Hydroacoustic survey on the spatial distribution pattern and day-night rhythmic behaviour of fishes in the Xiaonanhai reach of the upper Yangtze River

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Summary

To understand the spatial distribution patterns and fish behaviour in the Xiaonanhai reach of the upper Yangtze River at the end of the Three Gorges Reservoir, four acoustic surveys were carried out over longer periods in 2011 and 2012, which included two boat surveys and two fixed-station horizontal detections. The results showed that fish assemblages were unevenly distributed in the investigated areas, and were mainly concentrated in the section from Funixiu to Gaojiatuo. Fish behaviour was found to show a night-time activity peak. Additionally, fish moved much closer to the riverbank at night than during the day. Considering the intense human activities in this area, some suggestions are offered to mitigate the negative effects of shipping and hydroelectric construction by using design and operational logistics to support future fish conservation.

Introduction

It has been suggested that distribution and behaviour of fish species in streams are influenced by environmental factors and hydraulic conditions. Habitat selection and spawning activities are also affected by substrate type or riparian vegetation and chemical cues (Buisson et al., 2008; Paragamian et al., 2009). Water temperature may also be one of the main determinants of fish spatial distribution, affecting metabolism, breeding, development and growth (Jackson et al., 2001; Hardy and Litvak, 2004). Knowledge of fish distribution patterns and their behavioural rhythm is important for the understanding fish assemblages and taking measures for their conservation.

Hydroacoustic techniques are widely used in fisheries science and ecosystem research (Godlewskka et al., 2009). Recent technological improvements in instrument capabilities as well as both hardware and software, have promoted the use of this technology in studies of freshwater environments (Simmonds and MacLennan, 2005). The split-beam technique in particular provides three-dimensional positioning for each returning echo in space and time so that an accurate, nonintrusive quantification of fish behaviour (e.g. upstream-downstream movement) can be made (Daum and Osborne, 1998; Rakowitz and Zweimüller, 2000; Auer and Baker, 2007).

With about 378 fish species, the Yangtze River harbours a rich fish fauna, more than other Chinese rivers, indicating its extreme importance for biodiversity (Chen et al., 2009; Liu and Gao, 2012). Many of these fishes are endemic species or protected animals, and some are of high commercial value. The 154 endemic fish species account for about 40.7% of the total, of which 124 are endemic only to the upper reaches (He et al., 2011; Liu and Gao, 2012). However, the Yangtze region is also a highly developed economic area. Frequent human activities, e.g. damming, flow regulation, wetlands reclamations, overfishing, and waste drainage, have severely influenced the fish distribution in the watershed. Although some studies have dealt with the patterns of fish in spatial structure and diversity on a large scale in the Yangtze River (Fu et al., 2003, 2004; He et al., 2011), the patterns of fish distribution and behaviour have not been investigated within a small habitat scale.

The Xiaonanhai reach is located just above the famous Three Gorges Reservoir (TGR). It serves as a fish corridor for fishes in the TGR to migrate upstream for spawning, and the upper reach ichthyoplankton to drift into the TGR. However, this area is also important for shipping and there are plans to build a dam here. All of these human activities will severely impact the resident fishes.

The objective of this study was to determine the spatial distribution pattern of fishes in a particular river section (Xiaonanhai reach) to assess their occurrence in relation to the local habitat while at the same time exploring their day-night distribution in relation to the shoreline.

Materials and methods

Study area

The study was conducted in the main channel, from the section of Baishatuo to Youdong in the Xiaonanhai reach in the experimental zone of the Rare and Endemic Nature Reserve of the upper Yangtze River, 40 km upstream from Chongqing City (Fig. 1). Our study area was 10 km length, 200–800 m width, with an average depth of 9.8 m. This reach is natural flowing with a minimum monthly average discharge of 2932 m³ s⁻¹ and a maximum monthly average discharge of 38 900 m³ s⁻¹. Data on water levels and daily discharges were obtained from the Zhutuo hydrologic station (http://xxfb.hydroinfo.gov.cn/index.html). The side-arm channel was not included in our study because of the shallow water.

