Received: 23 September 2015 | Accepted: 17 May 2016
DOI: 10.1111/jai.13134

ORIGINAL ARTICLE

WILEY Journal of Applied Ichthyology DWK

Measuring fish length and assessing behaviour in a high-biodiversity reach of the Upper Yangtze River using an acoustic camera and echo sounder

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Summary

In the past decade improved acoustic hard- and software have enabled estimations of abundance and distribution patterns of aquatic organism, including non-intrusive monitoring of fish migrations and behaviour. In this study, a high frequency acoustic camera (DIDSON-LR, 1.2 MHz, 0.7 MHz) and a portable split-beam scientific echo sounder (Simrad EY60, 200 kHz) collected acoustic data on 192 and 157 individuals within 24 hr (19–20 April 2011) in the Mituo reach of the Yangtze River, China. Mean fish length estimated from the acoustic camera data was 18.7 ± 5.6 cm, with an average swimming speed of 0.19 ± 0.13 m s^{-1}. The mean fish target strength (TS) produced by the echo sounder was −43.8 ± 4.4 dB, which corresponded to 5.7–119.9 cm fish length when converted by three different TS-length equations. Average swimming speed was 0.11 ± 0.06 m s^{-1} from the echo sounder. Compared with the actual fish catch by the three layers of drift gill net in the survey area, the target length indicated by DIDSON was more accurate than the EY60 results, which were highly affected by the choice of TS length equations. It was determined that the two devices used synchronously could estimate fish length effectively to investigate their behaviour and distribution.

1 | INTRODUCTION

The Yangtze River contains one of the world's richest sources of freshwater fish and is home to 361 species/subspecies, with 177 endemic species/subspecies of which 69 are threatened (Fu, Wu, Chen, Wu, & Lei, 2003; Yu, Luo, & Zhou, 2005). The present list of 261 fish species in the upper Yangtze River represents a high diversity (Fan et al., 2006), whereby the river provides resources for fishing and aquaculture, as well as germplasm resources for fisheries and species conservation. Anthropogenic activity, such as hydraulic engineering and hydropower facilities, overfishing, waterway regulation, and dock projects are fragmenting the fish habitat in the Upper Yangtze, with a resultant declining biodiversity (Li, 2001). In recent decades, the number of threatened endemic species listed in the *China Red Data Book of Endangered Animals: Pisces* and the *China Species Red List*, has increased from 17 to 49, representing 39.5% of the endemic species in the Upper Yangtze, and 14.3% of the threatened fish species in China (Xu, Qiao, & Gong, 2012). According to recent studies, fishery resources in the basin show a trend toward smaller and younger fish (Duan et al., 2008). Investigation of the fish size and behaviour in the Upper Yangtze is critically important. Although biological properties such as lengths and weights of fishes can be obtained by traditional fishing gear and electrofishing (Wang, Tang, Ruan, Wang, & Xiong, 2015), the behaviour of fishes should be monitored on a long-term basis using additional techniques.

Observation of fish behaviour in natural waters is difficult, however, using instruments such as underwater video cameras, biotelemetry, and acoustic methods can be an improvement on traditional methods. Although video cameras allow direct observation in some circumstances, the images are affected by light, turbidity, and water currents. Biotelemetry has enabled acquisition of basic information on fish behaviour and physiology in nature to enable the development of bioenergetics models and identification of stressors (Cooke et al., 2004). Ultrasonic telemetry is widely used in aquatic animal behaviour research in large waterbodies and rivers (Kynard, Suciu, & Horgan, 2002) and has been used to locate spawning grounds and migration routes of Chinese sturgeon in the Yangtze River (Wang et al., 2014). However, ultrasonic telemetry involves tagging the monitoring target, plus the receiver has a limited range, making the method more suitable for individual animals or a single species in a discrete area, rather than the continuous, long range monitoring of fishes.

Acoustic methods have several advantages in *in-situ* observations. They can effectively estimate fish abundance, and determine individual fish or fish school distribution as well as fish behaviour patterns, even in turbid water and low light conditions, with no disturbance or injury to the fish (Simmonds & MacLennan, 2005).

Echo sounders can survey horizontally or vertically at typical fish locations such as migration routes, and spawning and feeding grounds, to survey diurnal or seasonal activity in rivers (Hughes, 1998; Johnson & Moursund, 2000; Steig & Iverson, 1998), lakes (Knudsen & Sægrov, 2002), reservoirs (Kubecka & Wittingerova, 1998; Tušer, Kubecka, Frouzova, & Jarolim, 2009), and estuaries (Boswell, Miller, & Wilson, 2007). The two Simrad EK60 spilt beam echo sounders at the 120 kHz frequency, had been used horizontally and vertically simultaneously, to address the spatiotemporal niche changes of freshwater fishes in an offshore-inshore system successfully (Muška et al., 2013). However, the beam of the split-beam echo sounder is narrow, and results must be interpreted with caution.

