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Species identification of Chinese sturgeon using acoustic descriptors and ascertaining their spatial distribution in the spawning ground of Gezhouba Dam

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This study has developed an improved subjective approach of classification in conjunction with Stepwise DFA analysis to discriminate Chinese sturgeon signals from other targets. The results showed that all together 25 Chinese sturgeon echo-signals were detected in the spawning ground of Gezhouba Dam during the last 3 years, and the identification accuracy reached 90.9%. In Stepwise DFA, 24 out of 67 variables were applied in discrimination and identification. PCA combined with DFA was then used to ensure the significance of the 24 variables and detailed the identification pattern. The results indicated that we can discriminate Chinese sturgeon from other fish species and noise using certain descriptors such as the behaviour variables, echo characteristics and acoustic cross-section characteristics. However, identification of Chinese sturgeon from sediments is more difficult and needs a total of 24 variables. This is due to the limited knowledge about the acoustic-scattering properties of the substrate regions. Based on identified Chinese sturgeon individuals, 18 individuals were distributed in the region between the site of Gezhouba Dam and Miaozui reach, with a surface area of about 3.4 km^2. Seven individuals were distributed in the region between Miaozui and Yanshouba reach, with a surface area of about 13 km^2.

hydroacoustics, fisheries acoustics, echo-signal, species identification, Chinese sturgeon, spatial distribution

Chinese sturgeon (*Acipenser sinensis* Gary) is a kind of migratory fish species, which matures in coastal waters and enters into rivers for spawning. This species was once widely distributed in almost all watersheds draining towards the western coasts of the Pacific Ocean[1]. Now they can be found only in the Yangtze River and its adjacent coastal and marine areas. Since the construction of the Gezhouba Dam in 1981, the migration channel of Chinese sturgeon to the upper reaches of the Yangtze River has been blocked. They are now restricted to spawning in a narrow reach just below the Gezhouba Dam site, where natural propagation takes place annually. However, in recent decades, there has been a sharp decline in the sturgeons' population sizes. The Chinese sturgeon is now categorized as an endangered species in the IUCN Red List and under State First Class protection in China[2−4].

Hydroacoustic (fisheries acoustics) methods have been applied in fisheries research for decades and are well established. They have been used to investigate fish abundances, temporal-spatial distribution and behaviours[5,6]. In addition, hydroacoustic sampling is completely unobtrusive and does not result in fish mortality,

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which is an important consideration when dealing with threatened or endangered species[7]. Since 1998, such methods have been used to estimate the Chinese sturgeon spawning stock in the spawning ground of Gezhouba Dam[2]. Due to limitations in technique, the echo-signals of Chinese sturgeon were differentiated from other targets based solely on echo-shape and echo length[8]. Due to the extreme subjective nature of this method, improvements in the methods of species identification were required.

Major developments in the acoustic technique occurred in the early to mid-1990s, incorporating split-beam hydroacoustic systems[9]. The split-beam transducer is composed of four separate units. These units are arranged geometrically so that both echo signal intensity and angle can be detected from the received echo signal[10]. By identifying the target's position in the sound beam, the split-beam target tracking technique also enables the estimation of swimming speeds and the identification of tracking paths of individual fish[11] (Figure 1). Owing to the different paths configuration of individual fish and that of non-fish, by comparison of the tracking paths, fish echo-signals can be distinguished from that of non-fish[12,13].

Moreover, split-beam echo sounders were developed for *in situ* measurements of TS, which enables correct compensation for the off-axis loss of sound intensity, by identifying the target's horizontal position in the sound beam[11,14]. Accuracy of the mean TS of individual scatters is increased by averaging the TS from several measurements of the same fish and assigning successive registrations to a single target track[15,16]. As sturgeons have a swim bladder and bony dorsal plates, it can be assumed they will produce the strongest backscatter of the demersal fishes. This backscatter is more feeble than sediment, so can be identified separately[17,18]. A TS of greater than −30 dB indicates the length of the fish may be greater than 60 cm, based on the empirical measures of target strength[19,20]. The TS of tracked fish ranged between −30 and −18 dB, which can be assumed as a possible signal of a sturgeon[7].

