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Spatial structure and bottom characteristics of the only remaining spawning area of Chinese sturgeon in the Yangtze River

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Summary

This study was performed to determine the spatial structure and bottom characteristics of the only remaining spawning area of Chinese sturgeon (*Acipenser sinensis*) located just downstream of the Gezhouba Dam. During the period 1996–2003, three methods were employed, including (i) the examination of the stomachs of opportunistic predatory fishes that feed on sturgeon eggs, (ii) tracking the mature sturgeons by ultrasonic tags and (iii) capturing eggs and yolk-sac larvae (ELS) at and near the river bottom by D-shaped bottom drift nets to monitor the spawning activities of *A. sinensis*. It was found that *A. sinensis* selected permanent locations to mate. There were two mating locations: an upstream mating area (UMA), in the tailrace of the Dajiang Hydroelectric Station and about 870 m far from the Gezhouba Dam (area, 0.1 km^2), and a downstream mating area (DMA), about 2500 m from Gezhouba Dam (area, 0.3 km^2). The DMA was the chief mating area and was used every year. The incubation area (for dispersal of fertilized eggs to incubate) was range from 870 m to 7 km from the dam. Generally, the total length of the spawning area was 5–7 km length (area 2.0–2.7 km^2) with the range slightly varied in different spawning activities. A relief map of the riverbed and a bottom hydroacoustic survey of the DMA found a deep depression and rocky substrate. These may be important characteristics of geomorphology for the spawning area of *A. sinensis*.

Introduction

Sturgeons are highly endangered species in need of serious protection and the sturgeons in China are no exception (Raymakers, 2006; Rosenthal et al., 2006). The Chinese sturgeon (*Acipenser sinensis* Gray), is a large, anadromous species with historical breeding populations in the Yangtze and Pearl rivers (YARSG, 1988). In the late 20th Century, the population of *A. sinensis* declined dramatically because of overfishing and habitat degradation (Wei et al., 1997; Xiao et al., 2006). The species was listed as a First Class Protected Animal by the national government in 1989. The hydroacoustic assessment on the size of spawning cohorts in 2002 indicated only about 200 individuals (Qiao et al., 2006). In addition, the stock assessment on juvenile sturgeons indicated that more than 90% of the juveniles originate from natural reproduction, although more than 7 million cultured larvae and juveniles have been released into the Yangtze River for stock restoration since 1983 (Zhu et al., 2002; Wei, 2003; Yang et al., 2005). Because the population is at present being mainly sustained by natural spawning, it is critically necessary to study spawning habitat at the only remaining spawning site just downstream of Gezhouba Dam.

Historical spawning areas of *A. sinensis*, were located in the mainstem of the upper Yangtze River, and a tributary, the lower Jinsha River, a reach covering about 600 river kilometers (rkm) (YARSG, 1988). Two potential spawning areas also have been reported in the Pearl River (Zhang, 1987). Approximately 21 potential historical spawning areas of the species have been reported in its native rivers. However, after damming of the Yangtze River by Gezhouba Dam at Yichang in 1981, the upstream spawning areas were no longer accessible and some fish alternatively spawned within a 30 km section below the dam (Yu et al., 1986; Hu et al., 1992). Recent studies found only one spawning area, which is directly downstream area of the dam (Wei et al., 1997; Yang et al., 2006). The two spawning areas in the Pearl River became unused in the late 1970s as a result of the stock decline (Zhang, 1987).

Early studies on spawning areas of *A. sinensis* were reported by Ke and Tian (YARSG, 1988). They documented the locations of several historical spawning areas by capturing mature sturgeons and examining the stomachs of predatory fishes that ate sturgeon eggs. They also described the spawning habitats by observing the riversides and analyzing a brief navigation channel map. Subsequent researchers (Yu et al., 1986; Hu et al., 1992; Wei et al., 1997) investigated the spawning areas below Gezhouba Dam during 1982–1993. The methods of all these studies were similar as before, but the description of spawning habitat was more intensive.

