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Evaluation of a Nature-like Bypass for Non-Salmonids in the Sesan River

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Abstract: In recent years, the hydropower development of the lower Mekong River has accelerated, accompanied by habitat loss and fragmentation. We conducted two experiments using video recordings and traps to evaluate the effectiveness of a nature-like rock ramp bypass in the Sesan River in 2019 and 2021. The results show that the fishway provides both upstream and downstream passage for at least 24 non-salmonid species of fish. The vast majority of fish choose to ascend from July to September, especially in August, and hardly between October and November. The fish inside the fishway prefer to move during the daytime (6:00–18:00), especially during August and September. An excessive water depth at the entrance can lower the number of ascending fish, whereas a higher water depth at the exit can cause the opposite result. Nevertheless, the size of fish monitored exhibits a decreasing trend, suggesting the nature-like bypass cannot completely mitigate the impact caused by this impassable Sesan II dam. Therefore, a quantitative assessment of the bypass is highly encouraged, whereas the selection of the tracked fish species and experimental period requires considerable deliberation. This study alleviates the dilemma of insufficient fishway evaluation in tropical countries, which can provide researchers with data support on future non-salmonid fishway designs.

Keywords: rock ramp fishway; nature-like bypass; fishway performance; non-salmonids; video monitoring; trap

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1. Introduction

There is increasing recognition that major rivers worldwide are facing many threats and damages [1], which can be reflected in the shrinkage of biodiversity in the freshwater ecosystems [2,3]. Habitat loss and fragmentation, one of the important threats, is closely related to dams, culverts, and other anthropogenic barriers [4–8]. These barriers often obstruct the upstream and downstream movements of fish, resulting in the damaging consequence of many migratory fish species not being able to finish a complete life cycle, such as reaching their spawning, rearing, and overwinter habitats [2,9–11]. Under these circumstances, many countries have been considering constructing fish passage facilities (i.e., fishways) to restore river connectivity [7,12].

A fishway is defined as a structure that provides fish with another approach to complete their upstream migration [13]. Early fishways were mainly distributed in North America and Europe, with the earliest recorded fishway dating back as far as the year 1662 (in France). However, they were mainly designed for economically and recreationally important fish species, such as Salmonidae fishes [14–17]. With the acceleration of hydropower development globally and the success of salmonid fishway designs in the northern hemisphere, these types of fishways were studied and constructed in a lot of developing countries where the ichthyofauna in their rivers consists of non-salmonid species, such as China and Brazil [15,16,18–21]. However, salmonids always have higher swimming capability than non-salmonids, which may have a higher probability to pass through the fishway. Many salmonid fishways have been found performing poorly when the target fish species were mainly non-salmonids [22–24].

Various fishway designs can be classified into two categories: technical (e.g., denil, vertical slot, and pool-and-weir) fishways and nature-like fishways (NLFs) [25,26]. NLFs (also known as nature-like bypasses) usually use materials (e.g., boulders, pebbles, gravels, and logs) from local sources and are designed to represent pools, rapids, and riffles in natural rivers, aiming to simulate the flow patterns of natural rivers [27–31]. In addition, NLFs can be classified into two typical types: rock ramp and pool riffle, in which the formal type is designed as a long sloping channel with interspersed boulders [20,26]. Because different sizes of natural materials in the channel can generate diverse hydraulic conditions across various species and sizes of fish, NLFs always boast a higher passage efficiency [14,16,32]. In addition, Kim et al. [33] found that some fish stayed inside the NLF for a considerably long period (>28 days), suggesting the fishway may be regarded as a small special habitat for some aquatic organisms, rather than simply a passing structure. Owing to these advantages of the NLF, they have always been afforded priority when terrain, river fall, space, and other conditions permit, especially for low-head dams [25,34–36].

Many fishery biologists and engineers are trying to improve the fish passage at dams, not only for upstream but also for downstream migration [37,38]. There remains a challenge when some freshwater fishes (e.g., salmon, trout, and adult eels) need to move downstream to their spawning grounds in the sea through the spillway structures and turbines [39]. There is evidence that downstream migrating fishes are likely to get injured or even die from the high-speed rotating blades of the turbines and turbulence caused by high velocity in the spillways [40,41]. Although a fish bypass can help downstream migrating fishes to reach the downstream waters safely, a small number of fishes choose to use the bypass to descend, which may be because its entrance cannot attract the fishes to enter [41,42]. Under this circumstance, physical deterrence devices (e.g., inclined fish guidance baffle, floating fish guidance system, and fish-guiding bar system) and behavioral ones (e.g., strobe lights, sound, electricity, pressure waves, and bubble screens) have been increasingly introduced globally to guide fishes to the bypasses or deter fishes from water intakes and turbines of hydropower plants [37,40,43–45]. However, the lack of understanding of the behavior responses of fishes to sound, light, water flows, and other sensory cues, to some extent, limits the further development of effective fish-guiding measures [45].

The Mekong River is the longest river in Southeast Asia, which is shared by six countries and serves nearly 70 million people. In recent decades, considerable attention has been paid to its abundant hydropower resources [46]. The hydro-ecological system consisting of the Mekong River and its tributaries provides many floodplain habitats with rich biodiversity and high productivity of fish and other aquatic organisms [47]. The Sesan, Sekong, and Srepok Rivers, three important tributaries of the Lower Mekong River, support nearly half of the fish species of the Lower Mekong River and have become a hotpot for hydropower development [48]. The Sesan II Hydropower Station located on the mainstream of the Sesan River is the largest water conservancy project in Cambodia. Notably, a rock ramp bypass (13°33′34″ N; 106°15′03″ E) installed on the right side of the main dam is used to mitigate the impact of the dam on migratory fish. We use the terms "nature-like fishway" and "nature-like bypass" interchangeably, with both referring to the Sesan II fishway.

A comprehensive evaluation of fishways is strongly encouraged because it offers engineers and dam managers worldwide an approach to design an ideal fishway, although it seems more like a conceptual goal [23]. In recent years, the evaluations of fishways using different monitoring methods have become increasingly common after their completion, and the number of evaluations remains valid, especially in tropical countries [49]. Under these circumstances, we conducted a pre-experiment using traps in the rock ramp bypass from 1 December to 8 December 2019. The sample results show that the collected fish were only non-salmonids and appeared mainly medium in size (the total length mainly ranged from 10 cm to 40 cm), showing that the fishway has met the preliminary requirement of migration for some fish species in the Sesan River.

