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Spatiotemporal Response of Fish Aggregations to Hydrological Changes in the Lower Pearl River, China, during the Main Spawning Season

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Abstract: The Pearl River is a global hotspot of fish biodiversity, yet has the most threatened endemic fish species in China. Since the establishment of the Changzhou Dam in the lower reach, changes in hydrological rhythm have negatively impacted fish downstream of the dam, but their spatiotemporal distribution in response to flood alteration has received little attention. In this study, hydroacoustic surveys were undertaken monthly in 2016 to monitor the distribution and behavior of fish. Fish densities were higher during the water discharge rising stage than during the falling stage, indicating that the fish aggregate during flooding (coefficient of variation [CV] > 100%) and depart after flooding (CV < 100%), especially aggregations of large fish. The target strength (TS) was allocated to two groups as per their frequency distributions, defined as small fish (−55 dB < TS < −40 dB) and large fish (TS > −40 dB). The sizes of both groups were significantly larger during the rising stage when compared to those during the falling stage ($p < 0.01$). Comparatively more fish were present with a greater average TS, and a substantially greater proportion of large fish was detected during rising stages. Hydrological variation importantly influences fish aggregations, including the numbers and sizes present, with the differences being particularly pronounced between the rising and falling stages. Combined with relevant studies, it is suggested that water releases from the Changzhou Dam should be regulated to satisfy fish spawning and migration demands during the main breeding season.

Keywords: fish distribution; hydroacoustic survey; hydrological variation; lower Pearl River; Changzhou Dam

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1. Introduction

River damming is perhaps the most dramatic anthropogenic factor affecting freshwater fish populations; dams cause habitat loss and fragmentation, change hydrological conditions, and cut off migration routes [1]. The alteration of flow patterns by the regulation and operation of dams can negatively affect the life history of freshwater fishes [2]. This situation has led to considerable research on dam-induced effects on fish community structure and diversity, as well as on larval fishes. Under cascade dam development on the Uruguai River, the fish assemblage in the upper stretch was mainly characterized by small- and medium-sized species at higher trophic levels, whereas sites downstream had more medium- and large-sized species, including several carnivorous fishes [3]. Xie [4] analyzed the potential risk posed by the Three Gorges Dam to three of China's ancient fish species. However, little is known about the behavioral responses of adult fish in general since it is difficult to draw general conclusions about their temporal and spatial distribution patterns from traditional catch statistics (e.g., trawl sampling and net sampling) [5]. Hydroacoustic techniques are widely used in fisheries for science and ecosystem research, as they are nonlethal, work in turbid waters, cover vast areas, and can be used to evaluate the temporal and spatial distributions and migration consistency of fish under natural conditions and over a large range [6]. Because collecting acoustic data constitutes a process of continuous sampling, and because the data conform to the requirements of spatial autocorrelation for a data structure, Petitgas et al. [7] used hydroacoustic data to map fish habitat hotspots. Li et al. [8] reported on fish species, sizes, and spatiotemporal distributions by combining catch statistics and hydroacoustic methods. Visual depictions of such findings can convey key information for fish habitat restoration and fishery management.

The Pearl River is the longest river in southern China and has the highest volume of runoff. The river has been identified as the most species-rich in China, as well as a global hotspot of fish biodiversity, with approximately 659 fish species historically recorded [9]. In the context of ever-increasing human activity along this water course, it also has the greatest number of threatened endemic species in China [10]. For example, Chinese sturgeon *Acipenser sinensis* and seasonal shad *Macrura reevesi* have disappeared from the Pearl River in recent years; in 1985, the percentage of the larvae of four carp species in ichthyoplankton (i.e., black carp *Mylopharyngodon piceus*, grass carp *Ctenopharyngodon idellus*, silver carp *Hypophthalmichthys molitrix*, and bighead carp *H. nobilis*) was 46.6%, but it dropped to 4.6% by 2008 [11]. Although a combination of factors undoubtedly contributes to such declines, hydrological connectivity is known to determine the pattern of biodiversity along the length of large rivers [12]. At present, there are 11 cascade dams in the main stream of the Pearl River, with the Changzhou Dam (CZD) being the last. Since all these dams became operational, about 90% of free-flowing water has been lost in the river's middle to lower reaches, excluding the section downstream of the CZD. Due to the lack of fish passage facilities (apart from the last two dams downstream), fish are not able to migrate through these dams when they are in normal operation.

