approximately 0.8H above the local pool bottom), where H denotes the local water depth.

2.4. Fish Passage Monitoring

2.4.1. Underwater Video Monitoring

A custom-developed underwater fish-monitoring system was installed at the upstream exit to document fish passage direction, abundance, size class, and taxonomic identity (Figure 2). The imaging hardware consisted of a Hikvision underwater camera (DS-2XC6225G0-L, Hangzhou Hikvision Digital Technology Co., Ltd., Hangzhou, China). The system also incorporated transmission cables, a digital recording unit, remote data-transmission modules, and an infrared-assisted observation component. Recording was continuous when the system and fishway were operational, whereas reliable species-level visual identification was restricted to periods of adequate water clarity (approximately 5–6 h/day). Monitoring extended from 14 April to 10 June 2021. Records from 18 April to 5 May, when gate operations caused dewatering of the monitored reach, were excluded from the passage summary. Video monitoring and PIT telemetry served distinct but com-

plementary purposes in this study. Video monitoring was used to document the occurrence, passage direction, abundance, size class, and observable taxonomic composition of naturally occurring fish at the upstream fishway exit, thereby providing independent evidence of natural fish use of the fishway. It was not used to identify PIT-tagged individuals or to estimate PIT-based passage success. PIT telemetry, in contrast, tracked known tagged individuals among successive monitoring sections (T1–T3) to quantify stage-specific progression. Accordingly, video and PIT records were interpreted as complementary rather than directly cross-validated datasets. Video monitoring at or near fishway exits has similarly been used to document the abundance, taxonomic identity, and timing of naturally passing fish, while PIT telemetry provides individual-based estimates of passage performance.

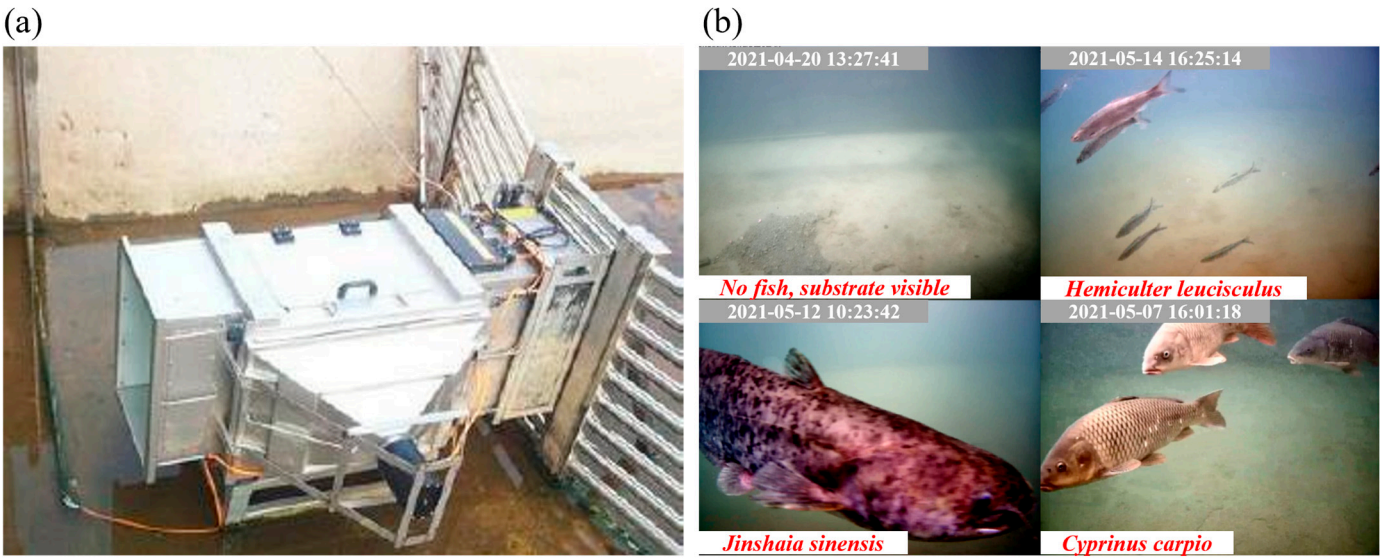


Figure 2. Underwater video monitoring system and representative observations: (**a**) camera channel; (**b**) representative video frames showing *Hemiculter leucisculus*, *Jinshaia sinensis*, and *Cyprinus carpio*, together with a frame showing no fish and the visible substrate.

2.4.2. Block-Net Sampling Procedure

On 10 June 2021, during the principal upstream-migration period, fish occupying the fishway were sampled using a block-net approach. The upstream exit was closed, and a seine or blocking screen was positioned within a suitable pool to retain fish in the sampled reach. Captured individuals were identified to species and measured for total length, standard length, and body mass. Vigorous individuals were eligible for transfer to temporary holding before PIT-tagging trials.