A formal experiment was conducted at the fishway from 24 to 28 May and 17 July to 30 November 2021 during the migratory season for the target fish species to further evaluate the fishway performance. We used video monitoring and traps to evaluate the performance of the Sesan II fishway across various species and sizes of fish. Evaluations of fishways in Southeast Asia are quite limited. To some extent, the evaluation of the Sesan II fishway can alleviate the lack of data in tropical countries and provide data support for researchers worldwide to design fishways for non-salmonids.

2. Materials and Methods

2.1. Study Site

The Sesan River is the largest tributary of the Mekong River with a basin area of 7960 km^2 and more than 278 km in total in Cambodia, which originates in the northern part of the GiaLai–KonTum Plateau in Central Vietnam. The Sesan II Hydropower Station Project is a low head (10.7 to 28.3 m high) run-of-river project operating with 8 bulb turbines (each with 50 MW, a rated flow of 252.5 m^3/s, and rated head of 21.7 m) capable of generating a total of 400 MW. It includes earth-rock dams, gravity dams, spillway structures, powerhouses, and a rock ramp nature-like bypass. The Sesan II Hydropower Station has a reservoir with a regulating storage capacity of 333.2 million m^3, a storage coefficient of 0.0082 (that is, daily regulation), a dead water level of 74.00 m, a normal water level of 75.00 m, and a multi-year average flow of 1310 m^3/s, which is situated in the mainstream of the Sesan River in northeast Cambodia (Figure 1).

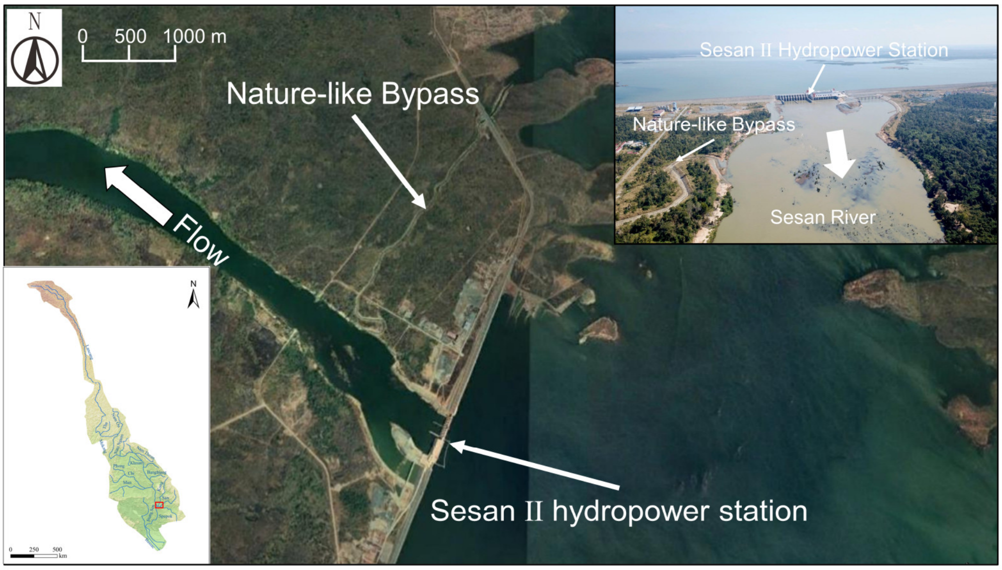

Figure 1. Location of the NLP at the Sesan II Hydropower Station.

The nature-like bypass (NLP) at the Sesan II dam allows the migrating fish to reach the upstream or downstream area to breed, which was designed and built for the protected and high-value fish with migratory and semi-migratory characteristics in the Mekong River basin, including the following 10 species: *Pangasianodon hypophthalmus*, *Probarbus jullieni*, *Poropuntius deauratus*, *Tenualosa thibaudeaui*, *Osphronemus exodon*, *Hypsibarbus malcolmi*, *Henicorhynchus lobatus*, *Cyclocheilichthys enoplos*, and *Pangasius larnaudii* (Table 1). The information on each fish species was searched on Fishbase [50] and the International Union for Conservation of Nature (IUCN) Red List of Threatened Species [51].

Table 1. Information on the target migratory fish species of the NLP.

	Fish Species	Ecological Habit	Migratory Month	States [1]
	Cypriniformes			
	Cyprinidae			
1	*Probarbus jullieni*	Demersal, Omnivorous	Nov. to Feb.	CR
2	*Poropuntius deauratus*	Benthopelagic, Omnivorous	Unknown	EN
3	*Cirrhinus molitorella*	Benthopelagic, Herbivorous	May to June	NT
4	*Hypsibarbus malcolmi*	Benthopelagic, Carnivorous	May, Nov. to Dec.	LC
5	*Henicorhynchus lobatus*	Benthopelagic, Omnivorous	Nov. to Feb., May to July	LC
6	*Cyclocheilichthys enoplos*	Benthopelagic, Omnivorous	Nov. to Feb., May to Aug.	LC
	Siluriformes			
	Pangasiidae			
7	*Pangasianodon hypophthalmus*	Benthopelagic, Omnivorous	May to July	EN
8	*Pangasius larnaudii*	Benthopelagic, Omnivorous	May to July	LC
	Clupeiformes			
	Clupeidae			
9	*Tenualosa thibaudeaui*	Pelagic, Omnivorous	Jan. to Feb., June to July	VU
	Perciformes			
	Osphronemidae			
10	*Osphronemus exodon*	Pelagic, Omnivorous	Nov. to Dec.	VU

Note: [1] Abbreviations: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC). The fish status is classified by the IUCN Red List of Threatened Species.