The river section downstream of the CZD, stretching ~350 km to the Pearl River estuary, constitutes an important habitat in the life cycles of many commercially valuable native fishes, with many spawning grounds and 136 species reported [13,14]. Based on a long-term database, barbel chub *Squaliobarbus curriculus*, black Amur bream *Megalobrama terminalis*, mud carp *Cirrhinus molitorella*, and the cyprinid *Xenocypris davidi* are the dominant fish species. The major reproductive season occurs between May and September, peaking from June to August. Mean water temperature, river discharge, atmospheric pressure, maximum temperature, and precipitation play important roles in larval occurrence patterns. Elevated temperatures shorten the spawning period, and river discharge shows significant coherence and an in-phase relationship with larval density [14–18].

Construction of the CZD in 2007 has greatly changed the hydrological characteristics of the lower Pearl River; flood duration and total flood volume have decreased, and flood fluctuations mainly occur between June and September [18]. Studies have confirmed the negative ecological effects of the dam on fishery resources, including substantial decreases in the common carp *Cyprinus carpio* population, an earlier spawning peak of silver carp, and spatial fracture in the fish community between upstream and downstream sections [18–20]. Fortunately, the dam has a fishway, providing a channel for multispecies upstream migrations. A total of 40 fish species in the fishway were sampled. These studies showed that the fishway was effective during the flood season, mitigating the negative impact of hydropower on fish to some extent [21,22]. To date, extensive studies have been conducted on fish community structure and diversity, resource changes, and influencing factors [14,20], whereas scarce research has considered the spatiotemporal distribution and behavior of fish below the CZD [23], despite the area's geographical importance.

Therefore, we conducted monthly hydroacoustic monitoring under the normal operation mode of the CZD during the main spawning season. The aim of the study was to gain an understanding of fish density and the temporal and spatial response of fish downstream of the CZD to changes in the flow pattern, to provide valuable information for water resources management in keeping with fishery conservation.

2. Materials and Methods

2.1. Study Area

The CZD is located in the main stream of the lower Pearl River. Before its construction, the river was unobstructed for ~700 km between the estuary and the first dam upstream; thus, most fish could complete their entire life cycle downstream. This closure dam now divides the lower reach into two sections, each ~350 km in length, upstream and downstream. The study area is located downstream of the CZD; it covers the main stem of the lower Pearl River (Figure 1) from Wuzhou City (23.46° N, 111.27° E) to Deqing County (23.13° N, 111.77° E), and contains three fish reserves. The survey area was ~83 km long, with a mean depth of 12.29 m and a maximum depth of 82 m.

