Ecological Processes

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Changes in fish resources 5 years after implementation of the 10-year fishing ban in the Chishui River, the first river with a complete fishing ban in the Yangtze River Basin

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Abstract

Background To rehabilitate the depleted fish resources of the Yangtze River Basin, China, a 10-year fishing ban has been implemented. This national initiative has attracted worldwide attention. The present study aimed to explore the ecological process and recovery effectiveness of this complete fishing ban in the Chishui River, the first river where the fishing ban was enacted in the Yangtze River Basin. Changes in fish resources were analyzed based on investigations conducted 5 years before (2012–2016) and 5 years after (2017–2021) the implementation of the fishing ban in four reaches along the longitudinal gradient.

Results A total of 140 fish species, including 127 native and 13 exotic species, were collected during the study period. The number of fish species as well as the diversity indices showed no significant temporal changes. However, 11 native species that had disappeared for many years appeared again after the fishing ban. The occurrence rates of some key protected species, *Procypris rabaudi*, *Acipenser dabryanus*, *Euchiloglanis davidi* and *Myxocyprinus asiaticus*, increased after the fishing ban, while *Coreius guichenoti*, *Percocypris pingi*, *Onychostoma angustistomata* and *Leptobotia rubrilabris* showed no obvious recovery. The fish assemblage structure in nearly all reaches (except the headwater) showed significant temporal changes with an increase in the relative abundance of larger body-sized species. The population structure of most dominant species improved greatly with the mean standard length and the mean body weight as well as the proportion of larger-sized individuals clearly increasing. In addition, the density of fishes changed dramatically with the catch per unit effort (CPUE) increasing by 140–210% for different study reaches.

Conclusions The present study confirmed that the complete fishing closure is an effective measure to facilitate fish resources recovery. These results provide valuable references for evaluating the effectiveness of the 10-year fishing ban policy in the entire Yangtze River.

Keywords The Yangtze River, Fishing ban, The Chishui River, Fish resources, Biodiversity conservation

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Introduction

Understanding the processes responsible for the dynamics of biological communities under multiple disturbances is fundamental in developing conservation practices. Overfishing is one of the primary contributing factors to the decline in fish resources around the world

(Allan et al. 2005; Yemane et al. 2005; Mota et al. 2014; Ding et al. 2017; FAO 2016, 2018). It affects fish resources in many ways, with resulting consequences manifested in changes in biodiversity and ecosystem goods and services (Allan et al. 2005). First, intensive fishing on certain targeted species can directly cause their populations to decrease or even to become extinct, and thus result in species diversity loss (Jennings and Kaiser 1998). Second, overfishing can change the population composition and assemblage structure, by removal of larger-bodied individuals or species (especially piscivores) from fish assemblages, leading to decreases in the capture size of certain species and simplification in the structure of fish assemblages (Jennings and Kaiser 1998). As the abundance and the captured size of fishes decrease, the fishery yields decline correspondingly. The loss of apex predators can also change the trophic relationships of food webs, which in turn affect the stability of the ecosystem (Jennings et al. 1999; Bianchi et al. 2000; Allan et al. 2005; Atkinson et al. 2011; McHugh et al. 2011; Mak et al. 2021).

Fishing closures have been proposed as strategies to mitigate the impacts caused by overfishing and facilitate the recovery of fish resources (Carvalho et al. 2019; Mak et al. 2021; Tuset et al. 2021; Jiang et al. 2022; Xie et al. 2022). One potential benefit of fishing closures is that they can eliminate fishing mortality. When fishing mortality is eliminated, the abundance and biomass of individuals increase (Jennings 2001). The recovery of ecosystems after fishing closures allows for the reallocation of biomass within fish assemblages (Tuset et al. 2021). In Roses Bay (north-west Mediterranean), noticeable increases in the abundance and biomass of all fish species were observed 2 years after the closure of trawl fishing (Tuset et al. 2021). In addition, positive effects on the population structure were observed with an increase in larger individuals (Tuset et al. 2021). In Hong Kong territorial waters, increases in the trophic level of the fish community, abundance and biomass of total fishes and of predatory fishes were observed 3 years after a ban on trawling (Mak et al. 2021). Similar results have also been observed in river systems. In the Zambezi River, overall catch rate of all fish species and the mean sizes of large cichlids were significantly larger at the fish protected areas than at the non-protected area (Simasiku and Hay 2023). In the Salween River Basin, area-based closures markedly increased fish richness, density and biomass compared to fished areas (Koning et al. 2020).

The Yangtze River has the highest fish species diversity in the Palearctic region, which historically supported 416 fish species with 178 of these species being endemic to this basin (Ye et al. 2011). At the same time, it is the most important freshwater fishery in China, which once provided 60% of the country's total inland fisheries production (Liu and Cao 1992; Liu et al. 2019). However, fish resources in the Yangtze River have declined dramatically in the past decades due to increased human activities, such as overfishing, dam construction, water pollution and invasion of exotic species (Ye et al. 2011; Liu et al. 2019; Chen et al. 2020). Among these human activities, overfishing is widely recognized as one of the major contributors (Ye et al. 2011; Liu et al. 2019, 2021a; Chen et al. 2020). In 2003, a seasonal fishing closure policy was officially initiated in the Yangtze River Basin, aiming to rebuild the depleted fish resources. However, the effectiveness of this policy was far from satisfactory due to the "retaliatory fishing" by fishmen after reopening as well as widespread illegal fishing (Duan et al. 2008; Chen et al. 2020; Liu et al. 2021a). As a result, stricter fishing bans were recommended. In 2016, an improved and prolonged fishing ban policy was implemented, with the closure area enlarged to cover the whole mainstem Yangtze River as well as its key tributaries and attached lakes, and the closure period was extended from 3 months (1 February to 30 April in the upstream and 1 April to 30 June in the mid- and down-stream) to 4 months (1 March to 30 June). In 2017, an experimental 10-year complete fishing ban began in the Chishui River, to explore the feasibility of a full-year fishing ban for the entire Yangtze River basin (Ministry of Agriculture and Rural Affairs of the People's Republic of China 2016). The entire mainstem as well as some headwaters of the Chishui River had been incorporated into "the National Natural Reserve for the Rare and Endemic Fishes in the upper Yangtze River" in 2005 (Fan et al. 2006). However, commercial fishing was not forbidden at that time for complex social and economic reasons. Because of continuous overfishing, fish resources in the Chishui River continued to decline (Li et al. 2015; Liu et al. 2020). The population size of many fish species decreased dramatically (e.g., *Procypris rabaudi*, *Bangana rendahli* and *Xenocypris davidi*) or even disappeared from catches (e.g., *Anguilla japonica*, *Luciobrama macrocephalus* and *Ochetobius elongatus*) (Liu et al. 2020). In addition, the capture sizes of main targeted species (e.g., *Spinibarbus sinensis* and *Pelteobagrus vachelli*) decreased significantly (Li et al. 2015; Liu et al. 2020). The implemented complete fishing ban was considered to be an important measure to restore the depleted fish resources in the Chishui River (Li et al. 2015; Liu et al. 2020).

As of 2021, commercial fishing in the Chishui River has been completely forbidden for 5 years. Whether or not this full-year fishing ban has facilitated the recovery of fish resources is receiving considerable attention. In this study, changes in fish resources were analyzed and compared based on investigations conducted 5 years before (2012–2016) and 5 years after (2017–2021) the implementation of the fishing ban in four reaches (headwater, upstream, midstream and downstream) along the longitudinal gradient of the Chishui River. The analyses covered several different aspects, including the species composition, the diversity indices, the occurrence rates of key protected species, the assemblage structure, the population structure of dominant species and the catch per unit effort (CPUE). We hypothesized that the implementation of complete fishing ban would be associated with positive changes in fisheries resources, including: (1) increases in the diversity indices; (2) increases in the occurrence rates of some key protected species; (3) changes in the structure of fish assemblages with increases in the dominance of larger body-sized species; (4) increases in the mean body size and the proportion of larger-sized individuals of dominant species; (5) increases in the catch per unit effort (CPUE). In addition, considering that the fish species may be varied in life history traits or initial population sizes and the four study reaches may be different in habitat characteristics or have experienced different fishing intensity prior to the ban, we hypothesized that the magnitude and rate of recovery may also vary by species and reach. We believe results obtained from this study will provide useful information for the development of adaptive management, which will not only benefit the Chishui River, but also the entire Yangtze River.

