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Effects of annual flow characteristics on the freshwater life history of Chinese sturgeon: concern inferred from the number of seaward migrating juveniles

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Abstract

Since 2003, the flow characteristics of the Yangtze River, currently the only river where the protected Chinese sturgeon, *Acipenser sinensis*, spawns and where the young grows to the 6 to 8 month juvenile stage, has been regulated by the operation of the Three Gorges Project. The number of seaward migrating juveniles captured (NSMJC) in the Yangtze estuary from 2002 to 2010 was significantly positively related (Pearson correlation, P (two tailed) <0.01; Lg (NSMJC) $= 0.870 + 3.930 \times$ AASC, $R = 0.940$, $P = 0.000$) to the annual sediment load and annual average sediment concentration (AASC) of the previous year, when adults entered the river and migrated upstream, used refuge areas, and spawned, and when early life stages were reared. This suggests that silt content may have a major effect on adult spawning success and rearing of early life stages. Based on the correlation between numbers of juveniles captured and numbers of adults in the spawning areas in the previous year (Pearson correlation, $R = 0.965$, P (two tailed) $= 0.008$), we speculated that the sediment characteristics affected the migration and gonad development of mature individuals and, indirectly, the number of juveniles reaching the Yangtze estuary during the following year. Decreased silt levels in the Yangtze River following installation of the Three Gorges Project may be having a deleterious effect on Chinese sturgeon reproduction and needs further research.

Keywords: *Acipenser sinensis*, Breeding migration, Silt concentration, Yangtze River, Three Gorges Project

Background

The Chinese sturgeon *Acipenser sinensis*, one of the world's largest anadromous fish species, is currently mainly distributed in the continental shelf of the west Pacific Ocean and the Yangtze River system (Yangtze Aquatic Resources Survey Group 1988). Since the 1970s, the wild population has declined dramatically because of environmental deterioration and overfishing (Wei et al. 1997) and especially since its migration route was blocked by the Gezhouba Dam, the first dam in the Yangtze main stream. Since 1989, the species has been listed as a first-level protected animal in China and since 2009 as a critically endangered species on the IUCN red list (Wei 2009). In the only remaining spawning area below the Gezhouba Dam, a hydro-acoustic assessment in 2002 indicated that the spawning cohort comprised only of 222 individuals (Qiao et al. 2006). Although artificial propagation and augmentation have been conducted since early 1983, both mark-recapture and molecular genetic identification have indicated that in the Yangtze estuary more than 90% of the *A. sinensis* juveniles originated from natural reproduction (Zhu et al. 2002; Yang et al. 2005). Thus, it is critically important to analyze the factors influencing the pre-spawning aspects of adult life history in the river, the reproduction period, and the early growth period to determine if river quality remediation is possible to improve spawning success and juvenile production.

In June and July, after reaching maturity in the sea (male ≥ 8 years, female ≥ 14 years), *A. sinensis* move into the Yangtze estuary (referred to as river kilometers (rkm) 0) and swim upstream to the middle reaches of the Yangtze River (mainly from Hukou to Yichang) (Figure 1), where they remain in pools for overwintering and through the summer of the following year. During this time, gonads gradually mature. In October to November, fish enter the spawning area (rkm 1,675) below the Gezhouba Dam (Yangtze Aquatic Resources Survey Group 1988; Kynard et al. 1995; Wei et al. 1997; Yang et al. 2006). After hatching, the yolk-sac larvae drift with the water flow and are dispersed for feeding along the river. They arrive at the Yangtze estuary April to August of the following year and gradually migrate into the sea (Yangtze Aquatic Resources Survey Group 1988; Wei et al. 1997; Wei et al. 2009). Most post-spawning adults move downstream quickly after spawning, returning to the downstream area or the shallow sea (Wei 2003; Yang et al. 2006).

Previous studies have indicated that the hydrological environment affects migration and natural reproduction of *A. sinensis*. According to Yangtze Aquatic Resources Survey Group (1988), when the water level fluctuated little and wind was from the south, Chinese sturgeon tended to travel upstream, while when the water level rose or fell sharply and the wind was northerly, the fish tended to remain in a fixed location. They found that, in addition to the effects of water temperature, the specific dates of the first and second spawning periods were related to water level and silt content as well as flow velocity. The final water level increase in the autumn had obvious effects on spawning activities (Yangtze Aquatic Resources Survey Group 1988). Other researchers have suggested that appropriate water temperature is essential for spawning. According to this premise, when water level, flow velocity, and silt content enter a downward trend from high levels and all hydrological elements are in a suitable range, spawning will begin (Wei 2003; Yang et al. 2007). By establishing a model of the hydrological environment