2.4.3. PIT Telemetry

Healthy fish obtained from river and fishway surveys were held for approximately 3–5 d before tagging. Individuals in good condition were anesthetized with MS-222 (tricaine methanesulfonate; Aladdin, Shanghai, China), and sterilized PIT tags were implanted intramuscularly into the dorsal epaxial musculature using a sterile injector [24]. The available field records document the PIT-tag mass as approximately 0.6 g; manufacturer, model, and tag dimensions could not be reliably recovered and are therefore not retrospectively reported. Dorsal-musculature implantation was used because the tagged fish were relatively large-bodied and provided sufficient muscle depth for tag placement while avoiding penetration of the visceral cavity; previous studies have shown high tag retention and minimal effects on growth and survival using this approach in larger fishes [25]. The implantation site was disinfected, and fish were given a minimum post-tagging recovery/observation

period of approximately 24 h. Prior to release, fish were required to maintain normal upright equilibrium, resume sustained voluntary swimming, and show no persistent abnormal behaviour, obvious bleeding, or severe external injury. These criteria constituted a field-based behavioural and external-condition screening rather than confirmation of complete physiological recovery. Because the smallest tagged fish weighed approximately 157 g, the maximum tag burden was approximately 0.38% of body mass. In total, 95 fish representing 12 species were tagged (Table 1).

Table 1. Species composition and body size of PIT-tagged fish.

Fish Category	Species	Number	Body Length (mm) Mean ± SD	Body Mass (g) Mean ± SD
Primary target	*Coreius guichenoti*	2	348.50 ± 33.23	760.09 ± 273.30
Primary target	*Onychostoma sima*	20	238.45 ± 25.07	324.97 ± 111.22
Primary target	*Procypris rabaudi*	17	323.41 ± 36.26	782.11 ± 205.47
Primary target	*Percocypris pingi*	1	395.00	831.62
Secondary target	*Schizothorax wangchiachii*	8	333.75 ± 62.85	802.53 ± 512.35
Secondary target	*Schizothorax chongi*	13	382.08 ± 56.79	1197.39 ± 421.65
Secondary target	*Schizothorax dolichonema*	9	427.89 ± 72.57	1692.97 ± 1102.37
Other	*Schizothorax prenanti*	20	345.35 ± 74.30	876.26 ± 487.25
Other	*Garra pingi*	2	340.50 ± 19.09	804.36 ± 24.54
Other	*Chanodichthys erythropterus*	1	240.00	197.70
Other	*Pseudobagrus truncatus*	1	222.00	161.29
Other	*Carassius auratus*	1	175.00	157.21

Tagged fish were assigned to three passage-target categories according to the original fishway design objectives, conservation priorities, and regional movement ecology: primary passage targets, secondary passage targets, and other species. Primary targets comprised species with particularly high conservation or passage priority, including *Coreius guichenoti*, whereas secondary targets mainly comprised rheophilic schizothoracine fishes with documented seasonal movement requirements. Other species were not designated as principal targets in the original fishway design, although some may also undertake local or seasonal movements. Three half-duplex RFID antenna systems were installed along the active fishway route (Figure 3). T1 was positioned approximately 2 m upstream of the No. 3 downstream entrance, T2 was located at the dam-site section, and T3 was positioned approximately 2 m downstream of the upstream fishway exit shown in Figure 1. Each antenna was installed across the corresponding vertical-slot opening. Tagged fish were released individually within the fishway section between Entrance 3 and T1, so detection at T1 represented arrival at the downstream monitoring checkpoint rather than attraction to, or entry into, the fishway from the natural tailrace. Tag identity, release time, and release location were recorded for each individual. Antenna-specific detection range and in situ detection efficiency were not quantitatively calibrated; missed detections were therefore possible, and absence of detection was not interpreted as definitive evidence that a fish failed to reach a monitoring section. Monitoring continued for 7 d after the final release, after which antenna records were exported for analysis. This predefined window was substantially longer than the typical passage times observed among fish that successfully reached T3, which were generally on the scale of tens of hours, but it was not demonstrated to be the optimal biological monitoring duration.



Figure 3. PIT antenna deployment (**a**,**b**) and tagged-fish release (**c**,**d**).

2.5. Performance Metrics and Statistical Treatment

Similarity in species composition between upstream and downstream survey reaches was summarized using the Jaccard coefficient, $J = a/(a + b + c)$, where a is the number of species shared by both reaches and b and c are the numbers unique to the upstream and downstream reaches, respectively. The coefficient ranges from 0 (no shared species) to 1 (identical species lists).

