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RESEARCH ARTICLE

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Underwater video monitoring of fish passage in the Mekong River at Sadam Channel, Khone Falls, Laos

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Abstract

This paper describes the first measurement of fish passage in the Mekong River at Khone Falls. The site was in the Sadam Channel, which was modified in 2013 to improve fish passage and mitigate closure of Sahong Channel for the Don Sahong hydropower project. Underwater cameras recorded 149 hr of discontinuous video from January 18 to 26, 2015, which showed a major upstream migration by small cyprinid fish. Daily catch surveys in the same channel showed most fish migrated on days when video records were almost complete. We used stratified hourly sampling to review 17% of the available video and counted 14,783 fish and identified 16 taxa. The most abundant species were *Labiobarbus leptocheilus*, *Henicorhynchus lobatus*, and *Henicorhynchus siamensis*, and these fishes migrated almost exclusively during daylight. We calculated passage rates for West Sadam Channel from video samples and extrapolated those results to Sadam Channel, by assuming equivalent passage rates for both East and West Sadam Channels. This assumption was based on observations that fish were evenly distributed between both banks below the confluence, and they migrated close to each bank, so we assumed that there was an even split at the confluence and neither channel was preferred for upstream passage. Although channel modification improved fish passage efficiency, we estimated that artisanal fishers caught 79% of migrating fish in Sadam Channel, so fishing pressure remains the greatest risk to successful fish passage. Active fisheries management will be necessary to sustain and further improve passage efficiency in future.

KEYWORDS

Don Sahong Dam, fish migration, Khone Falls, Mekong River, Sadam Channel, underwater video

1 | INTRODUCTION

1.1 | Hydrology and hydropower

The Mekong River originates in China and flows through Myanmar, Laos, Thailand, Cambodia, and Vietnam before discharging to the South China Sea (Figure 1). It is about 4,400 km long, with a catchment area of about 795,000 km^2 (Piman, Lennaerts, & Southalack, 2013). The average monthly discharge of the unregulated Mekong River at peak flow was 10 times greater than the minimum average monthly flow (Piman et al., 2013). Since 2000, active storage volume for hydropower production upstream of Cambodia increased from 9.1 km^3 to 44 km^3, increasingly regulating the discharge (Piman et al., 2013). In 2010, the Mekong River Commission (MRC) modelled the hydrological effects of water resource development in the Mekong Basin and predicted that by 2015, hydropower operations would significantly increase dry season discharge and reduce flood discharge (MRC, 2011). The projected change in seasonal discharge has made "run-of-river" hydropower projects (HPP) on the Mekong mainstream more economically attractive. The Government of Laos approved development of the first HPP on the lower Mekong mainstream at Xayaburi in 2013 and a second (Don Sahong) in September 2015. The Don Sahong Hydropower Project (DSHPP), on an anabranch of the Mekong River at Khone Falls, has a comparatively small reservoir volume (25 million m^3) and short water residence time (1–4 hr), so it will have minor effects on discharge and sediment transport in the Mekong River (MRC Secretariat, 2015). However, there has been widespread concern that the resultant closure of Sahong Channel, which occurred in January 2016 after this study

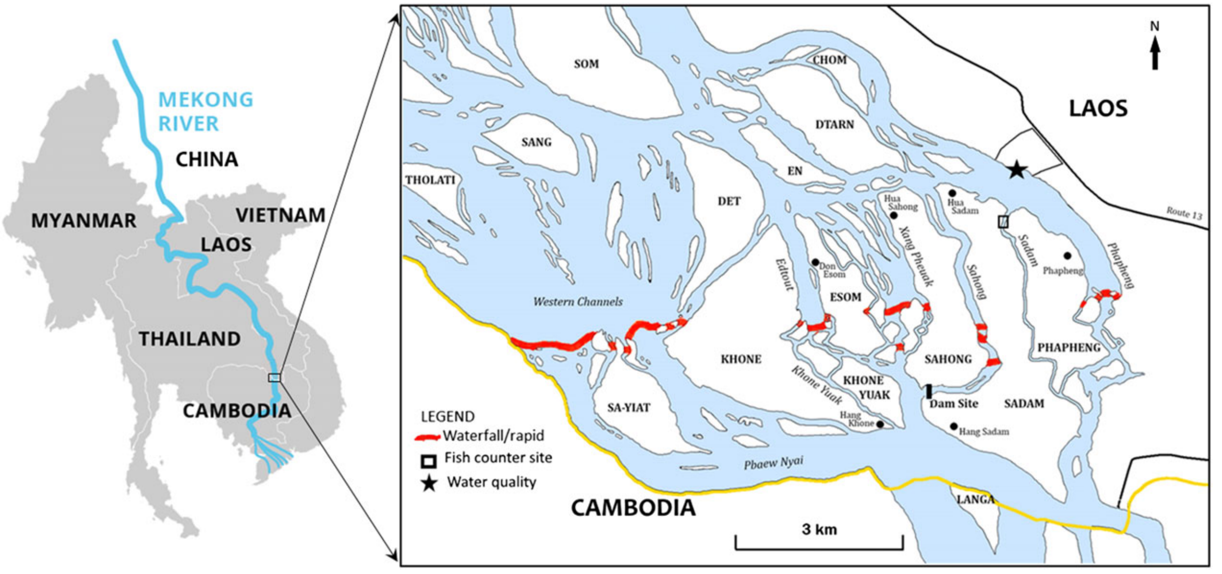

FIGURE 1 The main channels (italics) that cross Khone Falls. Flow is from northwest to southeast with the main waterfalls/rapids (red) and islands (upper case) and household survey fishing villages. [Colour figure can be viewed at wileyonlinelibrary.com]

was completed, will disrupt dry season fish migrations through the Khone Falls (e.g., Baird, 2007).

1.2 | Khone Falls fisheries

Capture fisheries provide food and livelihoods for millions of people in the Mekong River basin, and many species important to the capture fishery make long distance migrations (Hortle, 2009). Stream-bed elevation drops by about 30 m at Khone Falls, creating the greatest natural barrier to upstream fish migration in the mainstream Mekong. Although seven permanent channels debouch at Khone Falls, upstream fish passage through the steepest channels is blocked by near vertical cascades, whereas other channels that provide passage upstream in the wet season can become impassable in the dry season, when the hydraulic gradient is greatest (SMEC, 2016), and obstructions to migration pathways emerge (Roberts & Baird, 1995).