2.2. Fishway Design

The altitudes at the bottom of the entrance and exit are 47.3 m and 72.5 m, respectively. Moreover, the variation between the entrance and exit is 26.5 m. The water depth between the entrance and exit of the NLP is affected by seasonal hydrological variations. To control the water depth inside the fishway, several interspersed boulders were installed in the channel sections. The whole rock ramp bypass is 3286 m in total, which can be classified into three sections: inlet, channel, and exit sections. The entrance section located approximately 1 km below the dam is 180.49 m long, and 4–5 m wide, with a slope of 2%. The exit section is 55 m in length, 5 m in width, and at a slope of 1%, which is located at an auxiliary dam far from the main hub project. A sluice gate installed between the exit section of the bypass and the auxiliary dam can regulate the discharge of the exit, with a maximum operating discharge of 3.5 m^3/s. Notably, three rest pools of nearly 50 m in length were constructed in the channel section (2624.277 m long and 4–5 m wide), with an area requirement of more than 1000 m^2 (Figure 2). The mean designed velocity inside the NLP varies from 0.4 to 0.8 m/s and that inside the slot of boulders varies from 1.0 to 1.5 m/s. In addition, the normal operating water level of the fishway ranges from 74.00 m to 75.00 m. When the water level exceeds 75.00 m, the sluice gate is closed to ensure normal living conditions for fish, allowing the water flow to turn over the gate to replenish water in the pools (for more details, see Luo et al. [52]).

2.3. Fishway Monitoring

2.3.1. Fish Sampling

Fish sampling was conducted in the NLP between two periods: from 1 December to 8 December 2019 and from 24 May to 28 May 2021. The procedures of sampling were as follows: (1) we made sure that the fishway was under normal conditions (74.00 m < the upper water level < 75.00 m); (2) installed customized blocking nets (mesh size: 4 mm × 4 mm) at the entrance and exit to prevent other fish from entering the fishway; (3) installed three extra blocking nets at three rest pools to restrict the movement of fish; (4) closed the gate at the exit; (5) used a gill net (mesh size: 4 mm × 4 mm) to capture fish at each rest pool; (6) drained the three rest pools with water pumps; and (7) collected all fish in the pools. Then, the fish species, quantity, total length (TL), and wet body weight (BW) were identified and analyzed.

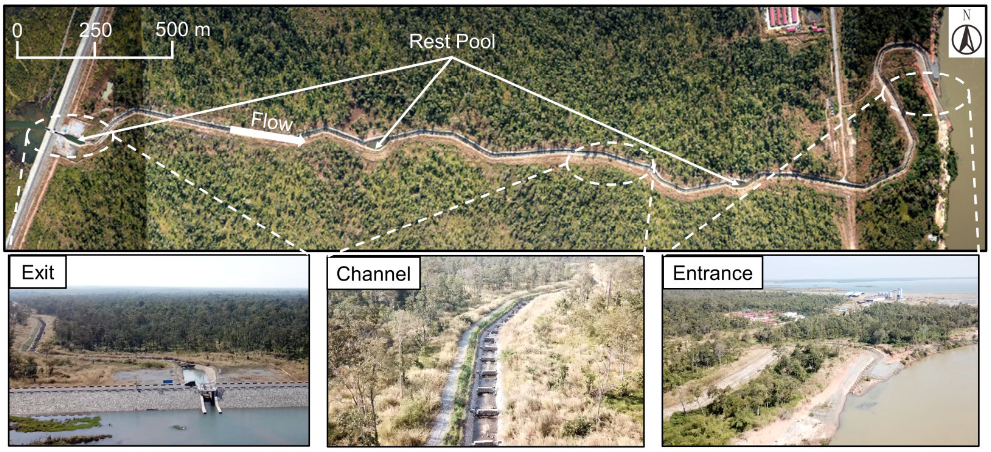

Figure 2. Aerial photographic representation of the nature-like bypass in the Sesan River.

2.3.2. Video Monitoring

Underwater video monitoring systems have been widely used in fishway monitoring, especially for fish behavior studies [53]. A video monitoring system using two high-resolution digital cameras (Axis P1354, 30 FPS, 1280 × 1024 pixels, each with a coverage area of 0.7 m^2) was installed at the fishway exit to observe the migration behavior of fish. When fish entered the scan area (with a length of 30 cm, a width of 20 cm, and a height of 110 cm), an infrared detection system, which was assisted by a lighting supplementation (only activated during the nighttime) to meet the observation requirement of distinguishing the fish outline under a nonluminous condition, was activated before the two cameras started to shoot. (Figure 3a,b). To eliminate useless videos as much as possible, both cameras were activated to film when any motion was detected by the infrared detection system (Figure 3c). If the fish passed back after a successful passage (always referred to "fallback" [32]), the video data were selected and it was decided whether they could be adopted, depending on the final locations of the fish (beyond or below the exit of NLP). Based on the filtered video data, the species of fish, fish size (total length and width), migrating direction, mean swimming velocity, and record time were identified and analyzed.

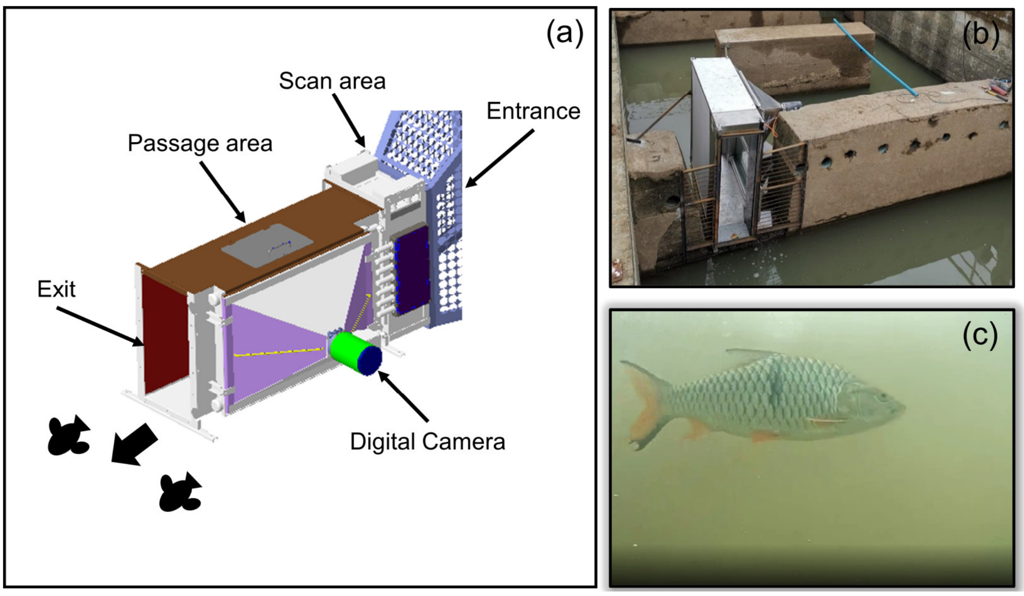

Figure 3. (**a**) Schematic diagram, (**b**) photographic representation, and (**c**) screenshot of the underwater video monitoring system.