The Dual-frequency Identification Sonar (DIDSON) (identification frequency 1.8 MHz; detection frequency 1.1 MHz) (Sound Metrics Corp., Bellevue, WA) can be used to observe fish behaviour in nearly zero visibility conditions (Moursund, Carlson, & Peters, 2003; Zhang, Wei, & Kang, 2014). The sonar emits multiple high frequency beams simultaneously, with high resolution and a short detection range. DIDSON has been used to: count fish at high and low passage rates (Galbreath & Barber, 2005; Petreman, Jones, & Milne, 2014); estimate fish size and behaviour (Becker, Whitfield, Cowley, Jarnegren, & Nesje, 2011; Doehring, Young, Hay, & Quarterman, 2011; Lilja, Romakkaniemi, Stridsman, & Karlsson, 2010; Mueller, Brown, Hop, & Moulton, 2006; Rakowitz et al., 2012; Tiffan, Haskell, & Kock, 2010; Zhang et al., 2014); detect the outline and shape of target fish and fins (Moursund et al., 2003); and identify species in spawning grounds according to fish size. The DIDSON sonar has been used to successfully identify species based on fish tail-beat frequency (Kang, 2011; Mueller, Burwen, Boswell, & Mulligan, 2010) and to estimate fish abundance (Boswell, Kaller, Cowan, & Wilson, 2008). The DIDSON and the split-beam echo sounder have been used in combination to observe fish behaviour variations and habitat types (Grabowski, Boswell, McAdam, David, & Marteinsdottir, 2012; Maxwell & Gove, 2004).

In the present study, the DIDSON acoustic camera and Simrad EY60 split-beam echo sounder were tentatively used in the Upper Yangtze Reserve. This study aimed to: (i) compare the fish sizes estimated from the acoustic instruments and captured by the fishing gear to verify the accuracy of the method; (ii) check the ability of the instruments to observe and analyse the fish behaviour, such as swimming behaviour, spatio-temporal distribution and diurnal behavioural changes; and (iii) evaluate the number of fishes passing through a river cross-section in a given time period.

2 | MATERIALS AND METHODS

2.1 | Survey area

The Mituo reach (28°52′N, 105°37′E) of the Yangtze River is in the Upper Yangtze Reserve, in Mituo, City of Luzhou, Sichuan Province, China. According to the international designation attributed by the United Nations Educational, Scientific and Cultural Organization (UNESCO), biosphere reserves are demarcated into three interrelated zones: core area, buffer zone, and transition area outside the buffer zone. The survey site is at the junction of the core area and buffer zone of the Upper Yangtze National Reserve (Zhang et al., 2016). The major protected species in the area are Chinese paddlefish *Psephuyrus gladius*, Dabry's sturgeon *Acipenser dabryanus*, Chinese sucker *Myxocyprinus asiaticus*, and several endemic fishes including largemouth gudgeon *Coreius guichenoti* (Sauvage & Dabry de Thiersant), Vachell's bagrid fish *Pelteobagrus vachelli* (Richardson), and bronze gudgeon *Coreius heterodon* (Bleeker). The region contains the spawning grounds of the four major Chinese carp species: black carp