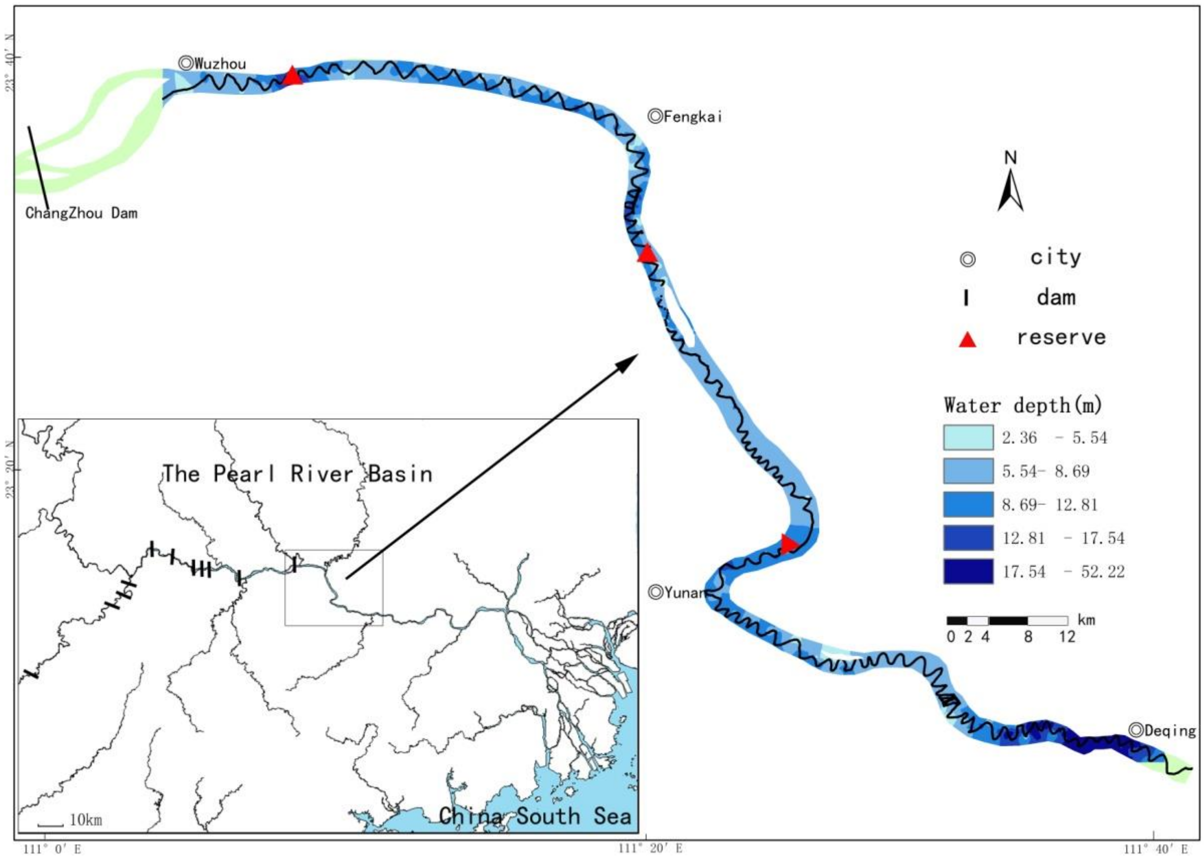

Figure 1. Map showing water depths of the lower Pearl River. The survey transects made with the echo-sounder are indicated by the black line. The red triangles represent the location of fish reserves.

2.2. Acoustic Study

Six acoustic detection surveys were conducted under different hydrological conditions (i.e., the water discharge rising stage and falling stage) downstream of the CZD from March to September 2016, and each survey lasted 2 days (Table 1). We used an EY60 split-beam echo sounder (Simrad, Horten, Norway) with a frequency of 120 kHz and an opening angle of 7° at −3 dB. The hydroacoustic measurements were conducted using an 8 m fishing boat at a speed of 8–10 km/h. The survey route followed dense, zigzag transects (Figure 1). Before each field survey, the acoustic system was calibrated with a −40.4 dB tungsten carbide sphere (diameter 23 mm), according to the standard procedure [24,25].

Table 1. Data from acoustic surveys in the Xijiang River section (middle and lower main stream of the Pearl River) under different hydrological conditions.

Survey Period	Discharge (m^3/s)	Depth (m)	Area (km^2)	Temperature (°C)	Dc	Hydrological Condition
24–25 March	4083	11.48	115	18.00	8.6	+
27–28 April	10,593	13.15	115	22.37	11.3	-
6–7 June	12,833	16.41	115	22.36	12.2	+
1–2 July	7500	13.47	115	28.06	9.8	-
16–17 August	9960	13.07	115	30.24	11	+
23–24 September	3670	11.36	115	29.41	8.7	-

Note: Area (i.e., the area covered by hydroacoustic surveys) was measured using Google Earth in April 2016. The values of degree coverage of the acoustic surveys (Dc) are all >8, indicating that the coefficient of variation was met for estimating fish density or fish abundance [26,27]. The symbol + indicates the rising stage, and - indicates the falling stage.