2.4. Data Analysis

PC software was used to implement remote status monitoring. All the video data were transmitted and submitted to the computer memory. The proportions obtained by the comparison between the size in the video and the actual size of the fish were used to obtain information on fish size, with no interference with the behavior or movements of fish [54]. Additionally, to better evaluate the status and trend of fishery resources upstream and downstream of the dam, we classified the captured fish into three categories depending on their body weight: small-sized (body weight $\leq$ 0.01 kg), medium-sized (0.01 kg < body weight $\leq$ 1 kg), and big-sized (body weight > 1 kg). In addition, we collected data on upper and lower water levels from July to November. Fish information and data analysis were recorded and performed in Microsoft Excel 2016 software, respectively. Some of the analytical results were presented as line and lollipop charts by Originpro 2021.

3. Results

3.1. Species Composition and Biological Characteristics of the Collected Fish in the NLP

In total, we collected 506 fish belonging to 18 species (8 orders, 11 families) from the traps in the NLP (Table 2). *Mastacembelus armatus* (Synbranchiformes, Mastacembelidae) accounted for the largest proportion (33.4%) of the catches, followed by *Hampala dispar* (25.1%) and *Sikukia gudgeri* (10.7%) belonging to Cyprinidae, Cypriniformes, whereas those of *Botia helodes*, *Botia modesta*, *Mystus singaringan*, *Hemisilurus mekongensis*, *Channa gachua*, *Channa striata*, and *Monotrete cambodgiensis* were extremely small, which accounted for proportions of less than 1%, respectively. Cyprinidae was the dominant family that used the NLP most frequently, which accounted for approximately half of the fish collected.

Table 2. Fish composition and biological characteristics in the NLP.

Order	Fish Species	*N* *	TL [1] (cm)	BW [1] (g)	May 2021	Dec. 2019
			Range	Range		
	Cypriniformes					
	Cyprinidae					
1	*Hampala dispar*	127, 25.1% (7, 2.2%)	6–17	10–70	+	+
2	*Sikukia gudgeri*	54, 10.7% (12, 3.8%)	10–50	20–1000	+	+
3	*Hampala macrolepidota*	24, 4.7% (26, 8.3%)	9–43	50–1500	+	+
4	*Puntioplites proctozystron*	22, 4.3% (59, 18.8%)	10–43	40–400	+	+
5	*Poropuntius deauratus*	8, 1.6%	9–17	30–70	+	
6	*Sikukia flavicaudata*	4, 0.8% (57, 18.2%)	9–24	10–50	+	+
7	*Osteochilus hasselti*	(2, 0.6%)	/	/		+
8	*Cirrhinus microlepis*	(1, 0.3%)	/	/		+
	Botiidae					
9	*Botia helodes*	2, 0.4% (9, 2.9%)	5–8	10	+	+
10	*Botia modesta*	1, 0.2% (6, 1.9%)	16	80	+	+
	Synbranchiformes					
	Mastacembelidae					
11	*Mastacembelus armatus*	169, 33.4% (21, 6.7%)	8–37	20–250	+	+
12	*Macrognathus siamensis*	(2, 0.6%)	/	/		+
	Synbranchidae					
13	*Monopterus albus*	31, 6.1% (3, 1.0%)	7–37	10–180	+	+
	Anabantiformes					
	Pristolepididae					
14	*Pristolepis fasciata*	32, 6.3% (34, 10.8%)	7–27	20–200	+	+
	Osteoglossiformes					
	Notopteridae					
15	*Notopterus notopterus*	12, 2.4% (16, 5.1%)	10–27	20–300	+	+
	Gobiiformes					
	Odontobutidae					

Table 2. *Cont.*

Order	Fish Species	*N* *	TL [1] (cm) Range	BW [1] (g) Range	May 2021	Dec. 2019
16	*Odontobutis aspro*	8, 1.6% (9, 2.9%)	9–15	10–50	+	+
	Siluriformes					
	Clariidae					
17	*Clarias fuscus*	6, 1.2% (8, 2.5%)	23–33	50–100	+	+
	Bagridae					
18	*Mystus singaringan*	2, 0.4% (12, 3.8%)	21–25	100–200	+	+
	Siluridae					
19	*Hemisilurus mekongensis*	(2, 0.6%)	/	/		+
	Anabantiformes					
	Channidae					
20	*Channa gachua*	2, 0.4% (1, 0.3%)	16–30	100	+	+
21	*Channa striata*	1, 0.2% (18, 5.7%)	19	200	+	+
22	*Channa micropeltes*	(1, 0.3%)	/	/		+
	Tetraodontiformes					
	Tetraodontidae					
23	*Monotrete cambodgiensis*	1, 0.2% (7, 2.2%)	14	80	+	+
	Beloniformes					
	Belonidae					
24	*Xenentodon canciloides*	(1, 0.3%)	/	/		+
	Total	506, 100% (314, 100%)	6–50	10–1500	18	(23)

Notes: [1] Abbreviations: Total length (TL); Body weight (BW). * Notice: The numbers in () in the third column represent the data in December 2019.

Based on the sample results of the pre-experiment, fish of more than 40 cm in length were not captured in 2021 (Figure 4a). The number of fish with a total length of less than 10 cm accounted for a larger proportion in 2021 (77%) than in 2019 (63%). Similarly, the body weight of fish exhibited a decreasing trend from 2019 to 2021, with the proportions of small-sized fish up to 73% and big-sized fish down to less than 1% (Figure 4b).

