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Living Status and Perspective of the Silver Carp (*Hypophthalmichthys molitrix*) in the Lower Reach of the Yangtze River: Insights from Population Distribution, Age Structure, and Habitat Preference Analyses

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Abstract: Using systemic, periodic surveys from 2015 to 2019, population distribution, speculated age and habitat preference were analyzed to assess the living status for the Silver Carp (*Hypophthalmichthys molitrix*) in the lower Yangtze River. Small Silver Carps became more temporarily abundant in spring and autumn, and the catch per unit effort (CPUE) fluctuated yearly. Spatially, going from Anqing (AQ) to Changshu (CS), Silver Carps in the 200 mm standard length(SL) group became less abundant, whereas those in the 400–600 mm and >600 mm SL groups steadily increased. According to the Von Bertalanffy growth equation, the Silver Carp exhibits isometric growth, and the inflection point of SL and body weight (BW) were 564.01mm and 2948.31g, respectively, with a growth characteristic index (φ) of 5.0655. The fish dominant age range was 0+ to 5 years, reflecting the young age composition of the fish. Furthermore, the habitat survey findings revealed that the Silver Carp has the different preference on habitat selection in different life history. Juvenile Silver Carps were comparatively staying in the lower Yangtze River, where there exists a relatively stable bifurcated river. Adult fishes were mostly found in the CS and Nantong(NT) section where the river is wide and the food is rich. When compared with the historical survey data, it was found that the Silver Carp live in the AQ through NT section. The living status and perspective of the Silver Carp in the lower reach of the Yangtze River were clarified, and future work should be more concerned with the strengthening of conservation and the restoration of adequate habitat.

Keywords: Silver Carps; coastal habitats; long-term survey; the Yangtze River; environmental factors; restoration and conservation

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1. Introduction

Fish migration, reproduction, mobility, and dispersal are all affected by the combined action of biological and non-biological factors in the aquatic environment on which they rely for existence [1]. The impact of human disturbance is the most significant among them. Habitat quality has declined considerably, and fishery stocks have fallen in varying degrees worldwide due to water diversion initiatives, pollution emissions, and overfishing [2,3]. Habitat quality can be used to assess the ability of ecosystems to provide adequate living conditions for individuals, populations, and communities [4,5]. By the same token, habitat quality is linked to fishery resource potential, and thus scientific recommendations to protect threatened stocks in fisheries is necessary [6].

Habitat selection refers to the selection and preference of animals for the type of place where they dwell, as well as the process by which the animal or its population finds a suitable place to live for a certain subsistence activity (e.g., foraging, migrating, breeding,

or escaping predators) [7]. The selection of suitable habitats for wildlife is a requirement for the natural reproduction of species [7]. Variation in habitat quality can cause differences in the spatial and temporal distribution patterns of populations and influence their habitat selection [8]. In this case, spatial and temporal distribution surveys on populations are widely used in wildlife studies to assess the environmental relevance for the population dynamics of species and their habitats [9–11]. Spatiotemporal distribution studies can uncover reasons for disparate population distributions by integrating the quality of and changes to fish habitats, and habitat changes can indirectly impact population resources by influencing the life history characteristics of fish populations between generations [12]. In tandem, because the structure of a fishery stock is formed over a long time in specific habitats, for which population age structure is a key tool for studying population dynamics [13,14].

The Yangtze River is the largest river in China, at more than 6300 km in length, and is rich in fish resources. The main stretch of the Yangtze River runs through central China from west to east, spanning diverse topography and geomorphology. Because of associated significant differences in climate and hydrology, habitat conditions have formed that are suitable for the reproduction and growth of many fish species, fostering an extremely rich aquatic biodiversity [15]. According to historic surveys, more than 400 fish species were originally distributed in the Yangtze River Basin, of which as many as 156 species are endemic [16]. However, persistent and expanding human disturbances have greatly damaged the basin's ecological environment, leading to a significant decline in fishery stocks [17]. Migratory fishery stocks in the lower reaches of the Yangtze River have incurred significant declines, and semi-migratory fish resources have also undergone varying degrees of decline [18].

The Silver Carp (*Hypophthalmichthys molitrix*), one of the four major Chinese carps, is widely distributed in its main water bodies and those of other Asian countries as well [19,20]. This fish has typical river-lake migratory characteristics and chooses differing water body types as habitats at different stages in its life history [21]. In China, the main spawning grounds for Silver Carp are distributed in the middle reaches of the Yangtze River [22]. According to survey work, as early as 1981, spawning numbers of the four major fish species in the middle and upper reaches of the Yangtze River were already in serious decline, being just 15.7% that in the 1960s [18], and yearly fish larvae have decreased from 6.7 billion in 1981 to 100 million in 2015 [23], a significant reduction in fish resources [24]. Research on Silver Carp' habitat utilization indicated that juveniles have an affinity for habitat on the margins of flood waters [25]. Although many studies have investigated the spawning grounds [26], early resources, [27] and genetic diversity [28] of the four major Chinese carps in the Yangtze River Basin, few have examined the spatial-temporal distribution patterns and the habitat preferences of Silver Carp [22].

Studying the habitat preferences of fish is conducive to understanding the living habits of fish, obtaining valuable fish distribution information, and scientifically managing fish resources in a sustainable manner. To reliably ascertain the current status of Silver Carp populations, with a view to scientifically protecting the Silver Carp resources in the Yangtze River, periodic surveys on Silver Carp were conducted in eight sections of the lower reaches of the Yangtze River. In this regard, through fundamental data analysis for Silver Carp resource assessment, exploration on the habitat selection process of Silver Carp, and studying the geographical and temporal features relating to habitat, we provide a scientific basis for a Silver Carp resource conservation plan.

2. Materials and Methods

2.1. Survey Period and Sampling Sites

From 2015 to 2019, the eight sections were chosen and monitored in the lower reaches of the Yangtze River, each section consisting of two survey sites, one on the left and the other on the right bank (Figure 1). Details for the eight sections areas follows:Anqing (AQ), Tongling (TL), Wuhu (WH), Dangtu (DT), Zhenjiang (ZJ), Jingjiang (JJ), Changshu (SC), and Nantong (NT). The AQ section is close to the middle reach of the Yangtze River, with

relatively rapid currents, low levels of human development, high coastal stability and rich vegetation. The water quality of the TL section is relatively clear, with more natural habitats but little coastal vegetation. The Wuhu section has shallow banks in the center of the river, rich vegetation along the shore, rock piles along the shore, and many kinds of small habitats. The embankment of the DT section has high stability, factories are distributed along the shore, and a large number of ships are docked on the left bank. The ZJ and JJ sections of the river are highly developed, with little vegetation along the coast replaced by factories and docks. The Changshu and Nantong sections of the river are close to the estuary and are significantly affected by tides, with high water salinity, well-developed shipping and turbid water quality. Samples of fish were collected daily from each section for five to seven days per month.