Methods

Study area

The Chishui River is the last free-flowing tributary in the upper Yangtze River, China. It originates from the Wumeng Mountains in Zhenxiong County, Yunnan Province, and empties into the upper Yangtze River in Hejiang County, Sichuan Province, with a length of 436.5 km and a drainage area of 20440 km^2 (Fig. 1). The river runs through a transitional zone from the Yunnan–Guizhou Plateau to the Sichuan Basin. Up to now, no dams have been built on the mainstem Chishui River. The diversified physical habitat and natural water flow supports a high diversity of fish species (Wu et al. 2011a). Our previous studies showed that the Chishui River contains at least 140 native fish species and 45 of these species are endemic to the upper Yangtze River

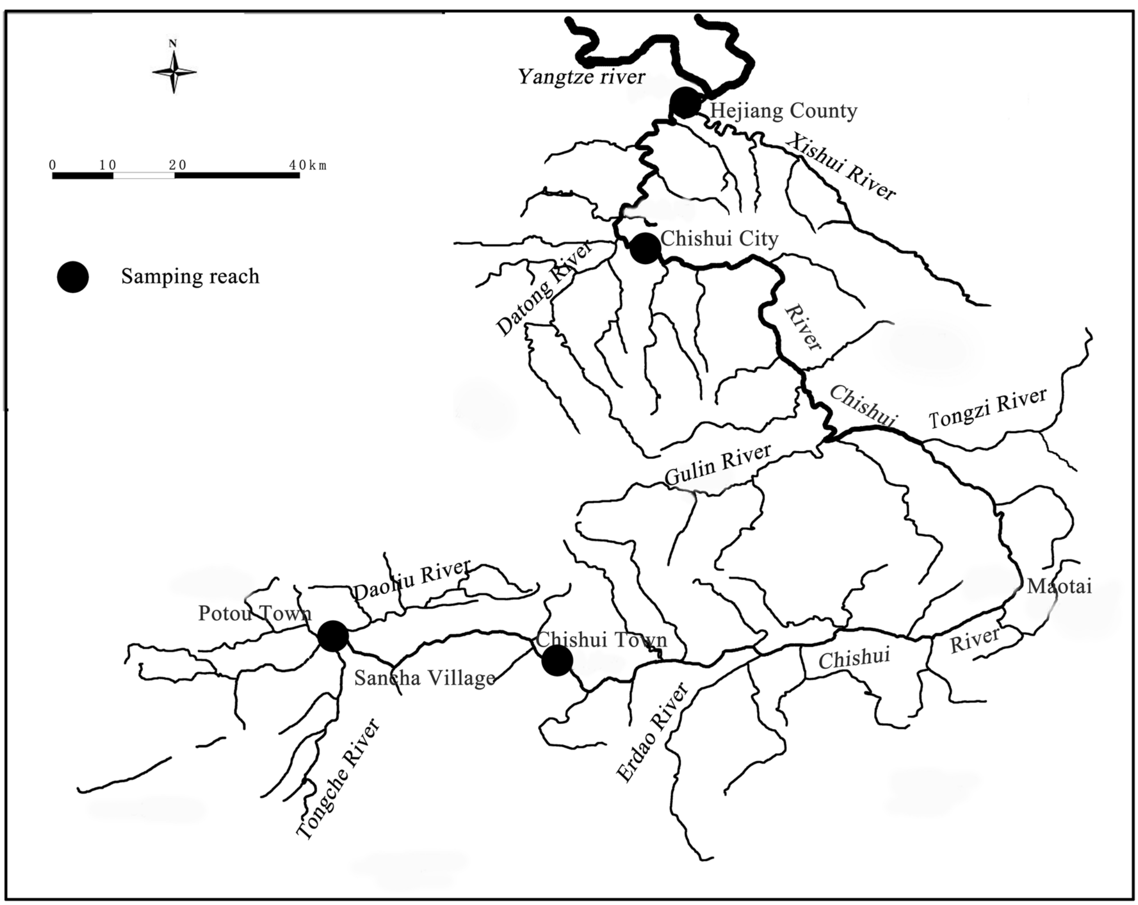

Fig. 1 Location of the four sampling reaches in the Chishui River Basin. Black circles represent the sampling locations

(Liu et al. 2015). The fish fauna changes significantly with the longitudinal gradient (Wu et al. 2011a; Liu et al. 2021b). The headwater (above Sancha Village) is located in the eastern Yunnan–Guizhou Plateau, which is characterized by high altitude (above 1000 m), low water temperature (below 20 °C all year round), shallow water (0.7 ± 0.5 m) and constricted channel (21.6 ± 14.4 m). The fish assemblage in this reach is dominated by species from Schizothoracinae, Labeoninae, Nemacheilidae and Balitoridae that were adapted to the high altitude, cold-water or lotic environments. The upstream (from Sancha Village to Maotai Town) is located on the slopping Yunnan–Guizhou Plateau, which is also characterized by high altitude (735.9 ± 239.6 m), rapid current (0.91 ± 0.32 m/s), shallow water (0.7 ± 0.4 m) and narrow channel (34.7 ± 14.5 m). The fish assemblage in this reach is dominated by species from Labeoninae, Barbinae and Balitoridae that prefer running water. The midstream (from Maotai Town to Chishui City) lies in the transitional area between the Yunnan–Guizhou Plateau to the Sichuan Basin, with a moderate altitude (302.5 ± 88.7 m), turbulent flow (1.53 ± 0.28 m/s), moderate water depth (2.6 ± 1.2 m) and channel width (44.3 ± 18.0 m). The fish assemblage in this reach is characterized by a mixture of limnophilic (e.g., Gobioninae, Bagridae and Cyprininae) and rheophilic (e.g., Danioninae and Barbinae) species. The downstream reach (from Chishui City to the river confluence) is located on the edge of the Sichuan Basin, with a low altitude (217.4 ± 19.8 m), reduced water flow (0.79 ± 0.44 m/s), deep water (4.8 ± 2.6 m) and wide channel (121.7 ± 35.7 m). Fish species from Cultrinae, Cyprininae, Gobioninae, Bagridae and Serranidae that prefer warm-water and limnophilic environment dominate the fish assemblage (Wu et al. 2011a; Liu et al. 2021b). Specifically, many fish species that have suffered adverse impacts from the construction of cascade hydropower stations in the mainstem upper Yangtze River can complete their whole life history in the Chishui River. Therefore, the Chishui River is recognized as the last refuge for rare and endemic fishes in the upper Yangtze River (Wu et al. 2011a; Liu et al. 2012, 2019). In January 2017, a complete fishing ban was first implemented in the Chishui River, to promote the recovery of fish resources in this ecologically important river and to explore the feasibility of a complete fishing ban for the entire Yangtze River Basin.

Fish sampling

Field investigations were conducted twice a year, namely spring (May–June) and autumn (September–October), in both the pre-fishing-ban period (2012–2016) and the post-fishing-ban period (2017–2021). A stratified sampling design was employed. At the watershed scale, four reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ) were sampled regularly. These reaches represented the typical habitat characteristics of the headwater, the upstream, the midstream and the downstream of the Chishui River, respectively (Liu et al. 2021b). The length of each reach ranged from 10 to 20 km. At the reach scale, three to five fixed sampling sites were located along each sampling reach with a length of 1–2 km, representing local accessible habitat types. To ensure continuity and comparability of the fish data, the sampling sites and sampling times have remained fairly stable during the whole study period. The sampling gears and sampling intensity also have remained essentially unchanged. Series of gillnets were used to collect fish specimens, because they allow for gear standardization and are easy to operate. On each sampling occasion, 10 gillnets with two mesh sizes (5 with 2 cm mesh and 5 with 5 cm mesh) were employed. Individual gillnets were 100 m long and 1.5 m deep. The gillnets were placed in the offshore water at approximately 18:00 at twilight and retrieved at 08:00 the next morning (Liu et al. 2021a). The duration of each sampling season varied from 10 to 20 days according to the river size of different reaches. In the headwater and the upstream, where the river was narrow and shallow, each sampling season lasted for about 10 days. While in the middle and lower reaches with deeper water and wider channels, each sampling season lasted for about 20 days (Table 1). In any case, each sampling site was sampled for 3–5 days. After sampling, all fish specimens were identified to species, and then measured (total length and standard length, to the nearest 1 mm) and weighed (to the neatest 0.1 g). Individuals that could be confidently identified were released downstream from the sites, while individuals that could not be identified in the field were fixed in buffered formaldehyde (10%) and transported to the laboratory for further taxonomic determination (Liu et al. 2020).

Data analysis

To detect changes in the species composition before and after the fishing ban, fish species collected in all the four reaches were pooled to the pre-fishing-ban period (2012–2016) and the post-fishing-ban period (2017–2021), and the total number of fish species as well as the number of native and exotic fish species were counted individually.