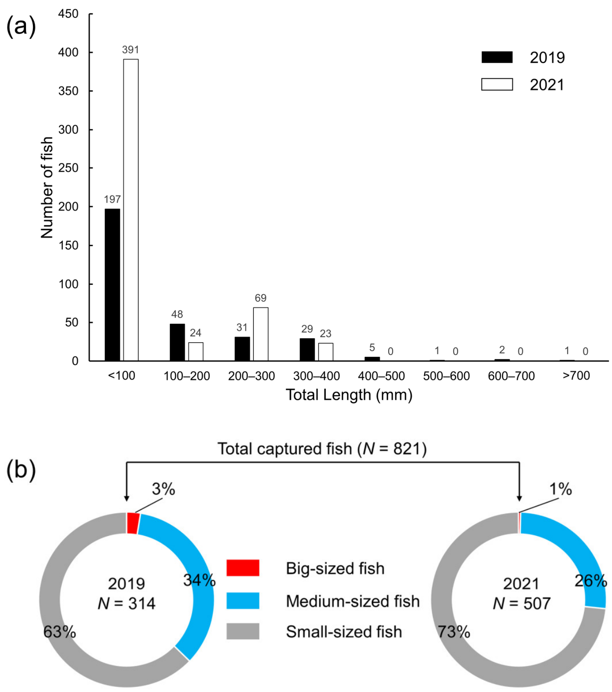

Figure 4. Distribution of (**a**) total length and (**b**) (wet) body weight of fish captured by traps in the NLP between 2019 and 2021.

A total of 314 fish belonging to 23 species (9 orders, 13 families) were collected, which were classified as small fish (63%), medium fish (34%), and large fish (3%). Compared with the pre-experiment, the catches of the formal experiment encompassed more species but had a smaller number of fish. Moreover, the proportion of small fish increased to 73%, with that of medium and large fish down to 26% and 1%, respectively. Notably, the dominant fish species changed to *Puntioplites proctozystron* (18.8%), followed by *Sikukia flavicaudata* (18.2%) and *Pristolepis fasciata* (10.8%).

3.2. Monitoring of Migration Behaviors at the Exit of the NLP

3.2.1. Upstream Migration Behaviors across Different Months

We mainly recorded the passing number of these 24 species that were identified in the traps between the two experiments (Table 2). Except for 5 unrecognized species across all the periods, including *Channa gachua*, *Botia modesta*, *Hemisilurus mekongensis*, *Clarias fuscus*, and *Macrognathus siamensis*, the number of fish from 19 species that successfully passed from July to November are shown in Figure 5.

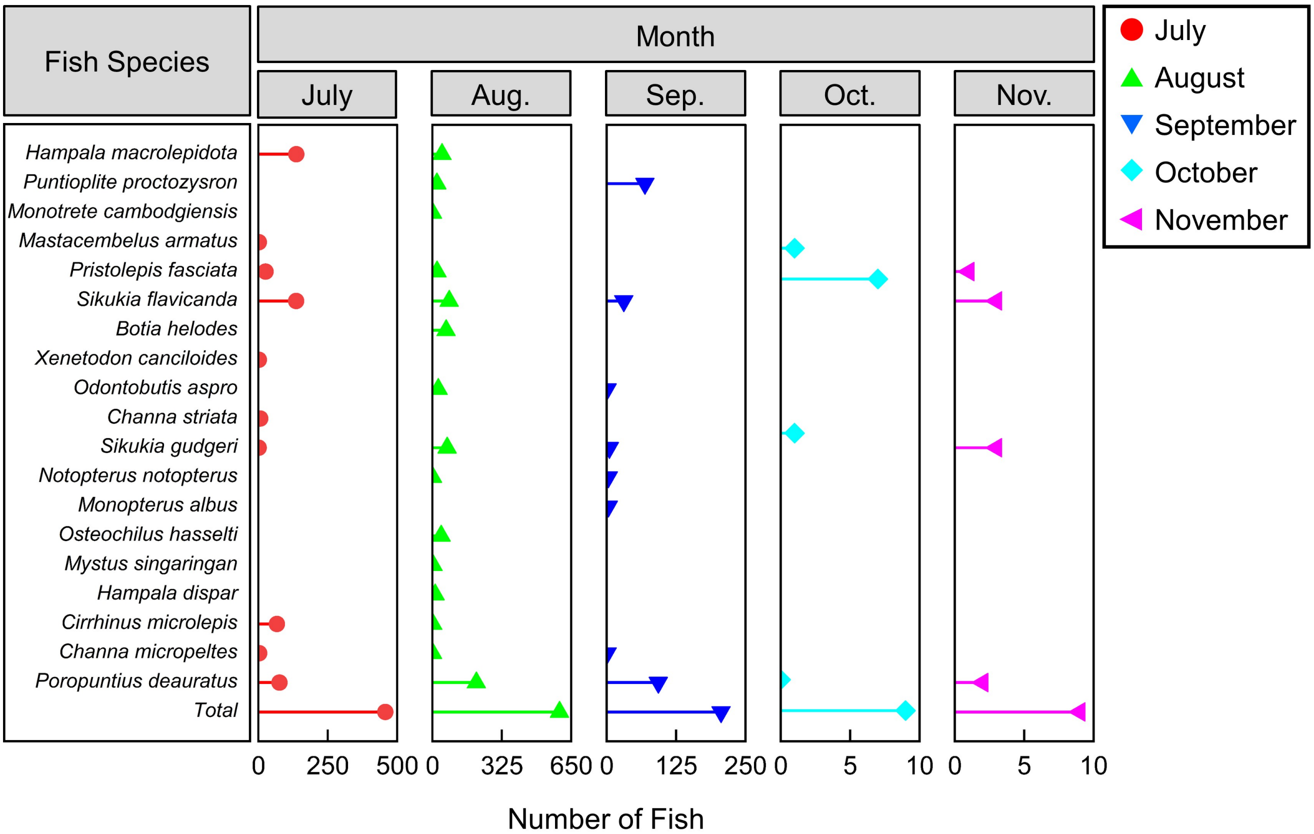

Figure 5. Difference in fish species and numbers from July to November in the NLP.

More species (N = 16) and number of fish (N = 595) were found using the NLP to ascend in August compared with other months, followed by 457 ascending fish belonging to 10 species found in July and 206 ascending fish (eight species) in September. However, nearly no fish chose to reach the upstream reservoir in October and November. The ascending species with proportions >10% in August included *Poropuntius deauratus* (N = 206, 34.62%), *Sikukia flavicanda* (N = 79, 13.28%), *Sikukia gudgeri* (N = 69, 11.60%), and *Botia helodes* (N = 64, 10.76%), with those in July including *Hampala macrolepidota* (N = 137, 29.98%), *Sikukia flavicanda* (N = 136, 29.76%), *Poropuntius deauratus* (N = 76, 16.63%), and *Cirrhinus microlepis* (N = 67, 14.66%).

