



## Spatial autocorrelation and heterogeneity of fish resources in the Xijiang River, Pearl River Basin, China

WU ZHI<sup>1,2,3</sup>, ZHU SHULI<sup>1,2,3</sup>, LI JIE<sup>1,2,3,4</sup>, LI YUEFEI<sup>1,2,3</sup>, XIA YUGUO<sup>1,2,3</sup> AND LI XINHUI<sup>1,2,3</sup>

<sup>1</sup>Pearl River Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou - 510 380, China

<sup>2</sup>Guangzhou Scientific Observing and Experimental Station of National Fisheries Resources and Environment Guangzhou - 510 380, China

<sup>3</sup>Experimental Station for Scientific Observation on Fishery Resources and Environment in the Middle and Lower Reaches of Pearl River, Ministry of Agriculture, Guangzhou - 510 380, China

<sup>4</sup>Key Laboratory of Aquatic Animal Immune Technology of Guangdong Province, Guangzhou - 510 380, China  
e-mail: lijie1561@163.com

### ABSTRACT

The Xijiang River, China, is a hotspot for fish biodiversity. Using hydroacoustic data collected from March to June 2016, the spatial autocorrelation and heterogeneity of fish resources were determined using geostatistical methods. We analysed the skewness, kurtosis and coefficient of variation for fish density along the river and also examined the spatial autocorrelation of these data using Moran's *I* statistic. Fish density was low in most of the survey areas. Moran's *I* values were all positive ( $z > 1.96$ ,  $p \leq 0.01$ ), which indicates significant spatial autocorrelation; however, the degree of spatial aggregation varied among months. Hotspot analysis revealed strong local spatial autocorrelation and varying "hot" and "cold" spots in different months. The spatial heterogeneity and directional variation of fish densities were assessed using geostatistical methods and the best-fitting semivariogram was an exponential model. Spatial autocorrelation accounted for 56-75% of the variation in the model, which indicates that fish distribution in the Xijiang River has a clear spatial structure. The results show the applicability of acoustic methods to study the spatial autocorrelation and heterogeneity of fish resources in rivers and provide a reference for the management of fish stocks.

Keywords: Fish resources; Hydroacoustic technology; Spatial autocorrelation; Variation characteristics; Xijiang River

### Introduction

Distributions of fish individuals, populations, and communities may be structured or random within a specific space (Ostrand and Wilde, 2002; Zhou *et al.*, 2003). Classical statistical methods (such as Principal Component Analysis, Variance Analysis) do not account for the location of and distance between samples. Geo-statistical analyses address this issue and are an effective tool to describe spatial data and analyse spatial variation and correlation (Yang *et al.*, 2012). Spatial autocorrelation tests can be used to quantitatively analyse and interpret the distribution of spatial data. Such methods have been applied in fisheries ecology, including evaluations of fishery resources and associated uncertainty, fishery hot spots and fish spatial heterogeneity (Walline, 2007; Woillez *et al.*, 2009; Yang *et al.*, 2014; Niklitschek and Skaret, 2016; Petitgas *et al.*, 2016; Bai *et al.*, 2021).

As the main tributary of the Pearl River, the Xijiang River has rich fisheries resources and high diversity and is an important aquaculture germplasm resource in China (Xia *et al.*, 2019). To date, extensive studies have been conducted on fish community structure and diversity,

spatial and temporal distribution patterns of resources and resource changes and influencing factors (Li *et al.*, 2010; Shuai *et al.*, 2016; Wu *et al.*, 2017; Shuai *et al.*, 2017a, b; Zeng *et al.*, 2017; Zhang *et al.*, 2020). These studies have laid a foundation for understanding the spatial distribution of fishes in the Xijiang River. However, due to the assumption of spatial-homogeneity, the spatiotemporal variation of the data is ignored. At the same time, as the spatial data are assumed to be independent from each other in classical statistical methods, the spatial autocorrelation of spatial data is ignored to a certain extent, which leads to deviation of the results. Hence this study was conducted using monthly acoustic data in the Xijiang River to determine fish distribution, and the spatial autocorrelation and heterogeneity of the data. The results can reveal the overall spatial pattern of fish resources, hot and cold spots and their variation and also can guide the management of fisheries resources and sampling design.