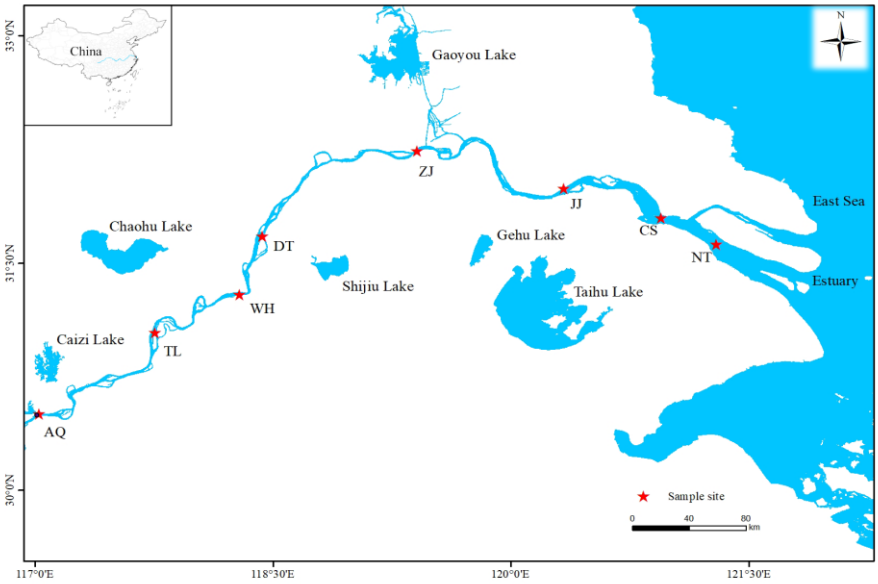


Figure 1. Sampling map of Silver Carp in the lower Yangtze River. Note: AQ, Anqing; TL, Tongling; WH, Wuhu; DT, Dangtu; ZJ, Zhenjiang; JJ, Jingjiang; SC, Changshu and NT, Nantong. Two survey sites were set in each section, one on the left and the other on the right bank.

2.2. Research Methodology

2.2.1. Fish Collection

The fishing net includes the trap net and multi-mesh gill net. A type of trap bet called a maze trap was used, and the four corners of the trap net are fixed in the water by four bamboo poles, with the mouth of the net facing upstream, showing a funnel shape, so it is difficult for the fish to get out of after entering the net. The length of a single trap net is 75 m, the net height is 5 m, the mesh size of the block net is 2.0 cm, and the capsule mesh size of the bag net is 1.0 cm. The length and height of a single multi-mesh gill net are 100 m and 2 m, respectively, and the mesh sizes are 2 cm, 4 cm, 6 cm, 8 cm, 10 cm and 14 cm. During the investigation, the trap net and multi-mesh gill net were lowered to the designated investigation waters before 4:00 p.m., and the nets were retrieved before 8:00 a.m. on the next day. For each catch, the standard length (SL, to 0.01 mm) and body weight (BW, to 0.1 g) were counted with aIP67 Metal Housing Waterproof Digital Caliper(Guilin Guanglu digital measurement and Control Co., Ltd., Guilin, China) and electronic balance(Shanghai Yaoxin Electronic Technology Co., Ltd., Shanghai, China), respectively. At the same time, about 10 scales were taken from the anterior and inferior part of the dorsal fin of the middle part of the fish, above the lateral line. The scales were removed and stored in scale bags and brought back to the laboratory as material for age identification.

2.2.2. Scale Identification

For each fish, three to five scales with regular shape that were intact were selected and gently cleaned of the epidermis and mucus with a brush, immersed in 5% ammonia-water for 24 h, and then rinsed with water and placed between two slides to make fish age identification slides. Observation and recording of annuli character and age was undertaken under a stereoscopic microscope (LEICA S9D) based on the annuli character of scales. To estimate fish age, the duplicate annuli count of two scale readers were compared and if the age differed, a third reading was performed. Age results were recorded as "1, 2, 3 . . . " indicating a further period of growth at this age. "0+" means having not yet reached the age of one year.

2.2.3. Habitat Investigation

Along the right bank of the Yangtze River's AQ to the estuary section (NT), a habitat survey was carried out. After reaching the river estuary, the survey was carried out from the Yangtze River's left bank upstream. Motorized fish boats were deployed at the same time to gather data on relevant habitat quality indicators in the river's center in each sampled section. Habitat complexity, vegetation diversity, human disturbance, and riparian land-use type [29] were visually assessed by flying a drone (DJI Phantom 4 pro v2.0; Quadcopter, SZ DJI Technology Co., Ltd., Shenzhen, China) to photograph the habitat within 1000m of the sampling site at a height of 120 m under clear weather conditions, and then bringing the photos(4096 $\times$ 2160) and videos(4K 60P) to the lab for their recording and analysis. Water temperature, dissolved oxygen, and PH were measured by a water quality analyzer (Thermo Fisher Scientific Inc., Waltham, MA, USA), nephelometric turbidity unit was measured by portable turbid meter(Hash Water Analysis Instruments Co., Shanghai, China).Flow velocity, depth, runoff and substrate data wereobtained by the Yangtze River Hydrological Information Network. Obtaining indicators of habitat quality such as embankment stability and river course changes requires the examining of the historical documentation [30] of relevant waterways or consulting experts (through the assistance of the Yangtze River Channel Management Bureau).

2.2.4. Habitat Assessment

UAV (unmanned aerial vehicle)-based photography and field investigation methods were used to explore the coastal habitats of the lower Yangtze River, from AQ to NT, throughout the sampling period. Following the evaluation methodology of river habitat indicators [29], the strengths and weaknesses of 10 habitat indicators were assigned a value based on a comprehensive evaluation that relied on examined aerial photographs from drones, expert opinions and other relevant data, in addition to the actual field conditions. A maximum total score of 20 points was given for each indicator, from which four grades of habitat quality were classified into four grades: excellent, good, average, and poor; their corresponding score intervals are 16–20, 11–15, 6–10, and 1–5, respectively. The evaluated river habitat index (RHI) score was acquired from a cumulative accumulation of 10 indicators, with a maximum total value of 200 points. Accordingly, by referring to the relevant classification grading criteria, an RHI > 150 was considered "excellent", and, likewise, 120 < RHI $\leq$ 150 was "good", 90 < RHI $\leq$ 120 was "average", 60 < RHI $\leq$ 90 was "poor", and RHI $\leq$ 60 was "bad" (Table 1).