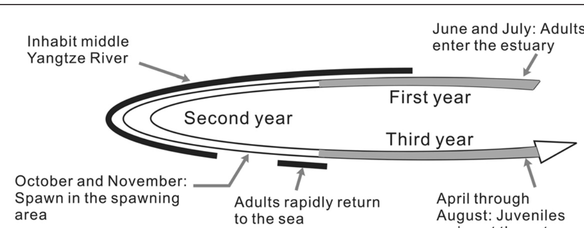

Figure 1 Diagram of the course of *A.* sinensis breeding migration (Yangtze Aquatic Resources Survey Group 1988).

influencing *A. sinensis* spawning, Zhang (2009) considered that silt content in the river dropped dramatically after completion of the Three Gorges Project (TGP) in 2003, declining more than 90%, probably having adverse effects on *A. sinensis* natural reproduction.

Studies have focused on river conditions before and after spawning to determine the environmental factors conducive to spawning (Yangtze Aquatic Resources Survey Group 1988; Wei 2003; Yang et al. 2007; Zhang 2009). The relationship of long-term hydrological and physical conditions such as annual flow characteristics (AFC) with various aspects of pre-spawning migration, refuge occupancy, spawning success, and early growth of *A. sinensis* is still unknown. We examined the relationship of the number of seaward migrating juveniles captured (NSMJC) in the estuary over a 9-year period to the river characteristics of annual runoff (AR), annual sediment load (ASL), and annual average sediment concentration (AASC) to better understand the relationship between production of juveniles and river parameters.

Methods

Study area

With the completion of the Gezhouba Dam in 1981, the migration route of *A. sinensis* to the historic spawning areas in the upper Yangtze River and lower Jinsha River was blocked, and fish were restricted to the middle and lower reaches of the Yangtze River (approximately 1,675 km river length, rkm 0 is at the estuary) (Figure 2) (Wei et al. 1997). These reaches flow through foothills and plains with many lakes and tributaries with point bars and islets of varying size (Yu and Lu 2005). Most of the river channels are 1,000 to 3,000 m wide and 10 to 40 m deep (Chen et al. 2007) with riverbed gradients of 0.579×10^{-4} to 0.097×10^{-4} (Yu and Lu 2005). The annual average water levels from 1950 to 2000 at Yichang and Datong stations were 43.83 (daily mean range 38.30 to 55.73 m) and 8.74 m (daily mean range 3.14 to 16.64 m), respectively, with flow rates of 13,900 (daily mean range 2,770 to 70,800 $m^3\ s^{-1}$) and 28,700 $m^3\ s^{-1}$ (daily mean range 4,620 to 92,600 $m^3\ s^{-1}$). Silt concentration was measured at 1.14 (daily mean

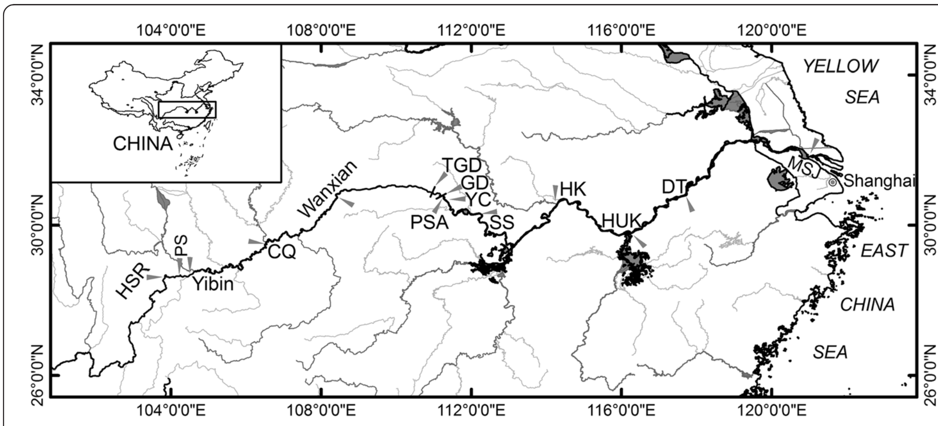

Figure 2 Study area of the middle and lower Yangtze River. Geographic data were from the National Fundamental Geographic Information System of China (1999). CQ, Chongqing; DT, Datong; GD, Gezhouba Dam; HK, Hankou; HSR, historic spawning reach; HUK, Hukou; MSJ, monitoring site for juvenile *A. sinensis*; PS, Pingshan; PSA, present spawning areas; SS, Shashi; TGD, Three Gorges Dam; YC, Yichang.

maximum 10.5 kg m^{-3}) and 0.486 kg m^{-3} (daily mean maximum 3.24 kg m^{-3}), respectively (Yu and Lu 2005). The flow velocity in most of the reaches is 1.0 to 1.5 m s^{-1} (Chen et al. 2007). Both the river channel and river banks are highly used by humans for navigation, fishing, sand extraction, and habitation. It is one of the most developed areas in China.