2.3. Data Analysis

Echoview Software (version 5.4, Myriax Pty Ltd., Hobart, Tasmania, Australia) was used to process and analyze the hydroacoustic data [28]. Only data from 1 m beneath the water surface to 0.5 m above the river bottom were used in the analysis. When fish density was low, the single-target echoes did not overlap [29]; therefore, the echo-counting method was adopted. Three main procedures were used for acoustic target recognition. (1) For noise removal, a target threshold of −55 dB was set, which ensured that most noise signals were excluded, and other noises were manually eliminated. (2) For single-target detection, the maximum one-way gain compensation was set to 10 dB with the target strength (TS) threshold being −55 dB to exclude the echoes of fish below the threshold value. (3) For fish track detection, 3 single echoes were detected from one target with a maximum gap of 2 pings. To detect fish tracks for evaluating TS and fish density, the single-target detection method and fish track detection method were used as per the image analysis [30], and the information on each individual fish (such as TS, depth in the water, and location) was then exported.

Because a TS–fish length relationship for Pearl River fish species was not available, an empirical equation was used to convert TS to fish length [31]:

$$\mathrm{TS} = 20 \log \mathrm{L_{cm}} - 67.4 \quad (1)$$

where TS is a logarithmic measure of the proportion of the incident energy which is backscattered by the target. The TS of the fish is a number which indicates the size of the echo. $\mathrm{L_{cm}}$ is the standard length of the fish.

The hydroacoustic transects were divided into elementary distance sampling units of approximately 150 m to separately estimate fish density and behavior [32].

Data from fish densities were imported into ArcGIS 10.1 (Esri, Redlands, CA, USA) for geostatistical simulations. Spatial changes in fish distributions were interpolated using the ordinary Kriging method, a linear interpolation that provides the best linear unbiased estimator for quantification in varied spaces [33]. The Jenks natural breaks classification method was used to divide fish density into six groups to ensure the minimum intra-class difference and the maximum inter-class difference. The survey area was divided into river sections of ~10 km each, as per river geomorphology, and eight sections were analyzed.

For the statistics, nonparametric tests (Kruskal–Wallis) were used for comparing the differences of fish density and TS in different months. The coefficient of variation (CV) was used to measure the dispersion of fish aggregations. All analyses were completed with the SPSS 22.0 software (Armonk, IL, USA). Significance levels for all analyses were set to $p < 0.05$.

3. Results

3.1. Fish Spatiotemporal Distribution

Fish densities from March to September ranged from 0.0071 to 1.77 ind/m^3, with an average density of 0.0275 $\pm$ 0.0668 ind/m^3 (mean $\pm$ SD). Table 2 shows the fish density of each elementary distance sampling unit calculated using the single-target detection method. The highest average density occurred in June, in the Fengkai River section, with a maximum value of 0.08 ind/m^3. The lowest average density occurred in September, in the Wuzhou River section, with a maximum value of 0.03 ind/m^3. The homogeneity test of variance showed that the associated probability was <0.05; therefore, a nonparametric test was used to analyze the differences in fish density in different months. Kruskal–Wallis (*K* sample) tests showed significant differences in fish density in different months ($p < 0.001$); that is, mean fish densities were significantly higher during the rising stage compared to the falling stage, except for in March (Figure 2), as fish aggregated during flooding periods (CV > 100%) and then dispersed after the flooding (CV < 100%) (Figure 3). Correlation analysis of fish density and dam water discharge in the different months showed a linear correlation ($r = 0.8784$, $p = 0.021$). Spatial distributions of fish densities acquired from ArcGIS are shown in Figure 4. Because of large differences in fish density, the depiction was divided into two groups to distinguish differences in distribution more clearly in different months; the same colors represent different numerical ranges in the two hydrological periods (i.e., rising and falling stages). Longitudinally, the distribution of fish downstream of the CZD was patchy, as the fish aggregations were different in the eight acoustic detection datasets. Fish densities were highest in the Wuzhou section in June, August, and September ($p < 0.05$) when compared to those in the other sections, and the densities in this river section were higher than the average density across the survey area, except for in April. There were no obvious patterns of fish distribution in the other river sections.

Table 2. Distribution of fish density in different months, from hydroacoustic surveys in 2016.