To explore changes in the species diversity, three diversity indices, including Margalef richness index (D) (Margalef 1958), Shannon–Wiener diversity index (H') (Shannon and Weaver 1949) and Pielou evenness index (J') (Pielou 1975), were employed. The values of these indices were calculated yearly for each reach and the differences before and after the fishing ban were compared,

Table 1 Sampling times for the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River, during the study period

Year	PT		CZ		CS		HJ	
	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn
2012	–	–	1 May–10 May	29 Sep–7 Oct	21 May–10 Jun	10 Oct–30 Oct	5 May–23 May	6 Oct–26 Oct
2013	21 May–28 May	5 Oct–14 Oct	22 May–3 Jun	10 Oct–19 Oct	2 May–22 May	29 Sep–18 Oct	1 May–21 May	28 Sep–18 Oct
2014	19 May–29 May	1 Oct–10 Oct	19 May–28 May	5 Oct–15 Oct	9 May–30 May	11 Oct–28 Oct	4 May–25 May	27 Sep–17 Oct
2015	4 Jun–14 Jun	1 Oct–10 Oct	10 Jun–20 Jun	27 Sep–8 Oct	11 May–30 May	21 Sep–20 Oct	3 May–21 May	28 Sep–18 Oct
2016	9 May–18 May	25 Sep–5 Oct	20 May–29 May	17 Oct–26 Oct	25 May–15 Jun	18 Oct–27 Oct	3 May–22 May	28 Sep–16 Oct
2017	5 May–14 May	10 Oct–19 Oct	5 May–14 May	4 Oct–12 Oct	2 May–22 May	20 Sep–18 Oct	14 May–2 Jun	2 Oct–22 Oct
2018	1 May–8 May	20 Oct–30 Oct	26 May–5 Jun	19 Oct–28 Oct	12 May–29 May	7 Oct–26 Oct	1 May–19 May	11 Oct–29 Oct
2019	10 May–29 May	10 Oct–19 Oct	20 May–28 May	15 Oct–24 Oct	12 May–31 May	21 Sep–10 Oct	6 May–25 May	5 Oct–26 Oct
2020	17 Jun–26 Jun	19 Sep–28 Sep	21 May–30 May	26 Sep–8 Oct	23 May–12 Jun	16 Sep–5 Oct	5 May–25 May	6 Oct–25 Oct
2021	22 May–1 Jun	11 Sep–19 Sep	29 May–8 Jun	15 Oct–25 Oct	28 May–15 Jun	25 Sep–24 Oct	4 May–25 May	6 Oct–26 Oct

– indicates samplings were not conducted in this season

respectively. Shapiro–Wilk test was used to determine the normality of all indices. Since the null hypothesis was rejected in some cases ($P < 0.05$), differences in the average values of aforementioned diversity indices before and after the fishing ban were tested with nonparametric Wilcoxon signed-rank test (Mak et al. 2021).

To explore the effectiveness of the fishing ban on the population increases of key protected species, the occurrence rates in pre-fishing-ban and post-fishing-ban stages were analyzed for each species that have been listed as the national Class I and Class II key protected wild animals of China. The occurrence rate was defined as the percentage frequency of occurrence of each species in the total number of sampling days.

To examine the degrees of similarity of the fish assemblage structure before and after the fishing ban, nonmetric multidimensional scaling (NMDS) ordination analyses were performed, based on the Bray–Curtis similarity matrix (Clarke 1993). Relative abundance data were $\log_{10}(x+1)$ transformed before calculating the Bray–Curtis similarity coefficient, to reduce the weight of dominant species (Clarke and Gorley 2006). Analysis of similarity (ANOSIM) was used to test differences in fish assemblages before and after the fishing ban. Similarity of percentage analysis (SIMPER) was used to identify the discriminating species that were most responsible for dissimilarities between different stages. In this study, species that contributed to 90% of the total average dissimilarity were considered as discriminating species (Clarke 1993). All these analyses were performed with the PRIMER 5 software package (Clarke and Warwick 2001), including modules "NMDS", "ANOSIM" and "SIMPER".

To detect changes in the structure of fish population, length and weight analyses were performed on 10 commercial-target species prior to the fishing ban, including *Schizothorax graham*, *Acrossocheilus yunnanensis*, *Garra imberba*, *Pseudogyrinocheilus procheilus*, *Hemibarbus labeo*, *S. sinensis*, *P. vachelli*, *Mystus macropterus*, *Leiocassis crassilabris* and *P. rabaudi*. These species were among the dominant species of the Chishui River according to the above SIMPER. Meanwhile, *P. rabaudi*, a national Class II key protected wild animals of China, can used to represent the population size changes of key protected species. Considering most species have short- or long-distance migratory behaviours, specimens of the same species collected from different reaches were pooled to analyse changes in their population structure. For each species, the mean standard length and body weight between pre-fishing-ban and post-fishing-ban stages were compared using Wilcoxon signed-rank test (Mak et al. 2021), and the length and weight frequency distributions were examined using two-sample Kolmogorov–Smirnov test (Tuset et al. 2021). Length and weight structure histograms were developed to depict changes in the size structure of these species (Simasiku and Hay 2022).

To explore changes in the density of fish resources, catch per unit effort (CPUE) defined as the weight of all fishes caught per day by 10 gillnets was calculated. Wilcoxon signed rank test was used to examine differences in CPUE before and after the fishing ban for each reach (Mak et al. 2021).

Results

Changes in species composition

A total of 140 fish species, including 127 native and 13 exotic species, were collected during the study period from 2012 to 2021 (Table 2). During the pre-fishing-ban period (2012–2016), 123 fish species were collected, including 116 natives and 7 exotics. During the

Table 2 Fish species collected during different time periods (pre-fishing closure period and post-fishing closure period) for the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River

Order	Family	Species	PT		CZ		CS		HJ		Total		Protection class
			Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	
Acipenseriformes	Acipenseridae	*Acipenser dabryanus* Duméril ★						+		+		+	I
Acipenseriformes	Acipenseridae	Hybrid sturgeon*		+						+		+	
Anguilliformes	Anguillidae	*Anguilla japonica* Temminck *et* Schlegel								+		+	
Cypriniformes	Cyprinidae	*Zacco platypus* (Temminck *et* Schlegel)	+	+	+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Opsariichthys bidens* Günther			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Tinca tinca* (Linnaeus)*								+		+	
Cypriniformes	Cyprinidae	*Mylopharyngodon piceus* (Richardson)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Ctenopharyngodon idella* (Valenciennes)		+		+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Squaliobarbus curriculus* (Richardson)							+	+	+	+	
Cypriniformes	Cyprinidae	*Pseudolaubuca sinensis* Bleeker					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Pseudolaubuca engraulis* (Nichols)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Sinibrama macrops* (Günther)					+	+			+	+	
Cypriniformes	Cyprinidae	*Sinibrama taeniatus* (Nichols) ★					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Ancherythroculter kurematsui* (Kimura) ★					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Ancherythroculter wangi* (Tchang) ★					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Ancherythroculter nigrocauda* Yih *et* Wu ★						+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hemiculterella sauvagei* Warpachowski ★			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hemiculter leucisculus* (Basilewsky)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hemiculter tchangi* Fang ★					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hemiculter bleekeri* Warpachowski					+		+	+	+	+	
Cypriniformes	Cyprinidae	*Chanodichthys erythropterus* (Basilewsky)							+	+	+	+	
Cypriniformes	Cyprinidae	*Chanodichthys mongolicus* (Basilewsky)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Chanodichthys dabryi* Bleeker								+		+	
Cypriniformes	Cyprinidae	*Culter alburnus* Basilewsky		+			+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Parabramis pekinensis* (Basilewsky)							+		+		
Cypriniformes	Cyprinidae	*Megalobrama pellegrini* (Tchang) ★					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Megalobrama amblycephala* Yih*						+	+	+	+	+	
Cypriniformes	Cyprinidae	*Xenocypris acrolepis* Bleeker					+	+	+		+	+	
Cypriniformes	Cyprinidae	*Xenocypris davidi* Bleeker					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Xenocypris microlepis* Bleeker								+		+	
Cypriniformes	Cyprinidae	*Distoechodon tumirostris* Peters					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Pseudobrama simoni* (Bleeker)					+	+	+	+	+	+	

Table 2 (continued)

Order	Family	Species	PT		CZ		CS		HJ		Total		Protection class
			Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	
Cypriniformes	Cyprinidae	*Hypophthalmichthys molitrix* (Valenciennes)				+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hypophthalmichthys nobilis* (Richardson)						+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hemibarbus labeo* (Pallas)	+		+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Hemibarbus maculatus* Bleeker			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Pseudorasbora parva* (Temminck *et* Schlegel)	+	+	+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Sarcocheilichthys sinensis* Bleeker					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Sarcocheilichthys nigripinnis* (Günther)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Gnathopogon imberbis* (Sauvage *et* Dabry)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Gnathopogon herzensteini* (Günther)★							+	+	+	+	
Cypriniformes	Cyprinidae	*Squalidus argentatus* (Sauvage *et* Dabry)			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Coreius heterodon* (Bleeker)							+	+	+	+	
Cypriniformes	Cyprinidae	*Coreius guichenoti* (Sauvage *et* Dabry) ★							+	+	+	+	II
Cypriniformes	Cyprinidae	*Rhinogobio typus* Bleeker			+		+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Rhinogobio cylindricus* Günther ★							+	+	+	+	
Cypriniformes	Cyprinidae	*Platysmacheilus nudiventris* Lo, Yao *et* Chen★			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Abbottina rivularis* (Basilewsky)						+	+	+	+	+	
Cypriniformes	Cyprinidae	*Abbottina obtusirostris* Wu *et* Wang ★							+		+		
Cypriniformes	Cyprinidae	*Saurogobio gracilicaudatus* Yao *et* Yang								+		+	
Cypriniformes	Cyprinidae	*Saurogobio dabryi* Bleeker			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Saurogobio gymnocheilus* Lo, Yao *et* Chen					+		+	+	+	+	
Cypriniformes	Cyprinidae	*Saurogobio punctatus* Tang, Li, Yu, Zhu, Ding, Liu & Danley				+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Gobiobotia abbreviata* Fang *et* Wang ★			+						+	+	
Cypriniformes	Cyprinidae	*Gobiobotia filifer* (Garman)					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Xenophysogobio boulengeri* Tchang ★								+		+	
Cypriniformes	Cyprinidae	*Rhodeus ocellatus* (Kner)			+		+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Rhodeus sinensis* Günther					+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Acheilognathus gracilis* Nichols								+		+	
Cypriniformes	Cyprinidae	*Acheilognathus chankaensis* (Dybowski)								+		+	
Cypriniformes	Cyprinidae	*Acheilognathus macropterus* (Bleeker)							+	+	+	+	
Cypriniformes	Cyprinidae	*Acheilognathus omeiensis* (Shih *et* Tchang) ★							+	+	+	+	
Cypriniformes	Cyprinidae	*Acheilognathus barbatulus* (Günther)								+		+	
Cypriniformes	Cyprinidae	*Spinibarbus sinensis* (Bleeker)	+	+	+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Spinibarbus hollandi* Ohima*								+		+	

