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Impact of the Three Gorges Dam on the spawning stock and natural reproduction of Chinese sturgeon in the Changjiang River, China*

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Abstract Chinese sturgeon (*Acipenser sinensis*) is the flagship species of the Changjiang River. The migration route of this species is blocked by the first dam, the Gezhou Dam, and its reproduction is affected by the Three Gorges Dam (TGD), one of the largest dams in the world. We studied the impact of the impoundment of the Three Gorges Reservoir (TGR) since 2003 on the spawning stock and the natural reproduction of the Chinese sturgeon by using our monitoring data from 1997 to 2013. Results indicate that TGR impoundment has delayed the first spawning dates of the fish from middle-late October to late November, decreased the amount of spawning activities from twice to only once each year, and significantly reduced egg production. In particular, the fish did not demonstrate any spawning activities in 2013. Therefore, TGR impoundment significantly affects the natural reproduction of the fish downstream of the TGD. The spawning stock size of the fish is also predicted to further decrease in the future, which will lead to a risk of population extinction. Ecological regulations must be imposed on decreasing the water temperature to 20°C before mid-October and increasing water discharge downstream of the TGD in October to induce spawning of the Chinese sturgeon.

Keyword: Chinese sturgeon; Three Gorges Dam; spawning activity; spawning stock; conservation

1 INTRODUCTION

Worldwide, two-thirds of the rivers are now obstructed by more than 845 000 dams (Fuggle and Smith, 2000), while more than 50 000 of these dams are located in the Changjiang River basin in China (Yang et al., 2005). Although these dams provide services, such as electricity, flood control, increased navigation capabilities, irrigation, and water resources, they also impose significant negative consequences on the riverine ecosystem and biodiversity (New and Xie, 2008).

The Three Gorges Dam (TGD), one of the largest hydroelectric projects in the world, is located in Yichang City in the midstream part of the Changjiang River. The Three Gorges Reservoir (TGR) was first filled with water in 2003, and the water level then increased to 175 m above sea level (ASL) in 2009. The TGR inundates approximately 600 km of the river and reaches up to Chongqing where the water level is 175 m ASL. The TGR is normally regulated by decreasing the water level to 145 m ASL to prevent flooding in May and refilling the water level to 175 m ASL from October to December. The TGD may physically, chemically, and biologically alter the aquatic ecosystem of the Changjiang River and particularly affects fish reproduction (Wu et al., 2004; Duan et al., 2008; Hayashi et al., 2008; Zhu et al., 2008; Wang et al., 2009; Gao et al., 2010; Yi et al., 2010a, 2012).

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The Chinese sturgeon (*Acipenser sinensis*) is one of three native sturgeons in the Changjiang River, the other two being the Chinese paddlefish (*Psephuyrus gladius*) and the Changjiang sturgeon (*Acipenser dabryanus*). As an anadromous species, the Chinese sturgeon grows in the Yellow Sea, the East China Sea, and the South China Sea and migrates upstream for reproduction. This species features a long life span (more than 35 years), late sexual maturity (8–26 years), and a huge body size (4 m length) (Gao et al., 2009). Historical records show that the fish reproduce upstream of the Changjiang and Zhujiang Rivers. The population of Chinese sturgeon has been almost extirpated in the last decades in the Zhujiang River. In the Changjiang River, Chinese sturgeon spawned from Xinshi to Fuling and reached from 600 km to 800 km upstream of the Changjiang River in October and November before construction of the Gezhou Dam (GD) in 1981 (Anonymous, 1988) (Fig.1). The GD blocked the spawning migration route of Chinese sturgeon and remarkably reduced its population size as evidenced by the recently measured spawning area located 3 km downstream of the GD, which represents less than 1% of the original spawning site (Gao et al., 2009) (Fig.1). The population of Chinese sturgeon has continuously declined, and this species was classified as a critically endangered species in the International Union for Conservation of Nature Red List in 2010.

