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Bottom substrate attributes relative to bedform morphology of spawning site of Chinese sturgeon *Acipenser sinensis* below the Gezhouba dam

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Summary

Characteristics of bottom substrates have caused wide concernas to their importance for sturgeon spawning ground requirements. Substrate requirements for spawning of Chinese sturgeon *Acipenser sinensis* have not yet been well studied because of the difficulties in investigating on a large and fast flowing river such as the Yangtze River. During 2007 and 2008, the underwater video surveys on the present spawning ground of *A. sinensis* were successfully conducted. Two kinds of substrates were documented: one stable infrastructure consisting of large boulders and cobbles mixed with pebbles and gravels, the other comprise sediments in transportation, especially coarse and fine sands. The large boulders (size range 20–50 cm), cobbles and pebbles (size range 10–20 cm), pebbles or gravels are estimated to account for 50, 30, 20% of the available substrates of the infrastructure on spawning ground according to our underwater video survey points, respectively. The transporting sands can be observed in most area, while the river sand embedded or covered the large structural compounds just occur in certain area and the substrate where spawning occurs annually and occasionally were similarly 'clean' of fine sediment. The eggs (embryos) of Chinese sturgeon have been observed 'hiding' in or adhering to the interstitial spaces between the clean large materials e.g. boulders, cobbles and pebbles during the 2007/2008 study period. Therefore the degree of cover of the larger particles by sand (embeddedness), which will directly affect the spawning habitat and subsequently influence survival of the new hatched larvae, were assessed by determining the topographic data in relation to water velocity. The multivariable correlation analysis and binary logistic regression analysis showed that the comparably topographic characteristics which had been confirmed to be suitable at the historic and present spawning sites would eventually contribute to the substrate deposition. The embeddedness of the sediment are obviously lower in shallow water with higher water velocity than in the deeper water with slower water current ($P < 0.01$) and the sites where the embryo occur can be predicted with the three physical variables: embeddedness of the sediment, water velocity and river bottom elevation. The bedform morphology with an adverse slope (channel slope adverse to the bottom elevation grads) formed by larger blocks of substrate, will improve the water turbulence at high current to carry the suspended or embedded fine sediments away from the spawning site and (in turn) provide enough interstitial spaces for effective egg deposition and incubation. Therefore the substrate requirements for the spawning habitat of Chinese sturgeon should be described and assessed more than just rocky and gravelly substrate, taking the embeddedness of sediment in well consider. The concepts of detailed description of the substrate requirements and their relationship with the overall bedform morphology has been shown to be essential to provide benefit for the rehabilitation of the spawning ground while fostering the conservation of the endangered species.

Introduction

Characteristics of bottom substrates have caused wide concern as to their importance for spawning ground requirements of sturgeons. Bemis and Kynard (1997) considered rocky substrate together with a moderate water velocity as the two important physical components characterizing a spawning habitat. Bedrock, boulder, gravel, cobble and coal cinder have been described as the preferred spawning substrate for sturgeons such as the lake sturgeon *Acipenser fulvescens* (Bruch and Binkowski, 2002; Caswell et al., 2004; Manny and Kennedy, 2002), white sturgeon *A. transmontanus* (Mcadam et al., 2005; McDonald et al., 2006), shortnose sturgeon *A. brevirostrum* (Arndt et al., 2006) and gulf sturgeon *A. oxyrinchus desotoi* (Sulak and Clugston, 1999), but some authors also mentioned spawning on clay (Arndt et al., 2006). Survival rates of the adhesive embryos on the river bottom are known to be best on the relatively 'clean' substrate (Manny and Kennedy, 2002). Therefore, it is important to understand how such clean substrate is formed and maintained in rivers while transporting sediments including the suspended and embedded fine sands and silts. Such scenarios are well studied for substrate requirements of salmond species (Barlaup et al., 2008; Soulsbya et al., 2001). Excessive sediment had caused the decline of the recruitment of white sturgeon (Mcadam et al., 2005). McDonald et al. (2006) had provided also a good example of a study on modeling hydraulics and subsequent sediment transport processes on white sturgeon spawning habitats on the Kootenai River to assess the potential capacity of the spawning habitat.