Table 2 (continued)

Order	Family	Species	PT		CZ		CS		HJ		Total		Protection class
			Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	
Cypriniformes	Cyprinidae	*Barbus capito* (Güldenstädt)*								+		+	
Cypriniformes	Cyprinidae	*Percocypris pingi* (Tchang)★	+	+		+					+	+	II
Cypriniformes	Cyprinidae	*Acrossocheilus monticolus* (Günther) ★				+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Acrossocheilus yunnanensis* (Regan)	+	+	+	+		+			+	+	
Cypriniformes	Cyprinidae	*Onychostoma simum* (Sauvage *et* Dabry)	+	+	+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Onychostoma angustistomata* (Fang) ★	+	+							+	+	II
Cypriniformes	Cyprinidae	*Cirrhinus mrigala* (Hamilton)*								+		+	
Cypriniformes	Cyprinidae	*Bangana rendahli* (Kimura) ★			+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Pseudogyrinocheilus procheilus* (Sauvage *et* Dabry)	+	+	+	+					+	+	
Cypriniformes	Cyprinidae	*Sinocrossocheilus labiata* Su, Yang *et* Cui ★	+	+	+	+					+	+	
Cypriniformes	Cyprinidae	*Garra imberba* Garman	+	+	+	+	+	+		+	+	+	
Cypriniformes	Cyprinidae	*Schizothorax dolichonema* Herzenstein★	+								+		
Cypriniformes	Cyprinidae	*Schizothorax grahami* (Regan) ★	+	+	+	+					+	+	
Cypriniformes	Cyprinidae	*Procypris rabaudi* (Tchang) ★	+	+	+	+	+	+	+	+	+	+	II
Cypriniformes	Cyprinidae	*Cyprinus carpio* Linnaeus	+		+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	*Cyprinu carpio L.* mirror*					+		+	+	+	+	
Cypriniformes	Cyprinidae	*Carassius auratus* (Linnaeus)	+	+	+	+	+	+	+	+	+	+	
Cypriniformes	Cyprinidae	Triploid crucian carp*								+		+	
Cypriniformes	Catostomidae	*Myxocyprinus asiaticus* (Bleeker)					+	+	+	+	+	+	II
Cypriniformes	Nemacheilidae	*Homatula variegatus* (Sauvage *et* Dabry)	+	+	+	+	+		+	+	+	+	
Cypriniformes	Nemacheilidae	*Homatula potanini* (Günther)★						+	+	+	+	+	
Cypriniformes	Nemacheilidae	*Homatula wujiangensis* Ding *et* Deng ★			+	+			+	+	+	+	
Cypriniformes	Nemacheilidae	*Triplophysa bleekeri* (Sauvage *et* Dabry)							+		+		
Cypriniformes	Botiidae	*Botia superciliaris* Günther			+		+	+	+	+	+	+	
Cypriniformes	Botiidae	*Botia reevesae* Chang ★			+		+				+		
Cypriniformes	Botiidae	*Parabotia fasciata* Dabry					+	+	+	+	+	+	
Cypriniformes	Botiidae	*Parabotia bimaculata* Chen ★					+	+	+	+	+	+	
Cypriniformes	Botiidae	*Leptobotia elongata* (Bleeker) ★	+		+	+	+	+	+	+	+	+	II
Cypriniformes	Botiidae	*Leptobotia taeniops* (Sauvage)					+		+	+	+	+	
Cypriniformes	Botiidae	*Leptobotia rubrilabris* (Dabry) ★								+		+	II
Cypriniformes	Cobitidae	*Cobitis sinensis* Sauvage *et* Dabry							+		+		
Cypriniformes	Cobitidae	*Misgurnus anguillicaudatus* (Cantor)	+	+	+	+	+	+	+	+	+	+	
Cypriniformes	Cobitidae	*Paramisgurnus dabryanus* Sauvage		+					+	+	+	+	

Table 2 (continued)

Order	Family	Species	PT		CZ		CS		HJ		Total		Protection class
			Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	
Cypriniformes	Balitoridae	*Beaufortia liui* Chang ★	+	+							+	+	
Cypriniformes	Balitoridae	*Lepturichthys fimbriata* (Günther)							+	+	+	+	
Cypriniformes	Balitoridae	*Jinshaia abbreviate* (Günther) ★			+					+	+	+	
Cypriniformes	Balitoridae	*Jinshaia sinensis* (Sauvage *et* Dabry) ★			+						+		
Cypriniformes	Balitoridae	*Sinogastromyzon sichangensis* Chang ★	+	+	+	+		+	+		+	+	
Cypriniformes	Balitoridae	*Sinogastromyzon szechuanensis* Fang ★					+	+	+	+	+	+	
Cypriniformes	Balitoridae	*Metahomaloptera omeiensis* Chang		+								+	
Siluriformes	Bagridae	*Tachysurus fulvidraco* (Richardson)		+		+	+	+	+	+	+	+	
Siluriformes	Bagridae	*Tachysurus nitidus* (Sauvage *et* Dabry)			+	+	+	+	+	+	+	+	
Siluriformes	Bagridae	*Tachysurus dumerili* (Bleeker)					+	+	+	+	+	+	
Siluriformes	Bagridae	*Pelteobagrus eupogon* (Boulenger)							+	+	+	+	
Siluriformes	Bagridae	*Pseudobagrus vachelli* (Richardson)			+	+	+	+	+	+	+	+	
Siluriformes	Bagridae	*Pelteobagrus ussuriensis* (Dybowski)			+	+					+	+	
Siluriformes	Bagridae	*Pseudobagrus crassilabris* Günther			+	+	+	+	+	+	+	+	
Siluriformes	Bagridae	*Pseudobagrus truncates* (Regan)	+		+	+	+	+	+	+	+	+	
Siluriformes	Bagridae	*Pseudobagrus emarginatus* (Regan)			+	+		+	+	+	+	+	
Siluriformes	Bagridae	*Pseudobagrus pratti* (Günther)			+	+	+		+	+	+	+	
Siluriformes	Bagridae	*Mystus macropterus* (Bleeker)			+	+	+	+	+	+	+	+	
Siluriformes	Siluridae	*Silurus asotus* Linnaeus			+	+	+	+	+	+	+	+	
Siluriformes	Siluridae	*Silurus meridionalis* Chen				+	+	+	+	+	+	+	
Siluriformes	Amblycipitidae	*Liobagrus marginatus* (Bleeker)				+			+		+	+	
Siluriformes	Amblycipitidae	*Liobagrus nigricauda* Regan							+		+		
Siluriformes	Amblycipitidae	*Liobagrus marginatoides* (Wu)★				+	+	+	+	+	+	+	
Siluriformes	Sisoridae	*Glyptothorax sinensis* (Regan)			+	+	+	+	+	+	+	+	
Siluriformes	Sisoridae	*Euchiloglanis davidi* (Sauvage) ★	+	+							+	+	II
Siluriformes	Ictaluridae	*Ictalurus punctatus* (Rafinesque)*					+			+	+	+	
Siluriformes	ctaluridae	*Clarias gariepinus* (Burchell)*					+			+	+	+	
Osmeriformes	Salangidae	*Protosalanx chinensis* (Basilewsky)*							+		+		
Cyprinodontiformes	Poeciliidae	*Gambusia affinis* (Baird *et* Girard)*							+	+	+	+	
Perciformes	Percichthyidae	*Siniperca kneri* Garman			+				+	+	+	+	
Perciformes	Percichthyidae	*Siniperca chuatsi* (Basilewsky)			+	+	+	+	+	+	+	+	
Perciformes	Percichthyidae	*Siniperca scherzeri* Steindachner					+	+	+	+	+	+	
Perciformes	Odontobutidae	*Odontobutis obscurus* (Temminck *et* Schlegel)							+	+	+	+	