PIT performance was summarized using stage-specific proportions with explicit denominators [7]. We calculated the release-to-T1 arrival proportion (ET1 = NT1/Nrelease), intermediate-route success (E12 = NT2/NT1), internal T1-to-T3 passage success (Epass = NT3/NT1), upper-segment success (E23 = NT3/NT2), and overall release-to-T3 success (Eoverall = NT3/Nrelease). Exact counts are reported together with percentages, and 95% Wilson score confidence intervals were calculated for pooled binomial proportions. Release-to-T1 transit time was defined as the interval from release to first detection at T1, intermediate transit time as the interval between first detections at T1 and T2, and T1-to-T3 passage time as the interval from first detection at T1 to first detection at T3. Because successful passage counts were small for several species and ecological groups, between-group results were treated descriptively and no inferential comparisons among species or groups were attempted. Because species were represented by unequal sample sizes and may differ in swimming capacity and behavioral responses, pooled PIT metrics were used only to describe the observed performance of the PIT-tagged experimental group under the monitored conditions and were not interpreted as estimates for the entire fish assemblage using the fishway.

3. Results

3.1. Fish Assemblage Context

Across the April and September 2021 surveys, 38 fish species representing 3 orders, 9 families, and 27 genera were recorded. The upstream sample comprised 66 individuals (45,525.37 g) from 19 species, whereas the downstream sample comprised 288 individuals (49,495.09 g) from 33 species (Figure 4). Fourteen species occurred in both reaches, yielding a Jaccard similarity coefficient of 0.368. Observed species richness and abundance were therefore higher in the downstream sample, although this contrast is presented only as ecological context and should not be interpreted as a direct estimate of dam impact.

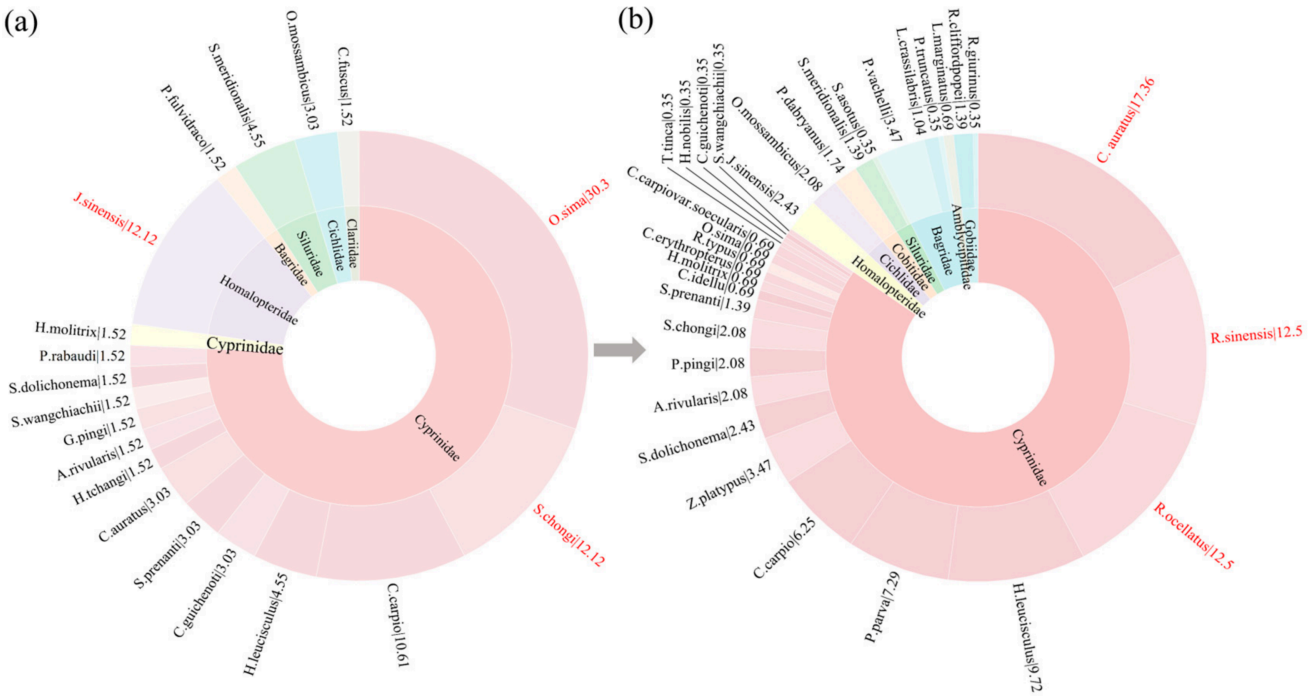


Figure 4. Upstream (**a**) and downstream (**b**) fish assemblages in April and September 2021. Species names highlighted in red indicate the three fish species with the highest proportions of individuals during each survey period.