The Chinese sturgeon is predicted to further suffer from the impacts of the TGD. Gao et al. (2014) showed that TGR impoundment delayed the first spawning time of Chinese sturgeon because of water temperature lag associated with flow regulation. Gao et al. (2013) also suggested that water temperature, changes in day-to-day discharge, and atmospheric pressure are key spawning cues for Chinese sturgeon. Previous study has indicated that TGR impoundment changed the water temperature and discharge downstream of the dam in October to November (Xiao and Duan, 2011). Zhang et al. (2012) further reported that TGR impoundment decreased sediments downstream, which may negatively influence the reproduction of Chinese sturgeon below the GD and their growth during their early life stages. Nevertheless, comprehensive investigation on the impact of the TGD on Chinese sturgeon by using long-term data has not been performed.

To monitor and evaluate the impact of the TGD, we conducted surveys on the spawning activities of Chinese sturgeon on the spawning ground below the GD since 1997 (Fig.1). The surveys were conducted annually from October to December since 1997 and covered years before and after the first TGR impoundment in June 2003. This study aimed to evaluate the impact of the TGD on Chinese sturgeon by analyzing long-term monitoring data to provide recommendations on conservation of Chinese sturgeon.

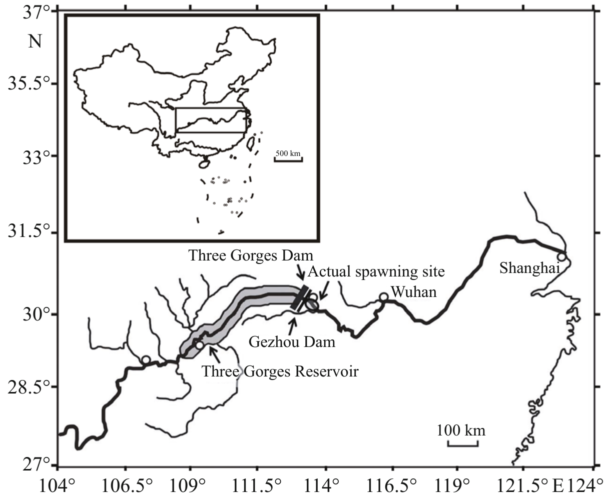

Fig.1 The location of the spawning site of the Chinese sturgeon below the Gezhou Dam

2 MATERIAL AND METHOD

2.1 Study area

Since the completion of GD construction in 1981, the reproductive migration route of Chinese sturgeon to the original spawning area in the upper Changjiang River and lower Jinsha River has been blocked. The spawning activities of Chinese sturgeon were then restricted to parts of the river below the GD. The current spawning ground of Chinese sturgeon is located within the reach approximately 3 km below the GD, itself within the middle reach of the Changjiang River (Fig.1) in Yichang City, 38 km downstream of the TGD. The topography of the spawning area is characterized by a rolling terrain, deep pools, steep slopes, and a rocky substrate (Zhang et al., 2011). The spawning stock of Chinese sturgeon usually accumulates around the spawning ground during the pre-spawning stage (Wang et al., 2012a). In 1996, the government of the Hubei Province established the Chinese Sturgeon Nature Reserve within the range of 80 km reach below the GD to conserve the natural reproduction of Chinese sturgeon. The 20-km reach downstream of the GD to Gulaobei is the core area of the natural reserve.

2.2 Hydroacoustic survey to estimate spawning stock size

We estimated the spawning stock size of Chinese sturgeon, or the number of mature Chinese sturgeon below the GD, through hydroacoustic detection. Hydroacoustic surveying was conducted before and after the spawning activities of Chinese sturgeon each year from 1998 to 2013. From 1998 to 2002, a Miriam FUSO-405 echo-sounder was used to collect acoustic data. During this period, hydroacoustic surveys were conducted mainly on the 3-km reach of the spawning ground below the GD. However, the device was broken and the hydroacoustic survey was not conducted in 2003. From 2004 to 2013, a Simrad EY60 echo-sounder with a composite 7° split-beam 200 kHz transducer was used for hydroacoustic surveying. A computer connected to a Garmin GPS controlled the echo-sounder and stored the data. Before surveying, the acoustic system was calibrated in situ with a standard 23 mm copper sphere [reference target strength (TS)=-40.4 dB at 1 490 m/s sound speed] (Foote et al., 1987). The survey mainly covered 16 km long reaches from below the GD to Aijiahe in the core area of the Chinese Sturgeon Natural Reserve. The transducer was mounted at a depth of 0.5 m on a rigid scaffold on the side of 10 m-long vessels that cruised at a speed of 10 km/h along zigzag transects. The transect length was 30–40 km. During the survey, the power of the General Purpose Transceiver unit was set to 240 W and the pulse duration was 64 µs. Acoustic data were analyzed with Sonar 5-Pro software version 5.9 (Balk and Lindem, 2004). The criteria used to extract individual sturgeon targets with the split-beam transducers were minimum and maximum returned pulse widths of 0.6–1.8 times higher than the transmitted pulse duration, a maximum gain compensation of 6 dB, and a maximum phase deviation of three-phase steps. The TS threshold was set to -45 dB in 40 log R time-varied-gain function. The main procedures to identify the echo-signals of Chinese sturgeon were referenced from Zhang et al. (2014). The accuracy for discriminating the echo-signals of Chinese sturgeon from those of other targets could reach 90.9% (Tao et al., 2009). The spawning stock size of Chinese sturgeon was estimated using the equations of Qiao et al. (2006). The spawning stock size before (1998–2002) and after (2004–2013) TGR impoundment was compared using the Mann-Whitney test to analyze changes.