This study aims to improve the identification methods to discriminate Chinese sturgeon signals from other targets. To this end, the authors improved the subjective approach to discriminate Chinese sturgeon signals from other targets, based on related study and field work experience. Classical statistical methods, such as PCA (principal components analysis) and DFA (discriminant function analysis) were then applied to rectify inaccurate classification in the initial identification. Acoustic descriptors and ancillary information were used in this rectification process, as described by Balk[12] and Lawson et al[21]. In addition, this study attempts to detail the identification pattern of Chinese sturgeon and assess their spatial distribution.

1 Materials and methods

1.1 Study area and data acquisition

Acoustic surveys were conducted in the downstream area of Gezhouba Dam in the Yangtze River. It is the recent spawning ground of Chinese sturgeon[2–4]. The

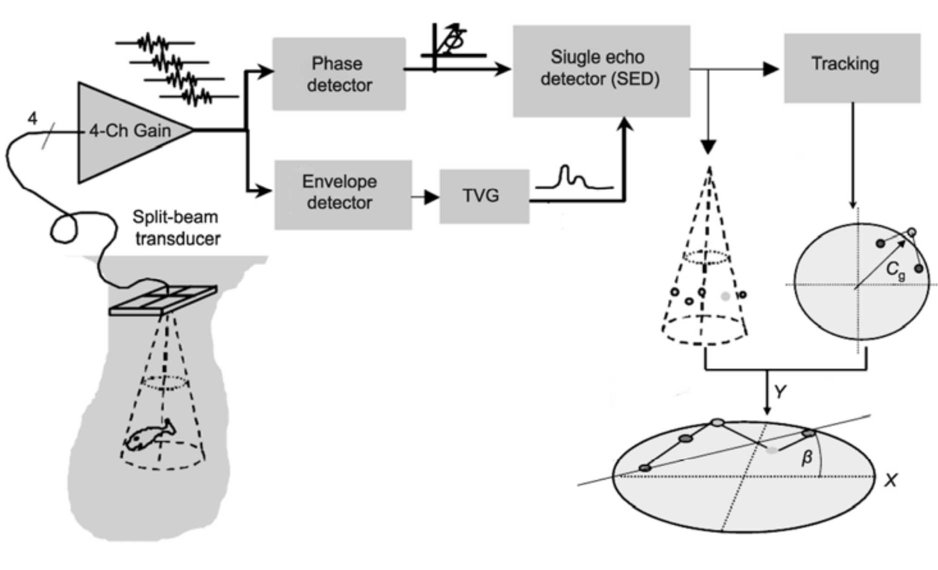

Figure 1 Schematic drawing illustrating processing of single fish tracked by a split-beam hydroacoustic system.

main survey area is from Gezhouba Dam to the the confluence of Aijia Creek with the Yangtze River, which is 16 km long and covers an area of 16 km^2 (Figure 2). The river width of the survey area varies from 560 to1660 m and the water depth varies from 15 to 25 m, except for a deep hole of about 41 m just near the Yichang dockyard[8]. The surveys were conducted in the Chinese sturgeon spawning periods, between 2005 and 2007 (Table 1). Data was collected at two specified periods in each year: pre-spawning and post-spawning, and the spawning activities were confirmed by searching for the eggs of Chinese sturgeon in the stomach content of predator species (eg. *Coreius guichenoti*, *Coreius guichenoti*, *Pelteobagrus vachelli*)[2].

Table 1 The detailed date for acoustic surveys

Year of surveys	Pre-spawning	Post-spawning
2005	Oct. 21 and 22, Nov. 10	Nov. 14 and 25
2006	Oct. 30 and 31	Nov. 15 and 16
2007	Oct. 22 and 23, Nov. 23	Nov. 24, Dec. 11 and 12

Acoustic surveys were conducted by the 6 m long boat, "Echo" sailing at the speed of about 10－12 km/h with dense zigzag transects (Figure 2). The geographical positions of soundings were recorded simultaneously by a GPS unit connected to the sounder. The transducer (ES200-7C, Split-beam) was fixed on a special frame in front of the boat at a depth of 0.4 m, and aimed straight downward.

A Simrad EY60 scientific echo sounder was used with an operating frequency of 200 kHz, along with a circular transducer with opening angle of 7° at −3 dB points. During the sampling, the GPT (General Purpose Transceiver unit) was connected to a portable computer, with a power output of 240 W, a pulse duration of 64 us, and a ping rate of *c.* 16 pings/s (since the ping interval was set to 0.06 s). The TS threshold was set to −60 dB, which was the lowest possible value that did not include too much noise in the echogram. At the beginning of each survey the whole system was calibrated *in situ*, according to the procedure described by Foote[19].

