LARVAL RESOURCES OF FOUR MAJOR CARP SPECIES AND THEIR RESPONSE TO HYDROLOGICAL INDICES IN THE CHANGSHA SECTION OF THE XIANGJIANG RIVER, CHINA DURING 2011-2020

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Abstract. Larvae of black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and bighead carp (*Hypophthalmichthys nobilis*) were collected at a stationary location in the Changsha section of the Xiangjiang River from May, 2011 to July, 2020, and the relationships between abundance of the larvae and hydrological indices were analysed. Our results showed that the first appearance time of the larvae exhibited obvious annual differences, most of which were concentrated in mid-to-late May and early June, whereas 2016 was advanced to early May, which was the earliest year in the investigated 10 years. Moreover, the larval emergence was concentrated in mid-to-late May from 2017 to 2020, which was significantly earlier than those in early June of 2011-2013. Larval compositions of the four major carp species were significantly different between different years. Only water temperature significantly correlated with the compositions of the four major carp larvae. Water temperature significantly correlated with the catch-per-unit-of-effort of *C. idella* larvae, and rainfall for 3 consecutive days significantly correlated with the catch-per-unit-of-effort of *H. nobilis* larvae.
Keywords: *black carp, grass carp, silver carp, bighead carp, catch-per-unit-of-effort, rainfall*

Introduction

Black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and bighead carp (*Hypophthalmichthys nobilis*) are major economic carp species in freshwater aquaculture in China. Although the vast majority of these carp species juveniles currently farmed in China are obtained through artificial breeding, the natural populations of these carp species in rivers and lakes have decreased dramatically, especially their larval populations, due to environmental pollution, shipping, sand dredging, construction of hydropower stations, and climate change (e.g., droughts, and floods) (Marcos-López et al., 2010; Li et al., 2013; Xu et al., 2015).

The Xiangjiang River is an important tributary of the Yangtze River in China. It flows from south to north and converges into the Yangtze River via Dongting Lake. The spawning grounds of these major carps in the Xiangjiang River are the important sources of supplementation for Dongting Lake and Yangtze River. The survey in 1952

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found that an 18 km section from Baifang to Linghekou was the main spawning grounds for these major carps in the Xiangjiang River. The spawning grounds of these major carps stretched to 75 km from Xianglushan to Zhanghepu in 1972; however, they were reduced to 25 km from Xianglushan to Chenjiazhou in 1982 (Tang et al., 1983; Gao et al., 2019). The destruction of spawning grounds of these major carps leads to a serious decline in their larvae (Ban et al., 2019; Tang et al., 2022).

Water temperature (WT), nutrition, light, salinity, dissolved oxygen, and water flow stimulation are the main factors affecting the development of carp gonads naturally. After the gonads mature, water flow stimulation is the key factor for spawning (Wang et al., 2000, 2020; Lorig et al., 2013;). Zhou et al. (1980) systematically explained the location and scale of the carp spawning grounds and the hydrological conditions required for natural reproduction during 1976 to 1977. Wu et al. (1988) studied the effects of WT, rainfall, velocity, and water level changes on the natural reproduction of grass carp in the Jinsha River section. Duan et al. (2008) have studied the effects of the Three Gorges Reservoir on the reproduction of floating spawning fish such as the four major carp species. In the past 50 years, research on the early resources of the four major carps in the Yangtze River has received widespread attention, but mostly concentrated on the main stream of the Yangtze River and the tributaries of the Minjiang River, Yalong River, and Hanjiang River (Chen et al., 2020; Ding et al., 2020; He et al., 2021). There are few reports about the impact of hydrological indices on the early resources of these carp species in the Xiangjiang River.

Operation of the dam has caused many changes in the water ecological environment of the river (Kuang et al., 2019), which in turn affects the river fish populations (Li et al., 2016). In order to reduce these impacts, in recent years, ecological scheduling of the water conservancy hubs in the upper and middle reaches of the Yangtze River have carried out. By monitoring the fish larval resources and the hydrological factors related to fish reproduction, the researchers preliminarily establish a quantitative relationship model between the four major carp reproductions and hydrological conditions to better carry out ecological management and water environment assessment (Xu et al., 2015; Ma et al., 2017; Zhou et al., 2019; Wang et al., 2019a). As part of the Xiangjiang cascade water conservancy development project, the Dayuandu Dam, Zhuzhou Dam and Tugutang Dam in the lower reaches of the spawning grounds of the four major carps were put into use in 1998, 2005 and 2016, respectively. This study mainly analyzes the relationship between the changes of larval resources of the four major carps and hydrological factors in the lower reaches of the Xiangjiang River from 2011 to 2020, and clarifies the reproduction behavior of the four major carps in the Xiangjiang River. This study intends to fill the gaps in the research on the current status of larval resources of the four major carps in the Xiangjiang River and their correlation with hydrological factors, and provide a reference for the ecological conservation of the four major carps in the Xiangjiang River.