2.3 Investigation on spawning time and dates

The spawning activities of Chinese sturgeon were investigated in October and November each year from 1997 to 2013 by finding the eggs of Chinese sturgeon in the stomach or intestine of benthic fishes (Deng et al., 1991). Benthic fishes, such as *Coreius guichenoti*, *Coreius heterodon*, and *Pelteobagrus vachelli*, intensely and immediately swallowed laid Chinese sturgeon eggs. We dissected the captured fishes and confirmed the spawning activity when sturgeon eggs were found in their stomach or intestine. Investigation on the spawning activity of Chinese sturgeon continued for about 27–61 d each year, and benthic fishes were collected from 2–6 fishing boats each day. These fishing boats were used to capture benthic fishes by placing gill nets in the spawning area from 1:00 A.M to 8:00 A.M. After we dissected the fishes and found the eggs of Chinese sturgeon in the stomach or intestine, the eggs were exenterated and counted. Spawning date was determined by observing the development phase of the undigested eggs (Deng et al., 1991). Those eggs had been eaten for only a short time and remained well-preserved. Therefore, we could almost estimate the spawning date fairly exactly because those eggs were not significantly affected in the stomach or intestine.

2.4 Estimating the quantity of eggs

The numbers of benthic fishes in the spawning ground were estimated through length-based cohort analysis (Jones, 1974, 1984). The quantity of eggs produced by Chinese sturgeon in the spawning ground was estimated based on the following formula:

$$N_e = \frac{\sum n_i \times E_i \times D}{P},$$

where N_e is the number of eggs spawned by Chinese sturgeon in the spawning ground below the GD each year, n_i is the number of the ith fish species in the spawning ground, E_i is the daily mean number of eggs eaten by each individual of the ith fish species, D is the number of the days during which the benthic fishes eat the Chinese sturgeon eggs, and P is the percentage of the eaten eggs to the produced eggs in the spawning ground. The quantity of eggs was compared before (1998–2002) and after (2004–2013) TGR impoundment and analyzed using the Mann-Whitney test. The relationship between the quantity of eggs and the number of spawning activities was estimated using Pearson's correction analysis.