1.2 Acoustic analysis

The Sonar-5 post-processing software (Lindem Data Acquisition, Norway) was used to detect the echo-signals and make measurements of target descriptors in the acoustic data. This software package can be used for three main tasks: abundance estimation (biomass estimation and counting); species behaviour studies and physical studies[13]. It is specifically designed to identify and count single fish tracks, which provide 106 acoustic variables and ancillary information on numbers of fish, swimming speed and direction and fish size distribution. The inbuilt single echo detector and envelope detector provide an improved single echo detection echogram (SED echogram)[22] and envelope echogram (also called an AMP echogram in sonar-5). A SED echogram can be used for single echo detection and tracking methods (STM methods), and an AMP echogram can be used for image analysis.

In this study, the STM method[23] was combined with image analysis to extract acoustic variables and ancillary

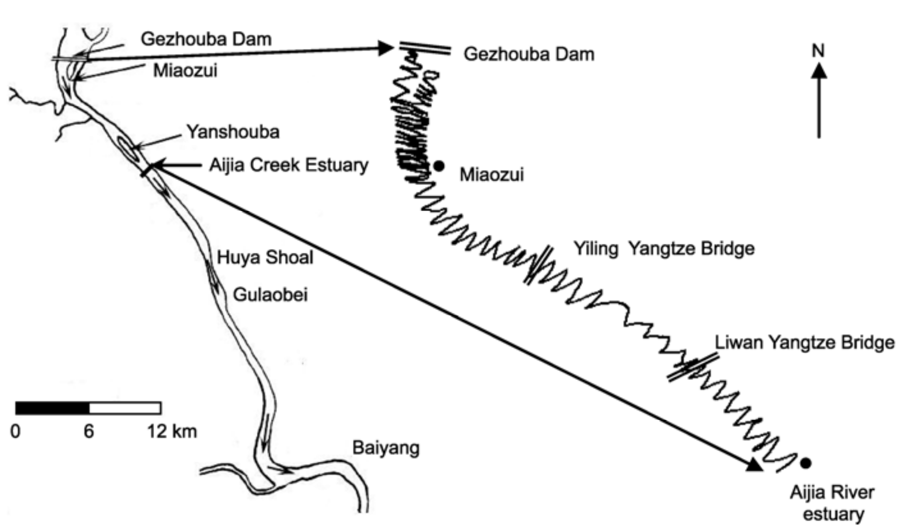

Figure 2 Map of the study area and survey transects based on ship-borne GPS data.

information on single targets. Meanwhile, the cross-filter detector (CFD) method was applied to detect sonar data with low signal to noise ratio in the course of analysis[12]. The main value setting of sonar parameters (Table 2) was proved to be the optimal settings by pre-analysis. The acoustic terminology used is as defined by MacLennan et al.[24].

Table 2 Main value setting of sonar parameters for single-target detection

Sonar parameter	Value Setting
Threshold of AMP (dB)	−100
Threshold of SED (dB)	−45
Absorption coef. (dB/km)	8.72
Two-way beam angle (dB)	−20.70
Receiver bandwidth (dB)	18.76
Sv transducer gain (dB)	25.50
TS transducer gain (dB)	25.50
Time varied gain (TVG)	40lg*R*[a)]
Min. echo length	0.8
Max. echo length	2.4
Max. phase standard deviation	1.2
Max. gain compensation (dB)	6

a) *R* indicates the range from transducer to the target.

1.3 Echo-signal identification and statistical analysis

All of the echo-signals obtained were classified into four groups, Chinese sturgeon, other fish species, sediments and noise (reverberation, bubble, debris, etc.). These were based on echo-shape, echo length, TS and tracking of the target in the sonar beam, according to the related study[7,8,12,17,18]. This is a subjective approach of classification. In this approach, the TS of tracked fish ranging from −30 to −18 dB was regarded as a possible signal of Chinese sturgeon, according to the study of lake sturgeon (*Acipenser fulvescens*)[7].