Most recent research on fish migration at Khone Falls is based on information gathered from artisanal fishers, who use the difficult passage conditions at Khone Falls advantageously, to trap migrating fish that accumulate downstream of waterfalls or rapids (Figure 1). One of the most important capture fisheries at Khone Falls is based on dry season migrations by herbivorous and omnivorous fish (e.g., *Labiobarbus leptocheilus*, *Henicorhynchus lobatus*, and *Henicorhynchus siamensis*) from floodplains and tributaries in Cambodia to feeding and refuge habitats in the mainstream Mekong River between Kratie and Pakse (Baird, Flaherty, & Phylavanh, 2003). Local ecological knowledge is that these species make repeated attempts to cross Khone Falls, initially choosing large (impassable) channels but eventually finding passage through smaller channels (Roberts & Baird, 1995).

The difficulties in accessing the channels, the highly variable discharge, and the great species diversity have prevented quantitative research into fish passage at Khone Falls. There is no published information on catches immediately above the major obstructions in channels that cross Khone Falls nor actual passage rates for any channels. Current opinions on the efficiencies of each channel for dry season fish passage are based on interviews with local fishers and field inspections of obstructions in the channels (Baird et al., 2003; Phonekhampheng & Thorncraft, 2010; Roberts & Baird, 1995). The present understanding is that Sahong, Xang Pheuak, and Sadam Channels are all effective fish passes for part of the year, with Sahong Channel judged most efficient. Popular media have distorted these scientific opinions, citing Sahong Channel as the only channel that can provide year-round upstream fish passage across Khone Falls (e.g., Tolson, 2013). Actual measurements of fish passage effectiveness and efficiency (sensu Larinier, 2000) are needed to resolve uncertainties in published opinions and provide baselines for assessing the benefits of channel modification.

In this study, we evaluated the usefulness of underwater video for monitoring fish passage at Khone Falls in the dry season. We determined the effectiveness of Sadam Channel as a fish pass (whether target species use it) and combined video and catch data to determine passage efficiency. We also gathered information on factors that could affect fish passage success, namely, the adequacy of attraction flow, extent of in-channel predation (by local fishers), burst swimming speed (as success of passage through the count chamber), numbers of individuals at peak passage, and diurnal movement.

2 | METHODS

2.1 | Channel modification to improve fish passage at Khone Falls

The DSHPP Environmental Impact Assessment proposed engineering modifications in selected channels to improve upstream fish passage year-round at Khone Falls (Phonekhampheng & Thorncraft, 2010).

The modified Khone Falls channels differ from "nature-like" man-made fish passes that attempt to mimic local habitats and flow conditions (Parasiewicz, Eberstaller, Weiss, & Schmutz, 1998), because they already provide effective passage for most species, albeit with diminishing efficiency during the dry season. Don Sahong Power Company (DSPC) began modifying Xang Pheuak Channel to improve fish passage in dry season of 2011 and has continued the programme each year. Sadam Channel modification began in April 2013, when the upstream entrance was excavated to increase discharge, and illegal gears were removed from all reaches. The entrances to both these channels will deepened further before HPP operations commence (SMEC, 2016), but they are already comparable with the largest man-made fish passes in the world (Table 1).

2.2 | Fish passage monitoring

We measured fish pass effectiveness by determining whether small cyprinids that are essential for livelihoods throughout the basin passed the Sadam Channel during their annual dry season migration.

Underwater video imaging is widely used for monitoring fish pass effectiveness (Armstrong et al., 2010) and offers high-image resolution, which is helpful for identifying the small, fast-swimming fish species that migrate across Khone Falls. Water transparency significantly limits the use of underwater video in the Mekong River, as it restricts camera range. Transparency is determined by concentrations of dissolved and suspended substances (Kirk, 2011). The data on suspended particulate matter in Mekong water are considerable (e.g., MRC water quality programme, 1995–2015), but published transparency data are extremely scanty. Fortunately, DSPC recorded transparency at Khone Falls for an annual hydrograph (2013–2014), and those data indicated transparency might be adequate for underwater video monitoring of fish passage during the dry season (December to April).

An acoustic survey method (DIDSON), which is not limited by transparency, has been used to record fish passage in the Mekong River (T. Coe, personal communication, 2014), but this technique lacks the image resolution needed to discriminate small migratory species.

Fish pass efficiency is defined as the proportion of a migrating population that successfully pass the obstacle (Larinier, 2000). This is usually determined by tagging individuals (Armstrong et al., 2010), but that approach was impossible at Khone Falls because the target species were too small and fragile to use conventional or PIT tags, and the handling stress would likely disrupt their migration, and smaller fishes migrate cryptically via fractures in the bedrock where flow is fast and turbulent. In this study, we inferred fish pass efficiency by combining the results of two different population-level surveys: (a) a measure of successful passage (underwater video) and (b) a measure of loss due to artisanal fishing (Cooke & Hinch, 2013).

2.3 | Survey timing

Artisanal fishers catch the first migrating small cyprinids below Khone Falls during the lunar month of the winter solstice (December). Their largest catches are when fish attempt to cross Khone Falls in mass migrations that are highly correlated with the day of the new moon. Most fish migrate in the second lunar month (identified hereafter as LM2), but lesser migrations have been recorded in LM1 and LM3 (Baird et al., 2003; Roberts & Baird, 1995).

The Mekong River is remarkable for the consistent size, duration, and timing of the single annual flood peak (Adamson, Rutherfurd, Peel, & Conlan, 2009). Recession usually commences in October, and discharge usually falls most rapidly in December, although sharp rises can occur (see Figure 4, December 2013). Safe construction and operation of the temporary video monitoring station required consistent low flow, so we delayed installing the counter until early January 2015 (LM2). Although that schedule precluded monitoring a migration in LM1, it reduced the risk of flood interference whilst monitoring migrations in LM2 and LM3.