Date	Average Density (ind/m^3)	SD	Max	95% Confidence Interval	CV (%)
24 March	0.0232 ^{A}	0.0141	0.0813	(0.0209, 0.0255)	60.78
27 April	0.0262 ^{B}	0.0207	0.2075	(0.0167, 0.0222)	79.01
6 June	0.0587 ^{C}	0.1581	0.9883	(0.0666, 0.1326)	269.34
1 July	0.0089 ^{D}	0.0071	0.0619	(0.0043, 0.0065)	79.78
16 August	0.0303 ^{A}	0.0238	0.1238	(0.0218, 0.0274)	138.03
23 September	0.0071 ^{BD}	0.0098	0.0983	(0.0085, 0.0128)	78.55

Note: Data superscripts without same letters indicate significant differences between groups.

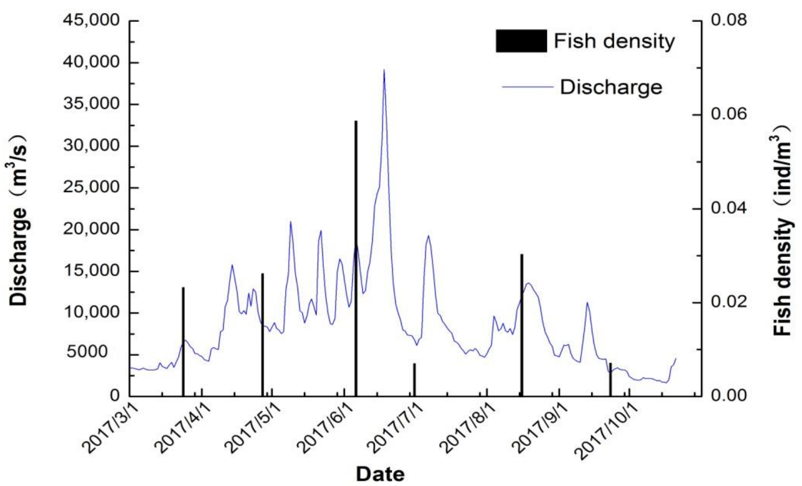

Figure 2. Fish density in relation to discharge distribution in different months in the survey area downstream of the Changzhou Dam.

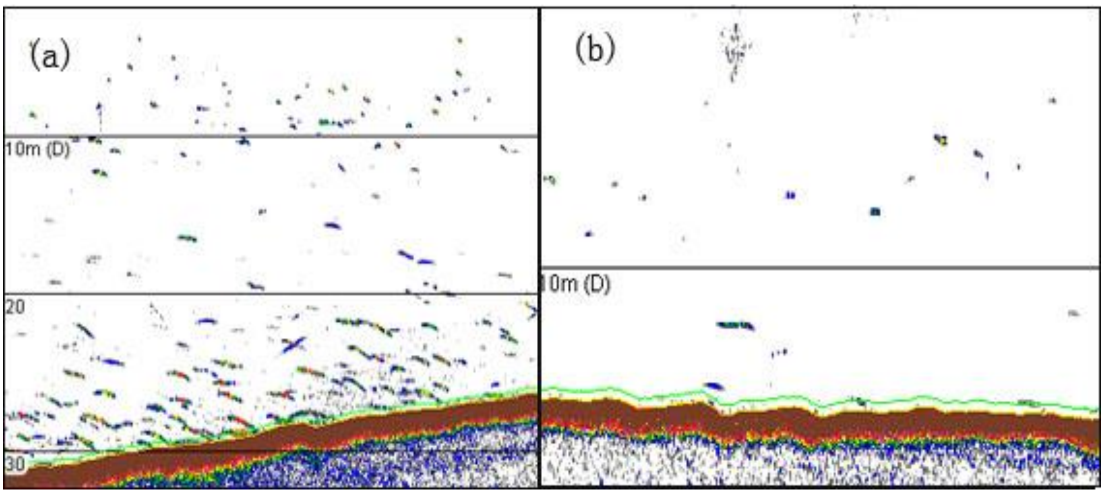

Figure 3. Echogram showing two types of fish distribution patterns at different depths. (**a**) Fish assembled; (**b**) fish dispersed.

