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Acoustic Telemetry Monitors Movements of Wild Adult Catfishes in the Mekong River, Thailand and Laos

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Abstract: Research on fish movement and habitat use in large tropical rivers is urgently needed to protect fisheries that are a primary source of protein for millions of people. In this pilot study, acoustic telemetry was used to monitor movements of wild catfishes in a 94.6 rkm reach of Mekong River, where it functions as the border between Thailand and Lao People's Democratic Republic (PDR). Twenty fish were tagged and released in May 2006 and monitored through May 2007 with 17 fixed-site acoustic receivers. Ten receivers had detection probabilities ranging from 0.67 to 1.00, and five receivers had detection probabilities of 0.50 or less. Detection probability was not correlated with river width. Eighteen (90%) of the tagged fish were detected by at least one receiver. Monitoring durations of individual fish ranged from 0.1 to 354.4 days. The longest total movement was 88.3 rkm, while the longest upstream movement was 52.1 rkm. Movement rates ranged from 0.1 to 156.7 rkm/d. This work provided preliminary data on movement patterns of wild Mekong catfishes. The methods and lessons learned from this study can be used for future positional telemetry research to address management-relevant uncertainties about migration corridors, habitat use, efficacy of fish reserves, and river development planning.

Keywords: conservation; telemetry; movement; migration; migratory fish; habitat; hydropower; tropical; transboundary; Southeast Asia

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1. Introduction

The Mekong River Basin supports one of the most diverse fish faunas in the world [1], harboring more species than any other river basin in Asia. Approximately 1000 species are believed to occur in the Mekong [2–4]. However, information on the ecology of Mekong fish is lacking [3] as is quantitative data on fish movement patterns. Migration, or predictable movement between distinct habitats made by a majority of an animal population [5], is an important part of many fishes' life history. An estimated 60–70% of Mekong fishes are migratory, making seasonal movements up or downstream or from the main channel to floodplain habitat [6]. These migrations are usually for breeding or dispersal, which are related to the annual hydrograph [1,7,8]. Most of the information on fish migrations and habitat use in the Mekong River is inferred from catch statistics and local knowledge [7,9]. Beyond this general understanding, empirical data on localized movement, seasonal migration patterns, and life history are limited. Therefore, research to understand these important life history attributes is urgently needed to create effective management plans, inform environmental impact assessments, and develop species conservation strategies.

In the Lower Mekong Basin, migratory fishes are critically important to the food security of local people [6]. Large-bodied migratory fishes, such as the Mekong giant catfish *Pangasianodon gigas* and giant barb *Catlocarpio siamensis*, are some of the most valuable species in the Mekong, selling for up to USD 100 per kilogram [10]. However, these fishes are often the most at-risk because of their high value and high vulnerability to anthropogenic pressures on the riverine ecosystem [10–12]. Of the Mekong's large fishes, catfishes (Siluriformes) are an important group. Several species are (or once were) staple food fishes, e.g., the striped catfish *Pangasianodon hypophthalmus* and spot pangasius *Pangasius larnaudii*. Many are also highly endangered, e.g., *P. gigas*, *P. hypophthalmus*, and *Pangasius sanitwongsei* [13]. These fishes are particularly important to the region and deserving of increased management attention because they are key components of many fisheries, are particularly vulnerable to overfishing and habitat degradation, and can serve as important flagship and umbrella species [14–19].

In a river system the size of the Lower Mekong Basin, tracking fish and generating long-distance movement data are expensive and difficult undertakings, which has resulted in a lack of this type of data for the region. However, remote tracking technologies can help answer management-relevant questions about fish movement and habitat use [20,21]. Of these technologies, radio and acoustic telemetry are two of the more popular methods for tracking long-distance fish movements in freshwater, each having their own advantages and disadvantages [21]. Acoustic telemetry has the edge in deep water and as such offers a promising method for tracking movements of large-bodied fishes in the Mekong, which has depths up to 80 m [21,22]. This method of tracking fish involves tagging fish with transmitters that actively broadcast an underwater acoustic signal, which is then detected and recorded at various locations with either mobile or fixed (stationary) receivers [20]. This method has been applied to numerous research questions, systems, and species [23], from assessing the site fidelity of giant manta rays *Manta birostris* in Indonesia [24] to describing the timing and water column locations of Atlantic salmon *Salmo salar* smolts migrating from European rivers to the Atlantic Ocean [25]. However, it has seen limited application in large, tropical freshwater systems (e.g., [26]) and is not commonly used to study wild fish movements in the Mekong River.

The goal of this pilot study was to demonstrate the effectiveness of acoustic telemetry as a tool for migratory fish research in the Mekong, and generate preliminary data on longitudinal (up- or downstream) movement patterns of large-bodied catfish species in the Mekong River in northern Thailand and Lao People's Democratic Republic (PDR). This section of the Mekong River is believed to be a critical habitat for many migratory fishes, including endangered species like the Mekong giant catfish that may migrate long distances from downstream areas to spawn in the complex habitat formed by deep pools and rapids found in this section of the river [7,27]. We focused on migratory catfishes because this group is an important component of the fish catch in the Lower Mekong Basin and thus supports fisheries and livelihoods, making these fishes highly significant to the people of the region. We further targeted catfishes that attain large body sizes because these are particularly vulnerable to overfishing and other threats [12,19,28,29]. Our study species attained maximum lengths of 120–240 cm, and included: *Bagarius yarrelli*, *Hemibagrus wyckioides*, *Pangasius bocourti*, *Wallago attu*, and *Pangasius conchophilus*. Our primary objectives were to examine: (1) the feasibility of using acoustic telemetry to study movements of wild fishes in the Mekong; (2) the distance and direction of fish movement (i.e., upstream or downstream); and (3) fish migration rates. The secondary objectives were to describe: (1) the swimming depth of a subset of acoustic-tagged fish and (2) the timing of movements throughout the day (i.e., nocturnal or diurnal). Taken together, these data can help characterize the scale and timing of fish movements and lay the groundwork for future telemetry studies in the Mekong.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Mekong River in northern Thailand and Lao PDR in Southeast Asia (Figure 1). The study area included 94.6 river kilometers (rkm) of the mainstem Mekong River between Chiang Saen, Thailand and the Thai–Lao border. This part of the river was chosen because it is relatively narrow (average width = 411 m) and deep when compared to the floodplain and delta habitats downstream. It also contains deep pool habitats, which are believed to be important spawning sites and dry season refuges for migratory fishes [30,31], and critical habitat for two of the Mekong's most imperiled fish species [19,32].