### Materials and methods

#### *Hydroacoustic data acquisition and analysis*

Hydroacoustic surveys were conducted in the Xijiang River on a zigzag track between Wuzhou (23.46°N,

111.27°E) and Deqing (23.13°N, 111.77°E) at a speed of 9-10 km h<sup>-1</sup> on 22 March, 28 April and 6 June in 2016 (Fig. 1). The survey area was 82.3 km long with a mean depth of 12.29 m and a maximum depth of 82 m.

A split-beam echo-sounder EY60 (Simrad, Horten, Norway) was used, with the following characteristics: frequency 120 kHz, sampling interval 16 ms and 40 log R TVG (time varied gain) amplification. The acoustic system was routinely calibrated with a tungsten carbide sphere (-40.4 dB; diameter 23 mm) before each measurement series (Demer *et al.*, 2015).

Acoustic data were processed in Echoview v. 5.4. When fish density was low, the single target echoes did not overlap (Rudstam *et al.*, 2009). Therefore, the echo counting method was adopted. A target threshold of -60 dB was set, which ensured that most noise signals were excluded and other noises were manually eliminated.

*Global spatial autocorrelation*

Moran's *I* statistic was used to analyse the overall spatial autocorrelation and global spatial patterns of fish resources (Zhang and Zhang, 2007) and was calculated as:

$$X = \frac{n}{S_0} \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} z_i z_j}{\sum_{i=1}^n z_i^2} \dots\dots\dots(1)$$

where *z<sub>i</sub>* is the deviation between the attribute value of element *I* and its mean value, *w<sub>ij</sub>* is the spatial weight of the elements *i* and *j*, *n* is the total number of elements and *S<sub>0</sub>* is the aggregate of all spatial weights.

After normalisation, *I* had a value between -1 and 1; values greater than 0 indicate a positive spatial correlation, values less than 0 indicate a negative correlation and 0 indicates that the data are random. The larger the value, the clearer the spatial correlation. The local autocorrelation analysis of fish density was carried out using the hot spot analysis tool in ArcGIS™ 10.1.

*Spatial heterogeneity analysis*

A semi-variance function was used to predict the degree of spatial variation and autocorrelation as follows (Parker-Stetter, 2009; Tao *et al.*, 2012):

$$\gamma(h) = \frac{1}{2 |N(h)|} \sum_{N(h)} (\rho(s_i) - \rho(s_j))^2 \dots\dots\dots(2)$$

where  $\rho$  is the fish density referenced to its location *S<sub>i</sub>* = [latitude, longitude]; lag (*h*) is the distance vector separating the observations, such that *S<sub>i</sub>* - *S<sub>j</sub>* = *h* and *N(h)* is the number of pairs of locations that were distance (*h*) apart.

To quantify the degree of spatial variation and autocorrelation of fish density in the Xijiang River, spherical and exponential models were fitted to all empirical variograms using the weighted least-squares method. To determine the best model fit, statistical errors such as the mean error (ME), root-mean-square error (RMS) and average standard error (ASE) were determined during the predictions. The ME provides a measure of bias, whereas RMS and ASE provide measures of accuracy (Tao *et al.*, 2012). When ME is close to zero, ASE is close to the RMS and the prediction variability is correctly assessed.

**Results**

*Fish density and global spatial autocorrelation*

The average fish densities were 29.29, 26.41 and 49.03 individuals per 1000 m<sup>3</sup> in March, April and June, respectively (Table 1). The skewness values (Sk) of fish density were all greater than 0, which indicates that the distribution was skewed to the right. The kurtosis values (Ku) were all greater than 3, that is, the fish density distribution showed a sharp peak. These results indicated that fish were mainly distributed at low-densities, with fewer high-density areas. The fish density varied over time, as shown by the coefficient of variation (CV).