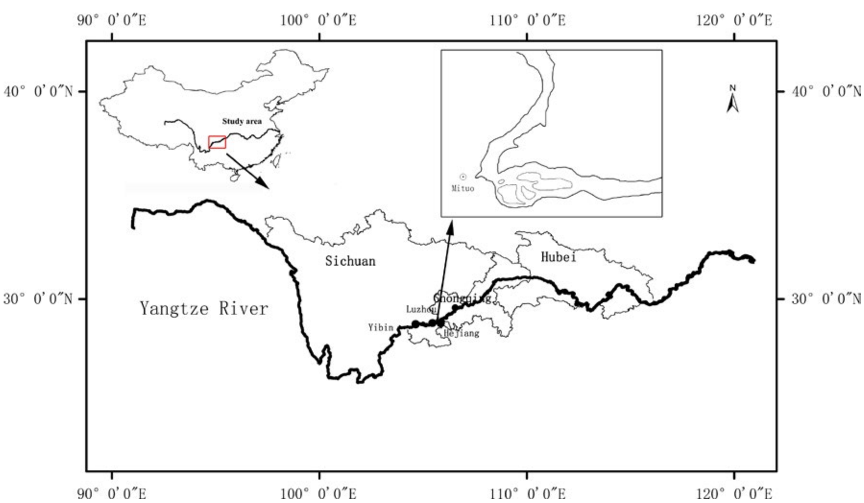

FIGURE 1 Study area, Upper Yangtze River reach

Mylopharyngodon piceus, grass carp *Ctenopharyngodon idellus*, silver carp *Hypophthalmichthys molitrix*, and bighead carp *Aristichthys nobilis*, plus the bronze gudgeon, as well as the nursery areas of the major protected species (Duan et al., 2008).

The survey was carried out in April 2011 in the Mituo area, where the river turns at an angle of approximately 124° (Fig. 1). River width at the survey area was 0.7–1.2 km. The average thalweg depth was 12.35 ± 7.73 m (the range is 3.42–48.40 m) (Zhang et al., 2016). The turning angle of the river creates a strong eddy flow mid-river at flood stage.

2.2 | Data collection

In this study the DIDSON 300 LR (identification frequency, 1.2 MHz; detection frequency 0.7 MHz) (Sound Metrics Corp., Bellevue, WA) and the EY60 split-beam echo sounder (200 kHz, Simrad, Norway) were positioned 30 cm apart and employed simultaneously. The devices were pole-mounted on a boat anchored near shore, fixed underwater at 1 m depth at an angle of 10° downward from the horizontal plane (Fig. 2).

The DIDSON 300 LR emits 48 beams spaced 0.6° apart at 0.7 MHz (low frequency mode), and the total field of view is 29° horizontal and 14° vertical. The effective detection range is, hypothetically, 80 m. The working frequency of the EY60 echo sounder is 200 kHz, the ping rate 1 ping s^{-1}, and the beam angle 7° × 7° with 150 w power and 0.128 ms pulse length. The calculated sound speed was 1476.03 m s^{-1} at a water temperature of 18°C, and the absorption coefficient 0.009 dB m^{-1}. Prior to the experiment, the EY60 was calibrated using a 13.7 mm copper sphere with reference target strength of −45 dB, according to the Simrad instruction manual. Data were collected continuously from 00:00:00 on 19 April to 00:00:00 on 20 April 2011.

Fishing was carried out in a 75 km stretch from Luzhou city to Hejiang county using three layers of drift gill nets (120 m long, 1.5 m high, 5.0 cm mesh size). Six fishing boats were divided into three groups, dragging the drift nets floating downstream about 8–10 km over the course of approx. 4 hr on a single day. The fishing area was from Mituo to Daqiao on 19 April 2011 (Fig. 1). Standard length (SL) (cm), total length (TL) (cm) and weight (g) of each captured fish were measured.

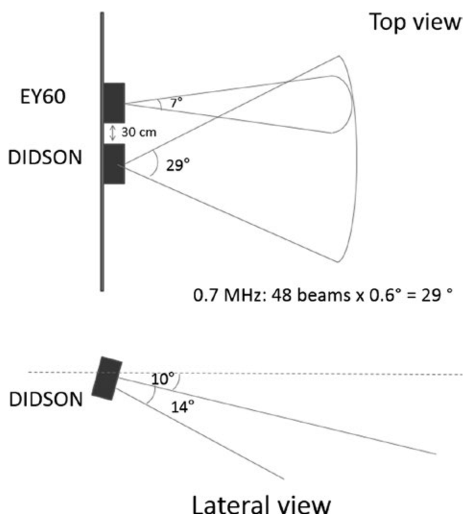

FIGURE 2 Survey system schematic. Top view = positioning of the two devices; lateral view = angle between the horizontal line and the device head

2.3 | Data analysis

Data were analysed by the fisheries acoustic data analysis software ECHOVIEW v. 5.4 (Myriax Pty Ltd, Hobart, TAS, Australia) (Myriax, 2016). For the DIDSON data, the quiet pings generated by background noise were subtracted from the pings produced by fish echoes (step 2 and 3 in Fig. 3). A convolution (3 × 3 median filter) was applied to smooth the image without significantly affecting fish shape (Kang, 2011; Myriax, 2016; Zhang et al., 2014). A multibeam target detection operator was created that generated multibeam targets from groups of adjoining data points (Fig. 3, step 5). Each target had a range and major axis angle corresponding to the geometric centre of the group. The length and thickness of target detection thresholds were set to be less than 35 cm and 18 cm, respectively (Fig. 3, steps 6 and 7). The multiple targets were converted to a single target track, and several target properties were obtained, including target length, angle, range, tortuosity, speed, and fish track change. The target length in the multibeam data was defined as the maximum distance between any two above-threshold samples in the multiple target (Kang, 2011; Myriax, 2016) affected by the major axis (horizontal or athwart-ship) angle and range. The angle (major axis and minor axis) was defined as the angle between the beam axis and the horizontal or vertical direction, with a positive numerical value indicating a starboard direction of the target. The range was defined as the distance from the transducer face to a target. Using major axis angle distribution of the targets in