Table 1. Habitat evaluation indicators and evaluation criteria for the lower Yangtze River.

No.	Evaluation Indicators	Metric Component	Excellent	Good	Average	Poor
1	Substrate	Proportion of sediment such as silt	<25%	25–50% (50% included)	50–75%	>75%
2	Habitat complexity	Number of small habitats species	>3	3	2	1
3	The flow rate and depth	Number of water flow types	>3	3	2	1
4	Embankment stability	Proportion of embankment erosion	<5%	5–25% (25% included)	25–45%	>45%
5	Stream changes	Proportion of stream change	<5%	5–10% (10% included)	10–15%	>15%
6	Water quantity condition	Proportion of the river channel exposed	<5%	5–15% (15% included)	15–25%	>25%
7	Vegetation diversity	Proportion of riparian vegetation cover	>50%	30–50% (30% included)	10–30%	<10%
8	Water quality conditions	Water grades	I	II	III	IV
9	Human disturbance	Proportion of river banks with roads	<10%	10–30% (30% included)	30–50%	>50%
10	Type of land use	Proportion of riparian cultivated soil	<10%	10–30% (30% included)	30–50%	>50%
Grade value			20,19,18,17,16	15,14,13,12,11	10,9,8,7,6	5,4,3,2,1

Note: Water grade classification according to Environmental Quality Standards for Surface Water (GB 3838–2002).

2.3. Data Analysis

Here, the power function in IBIM SPSS Statistics 25 was used to predict BW as a function SL, using this formula:

$$W = aL^b \quad (1)$$

where W isweight (kg), L islength (cm), a is the scaling factor, and b is the shape parameter, which can reflect the growth of Silver Carp. When $b < 3$, the growth pattern is negative allometric; when $b = 3$, Silver Carp is distinguished by normal growth.

A student's t-test was used to test the difference between the power index "b" and "3" of the regression equation of SL vs. BW [31], as follows:

$$\mathrm{t} = \frac{\mathrm{LSD}}{\mathrm{WSD}} \times \frac{|b-3|}{\sqrt{1-\mathrm{r}^2}} \times \sqrt{\mathrm{n}-2} \quad (2)$$

where LSD and WSD denote the standard deviation of the logarithm of SL and BW, respectively; the "n" and "r" are the number of specimens and correlation coefficient, respectively.

The caught Silver Carps were divided each month into different SL groups (at 50 mm intervals), using the ELEFAN I technique [32], to obtain monthly distribution frequencies of different SL groups of Silver Carp. Next, the asymptotic SL (L_∞), growth coefficient k, were estimated using FISAT-II software, and asymptotic BW (W_∞) were calculated by $W_\infty = aL_\infty{}^b$.

The theoretical age at zero length (t_0) of Silver Carp was estimated by the formula [33]:

$$\ln(-t_0) = -0.3922 - 0.2752 \ln L_\infty - 1.038 \ln K \quad (3)$$

It is assumed that its growth follows the von Bertalanffy growth equation [34], therefore fitting its Standard length and weight growth equationas follows:

$$L_t = L_\infty \left[1 - \mathrm{e}^{-k(t-t_0)}\right] \quad (4)$$

$$W_t = W_\infty \left[1 - \mathrm{e}^{-k(t-t_0)}\right]^{\mathrm{b}} \quad (5)$$

L_t and W_t are the SL (mm) and BW (g) of fish at age t, respectively; L_∞ and W_∞ areasymptotic SL (mm) and asymptotic BW (g), respectively; k is the growth coefficient; t_0 is the theoretical age at zero length, indicating the theoretical age when body length and weight are equal to 0; b is the correlation coefficient.

The first- and second-order derivatives of t in the growth equation (Equations (4) and (5)) can then be obtained as the growth rate and acceleration curve equations for SL and BW, respectively [35,36]:

$$dL/dt = L_\infty k e^{-k(t-t_0)} \quad (6)$$

$$dW/dt = bW_\infty k e^{-k(t-t_0)} \left[1 - e^{-k(t-t_0)}\right]^{b-1} \quad (7)$$

$$d^2L/dt^2 = -L_\infty k^2 e^{-k(t-t_0)} \quad (8)$$

$$d^2W/dt^2 = bW_\infty k^2 e^{-k(t-t_0)} \left[1 - e^{-k(t-t_0)}\right]^{b-2} \left[be^{-k(t-t_0)} - 1\right] \quad (9)$$

The growth inflection age of Silver Carp refers to that age when the growth rate reaches the maximum or the growth acceleration is 0. The calculated formula is [37]:

$$t_{tp} = \ln b/k + t_0 \quad (10)$$

The spatiotemporal variation in characteristics of Silver Carp was examined in two ways. The first was to calculate the proportion of the catch individuals of each SL group to the total catch individuals according to the year and quarter, and then compare the changed proportion of each SL group between quarters. The second was to calculate the proportion of SL groups in different river sections and compare the spatial changes of different SL groups. For this, data were analyzed in Origin 2018 software.

3. Results

3.1. Catch and Population Structure

A total of 2006 ship surveys were launched in the Yangtze River's lower reaches from 2015 to 2019, these catching a total of 5729 Silver Carps together weighing 9608.99 kg, accounting for 3.49% and 38.71% of the total fish weight and number catch, respectively (Table 2).

Table 2. Silver Carp sampling in each section of the lower Yangtze River.

Survey Section	CPUE Weight (Kg)	CPUE Number (Individuals)	TotalFish Weight (Silver CarpWeight)	Total Fish Number (Silver CarpNumber)
AQ	12.92	581.7	1524.56 (327.32)	68,641 (1414)
TL	18.31	725.65	1409.87(407.17)	55,875 (2034)
WH	6.04	76.26	930.16 (172.26)	11,744 (72)
DT	10.84	99.69	1355 (441.59)	12,461 (1599)
ZJ	34.1	53.21	13,640 (5850.20)	21,284 (398)
JJ	3.65	51.08	492.75 (96.78)	6896 (59)
CS	7.78	16.73	4442.38 (1287.85)	9553 (94)
NT	8.98	18.38	3825.48 (1025.99)	7830 (59)

Note: CPUE: catch per unit effort, serving as weight (kg) or number (tail) of each investigation a day.

The age of Silver Carps in the total catches spanned 0-14+ years. The dominant age class consisted of those 0–5 years old; whose correspondence between age and SL was listed in Table 3.

Table 3. Standard length-age comparison table of the Silver Carp population.