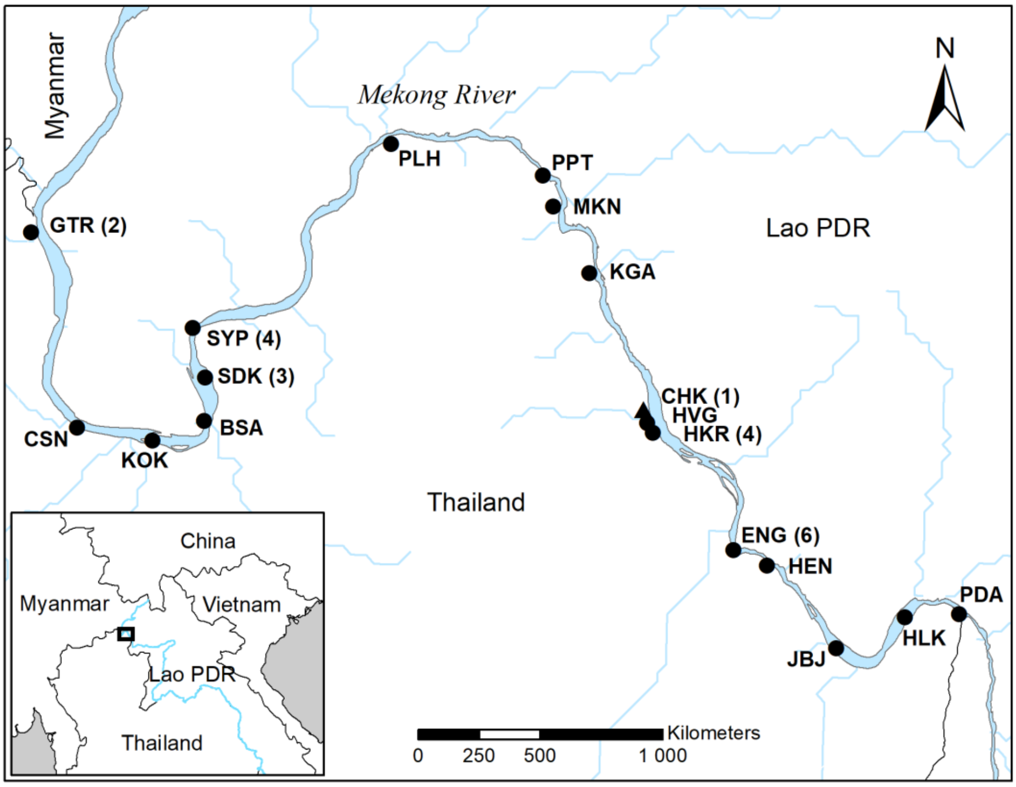

Figure 1. Map of the Mekong River study area in Thailand–Lao People's Democratic Republic (PDR), 2006–2007. Telemetry receiver locations are marked with black circles and labeled with the receiver site codes (see Table 1 for corresponding site names and additional receiver information). If fish were tagged and released at a receiver site, the number of fish released at that site is shown in parentheses next to the site code. One additional fish release site is marked with a black triangle: CHK (Chiang Khong).

2.2. Telemetry Monitoring

We used fixed-site telemetry stations to monitor movements of acoustic-tagged fish from May 2006 to May 2007 [33]. Telemetry receivers were installed near the mouths of major tributaries, at major fishing sites, and at narrow points of the Mekong River (range of river widths = 210–770 m; Figure 1, Table 1). These sites were chosen to maximize the probability of detecting tagged fish based on our knowledge of fish behavior, existing fisheries, and the results of earlier tests of tag and receiver performance. These tests showed that ultrasonic transmitters had strong signals up to 813 m from the receivers, although signal strength varied by location and even by day [34]. Local fishers also helped select stationary receiver sites based on their knowledge of fish movements, access, river conditions, and security. The telemetry sites included locations near the confluences of the Mekong and the Kok and Ing Rivers, and near Chiang Saen, Ban Saow Village, Huay Leuk, Hat Khrai, Meuang Gan, and Suan Dok villages (Figure 1, Table 1).

Table 1. Locations and detection probabilities of receivers used to monitor movements of acoustic-tagged catfishes in the Mekong River, northern Thailand, from May 2006 to May 2007.

Receiver Site Code	Receiver Site Name	Location (rkm)	Channel Width (km)	Number of Fish Detected	Number of Fish Missed	Detection Probability
GTR	Golden Triangle	0	0.51	3	-	-
CSN	Chiang Saen village	11.5	0.57	1	2	0.33
KOK	Sop Kok River	15.7	0.77	4	2	0.67
BSA	Ban Saow village	19.7	0.32	4	2	0.67
SDK	Suan Dok village	22.7	0.46	4	1	0.80
SYP	Sop Yap village	25.1	0.38	4	1	0.80
PLH	Pah Leh	42.5	0.62	4	1	0.80
PPT	Pha Pra Thai	52.0	0.35	4	1	0.80
MKN	Meuang Gan village	54.2	0.32	0	3	0.00
KGA	Kaeng Gai village	59.3	0.36	1	2	0.33
HVG	Huay Vieng village	68.3	0.64	4	0	1.00
HKR	Hat Khrai	68.9	0.59	2	1	0.67
ENG	Pak Ing River	77.7	0.44	3	0	1.00
HEN	Huay Eian village	79.9	0.31	6	0	1.00
JBJ	Jam Bong village	85.8	0.21	0	4	0.00
HLK	Huay Leuk village	90.9	0.60	2	2	0.50
PDA	Pa Dai village	94.6	0.26	2	-	-

One acoustic receiver was installed at each site. We used Vemco VR2 receivers (Vemco, Inc., Shad Bay, Nova Scotia) attached to bamboo rafts constructed by local residents. The typical bamboo raft consisted of four to eight bamboo logs approximately 2 m in length and 15 cm in diameter with a 1.5 m center pole (Figure 2). The receivers were attached to the center pole approximately 0.5 m beneath the water with hose clamps and then additionally secured with bailing wire and nylon rope. The raft was placed in the river approximately 5–20 m from shore, anchored with a rock, then secured to shore with nylon rope. The raft was monitored by local residents who adjusted its position relative to shore as the water level changed. Local residents were paid 1000 Thai Baht (approximately USD 28) every three months to monitor a raft.

2.3. Fish Capture and Tagging

Tagging fish with acoustic transmitters was conducted from 5–20 May 2006. Catfishes were purchased from a network of local fishers at the capture location, typically for 160–200 Thai Baht per kilogram (USD 4–5). The fishers were informed of the project ahead of time and contacted us as soon as they caught a fish that would be suitable for tagging. We also conducted daily trips to popular fishing sites to obtain fish for tagging. Fish were selected based on condition and body weight such that the tag weight would be less than 2% of the body weight [22]. The fish were held in cages or tethered to bamboo poles prior to tagging. They were then transferred to a cradle and anesthetized with tricaine methanesulfonate (MS222, 50 ppm), measured for total length to the nearest 0.5 cm, and weighed to the nearest 0.1 kg before transmitters were implanted (Figure 3). Fish were held ventral side up and the anesthesia water was passed over the gills. Tagging consisted of making a small (~50 mm) incision just off the ventral midline at a point even with the dorsal fin. The acoustic transmitter was then inserted to the body cavity and the incision was closed with three or four monofilament sutures [35]. After implanting the transmitter, an individually numbered Carlin Dangler tag (Floy Tag, Inc., Seattle, WA, USA) was attached under the dorsal fin on the left side of the fish. The tag was labeled with the instructions “Please Return to the Department of Fisheries” in Thai, with a reward offer of 50 Thai Baht (USD 1.40). After tagging, fish were placed into an oxygenated 100–L tote to recover and were then released into low velocity water proximal to where they were captured and monitored until they regained equilibrium (typically 10–15 min).