Hydroacoustic surveys

A Simrad EY60 echosounder with a composite 7° split-beam 200 kHz transducer was used to collect the acoustical data (Table 1). A HP laptop computer connected to a Garmin GPS controlled the echosounder; collected data were stored on the hard disk. Before the field survey, the acoustic system
was calibrated *in situ* with a standard 23 mm copper sphere [reference target strength (TS) = −40.4 dB at 1490 m s⁻¹ sound speed] (Foote et al., 1987).

**Mobile detection.** Two mobile hydroacoustic surveys were conducted, each in September and October 2011. The transducer was mounted at 50 cm depth on rigid scaffolding on the side of the boat. During sampling, the power of the General Purpose Transceiver unit (GPT) was set to 240 W, with 64 μs pulse duration. The boat maintained a constant speed of 5 km h⁻¹ along zigzag transects. The total transect length was about 27 km, which translates to a coverage coefficient (Aglen, 1983) of approximately 6.3, defined as the ratio between the total length of transects and the square root of the area under study. According to Guillard and Verges (2007) and Godlewska et al. (2009), such coverage was high enough to expect the coefficient of variation for the estimated density/abundance to be well below 10%.

**Fixed detection.** Two fixed-horizontal detections were conducted in October 2011 and August 2012. Both detections were carried out during the day and at night. The survey boat was anchored in a stable position 3 m from the right bank, and the acquisition of acoustic data began after 10–15 min to avoid biases due to vessel activities and fish behaviour. The echosounder was fixed with an adjustable bracket to the side of the boat. The beam was aimed horizontally and perpendicularly to the river current.

### Table 1

Hydroacoustic survey technical data in three survey months of 2011 and 2012, using a fixed transponders station and boat surveys for short time periods

| Date             | Starting time each day | Ending time each day | Duration (h) | Water level (m) | Discharge (m³) | Survey method |
|------------------|------------------------|----------------------|--------------|-----------------|----------------|---------------|
| 16 September 2011| 11:19:48               | 14:46:25             | 3.5          | 200.4           | 7760           | Mobile        |
| 14 October 2011  | 11:08:12               | 14:30:13             | 3.3          | 200.6           | 8150           | Mobile        |
| 16–17 October 2011| 17:27:19              | 10:00:00             | 16.5         | 200.3           | 8450           | Fixed station |
| 29–30 August 2012| 18:19:01               | 11:55:54             | 17.5         | 204.2           | 16100          | Fixed station |

### Hydroacoustic data processing and statistical analyses

Acoustic data were analysed with Sonar 5-Pro software, version 5.9 (Balk and Lindem, 2004). The criteria used to extract the individual targets with the split-beam transducers were: minimum and maximum returned pulse width 0.6–1.8 times the transmitted pulse duration, maximum gain compensation of 6 dB and a maximum phase deviation of three phase steps. The TS threshold was set to −70 dB in 40 log R time-varied-gain function.

For the boat survey, the fish density was calculated based on the $S_v/TS$ scaling method (Balk and Lindem, 2004). The computational formula was:

$$P_v = \frac{S_v}{\pi \sum_{k=1}^{K} n_k r_k S_k}$$

The volume density $P_v$ defines the number of fish per unit volume of water, the unit of which is ind./1000 m³. $S_v$ is the volume backscattering strength, $N$ is the total number of detections, $K$ defines the $k$th size class, and $n_k$ the number of detections in size class $k$ (Balk and Lindem, 2004). For horizontal beaming, the conventional single-echo detector (SED) and fish track module was used. To confirm the track, all fish were manually examined in such a way that one fish track meant a series of contiguous single echoes with the same direction of movement on a horizontal plane (Tuenser et al., 2009).

The spatial distribution of fish was described using ArcGIS 9.3 software with Kriging interpolation. Movement of
detected fish was tested using the Chi-square test. Student’s t-test was used to compare the fish density (ind./1000 m³) and the distance to the riverbank. Statistical tests were performed with SPSS 20.0 (SPSS Inc., Chicago, IL, USA) with P value at 0.05.