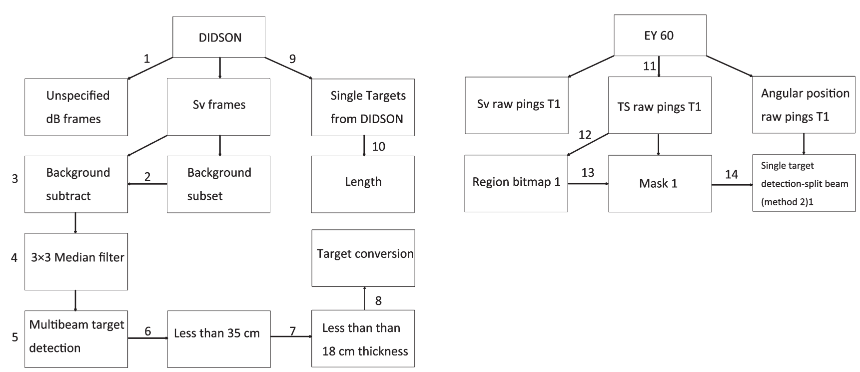

FIGURE 3 Data processing flow

a fish track, the swimming direction can be determined as upstream or downstream (Kang, 2011). The angle information can also be used to refine the fish track detected. Target thickness (cm) is the maximum range covered by the outline of samples per beam in the target, and was used to identify spurious targets. Tortuosity was calculated as the sum of the distances between adjacent targets in a detected track, divided by the straight-line distance between the first and final targets in the track, measured in three-dimensional space (Johnson & Moursund, 2000). Swimming speed (m s^{-1}) was calculated as the accumulated distance between targets in a fish track divided by the total time. The fish track change in range (m) is that the depth of the first target minus the depth of the final target in a fish track (Myriax, 2016).

TABLE 1 Parameters of single target detection settings

TS threshold (dB)	−50
Pulse length determination level (dB)	6
Minimum normalized pulse length	0.4
Maximum normalized pulse length	1.5
Maximum beam compensation (dB)	12
Maximum standard deviation of:	
Minor-axis angles (degrees)	1.2
Major-axis angles (degrees)	1.2

For the EY60 data, noise generated by the engine of passing boats, boil-eddy flow, and surface bubbles was set to be a 'bad data region' which would be eliminated, and fish signals manually defined as 'analysis region'. The region bitmap contained the analysis regions, and the mask leached the noise and left the useful data (Fig. 3, steps 12, 13). The thresholds were set to detect single targets as described in Table 1, and the mean target strength (TS) was converted to fish length. Data processing flow is shown in Fig. 3.

We used three conversion equations of TS values and fish length in side-aspect to obtain the mean fish length from the EY 60 data results. All equations are at 200 kHz frequency (Table 2). Equation (1) is based on the ex-situ measurement of TS values of 182 individuals belonging to 12 species riverine fish by dual-beam sonar. Fish standard length ranged from 4.7 to 48 cm (Kubecka & Duncan, 1998). Equation (2) is based on the measured TS values of four species with 54 individuals total by the split-beam sonar, and the fish TL ranged from 29 to 119 cm (Lilja, Marjomaki, Riikonen, & Jurvelius, 2000). Equation (3) is based on 12 barbel *Luciobarbus* sp. TL ranged from 6 to 70 cm (Rodríguez-Sánchez, Encina-Encina, Rodríguez-Ruiz, & Sánchez-Carmona, 2015).

Steady and homogeneous band echoes were obtained with the two echograms at a range of 20 m, thus the range threshold was set at this level. To compare the distance differences between the two devices,

TABLE 2 Horizontal TS-length relationships, TS = a logL + b derived from previously published studies

Species	Length	*a*	*b*	Frequency (kHz)	Orientation	Author	Code
Pool of freshwater species	SL (mm)	18.1	−82.5	200	All aspects	Kubecka and Duncan (1998)	(1)
Pool of freshwater species	TL (cm)	24.2	−68.3	200	All aspects	Lilja et al. (2000)	(2)
Barbel (*Luciobarbus* sp.)	TL (mm)	25.03	−99.4	200	Lateral	Rodríguez-Sánchez et al. (2015)	(3)

Where TL, fish total length; SL, fish standard length.