In the upstream sample, *Onychostoma sima* accounted for 30.30% of individuals, followed by *Schizothorax chongi* and *Jinshaia sinensis* (12.12% each). Upstream biomass was dominated by *S. chongi* (32.03%) and *Cyprinus carpio* (29.04%). In the downstream sample, *Carassius auratus* was most abundant (17.36%), followed by *Rhodeus sinensis* and *Rhodeus ocellatus* (12.50% each), while biomass was dominated by *C. carpio* (19.85%) and *C. auratus* (15.39%). Importantly, primary and secondary fishway target species occurred in the assemblages on both sides of the dam, confirming the presence of potential fishway users in the study reach.

3.2. As-Built Geometry and Hydraulic Conditions

3.2.1. As-Built Geometry

All 326 pools were inspected. The as-built vertical-slot width averaged 40.70 cm but ranged from 19.00 to 92.00 cm. Thirty-five pools had slot widths <30 cm and 158 had slot widths <40 cm; pool 180 also lacked a small baffle. Relative to the 0.40-m design width, these deviations were substantial and were corrected after the survey. Although the standard pools followed a repeated nominal design, these observations demonstrate that design repeatability did not imply complete as-built geometric uniformity among pools.

Because paired hydraulic measurements were not conducted before and after correction for individual pools, the hydraulic effect of each structural correction could not be quantified directly; the corrective work was intended to restore the nominal design geometry before operational monitoring.

3.2.2. Hydraulic Conditions

At upstream water levels of 1020.32 and 1021.21 m, measured vertical-slot velocities in a representative normal pool were approximately 0.90 and 1.08 m/s, respectively (Table 2), while fishway discharge increased from approximately 0.68 to 1.38 m^3/s. Entrance velocity remained comparatively low and stable at 0.43 and 0.37 m/s (mean approximately 0.40 m/s). By contrast, measurements in the external powerhouse tailrace, outside the standard fishway pools, showed a highly heterogeneous flow field, with local forward velocities up to 2.59 m/s and reverse velocities down to −0.97 m/s. These tailrace velocities were associated with the external downstream flow field and should not be interpreted as vertical-slot velocities generated by the head difference between adjacent fishway pools.

Table 2. Measured velocities (m/s) at representative fishway locations under two upstream water levels.

Upstream Water Level (m)	Location	Vertical Slot	Pool Center	Left Side	Right Side
1020.32	Entrance	—	0.43	—	—
	Rest Pool	1.02	0.55	0.45	0.55
	Normal Pool	0.9	0.46	−0.5	−0.58
	Exit	—	0.20	—	—
1021.21	Entrance	—	0.37	—	—
	Rest Pool	0.9	0.63	0.42	0.45
	Normal Pool	1.08	0.72	−0.43	−0.65
	Exit	—	0.15	—	—

Diagnostic CFD reproduced the hydrodynamics of a vertical-slot pool, including a high-velocity jet issuing from the slot, adjacent shear layers, and recirculation zones (Figure 5). Measured vertical-slot velocities in the representative normal pool were 0.90 and 1.08 m/s under the two monitored upstream water levels, whereas the simulated principal slot-jet velocity magnitude was approximately 0.9–1.1 m/s. Measured pool-center velocities were 0.46 and 0.72 m/s, compared with simulated values of approximately 0.6–0.8 m/s. These measured and simulated velocities were therefore broadly consistent in magnitude, particularly in the slot-jet region. The CFD acceleration field also indicated localized flow-acceleration magnitudes of approximately 1.9 m/s^2 near slot transitions; this is a different hydraulic variable from velocity magnitude and should not be interpreted as a maximum velocity. Because the field measurements and CFD outputs were not spatially co-located under identical hydraulic boundary conditions, formal point-by-point error metrics such as MAD or RMSE were not calculated. The CFD results are therefore interpreted as a diagnostic description of the modeled standard-pool configuration and should not be extrapolated to the entrance, exit, rest pools, or all 326 pools of the fishway.