Materials and methods

Sample collection

The collection of natural fish larvae was approved by the Department of Agriculture and Rural Affairs of Hunan Province of China (Approval number: Xiang(2021)Te001). The sample collection site (112.89° E, 28.34° N) located at Xiangluzhou section of the Xiangjiang River (*Appendix 1*). The fish larvae were collected using a trap net (net area of 2.7 m^2, net length of 4.8 m, net mesh of 0.5 mm, and the tail of the net connected to

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the fish larval collection box) on the river surface 2-10 m from the west bank (Duan et al., 2009) from May to July of each year from 2011 to 2020. The samples were fixed with 5% formaldehyde solution and transported to the laboratory for microscopic examination and identification according to Yi et al. (1988) and Cao et al. (2007).

Data collection

WTs during the larval occurring period of the four major carp species were recorded from 2011 to 2020. Daily flow (DF) and daily rainfall data were collected from a hydrological and meteorological monitoring station near the upstream spawning ground section (between Baifang and Chenjiazhou section). Since there are no flow and rainfall records to query before 2017, only the 2017-2020 data were analyzed.

Data analysis

This study uses catch-per-unit-of-effort (CPUE) to standardize and quantify larval resources of the four carps (Maunder and Punt, 2013). Redundant analysis (RDA) was conducted using the vegan (Dixon, 2003) and ade4 pacakges of R 4.2.0. Pearson correlation coefficient was used to describe the relationship between CPUE of these carp larvae and the changes in flow, rainfall and rainfall for 3 consecutive days (Rainfall3day) during the breeding period. Pearson correlation analysis was conducted using the psych, reshape2, and corrplot packages of R 4.2.0. Linear correlation analysis and drawn was conducted using the basicTrendline package of R 4.2.0. Non-parametric multivariate analysis of variance (PERMANOVA, Anderson, 2001) was conducted using R software with the vegan package of R 4.2.0.

Results

Annual differences in appearance time of larvae of the four major carps

A total of 9.58 million fish larvae were collected from 2011 to 2020, in which silver carp, grass carp, bighead carp, and black carp were 254,144 (2.65%), 31,991 (0.33%), 6,285 (0.07%), and 2,425 (0.03%) individuals, respectively (*Fig. 1*). The number of silver carp larvae was evidently more than total larvae of the other three major carp species. Larval appearance durations of the four major carp species were 28, 12, 26, 39, 28, 46, 43, 40, 39, and 39 days from 2011 to 2020, respectively (*Fig. 1B*). The first appearance time of the larvae exhibited obvious annual differences, most of which were concentrated in mid-to-late May and early June, whereas 2016 was advanced to early May, which was the earliest year in the investigated 10 years (*Fig. 1B*). Moreover, the larval emergence was concentrated in mid-to-late May from 2017 to 2020, which was significantly earlier than those in early June of 2011-2013 ($p < 0.05$; *Fig. 1B*).

The CPUE value of the four major carp species in 2014 reached a 10-year peak, as high as 1100 ind/(net•h), followed by 2015 with a CPUE value of approximately 450 ind/(net•h), whereas the CPUE values of the four major carp species in the other years were relatively low (*Fig. 2A*). Larval compositions of the four major carp species were significantly different between different years (PERMANOVA, $p = 0.005$). Grass carp only dominated in 2019. The numbers of silver carp and grass carp larvae were similar and each accounted for nearly half in 2011 and 2016. For the remaining 7 years, CPUE of the silver carp larvae had a greater advantage than those of the other three major carps (*Fig. 2B*).