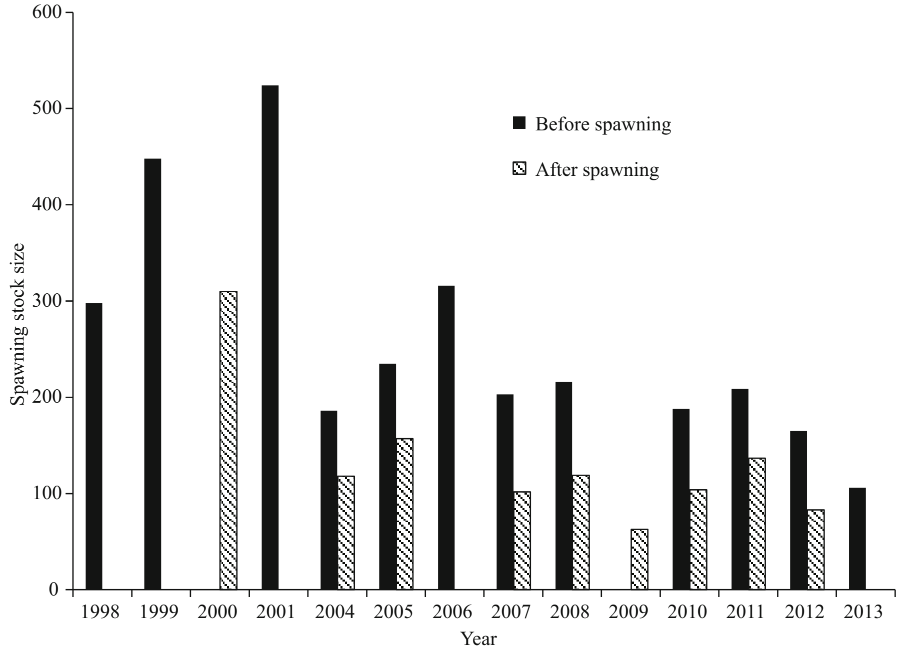

Fig.2 The spawning stock size of the Chinese sturgeon investigated by hydroacoustic survey below the Gezhou Dam from 1998 to 2013

The missing values were because the hydroacoustic survey did not catch the echo signal from the Chinese sturgeon.

The Mann-Whitney test and Pearson's correction analysis were performed using the "Past" software (Hammer et al., 2008).

3 RESULT

3.1 Spawning stock size

The spawning stock size of Chinese sturgeon significantly declined from 1998 to 2013 (Fig.2). Before TGR impoundment (1998–2002), hydroacoustic data showed that the number of adult Chinese sturgeons before spawning activities was approximately 298–524 individuals with a mean of 423±115. After TGR impoundment (2004–2013), the number decreased to 106–316 individuals with a mean of 203±56 (Mann-Whitney test, $P<0.05$). The mean number of adult sturgeons after spawning activities decreased by 64.4% after TGR impoundment compared with that before the impoundment.

3.2 Spawning times and dates

Before TGR impoundment, Chinese sturgeon performed two spawning activities each year from 1997 to 2002, except in 1998 when only one spawning activity was noted. After TGR impoundment, these sturgeons presented only one spawning activity each year from 2003 to 2011. However, two activities occurred in 2012 (Fig.3). Chinese sturgeon did not reproduce in the Changjiang River in 2013.

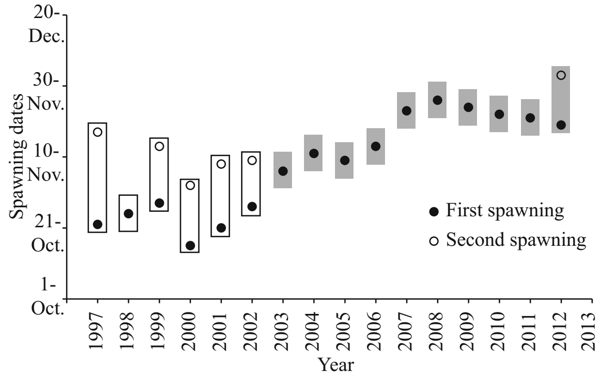

Fig.3 Time of the spawning activities of the Chinese sturgeon in the spawning site below the Gezhou Dam from 1997 to 2013

The first spawning dates ranged from October 16 to November 26. According to our data, the second spawning activities occurred from November 2 to December 3 from 1997 to 2002 (Fig.3). The first spawning dates of Chinese sturgeon was delayed from the middle-late period of October to the end of November (Fig.3), which is more than 1 month late.

3.3 Quantity of eggs

The quantity of Chinese sturgeon eggs were 15.0±11.1 million before TGR impoundment (1997–2002) and 4.4±2.9 million after TGR impoundment

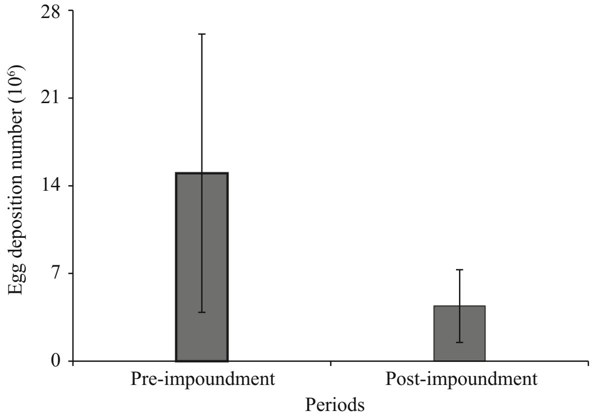

Fig.4 The quantity of the eggs produced by the Chinese sturgeon in the spawning site below the Gezhou Dam between pre- and post- impoundment of the Three Gorges Reservoir (mean±S.D.)