Results
Spatial distribution pattern of fish in the Xiaonanhai reach
Average fish density for the Xiaonanhai reach was 27.2 ind./1000 m³, with a maximum density of 191.8 in September 2011; and 44.6 ind./1000 m³, with a maximum density of 244.8 in October 2011. The latter was significantly greater than the former (P < 0.05). The average fish density for each section of the Xiaonanhai reach is shown in Table 2. The highest fish density of 65.1 was found in the section from Funixi to Gaojiatuo in September, and 94.2 in the same place in October. Fish were seldom detected in the section between the Baishatuo and Xiaonanhai station, with the lowest fish density of 9.7 in September and 16.4 in October, respectively. Overall, the fish distribution in the Xiaonanhai reach was patchy; the most striking feature was the peak-shaped distribution in fish density along the direction of the water flow. Although the fish density varied with time, most fish remained in the ‘core area’ – the section from Funixi to Gaojiatuo, showing a relatively strong coupling to a specific area (Fig. 2).

Temporal pattern of fish behaviour in the Xiaonanhai reach
A total of 4446 fish specimens were tracked during the two fixed sampling periods. Figure 3 shows examples of numerous single fish tracked in the beam during the study period. The three-dimensional fish track (Fig. 3b,d) was used for judging the orientation of the fish.

A day-night distribution of fish activity was found, with a night-time peak. The number of fish detected at night accounted for 68.7% of the total in October 2011, and 64.0% in August 2012 (Fig. 4). There was no significant trend in fish movement in October, but a significant trend was found in August, with 688 fish swimming upstream and 1552 swimming downstream through the Xiaonanhai reach (Chi-square test, P < 0.05).

A shore-oriented pattern of fish movement was also found. In August, the average distance to the right bank was 11.6 ± 2.5 m at night and 14.2± 3.1 m during daytime. In October, the average distance to the right bank was 21.4± 7.7 m at night and 28.2± 6.9 m during daytime, respectively. Statistical analysis showed that in August the fish were closer to the riverbank than in October (t-test, P < 0.05) (Fig. 5).

Discussion
The present study provides an overview of the spatial distribution pattern and specific results of day-night rhythmic behaviour of fishes in the Xiaonanhai reach of the upper Yangtze River. However, one limitation is that our study
was conducted over only one season and may have missed other annual seasons where fish distribution and activity patterns are very different. Therefore, a long-term observation should be made for a better understanding of the spatial distribution and behavioural rhythms of fishes.

Spatial distribution pattern
Our results show that fishes are unevenly distributed in the investigated area and mainly congregate in the section from Funixi to Gaojiatuo. Other studies have also noted this uneven spatial distribution (Lyons, 1998; Tao et al., 2012). It is suggested that variations in fish distribution are associated with spatial and temporal changes in the channel.
morphology and availability of resources, discharge patterns, stream size and canopy openness, current velocity and alkalinity, and the gradual change in habitat such as in substrate composition and water depth, as well as amount and type of cover available (Pusey et al., 1995; Abes and Agostinho, 2001). For the spatial distribution pattern observed in our study, there are at least two possible explanations. Firstly, high fish density may be related to habitats with high structural complexity. In the Xiaonanhai reach, our acoustic data showed that the places where fish concentrated had a complex topography and water depth >30 m. These areas provide refuges and feeding grounds for fish. Secondly, the substrate type (bottom materials) is an important variable influencing fish distribution. Different ecological preferences in different taxa or function groups, such as substrate usage, can result in habitat partitioning among fish assemblages. We found that Coreius heterodon and Coreius guichenoti were the dominant species in our investigated area, and are fish that prefer areas with rocky or gravelly substrates (Diao and Li, 1993; Zhang et al., 2011; Tao et al., 2012). During our surveys the substrate in the section of the Xiannanhai station was of a type of coarse and fine sand, whereas the substrate in the section from Funuixi to Gaojiatuo was large boulders and cobbles mixed with pebbles and gravel. Consequently, the areas in the section from Funuixi to Gaojiatuo may be a suitable habitat for the two species as well as other rheophilic species.