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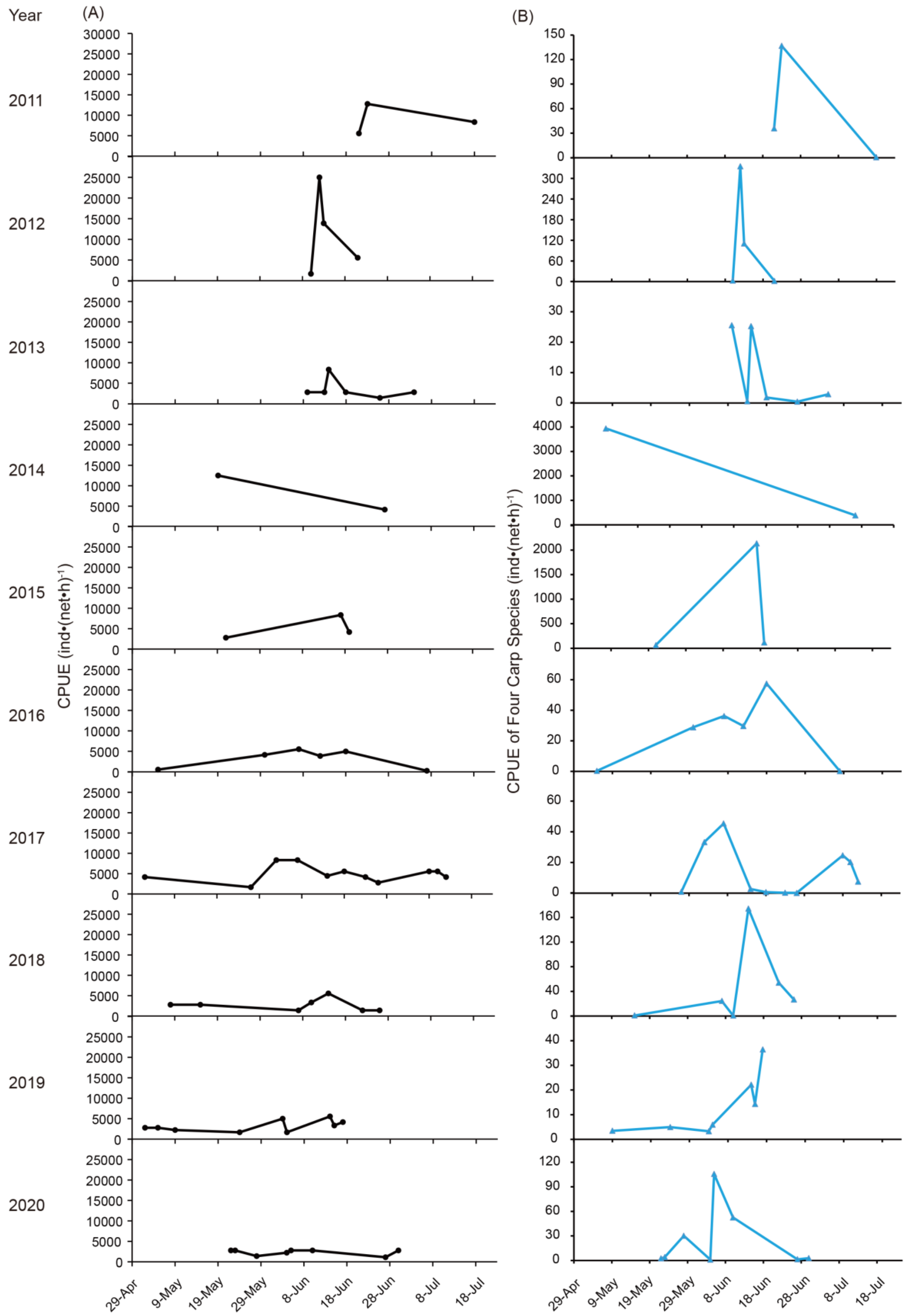

Figure 1. *Catch-per-unit-of-effort (CPUE) of all wild fish (A) and four major carp species (B) larvae during 2011-2020. Points in each graph in panel (A) indicate sampling times and triangles in each graph in panel (B) indicate sampling times when the four major carp species were detected. The four major carp species are Mylopharyngodon piceus, Ctenopharyngodon idella, Hypophthalmichthys molitrix, and Hypophthalmichthys nobilis*

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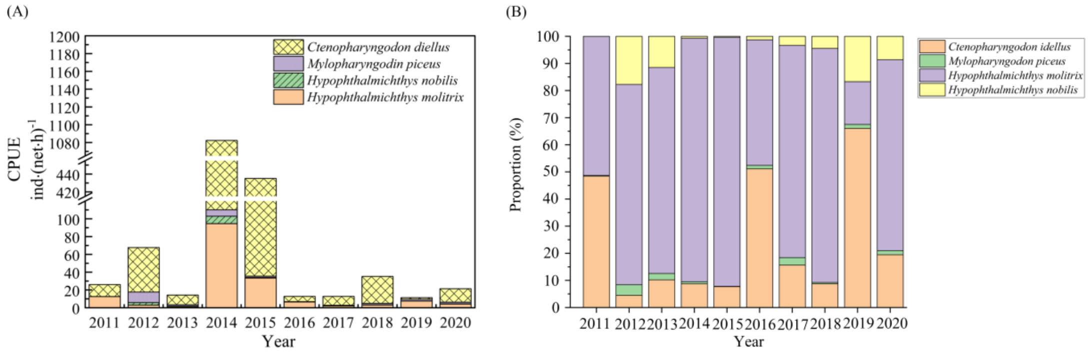

Figure 2. *Annual variations of catch-per-unit-of-effort (CPUE) (A) and proportions (B) of larvae of four major carps*

Correlation between hydrological indices and the larvae of four major carp species