Given that the video in July only monitored half of the month, the number of upstream migrations in July could be assumed to have doubled. Consequently, the fish's willingness to ascend the NLP exhibited a decreasing trend as the season progressed.

3.2.2. Circadian Rhythms of Upstream and Downstream Migration Behaviors

We classified 24 h of a day into four six-hour sections: morning (6:00–12:00), afternoon (12: 00–18: 00), evening (18:00–24: 00), and night (0: 00–6:00). As is shown in Figure 6, based on the video data across the four six-hour sections from July to November, the upstream and downstream migration of fish in the NLP frequently appeared during the morning and afternoon (collectively daytime), rather than the evening and night (collectively nighttime). For upstream migration, the proportion of migration during the daytime was largest (92.43%) in August and smallest (58.87%) in November, whereas for downstream migration, those during the daytime had the largest (95.13%) proportion in September and smallest (58.78%) in July. Notably, fish hardly moved at night, with the proportions even down to zero in July and September.

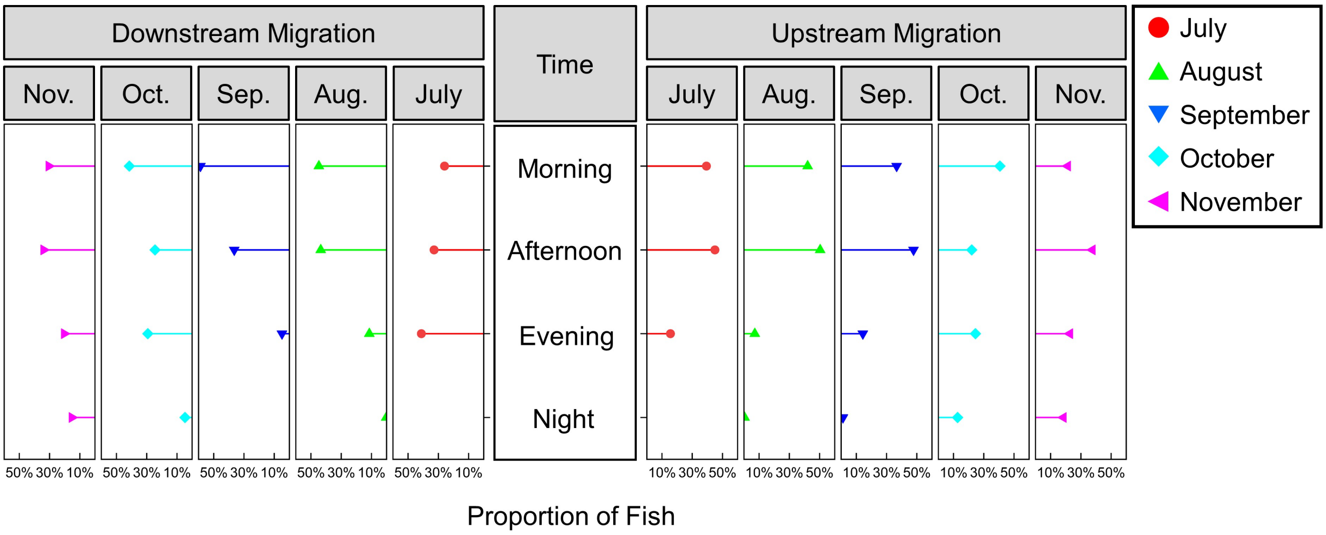

Figure 6. Circadian rhythms of upstream and downstream migration behaviors from July to November.

3.3. Influencing Factors of Effectiveness of the NLP

The potential factors that may affect the effectiveness of the fishway include the upper and lower water level, water depth, temperature, turbidity, and fishway design (e.g., fishway slope and length) [14,16,38,53,55,56]. In this study, we mainly focused on two important indicators, the water level and water depth of the NLP. As shown in Figure 7a, the lower water levels ranged from 49.53 m (11 August) to 56.20 m (20 October), suggesting a significant difference from July to November (one-way ANOVA: $F = 40.98 > F_{crit} = 2.44$, $P < 0.05$), which were persistently higher than 47.3 m (altitude at the bottom of the entrance). Additionally, the upper water levels ranged from 74.43 m (17 July) to 75.38 m (6 November), with a significant difference from July to November (one-way ANOVA: $F = 11.16 > F_{crit} = 2.44$, $P < 0.05$), which remained higher than 72.5 m (altitude at the bottom of the exit). Both water levels showed that there remained water across all the channels of the NLP. Moreover, the sluice gate at the exit was kept closed during the whole period (17 July to 30 November), suggesting fish beyond the exit could go downstream from the surface of water, and vice versa.