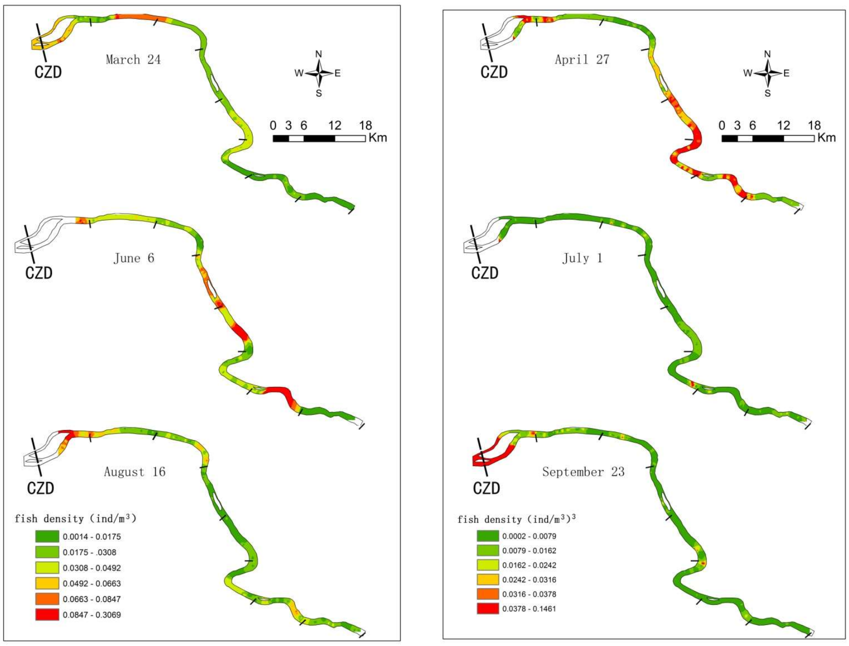

Figure 4. Longitudinal distribution of fish densities in the six hydroacoustic surveys (see Table 1 for dates).

3.2. Fish Size Differences

The average values of TS in the months from March to September, respectively, were −51.46, −49.57, −51.66, −49.01, −49.87, and −48.24 dB, revealing a higher average TS during the rising stage than during the falling stage, apart from in March. Figure 5 shows the size distribution for TS; the proportion of small fish was greater than that of large fish across the survey period. To analyze the difference, the TS was separated into two parts at a threshold of −40 dB, from which two kinds of fish assemblages were observed: at a TS threshold range of −55 dB to −40 dB and at a TS threshold greater than −40 dB. Moreover, there were more fish aggregated at the TS threshold of −55 to −40 dB when compared to at the TS threshold greater than −40 dB in each month. The aggregations of TS distributions at a threshold greater than −40 dB in the rising stages were 10.89% (March), 9.45% (June), and 8.22% (August), and in the falling stages they were 2.06% (May), 1.54% (July), and 4.72% (September), which revealed a substantial increase in large fish during the rising stage, and the opposite during the falling stage.