In 2017, large-scale larvae occurred at the beginning of flow increase, and the larval occurrence period disappeared during the rapid flow growth. When the flow reached its peak in the early July, the second batch of grass carp, black carp, and silver carp larvae occurred at peak (*Fig. 3*). The peak of flow in 2018 occurred in early May, with very few larvae emerged. In June, the flow was continuously fluctuating, and larvae of the four major carps occurrence were mostly concentrated in this period. It is worth noting that the daily flow fluctuation during the large-scale larval occurrence was about 370 m^3/(s•d), and the lowest flow rate was less than 500 m^3/s, which was the lowest flow level during the larval occurrence period in 2017 to 2020. The larval peak of black carp, grass carp, and silver carp occurred when the flow had a peak in May, 2019 (*Fig. 3*). The larval occurrence period of the four major carp species also occurred when the peak flow occurred in June. There was a flow peak in early May 2020. During its gradual decline, black carp had a larval peak (*Fig. 3B*), whereas grass carp, silver carp, and bighead carp had two larval peaks (*Fig. 3A, C, D*). Then, during the increase in flow, large-scale larvae occurred in all four major carps. When the flow reached the maximum value, there was no larval occurrence period of the four major carps, and then the flow dropped sharply and then increased slightly, only the larval peak of bighead carp occurred (*Fig. 3D*).

The average daily flow from 2017 to 2020 were 2,703, 831, 1,694, and 1,376 m^3/s, respectively; and the average larval CPUEs of the four major carps were 12.7, 35.1, 11.3, and 21.4 ind/(net•h), respectively. The average daily flow in 2018 was much lower than other years, whereas the larval CPUEs of the four major carps were the highest, indicating that the number of the four major carp larvae and flow did not show a positive correlation at the inter-annual level (*Fig. 4*).

The first batch of the four major carp larvae occurrence periods in the Xiangjiang River in 2017 was accompanied by small-scale rainfall in late May. When the rainfall reached its maximum in early July, the second larval occurrence period of grass carp, black carp and silver carp occurred (*Fig. 4*). The rainfall from May to July 2018 is mainly divided into two periods of continuous rainfall. The four major carp larval occurrence periods mostly occur in the second period. In 2019, the rainfall in the spawning river section mostly occurred intermittently in the form of 3-4 consecutive days, and the larval occurrence period also occurred during these periods. In 2020, the larval occurrence periods mostly occur during the continuous rainfall period in mid-to-late May. When the rainfall reaches its maximum in mid-June, only bighead carp larval peak occurred (*Fig. 3D*).

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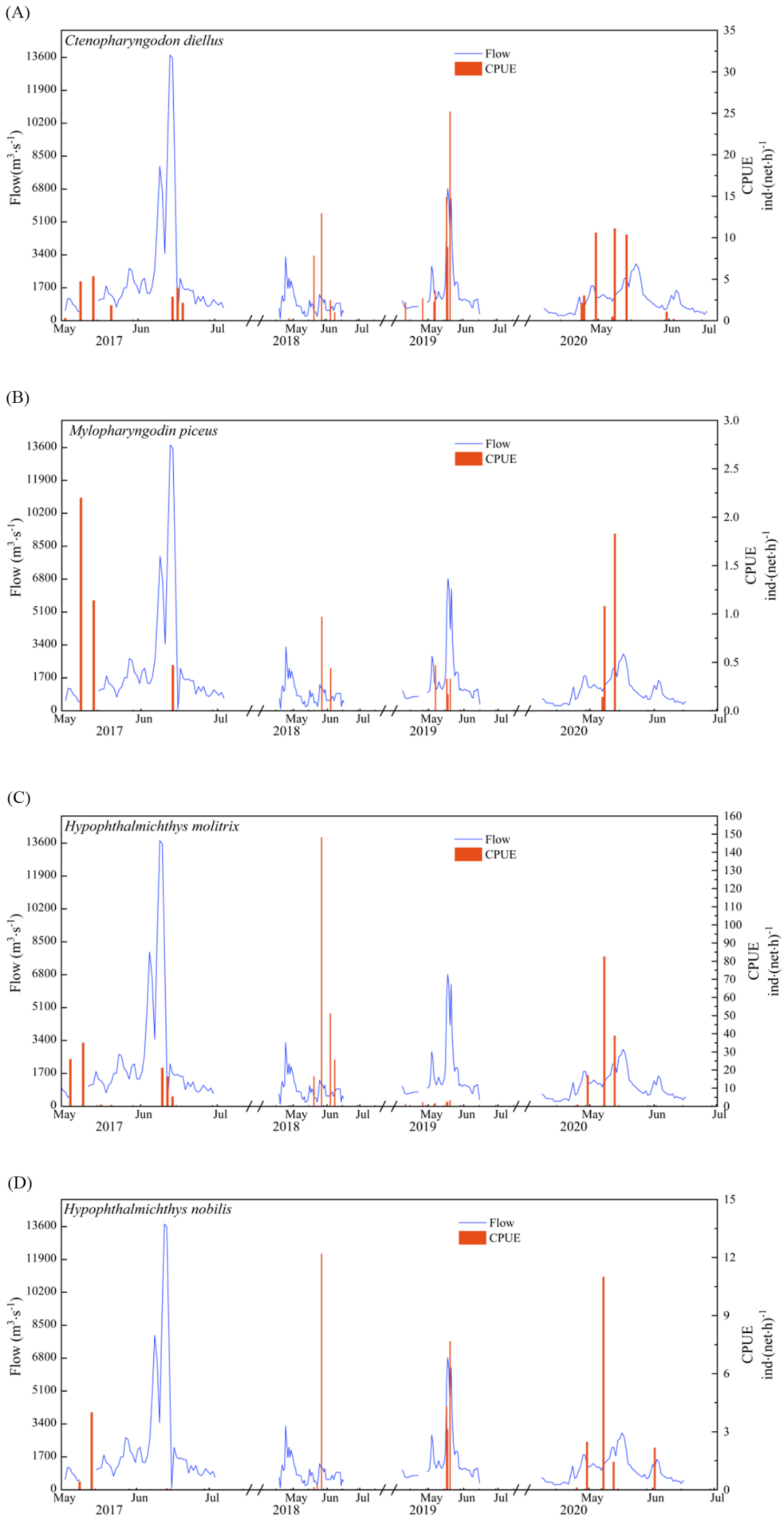