3.3. Passage Observations from Video and Block-Net Sampling

3.3.1. Video Monitoring

After records affected by dewatering were excluded, the video/infrared system recorded approximately 64 fish per monitored day in April, 96 in May, and 124 in June, with an overall mean of approximately 100 fish per monitored day (Figure 6). Daily counts ranged from 23 fish on 6 May to 237 fish on 4 June. Among fish that could be identified

taxonomically, *Jinshaia sinensis* was dominant (approximately 62%), followed by *Triplophysa anterodorsalis* (approximately 27%) and *Hemiculter leucisculus* (approximately 8%). Because species-level identification depended on water clarity and was not available continuously, these values characterize observed passage during monitored periods rather than standardized 24-h species-specific use. These observations describe natural fish occurrence and passage at the upstream exit and should not be interpreted as passage rates or species-specific outcomes for the PIT-tagged experimental fish.

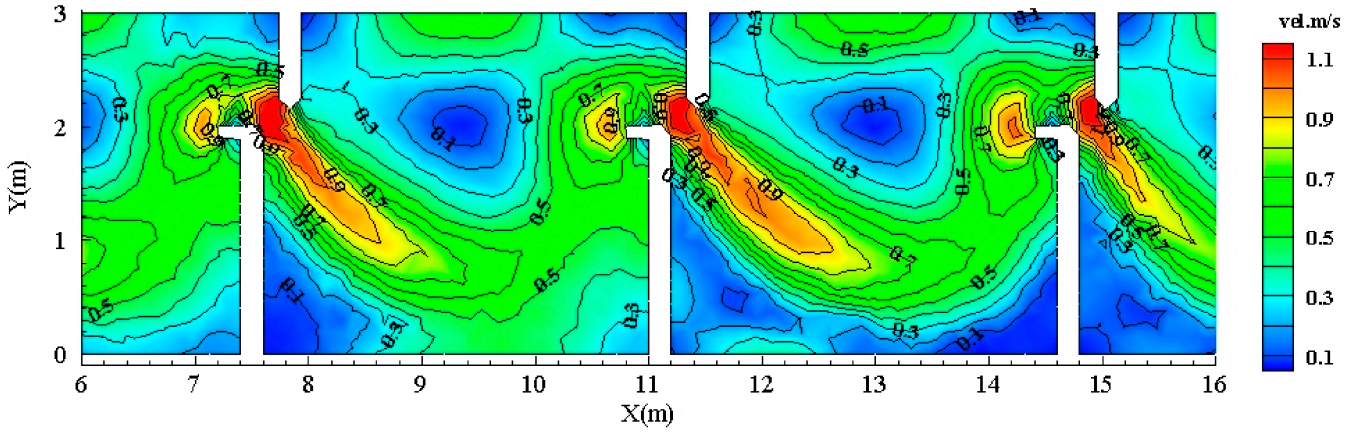


Figure 5. Simulated velocity-magnitude fields in two consecutive normal pools under hydraulically stable conditions, extracted on a horizontal plane 0.2H below the free surface (approximately 0.8H above the local pool bottom), where H is the local water depth. The contours show velocity magnitude (m/s).

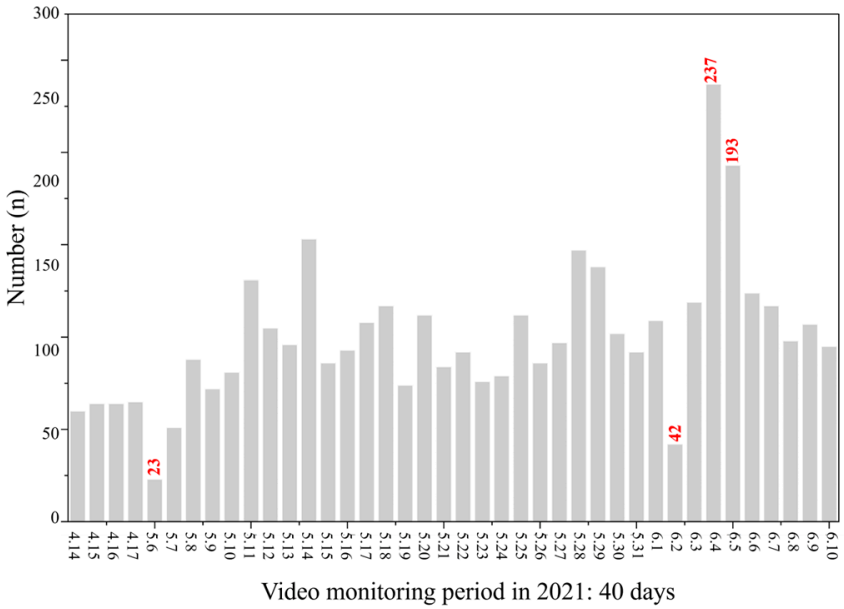


Figure 6. Fish counts recorded by the video/infrared monitoring system during the 2021 monitoring period. Red labels identify the two lowest daily counts (23 and 42 fish) and the two highest (237 and 193 fish).