Table 2 (continued)

Order	Family	Species	PT		CZ		CS		HJ		Total		Protection class
			Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	
Perciformes	Odontobutidae	*Micropercops swinhonis* (Günther)							+		+		
Perciformes	Gobiidae	*Rhinogobius giurinus* (Rutter)				+	+	+	+	+	+	+	
Perciformes	Gobiidae	*Rhinogobius szechuanensis* (Liu) ★							+		+		
Perciformes	Gobiidae	*Rhinogobius cliffordpopei* (Nichols)							+		+		
Perciformes	Gobiidae	*Mugilogobius myxodermus* (Herre)							+		+		
Perciformes	Belontiidae	*Macropodus chinensis* (Bloch)							+		+		
Perciformes	Channidae	*Channa argus* (Cantor)					+	+	+	+	+	+	
Perciformes	Percidae	*Sander lucioperca* (Linnaeus)*							+	+	+	+	
Synbranchiformes	Synbranchidae	*Monopterus albus* (Zuiew)					+		+	+	+	+	

I and II refer the protection class of this species in the national key protected wild animals of China

+ indicates species occurred in this sampling period

★ indicates endemic species of the upper Yangtze River

* indicates exotic species

post-fishing-ban period (2017–2021), 126 fish species were collected, including 114 natives and 12 exotics. The total number of fish species and the number of native species exhibited little change, while the number of exotic species increased from 7 to 12.

Eleven native species (*Acipenser dabryanus*, *A. japonica*, *Culter dabryi*, *Xenocypris microlepis*, *Saurogobio gracilicaudatus*, *Xenophysogobio boulengeri*, *Acheilognathus gracilis*, *A. chankaensis*, *A. barbatulus*, *Leptobotia rubrilabris* and *Metahomaloptera omeiensis*), which had disappeared for many years in the Chishui River, reoccurred in the post-fishing-ban period. Six exotic species (hybrid sturgeon, *Tinca tinca*, *Spinibarbus hollandi*, *Barbus capito*, *Cirrhinus mrigala* and triploid crucian carp) were recorded for the first time in the post-fishing-ban period.

Changes in diversity indices

The annual mean values of the three diversity indices, including D, H' and J', before and after the implementation of the fishing ban for the four study reaches, are given in Table 3. Tests revealed that all the diversity indices examined showed no significant changes before and after the fishing ban for all study reaches (Wilcoxon signed-rank test, all cases $P > 0.05$).

Changes in the occurrence rates of key protected species

During the study period, nine key protected fish species (*Acipenser dabryanus*, *Coreius guichenoti*, *Percocypris pingi*, *Onychostoma angustistomata*, *P. rabaudi*, *Myxocyprinus asiaticus*, *Leptobotia elongate*, *Leptobotia rubrilabris* and *Euchiloglanis davidi*), that have been listed as the national Class I and Class II key protected wild animals of China, were collected (Table 2). Among these species, the occurrence rate of *P. rabaudi* was observed to increase after the fishing ban in all reaches. In addition, the occurrence rate of *A. dabryanus* in the HJ reach, *E. davidi* in the PT reach, and *M. asiaticus* in the CS and HJ reaches, also increased. However, the occurrence rates of *C. guichenoti*, *P. pingi*, *O. angustistomata*, *L. elongate* and *L. rubrilabris* showed no increasing trends (Table 4).

Changes in the structure of fish assemblages

NMDS ordination plots showed that the fish assemblages in the four study reaches all exhibited certain changes before and after the implementation of the fishing ban (Fig. 2).

Similarity of percentage analyses (SIMPER) revealed that the average dissimilarity in fish assemblages before and after the fishing ban was 32.18%, 40.76%, 39.18% and 65.67% for PT, CZ, CS and HJ reaches, respectively. In the PT reach, the relative abundances of *S. graham*, *P. procheilus* and *Onychostoma sima* increased after the fishing ban, while *A. yunnanensis* and *Zacco platypus* showed the opposite tendency. In the CZ reach, the relative abundances of *H. labeo*, *A. yunnanensis*, *O. sima* and *P. procheilus* increased after the fishing ban, while *G. imberba*, *Pseudobagrus truncates* and *Z. platypus* decreased. In the CS reach, the relative abundances of *Saurogobio dabryi*, *Pelteobagrus nitidus* and *P. vachelli* increased, while *M. macropterus*, *H. labeo* and *Squalidus argentatus* decreased. In the HJ reach, the relative abundances of some larger body-sized species, such as *P. vachelli*, *L. crassilabris* and *M. macropterus* increased, while smaller sized *S. argentatus* and *Rhinogobius giurinus* decreased (Table 5).

ANOSIM further confirmed that the structure of fish assemblages in CZ, CS and HJ reaches changed significantly after the fishing ban (all cases $P < 0.05$). However, changes of the fish assemblage in the PT reach were not statistically significant (Global $R = 0.025$, $P > 0.05$).

Changes in the population structure of dominant species

Results showed that the mean standard length of most examined species increased significantly after the fishing ban (Wilcoxon signed-rank test, $P < 0.05$), except for *P. procheilus*, *H. labeo* and *P. yachelli*, which presented no significant temporal changes (*P. procheilus* and *P. yachelli*) or decreased (*H. labeo*) in the mean standard length (Wilcoxon signed-rank test, $P > 0.05$) (Table 6). The mean body weight also increased for nearly all the examined species after the fishing ban (Wilcoxon signed-rank test, $P < 0.05$), except for *P. procheilus* and *P. vachelli* which showed no significant temporal changes (*P. procheilus*) or a decreased trend (*P. vachelli*) in the mean body weight (Wilcoxon signed-rank test, $P < 0.05$) (Table 6).

Further analysis on the distribution of standard length and body weight showed significant changes for all the examined species after the fishing ban (Kolmogorov–Smirnov test, all cases $P < 0.05$), with the proportion of larger-sized individuals clearly increased (Figs. 3 and 4). These results suggested that the population structure of these species improved after the fishing ban.

Changes in the catch per unit effort (CPUE)

During the pre-fishing-ban period, the annual average CPUE of the four study reaches in the Chishui River varied from 3.7 ± 1.2 kg/day (CZ reach) to 5.0 ± 1.3 kg/day (HJ reach). However, during the post-fishing-ban period, the annual averaged CPUE increased to 5.2 ± 1.9 kg/day (CZ reach) to 10.6 ± 1.4 kg/day (HJ reach). Analyses showed that the CPUE increased significantly after the fishing ban for all study reaches (Wilcoxon signed-rank test, all cases $P < 0.05$), with the rate increase ranging from 140% (CZ reach) to 210% (HJ reach) (Fig. 5).

Table 3 Mean values of the three diversity indices (Mean ± SD), Margalef richness index (D), Shannon–Wiener diversity index (*H*′) and Pielou evenness index (*J*′), before and after the implementation of the fishing ban for the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River

Indices	PT		*P*	CZ		*P*	CS		*P*	HJ		*P*
	Pre-	Post-		Pre-	Post-		Pre-	Post-		Pre-	Post-	
D	2.17 ± 0.22	2.22 ± 0.32	> 0.05	3.69 ± 0.09	3.85 ± 0.58	> 0.05	5.47 ± 0.56	5.53 ± 0.58	> 0.05	7.76 ± 0.33	7.06 ± 1.28	> 0.05
H′	1.77 ± 0.10	1.81 ± 0.09	> 0.05	2.41 ± 0.11	2.25 ± 0.17	> 0.05	2.60 ± 0.07	2.58 ± 0.20	> 0.05	2.68 ± 0.37	2.76 ± 0.15	> 0.05
J′	0.63 ± 0.04	0.68 ± 0.07	> 0.05	0.72 ± 0.04	0.67 ± 0.04	> 0.05	0.67 ± 0.03	0.67 ± 0.04	> 0.05	0.63 ± 0.09	0.66 ± 0.03	> 0.05

The results of nonparametric Wilcoxon signed-rank test are presented for comparison before and after the fishing ban

Table 4 Changes in the occurrence rates which are defined as the percentage frequency of occurrence in the total number of sampling days of the 9 key protected species before and after the implementation of the fishing ban for the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River

Species	PT		CZ		CS		HJ	
	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
A. dabryanus	–	–	–	–	0.00	0.48	0.00	21.92
C. guichenoti	–	–	–	–	–	–	2.18	2.74
P. pingi	12.70	11.11	0.00	4.44	–	–	–	–
O. angustistomata	3.17	3.70	–	–	–	–	–	–
P. rabaudi	3.17	14.81	3.39	37.78	36.22	42.38	25.33	46.55
M. asiaticus	–	–	–	–	0.00	7.62	8.30	15.07
L. elongate	1.59	0.00	20.68	20.00	0.26	0.48	0.87	1.37
L. rubrilabris	0.00	0.46	–	–	–	–	–	–
E. davidi	22.22	37.04	–	–	–	–	–	–