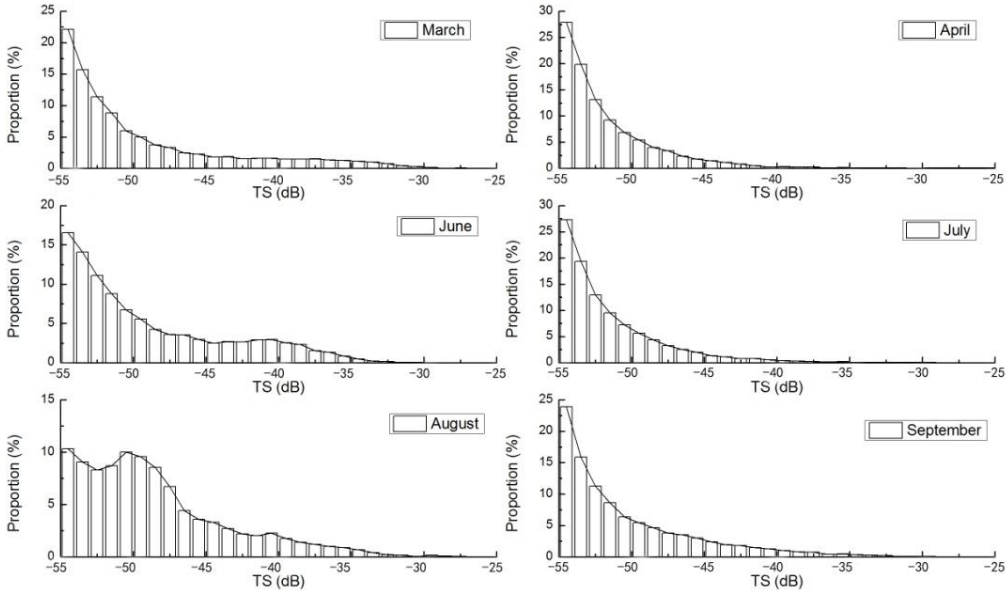

Figure 5. Target strength (TS) distributions in different months in 2016.

To reveal differences in the fish assemblages, fish lengths were converted from TS (Equation (1)) to delineate the proportions of the two groups (i.e., large and small fish). Figure 6 shows the range of the fish length distribution and the probability density. Fish ranged in length from 4 to 110 cm and the lengths were not evenly distributed, as the data were obviously discrete. According to a nonparametric test, the average fish lengths were larger in the rising stage compared to those in the falling stage for both size groups: 22–130 cm for large fish and 4–22 cm for small fish, except in March ($p < 0.01$).

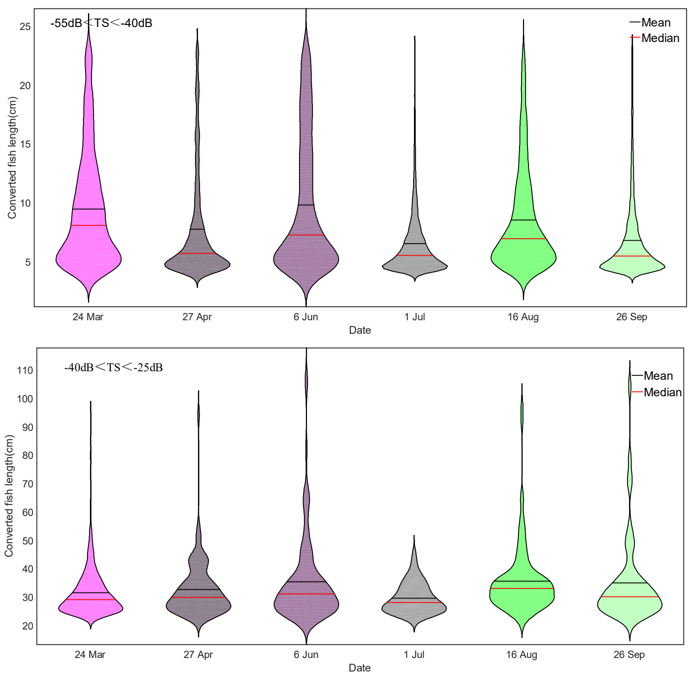

Figure 6. Converted fish length distributions in different TS groups. The vertical length and the horizontal width of each violin graph represent the distribution range of converted fish length and the probability density, respectively. The black and red horizontal lines represent the mean and median of the data distribution, respectively, and the rectangular area between the lines indicates the inter-quartile range.

4. Discussion

The altered flow patterns caused by regulation and operation of the CZD have negatively affected the life histories of fishes in the lower Pearl River. Studies to date have focused mainly on fish communities and their spawning grounds [20,34]. Comparatively, little is known about the temporal and spatial response of fish to hydrological changes because it is difficult to gauge using traditional sampling techniques [5]. In this study, the spatiotemporal distribution of fish in the main breeding season was mapped out using hydroacoustic data. Fish were unevenly distributed across the survey area, as fish densities differed significantly between the two hydrological conditions ($p < 0.01$). This result also reflects fish migration in response to changes in habitat conditions. Variations in the spatiotemporal distribution of fish can be attributed to several possibilities.

First, numerous studies have shown that fish distributions are directly correlated with hydrology, especially in spawning populations. High-flow discharge from the dam results in high river flow velocities and abundant nutrients, which play an important role in various fish behaviors, such as migration, feeding, and reproduction [35,36]. In general, fish in the survey area aggregated during the rising stage and departed after the period of flooding, especially aggregations of large fish.