All results have been reported in relation to the new moon day (NM 0), (e.g., January 20, 2015, is NM 0 of LM2, January 19 is

TABLE 1 Characteristics of modified Khone Falls channels and some of the largest man-made fish passes

Fish pass/channel	Type of fish pass	Length (km)	Minimum width (m)	Minimum discharge[a] ($m^3 s^{-1}$)	Maximum discharge[a] ($m^3 s^{-1}$)	Mean slope (%)	Reference
Xayaburi HPP, Laos	Ladder + ramp plus lift + lock	0.9	16	90	240	3.1	Morier-Genoud (2015)
Xang Pheuak Channel, DSHPP, Laos	Braided natural channel	6	190	60	3,796	0.3	SMEC (2016)
Rheinfelden HPP, Switzerland	Nature-like	0.9	60	10	35	0.8	Gebler and Lehmann (2013)
Sadam Channel, DSHPP, Laos	Braided natural channel	6	10	7	244	0.3	SMEC (2016)
Lajeado HPP, Brazil	Vertical slot	0.9	5	3.3§		4.3	Agostinho, Agostinho, Pelicice, and Marques (2012)
Itaipu HPP, Brazil	Nature-like + vertical slot	10	5	1.4§		1.2	Makrakis, Miranda, Gomes, Makrakis, and Junior (2011)
Melk HPP, Austria	Nature-like	1	12	1.4	3.2	1.2	Schmutz and Mielach (2015)

Note. § = mean value. DSHPP = Don Sahong Hydropower Project; HPP = hydropower project.

[a]Passes ranked in descending order of minimum discharge. Discharges of modified Sadam and Xang Pheuak Channels estimated from Mekong discharge at Pakse between 2011 and 2014.

NM-1, and January 21 is NM+1). The first video survey was over 9 days in LM2 (NM-2 to NM+6 or January 18–26, 2015). A second survey was conducted from NM-1 to NM+2 in LM3 (February 17–20, 2015).

2.4 | Study site and fish counter

A temporary "V" shaped filter fence was constructed in the narrower western branch of upper Sadam Channel (Figure 2). The fence guided fish into a narrow raceway where two submersible video cameras were mounted at different depths facing downstream (Figure 3). The upper camera displayed the entire chamber except for a few centimetres below the surface. Most fish passed close to the sides or bottom of the chamber to avoid the highest water velocities. A 2HP portable 240 V generator provided electric power.

2.4.1 | Counting and ID

Observers reviewed a subset of the video records and counted those fish that passed the count chamber in the upstream direction. They identified fish by unambiguous Lao names, which were assigned scientific names using Baird (2001), Kottelat (2001), and subsequent revisions. If two species were identified in a sample, the count was attributed to the dominant species. Subdominants were not enumerated because of the difficulty in identifying every fish.

Environmental effects or fishing pressure can produce large interhour variation in passage rates of migrating fish, so we used stratified hourly sampling to improve passage rate precision (Xie & Martens, 2014). The upstream fish passage rate per hour (P) was

$$P = \mu \times R\,\mathrm{max},$$

where μ = mean fish sample^{-1} that hour and R_{max} = 120 samples h^{-1}, except for 2 hr each day that separated daylight and darkness. Daylight was astronomical daylight (when any ray of sunlight was in the sky), which was between 05:10 and 19:07. A technician checked the video monitor regularly to clear fouling from the cameras and note passage of migrating fish during daylight.

2.5 | Environmental variables

Water transparency was measured in Phapheng Channel (Figure 1) using a 0.6 or 1.2 m transparency tube (USEPA, 2010). The mean daily transparency was transformed to a 3-day moving average to minimize local inflow effects. Daily discharge was estimated from staff gauge levels in Sadam and Phapheng Channels (Figure 1) using rating curves reported in SMEC (2016). Sadam Channel discharge was also measured by ADCP (TDRI StreamPro™) on January 26, 2015. The relative discharge of East and West Sadam Channels during the LM2 survey was estimated by the multiple point method using stream velocities collected with a hand-held propeller flow metre (Swoffer™ 3000) during similar river stages in January–February 2016.

2.6 | Artisanal fishers

Since 2009, DSPC has recorded the daily fish catch of representative households from the villages on Sadam Island with traditional fishing rights in Sadam Channel (Figure 1 shows village locations). Households reported their total catch, the dominant species by weight, gears used, and fishing location each day. These data were collated and validated each week and stored in an MS Access database (Hortle, Hawkins, Phommanivong, & Singsua, 2014).

During 2015, there were 56 households in Hua Sadam and 91 households in Hang Sadam who could potentially fish the Sadam Channel. Daily fishing effort (households per day) and catch (kg) by

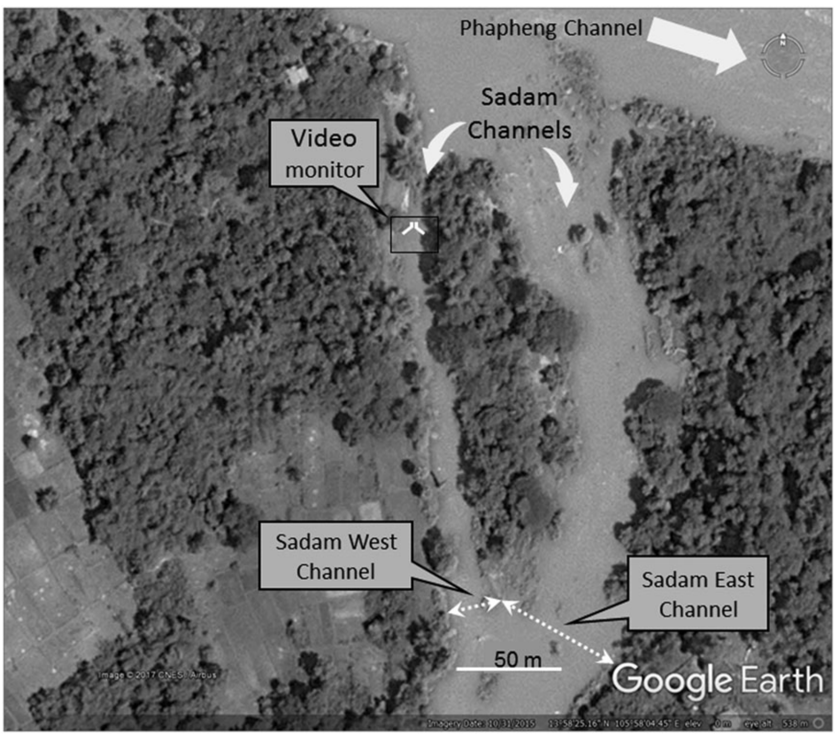

FIGURE 2 Location of the underwater video fish counter in West Sadam Channel, Laos, 13.97425°N, 105.96898°E. Image from October 31, 2015, with Sadam Channel discharge of 34 m^3 s^{-1}). Eye alt 435 m. Google Earth Pro V7.1.7.2600. CNES/Airbus 2017. [accessed May 15, 2017].