Monitoring of juvenile *A. sinensis* at the Yangtze estuary

During 2002 to 2010, a set net (with government permission) was deployed at the Xupu reach, Changshu City to monitor juveniles from upstream stretches (Figure 2). The river here is comparatively narrow, so the density of juveniles is higher than in other areas. The net employed was 2,377 m long, 750 m wide, and 4 m deep with 16 net bags and mesh size of 4 cm (measured from knot to knot). The effective net height varied with the water level but was generally at 2.5 m. The net was checked every day except in extremely bad weather, and fish were counted, measured (total and standard lengths), weighed, and released. Any injured fish were transported to the rescue center for treatment before release. Li et al. (2011) have reported the results of monitoring during 2002 to 2009.

Monitoring of Yangtze annual runoff characteristics

Data gathered at four major hydrological monitoring stations (Yichang, rkm 1,669.2; Shashi, rkm 1,521.2; Hankou, rkm 1,043.2; and Datong, rkm 553.9) were considered to reflect the runoff characteristics along the entire middle and lower reaches of the Yangtze River and were selected for analysis (Figure 2). The relevant hydrological indices used in this study included AR, ASL, and AASC. The surveys were done by the Changjiang Water Resources Commission, and we acquired the data from the *Yangtze Sediment Bulletin* (2002 to 2009). The survey was conducted according to the standards issued by the Chinese government, including *Code for liquid flow measurement in open channels* (GB50179-93) and *Code for measurements of suspended sediment in open channels* (GB50159-92), which are similar to the corresponding standards issued by the International Organization for Standardization.

Data analysis

Currently, any relationship between the AFC of the Yangtze River and freshwater life history of *A. sinensis* is unknown. In order to explore the relationship, a Pearson correlation coefficient was used for analysis, based on general knowledge of the species. For instance, as the breeding migration of the adults and seaward migration of the juveniles extend over three consecutive years in the river, the AFC over this period was analyzed with respect to its relationship to the NSMJC. The relationships were determined for each year, each consecutive 2 years, and the consecutive 3 years in the period. Subsequently, correlation analysis was conducted among AR, ASL, and AASC at each of the four hydrological monitoring stations to reveal relationships among the AFC. Finally, stepwise regression was used to ascertain the significance of AASC to the NSMJC.

Pearson correlation and stepwise regression methods were used to examine relationships between AFC and NSMJC (SPSS, version 16.0). Pearson correlation (test of significance, $P < 0.05$) was used to measure the strength of linear dependence between

Table 1 Hydrological status of four major monitoring stations in the middle and lower Yangtze River

Time range		Annual runoff ($\times 10^8$ m^3)				Annual sediment load ($\times 10^8$ t)				Annual average sediment concentration (kg m^{-3})			
		YC	**SS**	**HK**	**DT**	**YC**	**SS**	**HK**	**DT**	**YC**	**SS**	**HK**	**DT**
1950 to 2002[a]	Mean (initial year)	4,369 (1950)	3,942 (1955)	7,112 (1954)	9,052 (1950)	4.915 (1950)	4.337 (1956)	3.978 (1954)	4.269 (1951)	1.129 (1950)	1.098 (1956)	0.560 (1954)	0.475 (1951)
	Max	5,751	nd	9,808	13,600	7.540	nd	5.790	6.780	1.65	nd	0.772	0.697
	Min	3,475	nd	5,670	6,760	2.100	nd	2.330	2.390	0.578	nd	0.264	0.277
2003 to 2009[b]	Mean ± SD	3,956 ± 542	3,741 ± 448	6,628 ± 715	8,122 ± 810	0.572 ± 0.363	0.807 ± 0.433	1.193 ± 0.419	1.475 ± 0.479	0.138 ± 0.079	0.209 ± 0.099	0.176 ± 0.046	0.178 ± 0.042
	Max	4,592	4,210	7,443	9,248	1.100	1.380	1.740	2.160	0.239	0.352	0.233	0.239
	Min	2,848	2,795	5,341	6,886	0.091	0.245	0.576	0.848	0.032	0.088	0.108	0.123

Status before and after the Three Gorges Project. DT, Datong; HK, Hankou; nd, no data; SS, Shashi; YC, Yichang. [a]Initial years of monitoring are indicated in parenthesis; [b]the data for each year is shown in Table 2.