Standard Length(mm)	Age										Average Age
	0+ N (%)	1 N (%)	2 N (%)	3 N (%)	4 N (%)	5 N (%)	6 N (%)	7 N (%)	8 N (%)	9 N (%)	
10–59	105 (11.4)										—
60–109	457 (49.5)										—
110–159	276 (29.8)	356 (17.5)									0.6
160–209	86 (9.3)	597 (29.3)									0.9
210–259		689 (33.8)	203 (29.4)								1.2
260–309		377 (18.5)	377 (54.7)								1.5
310–359		18 (0.9)	96 (14.0)	134 (28.0)							2.5
360–409			13 (1.9)	248 (51.9)	48 (7.7)						3.1
410–459				96 (20.1)	393 (63.1)						3.8
460–509					175 (28.1)	189 (33.7)					4.5
510–559					7 (1.1)	355 (63.4)	98 (38.1)				5.2
560–609						16 (2.9)	137 (53.3)	34 (35.8)	6 (14.6)	2 (12.5)	6.2
610–659							22 (8.6)	61 (64.2)	35 (85.4)	11 (68.8)	7.3
660–709										3 (18.7)	9.0
Total	924	2037	689	478	623	560	257	95	41	16	
Average SL	93.3	178.3	272.0	367.1	437.2	495.0	547.4	591.0	628.8	662.7	

Note: The samples of silver carp aged 10 to 14+ were insufficient to be included in Table 3.

3.2. Seasonal Distribution Patterns of Silver Carps

The catch quantity of Silver Carp in autumn was significantly higher than that in spring, summer and winter, and the small Silver Carp (<200 mm) was most abundant (Table 4; Figure 2). In spring, many small (<200mm) and medium-sized (200–400mm) Silver Carps inhabited the DT section, although the latter was the more dominant group.Mostly medium-sized as well as large-sized Silver Carps (400–600mm) inhabited theCS section. In the other six sections of the river, small Silver Carp accounted for the highest proportion of fish caught. In summer, proportions of small Silver Carp decreased in all sections, while the proportion of medium and large-sized Silver Carps increased significantly in the ZJ, CS, and NT sections and more large Silver Carp (>600mm) appeared in the DT and NT sections. In autumn, the proportion of small Silver Carp in the AQ to DT section was the greatest, being least in the CS section. We found many medium-sized Silver Carp inboth the JJ and NT sections, and medium and large-sized Silver Carp dominated the ZJ and CS sections. In winter, most medium-sized Silver Carp were distributed in the TL, DT, JJ and NT sections, with the JJ section having the highest proportion. Although the proportion of small Silver Carp fell in the AQ, WH, and ZJ sections, small Silver Carp still dominated there, while the CS section was dominated by medium and large-sized Silver Carp (Table 4; Figure 2). These results showed that small and medium-sized Silver Carp were more prevalent in spring and autumn, mostly in the AQ, TL, WH, and DT sections, while medium and large-sized Silver Carp were more common in summer and winter, mainly in the section near the river's estuary.

Table 4. Characteristics of fish distribution in different seasons.

Season	Number (Individuals)	Standard Length/mm		
		Range	Mean Value	Dominant SL Class
Spring	861	13.29–640	275.96 ± 152.63	<200
Summer	998	31.9–770	324.36 ± 155.54	400–600
Autumn	2528	34.94–770	253.96 ± 155.26	<200
Winter	1342	11.92–700	292.59 ± 154.78	200–400

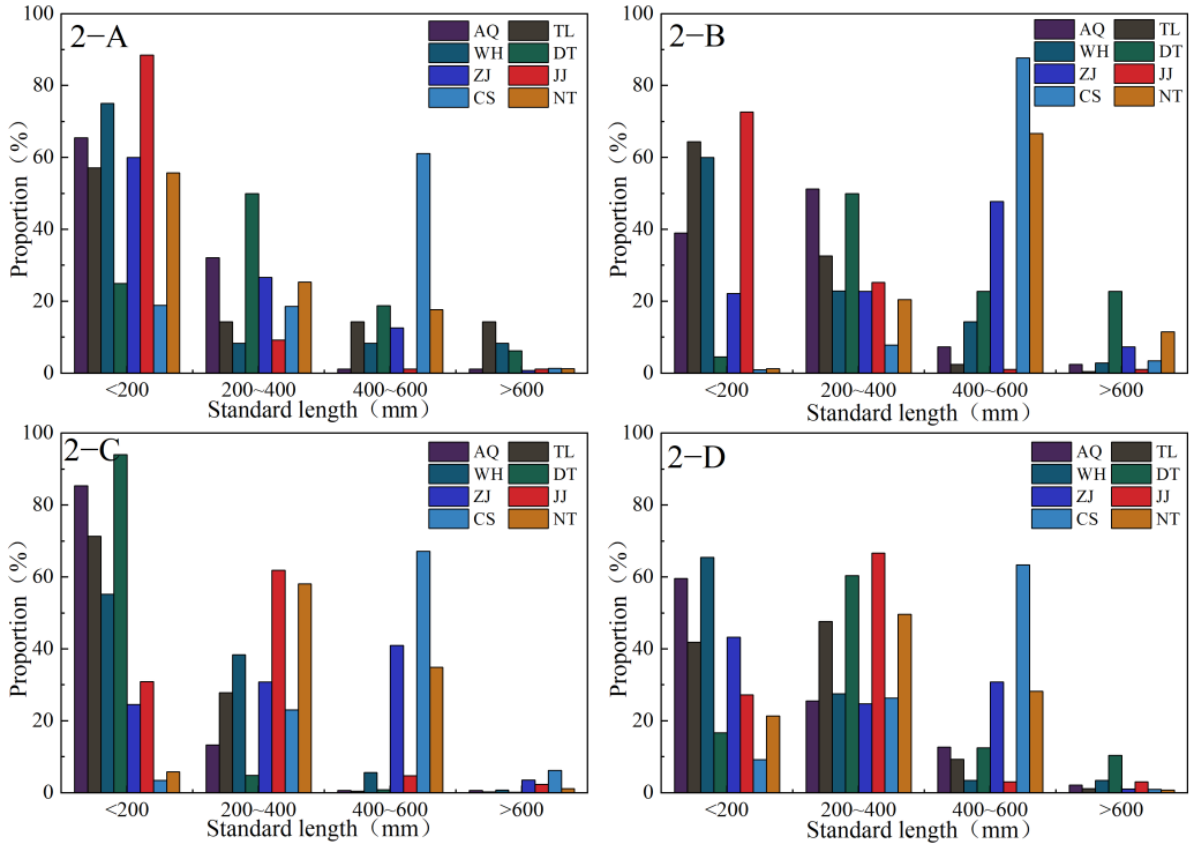


Figure 2. Seasonal distribution patterns of Silver Carp in the lower Yangtze River. (**2–A**)The proportion of Silver Carp in different SL groups in spring; (**2–B**) the proportion of Silver Carp in different SL groups in summer; (**2–C**) the proportion of Silver Carp in different SL groups in autumn; (**2–D**) the proportion of Silver Carp in different SL groups in winter.