Figure 3. *Diurnal variations of river flow and CPUE of the four major carp species in Xiangjiang River during 2017-2020. (A) grass carp (Ctenopharyngodon idella); (B) black carp (Mylopharyngodin piceus); (C) silver carp (Hypophthalmichthys molitrix); (D) bighead carp (Hypophthalmichthys nobilis)*

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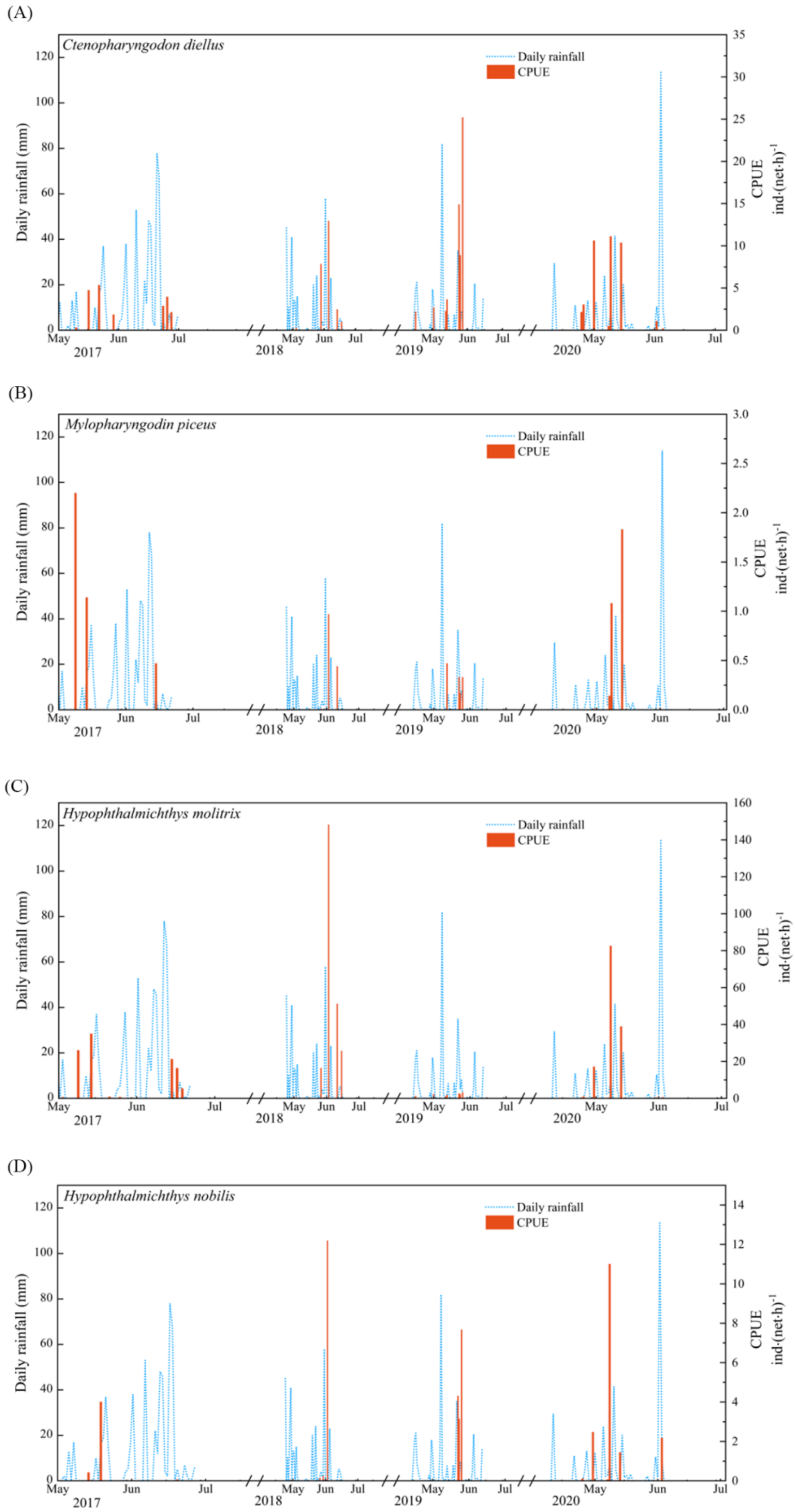