As a large anadromous species, the Chinese sturgeon (*Acipenser sinensis*) would migrate more than 2000 km to the upper Yangtze River for spawning, where the suitable substrates were inferred from geoscience knowledge of the Yangtze River as being rocky and gravelly (Wei et al., 1997; Yangtze Aquatic Resources Survey Group (YARSG) (1988). The same substrate characteristics were also identified as key elements of the spawning site formed on a 7 km long stretch downstream the Gezhouba dam (Hu et al., 1983). The dam

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blocks the migration route of the Chinese sturgeon to the historically known spawning sites. However, detailed substrate characteristics such as suspended and embedded sediments (fine sands, clay), which are important constituents of the bottom substrates, have seldom been considered but will essentially affect the quality of the microhabitat for spawning success. These factors were largely ignored in the past and scarcely considered in the previous studies because of methodological difficulties in investigating such detailed infrastructure on a large and fast flowing river such as the Yangtze River. In 2007, the first observations of the spawning ground using an underwater camera was conducted successfully, which improve our understanding of the substrates (Arndt et al., 2006; Du et al., 2008; Manny and Kennedy, 2002). From the seven spawning areas of the Chinese sturgeon (five historic and two recent), the comparability of the topographic characteristics have been identified with the turning structure and the adverse slope (Zhang et al., 2009). Therefore we hypothesize that the specific bedform morphology will relate to not only hydraulic and sediment transport characteristics, but will finally determine the spawning substrate requirements for Chinese sturgeon. Therefore, several study objectives need to be answered: (i) what are the detailed and specific characteristics of the bottom substrate at the presently used downstream spawning habitat? (ii) to what extent do the fertilized eggs spawned on this substrate depend on the rocky and gravely infrastructure? and (iii) what bedform morphology is needed for successful spawning and egg survival? To answer these questions, we investigated the present spawning ground using underwater video technology and tried to provide a dataset on the relationship between substrate attributes, hydraulic environment and bedform morphology. The results may be considered beneficial for conservation and rehabilitation measures on the spawning habitat for this endangered species.

Materials and methods

Study area

Historic spawning areas of *A. sinensis* were located in the mainstream of the lower Jingsha River and the upper Yangtze river, covering a stretch of about river 600 km (Fig. 1) Yangtze Aquatic Resources Survey Group (YARSG) (1988). After the construction of the Gezhouba dam, the present spawning ground was formed just downstream the Gezhouba dam, which is about 7 km long (Hu et al., 1983; Wei et al., 1997). In order to describe the substrate and topographic characteristics with geographic position clearly, we divide the present spawning ground into several zones according to the fixed references along the river bank (e.g. hill, wharf) and the construction of the Gezhouba dam (Fig. 1). The spawning ground has an about 90° turning structure within the 7 km stretch of the river and water mostly come from the Dajiang power plant, the Erjiang water relief sluice and the Erjiang power plant (Fig. 1). From 2003 onward, the Three Gorge Power station started to display function and the water in the Three Gorge reservoirs became more transparent with 1.5 m transparency in autumn which is more than ever before. This make it possible to investigate the 38 km downstream spawning ground of Chinese sturgeon using the underwater camera equipment (Du et al., 2008).