3.3.2. Block-Net Sampling

Block-net sampling on 10 June captured 15 species (1 cichlid, 6 cobitids, and 8 cyprinids), documenting multispecies occupancy of the fishway during that sampling event (Figure 7). The largest individual was *Cyprinus carpio* (total length 460 mm; body

mass 1621.5 g), whereas the smallest was *Pseudorasbora parva* (total length 40 mm; body mass 0.5 g). *Jinshaia sinensis*, *P. parva*, and *Hemiculter leucisculus* together comprised approximately 67% of the catch. One adult *Onychostoma* sima and one juvenile *Schizothorax wangchiachii*, both fishway passage targets, were also captured.

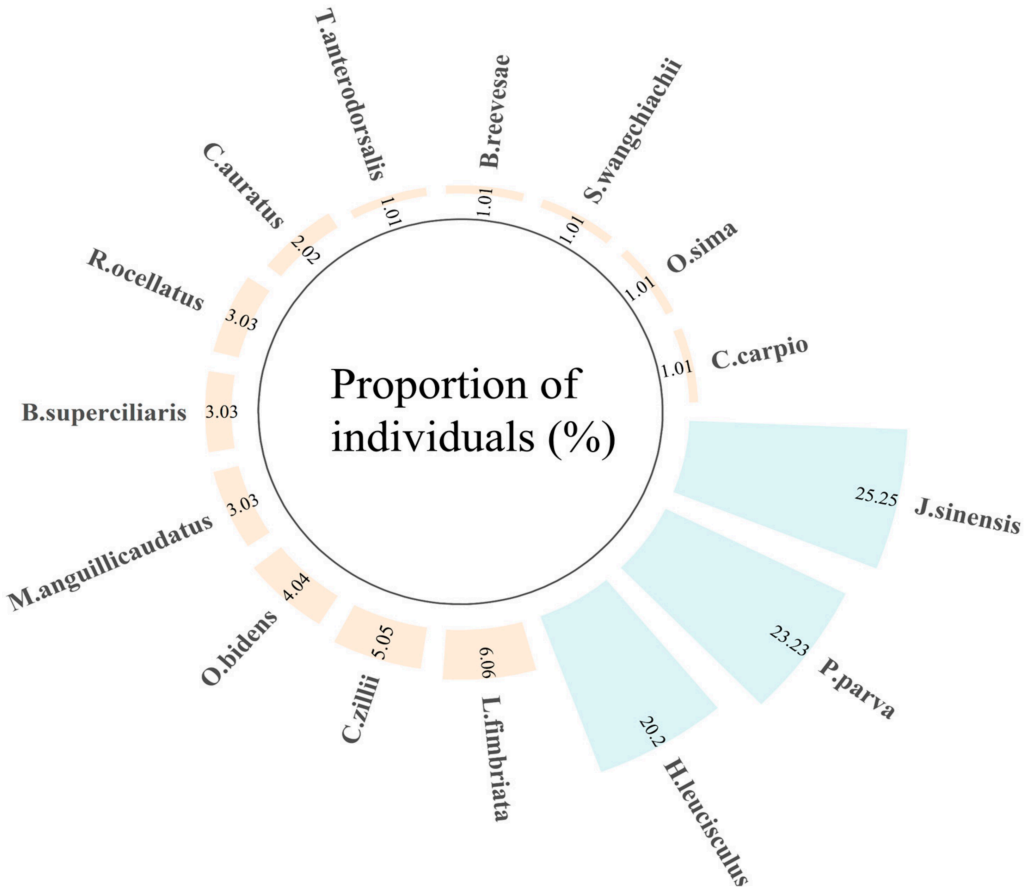


Figure 7. Species composition of fish captured by block-net sampling in the fishway on 10 June 2021. Light blue highlights the three most abundant species; light beige denotes the remaining species. Values are percentages of captured individuals.

3.4. PIT-Based Stage-Specific Performance

Of the 95 tagged fish released, 57 were detected at T1, 34 at T2, and 12 at T3 (Table 3). The pooled release-to-T1 arrival proportion was therefore 60.0% (57/95; 95% CI 49.9–69.3%). Conditional on detection at T1, 59.6% were subsequently detected at T2 (34/57; 95% CI 46.7–71.4%), and 21.1% reached T3 (12/57; 95% CI 12.5–33.3%). Upper-segment success from T2 to T3 was 35.3% (12/34; 95% CI 21.5–52.1%), and the observed release-to-T3 route-completion proportion was 12.6% (12/95; 95% CI 7.4–20.8%). These pooled proportions describe only the observed performance of the 95 PIT-tagged experimental fish under the monitored conditions. Because the 12 species were represented by unequal sample sizes, these values should not be interpreted as estimates of passage performance for the entire natural fish assemblage or for all target species of the fishway. The stage-specific pattern represents a progressive decline in detections along the monitored route after release rather than definitive evidence that every undetected fish physically failed to reach the next section.