Figure 4. *Diurnal variations of river daily rainfall and CPUE of the four major carp species in Xiangjiang River during 2017-2020. (A) grass carp (Ctenopharyngodon idella); (B) black carp (Mylopharyngodin piceus); (C) silver carp (Hypophthalmichthys molitrix); (D) bighead carp (Hypophthalmichthys nobilis)*

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RDA results showed that only WT significantly correlated with the compositions of the four major carp larvae ($p < 0.05$; *Fig. 5A*). Pearson correlation analysis showed that WT significantly correlated with the CPUE of *C. idella* larvae, and $Rainfall_{3day}$ significantly correlated with the CPUE of *H. nobilis* larvae ($p < 0.05$; *Fig. 5B-D*).

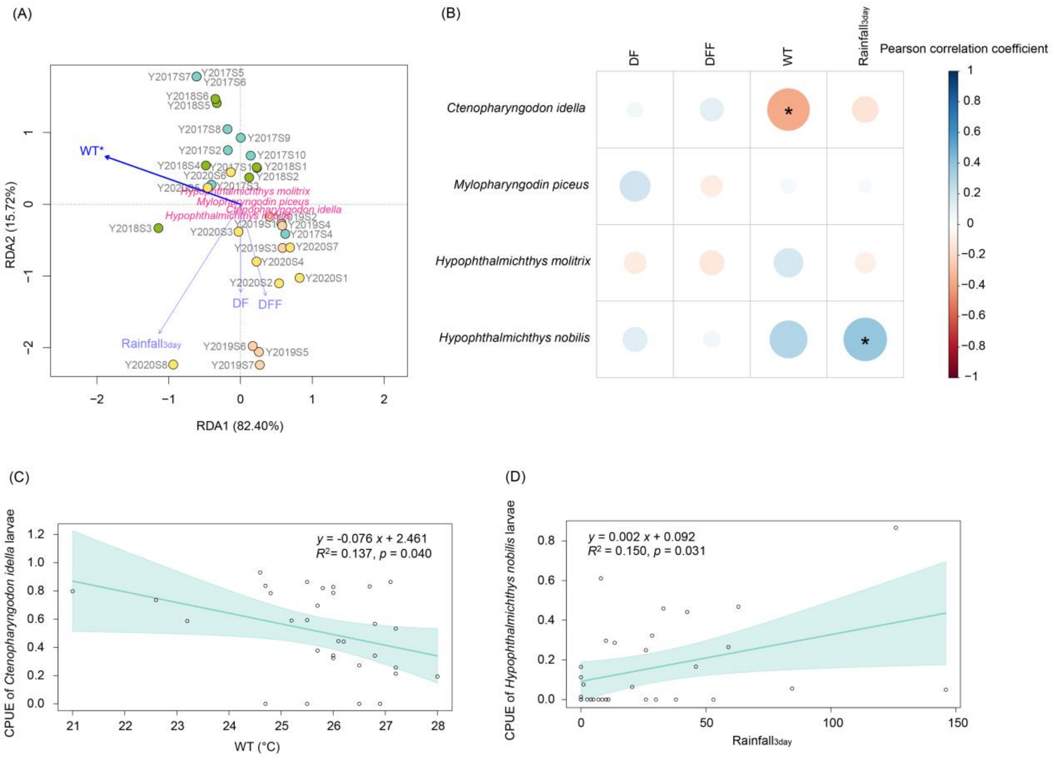

***Figure 5.** Correlation between hydrological indices and composition of major carp larvae during 2017 to 2020. (A) Redundancy analysis profile; (B) Pearson correlations between hydrological indices and composition of major carp larvae; (C) Correlation between water temperature and CPUE of Ctenopharyngodon idella larvae; (D) Correlation between rainfall for 3 consecutive days and CPUE of Hypophthalmichthys nobilis larvae. DF, daily flow; DFF, daily flow fluctuation; WT, water temperature. * p < 0.05*