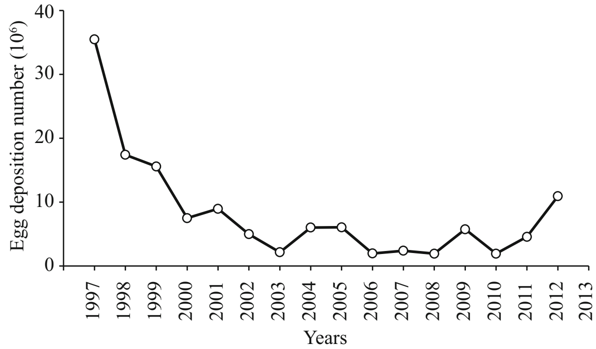

Fig.5 The quantity of the eggs produced by the Chinese sturgeon in the spawning site below the Gezhou Dam from 1997 to 2013

(2003–2013), which indicates a 70.8% decrease (Mann-Whitney test, $P<0.05$) (Fig.4). The maximum number of eggs was approximately 35.5 million in 1997. Approximately 2 million eggs were produced in 2003, 2006, 2008, and 2010 (Fig.5). The quantity of eggs was positively correlated with the number of spawning activities (Pearson's correction, $P<0.05$).

4 DISCUSSION

4.1 Impact on spawning stock size

The spawning stock size contained approximately 2 176 individuals, and the Chinese sturgeon was not influenced by the GD (Ke et al., 1992). Gao et al. (2009) estimated that the GD reduced the population size of Chinese sturgeon by 83%. Thus, after GD construction, the spawning stock size was approximately 370 individuals, which is similar to the annual mean of 423 individuals estimated by our hydroacoustic surveys between 1998 and 2002.

These results indicate that the spawning stock of Chinese sturgeon significantly declined after the TGR impoundment. As the Chinese sturgeon manifests late maturity at 8–26 years old, the sturgeons that spawned during 2003 to 2013 had been hatched before the TGR impoundment in 2003; thus, the impact will be observed 10–15 years after the impoundment, when the sturgeons hatched after the TGR impoundment are recruited to the spawning stock.

4.2 Impact on spawning times and dates

The spawning activities of Chinese sturgeon evidently changed after the impoundment. First, the first spawning dates were delayed after the TGR impoundment. Our monitoring data show that the first spawning activities occurred from October 16 to October 28 before the TGR impoundment (1997–2002). In the 1960s to 1990s, the first spawning activities were found to have occurred from October 12 to November 7 (Anonymous, 1988; Wei, 2003). After the TGR impoundment, the Chinese sturgeon reproduced in late November. The spawning dates have been delayed for more than 1 month. The suggests that the optimal spawning water temperature range for Chinese sturgeon is 17°C to 20°C (Chen, 2004). The dates when the water temperature reaches 20°C and the mean discharge in October were significantly correlated with the first spawning dates of the Chinese sturgeon (Gao et al., 2014). As the TGR impoundment induced a water temperature lag and reduced water discharge in October (Gao et al., 2014), this process may have delayed the spawning time of the Chinese sturgeon at the spawning ground below the GD.

Second, the amount of spawning activities reduced after the impoundment, which could be related to changes in environmental conditions. Water temperature, day-to-day discharge change, and atmospheric pressure are the key spawning cues for the Chinese sturgeon (Gao et al., 2013). After the TGR impoundment, hydrological conditions, such as water temperature and discharge below the GD, evidently changed (Xiao and Duan, 2011); these changes may be responsible for the reduced spawning times of the Chinese sturgeon. Changes in the spawning activities could furthermore have influenced the survival of the Chinese sturgeon juveniles and decreased the quantity of eggs produced, leading to a knock-on further decrease in recruitment to the population in the future.