Transit times were highly variable within each ecological group (Table 4). Mean release-to-T1 transit time was longest for primary target species (26.26 ± 13.23 h), whereas mean T1-to-T3 passage time among successful fish ranged from 29.04 ± 12.44 h for primary

targets to 37.70 ± 10.95 h for other species. Because only 12 fish reached T3, these transit-time summaries should be interpreted descriptively and not as precise population-level estimates.

Table 3. Numbers of PIT-tagged fish released and detected at successive monitoring antennas.

Fish Category	Released (*n*)	T1 Detected (*n*)	T2 Detected (*n*)	T3 Detected (*n*)
Primary target	40	21	11	5
Secondary target	30	22	16	4
Other	25	14	7	3
Total	95	57	34	12

Table 4. Release-to-T1, intermediate, and T1-to-T3 transit times of PIT-tagged fish by fish category (mean ± SD).

Fish Category	Release-to-T1 Transit Time (h)	Intermediate Transit Time/T1–T2 Time (h)	T1–T3 Passage Time (h)
Primary target	26.26 ± 13.23	26.65 ± 16.10	29.04 ± 12.44
Secondary target	13.47 ± 15.65	32.36 ± 20.22	30.40 ± 11.93
Other	11.69 ± 11.72	28.94 ± 14.36	37.70 ± 10.95

Category-specific release-to-T1 arrival proportions were 52.5% for primary targets, 73.3% for secondary targets, and 56.0% for other species. Conditional T1-to-T3 passage success was 23.8%, 18.2%, and 21.4%, respectively, and corresponding release-to-T3 route-completion proportions were 12.5%, 13.3%, and 12.0% (Table 5). The similarity of observed route-completion outcomes among categories, together with the small number of successful passages, precluded strong inference about differences among ecological groups.

Table 5. Stage-specific PIT passage metrics for the three fish categories and the pooled sample.

Fish Category	Release-to-T1 (%)	T1→T2 (%)	T2→T3 (%)	T1→T3 (%)	T3/Released (%)
Primary target	52.5 (21/40)	52.4 (11/21)	45.5 (5/11)	23.8 (5/21)	12.5 (5/40)
Secondary target	73.3 (22/30)	72.7 (16/22)	25.0 (4/16)	18.2 (4/22)	13.3 (4/30)
Other	56.0 (14/25)	50.0 (7/14)	42.9 (3/7)	21.4 (3/14)	12.0 (3/25)
Total number	60.0 (57/95)	59.6 (34/57)	35.3 (12/34)	21.1 (12/57)	12.6 (12/95)

4. Discussion

4.1. Stage-Specific Monitoring Reveals a Progressive Decline in PIT Detections

The principal biological result is the progressive decline in PIT detections across successive monitoring stages rather than any single value of "fishway efficiency." Sixty percent of released fish were detected at T1, 21.1% of fish detected at T1 subsequently reached T3, and 12.6% of all released fish reached T3 from the release location within the monitoring period. The fixed 7-d monitoring window is an important limitation: although it was substantially longer than the typical passage times observed among successful fish, some individuals may have remained within the fishway or completed passage after monitoring ended. The PIT experiment was also conducted in an open fishway without blocking nets at the entrance or upstream exit, and antenna-specific detection efficiency was not quantitatively calibrated. Consequently, absence of detection cannot be treated as definitive evidence of physical passage failure, and the magnitude of any bias associated with missed or late detections cannot be quantified retrospectively. These pooled values characterize the PIT-tagged experimental group rather than the fish community as a whole; unequal species

representation and potential interspecific differences in swimming capacity and behavior further limit community-level extrapolation. This distinction matters because attraction, entry, internal passage, and overall passage are frequently reported with different denominators [5,7]. For example, two vertical-slot fishways in the Toce River exhibited conditional passage efficiencies of approximately 60–65% despite low attraction efficiency [26], whereas a pool-and-weir fishway for *Gymnocypris przewalskii* showed entry and passage proportions of 13% and 5%, respectively [27]. A 1228-m vertical-slot fishway on the Dadu River likewise showed substantially higher success in individual sections than for whole-route completion [10]. Direct quantitative comparison among studies should nevertheless be made cautiously because sample sizes, species, monitoring configurations, and confinement conditions differ. In the present study, video observations were additionally constrained by water clarity and the monitored periods, while the block-net survey represented a single sampling event on 10 June and should therefore be interpreted as a snapshot of fishway occupancy rather than a temporally representative estimate of fish assemblage use.