Discussion

Since the 1950s, the four major carp resources in the Xiangjiang River have exhibited a declining trend. By the 1980s, the proportion of the four major carp larvae in all fish larvae fell from 35.3% to 18.5% in the Xiangjiang River (Tang et al., 1983; Sheng et al., 2017). In 2009, the proportion fell to 3.32%, and in 2010, this proportion further dropped to 2% in the Xiangjiang River (Xie et al., 2014). Since 2012, the Xiangjiang River fishing ban policy has been further upgraded, and the scale of reproduction and release of the four major carps had also expanded at a relatively rapid rate. During the period from 2011 to 2020, the proportion returned to 3.1%, of which the larval resources of the four major carps were the most abundant in 2014-2015. Since 2016, the larval resources of the four major carps have entered a shrinking stage again, which may be related to the Tugutang Dam in the lower reaches of their spawning grounds being put into use that year. Duan et al. (2009) also found that the larval abundance of the four major carps in the Yangtze River decreased sharply after the Three Gorges Dam was completed. Due to the different ecological strategies of different

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fishes, there are also big differences in the impact of the dam (Pereira et al., 2021). A similar phenomenon was found in this survey. As Dayuandu Dam (1998), Zhuzhou Dam (2005) and Tugutang Dam (2016) had been put into operation one after another, slow-flowing sections had appeared in the middle and lower reaches of the Xiangjiang River in recent years, and some river-type water areas had gradually evolved into reservoir-type waters, leading to an increase in plankton biomass, which may be an important reason why the proportion of silver carp and bighead carp has been higher than that of the mainstream of the Yangtze River in recent years (Xu et al., 2018).

During the peak periods of fish reproduction, WT is an important factor affecting its reproduction (Zitek et al., 2004; Smith et al., 2005). Kiernan et al. (2012) proposed that the expansion of native fishes was facilitated by the creation of favorable spawning and rearing conditions, e.g., elevated springtime flows, and cooler WT. WT conditions for the reproduction of the four major carps are 18-30 °C, and the most suitable WT is 21.5-23 °C (Yi et al., 1988). During the larval occurrence periods of the four major carps from 2011 to 2020, the WT records of the sampling river section were basically consistent with the above conclusion, which was 20.5-30.5 °C. In the later stage of this study (2018-2020), the time of the first appearance of the four major carp larvae was half a month earlier than the previous period (2011-2013), and the WT was also reduced by nearly 3 °C. The times from the first appearance to the last appearance of the larvae were from 22 to 40 days. This phenomenon reflected the inter-annual fluctuations in the maturity of the gonads in the four major carp breeding population in the Xiangjiang River. It may be caused by changes in the local WT distribution and river hydrological situations caused by the construction of upstream dams.

Flow is an important factor influencing the replenishment of fish resources. The river flow not only affects the larval survival rate, but an appropriate flow threshold is also an important condition for some fish spawn (Tondato et al., 2018; Schreier et al., 2020; Zeug et al., 2020). Vilizzi et al. (2019) found that small fish spawning is closely related to flow, but large fish such as silver perch (*Bairdiella chrysoura*) and golden perch (*Macquaria ambigua*) are affected by a combination of flow, flow duration and WT. This difference also provides theoretical support for the wider application of ecological scheduling in the protection of fish resources. Inter-annual differences in flow can cause inter-annual differences in larval resources (Balcombe et al., 2007). However, in this study, the average daily flow of the Xiangjiang River in 2018 was much lower than other years, but the CPUE value of fish larvae was the highest. This reflects that the decrease in flow did not necessarily lead to a decrease in the amount of larval resources. This may be due to the fact that the flow of the Xiangjiang River in 2018 is still higher than the flow threshold required for the four major carps reproduction, and it had not become a limiting condition for stimulating these fish reproductions.

Rainfall has an important impact on fish reproductive behavior (Nascimento et al., 2006). For some fish, the impact of rainfall even exceeds other environmental factors (Karnatak et al., 2018). Sanches et al. (2020) verified that species, even in lentic environments, respond positively to rainfall. Pearson correlation analysis showed that $\text{Rainfall}_{3\text{day}}$ significantly correlated with the CPUE of *H. nobilis* larvae. Wang et al. (2019b) also made similar findings when they studied the relationship between natural reproduction and hydrology of the four major carps in the Yangtze River. The impact of $\text{Rainfall}_{3\text{day}}$ on the reproduction of the four major carps not only occurs indirectly through the increase in flow, but also occurs through other conditions such as air pressure, WT, turbidity, and water flow characteristics.