In 1993, ultrasonic telemetry was introduced and two male sturgeons were tagged to develop the expertise needed for a serious telemetry study of adult movements to locate spawning areas (Kynard et al., 1995). In 1996, a D-shaped bottom drift net was developed to capture sturgeon eggs and yolk-sac larvae (early life stages = ELS) from the river bottom to identify spawning timing and document spawning locations (Wei, 2003). The two new methods employed in the following years (1996–2003) acquired much new spatial information about spawning activities (Yang et al., 2006; Wei et al., 2009). However, it still lacks an intensive understanding on the spatial structure of the spawning area. In this paper, according to the comprehensive investigations on the reproductive behaviour, the functional differentiation and spatial structure of the only remaining spawning area was tentatively identified. In particular, the bottom characteristics of the spawning area were determined by on-site surveys.

Materials and methods

Study area

The only remaining spawning area of *A. sinensis* is located just below Gezhouba Dam (2.6 km below the start of middle Yangtze River), covering a stretch of about 7 km river length (Rkm 1678–1671, Rkm 0 is at the Yangtze estuary). This stretch is a transitional reach from mountainous river to alluvial river with its riversides sufficiently being used by city construction. During the October–November spawning season of *A. sinensis*, width of the study reach was 598–1670 m and the average water depth was 13.1 m (when the water level was 44.0 m; Zhang et al., 2007). The daily average water level during the spawning seasons of 1983–2004 was 40.7–46.8 m, discharge was 7153–32 700 $m^3 s^{-1}$, and transect-averaged velocity at Yichang Hydrological Monitoring Station (located in the spawning reach) was 0.83–1.78 m s^{-1} (Yang et al., 2007). Because of the speciality of geographical location (throat of the upper and middle Yangtze River), navigation, waterway regulation and port construction are potential threats to this aquatic environment.

For the convenience of study, we used the same grid array over the spawning area for the habitat analysis as was used previously to plot adult movements (Yang et al., 2006) or drift egg captures (Wei et al., 2009). A Global Position System receiver was used to insure our surveys were within the appropriate grid of Fig. 1.

Examinations of stomachs of predatory fishes that eat sturgeon eggs

Previous studies documented that monitoring stomachs of predatory fishes that eat *A. sinensis* eggs is an effective method to reveal when adult sturgeons begin to spawn, and the spatial distribution of the predatory fishes may reveal the likely area sturgeon eggs are distributed (Yu et al., 1986; Hu et al., 1992;

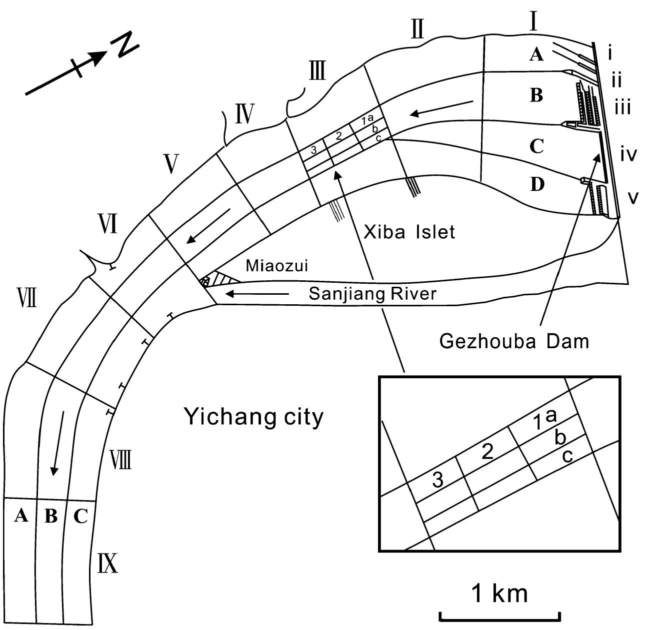

Fig. 1. Sketch map of *Acipenser sinensis* spawning area below Gezhouba Dam divided into observation grids. An example of further subdivisions of each grid is indicated within grid IIIB. Numerals (I–IX, 1–3), Letters (A–D, a–c) are labels for the subareas. Arrows indicate the flow direction. The dam comprises (i) Flushing sluice, (ii) No.1 ship lock, (iii) Dajiang power plant, (iv) Erjiang water relief sluice, (v) Erjiang power plant and otherwise