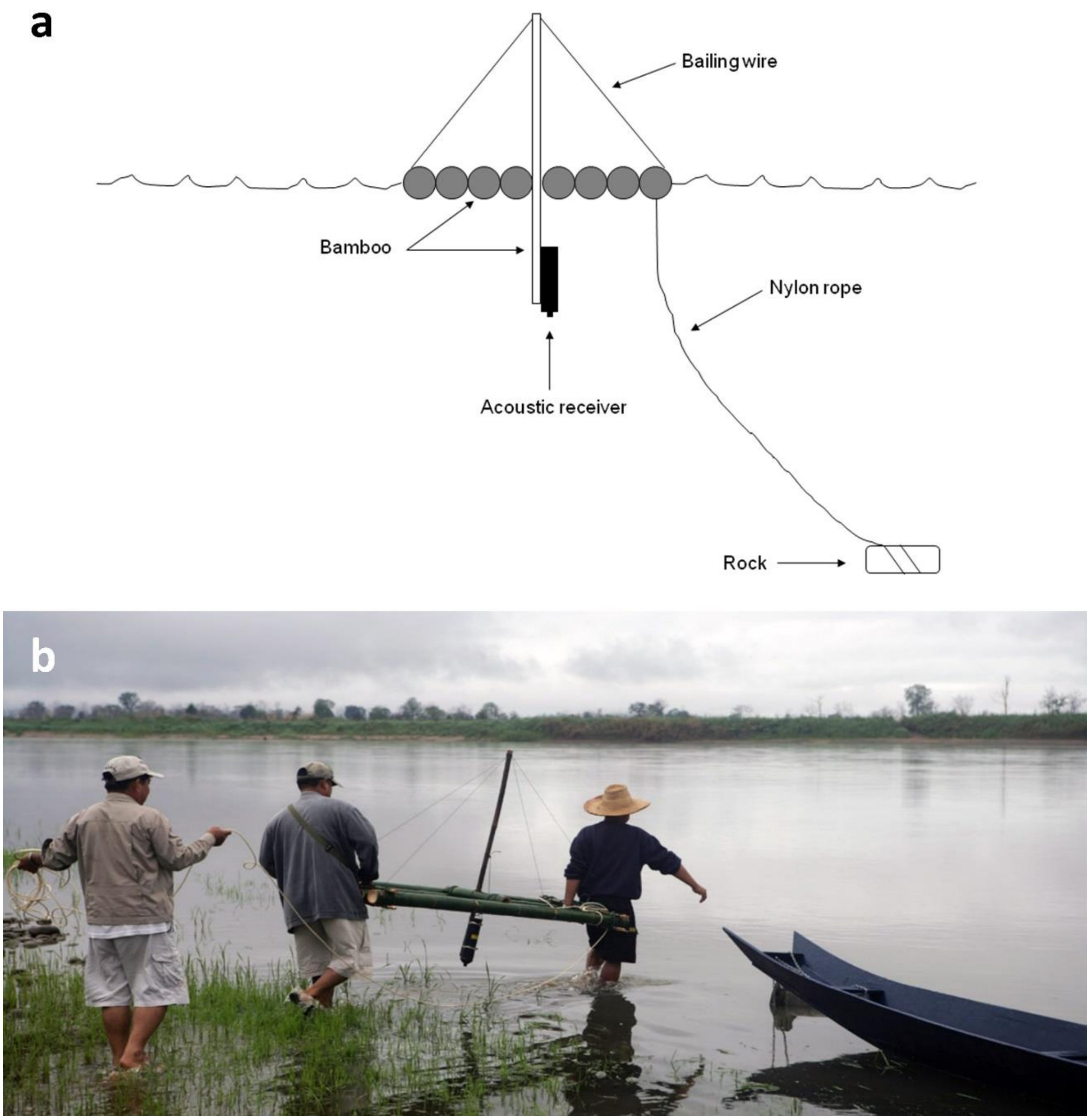

Figure 2. (**a**) Illustration of the receiver platform used to monitor acoustic-tagged catfishes in the Mekong River, Thailand–Lao PDR in 2006–2007. (**b**) Deployment of a receiver.

Catfishes were tagged with cylindrical Vemco acoustic transmitters that transmit a unique, digitally-coded signal (Figure 3). Five types of transmitters were used: V13-1L, V16-4H, V16-6H, V16P-4H, and V16P-6H. One fish received a V13-1L tag, ten fish received V16-4H tags, six fish received V16-6H tags, and three fish received V16P tags (n = 1 V16P-4H, n = 2 V16P-6H). The size specifications and operating parameters of the tags are listed in Table 2. The main differences among the tags were the size of the battery and whether or not a pressure sensor was included. The V13-1L tag was the smallest tag and had a slightly lower power output than the V16 tags. It also had a longer transmission interval, which allowed it to have a longer operating life with its smaller battery. The V16-4H tags had a smaller battery than the V16-6H tags, which affected the rated operating life, but not the power output. The V16P tags were the pressure tags, meaning that they had an attached sensor that recorded pressure, which was converted to depth (accuracy rated to $\pm$ 1.7 m at 34 m). Using these different tag types allowed us to tag the largest fish with long-lasting tags and also increase the sample size by including smaller fish while maintaining a safe fish-to-tag weight ratio. It also allowed us to collect depth data from a subset of fish, since the additional cost of the pressure sensors prohibited them from being added to all tags.

Figure 3. Photos of the fish capture and tagging process for acoustic telemetry tracking in the Mekong River, Thailand and Lao PDR. (**a**) Capture of a *B. yarrelli*. (**b**) Acoustic tags used in the study. (**c**) A fish anesthetized in the tagging cradle. (**d**) A *H. wyckioides* in the recovery tote showing the external tag.

Table 2. Vemco acoustic tag specifications and operating parameters. The transmission interval shows the minimum and maximum time intervals between transmission bursts; the tag randomly varies the transmission interval in order to maximize both detection probability and battery life. All tags operated at a frequency of 69 kHz.

Tag Type	Diameter (mm)	Length (mm)	Weight in Water (g)	Power Output (dB re 1 µPa @ 1 m)	Transmission Interval (s)	Rated Operating Life (d)
V13-1L	13	36	6.3	147	20–60	360
V16-4H	16	68	10.3	158	5–30	309
V16-6H	16	95	14.9	158	5–30	618
V16P-4H	16	71	11.7	158	5–30	279
V16P-6H	16	98	16.3	158	5–30	557

A total of 20 wild catfishes were tagged: ten *Bagarius yarrelli*, five *Hemibagrus wyckioides*, two *Pangasius bocourti*, two *Wallago attu*, and one *Pangasius conchophilus*. One specimen each of *B. yarrelli*, *H. wyckioides*, and *P. bocourti* were tagged with the V16P pressure transmitters. The fish were tagged and released at six locations within the receiver array (Figure 1). All fish were released within 2 km of a receiver.

2.4. Data Processing and Analysis

Acoustic receivers were downloaded approximately every two months in the field using a laptop computer. Files were screened to remove obvious errors and electronic background noise. The data were then coded, which involved inspecting all records for each fish and assigning a code to the records that defined the first and last detections of a fish at a given receiver site. Coding was facilitated by using an automated program developed with Visual Basic.NET software. Coded data were used to identify presence at receiver sites and calculate movement times (d) and rates (km/d) of tagged fish.