3.3. Section Distribution Characteristics of Silver Carp

The AQ and TL sections have many bifurcated channels which can provide an ideal habitat for juvenile fish growth. In both sections there were primarily small and medium-sized Silver Carp, with a significant predominance of small groups (<200 mm), followed by medium-sized groups (200–400 mm). In the WH and DT sections, multiple river bays there could attract foraging small and medium-sized Silver Carp; indeed, small and medium-sized Silver Carp are the dominant groups there. The ZJ section is distinguished by a complicated channel system, with several bays. There, the proportion of small Silver Carp increased steadily, but the proportion of medium to big-sized Silver Carp remained relatively stable. In the JJ section, the small and medium-sized Silver Carp are the dominant groups. The CS and NT sections are near the estuary and thus feature typical tidal characteristics, namely variation in salinity and plenty of prey. Medium and large-sized Silver Carp (400–600mm) are dominant in these two sections, but the proportion of large Silver Carp (>600mm) is clearly greater in the NT than in CS section, which showed an upward yearly trend. Together, these results revealed that the proportion of Silver Carp in the 200 mm length group decreased in the river sections spanning AQ to NT, that is, as one got closer to where the river empties into the sea; conversely, the proportions of Silver Carp in the 400–600 mm and >600 mm SL groups rose rapidly (Figure 3).

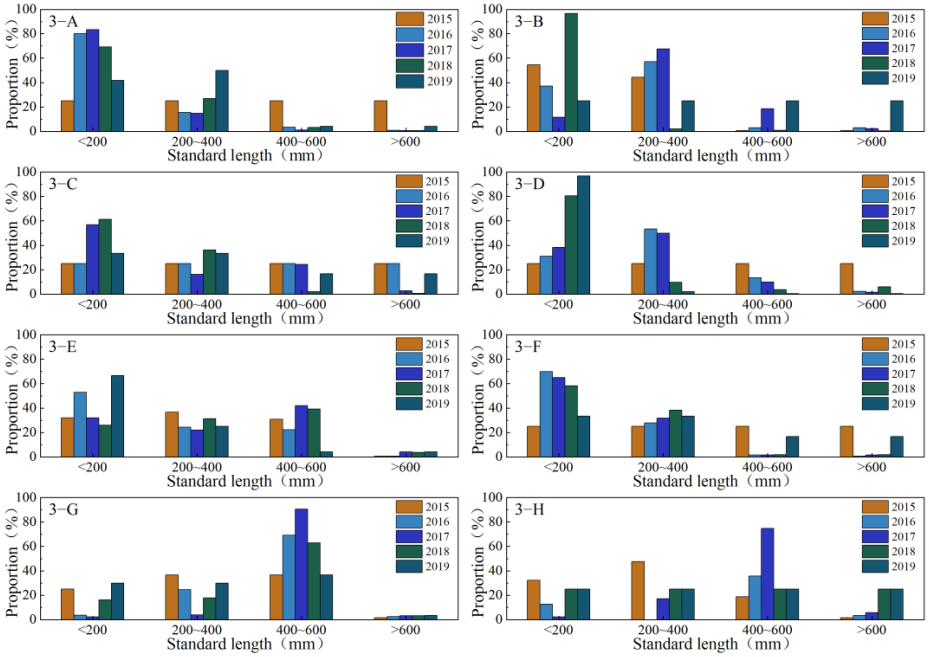


Figure 3. Section distribution characteristics of Silver Carp in the lower Yangtze River. The proportion of Silver Carp in different SL groups in AQ section (**3–A**), TL section (**3–B**), WH section (**3–C**), DT section (**3–D**), ZJ section (**3–E**), JJ section (**3–F**), CS section (**3–G**) and NT section (**3–H**).

3.4. Growth Characteristics of Silver Carp in the Yangtze River

The fitted relationship between SL (L) and BW (W) of Silver Carp is $W = 2.6804 \times 10^{-5} L^{2.9567}$ ($R^2 = 0.9674$, n = 4443). The estimated b was 2.96, which is very close to 3 and, therefore, the growth pattern of the Silver Carp population in the lower Yangtze River is isometric (growth rate $b \approx 3$; Figure 4).

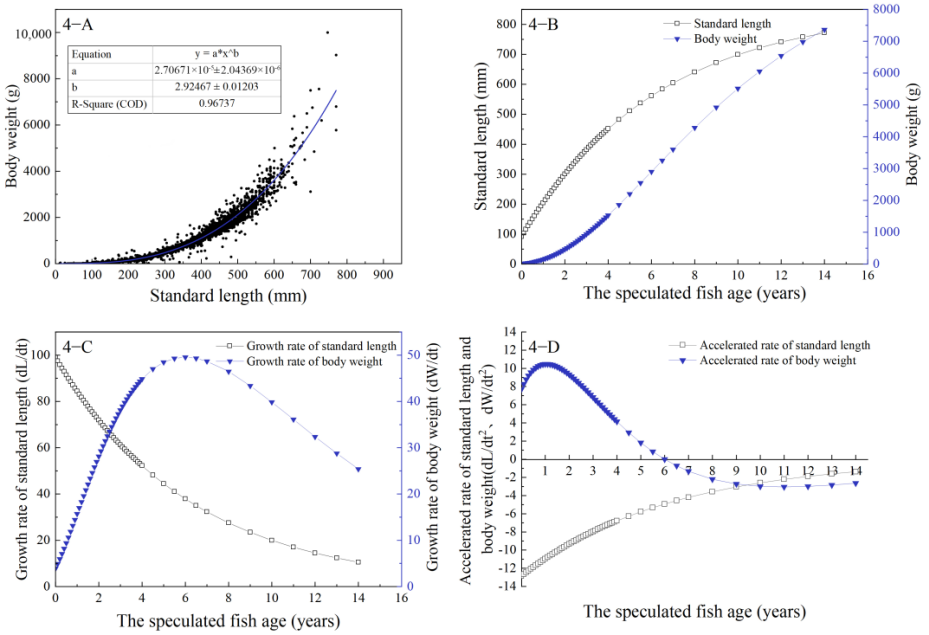


Figure 4. The growth correlation curve between SL and BW of the Silver Carp. (**4–A**) is for the growth fitting curve of Silver Carp; (**4–B**) is for the SL and BW of Silver Carp; (**4–C**) is for the growth rate of SL and BW of Silver Carp; (**4–D**) is for the trend of growth rate of SL and BW of Silver Carp.