Second, the area surveyed is a migration channel for fish in the Pearl River. The CZD is the dam nearest to the estuary and its establishment has blocked fish migration. The largest spawning grounds of four major Chinese carps once occurred upstream of the dam [37]. At the same time, because the sampling period was the main breeding season [15], large breeding populations congregated here; consequently, the fish density downstream of the dam was higher than that upstream [38].

Nevertheless, relevant studies have shown that the Changzhou fishway (built at the same time as the dam) is effective under normal operations, as a large number of fish are able to swim to the upstream side of the dam while the spillways are open during the flood period, and the number of native species increased with this connectivity [21–23,39,40]. Therefore, the operation mode of the CZD greatly affects the fishery resources of the lower Pearl River. Combined with relevant studies, the present results suggest that the operating days and the operating frequency of the spillways and the fishway must be increased for the purpose of fish resource protection and ecosystem management.

The TS of a fish indicates the size of the echo; the greater the TS, the stronger the echo relative to the transmission [41]. The TS threshold is usually determined in accordance with the object investigated and a real-time echogram. For instance, Lin et al. [36] investigated the river–reservoir transition zone at the Three Gorges Dam using a minimum TS threshold of −70 dB, a value commonly used for unknown fish species in various waters worldwide. Another study set a lower threshold, at −80 dB, to distinguish and evaluate fish abundance in the presence of gas bubbles [42]. In this study, the water was turbid with high sediment content during the flood and the water released from the dam carried many bubbles; because the TS of sediment and bubbles strongly overlaps with that of small fish, the minimum threshold was set to −55 dB.

For a more intuitive analysis of fish size, TS was converted to body length. As described above, the fish aggregations were manually separated into two size groups at a threshold of −40 dB; that is, small fish (<22 cm) and large fish (>22 cm). The combination of the converted fish lengths and biological information was useful to identify the species that spawn in the survey area [5]. Owing to limitations in identifying species using acoustic techniques, some researchers have combined net or larval fish sampling in order to make species-specific estimates [36,43]. Although the prohibition on fishing from 1 March to 30 June prevented this method of estimation, long-term data on catches and larval fishes revealed the probable species composition during the months surveyed [17,44,45]. Dominant fish species in the study area are barbel chub, black Amur bream, mud carp, and the cyprinid, which together contributed nearly 70% of the total biomass [14,20,35]. Typically, the minimum lengths of mature fish of these species range from 134 to 213 mm [46]. The present results show that the number of large fish (>22 cm) increased substantially during the flood stage; therefore, we speculate that the substantial increase in large fish during the flood period represented breeding populations.

It was important to link spatiotemporal changes in the fish aggregations acoustically detected during the main spawning season with actual spawning events. Successful ovulation is not only direct evidence of spawning but also indicates that adult fish are returning to their spawning ground [47]. Many studies have demonstrated that fish spawning is directly associated with hydrology and larval fish are produced in large numbers during flood peaks [16,17,34]. In the Pearl River, most reproduction of economically important fish species is affected by dam water discharge [11]. There was a greater proportion of larger individuals and higher fish density during the flood stage, indicating that the fish aggregate for spawning during the flood and depart afterward.

Previous studies have focused on the spawning grounds or the fish assemblages and behaviors in the downstream zone adjacent to the CZD. This research extended the study area by approximately 80 km from the CZD to gain knowledge of fish longitudinal distribution and behavior during different months of the main spawning season. The results show that the fish density in this area was higher than that in the upstream section, and fish aggregated in the downstream section during the flood period [38]. Combined with other relevant studies, we conclude that the stretch downstream of the CZD is critical for fish species diversity in the lower Pearl River. Thus, the stretch downstream of the dam should be assigned high priority to protect fish species and their habitats. In addition, spatiotemporal variations in fish density and distribution were proven during different hydrological conditions, and the variation was closely related to water discharge. To quantify the impact of the flooding phase on fish behavior, future research should focus on specific fish behavioral responses (migration, spawning, etc.) to the change in hydrological conditions, such as the substantial increases in aggregations of large fish observed during the flood period.

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Conflicts of Interest: The authors declare no conflict of interest.

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