YARSG, 1988; Deng et al., 1991). These predatory fishes mainly include bronze gudgeon (*Coreius heterodon* Bleeker), largemouth bronze gudgeon (*Coreius guichenoti* Savuage *et* Dabry) and darkbarbel catfish (*Pelteobagrus vachelli* Richardson), which are abundant in the Yangtze River. In each spawning season during 1996–2003, when river temperature decreased from 21 to 15°C, at least three fishermen were hired to catch predatory fishes around the spawning reach. The reach was divided into three segments: Gezhouba Dam to Miaozui (4 km), Miaozui to Wulong (3 km) and Wulong to Yanzhiba Islet (3 km; Fig. 1). Wulong and Yanzhiba Islet are the most downstream area and are not shown on Fig. 1. The catches in this area were analyzed separately. Drift nets (200 m long, 1.5 m wide, approximately 3 cm clear mesh) were used to capture predatory fishes and fishing occurred at the same time (dawn and dark) everyday and lasted about 5 h. In general, each boat conducted about 10 times of netting processes during this period. We examined the stomachs of predatory fishes every morning, but it also was done anytime if the catch increased sharply.

Determinations of mating and egg incubation areas

Tracking and ELS captures were combined to determine the precise spawning locations. The details of the methods please see Yang et al. (2006) and Wei et al. (2009) on the same research but for other purpose. Tagged fish locations from which newly spawned eggs were captured were likely mating areas. Besides the direct ELS captures from the river bottom (Wei et al., 2009), the locations of ELS by monitoring eggs inside predatory fishes were also used to determine the general up- and downstream distribution of ELS.

An Underwater Topographic Map from Gezhouba Dam to Huyatan (surveyed in October–December 2003; scale 1 : 10 000 m) provided by the Three Gorges Hydrological and Water Resources Survey Bureau of the Yangtze Water Resources Commission was used to plot fish and egg locations. And this topographic map was imported into ArcGIS 9.2 software (ESRI, Inc.) for measuring the extensions of the areas.

Bottom habitat investigation

The Underwater Topographic Map was also used to analyze the bedform morphology of the spawning habitat. It was imported into ArcGIS 9.2 software for the purpose of analysis. The riverbed surfaces were interpolated using Inverse Distance Weighted scheme with grid size of 21.6 m, and the topographic characteristics of the spawning area were analyzed by Geostatistical Analyst and 3D Analyst module.

During 26–30 November 2002 (spawning season), a 200 kHz BioSonics DT6000 split-beam echo sounder was used to collect acoustic data on substrate hardness and roughness in the downstream mating area (Fig. 2). The 6.6° transducer was positioned just below the water surface and was aimed down. A pulse duration value of 0.4 ms was used, and the pulse repetition rate was set at 4 pulses s^{-1}. Acoustic data were thresholded at a value of −60 dB (referenced to an on-axis target strength at 1 m). Transects were run perpendicular to the shore and essentially parallel to each other throughout the spawning area. Date for each transect recording were stored in a separate data file for later analysis. Data file format saves the digital waveform with no time-varied gain (TVG) applied. The appropriate TVG was applied to the data during analysis.