A worst case occurred in 2013, in which the reproduction of the Chinese sturgeon was stopped, indicating that current conservation measures cannot sustain the population of Chinese sturgeon. Artificial restocking and releasing contributed to approximately 10% of the recruitment (Institute of Hydrobiology, unpublished data). In cases when natural reproduction is completely inhibited, the species would become extinct because no recruitment would then occur in the future.

4.3 Impact on the quantity of eggs

The environmental conditions of the spawning ground of the Chinese sturgeon, fast-flowing, turbid, and with rock and gravel (Zhang et al., 2009; Wang et al., 2012b), make field observation to count the eggs scattered on the river bottom almost impossible. Under these conditions, investigation for the eggs in the alimentary canal of the benthic fishes offered the only feasible approach to estimate the quantity of the eggs. The results of these estimates should be considered with caution due to potential biases in the estimates. However, our results provided important information to understand the reproductive situation of the Chinese sturgeon, especially trends on the response of the egg amount to changes in the environment.

The quantity of eggs produced by Chinese sturgeon in the spawning ground below the GD sharply declined from 1997 to 2012. This decrease could be attributed to the following: reduction in the amount of spawning activity and shrinkage of the spawning area below the GD. Little information is available with regard to the physical and geographical features of the spawning ground (Du et al., 2011; Wang et al., 2012b). However, sediment concentrations in October and November significantly declined after TGR impoundment (Xiao and Duan, 2011). Therefore, we have suggested that the TGR impoundment may be responsible for this reduction in spawning area. Moreover, other human activities also may have contributed to the shrinkage of the spawning area. For instance, the construction of the separation levee project in the spawning ground reduced the weighted usable area (WUA) for the Chinese sturgeon spawning (Wang et al., 2011).

After GD construction, the spawning area could have a capacity for approximately 24.4 million eggs produced from each spawning activity (Chang, 1999). However, the present results indicated that an annual mean of only 4.4 million eggs were produced after the TGR impoundment. Therefore, we have provided a rough and simple assessment for the spawning stock size, which could reduce to

$$\left(\frac{\text{Quantity of eggs produced after GD construction}}{\text{Quantity of eggs produced before TGR impoundment}}\right) \times \begin{array}{c}\text{Spawning stock}\\ \text{size after TGR}\\ \text{impoundment}\end{array} = \left(\frac{4.4}{24.4}\right) \times 423 = 76 \cdot$$

Chinese sturgeon individuals in the future, leading to a risk of population extinction. The results of our hydroacoustic detection also indicate that the number of the Chinese sturgeon adults in the spawning stock has declined to 106 in 2013, which corresponded to the anticipated spawning stock size.

5 CONCLUSION

The TGR impoundment has significantly influenced the natural reproduction of Chinese sturgeon in the spawning ground below the GD. We predict that the spawning stock size of Chinese sturgeon will gradually decline in the future, leading to a high risk of population extinction. Moreover, if natural reproduction stops, this species would become extinct. Previous studies showed that environmental conditions, such as water temperature, discharge, and atmospheric pressure, significantly affect the spawning success of the Chinese sturgeon (Yi et al., 2010b; Gao et al., 2013, 2014). Therefore, ecological regulations must be imposed to induce spawning. First, the water temperature downstream of the TGD should be decreased to lower than 20°C before mid-October, and the period should be expanded within which the water temperature ranges from 17°C to 20°C. Second, water discharge downstream should be enhanced in October. Third, flow regulation should be carried out to create a day-to-day intermittent increase in the discharge when the water temperature is lower than 20°C and at the low atmospheric pressure nights.

References

Anonymous. 1988. The Biology of the Sturgeon in Yangtze and Their Artificial Propagation. Sichuan Scientific and Technical Publishing House, Chengdu, China. (in Chinese)

Balk H, Lindem T. 2004. Sonar4 and Sonar5-Pro Post Processing Systems, Operator Manual v5.9.4. University of Oslo, Oslo, Norway. 405p.

Chang J. 1999. Structure and Dynamics of the Spawning Stock of Chinese Sturgeon, *Acipenser sinensis*, in the Yangtze River. Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China. (in Chinese)

Chen X H. 2004. Studies on the Developments of Embryo and Gonad at Early Stages of Chinese Sturgeon, *Acipenser sinensis*. Sun Yat-Sen University, Guangzhou, China. p.130. (in Chinese)

Deng Z L, Xu Y G, Zhao Y. 1991. Analysis on *Acipenser sinensis* spawning ground and spawning scales below Gezhouba hydroelectric dam by the means of examining the digestive contents of benthic fishes. *In*: Williot P ed. Acipenser. Cemagref Publ., Bordeaux. p.243-250.