Day-night rhythmic behaviour of fishes in the Xiaonanhai reach

We found maximum activity and shore-oriented movement at night, which indicates the circadian rhythm of the fishes in the Xiaonanhai reach. Similar findings were found in Lucas et al. (1999) and Lilja et al. (2003), studies indicating that light intensity might affect the circadian rhythm of fish by influencing their period of diel activity. As mentioned, C. heterodon and C. guichenoti are the most abundant species in the Xiaonanhai reach, with diets mainly of benthic invertebrates. Previous studies showed that invertebrates had a circadian endogenous activity rhythm that peaked at night (Metcalfe et al., 1999; Ebner et al., 2009). Because of the nocturnal food availability, the two fish species may thus feed mainly at night. Meanwhile, temporal changes in temperature also seem to regulate light activity in another peak near noon, possibly a strategy for the avoidance of intra-specific competition and potential predators.

Regarding the distance to the riverbank, we found that fish tended to swim closer to shore at night than during daytime, possibly attributable to the increase in the prey density in the littoral zone at night (e.g. invertebrates) (Metcalfe et al., 1999). Another possible explanation is the intensive boating and navigation activities during daytime that produce a harsh environment in the littoral zones, leading to several negative effects including disturbance of habitat, increase of turbidity, flow velocity induced higher energy costs for feeding, as well as reduction of food resources such as invertebrates. These may result in fish swimming further away from shore during daytime.

Implication for conservation

Located above the TGR, the Xiaonanhai reach is heavily affected by shipping, which may severely impact fish behaviour and distribution. For fish conservation, based on the results of our investigation, we suggest that shipping routes should be arranged to avoid those areas of high fish density, while also avoiding near-shore ship traffic at night. The Xiaonanhai Dam is also in the planning stage along with the proposal of a fish passage. It is suggested that the fish pass to be designed and operated in such a way to attract fish primarily at night to ensure the passage of more fish. However, it should be noted that our study covered only one season, and a full observation of a year is needed to provide the most reliable and best management advice.

References

Abes, S. S.; Agostinho, A. A., 2001: Spatial patterns in fish distributions and structure of the ichthyocenosis in the Agua Nane stream, upper Paraná River basin, Brazil. Hydrobiologia 445, 217–227.
Aglen, A., 1983: Random errors of acoustic fish abundance estimates in relation to the survey grid density applied. FAO, Fish. Rep., pp. 300.
Auer, N. A.; Baker, E. A., 2007: Assessment of lake sturgeon spawning stocks using fixed-location, split-beam sonar technology. J. Appl. Ichthyol., 23, 113–121.
Balk, H.; Lindem, T., 2004: Sonar4 and Sonar5 Post Processing Systems, Operator Manual v5.9.4, University of Oslo, Norway, pp. 405.
Buisson, L.; Blanc, L.; Grenouillet, G., 2008: Modeling stream fish species distribution in a river network: the relative effects of temperature versus physical factors. Ecol. Freshw. Fish 17, 244–257.
Chen, D.; Xiong, F.; Wang, K.; Chang, Y., 2009: Status of research on Yangtze fish biology and fisheries. Environ. Biol. Fishes 85, 337–357.
Daum, D. W.; Osborne, B. M., 1998: Use of fixed-Location, split-beam sonar to describe temporal and spatial patterns of adult fall chum salmon migration in the Chandalar River, Alaska. N. Am. J. Fish. Manage. 18, 477–486.
Diao, X.; Li, Y., 1993: Fluctuation in fish resources at Chongqing reaches of Yangtze River. J. Southwest Agricult. Univ. 15, 179–183. (In Chinese).
 Ebner, B.; Clear, R.; Godschulz, S.; Beitzel, M., 2009: In-stream behavior of threatened fishes and their food organisms based on remote video monitoring. Aquat. Ecol. 43, 569–576.
 Fooie, K. G.; Knudsen, H. P.; Vestnes, G.; MacLennan, D. N.; Simmonds, E. J., 1987: Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep. 44, pp. 57.
 Fu, C.; Wu, J.; Chen, J.; Wu, Q.; Lei, G., 2003: Freshwater fish biodiversity in the Yangtze River basin of China: patterns, threats and conservation. Biodivers. Conserv. 12, 1649–1665.
 Fu, C.; Wu, J.; Xiang, F.; Li, G.; Chen, J., 2004: Patterns of diversity, altitudinal range and body size among freshwater fishes in the Yangtze River basin, China. Global. Ecol. Biogeogr. 13, 543–552.
 Godlewka, M.; Dugoszewski, B.; Doroszczuk, L.; Jóźwik, A., 2009: The relationship between sampling intensity and sampling error-empirical results from acoustic surveys in Polish vendace lakes. Fish. Res. 96, 17–22.
 Guillard, J.; Verges, C., 2007: The repeatability of fish biomass and size distribution estimates obtained by hydroacoustic surveys using various sampling strategies and statistical analyses. Int. Rev. Hydrobiol. 92, 605–617.
Hardy, R. S.; Litvak, M. K., 2004: Effects of temperature on the early development, growth, and survival of shortnose sturgeon, Acipenser brevirostrum, and Atlantic sturgeon, Acipenser oxyrinchus, yolk-sac larvae. Environ. Biol. Fishes 70, 145–154.