The change in SL and BW of Silver Carp's individual age can also be described by the Von Bertalanffy growth equation. The progressive SL (L_∞), growth coefficient (k), and initial age (t_0) were calculated here as 852.52 mm, 0.16, and 0.71, respectively, byapplying the ELEFAN I technique on FISATII software [32]. According to the relationship between SL and BW, the asymptotic BW (W_∞) was 10, 231.99g, with a growth characteristic index (φ) of 5.0655. Based on these parameters, the SL and BW growth equations of Silver Carp in the lower Yangtze River were determined as follows.

$$L_t = 852.52\left[1 - e^{-0.16(t+0.71)}\right] \tag{11}$$

$$W_t = 10231.99\left[1 - e^{-0.16(t+0.71)}\right]^{2.9567} \tag{12}$$

The empirical data on SL and BW of Silver Carp were then depicted as growth curves (Figure 4). The curve of SL as a function of age is an asymptote without an inflection point: the growth rate of SL decreases from fast to slow, and finally converge to the same value. The growth curve of BW and age is a sigmoid (S-shaped) gradual curve with an inflection point.

Next, the equations for Silver Carp's growth rate and acceleration was obtained as the first and second derivative of the growth equation of its SL and BW as follows.

Standard length growth rate:

$$dL/dt = 136.40e^{-0.16(t+0.71)} \tag{13}$$

Body weight growth rate:

$$dW/dt = 4840.47e^{-0.16(t+0.71)}\left[1 - e^{-0.16(t+0.71)}\right]^{1.9567} \tag{14}$$

Standard length acceleration:

$$d^2L/dt^2 = -21.82e^{-0.16(t+0.71)} \tag{15}$$

Body weight acceleration:

$$d^2W/dt^2 = 774.47e^{-0.16(t+0.71)}\left[1 - e^{-0.16(t+0.71)}\right]^{0.9567}\left[2.9567e^{-0.16(t+0.71)} - 1\right] \tag{16}$$

Specifically, for the age at the inflection point, t_{tp} = 6.07, the SL and BW of Silver Carp was 564.01 mm and 2948.31 g, respectively. Before the BW growth rate reaches this inflection point, a rapid growth stage is evident in the life history of Silver Carp, which has significant positive correlation with age; however, once beyond that inflection point, growth rate was negatively correlated with age, and Silver Carp entered the stage of slow growth.

In the acceleration curves of SL and BW for the Silver Carp (Figure 4), the latter increased at a fast pace prior to the 0+ age class, but thereafter decreased. At the inflection point of BW growth (6.07), the acceleration was 0, and it declined continually until it reached the lowest point at the 11age class.

3.5. Habitat Characteristics of Different River Sections

According to the habitat assessmentmethod, habitat composite index scores and evaluation results are displayed in Table 5. The RHI ranged from 73 to 117 across the eight river sections surveyed in the lower Yangtze River, with a small difference in grade level: Seventy-five percent of the river sections had a poor grade and 25% had an average grade. Because of its vast diversity of coastal vegetation, lack of farmed soil, nutrient-rich coastal soil, and strong bank stability, the AQ river stretch earned the best rank. The high intensity of human disturbance, high disturbance, and low diversity of vegetation on banks, low cover, and a single small habitat are features distinguishing the poorer habitats (Table 5).

Table 5. Habitat quality assessment in the lower Yangtze River.

Section / Indicators	AQ	TL	WH	DT	ZJ	JJ	CS	NT
Substrate	5	4	5	4	4	5	5	3
Habitat complexity	10	3	13	3	4	3	8	10
the flow rate and depth	7	6	9	8	8	5	3	8
Embankment stability	16	9	10	14	10	12	17	7
Stream changes	10	4	5	8	5	14	9	8
Water quantity condition	13	12	11	11	10	10	10	10
Vegetation diversity	20	8	13	9	6	7	8	6
Water quality conditions	9	9	8	8	7	7	6	6
Human disturbance	9	8	10	5	3	1	2	3
Type of land use	18	11	17	11	16	16	10	16
River habitat index	117	74	101	81	73	80	78	77

The Yangtze River's lower sections, from AQ to NT, include roughly 32 sandbars of various widths, and the water potential is rather flat due to the combined action of runoff and tide. The span of the river from the AQ to DT section was a typical fork-shaped river, with many bays and complex water flow patterns, as well as vital protected areas for the Yangtze finless porpoise and *Coilia nasus*, serving as important nursery sites for the Silver Carp.The RHI of AQ and WH was 117 and 101, respectively. There is good vegetation coverage along the shore, high bank stability, and little interference from human disturbance.The RHI of the TL and DT section was 74 and 81, respectively. Both sections have low scores for their habitat complexity index, which is mainly affected by human disturbance and water diversion projects.

The span from the ZJ to NT section was a typical tidal river with a short material cycle and a complex water environment, making it a critical feeding area for the Silver Carp. Therefore, many Silver Carp longer than 400 mm seek prey and grow here. The RHI of the ZJ, JJ, CS, and NT sections was 73, 80, 78, and 77, respectively, and therefore was rated as poor. The JJ and CS sections each have a single current, which is slow in its velocity, and deep water. The CS and NT section were close to the estuary, with a single sediment-dominated substrate, where there is a lot of shipping traffic and disturbances from human activities.

4. Discussion

4.1. Seasonal Distribution Characteristics of Silver Carp

Silver Carp, being a semi-migratory fish species, has a distinct seasonal distribution pattern [38]. In spring, lakes and estuaries harboring abundant prey will attract most of the foraging adult fish [39]. The DT and CS sections have complex water systems, many river bays, and are connected to many small fork rivers. Adult Silver Carp will enter the river bay and lakes to forage there, so the proportion of large-sized Silver Carp is small in either section. In summer, which is the breeding season of Silver Carp, the temperature of river water rises and the water level begins to rise; stimulated by the current, the adult fish group begin their reproductive migration from lakes to the Yangtze River's main stretch in the middle reaches [40,41], resulting in a general increase of medium-sized and large-sized Silver Carp in the eight river sections. Following the breeding season, the fish larvae enter lake-linking rivers to fatten up [40,41], such as the Wan River, which is connected the AQ section. However, salinity in the CS to NT sections is high, limiting the survival of fish larvae. Consequently, in autumn, the proportion of small Silver Carp is high from the

AQ to JJ sections, while it is always low going from the CS to NT sections. In winter, the Yangtze River's water level drops, and most adult fish migrate to the deep riverbed for overwintering [42]. Juveniles, on the other hand, remain in the deep water of lakes and other subsidiary water bodies [43]. Hence, the majority of small Silver Carp in the DT and CS sections migrate into the lakes, whereas medium to large size Silver Carp remain in the Yangtze River for overwintering. The seasonal dispersion patterns of adults are therefore clearly linked to their reproductive biological traits and local environment.