Stepwise discriminant function analysis (Stepwise DFA) was used to rectify inaccurate identification of tracked targets, which were obtained by a subjective approach of classification. A set of credible signals for each group was selected as a training database to establish the cluster centres of each classified group. Out of the possible 106 variables, a set of 67 acoustic and ancillary variables in the sonar-5 database were selected manually[12]. After that, the 67 selected variables were applied into the stepwise DFA, as additional descriptors of discrimination and identification, to rectify any inaccurate subjective classification. Stepwise DFA was also used to determine which of the 67 selected variables were significant in discrimination and identification.

Subsequently, PCA combined with DFA was used to ensure the significant variables (derived from stepwise DFA), to assess more definite descriptors of identification. PCA was used to extract the principal factors of the significant variables. In PCA analysis, a correlation matrix algorithm was used to ensure the loading of each variable. Correlations exceeding 0.7 were considered as a significant value in each principal factor[21]. DFA was then applied to verify the role of principal factors in discrimination and identification, and detail the identification pattern of Chinese sturgeon. The stepwise DFA, PCA and DFA were processed in the commercial statistical software package SPSS® (V.13.0).

2 Results

2.1 Main surveys information and results of subjective approach

Fourteen acoustic surveys have been carried out in the spawning grounds of Chinese sturgeon, from 2005 to 2007. In an analysis of all detected signals by subjective approach of classification, 22 echo signals of possible Chinese sturgeon, about 4400 echo signals of other fish species, and 300 echo signals of noise and sediments were obtained (Table 3).

2.2 Rectification of inaccurate classification of subjective approach by Stepwise DFA

Out of all detected echo signals, a total of 481 signals of

Table 3 Primary information obtained by acoustic surveys in the spawning ground of Gezhouba Dam during the spawning seasons

	2005		2006		2007	
	Pre-spawning	Post-spawning	Pre-spawning	Post-spawning	Pre-spawning	Post-spawning
Survey distance (km)	24.5	32.1	36.8	21.7	70.8	60.6
Length of the Survey Reach (km)	8	8	16	16	30	16
No. of possible Chinese sturgeon (ind)	6	3	5	1	6	1
No. of other fishes (ind)	563	578	636	772	1203	648
No. of surveys	3	2	2	2	3	2
Survey area	Gezhouba-Yiling Yangtze Bridge	Gezhouba-Yiling Yangtze Bridge	Gezhouba-Aijia Creek estuary	Gezhouba-Aijia Creek estuary	Gezhouba-Gulaobei	Gezhouba-Aijia Creek estuary

four groups were selected as a training database to establish the cluster centres of each classified group: 22 echo signals of possible Chinese sturgeon, 193 echo signals of other fishes species (163 of them are credible signals, 30 of them are similar in appearance to Chinese sturgeon), 76 echo signals of sediments (56 of them are credible signals, 20 of them are similar in appearance to Chinese sturgeon) and 190 echo signals of noise (more than 180 of which are credible). The 67 selected variables were then applied in Stepwise DFA to rectify any inaccurate subjective classification of 481 signals and determine the significant variables.

The results showed that stepwise DFA determined 24 variables, out of the 67 variables, as significant (Table 4). The correlation between detected signals and the defined cluster centre is presented in Figure 3.

The results for the 24 significant variables revealed that all together 25 Chinese sturgeon and 190 other fishes species echo-signals were detected in the last 3 years, and the identification accuracy is 90.9%, 98.4% respectively. The results also revealed that there is inaccurate classification in the subjective approach: one echo-signal of sediment and one echo-signal of noise had been classified as the Chinese sturgeon signal. Three signals of Chinese sturgeon had been classified as other fish species. One of them was classified as sediment (Table 5).

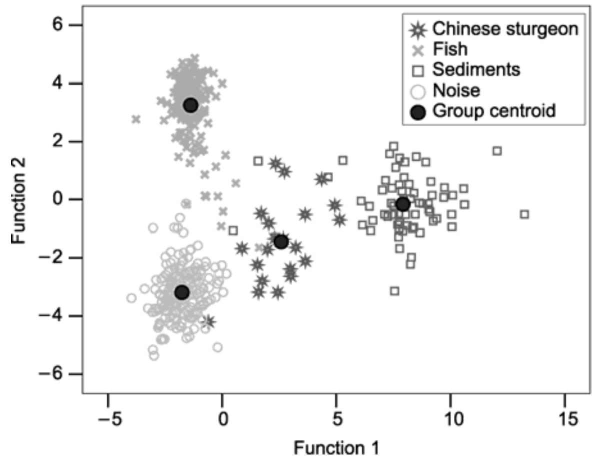

Figure 3 Scores of stepwise DFA for the four classified groups.