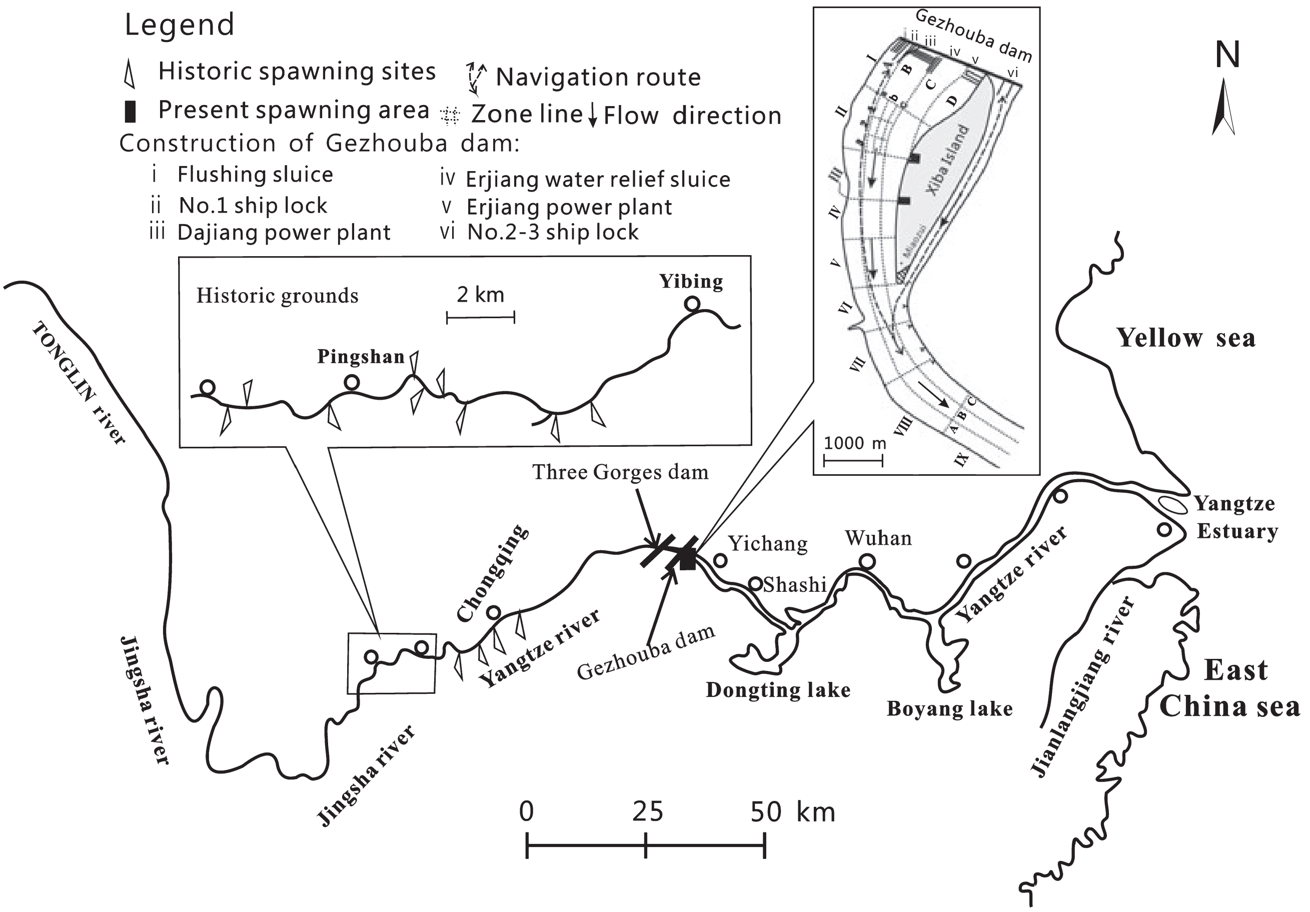

Fig. 1. Location of the historic and actual spawning sites of Chinese sturgeon in the Yangtze River

Bottom substrate surveys

Bottom substrate surveys on the present spawning sites of Chinese sturgeon below the Gezhouba dam were conducted with an underwater camera within 4 days after the spawning of Chinese sturgeon occurred. The discharge level of the spawning ground when video footage was collected was average 6880 $m^3 s^{-1}$ in 2007 and 8992 $m^3 s^{-1}$ in 2008, respectively. Bottom substrates were measured and photographed with a 640*480 resolution camera (Nikon IXY 600®; Japan) in an underwater kit and light was supplied with an adjustable deep-sea search light (RJW7100®; Shengzhen, China). The underwater kit was fixed on a self-designed stainless steel cage and then hung on steel wires of a hydrographic winch about 1 m higher than a 50 kg torpedo sinker at the end. The video records were firstly designed with 30 transects, using 5–8 sample points along each of transects within the 7 km reach downstream the Gezhouba dam and finally depended on control of the vessel. Every recording took nearly 15 min video film at each surveying point and the exact position of the surveying points was located with a Garmin GPS 60s receiver (Garmin Ltd.). Extensive video samples were set at the position where eggs of Chinese sturgeon were detected and collected using a D-shape bottom drift net after known spawning events (Wei et al., 2009). The sizes of bottom substrates were evaluated by using a close up focus of the camera and an appropriate screen size. The sampling was also assisted by the waterway cleaning-up project for navigation.

Topography and water velocity investigate

Topographic data and water velocity on the spawning ground were determined within 1 day using an echo sounder (HD-17A®; Hi-Target Surveying Instrument Co., Ltd., China) and an ADCP transducer (RDI-600®; RD Instrument) mounted from the bow of a boat and the investigations were conducted for several times during the spawning season.