– indicates species absent from this sampling reach

Discussion

Effectiveness of the fishing closure

The present study showed that fish resources in the Chishui River have improved to a large extent 5 years after the implementation of the 10-year complete fishing ban. These results accorded well with our hypotheses. The improvement in fish resources was indicated by the following positive changes. First, some species (e.g., *A. japonica*, *X. microlepis*, *X. boulengeri* and *L. rubrilabris*) that have not seen for many years began reappearing after the fishing ban. Second, the population size of some key protected species (e.g., *P. rabaudi*, *A. dabryanus*, *E. davidi* and *M. asiaticus*) have increased greatly compared to the pre-fishing-ban period (2012–2016), as demonstrated by the occurrence rates. Third, the structures of fish assemblages have improved with the relative abundances of some larger body-sized species (e.g., *S. graham*, *P. procheilus*, *O. sima* and *P. vachelli*) increased. Fourth, the population structure of most dominant species has improved with the mean standard length and mean body weight as well as the proportion of larger body-sized individuals clearly increasing. Finally, the density of fishes was elevated with the CPUE increasing significantly after the fishing ban. In general, the effectiveness of this complete fishing ban, after 5 years of fishing cessation, has been documented in different ways, including species composition, assemblage structure, population composition and fish density. Similar results have been revealed by several other studies, which together have proved fishing closure is a useful management tool to mediate the impact of overfishing and facilitate the recovery of fish resources (Carvalho et al. 2019; Mak et al. 2021; Tuset et al. 2021; Jiang et al. 2022; Xie et al. 2022). Intensive fishing on certain targeted species often tends to capture species with high economic value, directly causing their populations to decrease (Jennings and Kaiser 1998). *Procypris rabaudi* was one of the important commercial targets in the Chishui River before the fishing ban due to its high economic value, which thus suffered serious impacts from overfishing and the population decreased dramatically (Liu et al. 2020). Fortunately, the population size of this species increased after 5 years of fishing closure. These changes confirmed that fishing bans can remove fishing mortality and facilitate population recovery of these species (Jennings 2001). In addition, commercial fishing activities often tend to capture larger sized

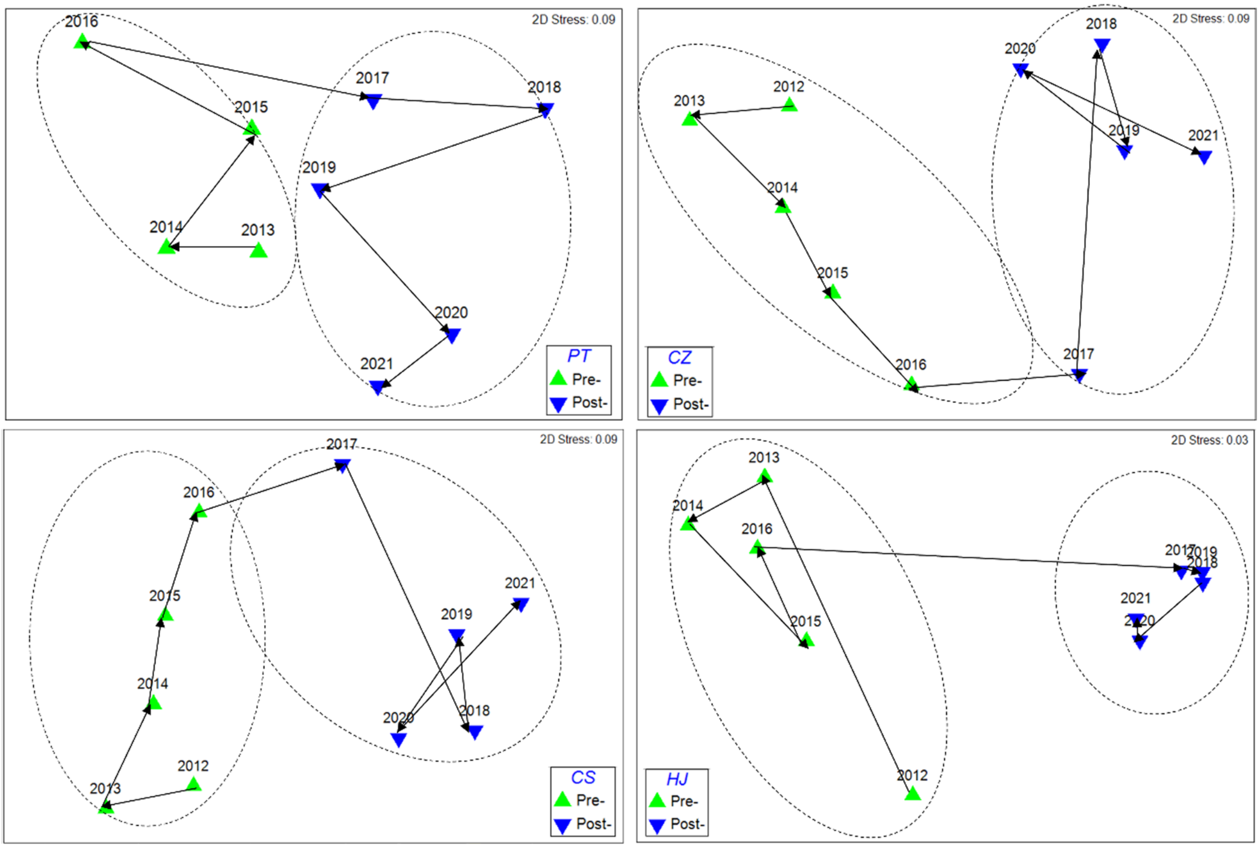

Fig. 2 Non-metric multidimensional scaling (NMDS) ordination demonstrating temporal changes in the structure of fish assemblages, before and after the implementation of the fishing ban for the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River

species or individuals, resulting in changes in both species composition of fish assemblages and size structure of some species (Liu and Cao 1992). After fishing activities ceased, the population size of larger sized species increased noticeably and their relative abundance in fish assemblages increased correspondingly. Similar changes also happened to the population structure of some species. Tuset et al. (2021) demonstrated that the recovery of larger adults is a common response of many species to the cessation of fishing pressure.

Inter-specific and inter-reach differences in recovery

The present study revealed that the key protected species showed different recovery rates after the implementation of the fishing ban. Specifically, the occurrence rates of *P. rabaudi*, *A. dabryanus*, *E. davidi* and *M. asiaticus* increased. However, some other key protected species, such as *C. guichenoti*, *P. pingi*, *O. angustistomata*, *L. elongate* and *L. rubrilabris* showed no obvious increases. This phenomenon might be caused by differences in their life history traits, initial population sizes and subsequent recruitment (Jennings 2001; Abesamis et al. 2014). For example, *P. rabaudi* is a widely distributed fish species in the upper Yangtze River, preferring rocky substrata and running water and does not rely on long distance migration to complete its life history. Before the fishing ban, this species still maintained a population in the Chishui River, especially in the mid-and-lower reaches, due to the more natural aquatic environment (Li et al. 2015). The relatively simple life history characteristics and larger initial population size may be beneficial for its population recovery (Jennings 2001). This may be why we observed the occurrence rate of *P. rabaudi* increasing rapidly in all study reaches after the cessation of fishing. In comparison, *C. guichenoti*, *L. elongate* and *L. rubrilabris* rely on long distance migration to complete their life history. Their spawning grounds are distributed mainly in the lower Jinsha River, and the juveniles and sub-adults enter the lower Chishui River to feed (Liu et al. 2012). However, after the construction of the Xiangjiaba Dam in the lower Jinsha River in 2008, their migration routes were blocked and their populations decreased dramatically in the mainstem upper Yangtze River (Liu et al.