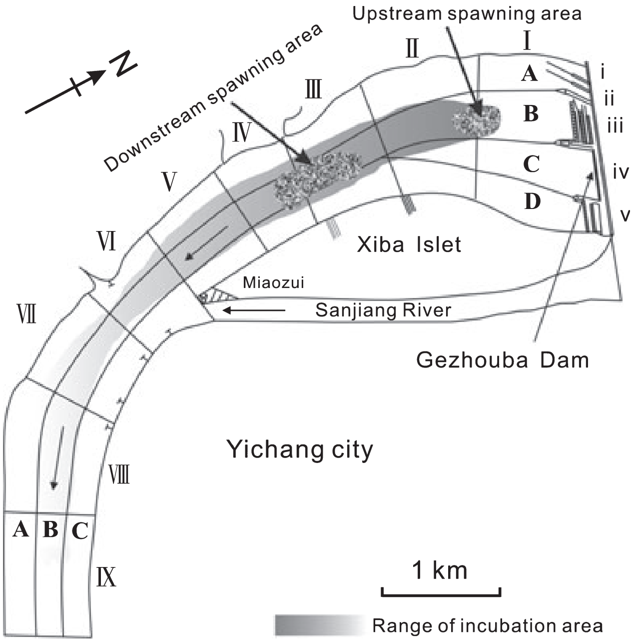

Fig. 2. Exact range of *Acipenser sinensis* spawning area and functional differentiation of subareas within the only remaining spawning area suggested by Yang et al. (2006), Wei et al. (2009) and this study. The gradually changed grey shading illustrates the abundance of ELS on the riverbed, darker means higher abundance. All further explanations on subarea labeling see caption of Fig. 1

A GPS receiver was attached to the DT6000 echo sounder and produced a geographical estimate of position for each acoustic ping.

BioSonics VBT (visual bottom typing) software was used to read the acoustic data files and analyze characteristics of the bottom echo and classify the surface sediment. The reflective characteristics were measured for each ping, and 20-ping averages were generated. The reflective characteristics were classified with a Fractal Dimension Analysis, which produces point estimates indicating hardness or roughness of the bottom. The 20-ping average values produced by the VBT analysis program each had a geographical position value. These positions were converted to decimal degrees and the data set was loaded into a graphing program called Surfer (Golden Software). Surface–contour plots of bottom classification were gridded using a Krieging process. The resulting surfaces were plotted in contour plots.

Results

Location of mating areas

Sturgeons actively moved and centralized to two main areas during the propagation periods: the adjacent area of IB and IIB and the adjacent area of IIIB and IVB (Table 1; Fig. 2). The areas were in accordance with the results of location and collection of sturgeon eggs at the river bottom (Table 1). Therefore, two primary mating areas were suggested although the areas slightly varied for different spawning activities (Fig. 2).

According to the measurement (Fig. 2), the upstream mating area was located about 870 m from the Dajiang Hydroelectric Station, and about 150 m downstream from the fast tailrace flows from the station. This area was estimated to cover 0.1 km^2. The downstream mating area was located in the channel of the mainstem (about 2.5 km downstream from Gezhouba Dam) and covered approximately 0.3 km^2.

Table 1
Locations of acoustic tagged *Acipenser sinensis* inferred spawned and dispersal center of eggs inferred from near bottom drift net surveys

Year	Spawning period	Located spawners	Location of spawners	Dispersal center of eggs
1996	First	4F, 1M	I2–3Bb	I2Bb
	Second	5F, 1M	III2–IV3Bb	IVBb
1997	First	3F	III2–IV3Bb	IIIBb
	Second	–	–	IVBb
1998	First	6F, 1M	IVBb	IVBb
1999	First	–	–	IB, IIIB
	Second	–	–	IB, IIIB
2000	First	–	–	IIIB
	Second	–	–	IVB
2001	First	–	–	IIB, IVB
	Second	–	–	IIB, IVB
2002	First	–	–	IIIB
	Second	–	–	IIIB
2003	First	–	–	IVB

F, female; M, male.
'–' means we can not ascertain whether the tagged fishes participated the spawning activity. All further explanations on section labeling see caption of Fig. 1.

They were 5 and 13 spawning periods in the up- and downstream mating areas during 1996–2003 (Table 1), respectively. Moreover, four spawning periods took place simultaneously in the upstream and downstream mating areas, only one spawning period only occurred in the upstream mating area. Spawning took place in the downstream mating area every year, and the area (based on adult use and captures of egg and free embryos) was larger than the upstream mating area.