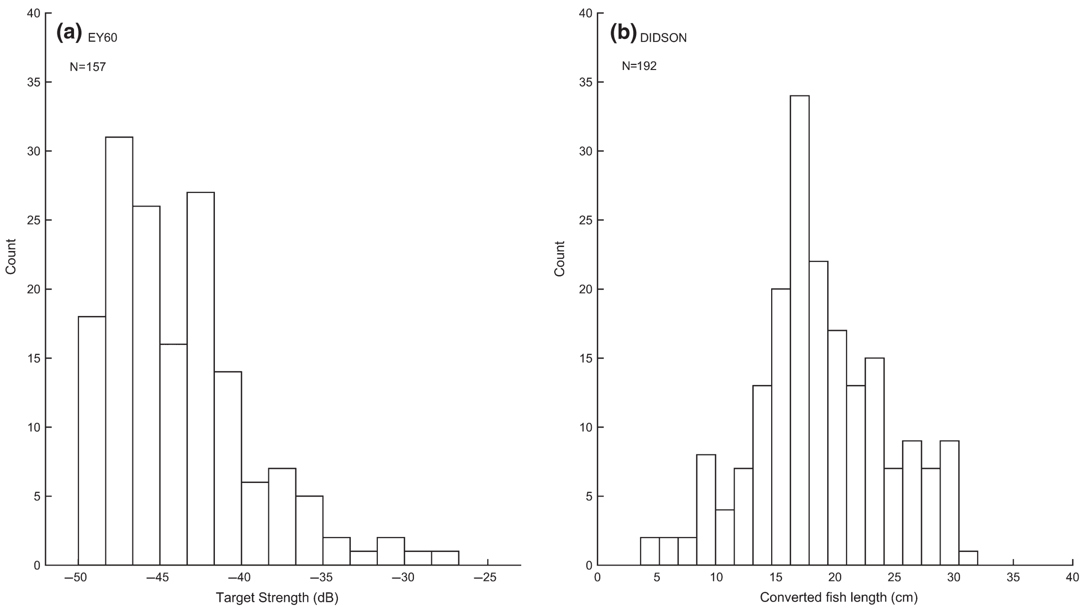

FIGURE 4 Distribution pattern of target strength from EY60 in the left panel (a). Converted fish length of all targets from DIDSON is shown in right panel (b).

we separated the detection range into 20 one-meter segments. SPSS v. 19 (IBM Corp., New York) was used for statistical analysis.

3 | RESULTS

3.1 | Fish count and size

The fish track numbers obtained within 24 hr from the DIDSON and EY60 were 192 and 157, respectively. Mean and standard deviation of target lengths measured by DIDSON was 18.7 ± 5.6 cm (Fig. 4, Table 3), with an average 0.7 ± 7.3° angle and average 14.0 ± 4.4 m range. Mean tortuosity value was 2.11 ± 2.63, and, in 75.92% of the targets, tortuosity ranged from 1 to 2. Mean TS of the fish tracks identified by EY60 was −43.8 ± 4.4 dB (Fig. 4), and converted to fish length by the formulae (1), (2) and (3) (Table 3).

Table 3 Fish length converted from the three methods

Methods		Length (cm)		Std. (cm)	Range (cm)
DIDSON		TL	18.7	5.6	5.6–32.0
EY60	(1)	SL	16.7	14.8	6.3–119.9
	(2)	TL	11.4	6.6	5.7–52.0
	(3)	TL	18.3	10.1	9.4–79.8
Capture		TL	22.9	4.4	10.5–36.0

TL, total length; SL, standard length.

TABLE 4 Fish species captured in drift nets

Species	*n*	*P* %	TL (cm)	SL (cm)	*W* (g)
Pseudobagrus vachelli	54	32.3	20.8	17.7	113.9
Coreius guichenoti	51	30.5	24.3	20.1	152.2
Rhinogobio ventralis	44	26.3	22.4	18.2	128.8
Leiocassis longirostris	6	3.6	28.3	24.6	241.2
Coreius heterodon	4	2.4	29.2	24.5	200.3
Myxocyprinus asiaticus	2	1.2	14.4	11.5	43.5
Others	6	3.6	26.4	22.7	156.5

n, fish number; *P*, proportion of occurrence; TL, total length; SL, body length; *W*, weight.