Table 4 Definitions and units of descriptors used for identification, which were determined by Stepwise DFA

Variables	Definitions a)
NrE	number of detected echoes in a track
SuMP	sum of missing ping within a track
Duration (s)	total time between first and last echo in a track
mTSc (dB)	mean off-axis-compensated target strength, $\text{mTSc} = \overline{\text{TSc}} = 10\log\left(\frac{1}{n}\sum_{i=1}^{n}\text{TS}_i\right)$
MSigma (m^2)	mean acoustic cross section area, TSc=10log(sigma/4π)
CV_{TSC} (%)	coefficient Variation in mTsc
GC (dB)	two-way Gain compensation
Ath.cg (°)	center of gravity seen from transducer calculated as mean (Ath)
R(c.g) (m)	center of gravity seen from transducer calculated as mean (R)
Exact.range (m)	excat range=mean(R)+transducer draft
Std_{Alo}	spreading of the echoes around the track along Alo- axis calculated as Std(Alo)
SM1	smooth 1: Distance ratio between the 3 dim. Euclidean first-last echo distance and the sum distance normalised by log(NrE)
Angular dist. (°)	eucledian angular distance between first and last echo
Ratio.+/−Ath.Move (%)	ratio of track movement in +/− athwart direction
Ratio.+/−Alo.move (%)	ratio of track movement in +/− alowart direction
V*x* (m/s)	velocity in Ath/x direction between first and last echo
Sum|V*y*| (m/s)	sum of all abs [Echo.V*y*(*i*+1)−Echo.Vy(*i*)], *i* = 1to all echo
Std_y	std. of velocity between all echoes in the Y direction
Dist.to.Bottom (m)	mean distance between the tracked fish and the defined bottom line
F_−6dB (dB)	foreground sv -6dB: sv within the track down to 6dB below the peak
B_−6dB (dB)	background sv-6dB : sv surrounding the track below 6 dB from the peak
Echo.CG (m)	mean echo center of gravity estimated from the AMP echogram −18 dB below the peak
Mean area (m)	mean.area=(No. of samples*meter per sample/nr of echoes), measured −6 dB below peak
Wide/height	wide/height=(No. of detection/ mean echo length measured), measured −6 dB below peak

a) Cite from the introduction in Sonar 5 software and the operator Manual[13], Ath (Athwartship) is indicated as *X* axis; Alo (Alongship, sailed direction of ship) is indicated as *Y* axis; and Range is indicated as *Z* axis (the depth of target in vertical model).

Table 5 The discriminated results of echo-signals of Chinese sturgeon and other targets.

Groups		Predicted group membership				Total No. obtained by subjective approach
		Chinese sturgeon	Other fish species	Sediment	Noise	
Percentage (%)	Chinese sturgeon	90.9	0	4.5	4.5	100.0
	Other fish species	1.6	98.4	0	0	100.0
	Sediments	2.6	0	97.4	0	100.0
	Noise	0	0	0	100.0	100.0
Count	Chinese sturgeon	20	0	1	1	22
	Other fish species	3	190	0	0	193
	Sediments	2	0	74	0	76
	Noise	0	0	0	190	190
Total No. after rectification		25	190	75	191	481

2.3 Determination of more definite descriptors by combination of PCA and DFA

PCA analysis was used to lessen the listed significant variables (Table 4). The results showed that the Bartlett's test of sphericity is extremely significant (P = 0.000), and KMO = 0.8. Therefore all of the variables are suitable for PCA analysis. In an analysis of the listed variables, PCA extracted six principal factors from these variables. These together explained 78% of all variation (Table 6).

Table 6 The six principal factors and strongly correlated variables

Principal factor	Explanation of all variation	Strongly correlated variables
Factor 1	29%	Std_{Alo}, Sum|Vy|, Std_y
Factor 2	21%	SM1, angular Dist.
Factor 3	12%	GC, Exact.range, echo.CG
Factor 4	8%	Nr.E, SuMP, duration
Factors 5 and 6	8%	mSigma, CV_{TSc}

Subsequently, DFA applied the strongly correlated variables of six principal factors (Table 5) to the identification of selected 481 signals. Results indicated that, there were 33 counts of Chinese sturgeon signals, 185 other fish species signals, 68 sediment signals and 195 noise signals. The accuracy of identification of Chinese sturgeon is 68.2%, and the accuracy of identification of other fish species, sediments and noise is 97%, 80.2% and 96%, respectively (Figure 4). Such principal factors were able to identify Chinese sturgeon from other fish species and noise with an adequate accuracy. However, which were poor at discerning Chinese sturgeon from sediments, for 14 signals of sediment had been wrongly classified as Chinese sturgeon.