The effectiveness of our telemetry array was evaluated by calculating the detection probability of each receiver. The detection probability of a receiver was defined as the number of unique fish detected divided by the sum of the number of unique fish detected and the number of unique fish missed. Missed detections were defined as fish that were not detected by the receiver, but were known to have passed the receiver because of detections (or releases) at sites up- and downstream of that receiver at different points in time.

A receiver's detection probability was calculated with the following formula:

$$p_i = u_i/(u_i + m_i), \tag{1}$$

where p_i = the probability of detecting a tagged fish at receiver i, u_i = the number of unique fish detected by receiver i, and m_i = the number of unique fish that were not detected by receiver i, but were known to have passed receiver i because of detections at upstream and downstream sites.

The total distance traveled by an individual fish was calculated by summing all upstream and downstream movements, beginning with the fish release site. Distances were calculated in river kilometers (rkm), which were produced using ArcGIS. Total upstream and total downstream distances were calculated by summing all of the individual upstream or downstream distances moved by the fish. Upstream and downstream movement rates (rkm/d) were calculated by dividing the total upstream or downstream movement distances by the time it took them to move between receivers, i.e., the time between the last detection on the previous receiver (or fish release site) and the first detection on the next receiver. If an individual fish made multiple downstream movements with periods of rest or upstream movement in between, all of the individual downstream movements were summed to obtain the total downstream distance, and only the time that the fish was moving downstream was used to calculate the downstream movement rate (i.e., the time the fish spent resting or moving upstream was not included in the calculation of downstream movement rate). This same procedure was applied to fish that made multiple upstream movements.

Because the transmitters could be detected by the receivers as far away as 0.8 km [34], movement distances should be considered to have a precision of ±0.8 rkm. Thus, movement distances that were less than 0.8 rkm (i.e., from a fish release site to the first receiver) in actuality may have been even smaller. Therefore, the movement distances presented here should be considered "detected movements," which may be overestimates at finer scales. This also translates into the calculated movement rates, in that fish that were detected moving short distances may have faster movement rates than actually calculated. Movement rates were not calculated for fish that moved less than 0.8 km.

Movements were also classified by direction (upstream or downstream) and timing (diurnal or nocturnal). Diurnal movements were defined as having occurred between 06:00–19:59 h and nocturnal movements between 20:00–05:59 h.

3. Results

Most receivers had relatively high detection probabilities: three had perfect detection probabilities (1.00), four had a detection probability of 0.80, three had a detection probability of 0.67, and five had a detection probability of 0.50 or less (Table 1). (Detection probability could not be calculated for the two receivers on the ends of the receiver array because fish were not released outside of the array.) Fish were recorded on 15 (88%) of the 17 receivers

(Table 1). Nine receivers recorded fewer than four fish, while eight receivers recorded four to six fish. The HEN receiver detected the most fish ($n = 6$), while the closest downstream receiver to HEN, JBJ, missed the most fish ($n = 4$) and had zero detections. MKN also had zero detections and missed three fish. There was no relationship between channel width and number of fish missed or number of fish detected. JBJ, the poorest performing receiver had the narrowest channel width (0.21 km). The receiver at the widest channel width, KOK, performed relatively well, detecting four fish and missing two fish (mean number of fish missed across receivers was 1.3). The receiver at the second widest channel width, HVG, had a 100% detection rate, detecting four fish and missing zero fish (Table 1).

The percentage of fish detected by receivers and their monitoring durations varied widely by species and individual. In total, eighteen (90%) of the 20 tagged fish were detected by the receivers, while two fish (10%), a *B. yarrelli* and a *H. wyckioides*, were never detected after release (Table 3). Fifteen fish were monitored for less than 20 days, while five fish were monitored for more than 94 days. Nine of the 10 tagged *B. yarrelli* were detected after release (six by more than one receiver), with monitoring durations ranging from 3.4 to 354.4 d. Three *B. yarrelli* were only detected by one receiver, including one that was monitored for 94.8 d. One of the five *H. wyckioides* was recaptured by a fisherman near the release site the same day it was tagged without being detected by any receiver. Two *H. wyckioides* were detected by more than one receiver with monitoring durations of 8.4 and 336.1 d. The individual monitored for 336.1 d was recorded by six different receivers. Two other *H. wyckioides* were recorded by only one receiver and were monitored for 0.1 and 0.5 d. All of the *P. bocourti*, *W. attu*, and *P. conchophilus* were recorded by the receivers, with monitoring durations ranging from 0.1 to 9.7 d (Table 3).

Movement distance, direction, and rate also varied among the fish. The shortest detected distance traveled was 0.6 rkm, made by the one tagged *P. conchophilus* (Table 4), but because this distance was within the estimated detection range of our receivers, it was not considered valid. However, the time between this fish's receiver detections was one hour and 16 min, suggesting that the fish may have moved upstream at least some distance; therefore, we will continue to discuss this fish's movement throughout the results. The next shortest distance was made by two *H. wyckioides*, both of which traveled 2.2 km downstream. The longest total distance traveled was 88.3 rkm (52.0 rkm downstream, 36.3 rkm upstream) by a *W. attu* (Table 4).

Five fish moved both upstream and downstream, three fish moved only upstream, and six fish moved only downstream (Table 4). Downstream movement distances ranged from 2.2 to 52.0 rkm. The longest downstream movement was made by a *W. attu*, the same fish that also moved the longest total distance. A total of eight fish moved upstream after tagging: five *B. yarrelli*, one *H. wyckioides*, one *W. attu*, and one *P. conchophilus* (Table 4), although the short *P. conchophilus* movement may not have been a true movement. Upstream movement distances ranged from 17.4 to 53.2 rkm (not including the 0.6 rkm detected for the *P. conchophilus*), both of which were made by *B. yarrelli* individuals.

Across species, downstream movement rates ranged from 0.1 to 156.7 rkm/d, while upstream movement rates ranged from 0.3 to 25.3 rkm/d (Table 4). The fastest movement was made by a *W. attu* that moved 52 rkm downstream in eight hours (Table 4). The slowest movement rates (0.1 rkm/d downstream) were made by a *B. yarrelli* and an *H. wyckioides*: the *B. yarrelli* moved 19.8 rkm (SDK to PLH) over 232 days and the *H. wyckioides* moved 16.9 km (ENG to PDA) over 333 days.

Table 3. Movement characteristics of wild catfishes monitored in the Mekong River, northern Thailand and Lao PDR from May 2006 to May 2007. "Total days monitored" is the number of days between the release time and the last time the fish was detected by the receiver array; this was zero if a fish was never detected by a receiver. "Total distance traveled" was zero if a fish was released nearby a receiver and was only detected by that receiver.