Table 2 Hydrological status and correlation (*C*)

Year	Annual runoff (×10^{8} m^{3})				Annual sediment load (×10^{8} t)				Annual average sediment concentration (kg m^{-3})				Juveniles captured in the Yangtze estuary
	YC	SS	HK	DT	YC	SS	HK	DT	YC	SS	HK	DT	
2000	4,712	nd	7,420	9,266	3.9	nd	3.36	3.39	0.828	nd	0.451	0.366	
2001	4,155	nd	6,553	8,250	2.99	nd	2.85	2.76	0.718	nd	0.435	0.336	
2002	3,928	3,745	7,687	9,926	2.28	2.41	2.39	2.75	0.578	0.642	0.31	0.277	347
2003	4,097	3,924	7,380	9,248	0.976	1.38	1.65	2.06	0.238	0.352	0.224	0.223	718
2004	4,141	3,901	6,773	7,884	0.64	0.956	1.36	1.47	0.155	0.246	0.201	0.186	147
2005	4,592	4,210	7,443	9,015	1.1	1.32	1.74	2.16	0.239	0.313	0.233	0.239	48
2006	2,848	2,795	5,341	6,886	0.091	0.245	0.576	0.848	0.032	0.088	0.108	0.123	68
2007	4,004	3,770	6,450	7,708	0.527	0.751	1.14	1.38	0.131	0.198	0.176	0.179	20
2008	4,186	3,902	6,728	8,291	0.32	0.492	1.01	1.3	0.077	0.127	0.149	0.157	45
2009	3,822	3,686	6,278	7,819	0.351	0.506	0.874	1.11	0.092	0.137	0.139	0.142	20
2010													11
$C_{F\text{-}J}$ (*P*)	0.147 (0.705)	−0.228 (0.623)	0.162 (0.677)	0.274 (0.475)	0.857* (0.003)	0.648 (0.116)	0.824* (0.006)	0.747** (0.021)	0.880* (0.002)	0.694 (0.083)	0.874* (0.002)	0.815* (0.007)	
$C_{S\text{-}J}$ (*P*)	0.305 (0.424)	0.297 (0.474)	0.642 (0.062)	0.733** (0.025)	*0.893** (0.001)	*0.962** (0.000)	*0.917** (0.001)	*0.941** (0.000)	*0.900** (0.001)	*0.967** (0.000)	*0.861** (0.003)	*0.902** (0.001)	
$C_{T\text{-}J}$ (*P*)	0.049 (0.908)	0.096 (0.821)	0.539 (0.168)	0.621 (0.100)	0.590 (0.124)	0.659 (0.075)	0.626 (0.097)	0.627 (0.096)	0.599 (0.117)	0.669 (0.069)	0.622 (0.100)	0.599 (0.117)	
$C_{FS\text{-}J}$ (*P*)	0.363 (0.336)	0.216 (0.642)	0.582 (0.100)	0.684** (0.042)	0.896* (0.001)	0.846** (0.016)	0.909* (0.001)	0.912* (0.001)	0.915* (0.001)	0.853** (0.015)	0.905* (0.001)	0.912* (0.001)	
$C_{ST\text{-}J}$ (*P*)	0.296 (0.477)	0.354 (0.437)	0.829** (0.011)	0.921* (0.001)	0.824** (0.012)	0.943* (0.001)	0.865* (0.006)	0.908* (0.002)	0.828** (0.011)	0.950* (0.001)	0.820** (0.013)	0.861* (0.006)	
$C_{FST\text{-}J}$ (*P*)	0.455 (0.257)	0.268 (0.608)	0.719** (0.044)	0.826** (0.012)	0.855* (0.007)	0.743 (0.091)	0.868* (0.005)	0.870* (0.005)	0.873* (0.005)	0.763 (0.078)	0.869* (0.005)	0.864* (0.006)	

Hydrological status at four major monitoring stations in the middle and lower Yangtze River and correlation (*C*) with the number of *A. sinensis* juveniles captured in the Yangtze estuary. Pearson correlation was used. The number of juveniles was logarithmically transformed.

Subscript of *C* indicates the relationship between each year (F, first; S, second; T, third; . . .; FST, first to third years; Figure 1) and number of captured juveniles (*J*); DT, Datong; HK, Hankou; nd, data; SS, Shashi; YC, Yichang. *Correlation is significant at $P < 0.01$ (two tailed); **correlation is significant at $P < 0.05$ (two tailed).

AFC and NSMJC (logarithmically transformed) and among AFC. Stepwise regression (probability of F, entry ≤ 0.05, removal ≥ 0.10) adds and removes indices to the regression model to identify a useful subset for predicting NSMJC (logarithmically transformed). ANOVA (F-test) was used to test the significance ($P < 0.05$) of the model.