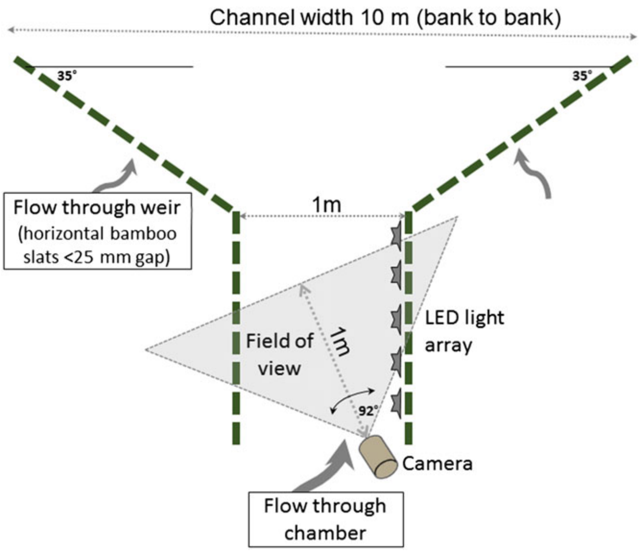

FIGURE 3 Plan view of the fish counting chamber with arrows indicating the flow direction. A filter fence (horizontal bamboo slats, gap <25 mm) completely blocked the channel to guide fish into the raceway. Two cameras, top mounted 0.15 m below the water surface, were adjusted in situ to maximize the field of view. The raceway was lined with white vinyl to improve image contrast and prevent cryptic migration. LED lights fixed to the eastern wall illuminated the chamber at night. Monochrome cameras (Sony™, IR37CSHR-W36) had frame rate of 25 frames per second, sensitivity of 0.5 Lux without IR LED/F2.0, field of view of 92°, and inbuilt infrared LED light (850 nm × 30°). Video compression software (MV360™ v2.36.1) before discharging to the South China sequentially in 1 hr "episodes" on a hard disc drive. [Colour figure can be viewed at wileyonlinelibrary.com]

all artisanal fishers in Sadam Channel (Total $_{ALL}$) was estimated from the total DSPC household catch from Sadam Channel that day (Total $_{DSPC}$) as follows:

$$\text{Total}_{ALL} = \text{Total}_{DSPC} \times \frac{\text{h'holds with potential access to Sadam Channel}}{\text{reporting DSPC h'holds}}.$$

The Government of Lao PDR proclaimed a Fishery Law in 2009, which prohibited some gears that have been in common use at Khone Falls. Government agencies supported by DSPC have been educating artisanal fishers at Khone Falls about the new law and monitoring the location and number of illegal gears at Khone Falls since 2012 (Philavong, 2014).

3 | RESULTS

3.1 | Discharge

During the LM2 video survey, the mean discharge estimated from gauge boards in Phapheng Channel was 2,023 $m^3 s^{-1}$ ± 2%, and Sadam Channel was 15.1 $m^3 s^{-1}$ ± 8% (range 13.9 to 17.2 $m^3 s^{-1}$). Sadam Channel discharge measured by ADCP on NM+6 was 15.5 $m^3 s^{-1}$ ± 7%, which closely matched the gauge board estimate of 15.3 $m^3 s^{-1}$. Subsequent measurements in East and West branches showed West branch comprised 52%, when mean Sadam Channel discharge was 13.3 ± 0.7 $m^3 s^{-1}$ (n = 3).

During the video survey, the mean flow velocity in the count chamber varied from 0.5 m s^{-1} to 0.8 m s^{-1}. These variations were not caused by change in Sadam Channel discharge but by algal filaments, which periodically blocked the filter fence and raised the hydraulic head, until cleared manually. The greatest variations occurred from NM 0 until midday on NM+2, when we lowered the fence height to permanently reduce the maximum hydraulic head. The maximum flow velocity thereafter was 0.5 m s^{-1}.

3.2 | Water transparency

The limited data available showed a seasonal pattern of extremely low transparency during flood, which increased as the recession progressed (Figure 4). The recession of 2013–2014 was interrupted by high discharge during December, and transparency was below 0.50 m in LM1 and LM2, whereas dry season transparency was higher for longer during the same period in 2014–2015, which facilitated underwater video monitoring.

3.3 | Video survey of fish passage

The duration of the LM2 survey was 193 hr, from 06:00 on NM-2 until 08:00 on NM+6. However, 44.3 hr of potential video were lost (Table 2). Short-term power failures occurred on NM 0

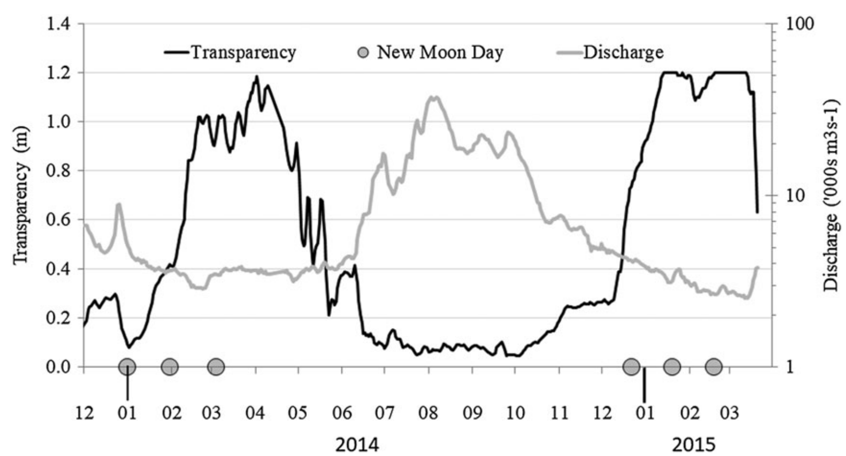

FIGURE 4 Water transparency (3-day moving average) in Phapheng Channel (LH axis) and Mekong River discharge at Pakse (RH axis log-scale) over two dry seasons (2013–2015). Upstream migrations by small cyprinids may occur in each of the first three lunar months each year, around the new moon days. The maximum scale reading of the transparency instrument (1.2 m) was frequently exceeded during the 2014–2015 dry season