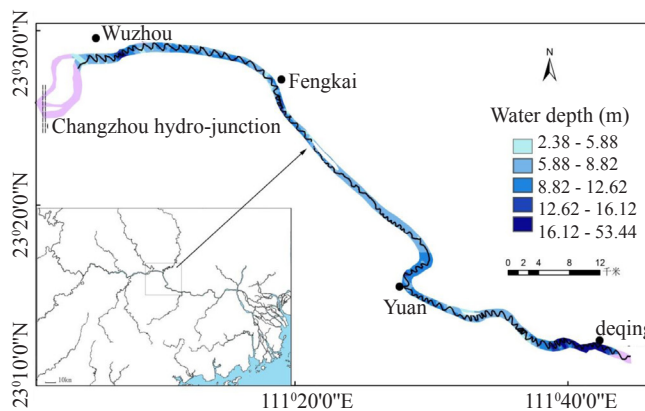


Fig. 1. Acoustic survey area in the Xijiang River, China. The black line represents the track used for sampling

Table1. Global autocorrelation sample statistical parameters

Samling day	Average density (Ind. per 1000 m <sup>3</sup> )	Standard error	Max value	Kurtosis	Skewness	CV (%)	Morans I	Z score	p-value
22 Mar 2016	29.98	1.48	127.68	3.60	1.566	1.55	0.42	4.46	0
28 Apr 2016	26.41	1.14	190.49	11.46	2.21	1.36	0.32	13.22	0
06 Jun 2016	49.03	3.07	470.11	30.77	4.60	4.77	0.21	2.47	0.01

Moran’s *I* values were all positive, which indicates that the distribution of fish showed significant spatial clustering in the Xijiang River during the survey period, but the degree of spatial aggregation varied between months ( $Z > 1.96$ ,  $p \leq 0.01$ ).

*Local spatial autocorrelation of fish density*

Overall, the distribution of fish resources in the Xijiang River showed spatial aggregations and these “hot spots” (red areas) appeared in different months ( $Z > 1.65$ ,  $p < 0.01$ ). Fish densities were high in these areas and the densities around them were also high. “Cold spots” (blue areas) appeared in April ( $Z < -1.65$ ,  $p < 0.01$ ), which indicated a low fish density and the densities around them were also low. Most areas were yellow ( $Z$ -values between  $-1.65$  and  $+1.65$ ). In these areas, the spatial autocorrelation was weak and the fish distribution was random (Fig. 2). The results showed that some small areas in the study

area had strong local autocorrelation (red area), while the overall autocorrelation was weak (yellow zone) and the fish resource density showed uneven local distribution characteristics of “hot” and “cold”.

*Spatial heterogeneity of fish density*

On comparing the spherical and exponential models using the weighted least-squares method, the ME of the exponential model was closest to 0 and the RMS values for each month were the smallest, so this model was considered optimal (Table 2).

The nugget ( $C_0$ ) values describe the sampling error (uncertain variation) and/or microscale variation. The results showed that  $C_0$  had a small range (0.2-1.5), which indicated that random factors had little influence on fish density, namely, scales less than 100 m had little effect on fish density. Increasing the sampling density would not significantly influence the spatial structure of the fish