The boat was controlled along the planed transects with a real-time navigation system of a SF-2050G DGPS as receiver (Navcom Technology, Inc.,) using also a navigation software (South Surveying & Mapping Instrument Co., Ltd., China) during all the surveys. The distance between the planed transects during the investigation of topography data and water velocity is 50–80 and 200–300 m respectively. Boat speeds typically averaged around 2 m per s for a survey, generally with lower speeds in shallow or slow water.

Data analyze

The substrate attributes were described following the method summarized by Bain and Stevenson (1999). With our concern on the sediment transportation, we tried to measure the extent to which interstitial spaces between coarse substrate particles were filled with fine material. So, the 'embeddedness' was used as a substrate attribute reflecting the degree (percentage) of coverage by vision to which larger particles (larger than 10 mm, such as boulder, cobble, pebble, and large gravel) are surrounded or covered by small sediment particles (smaller than 10 mm, such as sand, silt, or clay) following the qualitative assessment method summarized by Bain and Stevenson (1999).

The topography data collected at discharge level of 1500 $m^3 s^{-1}$ were imported into ArcGIS 9.2 software (Environmental Systems Research Institute, Inc.,) and the riverbed surface were interpolated using Inverse Distance Weighted scheme with grid size of 5 m as mentioned by Zhang (Zhang et al., 2009). Channel slope and channel aspect were consequently analyzed and extracted value to the underwater video surveying points for statistical analysis.

Acoustic doppler current profiler (ADCP) data sets contain velocity values in ensembles (vertical sets of bins through the water column). Depth-averaged values of the water velocity collected at the discharge of 8500 $m^3 s^{-1}$ for each ensemble, as computed from the bin values every 10 intervals, were used for generating the two-dimensional velocity arrows in ArcGIS 9.2 software (ESRI Inc.,).

The interrelation between the physical variables (embeddedness, elevation, velocity, channel slope and channel aspect) of each underwater survey points was calculated with Spearman correlation analysis by the statistical software SPSS 13.0 and a binary logistic regression analysis was also performed in order to understand whether the physical variables can predict where embryos occur in the river.

Results

Totally 113 underwater video points (53 in 2007 and 60 in 2008) were sampled and analyzed as shown in Fig. 2, presenting also the 'embeddedness' points (Fig. 2b).

Underwater video observations showed that the river bed infrastructure of the entire spawning site wasdominant boulders (range 20–50 cm long diameter) accounting for nearly 50% of the bottom surface, while cobbles and pebbles were subdominant (range 10–20 cm in long diameter) accounting for 30% while the remainder were smaller pebble or gravel (< 10 cm in long diameter). With the sediment transporting, the river bed infrastructure were either exposed, embedded or buried by the sand or clay at different points. The suspended materials (fast moving sand or clay) were observed mostly at the surveying points (nearly 84.1%), while the embedded sediments (coarse or fine sand) were often observed in the deeper areas (Figs 2b and 3d). As shown in the Figs (2b,c and 3d), the higher embeddedness (30–70%) was mainly in the V-VII area, where elevation and water velocity are both lower than in the other areas.

Spawning occurred in 2007 and 2008 were confirmed by the video samples (Figs 2a and 3a,b) while the embryos of Chinese sturgeon deposited in or adhered to the interstitial spaces between the larger particles (boulder, cobble and pebble) were clearly observed (Fig. 3a,b). In 2007, spawning occurred at the site (IV–V area) as it happened annually before from 1981 to 2006, while it ceased in 2008 and occurred in area I with an absolutely low scale (Fig. 2a).

Important evidences were found that the interstitial spaces where the eggs were deposited were very clean (no fine particles) and depth average water velocities were higher (1.5–2.2 $m s^{-1}$) (Fig. 2c) than in nearby areas (1.0–1.3 $m s^{-1}$). The areas IV_1B–V_1B, where spawning usually occurred in past years were similarly 'clean' with no embedded sediments found in 2007 or 2008 (Figs 2b and 3a,b) and the $I_{2–3}C$ area, where spawning happened in 2008, was also 'clean' with an 'embeddedness' < 5% and especially embedded with coarse sands with a particle size of about 5–10 mm diameter.