Experimental fishing data resulted in 167 fish from 11 species in the surveyed area. Main species were Vachell's bagrid fish, largemouth gudgeon, and *Rhinogobio ventralis* at 32.2%, 30.5%, 26.3%, respectively (Table 4). Mean fish TL and SL were 22.9 ± 4.4 cm (10.5–36.0 cm) and 19.1 ± 3.9 cm (8.5–31.5 cm), respectively. Mean weight was 136.9 ± 64.5 g (13.0–464.0 g). Among the catches were two Chinese suckers *Myxocyprinus asiaticus*, listed as Class II nationally vulnerable, as well as largemouth gudgeon and *Rhinogobio ventralis*, endemic to the Upper Yangtze River. Twenty fish were captured on 19 April 2011 from the area in which the acoustic data was collected, with a mean TL of 21.1 ± 4.4 cm, mean SL of 17.9 ± 3.6 cm, and mean weight of 106.9 ± 57.5 g. This indicates that the length estimated by DIDSON was closer to the actual length than that of EY60. Maximum lengths estimated using DIDSON and the captured fish SL were similar (32.0 and 31.5 cm, respectively). The independent sample non-parametric test (Mann-Whitney U test) was used to identify the differences between the length of the actual fish captured and the converted devices, separately. The DIDSON data showed no significant difference from the measured fish length (Mann-Whitney *U* test, $P = .17 > .05$). The three EY60 results showed significant differences from the catch data (Mann–Whitney *U* test, $P = .00 < .05$).

3.2 | Fish swimming speed

According to published results (Zhang et al., 2016), the flow rate was 8520 m s^{-3} (daily mean range 1920–53,400 m s^{-3}) at the Zhutuo hydrological monitoring station. Depth-average velocity

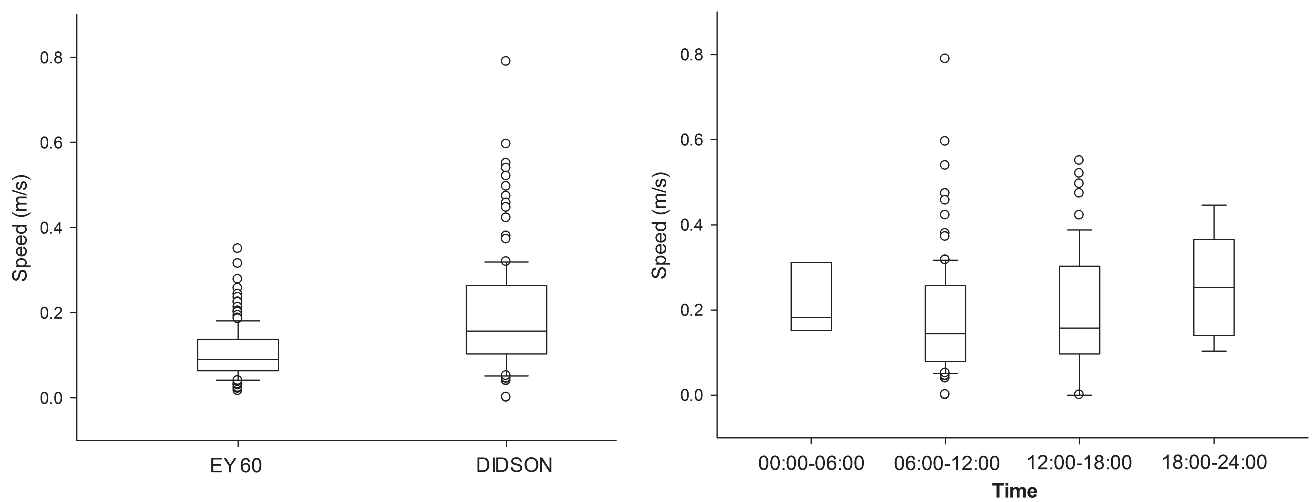

FIGURE 5 Left panel: average swimming speed estimated by DIDSON and EY60. Right panel: speed distribution pattern over 24 hr, with average speed (m s^{-1}), first and third quartiles (bars); hollow circles = outliers