TABLE 2 Daily video sampling results during the second lunar month video survey

Date	Day code[a]	Available video[b] (hr)	Total samples (#)	Valid samples[c] (#)	Invalid samples[c] (#)	*f* daylight[d]	Fish present (# of samples)	Comments
18-Jan	NM-2	18.0	217	217	0	0.10	5	No samples before 06:00. Lower sample rate prior to migration.
19-Jan	NM-1	24.0	286	285	1	0.10	4	Lower sample rate prior to migration.
20-Jan	NM 0	23.4	828	583	245	0.26	296	Lost 0.5 hr of daylight video (09:00 to 10:00). Algal fouling high.
21-Jan	NM+1	20.2	755	617	138	0.25	228	Lost 1.5 hr of daylight video (14:00 to 15:30). Algal fouling high.
22-Jan	NM+2	24.0	759	757	2	0.28	160	Modified filter fence to reduce flow rate and reduce algal fouling in count chamber. Fish numbers underestimated between 14:00 and 18:00 due to hole in filter fence.
23-Jan	NM+3	8.0	123	123	0	0.06	58	Lost all video and passage rate not estimated after 08:00. Although some fish passed count chamber between 11:00 and 12:00.
24-Jan	NM+4	0.0	0	0	0	0.00		Lost all video from this 24-hr period due to software error.
25-Jan	NM+5	24.0	83	82	1	0.03	3	Lower sample rate as migrating fish diminished.
26-Jan	NM+6	7.0	21	21	0	0.02	1	Survey ended at 08:00 and sampling ceased.
All	Daylight	85.9	1,909	1,777	132	0.13	714	
All	Night	62.7	1,163	908	255	0.09	41	
All	Total	148.7	3,072	2,685	387	0.12	755	

Note. The survey started at 06:00 on January 18, 2015, and ended at 08:00 on January 26, 2015. There were potentially 1,674 daylight samples and 1,206 night samples in 24 hr. NM = new moon day.

[a]New moon day (NM 0) was January 20, 2015.

[b]Hours of video collected each day varied because (a) the hours before the survey started (NM-2) and after the survey ended (NM+6) were not included, (b) video was not collected during brief power outages (NM+1 and NM+2), and (c) video records collected on NM+3 and NM+4 were lost due to software error.

[c]Samples were invalidated if the camera field of view was obscured.

[d]Sample fraction (*f*) was # of valid daylight samples/# of potential daylight samples.

(09:15–09:50) and on NM+1 (01:00–03:45 and 14:00–15:00). A software error caused loss of 16 hr of video before review (NM +3, 08:00 to 24:00) and 24 hr on NM+4. The field notes from NM+3 recorded a small number of migrating fish between 11:20 and 12:00 but no migrating fish on NM+4.

There were 148.7 hr of recorded video available and observers inspected 3,072 30-s video samples. They classified 387 (12.6%) samples as invalid because the field of view was obstructed, usually by filamentous algal material that fouled the cameras (Table 2). Invalid samples were most frequent at night (255) when the counter was unattended. People also obstructed the cameras whilst removing fouling material (27 of 132 invalid daylight samples). A deflection barrier constructed upstream of the counter on NM+2, eventually reduced algal fouling.

The sample fraction (*f*), where *f* is number of valid (enumerated) samples /number of potential samples, is reported in Table 2 for daylight samples when most fish migrated. We reviewed fewer samples on days when passage rates were low, (*f* between 0.10 and 0.02) and increased the review rate when fish were migrating (*f* between 0.25 and 0.28).

Fish were not observed in large numbers until first light (05:10) on NM 0 (Figure 5). The migration peaked that afternoon with counts of 200 fish per 30-s sample. The migration was relatively continuous until last light (19:07), when it ceased abruptly. The pattern of migration on NM+1 and NM+2 was similar, albeit with lower numbers of fish. There were three peak migration periods each day, soon after first light, around midday, and then from late afternoon until last light. Fish migrated almost exclusively in daylight, as less than 1% of the migrating fish were observed at night.

A second survey in LM3 recorded 80 hr of video continuously over 4 days. This was curtailed on NM+2 after no migrating fish were observed. Subsequent stratified sampling of daylight samples confirmed that migrating fish were absent.

3.4 | Artisanal fish catch survey

Although two villages on Sadam Island have traditional fishing rights in Sadam Channel, the DSPC survey found almost all the Hang Sadam households fished the Mekong downstream during the small cyprinid migrations. Therefore, the artisanal catch for Sadam Channel during the LM2 video survey was estimated solely from Hua Sadam household surveys. Fishing effort in Sadam Channel increased daily as catches rose until the peak on NM+2, when every DSPC survey household fished (equivalent to 56 Hua Sadam households; Figure 6). The total daily catch fell for the first time on NM+2, and the decline continued each day thereafter. There were no survey reports on NM +5 because all households participated in a communal village activity. However, the low catches on NM+4 and NM+6 indicated that the migration had effectively ended on NM+3. The greatest daily catch from Sadam Channel was 368 kg on NM+1, and the total catch of all

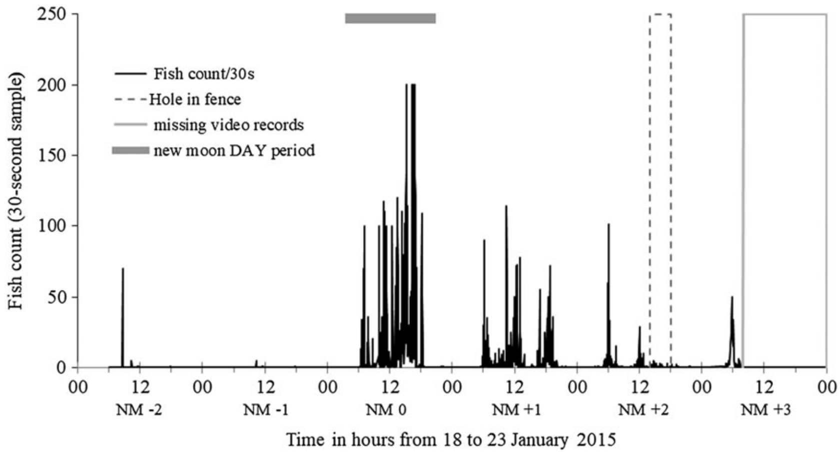

FIGURE 5 Fish counts from underwater video samples from survey commencement (06:00 on NM-2) until 08:00 on NM+3. Counts between 14:00–18:00 on NM+2 underestimated the true passage rate due to a hole in the filter fence. No video from NM+3 after 08:00 was available for review