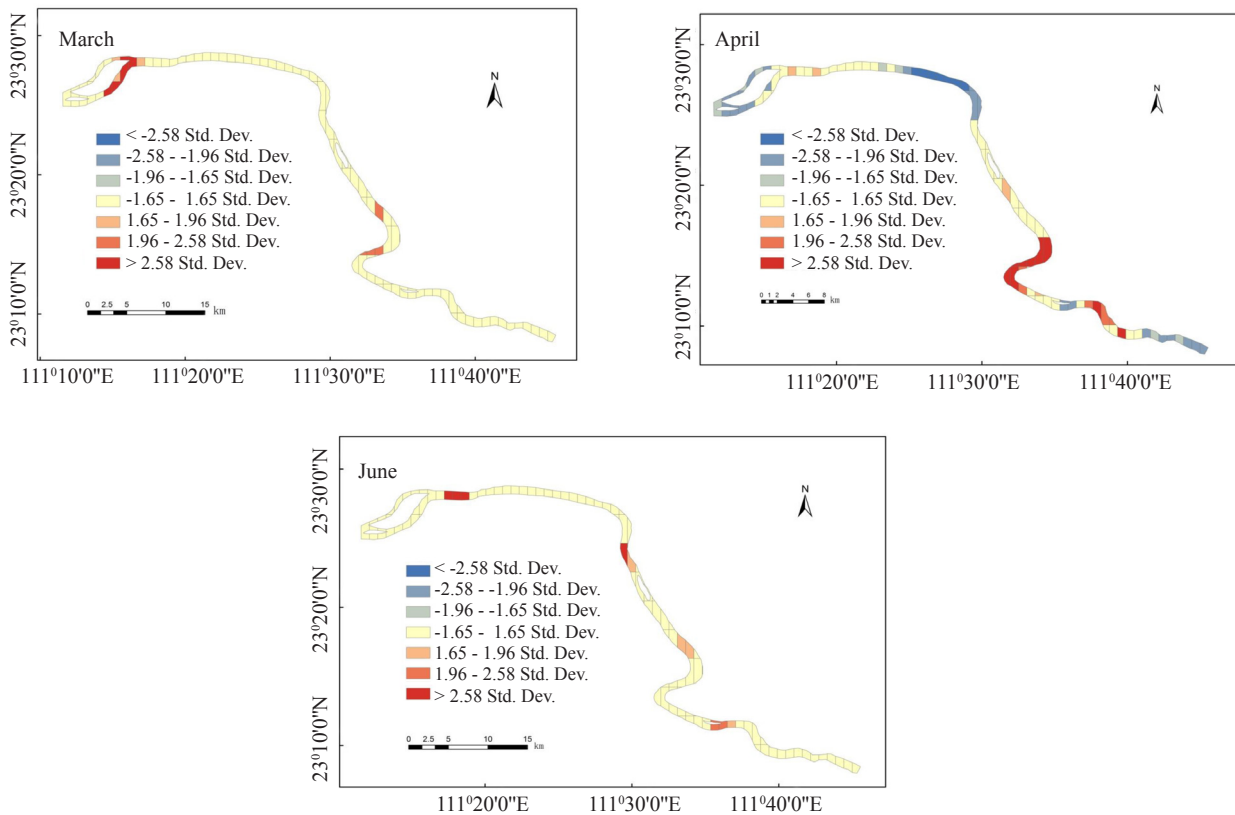


Fig. 2. Hotspots of fish resources in 2016 in the Xijiang River

Table 2. Parameters of semivariograms for fish density

Sampling day	Theoretical model parameters							Error statistics		
	Model	Nugget	Sill	Range /m	Partial Sill/Sill	Fractal	R <sup>2</sup>	RMS	ME	ASE
22 Mar 2016	sph	0.122	0.374	19.1	0.674	1.982	0.237	0.015	0.023	0.016
	exp	0.114	0.377	27.9	0.695	1.982	0.264	0.015	0.018	0.016
28 Apr 2016	sph	0.267	0.711	32.56	0.624	1.856	0.877	0.014	0.002	0.015
	exp	0.263	1.06	35.25	0.751	1.856	0.869	0.013	0	0.014
06 Jun 2016	sph	0.236	0.536	10.53	0.561	1.888	0.897	0.034	0.039	0.028
	exp	0.19	0.545	11.79	0.651	1.888	0.872	0.033	0.019	0.028