Interrelation analysis between the physical parameters (embeddedness, elevation, velocity, channel aspect andchannel slope) showed that the embeddedness of the underwater survey video points was obviously negative to its elevation and water velocity ($P < 0.01$) (Table 1). That means the embeddedness of the sediment on the bottom is lower in shallow water with

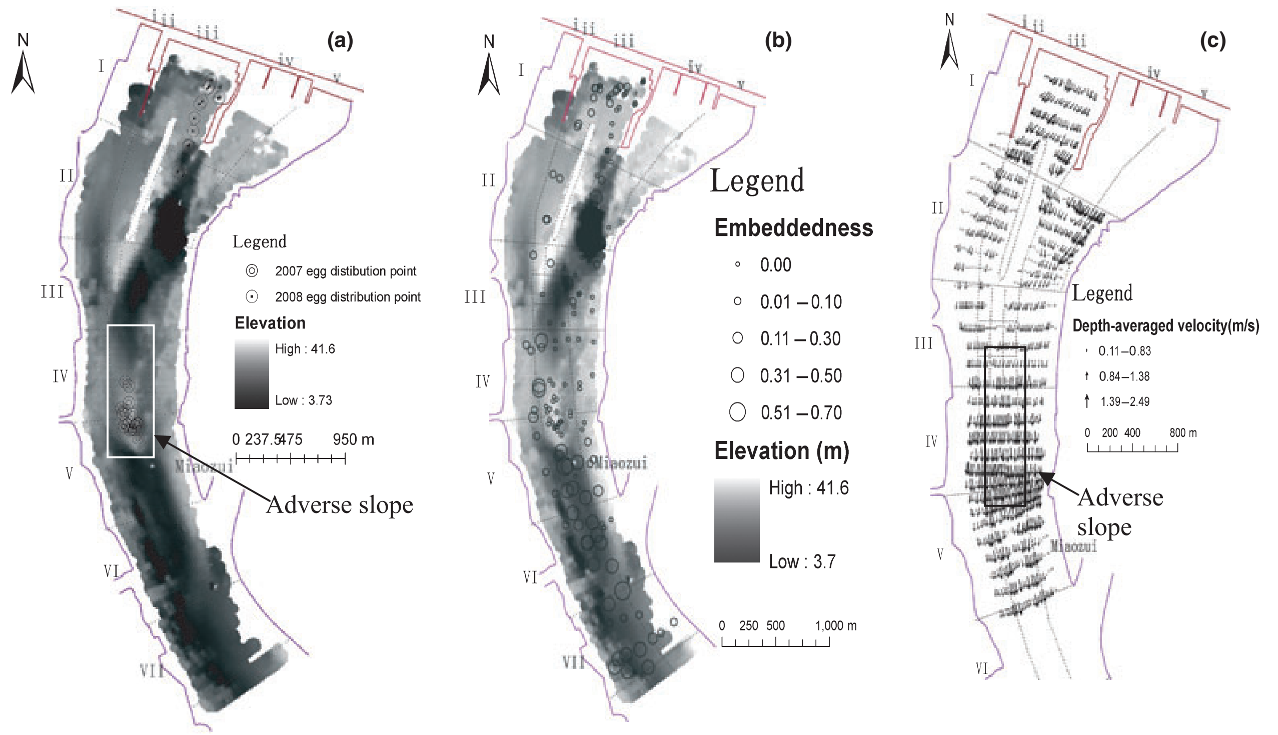

Fig. 2. Topography of the present spawning site of Chinese sturgeon below the Gezhouba dam with relative distribution of fertilized eggs (a), 'embeddedness' of the sediments (b) and the depth-averaged velocity (c) investigated in 2007 and 2008 biennium monitoring. The discharge levelsat the respective elevations are given and water velocitiesat those times were 15 000 and 8500 $m^3 s^{-1}$, respectively