Species	Length (cm)	Weight (kg)	Date Tagged	Tag Type	Total Days Monitored (d)	Total Distance Traveled (rkm)	Receivers with Records (count)	Moved Upstream? (yes/no)	Recorded During Day (d) or Night (n)
B. yarrelli	92.5	4.5	5-May	V16-4H	17.8	43.8	6	yes	dn
	72.0	n/a	9-May	V16-4H	106.4	39.4	4	yes	dn
	82.0	4.2	9-May	V16-4H	4.2	0.0	1	no	d
	77.0	3.9	11-May	V16-4H	3.4	26.9	2	no	dn
	147.0	30.0	13-May	V16-4H	0.0	-	0	-	-
	84.0	5.6	16-May	V16-6H	140.7	35.8	5	yes	dn
	96.5	6.3	16-May	V16-6H	354.4	37.2	2	yes	dn
	82.0	4.7	16-May	V16-6H	94.8	0.0	1	no	dn
	121.0	17.5	19-May	V16P-6H	6.9	26.9	1	no	dn
	106.0	8.0	20-May	V16-6H	19.9	53.2	5	yes	dn
H. wyckioides	81.0	3.5	8-May	V16-4H	8.4	2.2	2	no	n
	71.0	3.0	14-May	V13-1L	0.0	-	0	-	-
	90.0	5.0	16-May	V16-6H	0.5	2.2	1	no	n
	89.5	6.5	17-May	V16P-6H	336.1	69.0	6	yes	dn
	79.0	4.6	17-May	V16-6H	0.1	0.0	1	no	n
P. bocourti	93.0	9.5	14-May	V16-4H	0.8	11.0	2	no	n
	77.0	6.4	19-May	V16P-4H	0.8	25.7	2	no	dn
W. attu	98.0	n/a	9-May	V16-4H	5.3	88.3	3	yes	dn
	82.5	3.3	15-May	V16-4H	9.7	0.0	1	no	dn
P. conchophilus	75.0	5.5	20-May	V16-4H	0.1	0.6	1	yes	dn

Table 4. Movement distances and rates of wild catfishes monitored in the Mekong River, northern Thailand and Lao PDR between May 2006 and May 2007. The first five columns are repeated from Table 3 for convenience.

Species	Length (cm)	Weight (kg)	Total Days Monitored (d)	Total Distance Traveled (rkm)	Downstream Distance (rkm)	Downstream Movement Rate (rkm/d)	Upstream Distance (rkm)	Upstream Movement Rate (rkm/d)
B. yarrelli	92.5	4.5	17.8	43.8	-	-	43.8	2.5
	72.0	n/a	106.4	39.4	19.7	0.4	19.7	0.6
	82.0	4.2	4.2	0.0	-	-	-	-
	77.0	3.9	3.4	26.9	26.9	7.8	-	-
	147.0	30.0	0.0	-	-	-	-	-
	84.0	5.6	140.7	35.8	15.2	0.2	20.6	0.3
	96.5	6.3	354.4	37.2	19.8	0.1	17.4	0.3
	82.0	4.7	94.8	0.0	-	-	-	-
	121.0	17.5	6.9	26.9	26.9	4.3	-	-
	106.0	8.0	19.9	53.2	-	-	53.2	2.7
H. wyckioides	81.0	3.5	8.4	2.2	2.2	0.3	-	-
	71.0	3.0	0.0	-	-	-	-	-
	90.0	5.0	0.5	2.2	2.2	4.1	-	-
	89.5	6.5	336.1	69.0	16.9	0.1	52.1	15.3
	79.0	4.6	0.1	0.0	-	-	-	-
P. bocourti	93.0	9.5	0.8	11.0	11.0	14.2	-	-
	77.0	6.4	0.8	25.7	25.7	32.8	-	-
W. attu	98.0	n/a	5.3	88.3	52.0	156.7	36.3	25.3
	82.5	3.3	9.7	0.0	-	-	-	-
P. conchophilus	75.0	5.5	0.1	0.6	-	-	0.6	-

Examining the timing of fish movements over the duration of the study period showed that rapid upstream movements occurred between April and July (Figure 4). Several fish moved upstream almost immediately after tagging in May or June, but the two fish that were monitored for nearly a year waited until the following March or April to move upstream. Several fish had multidirectional movement tracks. Generally, the transition between moving upstream and downstream was gradual, but one *W. attu* moved 52 rkm downstream and then 36.3 rkm upstream within the same day. The two *P. bocourti* moved downstream after tagging and, apparently, out of the study area (the downstream-most receiver was PDA at rkm 94.6) for the remainder of the study (Figure 4).

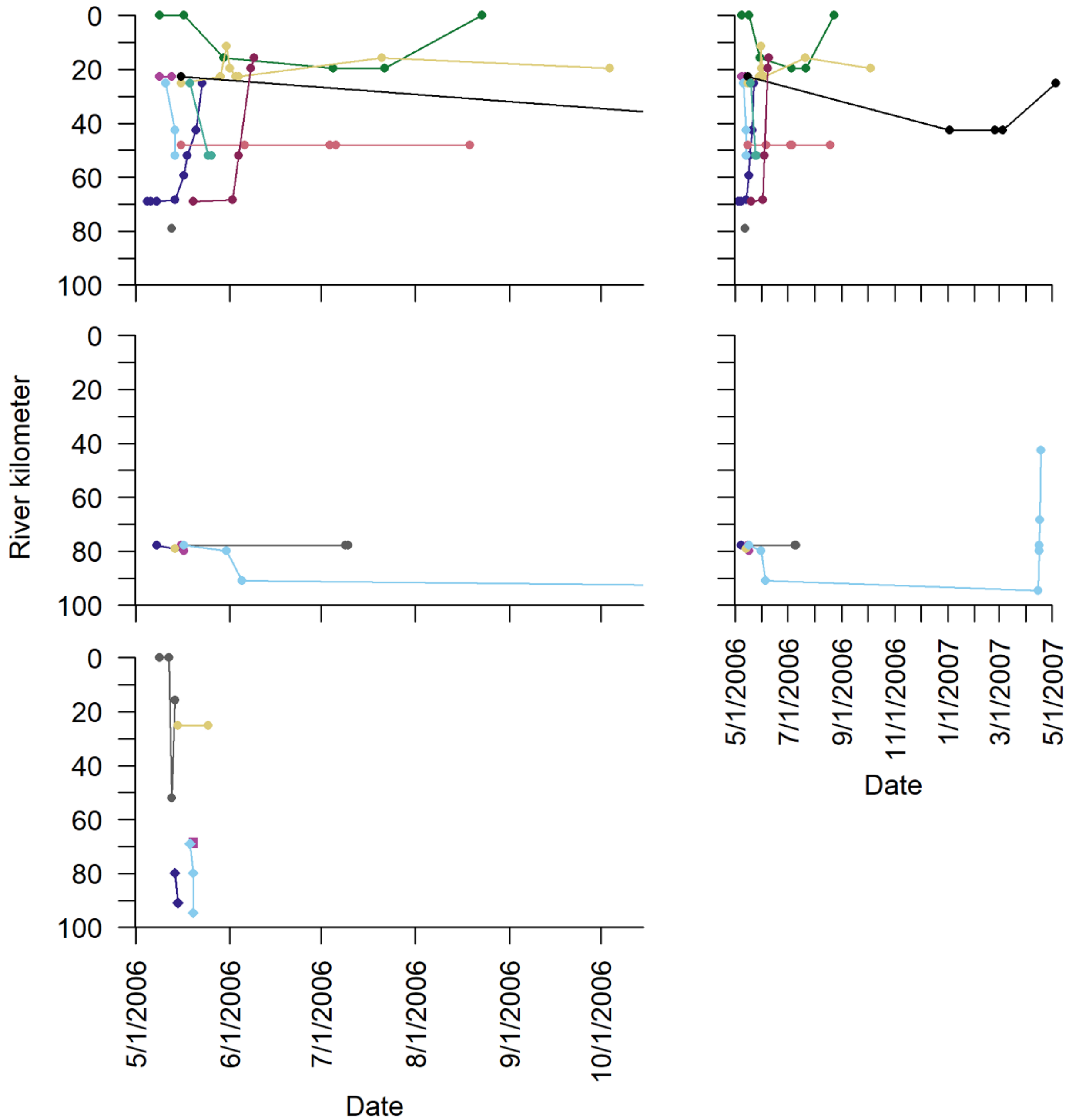

Figure 4. Movements of acoustic-tagged catfishes in the Mekong River, Thailand and Lao PDR. Each point represents a detection by an acoustic receiver. River kilometer corresponds to the location of the receiver within the study area, with zero being the location of the first receiver in the array, Golden Triangle (GTR), which is also the most upstream receiver. The panels on the right show the same data as the panels on the left, but with the dates extended through 5/1/2007 to show the full datasets for two fish monitored for nearly one year. Top panels: *B. yarrelli*; middle panels: *H. wyckioides*; bottom panel: *W. attu* (circles), *P. bocourti* (diamonds), and *P. conchophilus* (square).