Results

Hydrological status before and after TGP

Table 1 shows the hydrological status reported at four monitoring stations along the middle and lower Yangtze River before and after the commissioning of the TGP. The major changes following damming of the river were reductions in ASL and AASC. AR also declined, but the decrease was not significant. From Datong to Yichang, much closer to the TGP, the decrease in ASL and AASC was much greater.

Correlations of hydrological status with the number of captured juveniles

Table 2 shows the relationship of NSMJC in the Yangtze estuary with AFC of the Yangtze River in the preceding 3 years, from broodstock entering the Yangtze River to the offspring completing migration to the sea (Figure 1). The NSMJC showed positive correlation with AR, ASL, and AASC recorded at the four monitoring stations in the preceding 3 years. In addition to a significant positive correlation with Datong station AR, significant positive correlations were observed between NSMJC and ASL and AASC at the four stations. Significant correlations were seen in $C_{\text{F-J}}$, $C_{\text{S-J}}$, $C_{\text{FS-J}}$, and $C_{\text{ST-J}}$. Further analysis revealed that higher $C_{\text{S-J}}$ is the primary reason for increase in $C_{\text{FS-J}}$ and $C_{\text{ST-J}}$. In other words, the number of juveniles captured at the Yangtze estuary showed a positive correlation with ASL and AASC recorded at the four hydrological stations in the previous year; hence, higher ASL or AASC resulted in a greater number of juveniles in the Yangtze estuary in the following year.

Since AR, ASL, and AASC showed differing correlations with NSMJC, a correlation analysis was conducted to probe the relationships among hydrological parameters (Table 3). Results indicated that ASL was significantly correlated with AASC at the four stations. With the exception of AR and ASL in Datong, no significant correlation was observed between AR and ASL (AASC).

A stepwise regression analysis was conducted to determine the year in which the silt concentration was most highly related to NSMJC (Table 4). It is showed that under the criteria 'probability of F to enter ≤ 0.05', regression equations can be computed with the variable 'silt concentration'. Except at Shashi station, the silt concentration in the

Table 3 Pearson correlations of AR, ASL, and AASC

	Yichang			Shashi[a]			Hankou			Datong		
	AR	**ASL**	**AASC**	**AR**	**ASL**	**AASC**	**AR**	**ASL**	**AASC**	**AR**	**ASL**	**AASC**
AR	1			1			1			1		
ASL (*P*)	0.540 (0.107)	1		0.432 (0.285)	1		0.637* (0.048)	1		0.787** (0.007)	1	
AASC (*P*)	0.501 (0.140)	*0.995*** (0.000)	1	0.361 (0.380)	*0.996*** (0.000)	1	0.532 (0.113)	*0.988*** (0.000)	1	0.671* (0.034)	*0.983*** (0.000)	1

Correlations at four major hydrological monitoring stations in the middle and lower Yangtze River from 2000 to 2009. AASC, annual average sediment concentration; AR, annual runoff; ASL, annual sediment load. *Correlation is significant at $P < 0.05$ (two tailed); **correlation is significant at $P < 0.01$ (two tailed); [a]during 2002 to 2009.

Table 4 Stepwise regression analysis and number of *A. sinensis* juveniles (*J*)

Model[a]	*n*	Variables entered	Variables removed	Excluded variables	Regression equation	*R*	*P*
$R_{\text{YC-J}}$	8	$\text{AASC}_{\text{YC-S}}$		$\text{AASC}_{\text{YC-F}}$, $\text{AASC}_{\text{YC-T}}$	$\text{Lg}(J) = 1.346 + 2.105 \times \text{AASC}_{\text{YC-S}}$	0.919	0.001
$R_{\text{SS-J}}$	6	$\text{AASC}_{\text{SS-S}}$		$\text{AASC}_{\text{SS-F}}$, $\text{AASC}_{\text{SS-T}}$	$\text{Lg}(J) = 0.975 + 3.086 \times \text{AASC}_{\text{SS-S}}$	0.965	0.002
$R_{\text{HK-J}}$	8	$\text{AASC}_{\text{HK-F}}$		$\text{AASC}_{\text{HK-S}}$, $\text{AASC}_{\text{HK-T}}$	$\text{Lg}(J) = 0.851 + 3.985 \times \text{AASC}_{\text{HK-F}}$	0.865	0.006
$R_{\text{DT-J}}$	8	$\text{AASC}_{\text{DT-S}}$		$\text{AASC}_{\text{DT-F}}$, $\text{AASC}_{\text{DT-T}}$	$\text{Lg}(J) = 0.342 + 7.324 \times \text{AASC}_{\text{DT-S}}$	0.893	0.003