Du H, Wei Q W, Zhang H, Liu Z, Wang C, Li Y. 2011. Bottom substrate attributes relative to bedform morphology of spawning site of Chinese sturgeon *Acipenser sinensis* below the Gezhouba dam. *Journal of Applied Ichthyology*, **27**(2): 257-262.

Duan S W, Liang T, Zhang S, Wang L J, Zhang X M, Chen X B. 2008. Seasonal changes in nitrogen and phosphorus transport in the lower Changjiang River before the construction of the Three Gorges Dam. *Estuarine*, *Coastal and Shelf Science*, **79**(2): 239-250.

Foote K G, Knudsen H P, Vestnes G, MacLennan D N, Simmonds E J. 1987. Calibration of acoustics instruments for fish density estimation: a practical guide. ICES, Copenhagen. 69p.

Fuggle R, Smith W T. 2000. Experience with dams in water and energy resource development in the People's Republic of China. World Commission on Dams, Country Review Paper.

Gao X, Brosse S, Chen Y B, Lek S, Chang J B. 2009. Effects of damming on population sustainability of Chinese sturgeon, *Acipenser sinensis*: evaluation of optimal conservation measures. *Environmental Biology of Fishes*, **86**(2): 325-336.

Gao X, Li M Z, Lin P C, Duan Z H, Liu H Z. 2013. Environmental cues for natural reproduction of the Chinese sturgeon, *Acipenser sinensis* Gray, 1835, in the Yangtze River, China. *Journal of Applied Ichthyology*, **29**(6): 1 389-1 394.

Gao X, Lin P C, Li M Z, Duan Z H, Liu H Z. 2014. Effects of water temperature and discharge on natural reproduction time of the Chinese Sturgeon, *Acipenser sinensis*, in the Yangtze River, China and impacts of the impoundment of the Three Gorges Reservoir. *Zoological Science*, **31**(5): 274-278.

Gao X, Zeng Y, Wang J W, Liu H Z. 2010. Immediate impacts of the second impoundment on fish communities in the Three Gorges Reservoir. *Environmental Biology of Fishes*, **87**(2): 163-173.

Hammer Ø, Harper D A T, Ryan P D. 2008. PAST: Paleontological Statistics, ver.1.81. Paleontological Museum, University of Oslo, Noruega, Also available on line: http://folk.uio.no/ohammer/past/index.html.

Hayashi S, Murakami S, Xu K Q, Watanabe M. 2008. Effect of the Three Gorges Dam Project on flood control in the Dongting Lake area, China, in a 1998-type flood. *Journal of Hydro-Environment Research*, **2**(3): 148-163.

Jones B W. 1974. World resources of hakes of the genus *Merlucius*. *In*: Jones F R H ed. Sea Fisheries Research. Paul Elek (Scientific Books) Ltd., London. p.139-166.

Jones R. 1984. Assessing the effects of changes in exploitation pattern using length composition data (with notes on VPA and cohort analysis). FAO Fish. Tech. Pap. No. 256. 118p.

Ke F E, Wei Q W, Zhang G, Hu D, Luo J, Zhuang P. 1992. Investigations on the structure of spawning population of Chinese sturgeon (*Acipenser Sinensis* Gray) and the estimate of its stock. *Freshwater Fisheries*, (4): 7-11. (in Chinese)

New T, Xie Z Q. 2008. Impacts of large dams on riparian vegetation: applying global experience to the case of China's Three Gorges Dam. *Biodiversity and Conservation*, **17**(13): 3 149-3 163.

Qiao Y, Tang X, Brosse S, Chang J. 2006. Chinese sturgeon (*Acipenser sinensis*) in the Yangtze River: a hydroacoustic assessment of fish location and abundance on the last spawning ground. *Journal of Applied Ichthyology*, **22**(S1): 140-144.

Tao J P, Qiao Y, Tan X C, Chang J B. 2009. Species identification of Chinese sturgeon using acoustic descriptors and ascertaining their spatial distribution in the spawning ground of Gezhouba Dam. *Chinese Science Bulletin*, **54**(21): 3 972-3 980.