4.2. Habitat Preferences of Silver Carp

There are great differences in hydrological and nutritional conditions among habitat types, and Silver Carp differing in size have pronounced preferences for certain habitats, which manifests in the seasonal and river section distribution characteristics of Silver Carp [44]. In our study, small Silver Carp (<200mm) were mainly caught from the AQ to the JJ sections, while in sections CS and NT there were more medium- and large-sized Silver Carp (400–600mm). This distribution pattern may be caused by the fact that the AQ section is a relatively stable bifurcated river, with some complex shoals, yet is still connected with the Wan River. The complex ecosystem with its connected features of large rivers and lakes can provide a more adequate place for small Silver Carp to quickly grow and gain weight (fattening), and the adjacent section also offers a relatively superior habitat for them. Nevertheless, some larvae and juveniles produced in the Yangtze River's middle reaches directly enter river-linking lakes for fattening, and the majority of larval and juvenile fish drift along the river when feeding [38]. Therefore, most Silver Carp caught from the AQ to JJ sections were in fact small Silver Carp, and they favored a natural water habitat. Although many factors influence the quality and distribution of fish habitats, river sediment type is closely linked to the natural reproduction of migratory fish [45]. Floods occur frequently in the lower Yangtze River in summer, and the water potential changes dramatically; the sudden increase in runoff and splash erosion of rainwater together cause riverbed sediment to move towards the estuary. Under the force of tide, substantial amounts of sediment accumulate in CS, NT, and other sections, resulting in an augmented concentration of suspended solids in the water body and reduced habitat suitability for fish [46]. Meanwhile, the CS to NT sections are both typical tidal sections with complex water flow patterns, where the greater turbidity and salinity will also limit the suitability of this habitat for fish, thus decreasing their abundance [47], leaving these aquatic areas unsuitable for small Silver Carp's fattening. On the other hand, periodic tidal action also promotes the material circulation and energy flow from the CS to the NT section, which greatly improves ecosystem productivity. Such a complex and varied tide-sensing habitat with ample prey provides suitable food resources and places for the fattening up of large Silver Carp [38]. Hence, compared with the lake-linking rivers such as that in the AQ section, large Silver Carp may choose the tidal river sections from CS to NT as their preferred habitat.

Considering their proximity to the sea, which entails predictable river–sea interactions and large changes in hydrological indicators due to alternating high and low tides, CS and NT sections were deemed as poor in the habitat quality assessment (Table 5). This reduced habitat suitability was driven by high human interference, low diversity of vegetation on both sides of the river, low plant coverage, and a single microhabitat. The habitat in both sections is mostly unsuitable for the survival of very young Silver Carp with weak environmental adaptability. On the contrary, the high tide brings abundant natural prey [48], and, because larger, senior Silver Carps have better environmental adaptability, the majority of them congregate in the CS and NT sections for feeding and fattening. However, since Silver Carp is a common species, and this fish has good swimming ability and strong adaptability, it has no obvious preference for its habitat, but it has a preference for a natural water habitat [49].

4.3. Age Structure Characteristics of Silver Carp Population

Both genetics and the environment influence population age structure and growth, and fish species acquire distinct growth patterns in response to diverse environmental conditions [50]. The numerical variation in fish populations can be inferred by analyzing and evaluating their population age structures. A continually reproducing population may theoretically have a dynamic equilibrium state in the age structure, wherein the quantity and proportion of individuals in each age class changes negligibly in the absence of interference from external environmental influences [35]. The age distribution of the population will change as the external environment changes and the influence of environmental factors strengthens; thus, variation in age structure can be utilized to anticipate the trends of changes occurring in fish populations. During the years 1981–2003, the population age structure and dominant age class of Silver Carp in the Yangtze River's main stretch displayed varying degrees of simplification [25,51,52], but the age structure of Silver Carp has become more complex every year from 2003 through 2017 [53,54]. Overall, the age range of Silver Carp in our study indicated an age structure complexity similarity in degree to that found in the Middle Yangtze River in 2016–2017 [53] (Table 6). While the age structure is complicated, the proportion of younger Silver Carps is increasing in 2015, 2016, and 2017 (Figure 5), respectively, with the dominant age class being 0+ to fiveyears old. In 2018 and 2019, there was a significant increase in the proportion of 0+ to two-year-old Silver Carp and a significant decrease in the proportion of three to five year-old Silver Carp, with the age structure tending to be simpler and constituted more by the young fish (Figure 5). It appears that external effects on Silver Carp intensified in 2018 and 2019, leading the population's age structure to simplify further, which might be linked to habitat deterioration along the river due to fishing by humans. The likely cause of this phenomenon is that the age structure of the Silver Carp population was relatively stable in 2016 and 2017: the proportion of individuals of all ages in the dominant age class was relatively balanced; more individuals had reached sexual maturity, and the proportion of one-year-old Silver Carp increased rather than decreased. In 2018, the dominant age class was 0+ to twoyears, with a declining proportion of senior individuals, fewer sexually mature individuals, and low population replenishment, such that the 0+-aged individuals declined significantly in 2019, while one-year old individuals, which developed from eggs produced in 2017, continued to show an increasing trend. If this interpretation is correct, the proportion of one-year-old Silver Carp will decline dramatically by the 2020s, while the number of Silver Carp that are two years old will grow to some currently unknown amount.

Table 6. Age structure of different Silver Carp populations in the Yangtze River.