Stepwise regression analysis between annual average sediment concentration at four stations, and the number of *A. sinensis* juveniles (*J*) captured at the Yangtze estuary. AASC, annual average sediment concentration. Subscripts indicate stations (DT, Datong; HK, Hankou; SS, Shashi; YC, Yichang) and year (F, first; S, second; T, third). [a]Criteria: probability of *F* to enter ≤ 0.05, probability of *F* to remove ≥ 0.10.

preceding year seems to have the greatest impact, with a significant contribution to NSMJC. For the mean value of silt concentration of the four stations in the previous year ($\text{AASC}_{\text{Mean-S}}$), a regression analysis was conducted with NSMJC using the following equation: $\text{Lg (NSMJC)} = 0.870 + 3.930 \times \text{AASC}_{\text{Mean-S}}$ ($R = 0.940$, $P = 0.000$).

Discussions

This study shows that the number of *A. sinensis* captured at the estuary is closely correlated with the silt content of the middle and lower reaches of Yangtze River in the previous year. It may be that silt content affects the migration, refuge, and/or reproduction of adult fish or the hatching, survival, and/or growth of the eggs or larvae. Assessment by Yang et al. (unpublished data) of the breeding colony below Gezhouba Dam and the monitoring of juveniles reported by Li et al. (2011) showed that the size of the breeding colony in the spawning area below the Gezhouba Dam has a close positive correlation with the population of juveniles in the following year (Pearson correlation 0.965, *P* (two tailed) = 0.008). Capture of early life stages of the fish from the river bottom by D-nets also showed that when the number of adults entering the spawning area was fewer, the number of early life stages was also fewer (Wei et al. 2009). Accordingly, the number of juveniles that migrated to the Yangtze estuary in the subsequent year was also fewer. Thus, the number of juveniles is directly affected by the size of the breeding colony in the spawning area below the Gezhouba Dam in the previous year. We speculate that silt levels in the Yangtze River affected reproduction by mature fish as well the number of juveniles reaching the Yangtze estuary the following year. We have conducted studies on the relationship between sediments and gonadal development of the broodstock below Gezhouba Dam. The status of gonadal development of the broodstock was determined by ultrasonography and abdominal puncture methods, and the related hydrological elements (including sediment characteristics) were obtained from Yichang hydrological monitoring station. It showed that higher sediment concentration tended to correlate with better gonad development status (Zhang et al., unpublished data). This information will be issued in a report in the near future. However, currently, there is no direct evidence that silt content can affect the migration of the fish.

After the study on white sturgeon spawning habitat in an unregulated river, Perrin et al. (2003) hypothesize that reduced light attenuation due to turbidity may substantially influence habitat suitability for spawning within the range of available water depths and velocities. *A. sinensis* also exhibit a degree of active selectivity with respect to sediment concentration during natural reproduction (Yangtze Aquatic Resources Survey Group 1988; Wei 2003; Yang et al. 2007). The present study indicates that the AASC in the Yangtze River also has an impact on the breeding migration of *A. sinensis*. Results showed that (Wei et al. unpublished data), in years of lower sediment concentration, fewer reproducing individuals and more individuals with dysgenesis of the gonads were observed in the spawning area below the Gezhouba Dam in the breeding season. The sediments may serve to promote migratory behavior and gonadal development. Figure 3 shows annual average sediment concentration in the main stream of the Yangtze River and tributaries (Wen 1999; Yu and Lu 2005), from the estuary (Nanjing) to historic spawning areas (Yangtze Aquatic Resources Survey Group 1988; Wei et al. 1997). Upstream, in Yibin, sediment concentration was approximately 1.72 kg m^{-3}. The sediment increases along the river and reaches its highest concentration in the historic spawning areas. According to previous studies and recent catch data, stretches between Shashi and Yueyang, which have higher sediment concentrations than the downstream areas below Yueyang, are currently the main areas of habitation for *A. sinensis* broodstock during breeding migration (Yangtze Aquatic Resources Survey Group 1988; Wei et al., unpublished data).

From this analysis, we concluded that sediment may act as an important environmental factor influencing migration and reproduction of *A. sinensis.* The sediment concentration in the mainstream of the Yangtze River is higher than in its tributaries, with the exception of the Modaoxi, Hanjiang, and Jialing Rivers. The average runoff levels of the Modaoxi, Hanjiang, and Jialing were 1,710, 63, and 2,120 m^3 s^{-1}, respectively, compared with 13,900 m^3 s^{-1} (Yichang) for the Yangtze River (Wen 1999; Yu and Lu 2005). The Jinsha and Minjiang Rivers meet at Yibin. Although the average flow of the two rivers is similar (4,832 and 2,850 m^3 s^{-1}, respectively), the average sediment concentrations were 1.72 and 0.59 kg m^{-3}, respectively (Yu and Lu 2005) (Figure 3). This difference probably accounts for Chinese sturgeon migrating and breeding only along the Jinsha River, the main stream of Yangtze River.