The three fish tagged with pressure transmitters were recorded by several receivers, but only one receiver generated depth data for a fish for longer than ten minutes. This fish, the *B. yarrelli*, was detected for over 17 h at the Pha Pra Thai receiver (rkm 52), which gathered 126 telemetry records. Its median depth was 19.4 m (mean = 19.7 m, range = 5.8–29.2 m). This fish was actively moving between 5.8 and 25.2 m from 16:26 to 17:06 (Figure 5). Then, at 17:41, it descended to 28.8 m, where it remained until 08:12 the following morning. At 09:05, the fish moved toward the surface, where it fluctuated between 8–11 m until 09:14 when the receiver stopped detecting it (Figure 5). The *H. wyckioides* and *P. bocourti* were recorded at the Huay Eian receiver (HEN, rkm 79.9), but monitoring durations were only 5–6 min. The median depth for the *H. wyckioides* was 10.9 m (range = 7.9–12.8 m; 16 records) and median depth for the *P. bocourti* was 17.5 m (range = 8.2–23.9 m; 16 records). The H. wyckioides was also recorded by the Huay Leuk receiver (HLK, rkm 90.9) at a median depth of 3.8 m (range 1.5–64 m) over a 1.5-min period.

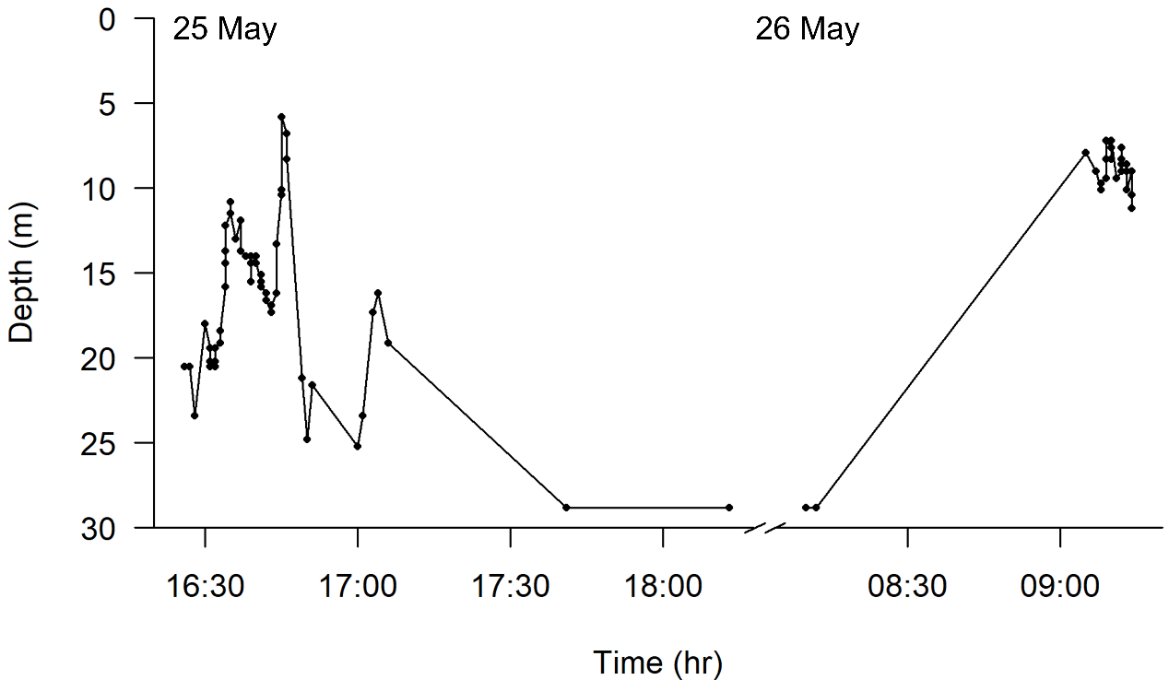

Figure 5. Depth profile of one *Bagarius yarrelli* monitored for approximately 17 h at the Pha Pra Thai receiver (PPT) in the Mekong River, Thailand. The maximum depth of the river at this location is not shown on the graph because the maximum depth is not known. Forty-four data points are obscured by the break in the x-axis: all except two have the same value as the two points before and after the break (28.8 m); the other two points are 29.2 m.

Thirteen (72%) of the 18 detected catfishes were detected by receivers both during the day and at night, while four (22%) were detected only at night and one (6%) was detected only during the day (Table 3). Therefore, 17 (94%) of the 18 detected fish were detected at night, while 14 (78%) were detected during the day. Eight of the detected *B. yarrelli* were recorded both during the day and at night; one was recorded only during the day. Three of the four detected *H. wyckioides* were recorded at night only and one was recorded during the day and night. One *P. bocourti* was detected during the day and night, and the other was detected at night only. Both *W. attu* and the lone *P. conchophilus* were recorded during the day and at night (Table 3).

4. Discussion

Data on fish migrations are urgently needed in the Lower Mekong Basin, where people depend on migratory fishes for their livelihoods and these same fishes are heavily threatened by human development such as hydropower. Understanding the scale, timing, and triggers of fish migrations can help inform management and policy decisions, such as dam siting, flow regulations, and habitat restorations. Up until now, most information about fish migrations has been provided by fish catch data and the knowledge of local fishers [17,36], neither of which provides a complete picture of these migrations. Our pilot study was the first to use positional telemetry to quantify movement characteristics of wild fishes in the Mekong River. The study results demonstrated that acoustic telemetry is a viable tool to address knowledge gaps about migratory fishes in the Mekong and provided preliminary information about wild catfish migrations.

A primary goal of our study was to demonstrate the utility of acoustic telemetry for quantifying characteristics of catfish migrations in the Mekong River. Overall, the receiver array performed relatively well. Ten out of 15 receivers had detection probabilities of 0.67 or greater (Table 1). Moreover, 90% of tagged fish were detected after release, which is higher than reported in a similar study done by Mitamura et al. [37] wherein 43% of immature, hatchery–reared Mekong giant catfish *P. gigas* were detected after release (however, Mitamura et al. [37] only used five to seven acoustic receivers across three years in a study area that spanned approximately 600 km). Our detection rate was also just as good or better than a recent study in a large Amazon tributary where 76% and 93.4% of the two catfish species tagged were detected after release [26], and in this study the authors used stationary acoustic and radio receivers as well as mobile tracking. The relative success of our receiver array suggests that acoustic telemetry is a reliable method for tracking fish movements in the Mekong River. It also suggests that scaling up this study to include more receivers and tags will produce finer, more reliable results.