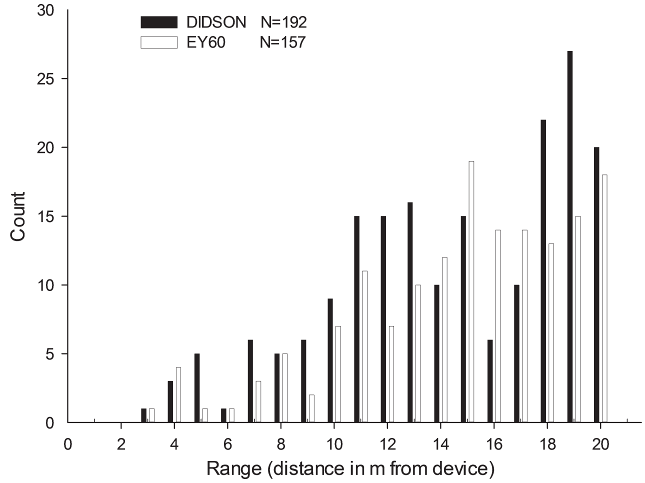

FIGURE 6 Numbers of fish detected relative to distance from two devices

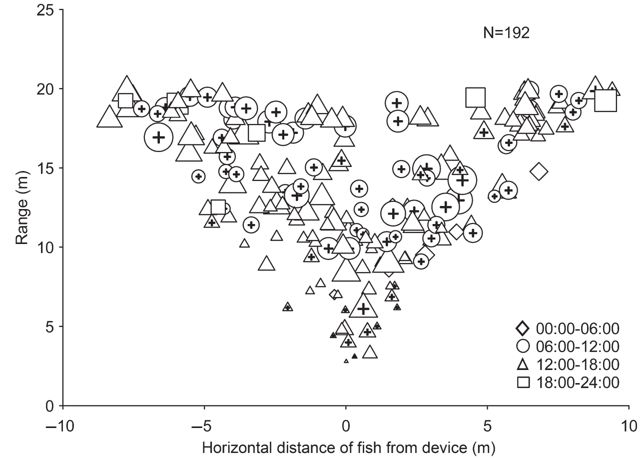

FIGURE 7 Distribution of target length from DIDSON relative to range, horizontal position, and time. The patterns with '+' in center represent fish swimmingtoward the device, no '+' in center patterns represent fish swimming away from the device. The bubble size represents the target length.

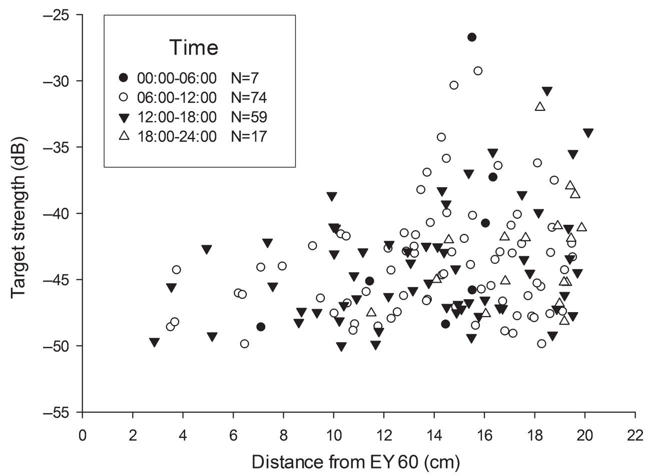

FIGURE 8 Distribution of target strength with respect to the distance from EY 60 in 24hr. The targets include all species.

of the survey area was slow (<1 m s^{-1}), and the average Froude number was less than 0.1, meaning that this region was a flowing stream. Average fish active swimming speed was calculated by DIDSON as 0.19 ± 0.13 m s^{-1} (0.0–0.78 m s^{-1}), 39% of targets downstream and 61% upstream. With the EY60, average fish swimming speed was 0.11 ± 0.06 m s^{-1} (0.02–0.35 m s^{-1}). DIDSON data were separated into four intervals over 24 hr, and showed daytime speeds as slower than at night (Fig. 5); however, differences among the four intervals were not significant (One-way ANOVA, F = .979, P = .404 > .05).

3.3 | Fish distribution

The detection range was separated into 20 one-meter segments. The number of targets detected by the two devices in each segment were counted and compared. Differences between the two devices were observed at 5 m, 12 m, 16 m, 18 m, and 19 m (Fig. 6). The majority of DIDSON targets (81.3%) were observed at a range of 10–20 m, with 62.5% appearing at 06:00–12:00 hr. In this time interval, the percentage of targets longer than 10 cm was 95.8%, with 88.3% targets appearing at a range of 10–20 m. Seventy-two targets were longer than 20 cm (24.4 ± 3.2 cm), 54.4% of which appeared during 06:00–12:00 hr (Fig. 7). Fish tracking data showed that 52.9% of targets swam away from the device. Target position distribution in the four time intervals is shown in Fig. 7. Spearman correlation analysis showed a positive correlation between length and detection range (n = 192, R^2 = .497, P < .01).