Table 5 SIMPER analysis showing the percentage of dissimilarity between pre- and post-fishing ban period in the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River, and the species that most contribute to this dissimilarity for the relative abundance data

Species	PT (Average dissimilarity = 32.18)			CZ (Average dissimilarity = 40.76)			CS (Average dissimilarity = 39.18)			HJ (Average dissimilarity = 65.67)		
	AV. Abundance		Contrib. %	AV. Abundance		Contrib. %	AV. Abundance		Contrib. %	AV. Abundance		Contrib. %
	Pre-	Post-		Pre-	Post-		Pre-	Post-		Pre-	Post-	
S. grahami	29.20	37.17	19.97									
A. yunnanensis	49.27	26.28	36.14	8.38	17.36	11.20						
P. procheilus	5.46	18.46	20.20	12.60	15.94	6.61						
Z. platypus	6.01	5.92	7.39	6.90	3.78	6.59						
O. sima	3.90	4.23	5.49	3.25	7.74	8.03	0.20	1.03	1.16			
P. variegatus	1.67	1.27	2.12									
G. imberba				27.56	11.24	19.95						
L. elongate				2.68	0.74	2.56						
P. rabaudi				0.04	1.43	1.71						
H. labeo				17.05	24.10	14.34	16.35	13.14	8.71	2.35	6.81	3.93
L. crassilabris				1.77	0.58	1.72	10.70	7.35	5.40	0.50	12.90	9.44
P. truncates				8.73	5.79	7.03	7.18	2.54	5.98	0.05	1.51	1.11
S. sinensis				0.66	2.46	2.65	4.09	2.51	2.51	1.18	1.64	0.73
C. carpio				0.18	2.49	2.99				1.86	0.89	1.09
S. chuatsi				5.09	1.31	5.43	2.00	0.97	1.32			
S. argentatus							9.16	8.31	6.25	28.71	3.30	19.35
P. vachelli							11.98	12.56	10.39	3.03	21.81	12.77
R. typus							2.58	2.51	1.95	0.54	1.70	0.89
A. kurematsui							3.53	3.19	2.31	0.37	1.39	0.81
M. macropterus							12.59	5.44	9.85	0.49	11.63	8.48
S. dabryi							6.94	19.17	15.61	7.68	8.38	4.11
C. auratus							2.64	1.45	2.74	6.00	3.10	2.71
P. nitidus							1.53	13.70	15.55	1.25	4.54	2.51
R. giurinus										12.48	0.69	8.98
P. simony										3.71	2.02	2.28
P. sinensis										3.17	2.17	2.03
H. tchangi										3.19	0.92	1.73
R. sinensis										2.27	0.03	1.71
P. fulvidraco										0.75	2.63	1.43
C. mongolicus										2.41	1.48	1.16
S. asotus										0.80	1.70	0.99
A. nigrocauda										1.40	1.03	0.70
M. pellegrini										0.33	1.20	0.67
C. alburnus										1.33	0.85	0.65

For each species, the average values of relative abundance (AV. Abundance) in each period and the contribution to dissimilarity (Contritb. %) are provided. Species contributing up to 90% of cumulative dissimilarity are listed

2012). Because of recruitment failure, the populations of these species in the Chishui River also decreased dramatically and did not show an increasing trend, even though the strict fishing ban policy was implemented. For these migratory species, local fishing closure can only have benefits for some of their life history stages. Large-scale fishing closure combined with other protection measures from a watershed perspective may be needed to promote their population recovery.

Meanwhile, the present study revealed that the density of fish resources in the Chishui River increased significantly after the fishing ban for all study reaches, as demonstrated by the CPUE. However, the recovery rates varied in different reaches. Specifically, in the

Table 6 Mean standard length and mean body weight of the main dominant species before and after the implementation of the fishing ban in the Chishui River

Species	Mean standard length ± SD (mm)		*W* test	*KS* test	Mean body weight ± SD (g)		*W* test	*KS* test
	Pre-	Post-			Pre-	Post-		
S. grahami	116.9 ± 65.0	150.6 ± 54.3	**< 0.05**	**< 0.05**	57.8 ± 124.7	82.3 ± 135.8	**< 0.05**	**< 0.05**
A. yunnanensis	123.1 ± 33.6	143.3 ± 37.0	**< 0.05**	**< 0.05**	42.1 ± 41.7	68.9 ± 60.3	**< 0.05**	**< 0.05**
G. imberba	152.8 ± 38.2	177.9 ± 44.6	**< 0.05**	**< 0.05**	76.9 ± 54.4	126.6 ± 99.5	**< 0.05**	**< 0.05**
P. procheilus	126.0 ± 33.1	131.2 ± 25.7	> 0.05	**< 0.05**	49.4 ± 43.2	52.2 ± 34.1	> 0.05	**< 0.05**
H. labeo	141.6 ± 31.5	140.5 ± 36.6	**< 0.05**	**< 0.05**	56.7 ± 39.6	56.8 ± 41.2	**< 0.05**	**< 0.05**
S. sinensis	193.1 ± 82.8	224.6 ± 86.9	**< 0.05**	**< 0.05**	294.1 ± 327.7	451.9 ± 491.2	**< 0.05**	**< 0.05**
P. vachelli	158.6 ± 50.2	165.5 ± 44.9	> 0.05	**< 0.05**	81.4 ± 88.1	77.0 ± 72.6	**< 0.05**	**< 0.05**
M. macropterus	174.6 ± 52.8	207.1 ± 53.5	**< 0.05**	**< 0.05**	58.8 ± 46.5	91.1 ± 57.9	**< 0.05**	**< 0.05**
L. crassilabris	127.9 ± 34.9	156.2 ± 40.1	**< 0.05**	**< 0.05**	40.5 ± 29.7	61.7 ± 37.9	**< 0.05**	**< 0.05**
P. rabaudi	130.1 ± 66.5	153.2 ± 68.8	**< 0.05**	**< 0.05**	109.3 ± 187.4	149.1 ± 227.3	**< 0.05**	**< 0.05**

The results of Wilcoxon signed-rank test (*W* test) and Kolmogorov–Smirnov test (*KS* test) are presented for comparison before and after the fishing ban. Bold type denotes a significant difference

headwater and upstream the CPUE showed a relatively lower increasing rate (about 140%), while those in the midstream and downstream nearly doubled. These differences might be caused by the spatial changes in habitat characteristics and commercial fishing intensity prior to the ban. Previously studies have indicated that the number of fish species as well as the total fish biomass in the Chishui River increased gradually along the upstream–downstream gradient, because of the increase in living space, habitat availability and food diversity (Wu et al. 2011a, 2011b). In addition, the middle and lower reaches have suffered more intensive commercial fishing than the upper reaches prior to the fishing ban (Liu et al. 2021a, b). Thus, the middle and lower reaches may have a greater recovery potential if the fishing activities were completely banned. In addition, after the fishing closure resulting in an increase of fish resources and the improvement of the aquatic eco-environment, many fishes began to enter the lower Chishui River from the mainstem Yangtze River. For example, *A. dabryanus* and the four major Chinese carps (*Mylopharyngodon piceus*, *Ctenopharyngodon idella*, *Hypophthalmichthys molitrix* and *Hypophthalmichthys nobilis*) mainly lived in the mainstem Yangtze River before the fishing ban, but many individuals of these species have entered the lower Chishui River to feed or spawn in recent years. This explains why the mid- and downstream showed a higher increasing rate of CPUE than the upper reaches.

Suggestions for future conservation

The present study revealed that fish resources in the Chishui River have recovered noticeably after 5-year implementation of the fishing ban. However, the species diversity as well as the population size of some key protected species still do not show obvious recovery trends. Many studies have demonstrated that overfishing is just one of the major pressures affecting the fish resources (Liu et al. 2019; Chen et al. 2020; Zhang et al. 2020; Wang et al. 2022). Although fishing closure can eliminate the effect of overfishing, it cannot compensate for all loss caused by multiple human activities. Therefore, more comprehensive protection measures are suggested, to further facilitate the fish resources rehabilitation and biodiversity conservation in the Chishui River.

First, strengthen the management of the fishery. The fishing ban effectively controlled commercial capture. However, illegal fishing still exists in the Chishui River Basin, especially in some remote mountain areas. This phenomenon weakens the efficiency of the fishing ban to some degree (Liu et al. 2021a). The present study showed that the population of most protected species have increased after 5 years of fishing cessation, which proved that a fishing ban is an effective measure in restoring the fish resources. However, for some species with a relative low population base or complex life history, more time and comprehensive conservation measures may be needed for their population to recover. Therefore, the present fishing-ban policy should be continued to provide favorable opportunity and sufficient time to further promote the restoration of fish resources. Illegal fishing activities could be controlled more strictly, to minimize the impact of fishing as far as possible (Liu et al. 2021a). In addition, education and outreach activities could be strengthened, to improve the community knowledge and attitudes about the complete fishing-ban policy as well as other conservation measures (Leisher et al. 2012).

Second, control the invasion of exotic fishes. The present study showed that the number of exotic species