This leads to the question of why *A. sinensis* historically breed in the Yangtze River in preference to the many Pacific west coast rivers (Figure 4). Research has shown that *A. sinensis* spawning requires a temperature range of 18°C to 20°C and sediment

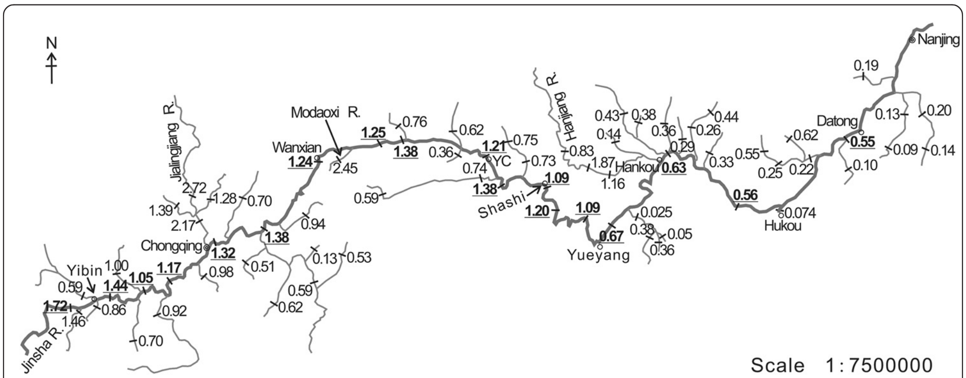

Figure 3 Annual average silt concentrations (kg m^{-3}). Concentrations in the main stream of the Yangtze River and its major tributaries in 1950 to 2000 (Wen 1999). Data in bold and without bold indicate the silt concentration in the main stream and in tributaries, respectively.

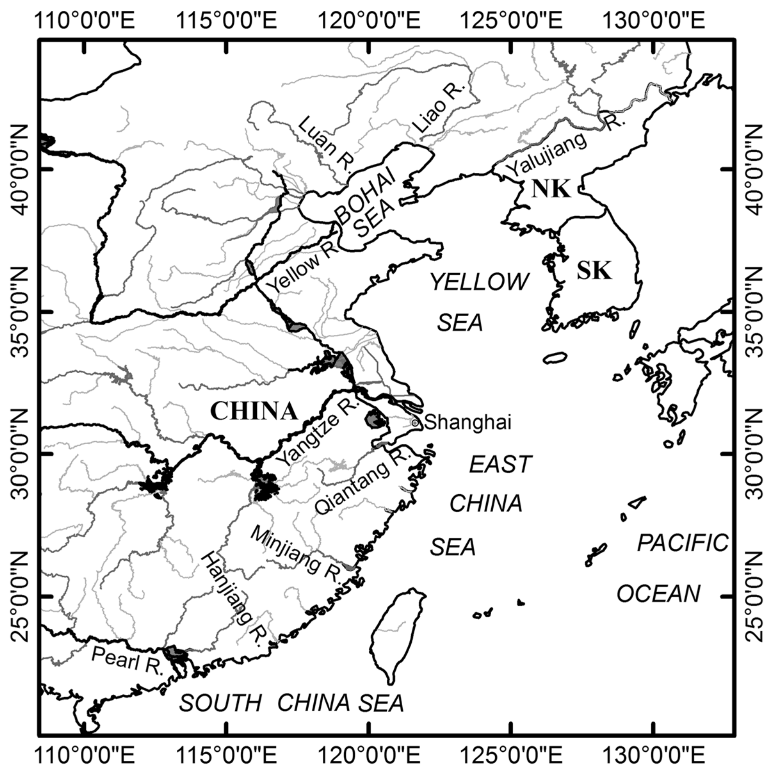

Figure 4 Distribution of major rivers flowing into the Western Pacific near the habitat of *A. sinensis*. Geographic data were from the National Fundamental Geographic Information System of China (1999). NK, North Korea; SK, South Korea.