Location of incubation area

Spatial distribution of ELS captures (CPUE) across transects showed that most were captured in the center and inside-of-the-curve transects (Table 2). Most ELS were captured in the B and C sections of transects II–V. The captures of many ELS in transect I-B only occurred during 2 years.

Predatory fishes with sturgeon eggs in their stomachs occurred from Gezhouba Dam to Yanzhiba Islet (Table 3). However, the time when predatory fishes were captured that had eaten sturgeon eggs in the lower reach (Miaozui to Yanzhiba Islet) was later than the fish upstream of Miaozui. The duration that eggs occurred in stomachs was also less in the lower two segments, averaging 0.52 days (11.9%) and 3.00 days (69.2%) less than captures between Gezhouba Dam and Miaozui (all years combined, 1996–2003). The percent of predatory fishes that contained sturgeon eggs was also less in the lower two segments, averaging 13.16% less than the areas upstream of Miaozui. There were sturgeon eggs in the Miaozui to Yanzhiba Islet reach, but the density of eggs was likely much less than in the upstream areas. So the major incubation area (for dispersal of fertilized eggs to incubate) was range from 870 m to 7 km from the dam (Fig. 2).

Bottom characteristics of the spawning area

The bathymetry map (Fig. 3) shows the shape and characteristics of the mainstem channel in Area I–VIII. The river

Table 2
CPUE (ind per 1000 m^3) of ELS of *Acipenser sinensis* in each subarea determined by standard near bottom drift net surveys during 1996–2003

Subsection	Lateral section	1996		1997	1998	1999		2000	2001		2002		2003
		First	Second	First	First	First	Second	Second	First	Second	First	Second	First
I	B	1.0	–	–	–	454.3	0	–	–	–	–	–	–
II	A	–	–	–	–	0	4.4	–	–	–	3.0	–	–
	B	1.3	0	–	–	33.1	0.5	0	143.4	1.8	0.3	–	–
	C	–	–	–	–	108.4	–	–	19.2	6.0	–	—	–
III	A	0	–	–	0	–	0	0	–	–	82.9	–	–
	B	0	2.2	108.5	6.7	47.7	1.2	22.9	–	1.1	1.2	–	0
	C	–	–	23.1	0	0	–	–	–	–	0	–	0
IV	A	–	–	–	0	1.2	0	1.5	5.1	–	0	–	–
	B	–	1272.3	66.7	44.9	3.2	8.0	6.3	34.4	2.6	23.9	16.2	530.3
	C	–	0	0.1	1.9	110.4	–	0.04	–	–	0	–	–
V	A	0	–	0	8.1	–	–	0	10.9	–	0.9	0	–
	B	0	–	33.1	1032.5	–	0	0.8	6.7	1.2	53.0	4.4	51.3
	C	–	–	7.9	0	–	–	13.6	–	–	0.2	–	–

'First' and 'Second' indicate the batch of spawning events in the year.
'–' means did not capture ELS in this subarea. All further explanations on section labeling see caption of Fig. 1.

Table 3
Monitoring on spawning of *Acipenser sinensis* by examining the stomachs of opportunistic predatory fishes during 1996–2003

Year	Spawning period	Gezhouba Dam–Miaozui (4 km)			Miaozui–Wulong (3 km)			Wulong–Yanzhiba Islet (3 km)		
		Days	Percent	Eggs / fish	Days	Percent	Eggs / fish	Days	Percent	Eggs / fish
1996	First	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
	Second	6	38.7	9.9	5	17.6	2.8	4	14.4	1.8
1997	First	6	70.1	35.5	2	20.0	12.3	1	100.0	32.0
1998	First	5	45.6	8.7	8	20.2	4.6	ND	ND	ND
1999	First	7	41.3	8.3	4	46.2	3.2	ND	ND	ND
	Second	3	21.5	4.6	2	4.5	0.8	ND	ND	ND
2000	Second	6	4.7	0.3	5	18.1	1.7	6	35.3	3.5
2001	First	4	50.0	6.0	2	10.0	0.1	ND	ND	ND
	Second	3	11.7	0.2	0	0.0	0.0	ND	ND	ND
2002	First	5	11.0	1.0	8	0.9	0.4	ND	ND	ND
	Second	2	10.4	0.5	1	7.1	0.2	ND	ND	ND
2003	First	5	40.0	7.6	5	33.1	4.4	5	46.8	7.7