Year	Sampling point	Age proportion							Reference
		1	2	3	4	5	6	7	
1981	The main stream	–	–	33.3	44.4	18.5	0	3.7	[25]
1991–1992	Swan oxbow	66.57	30.60	1.49	1.19	0.15	–	–	[55]
1994–1999	Middle sections	24.24	51.52	16.16	3.01	5.05	–	–	[21]
2001–2003	Jingzhou	15.38	61.54	23.08	–	–	–	–	[56]
2008–2010	Upper sections	8.8	16.9	29.1	16.2	20.9	8.1	–	[54]
2016–2017	Yichang–Jinzhou	0.78	12.11	21.48	27.73	23.44	7.81	6.64	[53]
2015–2019	Anqing–Nantong	35.57	12.04	8.36	10.88	9.78	4.50	1.65	This study

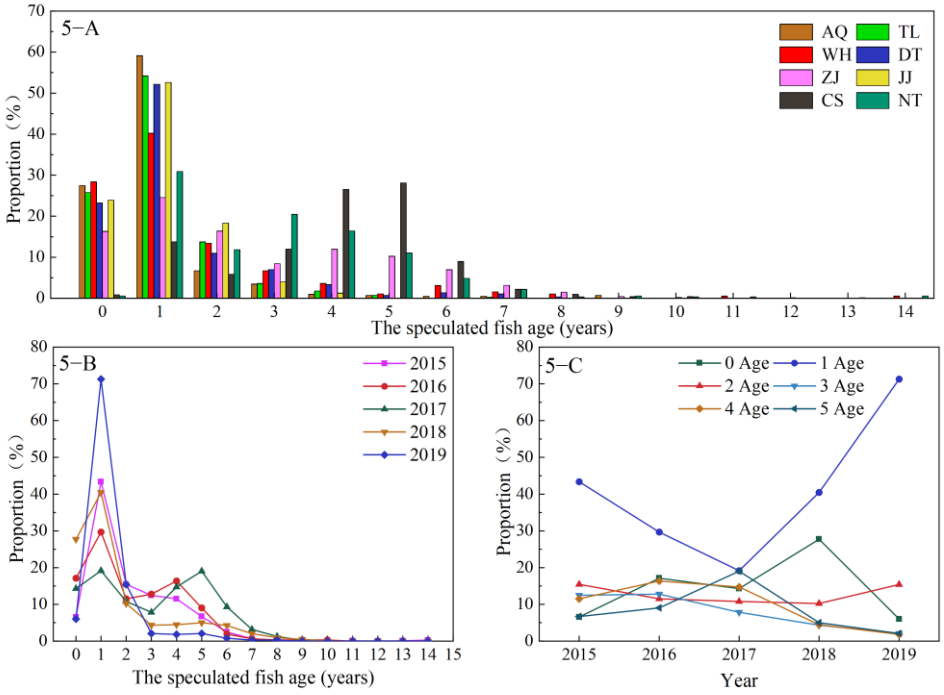


Figure 5. Proportion of Silver Carp by the speculated age. (**5–A**) the proportion of Silver Carp by speculated age in the eight river sections; (**5–B**) the proportion of Silver Carp by the speculated age in 2015-2019; (**5–C**) the proportion of Silver Carp by 0–5years-of-age in 2015–2019.

4.4. Growth Differences of Silver Carp in the lower Yangtze River

When comparing the growth parameters of Silver Carp in this study to those of different river sections in the Yangtze River, we found that the b parameter values of each river section ranged from 2.7546 to 3.0510 (Table 7). The b values could be used to determine whether the fish grew at a uniform rate [57] (i.e., $b = 3$), which would imply that Silver Carp's growth is generally constant. There were no significant differences between band k values and age at the inflection point (t_{tp}) in a study of different populations of Silver Carp in the estuary, middle, and upper reaches of the Yangtze River, but the theoretical initial age (t_0), progressive SL (L_∞), asymptotic BW (W_∞), and BW at inflection point (W_{tp}) did differ from the results of our study. An explanation for this discrepancy might be that fish development is affected by changes in habitat conditions in various water locations, interspecific competition pressure and prey resources [28,58].With diverse river shapes, linked lakes, and frequent tides supplying abundant prey for Silver Carp, the Yangtze River's lower areas are vital high-quality habitat for Silver Carp, assuring robust germplasm resources.

The growth characteristic index (φ) of Silver Carp combines the effects of L_∞ and k, which can be used to compare the growth performance of Silver Carp populations in different geographical locations in the Yangtze River Basin. The reported φ values of Silver Carp in the main stretch of the Yangtze River shows a trend of decreasing year by year, according to Pan's statistical analysis of the estuary section of the lower Yangtze River and the middle and upper reaches of the Yangtze River [53]. That is quite different from the φ values of Silver Carp in the lower reaches of the Yangtze River below the estuary found in the present study. The φ of Silver Carp from the AQ to NT section evidently surpasses that from the middle and upper reaches of the Yangtze River, suggesting that Silver Carp in the AQ to NT section of the river's lower reaches perform better in terms of growth.

Table 7. Growth parameters of different populations of Silver Carp.

River section	b	k	t_0	t_{tp}	L_∞/mm	W_∞/g	W_{tp}/g	φ	Reference
Swan oxbow	-	0.1483	−0.4965	6.9	1105	23,814	7038	3.26	[55]
Old ways of the River	2.9411	0.2087	0.0311	6.9	940	19,293	5571	3.27	[59]
Yangtze River Estuary	2.9800	0.2046	−0.0316	5.3	1050	24,005	7088	3.35	[60]
Middle and upper reaches	3.0510	0.203	−0.487	5.0	1030	24,127	7187	3.33	[61]
The upper reaches	2.9925	0.1882	−0.2165	5.8	1037	19,865	6198	3.31	[54]
Middle reaches (YC–JZ)	2.7546	0.1603	−0.8900	5.4	1047	14,814	6094	3.24	[53]
Lower reaches (AQ–NT)	2.9567	0.1648	−0.7068	6.1	852.5	10,232	2948	5.07	This study

Note: b is the shape parameter;k isthe growth coefficient; t_0 is the theoretical age at zero length; t_{tp} is the age at the inflection point; L_∞ is the asymptotic standard length; W_∞ is the asymptotic body weight; W_{tp} is the body weight at inflection point; φ is the growth characteristic index.

5. Conclusions

Fish have various and unique habitat selection strategies in the life cycle during growth and reproduction. The habitat environment has a very significant impact on the survival of fish. Therefore, the degradation of suitable habitat in the Yangtze River largely limits the living situation of Silver Carp in the Yangtze River. This study has shown the seasonal distribution features of Silver Carp population proportions in various size classes from the AQ to NT section, as well as the Silver Carp population's age structure and growth performance. Interestingly, small Silver Carp prefer to select the unique habitat from the AQ to JJ sections for nursing, whereas big Silver Carp prefer the tidal habitat from the CS to NT sections for feeding. Given these findings, we now need to investigate the habitat selection preferences of Silver Carp populations in the Yangtze River's lower reaches of themselves promoted mechanisms. Furthermore, the mechanisms by which to complementthe Silver Carp population resources and provide a timely reference basis for protecting the Silver Carp population in the Yangtze River. It is a consensus that destroying the environment will affect the survival of wild animals, but a wide range of environmental protection and restoration is bound to affect economic development. As a result, habitat conservation should be integrated with Silver Carp habitat preferences, with an emphasis on the protection and restoration of habitats that Silver Carp prefer. This approach can reducecosts while also encouraging widespread environmental conservation and restoration.

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