concentration of 0.2 to 0.3 kg m^{-3} (Yang et al. 2007). *A. sinensis* has also been found in the lower Yellow River and in western North Korea (Yangtze Aquatic Resources Survey Group 1988), but the average temperature of the China offshore seabed in May (Su and Yuan 2005) suggests that the four rivers lying to the north of the Yellow River may not be suitable for *A. sinensis* breeding due to low water temperature or excessively high sediment concentration (Table 5). The Qiantang and Mingjiang Rivers, flowing into the East China Sea, have historically had a small *A. sinensis* population (Yangtze Aquatic Resources Survey Group 1988). The species has disappeared in this area, possibly be due to the small quantity of water and low sediment concentration. The Hanjiang River has higher sediment levels at 0.28 kg m^{-3} but insufficient quantities of water. The Pearl River, more similar in water quantity and sediment concentration to the Yangtze River, supports a larger *A. sinensis* population. Suspended sediment is gradually dispersed in a fan-shape pattern into the southern Yellow Sea and the East China Sea from the Yangtze estuary (Che et al. 2003; Liu et al. 2006; Shi 2010). The concentration gradient of suspended matter is likely the signal that guides the adult *A. sinensis* to the estuary entrance for breeding migration.

Breeding migration patterns of fish are the result of many factors, including history, environment, internal physiology, and heredity. Navigation is associated with the sun, moon, aurora borealis and aurora australis, and the geomagnetic field as well as with water flow, temperature, and chemistry and other environmental factors (Yin 1995). Research has indicated that some fish species respond to turbidity resulting from

Table 5 Annual runoff characteristics of rivers

Region	River	Annual runoff ($\times 10^8$ m^3)	Annual sediment load ($\times 10^4$ t)	Annual average sediment concentration (kg m^{-3})
Bohai Sea	Liaohe	86.98	1,849.17	2.13
	Luanhe	48.69	2,267.60	4.66
	Yellow	430.78	111,490.00	25.88
Yellow Sea	Yalujiang	251.34	195.34	0.08
East China Sea	Yangtze	9,322.67	46,144.00	0.49
	Qiantangjiang	342.39	436.84	0.13
	Minjiang	615.87	767.70	0.12
South China Sea	Hanjiang	258.78	718.72	0.28
	Pearl	3,550.32	8,053.25	0.23

Rivers flowing into the Western Pacific near the habitat of *A. sinensis* (Cheng and Zhao 1985). For the locations of the rivers, see Figure 4.

suspended silt during migration. Atlantic salmon (*Salmo salar*), white bass (*Morone chrysops*), and belligerent sculpin (*Megalocottus platycephalus laticeps*) avoid turbid water; common carp (*Cyprinus carpio*) and mudfish (*Parasilurus asotus*) behave in an opposite manner (Li 2001). *A. sinensis* possesses a variety of sensors such as those for vision, smell, and taste, and a lateral line system, which provide sensitivity to water sediment. It also possesses well developed pit organs. Studies have confirmed that pit organs can detect flow and pressure (Chai 2006). Studies have also shown that, prior to *A. sinensis* natural breeding activity, a gradual reduction in sediment must occur. *A. sinensis* will breed only when sediment concentration reaches suitable levels (Yangtze Aquatic Resources Survey Group 1988; Wei 2003; Yang et al. 2007). In addition, spawning has been shown to cease following the dramatic increase of sediment concentration resulting from flood water release (Wei 2003).

Since the operation of the TGP began in 2003, sediment concentration in the middle and lower reaches of the Yangtze River has been significantly reduced, it is reported that the AASC at Yichang station will decrease by 64.5 % in the next 20 years (Changjiang Water Resources Commission 1997). This study confirmed that sediment reduction has had adverse effects on the breeding migration of *A. sinensis*. In addition, there is concern over whether the drastic decline in silt concentration may also have an impact on mating and spawning behavior. In accordance with the existing research, sediment concentration, light conditions, and water depth interact in triggering spawning activity. Silt concentration directly influences illumination of the aquatic environment (Yangtze Aquatic Resources Survey Group 1988); hence, the potential negative impacts of low sediment concentration on *A. sinensis* spawning needs to be seriously considered.

Conclusions

The number of seaward migrating juveniles captured in the Yangtze estuary from 2002 to 2010 was significantly positively related to the annual sediment load and annual average sediment concentration of the previous year, when adults entered the river and migrated upstream, used refuge areas, and spawned, and when early life stages were reared. This suggests that silt content may have a major effect on adult spawning success and rearing of early life stages. Based on the correlation between numbers of juveniles captured and numbers of adults in the spawning areas in the previous year, we speculated that the sediment characteristics affected the migration and gonad development of mature individuals and, indirectly, the number of juveniles reaching the Yangtze estuary during the following year. Decreased silt levels in the Yangtze River following installation of the Three Gorges Project may be having a deleterious effect on Chinese sturgeon reproduction and needs further research.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
WGL and QWW conceived the project. CL and HZ designed the experiments. QWW and HZ performed the experiments. HZ and XSW drafted the manuscript. All authors read and approved the final manuscript.

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