Days and percent indicate the durative time and proportion of predatory fishes with stomachs had sturgeon eggs, respectively. Eggs / fish indicates the number of sturgeon eggs per predatory fish ate. ND means that the density of predatory fishes was too low to capture.

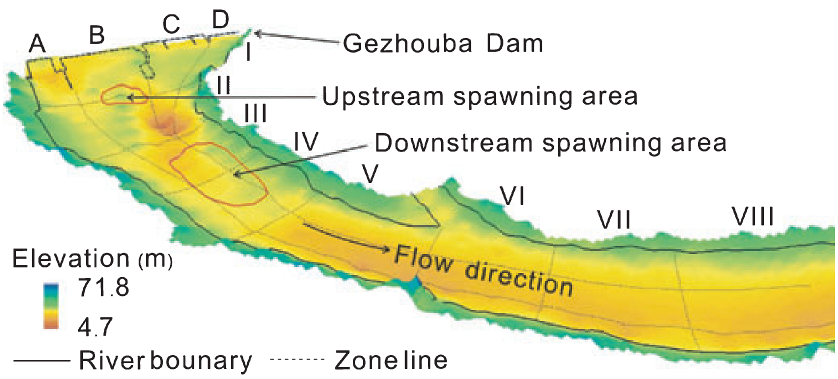

Fig. 3. Side view of a 3-dimensional surface representing the bathymetry in area I–VIII in October–December 2003. All further explanations on subarea labeling see caption of Fig. 1

bottom in up- and downstream spawning areas were very similar, characterized by a deep area upstream and a gradual slope downstream. The bottom classification data (Fig. 4) suggest that the deep areas (mainly in the center of the river) had harder or rougher reflective characteristics. This suggests that the riverbed in the deep areas were composed of rocks. Generally, the total length of the spawning area was 5–7 km length (area 2.0–2.7 km^2) with the range slightly varied in different spawning activities.

Discussion

In previous studies (Yu et al., 1986; YARSG, 1988; Deng et al., 1991; Hu et al., 1992), sturgeon eggs from the stomachs