4.2. Hydraulic and Structural Bottlenecks

The hydraulic evidence also shows why the observed route-completion pattern cannot be diagnosed from a single representative velocity. Measured slot velocities of 0.90–1.08 m/s were within or close to the reported critical swimming-speed range of several regional schizothoracine fishes, including *Schizothorax chongi* (approximately 1.10 m s^{-1}), although swimming capacity varies among species, body sizes, and environmental conditions [28]. Diagnostic CFD indicated localized flow-acceleration magnitudes of approximately 1.9 m/s^2 together with strong recirculation near structural transitions; this acceleration quantity is distinct from velocity magnitude. In addition, the pre-commissioning survey documented slot widths from 0.19 to 0.92 m before correction. Because paired hydraulic measurements were not conducted before and after correction for individual pools, the hydraulic effect of each structural correction could not be quantified directly; the corrective work was intended to restore the nominal design geometry before operational monitoring. Vertical-slot performance depends on the spatial flow structure of jets, shear layers, recirculation zones, slot geometry, and recovery areas rather than on a section-averaged velocity alone [8,29,30]. The approximately 0.40 m/s entrance flow was also embedded within a tailrace containing much stronger forward and reverse currents. Because only one operating configuration was evaluated, the data cannot partition the relative effects of entrance attraction, local hydraulic barriers, route length, or migratory motivation. The results therefore show that compliance with nominal design thresholds alone was insufficient to explain the observed stage-specific movement pattern.

Rest pools were intended to provide lower-energy recovery opportunities during the long ascent. However, the present PIT configuration did not quantify residence time or recovery behaviour within individual rest pools, so their biological effectiveness cannot be directly evaluated from this dataset. The observed route-completion proportion should therefore not be used by itself to infer that the rest pools were ineffective. Additional antennas or behavioural observations around representative rest pools would be required to assess their actual use and to determine whether their hydraulic configuration or spacing should be further optimized.

4.3. Engineering Implications for Adaptive Operation

The main engineering implication is that post-construction fishway evaluation should be treated as an adaptive ecological-engineering process rather than as a one-time compliance exercise. First, as-built slot geometry should be surveyed systematically because deviations of the magnitude observed here can alter discharge distribution, jet structure,

and the effective passage corridor. Second, attraction flow should be adjusted jointly with gate settings, supplemental inflow, tailwater level, and turbine operation so that the entrance presents a persistent and detectable hydraulic signal without generating excessive local velocities. Controlled comparisons among operating modes are needed to identify hydraulic "windows" that maximize entry and subsequent passage [22,23]. Third, long fishways should be instrumented at multiple internal sections so that stage-specific declines in detections can be localized rather than inferred solely from entrance and exit counts. The observed PIT proportions should also be interpreted in the context of freshwater migratory behaviour. Many potamodromous and river-resident fishes exhibit facultative or partial migration, and movement propensity can vary with season, discharge, temperature, reproductive state, and individual condition [31,32]. Water temperature, dissolved oxygen, and turbidity were not systematically recorded throughout the PIT trial; their potential effects on fish activity and passage behaviour therefore could not be evaluated and remain a limitation of the present study. Consequently, non-detection during a short monitoring interval cannot be assumed to represent an inability to negotiate the fishway. The present results should therefore be regarded as an initial stage-specific diagnostic rather than a definitive estimate of annual or population-level fishway efficiency.

5. Conclusions

Integrated post-construction monitoring of the 1486-m Jinsha vertical-slot fishway revealed a mismatch between nominal hydraulic suitability and observed stage-specific movement performance under the monitored conditions. Pre-commissioning inspection identified substantial deviations in vertical-slot geometry, while field measurements and diagnostic CFD showed that moderate representative velocities coexisted with strong spatial heterogeneity, including localized flow acceleration and recirculation. PIT telemetry showed that 60.0% of released fish were detected at T1, 21.1% of fish detected at T1 subsequently reached T3, and 12.6% of all released fish reached T3 from the release location within the monitoring period. These values should be interpreted as observed detection and route-completion proportions for the PIT-tagged experimental group rather than absolute fishway efficiency, because migratory motivation, migration timing, partial migration, sample size, the open fishway configuration, unquantified antenna detection efficiency, and the relatively short monitoring period may all have influenced the observed pattern. The progressive decline in PIT detections, entrance-flow context, and local hydraulic/structural heterogeneity identify priority targets for controlled adaptive testing. For long fishways, ecological connectivity should therefore be evaluated using stage-specific biological metrics coupled with as-built quality control and replicated operational trials of supplemental flow, gate settings, and water levels.

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