It is therefore clear that Chinese sturgeon can be discriminated from other fish species and noise using certain descriptors, such as the behaviour variables (Std_{Alo}, Sum|Vy|, Std_y, Exca.range, which equate to swimming speed and depth of the distribution[21]), echo characteristics (SM1, GC, Echo.CG, Nr.E, SuMP, and duration) and acoustic cross-section characteristics (angular.Dist, mean.sigma, CV_{TSc}). However such descriptors could not discern Chinese sturgeon from sediment reliably.

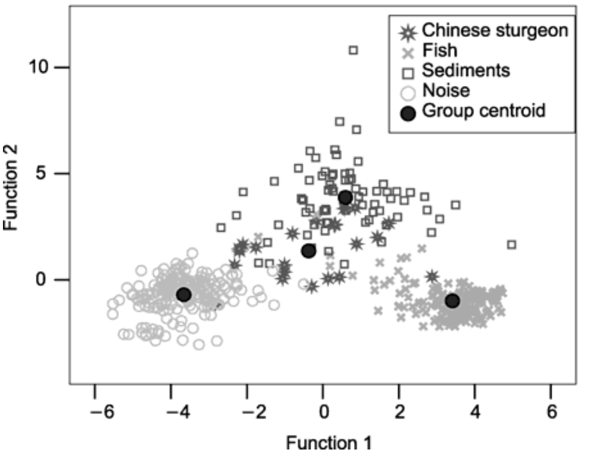

Figure 4 Scores of DFA function for the four classified groups. All of the variables were derived from PCA factors scores.

2.4 Typical echo-signals of Chinese sturgeon and their distribution on the spawning ground

There were 25 Chinese sturgeon detected in the study area from 2005 to 2007. The typical echo-signal and tracking path is presented in Figure 5.

Of the 25 identified individuals, 18 were distributed in Gezhouba Dam and Miaozui region, 3 near the Yiling Yangtze Bridge and 4 near Yiwan Yangtze Bridge and the Yanshouba region. More than 70% of the detected sturgeon were distributed in the region between the site of Gezhouba Dam and Miaozui reach, with a surface area of about 3.4 km^2. Less than 30% of the detected sturgeon

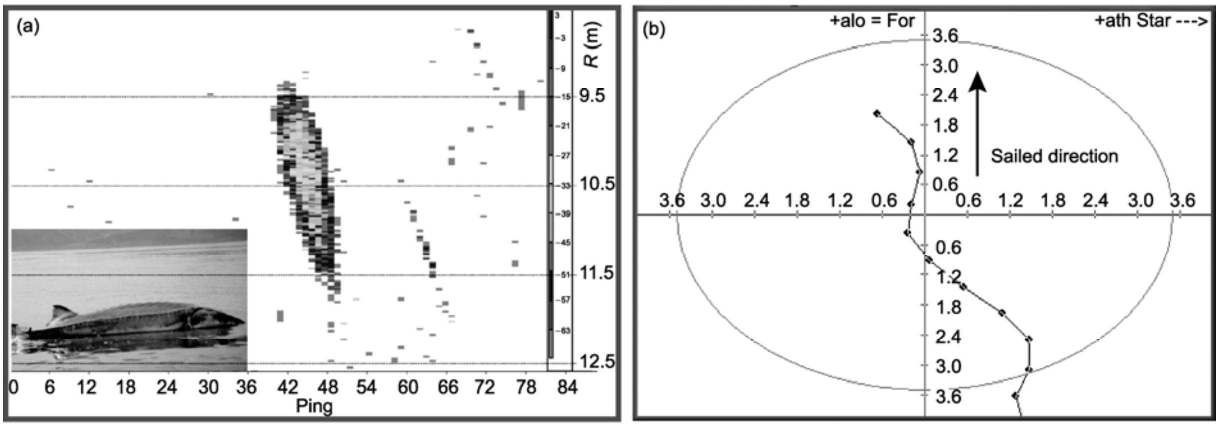

Figure 5 Typical echo-signal of Chinese sturgeon (a) and its tracked position in the sonar beam (b).

were distributed in the region between Miaozui and Yanshouba reach, with a surface area of about 13 km^2 (Figure 6).