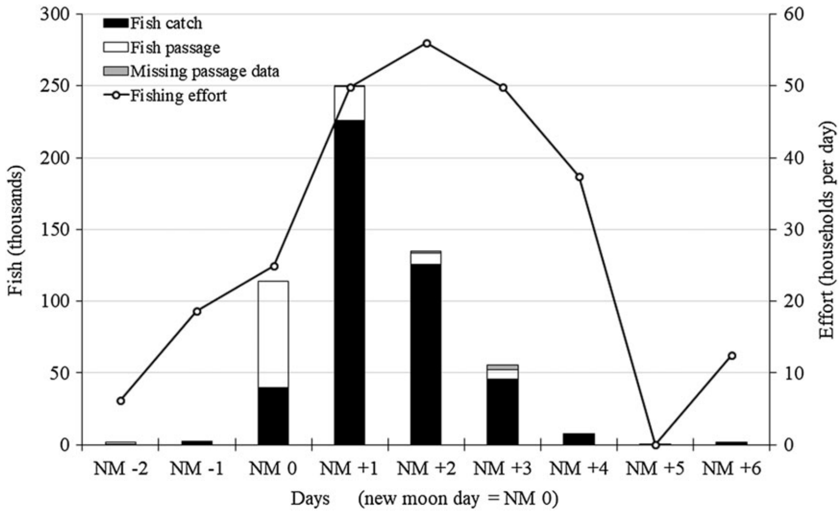

FIGURE 6 Passage or capture of migratory fish in Sadam Channel (January 18 to 26, 2015). Passage rates (thousands of fish day^{-1}) extrapolated from West Sadam Channel fish counter. Missing data are rate estimates for periods when video records were missing or systematically underestimated. Daily artisanal catch was extrapolated from Don Sahong Power Company household surveys

fish by surveyed households was 734.5 kg (Table 3). We estimated that the total artisanal catch of migrating small cyprinids from Sadam Channel during the LM2 video survey was 4,541 kg, which was 29% of the catch from all surveyed channels (Table S1).

3.5 | Taxonomic composition of migrating schools

Video observers identified a dominant species in 692 (92%) of the samples with fish present and a subdominant species in 344 of those samples (Table 3). The angles at which fish presented to the camera and their passage speed made identifying every fish in every sample impossible. Identified fish belonged to 7 families and 16 different taxa. Cyprinidae was the most diverse and abundant family. Nine cyprinid species comprised more than 80% of all identified fish occurrences (Table 3). *L. leptocheilus* occurred most frequently (64% of samples). Observers identified *H. lobatus* in 271 samples and *H. siamensis* in 73 samples. No large fish (e.g., pangasiids or silurids) were observed. Fish were only present in 41 night-time samples. Seven different taxa were represented, including two species, *Scaphognathops bandanensis* and *Cosmochilus harmandi*, which were not observed in daylight (Table 3).

DSPC survey households only identified six cyprinid taxa in their catches, because they reported dominant species by biomass, which biased identifications against smaller less common species. As in the video survey, *L. leptocheilus* occurred most frequently (38 of 41 catch samples), but unlike the video survey, the frequency of occurrence of the combined *Henicorhynchus* spp. was very similar (37). Two large species with single occurrences in household catches were not observed in video samples, so were likely nonmigrating. These increased the number of taxa to 18 (Table 3).

The semiquantitative estimates of abundance by taxa (Table 3) showed *L. leptocheilus* was the most abundant taxon in both surveys (73% of fish counted and 60% of catch biomass). The second most dominant taxon was *Henicorhynchus* spp., which accounted for 22% of all fish counted and 40% of household catch biomass.

3.6 | Passage rates

We calculated hourly passage rates for Sadam West Channel from video sample counts and summed the hourly rates that were to estimate passage rates each day during the migration (see Section 2).

3.6.1 | Missing data

We estimated passage rates for 30 daylight hours where counts were either missing or underestimated as follows. A rate for 1 hr of video

TABLE 3 Frequency of occurrence and abundance of in Sadam Channel during LM2 from video and household catch surveys.

	Data type	Frequency of Occurrence[a]			Abundance[b]	
	Sample method	Video		H'hold catch	Video	H'hold catch[c]
	Units	(# samples)	(# night samples)	(# samples)	(# indiv.)	(kg)
Family	**Species**					
Cyprinidae	*Labiobarbus leptocheilus*	445	12	38	10,837	439.3
Cyprinidae	*Henicorhynchus lobatus*[d]	271	13	37[d]	2,210	290.6[d]
Cyprinidae	*Garra fasciacauda*	84	5		113	
Cyprinidae	*Henicorhynchus siamensis*[d]	73			1,093	[d]
Cyprinidae	*Mekongina erythrospila*	1		1	1	0.3
Cyprinidae	*Paralaubuca typus*	7			87	
Cyprinidae	*Poropuntius laoensis*			1		0.3
Cyprinidae	*Scaphognathops bandanensis*	3	3[e]	1	3	3.0
Cyprinidae	*Scaphognathops stejnegeri*			1		1.0
Cyprinidae	*Cosmochilus harmandi*	1	1[e]		1	
Cyprinidae	*Sikukia gudgeri*	1			2	
Gyrinocheilidae	*Gyrinocheilus pennocki*	59	5		153	
Cobitidae	*Acantopsis/Acanthopsoides* spp.	45			17	
Cobitidae	*Yasuhikotakia modesta*	20			3	
Sisoridae	*Glyptothorax laosensis*	10	2		21	
Channidae	*Channa striata*	1			1	
Gobiidae	Gobiidae	13			15	
Tetraodontidae	*Pao leiurus*	2			1	
Not identified	Not identified	63	0		226	
Total	Number of identified taxa	16	7	6		
Total	Samples with fish present	755	41	41		
Total	Occurrences of different taxa	1,099[f]	41	79		
Total	Abundance (indiv. fish or biomass)				14,783	734.5

[a]Number of samples when this taxon was either dominant or sub-dominant.

[b]Total number of fish when this taxon was dominant.

[c]Abundance of these taxa was overestimated in samples when unidentified species were present as survey only identified dominant and sub dominant taxa.

[d]Artisanal fishers combined *Henicorhynchus siamensis* and *H. lobatus* as *Henicorhynchus* spp.

[e]Only occurred in night samples.

[f]Frequency of occurrences: Total (1,099) = Not identified (63), Dominant (692), Sub dominant (344).

missed on NM+1 (power failure) was interpolated from adjacent hourly rates. On NM+2, the 4 hr of counts that were underestimated when the filter fence was damaged was corrected by substituting the mean pass rate from the longer period that day when the fence was undamaged. This correction increased the NM+2 daily rate by 18%. On NM+3, the morning peak passage was recorded, but there were no counts for the remaining 11 daylight hours, so we used the ratio of morning peak (05:00 to 08:00)/total daylight passage on NM+2, to estimate a daily pass rate for NM+3. That missing data correction increased the estimated daily rate for NM+3 by 55%. Although there were no daylight video samples for NM+4, the household catch data indicated the migration had ended on NM+3, so we did not compensate for missing data on NM+4 nor for any missing night video records, because migration at night was insignificant.