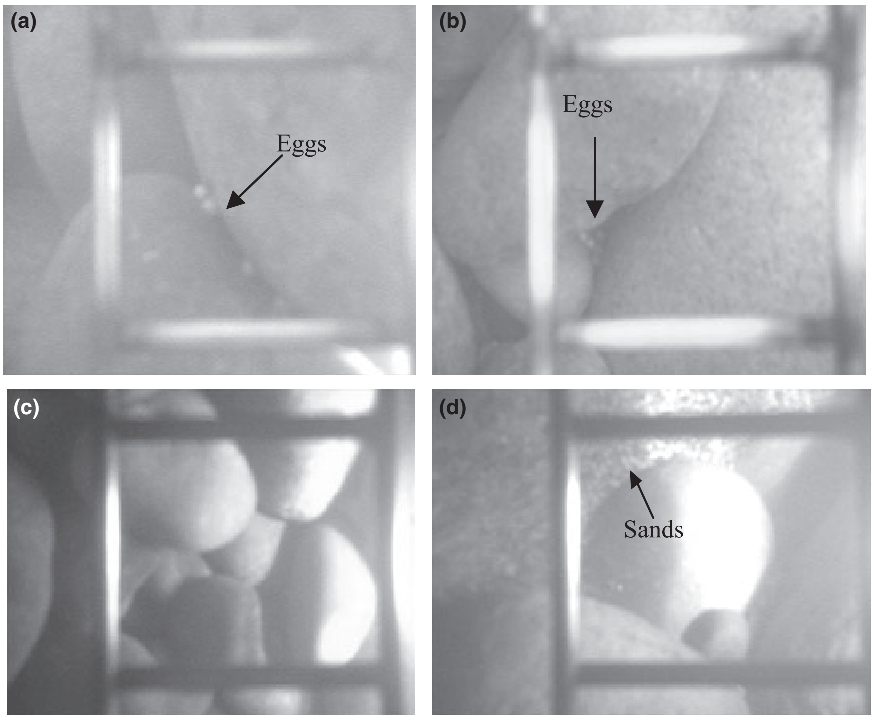

Fig. 3. The screenshots of the underwater videos to document spawned sturgeon eggs on various substrates. (a) The scattered eggs (embryos) adhering to the interstitial space of boulders; (b) Eggs (embryos) mass hiding in interstitial space of the boulders; (c) The clean interstitial spaces of the pebbles and gravels; (d) Sands filling the interstitial space of the boulders with about 50% embeddedness

higher water velocity than in the deeper water with lower water velocity and will effect by the channel aspect. The channel slope was changed with the elevation ($P < 0.05$) and obviously have a negative effect on the water velocity ($P < 0.01$) (Table 2, Fig. 3c).

The binary logistic of regression analysis of the embryo disposal site (where embryos occur in the river,'1': yes and '0': no) to its physical variables (embeddedness, elevation, velocity, channel aspect andchannel slope) indicated that the embryo dispersal sites can be predicted by the three variables: embeddedness, water velocity and elevation ($P < 0.01$) (Table 2). The channel slope and aspect was excluded in the equation for their less contribution to the significance of the model ($P > 0.05$).

Table 1
Interrelations between the physical variables by Spearman correlation analysis (n = 131)

Parameter	Embeddedness	Elevation	Velocity	Channel aspect	Channel slope
Embeddedness					
Correlation Coefficient	1.000	−0.391*	−0.313*	−0.107	−0.033
P	–	0.000	0.000	0.226	0.707
Elevation					
Correlation Coefficient	−0.391*	1.000	0.118	0.150	−0.183**
P	0.000	–	0.185	0.089	0.038
Velocity					
Correlation Coefficient	−0.313*	0.118	1.000	−0.169	−0.297*
P	0.000	0.185	–	0.055	0.001
Channel aspect					
Correlation Coefficient	−0.107	0.150	−0.169	1.000	0.129
P	0.226	0.089	0.055	–	0.144
Channel slope					
Correlation Coefficient	−0.033	−0.183**	−0.297*	0.129	1.000
P	0.707	0.038	0.001	0.144	–

*Correlation is significant at the 0.01 level (2-tailed).
**Correlation is significant at the 0.05 level (2-tailed).

Table 2
Binary logistic regression analysis between embryo dispersal site and its physical variables (embeddedness, elevation, velocity, channel aspect andchannel slope)

Parameter	Coef	SE coef	Wald	P	OR	95% CI
Embeddedness	−41.421	16.636	6.200	0.013	0.000	0.00–0.00
Elevation	0.570	0.152	14.044	0.000	1.769	1.313–2.383
Velocity	2.578	1.031	6.250	0.012	13.170	1.745–99.385
Constant	−23.013	5.934	15.042	0.000	0.000	

Channel aspect and channel slope were excluded in the equation; Log-likelihood value is −45.567; Nagelkerke R Square is 0.560, chi-square of the model coefficient is 64.956 ($P < 0.001$).