Wang C Y, Wei Q W, Kynard B, Du H, Zhang H. 2012a. Migrations and movements of adult Chinese sturgeon *Acipenser sinensis* in the Yangtze River, China. *Journal of Fish Biology*, **81**(2): 696-713.

Wang J X, Bi Y H, Pfister G, Henkelmann B, Zhu K X, Schramm K W. 2009. Determination of PAH, PCB, and OCP in water from the Three Gorges Reservoir accumulated by semipermeable membrane devices (SPMD). *Chemosphere*, **75**(8): 1 119-1 127.

Wang Y K, Xia Z Q, Wang D. 2011. Assessing the effect of Separation Levee Project on Chinese sturgeon (*Acipensor sinensis*) spawning habitat suitability in Yangtze River, China. *Aquatic Ecology*, **45**(2): 255-266.

Wang Y K, Xia Z Q, Wang D. 2012b. Characterization of hydraulic suitability of Chinese sturgeon (*Acipenser sinensis*) spawning habitat in the Yangtze River. *Hydrological Processes*, **26**(23): 3 489-3 498.

Wei Q W. 2003. Reproductive behavioral ecology of Chinese sturgeon (*Acipenser sinensis*) with its stock assessment. Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China. (in Chinese)

Wu J G, Huang J H, Han X G, Gao X M, He F L, Jiang M X, Jiang Z G, Primack R B, Shen Z H. 2004. The three gorges dam: an ecological perspective. *Frontiers in Ecology and the Environment*, **2**(5): 241-248.

Xiao H, Duan Z H. 2011. Hydrological and water chemical factors in the Yichang reach of the Yangtze River pre-and post-impoundment of the Three Gorges Reservoir: consequences for the Chinese sturgeon *Acipenser sinensis* spawning population (a perspective). *Journal of Applied Ichthyology*, **27**(2): 387-393.

Yang S L, Zhang J, Zhu J, Smith J P, Dai S B, Gao A, Li P. 2005. Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response. *Journal of Geophysical Research*: *Earth Surface* (*2003-2012*), **110**(F3): F03006.

Yang S R, Gao X, Li M Z, Ma B S, Liu H Z. 2012. Interannual variations of the fish assemblage in the transitional zone of the Three Gorges Reservoir: persistence and stability. *Environmental Biology of Fishes*, **93**(2): 295-304.

Yi Y J, Wang Z Y, Yang Z F. 2010a. Impact of the Gezhouba and Three Gorges Dams on habitat suitability of carps in the Yangtze River. *Journal of Hydrology*, **387**(3-4): 283-291.

Yi Y J, Wang Z Y, Yang Z F. 2010b. Two-dimensional habitat modeling of Chinese sturgeon spawning sites. *Ecological Modelling*, **221**(5): 864-875.

Zhang H, Wang C Y, Yang D G, Du H, Wei Q W, Kang M. 2011. Spatial distribution and habitat choice of adult Chinese sturgeon (*Acipenser sinensis* Gray, 1835) downstream of Gezhouba Dam, Yangtze River, China. *Journal of Applied Ichthyology*, **30**(6): 1 483-1 491.

Zhang H, Wei Q W, Du H. 2009. A bedform morphology hypothesis for spawning areas of Chinese sturgeon. *Environmental Biology of Fishes*, **84**(2): 199-208.

Zhang H, Wei Q W, Kyanrd B E, Du H, Yang D G, Chen X H. 2011. Spatial structure and bottom characteristics of the only remaining spawning area of Chinese sturgeon in the Yangtze River. *Journal Applied Ichthyology*, **27**(2): 251-256.

Zhang H, Wei Q W, Li C, Du H, Liao W G. 2012. Effects of high water level on the river residence period of juvenile Chinese sturgeon *Acipenser sinensis* in the Yangtze River. *Knowledge & Management of Aquatic Ecosystems*, **405**(2): 02p1-02p14.

Zhu H M, Xiang S, Yang K, Wu X H, Zhou X N. 2008. Three Gorges Dam and its impact on the potential transmission of schistosomiasis in regions along the Yangtze River. *Ecohealth*, **5**(2): 137-148.