He, Y.; Wang, J.; Lek, S.; Cao, W.; Lek-Ang, S., 2011: Structure of endemic fish assemblages in the upper Yangtze River Basin. River Res. Appl. 27, 59–79.

Jackson, D. A.; Peres-Neto, P. R.; Olden, J. D., 2001: What controls who is where in freshwater fish communities - the roles of biotic, abiotic, and spatial factors. Can. J. Fish. Aquat. Sci. 58, 157–170.

Lilja, J.; Keskinen, T.; Marjomaki, T. J.; Valkeajarvi, P.; Karjalainen, J., 2003: Upstream migration activity of cyprinids and percids in a channel, monitored by a horizontal split-beam echosounder. Aquat. Living Resour. 16, 185–190.

Liu, H.; Gao, X., 2012: Monitoring fish biodiversity in the Yangtze River, China. In: The biodiversity observation network in the Asia-Pacific Region. S. Nakano, T. Yahara and T. Nakashizuka (Eds). Springer, Japan, pp. 165–174.

Lucas, M. C.; Mercer, T.; McGinty, S.; Armstrong, J. D., 1999: Use of a flat-bed passive integrated transponder antenna array to study the migration and behavior of lowland river fishes at a fish pass. Fish. Res. 44, 183–191.

Lyons, J., 1998: A hydroacoustic assessment of fish stocks in the River Trent, England. Fish. Res. 35, 83–90.

Metcalf, N. B.; Fraser, N. H. C.; Burns, M. D., 1999: Food availability and the nocturnal vs. diurnal foraging trade-off in juvenile salmon. J. Anim. Ecol. 68, 371–381.

Paragamian, V. L.; McDonald, R.; Nelson, G. J.; Barton, G., 2009: Kootenai River velocities, depth, and white sturgeon spawning site selection - a mystery unraveled? J. Appl. Ichthyol. 25, 640–646.

Pusey, B.; Arthington, A.; Read, M., 1995: Species richness and spatial variation in fish assemblage structure in two rivers of the Wet Tropics of northern Queensland, Australia. Environ. Biol. Fishes 42, 181–199.

Rakowitz, G.; Zweimüller, I., 2000: Influence of diurnal behavior rhythms and water-level fluctuations on the migratory activities of fish in a backwater of the River Danube: a hydroacoustic study. Aquat. Living Resour. 13, 319–326.

Simmonds, J.; MacLennan, D. N., 2005: Fisheries Acoustics: Theory and Practice. Blackwell Science Ltd., Oxford, pp. 437.

Tao, J.; Gong, Y.; Tan, X.; Yang, Z.; Chang, J., 2012: Spatiotemporal patterns of the fish assemblages downstream of the Gezhouba Dam on the Yangtze River. Sci. China Life Sci. 55, 626–636.

Tušer, M.; Kubečka, J.; Frouzová, J.; Jarolím, O., 2009: Fish orientation along the longitudinal profile of the Rimov reservoir during daytime: consequences for horizontal acoustic surveys. Fish. Res. 96, 23–29.

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. J. Appl. Ichthyol. 27, 251–256.

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