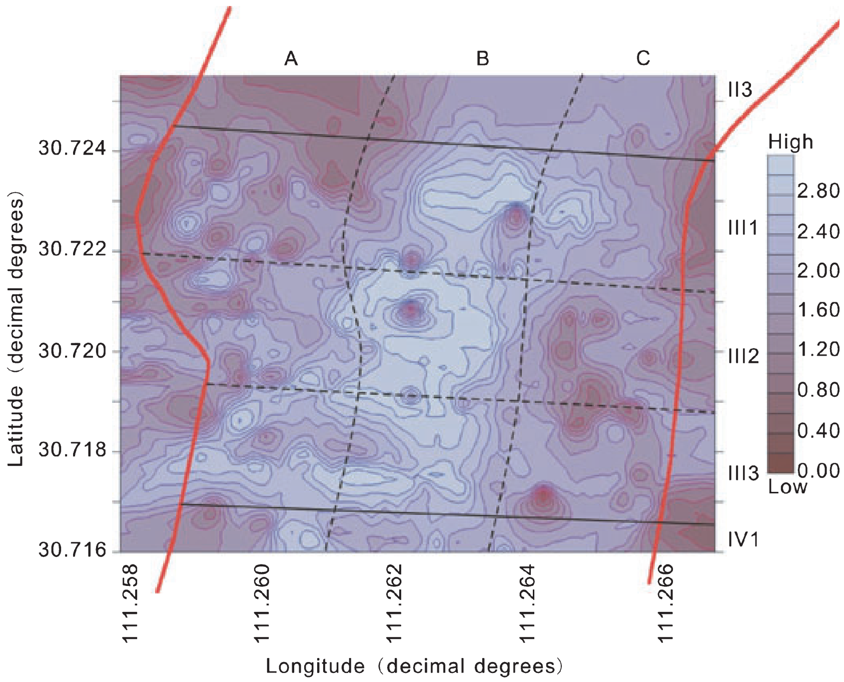

Fig. 4. Plan view of area II3–IV1 indicating relative hardness ⁄ roughness index (parameter of echo signal related to substrate property) of riverbed substrate in 2002. Area II3–IV1 is subareas in *Acipenser sinensis* spawning area, all further explanations on subarea labeling see caption of Fig. 1. Thick red lines indicate the river shoreline

of predatory fishes were used to estimate the spawning time and the spatial distribution of predatory fishes with sturgeon eggs in stomachs was used to estimate the distribution of sturgeon eggs. However, eggs obtained from fish stomachs were often digested and difficult to distinguish the developmental stages. Also, the developmental process of the eggs may be affected by the temperature or conditions in stomachs. Using the spatial distribution of predatory fishes with sturgeon eggs to reveal the spatial distribution of sturgeon eggs on the riverbed neglects the potential movements of predatory fishes in any direction and the downstream movement of drifting eggs. In addition, sampling ELS from predator stomachs may miss a spawning event. A spawning event revealed by the movement of tagged adult sturgeons was documented by ELS capture at the river bottom, but captured predatory fish did not contain any sturgeon eggs. An integrated method used in this study is a better and more reasonable method to determine the precise timing and location of spawning. This method has been used for more than 18 years during studies of shortnose sturgeon (*A. brevirostrum*) in the Connecticut River (Kieffer and Kynard, 1996).

Previous studies (Yu et al., 1986; Deng et al., 1991) suggested that an unsteady spawning area was existent at the head of Yanzhiba Islet (about 8 km from Gezhouba Dam) because they found predatory fishes with stomachs have sturgeon eggs in this reach. Spawning locations in this study revealed that the sturgeon did not spawn at the head of Yanzhiba Islet during 1996–2003. However, predatory fishes with sturgeon eggs in stomachs still occurred in this area. It suggests that the unsteady spawning area reported by the previous studies (Yu et al., 1986; Deng et al., 1991) probably was not existed. The eggs occurred in the stomachs of the predatory fishes that captured at the head of Yanzhiba Islet probably came from the spawning area below Gezhouba Dam.

The downstream mating area was more effectively than the upstream mating area (Wei, 2003). This may be because of the more suitable bedform geomorphology (adverse slope and rocky substrate) exists in the downstream mating area, which makes the other microhabitat variables (e.g. substrate quality, hyporheic exchange, hydraulic habitat complexity) suitable to trigger spawning activities (Zhang et al., 2007, 2009). Spawning locations revealed slight variations in different spawning activities during the study period, the variations of microhabitat variables may be the primary reason. The number of mature sturgeons that spawned in a propagation period also may have large influence on the spawning location. On the whole, the function (for spawning, incubation or both) of the subareas is not uniform and can be identified by the methods used in this study.

The maintenance of spawning activities on the last spawning area for Chinese sturgeon seems the basis for most recruitment in the wild population. Monitoring spawning activities (e.g. reproductive occurrence, spawning stock biomass and structure, embryo numbers and emergent larvae) (Wei, 2003; Xiao et al., 2006; Yang et al., 2006) should continue in the future so that measures can be taken in case spawning completely fails. Further study should focus on enhancing the reproductive scale and efficiency on the last spawning area, as it is likely the only effective method to restore the wild stock. Also, improvement of the last spawning area and the construction of additional suitable spawning habitats are suggested to enhance the likelihood for improving recruitment and preventing losing the last population.

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