3 Discussion

In the present study, the authors have demonstrated an improved method for identification of Chinese sturgeon and other targets, which has reliably assessed Chinese sturgeon distribution.

The hydroacoustic identification of individual species is at an early stage of development and is limited by serious physical uncertainties[25]. Discrimination of echoes depends upon many factors, not the least of which are the resolution of the echo sounder (i.e. frequency, pulse duration, ping rate, and platform stability) and the experience of the scrutinizer[26]. This means that corroboration of the classifications had to come from other data sources, combined acoustic-trawl methods have proven to be an effective way to overcome that drawback[17,21,25]. However, Chinese sturgeon is a highly endangered species, and is rare in the study area, so such methods are impractical. Fortunately, one of the most promising techniques to discriminate species is TS differencing[27]. Auer and Baker[7] have provided an acoustic measurement for sturgeon *in situ*. However, there is a contradiction between the limitations of the equipment (eg. 3 dB open angle of transducer is 7°, detect diameter is 1.2 m at the range of 10 m , and 2.4 m at the range of 20m)[13], and the large size of mature Chinese sturgeon (average of 2.5 m)[1,2]. Therefore in acoustic sampling, the total

Figure 6 Distribution of Chinese sturgeon in the spawning ground of the Gezhouba Dam, obtained by acoustic surveys during the spawning seasons.

length of a fish body usually cannot be ensonified in the sonar beam completely. TS can therefore be used as just a reference index. Moreover, the classification of signals by echo lengths, shape and tracking is somewhat subjective. Therefore such results have been verified by other descriptors of the targets in this study.

Acoustic observation and assessment of fishes are highly influenced by fish species, target size, flesh, fat content, backbone, the shape and the size of swim bladder, etc.[28,29]. And a swim bladder has a markedly different impedance to fish flesh, which makes it a very significant acoustic reflector. Evidence shows that often about 90% of echoes from a fish is due to the swim bladder alone[30]. Chinese sturgeon have some specific morphological characteristics (e.g. backbone), which can result in a particular reflection and backscattering characteristics from other targets[27]. Therefore all of those features and the inclusion of other descriptors, such as fish behaviour[21], have been used as additional descriptors in discrimination and identification. These have been proven to be effectual means for Chinese sturgeon identification.

However, the accuracy of identifying species, as acoustically observed targets can vary enormously, depends on which variables are used[21]. Firstly the PCA was applied to extract the principal factors of 67 selected variables, and then the factors were applied in DFA to correct any misclassification. The results show that the accuracy of Chinese sturgeon and sediments is only 58% and 56.1% (not shown in the results). Some of the variables had interfered with the discrimination severely. To overcome this, stepwise DFA was applied to eliminate the interfering variables, which resulted in high accuracy of identification (Table 5).

As for more definite descriptors of discrimination and identification, the results demonstrate that Chinese sturgeon can be discriminated from other fish species and noise, by certain descriptors such as the behaviour variables, echo characteristics and acoustic cross-section characteristics (Figure 4). However, identification of Chinese sturgeon from sediments is more difficult and needs more variables (Figure 3). Given that Chinese sturgeon is a demersal species found close to the riverbed[1−4], it is difficult to resolve fish echoes against the generally stronger reflection from the bottom. Because of the finite width of the acoustic beam, there is a "dead zone" where echoes from near-bottom fish are received after the start of the riverbed echo[31]. What is more, in study regions where the acoustic-scattering properties of the substrate are unknown, near-boundary detection problems suggest that the application of acoustics for identification of some demersal species is problematic[29]. In order to identify Chinese sturgeon from other targets, not only identification pattern, but the technique for physical properties of the substrate requires improvement.

The existing studies had used ultrasonic telemetry to track individual Chinese sturgeon movements and locate the spawning area of Chinese sturgeon[3,32], but such methodology cannot reveal their spatial distribution. In the present study, we revealed the fish distribution after the precise signals of Chinese sturgeon were obtained. However, the distribution acquired is preliminary, as apposed to a general portrait of the spatial and temporal variation in sturgeon abundance and distribution, which also requires further study.

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