Of the EY60 targets, 45% were detected at a 15–20 m range. The target percentage detected from 06:00 to 12:00 hr was 47.1%; 42.9% of targets >−35 dB appeared at 06:00–12:00 hr and at 14 to 15 m, and 80.9% of targets swam away from the transducer. The TS distribution pattern relative to range is shown in Fig. 8. TS and range were positively correlated (n = 157, R^2 = .235, P < .01). There were no significant differences in target length in the four time segments.

4 | DISCUSSION

The target length converted from the DIDSON multibeam data was affected by the baseline threshold set. Kang (2011) chose length <36 cm and a major axis angle of −10°to 10° for thresholds and obtained two groups of length data. Other parameters influencing length included the vertical direction and tortuosity of the target. Target length was negatively correlated with the vertical direction and tortuosity (Zhang et al., 2014). The estimated fish length agrees well with the actual length when the fish is positioned perpendicular to the centre of the multi-beam array (Tušer et al., 2014). In the present study, targets almost perpendicular to the beam axis were selected. A calculation of these factors may improve the accuracy of target identification and length conversion.

The echo sounder TS is affected by factors such as the frequency and angle of the incident sound wave, the shape and body length of the fish, and whether it possesses a swim bladder. When the sound wave is in a horizontal direction, the angle between the fish body and the wave is the most important factor affecting TS. There is a cosine relationship between the angle and TS, as is the angle of yaw in degrees (Kubecka, 1994; Kubecka & Duncan, 1998; Lilja et al., 2000). Information on TS relative to actual measurements of freshwater fish in the Mituo reach from the side-aspect is lacking, thus we calculated the corresponding length using formulae based on other species. To ensure the accuracy of the length conversion, we used the mean TS from the fish tracks. The mean converted length results were smaller than the catch data. Hence, use of the appropriate equation to convert TS to length of the local species is the key to an accurate estimation of fish size from the split-beam echo sounder. The relationship between TS and the length species in the Yangtze River relative to the beam incident angle is a topic for future investigation.

In the survey area, the majority of fish species are demersal and omnivorous, staying in deep water in the daytime and swimming up to forage at night. However, there were no significant differences in the fish swimming speed measured in the four time segments.

The length as measured by both devices was positively correlated with the range. Burwen, Fleischman, and Miller (2010) measured a tethered Chinook salmon at different distances using a DIDSON-LR, and no range dependency in accuracy of length estimates was observed.

Data of the two devices show differences at 5 m and 9 m, more at 5 m. Maxwell and Gove (2004) also reported differences between DIDSON and a split-beam sonar in the first 5 m. Although the DIDSON collected clear sonic images of fish, indicated behaviour, and provided accurate upstream-downstream target resolution, it has some limitations; the detection range is also shorter than that of the echo sounder. Due to its lower resolution in the high frequency mode, estimated length may be 10–20% less than manually measured lengths (Brisson, 2010). The DIDSON lacks a time-varied gain to compensate for beam-spreading loss and a linear range-dependent gain for attenuation. In addition, no calibration process has been defined for acoustic cameras (Martignac, Daroux, Bagliniere, Ombredane, & Guillard, 2014). The narrow beam angle of the echo sounder affected close range count results. To obtain both long-range detection and accurate monitoring of fish behaviour, the two devices should be used together. This study represents the first successful coordinated use of the two instruments in the Upper Yangtze.

The DIDSON and EY 60 echo sounder produce synchronous information on fish length and behaviour without injury or disturbance to the fish. The DIDSON mean fish length estimates were not significantly different from manual measurements. Converted data obtained with EY 60 produced results significantly different from the actual catch. This method is effective for studying the influence of anthropogenic activity on Upper Yangtze Basin fishes and offers implications for river management and conservation. Further study will focus on TS relative to ex situ measurements of local fish species and in situ observations in other Upper Yangtze River areas. Adding survey sites at different habitats in typical periods such as the spawning season, etc., to monitor the variation law of fish species could also monitor the fish behaviour from the vertical and horizontal direction synchronously.

ACKNOWLEDGEMENTS

The assistance of members of the Endangered Fish Conservation Group of the Yangtze River Fisheries Research Institute, Chinese Academy of Fishery Sciences is acknowledged. This study was supported by the Chinese Paddlefish Funds of the China Three Gorges Project Corporation, and The National Natural Science Foundation of China (31000221).

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