The highest daily passage rate occurred on NM 0, when we counted 10,564 fish and calculated that 37,071 fish (CV% ≤ 5.5%) passed West Sadam Channel. That passage rate precision was derived from sample fraction $f > 1/6$ based on evidence from an empirical study by Xie and Martens (2014) that systematic hourly sampling with sample fraction $f = 1/6$ would give passage rate estimates with CV% ≤ 5.5%.

Altogether, we counted 14,783 fish in video samples (Table 3) and calculated 56,004 fish passed West Sadam Channel based on those counts. We estimated approximately 2,800 more fish passed West Sadam Channel uncounted, during equipment failures.

3.6.2 | Uncertainty in Sadam Channel passage rate

East Sadam Channel is 60 m wide and West Sadam Channel 25 m wide at their confluence (Figure 2), so although discharges were equivalent, the hydrodynamic characteristics of each entrance were likely different. Nevertheless, we assumed that the upstream migrating schools would maintain their observed behaviour of staying very close to the bank and not switching to a more preferred channel until they encountered an obstacle. Therefore, we distributed fish passage equally between the two branches because daily catch rates with standardized gears below the confluence were similar on both banks (DSPC, January 2015, unpublished).

We also assumed unobstructed upstream passage in both channels, which ignored a slight systematic underestimate of passage by the smallest fish, which were obstructed by high flows through the counter on NM 0 and NM+1. On that basis, we estimated that the maximum daily fish passage rate of Sadam Channel was 74,100 fish day-1 on NM 0, and the total fish passage over the LM2 migration was about 119,200 fish (Table 4). Figure 6 shows the estimated total fish passage each day, including uncounted fishes.

3.7 | Artisanal fish catch

Over the video survey period, catch survey households reported 730 kg of migrating fish from Sadam Channel, which we estimated was equivalent to a catch of 4,541 kg by all artisanal fishers (Table 3 and Table S1). Daily catches of *L. leptocheilus* and *Henicorhynchus* spp. (*H. lobatus* and *H. siamensis*) in Table 3 were converted to numbers of individual fish using biomass of specimens collected in Sadam Channel during the video survey (Table 4).

We inferred a daily passage efficiency for Sadam Channel from the ratio

$$\frac{\text{number passing (fish/day)}}{\text{number caught} + \text{number passing (fish/day)}},$$

where 1.0 = 100% passage success. The highest passage efficiency for the period NM 0 to NM+3 was 65% on NM 0. This progressively fell as artisanal fishing effort increased, and mean passage efficiency for the entire survey was 21%.

4 | DISCUSSION

This study demonstrated that fish passage at Khone Falls is measurable by underwater video, despite the seasonal constraint of poor water transparency. The braided channels offer many locations where temporary fish counters can be installed in the dry season, with guidance filter fences to ensure migrating fish pass within camera range.

In 2015, transparency was adequate for underwater video monitoring during all three lunar months when small cyprinid migrations can occur. Transparency was poorer in 2014, because of unseasonal rainfall in the Upper Mekong Basin (MRC, 2015). Discharge and sediment load are the most important determinants of river water transparency (Kirk, 2011), and resource development now occurring in the Mekong Basin could significantly alter both these processes. Dry season discharge has already increased due to hydropower development (SMEC, 2016), and the rapid expansion of agricultural land-use predicted by MRC (2011) will likely contribute higher sediment loads to the river. Dry season transparency is potentially a sensitive indicator of these development impacts. More importantly, this parameter is the predominant driver of autochthonous benthic primary production in the lower Mekong mainstream, which is essential for sustaining secondary production (Ou & Winemiller, 2016). Remarkably, despite its profound influence on aquatic ecosystem function in the dry season, there are almost no published records of Mekong River transparency. We recommend that every water quality monitoring programme in the Mekong Basin should consider including this parameter in future.

TABLE 4 Abundance of migrating small cyprinids in Sadam Channel (January 2015) and Xang Pheuak Channel (1990s)

	Sadam Channel 2015	Sadam Channel 2015	Xang Pheuak(1990s)[a]
Measurement (method)	Fish passage (video)	Catch (household survey)	Catch (household survey)
Unit	(number of fish)	(kg)	(kg)
Abundance in samples	14,783[b]	729.8[c]	15,705
Maximum fish d^{-1} (catch day)	74,143(NM 0)	203,174 fish (368 kg)[d, f](NM+1)	n/a
Total fish estimate	119,236[e]	448,329 fish (4,541 kg)[d, f]	n/a
Taxon	Composition (as % total)		
Labiobarbus leptocheilus	73	60	5
Henicorhynchus spp.[g]	22	40	51
Paralaubuca typus	1	0	33
Others	4	0.6	11

Note. n/a = not available; NM = new moon day.

[a]Mean catch from five seasons (1995–1999) by an artisanal fishery for migrating small cyprinids in Xang Pheuak Channel (from Baird et al., 2003).

[b]Total fish counted in video samples from West Sadam Channel.

[c]Combined catch of *L. leptocheilus*, *Henicorhynchus lobatus*, and *Henicorhynchus siamensis*. The contribution of other species was insignificant (4.6 kg).

[d]Daily total catch (kg) was converted to kg of dominant species, then to number of fish, using *L. leptocheilus* (9.7 g [*n* = 154]); *Henicorhynchus* spp. (10.9 g [*n* = 25], where *H. lobatus* 9.1 g [*n* = 9], and *H. siamensis* 14.4 g [*n* = 16]) were apportioned in the ratio 2:1 as the relative abundance of *H. lobatus* and *H. siamensis* in all video samples.

[e]Video counts (West Sadam Channel) were converted to hourly passage rates and summed to give daily and total passage rates. When video records were missing or underestimated, supplementary passage rates were estimated from counts collected that day (except NM+4, when passage rate was estimated as zero). West Sadam Channel passage rates were doubled to estimate a total passage rate for Sadam Channel.

[f]Total catch (kg) by Don Sahong Power Company (DSPC) households in Sadam Channel each day was divided by the number of DSPC households that day and multiplied by the total number of fishing households in Hua Sadam village (56) to estimate the total daily artisanal catch.

[g]*H. lobatus* and *H. siamensis* data are combined as *Henicorhynchus* spp., because DSPC households did not distinguish between these taxa.