density distribution. The partial sill (C) describes the spatial component of the semivariance ( $\gamma$ ). The sill ( $C_0 + C$ ) is the asymptote of the variogram that occurs within the predicted range (structural variation), and values ranged from 0.37 to 1.06. The ratio of the nugget to the sill ( $C_0 / C_0 + C$ ) ranged from 0.56 to 0.75, which indicated that fish density had a good spatial structure and exhibited moderate spatial autocorrelation. The fractal dimension values were between 1.85 and 1.98, which indicated high spatial heterogeneity caused by the spatial autocorrelation

## Discussion

Geostatistical models can be used to assess the spatial variability of data and establish statistical relationships based on location (Woillez *et al.*, 2009). At their core, these models can help elucidate patterns of spatial dependence, correlation, or autocorrelation. These methods have been widely used in marine fisheries but rarely for freshwater systems (Zhang and Lin, 2005; Feng *et al.*, 2014; Du *et al.*, 2017). In marine surveys, sampling points generally cover a continuous grid, while river sampling points are linearly distributed. Acoustic data collection is a continuous sampling process and the data conform to the requirements of spatial autocorrelation for a data structure (Tao *et al.*, 2012). Additionally, compared with traditional methods (such as gillnet sampling and fishing), acoustic surveys have the advantages of higher spatiotemporal accuracy, greater coverage, and a high volume of data. Therefore, acoustic data are suitable for analysing spatial correlation and heterogeneity in river fisheries research. This study collected acoustic data during the closed fishery season in the Pearl River when human interference is low and thus, is likely to accurately reflect the natural ecological patterns of the river.

In acoustic surveys, high fish densities are often encountered but these spots may create uncertainty in resource assessments (Petitgas *et al.*, 2016). Such uncertainty can be reduced by understanding the spatial predictability of hot and cold spots in a specific environment. Geostatistical methods can elucidate the spatial relationships between high fish densities and other values by setting global/local spatial thresholds (Feng

*et al.*, 2014). Hot spot analysis is used to identify spatial clusters of high and low values. This method has been applied in studies of patterns of habitat change and species richness in fisheries ecology (Nelson and Boots, 2008; Stuart-Smith *et al.*, 2013; Yasuda *et al.*, 2014).

Our results revealed that fish densities in the Xijiang River showed uneven local distribution with both “hot” and “cold” spots; some small areas had strong local autocorrelation, but overall autocorrelation was not strong. The distribution of fish is associated with the spatial distribution and orientation of various biological and abiotic factors. The study area is a fish migration channel and the study period was the main fish breeding season. As fish migration was ongoing, there were no fixed “hot” or “cold” spots over the study period (Tan *et al.*, 2011; Shuai, *et al.*, 2016). Fish community structure in the Xijiang River has also changed significantly in recent decades (Li *et al.*, 2010; Shuai *et al.*, 2017b). The main drivers of this change are human activities and environmental change, which affect habitat suitability and distribution (Li *et al.*, 2019). The duration of this study was short and it was difficult, therefore, to analyse the causes of the formation of hot spots in the Xijiang River. Long-term studies are needed to predict spatial trends in fisheries resources and analyse their relationships with the environment to understand fish adaptation and habitat selection.

Approximately 25-44% of the spatial heterogeneity could be attributed to uncertainty or sampling error, which indicated that the spatial distribution was well expressed and recorded. Therefore, the influence of spatial autocorrelation should be considered when studying the relationships between fish and their environment in the Xijiang River. At the same time, because of the existence of spatial autocorrelation, it is important to choose an appropriate model for the regression analysis. For example, when ordinary statistical models are used, the results may be greatly skewed or even incorrect. Therefore, models such as the generalised linear model, generalised additive model, or generalised linear mixed model are needed to effectively address spatial autocorrelation and improve the accuracy of the model.

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