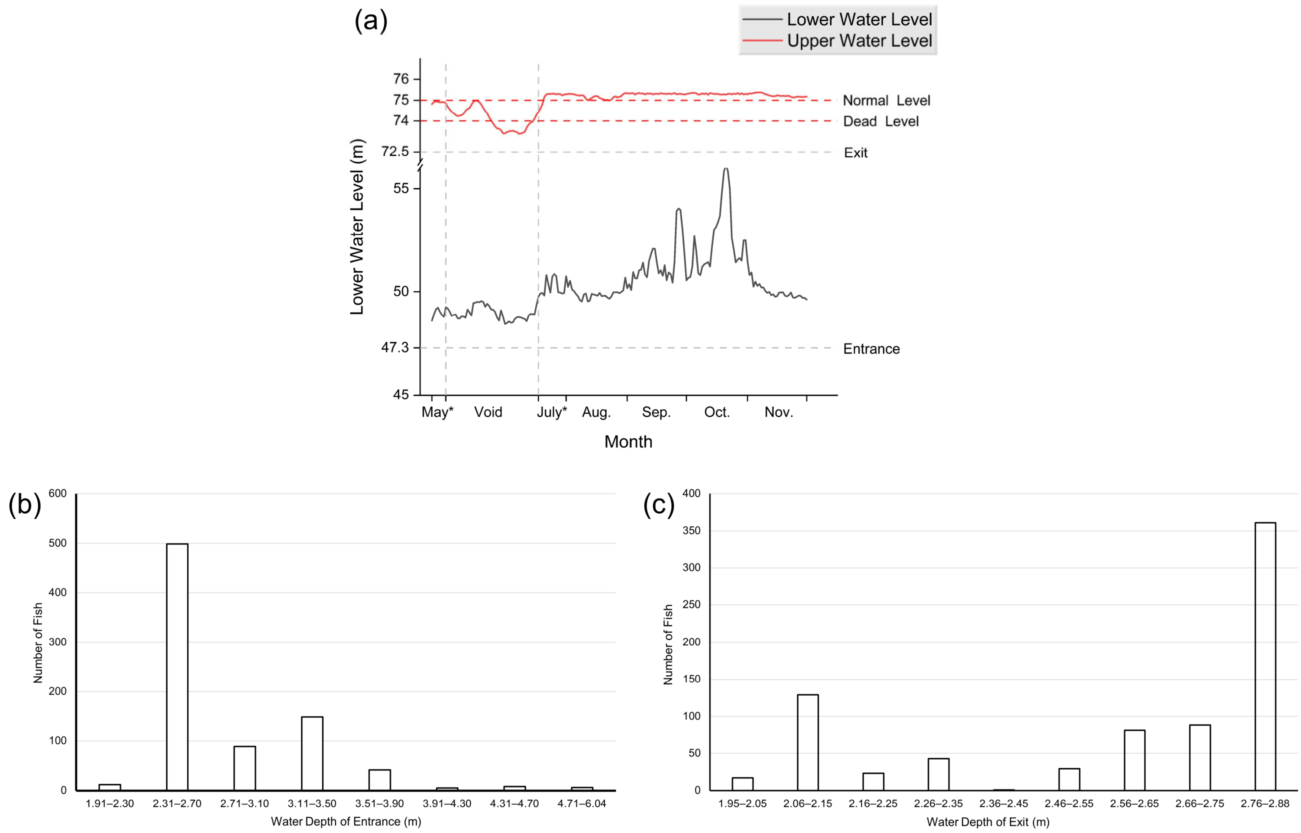

Figure 7. (**a**) Upper and lower water levels during the entire monitoring period. Relationship between the water depth of (**b**) entrance and (**c**) exit and the number of ascending fish. May* implies the periods of sampling (24 May to 28 May) and July* implies an incomplete monitoring period (17 July to 31 July). "Void" implies no sampling or monitoring data during this period.

The water levels and water depths have a similar effect on the fish population because higher upper and lower water levels can directly cause higher water depth at the fishway exit and entrance, and vice versa. As shown in Figure 7b, most fish (N = 499, 61.7%) chose to use the NLP when the water depths of the entrance varied from 2.31 m to 2.70 m (that is, lower water level varied from 49.61 m to 50 m). In particular, among 499 fish, 440 fish were monitored when the lower water level varied from 49.90 m to 50.00 m. The relationship between lower water levels and the fish population appeared high in the middle (lower water level = 49.93 m, N = 110) and low on both sides. Moreover, as shown in Figure 7c, when the water depths of the exit varied from 2.76 and 2.88 m (that is, the upper water level varied from 75.26 m to 75.38 m), 361 fish (accounting for nearly 50% of the total fish) used the NLP. As the upper water level reached the normal storage level (75.00 m), the passing number which accounted for 72.1% (N = 559) obviously increased compared with that lower than 75.00 m. Different from the relationship mentioned above, it showed an overall positive correlation when the water depths of the exit increased.

4. Discussion

From 24 to 28 May 2021, a total of 507 fish belonging to 8 orders, 11 families, and 18 species were found using the NLP to ascend or descend, showing that the NLP plays a significant role in the migration of various species of fish in the Sesan River. The dominant species in the NLP were found to be *Mastacembelus armatus* (33.4%) belonging to Synbranchiformes, Mastacembelidae. In addition, *Hampala dispar* (25.1%) and *Sikukia gudgeri* (10.7%), belonging to Cyprinidae, Cypriniformes, accounted for a large proportion, only second to that of *Mastacembelus armatus*. Moreover, a total of 314 fish belonging to 9 orders, 11 families, and 23 species used the NLP from 1 to 8 December 2019. The dominant family found in both experiments was Cyprinidae, which accounted for 47.23% and 52.23% of the total collected fish in 2019 and 2021, respectively. No target species were captured in the NLP in the two experiments except one target species (*Poropuntius deauratus*). Fish with a total length of more than 40 cm were not captured in 2021, which may be due to two factors: (1) different target fish species used the NLP to migrate in different months; and (2) low flow and water depths caused by the low upper water level during May made it hard for large-sized fish to pass through the NLP. Due to the distribution of body weight, we found that small-sized fish accounted for the largest proportions in both experiments, with the proportion of small-sized fish accounted for 63% (2019) and 73% (2021), respectively. Additionally, monthly sampling for the whole year is highly encouraged to comprehensively analyze the monthly difference in species composition and biological characteristics inside the fishway.

The fish preferred to ascend beyond the exit from July to September, especially July and August, whereas nearly no fish chose to go upstream from October to November. The monitoring system to monitor fish behavior was installed on July 17, suggesting only half a month was monitored compared with the other whole months. The difference among the monthly number of ascending fish showed a significant downward trend as the season progressed. This may be due to the lower upstream water level and temperature inside the fishway during the dry season, resulting in a lower willingness of fish to go upstream. These two metrics can highly affect the passage effectiveness of the NLP and even influence its normal operation [33,54]. Information on the migratory and breeding months of the target fish species (*Poropuntius deauratus*) remains limited, whereas we can infer from the results of sampling and video monitoring that its potential migratory months are from July to September, especially August. In addition, the dominant species (*Hampala dispar* and *Mastacembelus armatus*) captured in May 2021 were hardly found reaching the exit during the entire period of the normal experiment. This may be because the flow in the NLP during the dry season is slow, exactly meeting the preference in the habitat with a low flow speed for *Hampala dispar* belonging to the family Cyprinidae [57]. Additionally, *Mastacembelus armatus,* belonging to the family Mastacembelidae, always lays eggs from April to June and prefers to live in crevices and under rocks in the rivers rather than to ascend during the other months [58]. Notably, *Sikukia gudgeri* can be considered to add to the target species of the NLP due to its large proportion accounted for in the total fish captured and recorded.