Some simple technical modifications could improve this underwater video survey. Blind trials should be incorporated to assess observer error in reviewing video samples. Colour video with frame rate faster than 25 frames per second should improve fish identification, and new developments in computer-aided image analysis (Shortis & Otis, 2014) may speed up data collection. Smaller night sample fractions will reduce counting effort with minimal effect on passage rate precision. Finally, dry season monitoring of fish passage at Khone Falls will need to carefully manage the ubiquitous drifting algal filaments that adversely affected image quality and fish guidance system performance during this study.

4.1 | Effect of Sadam Channel modifications on fish passage

4.1.1 | Attraction flow

Sadam Channel median discharge in January 2015 was 50% higher than before 2000, which would have increased the attraction flow at Phapheng confluence from 0.5% to 0.7% (SMEC, 2016). Both attraction flows seem grossly inadequate when compared to United States/European fishway designs that specify attraction flows of 5–10% (Williams, Armstrong, Katopodis, Larinier, & Travade, 2012). However, the numerous large fish traps present in Sadam Channel during previous dry seasons (see below) suggest migrating small cyprinids that were entering Sadam Channel in large numbers well before channel modifications increased the discharge. As upstream migrating small cyprinids typically stay very close to channel banks, any fish following the western bank of Phapheng Channel would necessarily encounter Sadam Channel entrance, which is large enough to pass large schools.

4.1.2 | Passage effectiveness and efficiency

No passage rates have ever been reported for Sadam Channel prior to its modification, but there is evidence that fishing pressure during past dry season migrations was so intense that successful passage was rare. In January 1994, Roberts and Baird (1995) reported that filter fences completely blocked both East and West Sadam Channels. Satellite images showed large fish traps almost completely blocked Sadam Channel in at least five different locations in October 2010 (Google Earth Pro, 2017), and in February 2013, we observed filter fences that completely blocked both branches of Sadam Channel 800 m below the Phapheng Channel diffluence (Figures 7 and S1).

Migrating schools enter (and are caught in) impassable Khone Falls channels before eventually finding other channels with upstream passage (Roberts & Baird, 1995). This behaviour means changes in artisanal catch at various locations can show long-term trends in composition of the migrating schools. The three dominant migrating species caught by households in this study comprised 56% of the artisanal catch from a filter fence fishery in Xang Pheuak Channel below Khone Falls between 1995 and 1999 (Baird et al., 2003). *Paralaubuca typus* was the most abundant species in the combined 1990's surveys and ranked first or second in abundance each year but was not dominant in any household catch in 2015 and occurred very rarely in video samples (Table 4). The disappearance of *P. typus* from migratory fish catches in Sadam Channel is consistent with its current IUCN Red List classification in the Mekong Basin. Conversely, *L. leptocheilus* was much more abundant in 2015 relative to the 1990s, when it comprised only 5% of the mean overall biomass.

Daily passage rate for West Sadam Channel estimated from video monitoring counts that were very precise although rates were underestimated when the counter was impassable to the smallest fishes and when the filter fence failed on NM+2. Rates estimated when daylight video records were lost on NM+3 and NM+4 that were less precise but also less important for estimating an overall migration rate because household catch data indicated that these periods were at the end of the migration. Extrapolation of passage rates from West to East Sadam Channel was the greatest source of uncertainty in Sadam Channel passage rates.

Although hydrodynamic conditions at downstream entrances to East and West Sadam anabranches were likely different, we assumed equal passage rates for the two channels, because we believed that observed behaviour of upstream migrating fish to stay close to the channel banks, probably to avoid strong currents, would discourage schools from switching channels at the confluence. This uncertainty could be avoided in future surveys, either by establishing a fish counter in both channels or by blocking the downstream entrance to one channel completely and forcing all fish to pass a single counter. Overall,

FIGURE 7 Filter fence trap (downstream view) completely blocking a branch of Sadam Channel (image by authors on February 10, 2013). [Colour figure can be viewed at wileyonlinelibrary.com]

we concluded that the uncertainty in passage rates due to underestimated and missing data in West Sadam Channel and the unmeasured passage rate in East Sadam Channel did not materially alter the overall findings of the study, that there was a substantial passage of migratory fish on NM 0 but the passage rate on the following migration days was significantly depleted by artisanal fishing pressure, as illustrated in Figure 6.

Khone Falls is a partial biogeographical barrier that limits upstream dispersion by some species (Roberts & Baird, 1995). Adamson, Hurwood, Baker, and Mather (2009) invoked this barrier as the reason for two genetically distinct populations of *H. siamensis* in the Lower Mekong Basin. If so, will modifying Sadam and Xang Pheuak Channels to promote fish passage facilitate genetic mixing between these distinct *H. siamensis* genotypes?

We observed numerous *H. siamensis* individuals migrating upstream across Khone Falls via Sadam Channel in January 2015, but we doubt that was unusual. Poulsen et al. (2004) proposed that *H. siamensis* crosses Khone Falls in the early dry season and stays in feeding/refuge habitat immediately upstream until the next flood, when most individuals return downstream to spawn. Results from Adamson, Hurwood's et al. (2009) survey indirectly supported that distribution, as they recorded two individuals of the "below falls" genotype above Khone Falls, and the nearest samples were from the Mun/Mekong confluence more than 100 km upstream.

4.1.3 | Artisanal catch

Artisanal catch records have long been the principal data sources for fisheries studies at Khone Falls. Catch data used in this study were reliable because valued fishing locations are identified and known by all (Baird et al., 2003), fisher's livelihoods depend on accurate identification and weighing of catches, and DSPC regularly validated individual records. A livelihood survey of all households on islands affected by DSHPP found the mean annual fishing effort and catch by the 60 DSPC surveyed households was only 6% more than the mean for all other (213) fishing households (DSPC June 2015, unpublished). Thus, we concluded that the DSPC catch survey data provided an accurate and scaleable estimate of dominant species and total artisanal catch from Sadam Channel during the video survey.

DSPC channel modification has possibly made Sadam Channel more attractive to migrating fish, and the channel is certainly more passable now than in the past. Additional channel modifications could potentially improve passage efficiency. But the susceptibility of Sadam Channel to fishing pressure was evident from the reduction in passage efficiency when artisanal effort increased after NM 0. That result indicates that measures to reduce fishing pressure, like removal of the illegal traps identified by Philavong (2014), are likely to deliver greater gains in fish passage efficiency for Sadam Channel.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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