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Conclusions

The larvae of the four major carps began to appear in early May and ends in early- and mid-July. The peak period was mostly from late May to the end of June. When the WT rises to 20.5 °C, the river section that the spawning grounds continued to rain for three days, the daily flow was not less than 500 m^3/s, and the daily flow fluctuation reached 370 m^3/(s•d) was easier to stimulate these fish to spawn. These conditions were still relatively easy to achieve even after the operation of water conservancy cascade development projects in recent years. Therefore, the impact of the construction of large-scale water conservancy projects on the replenishment of the four major carp resources in the Xiangjiang was not currently reflected in the breeding behavior of broodstock during the breeding season. Its possible effects on broodstock migration, gonadal development, and egg seedling drifting may be the main target of follow-up research.

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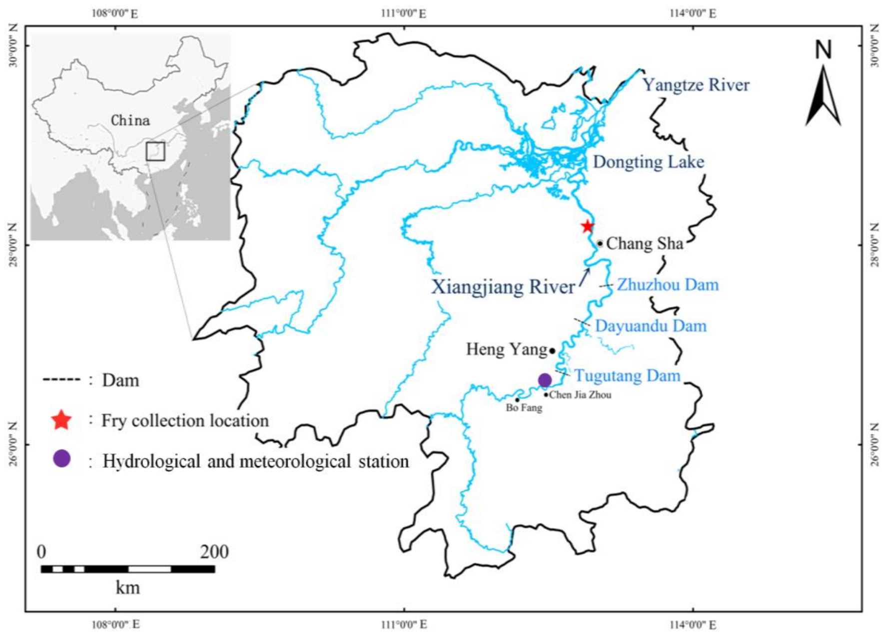
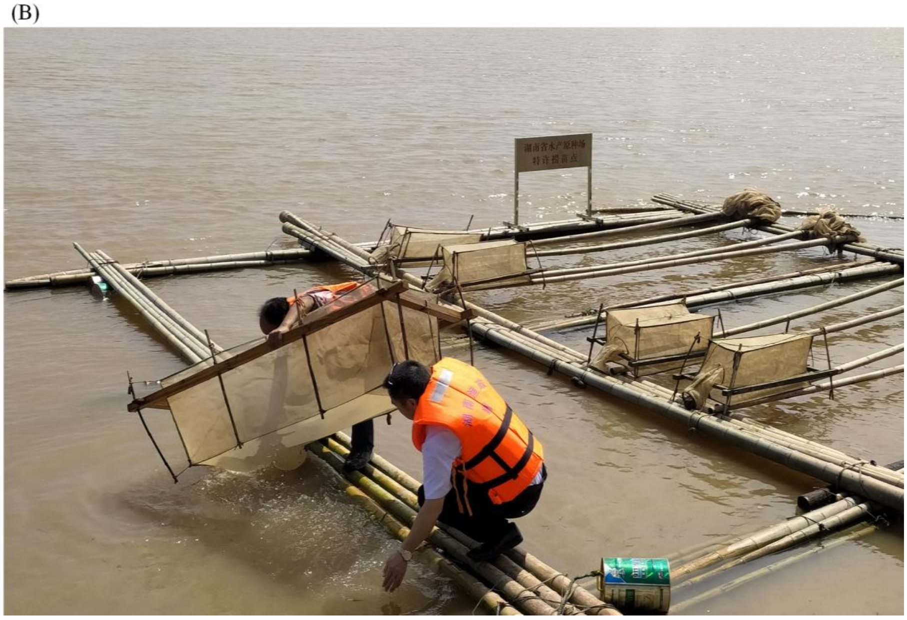
APPENDIX

(A)



(B)



***Appendix 1.** Sampling sites of larvae of four carps (A) and a photo of sampling site (B) in Xiangjiang River*

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