During the entire day, the fish preferred to move upstream and downstream during the daytime, whereas they hardly move from 0:00 to 6:00, which appeared different from the monitoring conclusion of the Sangju nature-like fishway [33] and Zhentou I vertical slot fishway [2], but similar to that of the Xiniu vertical slot fishway [55]. Naughton et al. [59] found that low visibility caused by low light levels and high turbidity can, to some extent, decrease the possibility of a successful passage for *Oncorhynchus nerka*. Kim et al. [33] proposed the ecological habitat of each species and their survival strategy of avoiding visual predators may be the reason that different fish species chose to use the Sangju nature-like fishway during a different time of day. However, the circadian rhythm remains complex and needs more experiments aimed at different fish species. Additionally, two indirect factors cannot be ignored, including a sharp decrease of light levels during the nighttime and lower detection efficiency caused by high turbidity. Nevertheless, the circadian rhythms of migration behaviors showed a monthly variation, exhibiting that the proportion of ascending during the nighttime increased in October and November. This may be due to the limited number ($N < 10$) of the total detected fish during these two months, suggesting the proportions were regarded as unstable. Moreover, it is also worth noting that the NLP meets the requirement of not only upstream but downstream migration. Recent studies focused on evaluating the fishway performance mainly for the upstream passage, whereas the downstream passage remains in extremely pressing need in diadromous fishery management, especially for those endemic fish species with their habitats located downstream of the dams.

The lower and upper water levels directly influence the water depth at the entrance and exit. As is shown in Figure 7a, there were no no-water problems in the pools of the NLP during the whole period, ensuring a suitable natural environment for all fish species. As was posited by some researchers, a nature-like fishway design usually has a relatively higher passage efficiency than the technical fishway type [14,16,32], but a successful passage also depends on the attraction and entrance efficiency [14,23,32]. The NLF usually has a relatively lower attraction efficiency due to its special design, which limits its generalization worldwide. We found that the number of ascending fish decreased with the increasing downstream water level and vice versa, which may be because the excessive water depth of the entrance can decrease the flow speed, hereafter making it hard to be detected by fish. In addition, the increasing upper water level can further bring a higher bypass discharge, stimulating fish to ascend. Notably, other factors that may be opposed to our conclusions need to be considered. They include the fact that: (1) extremely high turbidity caused by high discharge can make it hard to distinguish species; (2) fish may not be detected when they pass in the blind area of both cameras; (3) although the lighting supplementation can contribute to night monitoring, it may influence the avoidance behavior of fish; and (4) some fish may prefer to stay inside the fishway rather than to ascend due to their unique ecological habitat.

Both the effectiveness and efficiency of the fishway can contribute to comprehensively evaluating the fishway performance separately [60,61]. Because the fishways constructed in the early 20th century were mainly designed for salmonids or other migratory species, researchers used to focus on their migration behavior and passing number, rather than tracking an individual fish. However, with the popularity of fishway construction worldwide, there occurs a dilemma that many species of fish do not use the fishway to ascend. Consequently, the quantitative indicator (that is, passage efficiency) has been paid increasing attention to further evaluate fishway performance. The variations in the indicators of the evaluation suggest changes from direct methods, including traps and video monitoring, to indirect methods, which mainly include passive integrated transponder and acoustic and radio telemetry. However, we believe the fishway effectiveness is not a skippable step, especially for fishways that have never been evaluated before. The results of fishway effectiveness can reflect the natural movement behavior of pooled fish schools, allowing data support to be provided for the selection of the most suitable tracked species and experimental periods. That is why we focused on analyzing the fish behaviors of 24 species (the total number of species captured in both experiments) via video systems, aiming to find out the monthly and daily difference in fish preferences for migration and dominant species (families) in the NLP [23,54,62–65].

5. Conclusions

This study was the first to evaluate fishway effectiveness in Cambodia using gill net sampling and video monitoring, which gave more insights into fishways and migratory characteristics of the target migratory fish species in Southeast Asia. This study addressed a number of broad questions including which fish species are located near the Sesan II NLP, which species use the NLP, and the monthly and diurnal variations of fish's behavior when they pass the fishway. A total of 507 fish across 18 species and 314 fish across 23 species were found using the NLP from 24 to 28 May 2021 and 1 to 8 December 2019, respectively. Based on the video data, 19 species used the NLP to ascend, except for 5 species including *Channa gachua*, *Botia modesta*, *Hemisilurus mekongensis*, *Clarias fuscus*, and *Macrognathus siamensis*. From the video-monitoring period from 17 July to 30 November 2021, the movements of the fish mainly concentrated between mid-July and August. During the entire day (0:00 to 24:00), the fish used the NLP most frequently during the daytime (6:00 to 18:00), and hardly used it during the night (0:00 to 6:00). There were more fish passing the NLP when the water depths of the entrance and exit varied from 2.31 m to 2.70 m and 2.76 m to 2.88 m, respectively.

The results of this study showed that the Sesan II NLP provided a migration route for at least 23 non-salmonid species, but only 1 (*Poropuntius deauratus*) of the 10 target migratory species of the NLP was found to be using the NLP during the whole video monitoring period. Moreover, based on the results of sampling in two experiments, the size and body weight of captured fish displayed a decreasing tendency. Therefore, the Sesan II NLP has the capacity to restore connectivity between the upstream and downstream areas, but it remains unclear how much it can restore. Compared with technical fishways, low attraction for fish at the entrance and excessive water velocity in the channel section always limit the generalization of the nature-like fishway construction globally. In this case, given the upper water level slightly changed, whereas the lower one significantly changed, equipping attractive and guiding devices at the entrance could make it easier for fish to find and enter the fishway. Due to the relatively low number of fish passing the NLP, further studies, such as a preliminary swimming test, a quantitative assessment using telemetry technology, and investigations on the migration patterns of some endemic fish species, are highly encouraged. Additionally, for the Sesan II Hydropower Station, supplementary means (e.g., breeding stations for endemic fish species) could be adopted to improve the fish resource quality in the upper and lower Sesan River. Comprehensive evaluation data of fishways will hopefully contribute to the improvement of non-salmonid fishway designs.

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