Discussion

Bottom substrate as well as hydrological conditions, topography, and water velocity were considered as the important factors triggering the natural reproduction of Chinese sturgeon but this was not yet previously been well documented (Zhang et al., 2007, 2009). Our recent study shows that Chinese sturgeon spawning behaviors might be more restricted to specific patterns of the bottom substrate than just to the rocky or gravelly substrates. The interstitial spaces of the larger blocks can provide suitable incubation areas for the eggs as well as offering room for the embedded sediments, which may compete with the eggs by filling the space or covering them and thereby blocking the interstitial water exchange which affects in turn gas transfer [e.g. oxygen supply and exchange of carbon dioxide (the respiratory end product)] (Manny and Kennedy, 2002). The interstitial spaces also provide effective hiding spaces for the embryos allowing them to passively escape from egg-predators which are known to accumulate during the spawning season as opportunistic feeders. The fine sediments over settled also will degrade the habitat for the larvae and fingerlings of the sturgeon and cause the decrease of the recruitment of the new generation (Mcadam et al., 2005). Therefore, the ‘embeddedness’ of the sediment may directly affect the choice of site where the Chinese sturgeon broodstock will finally spawn. Also, such knowledge will assist us to improve more effective the microhabitat environment needed for achieving good survival of the new generation.

Approximately 20 more historic spawning sites were reported in the past, all located within a 600 km long stretch in the mainstream of the lower Jiangsha River and the upper Yangtze River Yangtze Aquatic Resources Survey Group (YARSG) (1988). From the five certain spawning sites and the present spawning site below the Gezhouba dam we have found similar slope characteristics (Fig. 2 III–IV area). Channel slope as well as channel aspect and the elevation represent the important elements of the topography characteristics. The interrelation analysis of the physical variables in the present spawning ground of Chinese sturgeon showed that the embeddedness obviously changed with the water velocity ($P < 0.01$), the water velocity changed obviously with the channel slope ($P < 0.01$), and channel slope was obviously related to the river bottom elevation ($P < 0.05$). Therefore, the certain river bottom morphology of the Chinese sturgeon may play an important role in regulating the structure of water current, the arrangement of bottom substrates and consequently may determine where the Chinese sturgeon will spawn. The binary logistic regression also suggested that the embryo disposal sites could be predicted by the three investigated physical variables of the spawning sites: embeddedness, water velocity and elevation. Investigations carried out between 1997 and 2007 found that the eggs (embryos) of Chinese sturgeon captured by bottom drift nets were distributed at the middle to the end of the slope where it was proven that ’clean’ substrates existed during the biannual study period in 2007 ⁄ 2008 (Wei et al., 2009). The water velocity that sped up according to the slope (Fig. 2c) may explain why the eombeddedness is very low at the end of the slope and how this topography contributes to the choice of spawning site and the subsequent spawning success (Zhang et al., 2007). Therefore, according to our understanding of the substrate attributes, the bedform morphology of the river suitable for the Chinese sturgeon can be emphasized with an adverse slope which is formed by larger blocks of substrate, improving the water current to carry the suspended or embedded sediments away from this site and (in turn) providing enough interstitial spaces for effective egg deposition and incubation (Zhang et al., 2009). That may explain why some spawning grounds will be in function year by year Yangtze Aquatic Resources Survey Group (YARSG) (1988) and that may be the reason why some population may return to the same spawning ground for spawning and show some 'homing' activities (Bemis and Kynard, 1997).

The substrate requirements presently meet the needs of sturgeons will allow to relocate the potential spawning habitat for sturgeons and encourage artificial rebuilding of spawning beds as a possible option (Barlaup et al., 2008; McDonald et al., 2006). When we re-checking the topography of the last spawning ground again, we found the absolutely low elevation area V_1–VII (Fig. 2a) is just below the present spawning sites of the Chinese sturgeon which now used annually. With the water velocity decreasing (Fig. 2c), the transported sediments will unfortunately aggregate and burry the rocky and gravely substrates. The siltation (embeddedness) of this substrate in this area is very high with 50–70% (Fig. 2b). This process may become the key point that limits the available scale of the spawning ground not only for deposition of the fertilized eggs but also for its suitability for embryos incubation. If our concept of the relationship between the substrates and bedform morphology will be supported in future studies, we could actively rehabilitate the spawning ground by transplanting larger substrates such as boulders, pebbles and cobbles into the V_1–VII area similarly to measures that had been done for salmonid spawning grounds (Barlaup et al., 2008), which will elevate the riverbed and prolong the spawning substrate for embryosdisposal. So, the better knowledge of the substrate requirements will benefit for conservation and rehabilitation the spawning habitat of sturgeons.

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