Although our receivers performed relatively well, it is important to note that all but three receivers missed fish (Table 1). We should also note that, in an ideal study, tag range testing would have been carried out within the study area prior to the study to estimate detection probability. This is because many environmental factors can affect detection probability such that even if a tag is in range it is not detected. Since our method of calculating detection probability could not account for this, our detection probability estimates should be considered maximum estimates. As it was, our detection probability estimates were highly variable and there was a low number of detections in general. This may suggest that the fixed receiver coverage was insufficient to adequately capture migratory behaviors. All of the receivers except one were located on the Thai side of the river and thus fish moving on the Lao side may have been out of range of the receivers. In their study, Mitamura et al. [37] partly attributed the low number of fish detections to only having receivers on the Thai side of the river. However, our results showed no correlation between river width and receiver performance (Table 1), suggesting that the river widths at receiver locations were appropriate for our acoustic transmitters and receivers, which also agrees with previous tag testing [34]. Therefore, some other variable, or variables, must have affected detection probability.

One possibility is that the receiver setup used in this study may have hindered detection of catfish movements. Acoustic telemetry systems are sensitive to location and method of deployment [33]. Our receivers were positioned approximately 0.5 m beneath the surface and near the shore, which may have made it harder to detect the more benthic-oriented catfishes. With a single receiver at each site, detection probability would be optimized with a mid-channel deployment and possibly a bottom-mounted setup [38]. In this study, mid-channel deployment was not possible due to Lao border restrictions. We also decided against a mid-channel, bottom-mounted setup due to the heavy boat traffic and difficulty of retrieval. The strong river fluctuations (water levels may fluctuate as much as 10 m from dry season to rainy season) also put anything left unattended at a high risk of being swept away. Furthermore, unattended equipment is often stolen. The benefits of our setup were that it was inexpensive, receivers were easy to retrieve, and having local people attend the raft near the shore provided security from loss and theft. However, these benefits should be carefully considered in relation to optimal acoustic performance and specific local conditions when designing future studies.

Acoustic receivers are also very sensitive to noise from boat traffic, current, and wave action [22,33], and the daily fishing and cargo boat traffic in the study area may have interfered with tag detection. However, we find this unlikely because 53.5% of tag detections occurred during the day, which is when boat traffic was heaviest. Although no formal analysis was conducted, it is likely that the best-performing receivers were in locations with deep, non-turbulent water and relatively little boat activity. It is also possible that fish were captured in fisheries, shed their tags (which can be common in catfish species [39]), or died and were not further detected.

Different species also inherently have different detection probabilities due to differences in behavior. For example, *B. yarrelli* is considered to be relatively sedentary compared to the other study species. Thus, *B. yarrelli* individuals may have moved relatively short distances within the study reach and remained relatively inactive for long periods of time, which would increase the probability of being detected. In contrast, Pangasiids are highly migratory, fast-moving pelagic species, which would make them more difficult to detect especially with receivers on only one side of the river. This may partially explain why *P. bocourti* and *P. conchophilus* individuals were detected by only 1 or 2 receivers, while four *B. yarrelli* individuals were detected by four to six receivers (Table 3). We do not believe that the different tag types used in this study had a significant effect on detection probability because the primary difference in the V16 tags was the size of the battery and, according to Vemco [40,41], the battery size did not affect the power output (Table 2), which is responsible for determining the detection range and thus partially responsible for determining detection probability.

Improving detection probabilities and increasing the understanding of fates for individual fish would require tagging more fish to account for tagging and fishing mortality, mobile tracking to detect tags between or outside the boundaries of fixed receiver sites, and a more comprehensive network of fixed receiver stations placed at strategic locations along the river, such as constricted areas, mouths of tributaries, both sides of the river, and critical habitat [22,38]. Shortening the burst rate of tag signal transmissions also increases detection probability, but has to be balanced with battery life [22]. These steps would significantly increase the probability of detecting tagged fish and providing data suitable for inferences about migration behavior, habitat use, and transboundary movements.

We also demonstrated that the tagging methods used in this study were successful at keeping fish in good condition to be tracked long-term. Eight fish moved upstream after tagging and four of those fish were monitored for long periods of time (106.4–354.4 days, Table 3). Two fish also had relatively rapid upstream movement rates (15.3–25.3 km/d, Table 4). This shows that the tagging and handling methods were effective at keeping fish in healthy condition. However, six fish moved only downstream and three fish remained stationary after tagging, suggesting a possible handling or tagging effect. Research has shown that adult fishes handled in riverine studies may delay their migration or move downstream after release (e.g., [42–44]). Many studies have documented sub-lethal effects, including decreased survival [45], altered behavior [46–48], and loss of swimming capacity [49–52]. Furthermore, stress from handling and tagging may cause some fish to die prematurely. Distinguishing mortality from other fates has been difficult for unrecovered individuals in many studies of fish (e.g., [53–55]) and other taxa [56–58]. In our study, two tagged fish, a *H. wyckioides* and a *B. yarrelli*, were never detected on any of the 17 receivers. The *H. wyckioides* was captured by a fisher 100 m downstream from the release site in 3.5 m of water only six hours after release, indicating that the fish may have been affected by the tagging and was more susceptible to capture. The fisher reported the fish after reading the script on the external tag. The *B. yarrelli* may have died, lost tags, emigrated to unmonitored areas, or been harvested in fisheries and not reported to the researchers. There is extremely high fishing pressure in the Mekong River, so these fish have a high probability of being removed by fishers. Increasing the number of fish tagged, increasing telemetry coverage (including mobile tracking), and implementing rewards for tag returns can help partition harvest and tag loss from other fates. While it was not possible to evaluate or measure sub–lethal effects of capture, handling, anesthesia, and surgery on fish in this study, the procedures used in this study are consistent with those used in other telemetry studies [59–61] and should have produced good results.

Future positional telemetry work in the Mekong would do well to implement studies to determine the effects of tagging on the fish and gain a better understanding of possible altered behavior and mortality due to tagging. Such studies need to be done at the species level since individual species often respond differently to tagging and handling [39]. In our study, *B. yarrelli* appeared to recover more quickly from tagging than the other species, especially the Pangasiids, which may partially explain the lack of upstream movement by *P. bocourti* and *P. conchophilus* individuals (Table 3). Ideally, researchers conducting future telemetry studies would test for species-specific non-lethal effects from tagging and handling prior to implementing large-scale studies. This will lead to more reliable results since conclusions from tagging studies depend on the assumption that tagged fish represent sampled populations and behave similarly to untagged fish.

Another important goal of the study was to provide information about wild catfish movement in the Mekong. We characterized movement distance, direction, depth, and timing for five species. The small sample sizes for our species coupled with high individual variation in movement characteristics preclude drawing firm conclusions about species-specific migration characteristics. However, we can draw out important lessons from our results for future work in this region. Of note is the two species with larger sample sizes, *B. yarrelli* and *H. wyckioides*, had one or more individuals that was monitored for more than 94 days, suggesting that the larger the sample size, the more likely it is to have individuals that are monitored for long periods of time. Additionally, although *P. bocourti* and *W. attu* had low sample sizes, they had the highest movement rates of all the species, suggesting that these two species may migrate more rapidly than the other species. Migration rates are important to understand for proper species management, and this result shows that monitoring the migration of different species is important in a multi-species assemblage.

Although the sample sizes were small, the movement rates of our wild catfishes (range = 0.1–156.7 rkm/d, mean = 14.9 rkm/d, median = 2.6 rkm/d; Table 4) were overall similar to those of Pangasiids and cyprinids in previous studies in the Mekong. Hogan et al. [62] found that the large catfish *Pangasius krempfi* migrated over 700 km in approximately 150 days (5 km/d). Hogan et al. [63] reported that the river catfish *P. hypophthalmus* migrated approximately 300 km in 90 days (3 km/d). Mitamura et al. [37] reported upstream movement rates of 7–19 km/d for hatchery-reared Mekong giant catfish *P. gigas*. Baird et al. [36] hypothesized, based on catch data, that small cyprinids moved approximately 20–30 km/day in the Mekong River in southern Laos. The rapid downstream movement made by the *W. attu* in our study (156.7 rkm/d) was an outlier and was also much higher than rates reported in previous studies. On the other hand, the extremely low movement rates made by some of our fish (Table 4) most likely resulted from fish remaining relatively stationary for long periods of time before moving rather than direct, uniform movements between receivers. Although our results show similarities to other studies and species, the high variation both among and within species reemphasizes the need for larger sample sizes to adequately understand species-specific migration rates.

Examining the timing of fish movements also revealed high inter- and intraspecific variation. Most of the fish in our study exhibited unidirectional movement or gradual changes between upstream and downstream movements (Figure 4). However, two fish exhibited relatively rapid directional changes (Figure 4). Rapid, upstream movements typically occurred between April and July (Figure 4), which is consistent with previous knowledge that suggests that the transition from dry season to rainy season is an ecological trigger for fish migrations [7]. We also showed that nearly all (72%) of the fish moved both during the day and at night (Table 3). Ninety-four percent were observed to move at night versus 78% during the day. The high percentage of fish with records during the day is somewhat unexpected because many catfishes are presumed to be nocturnal [64,65].

Understanding life-history traits such as when fish are actively swimming is important for applications such as designing appropriate fishways and modifying dam operations to facilitate fish passage [66].

Knowing where fish position themselves in the water column is useful for delineating fish reserves, setting fishing regulations, and designing fish passage structures. The three fish with depth tags utilized depths between 1.5 and 64 m. This shows that large Mekong catfishes move vertically in the water column throughout the day and may require access to deep water habitats. Natural deep-water pools are widely recognized as important habitats for a variety of Mekong River fishes [8,9,15,30,67,68] and this study provided quantitative support for those reports. It also confirmed that these fishes are susceptible to fishing at different depths and that they may be especially vulnerable to fishing in deep pools in the dry season when deep-water habitat in surrounding areas is unavailable.

Increasing species sample sizes is critical for future larger-scale positional telemetry studies, but this can prove to be difficult to achieve, as we discovered in this pilot study. Both *Pangasius* species represented in our study are believed to be widespread in the Mekong River, but neither were captured in sufficient numbers to make robust sample sizes. The study timing may have impacted these fishes' availability because catches of certain species are often seasonal. Additionally, the collection effort was spread out among many individual fishers using small-scale gill nets, trot lines, and traps, so sourcing fish for tagging was a significant challenge. The fish that are captured must also be in excellent condition, be maintained in good condition long enough for researchers to come and tag them, and be large enough for tagging, which also reduces the pool of available fish. Because of these challenges, we recommend that researchers use available knowledge (e.g., catch data and local knowledge) about the locations and timing of occurrence and availability of species of interest to select study species prior to implementing an acoustic tracking study. Other opportunities for increasing sample sizes include focusing efforts in places with higher concentrations of fishers, concentrating effort in highly productive areas, or utilizing a trapping operation. Using hatchery-raised fish is another option, but hatchery fish may not exhibit the same behavior as wild fish.

This study was limited in its scope in that it had a small sample size, a low number of receivers, receivers positioned on only one side of the river, and a duration of only one year. Nevertheless, the study yielded several results that we expect will be useful for future positional telemetry work in this region. Noteworthy findings of the pilot study included: (1) successfully tagging and tracking two fish over 300 days and three fish over 50 km, (2) developing methods to deploy receivers in a river where seasonal flow varies by as much as an order of magnitude, (3) cooperating successfully with fishers and other local people to obtain wild fish and monitor receivers, and (4) determining the first quantitative estimates of movement rates and swimming depths for poorly understood species that have high commercial and conservation value. We believe that these study elements will be critical components of any future Mekong positional telemetry study and should not be overlooked.

Acoustic receivers were particularly well suited for monitoring fish movements in the study area. In addition to being substantially less expensive than an equivalent radio telemetry monitoring system, they are more easily concealed, have fewer attendant parts (i.e., antennas, power cables, solar panels, security boxes, etc.), and were easy for local residents to monitor. Perhaps the most important element contributing to the success of this project was the use of local fishers to capture fish and monitor the receiver platform. Fishers had an incentive to cooperate because they were paid above-market rates for captured fish. With few exceptions, the captured fish were in good condition upon our arrival for tagging. Moreover, none of the telemetry equipment was stolen or vandalized during the one–year duration of the project despite constant human presence and heavy boat traffic in the area. We also enlisted the help of local drivers and translators to facilitate the work. Cooperation and coordination with state and local fisheries and land management agencies were essential to implementing this project.

Although the size of the Mekong River presents significant challenges for studying fish migrations, the results of our pilot study demonstrate that a scaled-up acoustic telemetry study with more tagged fish and better receiver coverage should be very successful in describing fish migration patterns in the Mekong River. Furthermore, such large-scale studies have already been successfully implemented in other large rivers. In North America, large acoustic receiver arrays successfully track fish movement over long distances in the Columbia and Fraser rivers and along the Pacific and Atlantic Coasts [69,70]. In the Amazon Basin, catfishes have been tracked over 300 km using combined acoustic and radio telemetry [26]. Given the importance of migratory fish in the Mekong River and the accelerating pace of hydropower development and other pressures, a similar acoustic array, shared between the four countries of the Lower Mekong Basin, would prove extremely beneficial.

5. Conclusions

This study highlights the potential of acoustic telemetry to study Mekong fish movement as well as the need for further studies of fish movements in the Mekong River system. Mekong fisheries are among the most productive river fisheries in the world and critical to the long-term food security of approximately 60 million people who live within the Mekong River Basin. Several large dams have already been completed upstream in China, two dams have been built in Lao PDR, and plans are underway for additional dams on the lower Mekong River [71–74]. The fragmentation of the Mekong River will have steep consequences for both fisheries production and biodiversity. Nonetheless, there is a paucity of information on the life histories of tropical Asian fishes [14] and this lack of knowledge hinders effective conservation [1]. Information on fish movements will help to better predict the response of fish communities to changed river hydrology, migration barriers, and harvest, and help with the design and placement of planned hydropower to minimize environmental impacts.

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