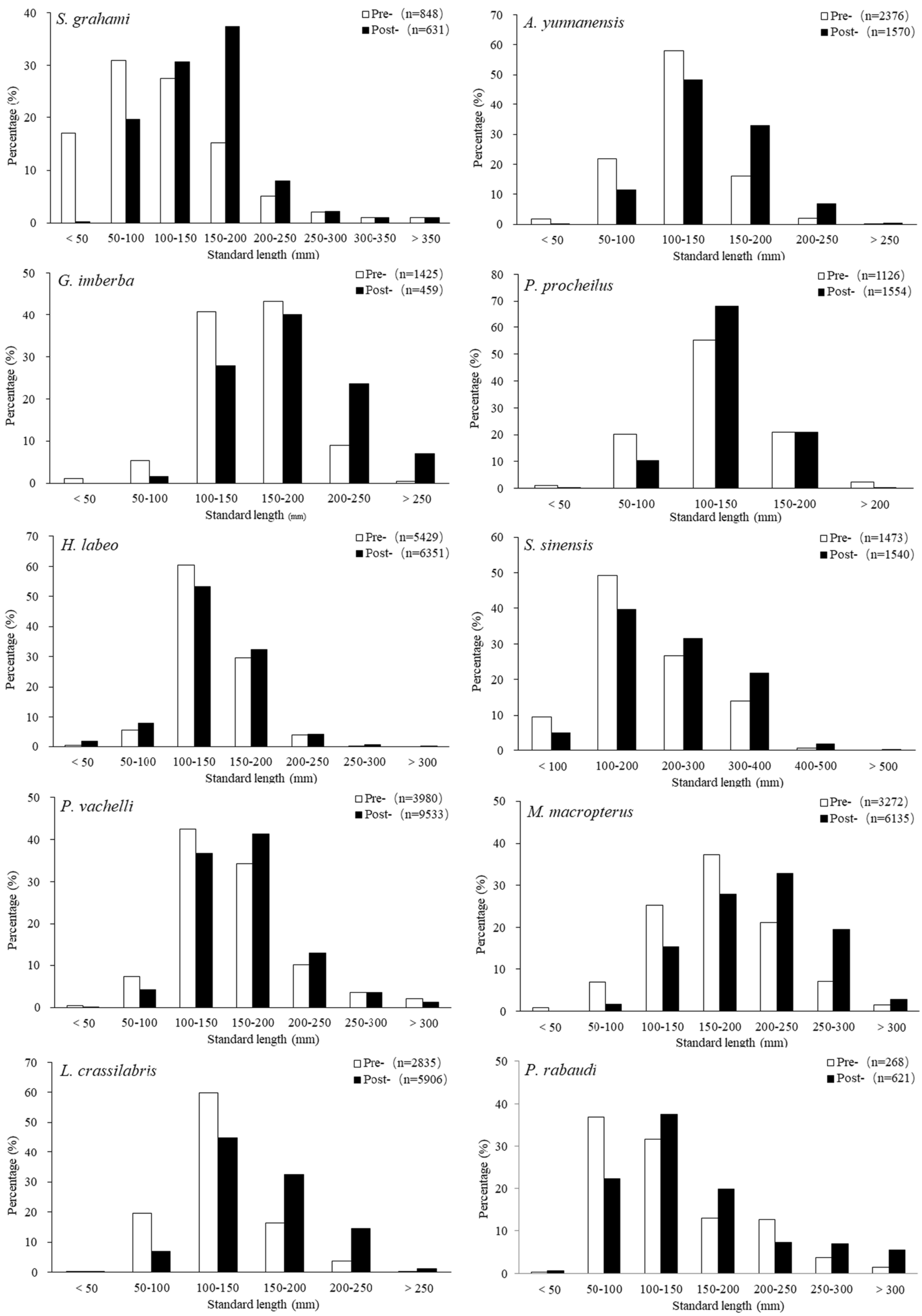

Fig. 3 Changes in the length–frequency distributions of the main dominant species before and after the implementation of the fishing ban in the Chishui River. *n* number of sampled individuals

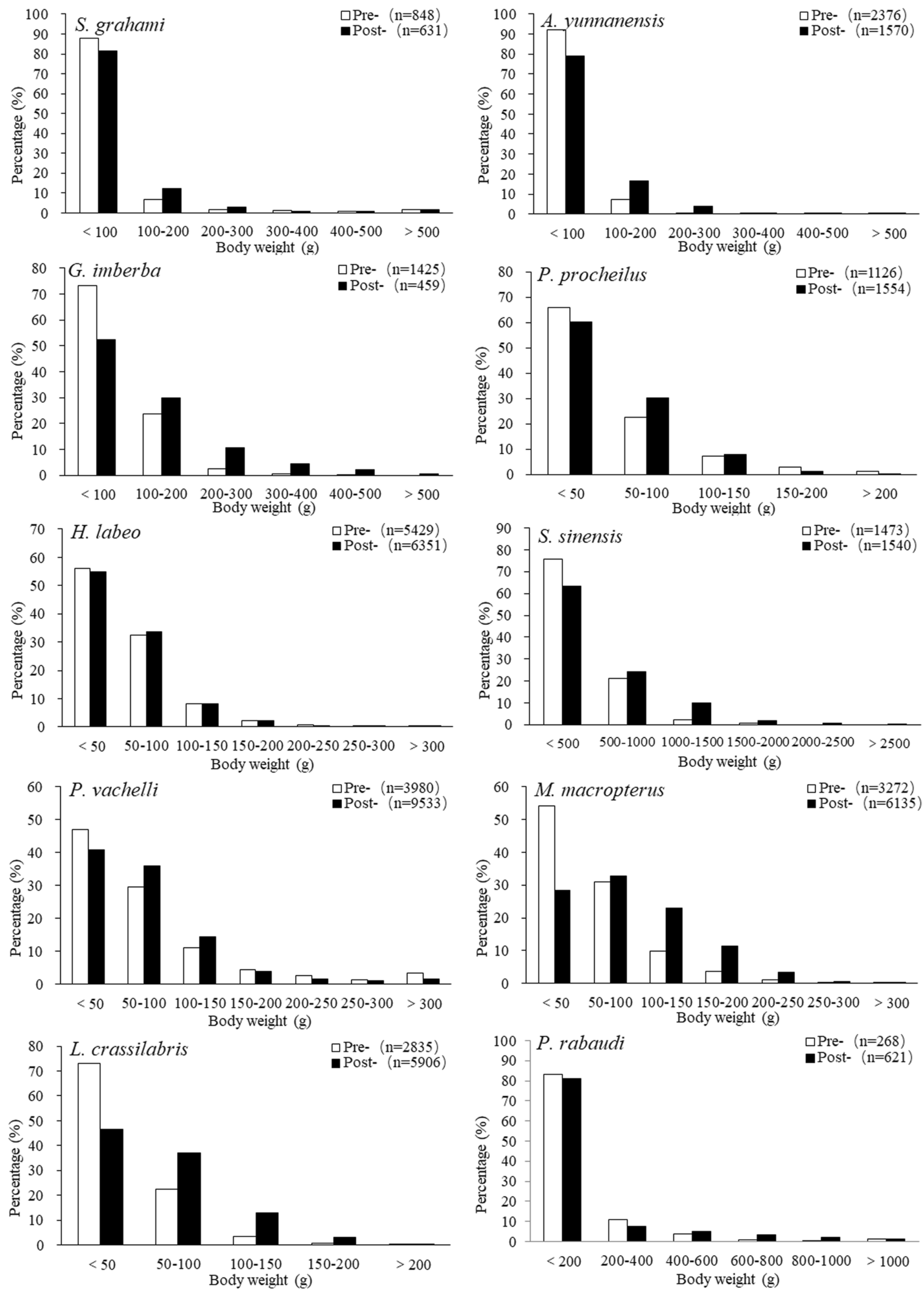

Fig. 4 Changes in the weight–frequency distributions of the main dominant species before and after the implementation of the fishing ban in the Chishui River. *n* number of sampled individuals

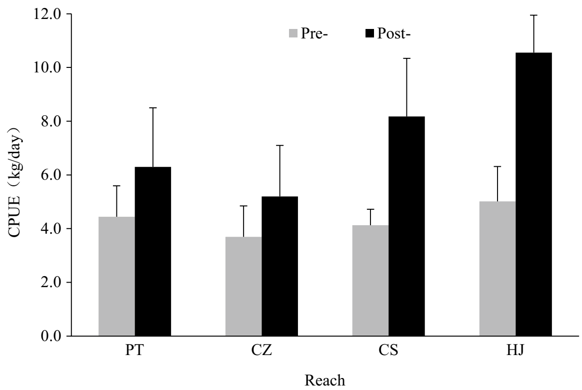

Fig. 5 Changes in the catch per unit effort (CPUE) of fishes before and after the implementation of the fishing ban for the four study reaches, Potou Town (PT), Chishui Town (CZ), Chishui City (CS) and Hejiang County (HJ), in the Chishui River. The error bars show the mean ± standard deviation (SD)

has increased after the implementation of the fishing ban, with six exotic species (hybrid sturgeon, *T. tinca*, *S. hollandi*, *B. capito*, *C. mrigala* and triploid crucian carp) recorded for the first time. These species may have escaped from aquaculture fish farms or released by human beings intentionally. Although none of these species have established stable populations, the potential impact cannot be ignored, because exotic species can affect aquatic ecosystems at the individual, population, community and ecosystem levels (Mota et al. 2014). Strict management of fish farms and better release strategies for fishes are urgently needed, to avoid the potential risks of invasion of exotic species (Zhang et al. 2020).

Third, recover the populations of key protected species. The present study showed the population size of the most protected species increased remarkably after the fishing ban. However, some key protected species (e.g., *C. guichenoti*, *P. pingi*, *O. angustistomata*, *L. elongate* and *L. rubrilabris*) still showed no obvious recovery due to the low population base or complex life history. Artificial fish propagation and release may be an effective way to promote their population restoration (Zhang et al. 2020). Nowadays, artificial reproductive techniques of *C. guichenoti*, *P. pingi* and *L. elongate* have made some progress, but large-scale production cannot yet be realized. In future, we should strengthen research on the artificial propagation technology of these fish species, to provide enough specimens for field population recovery.

Fourth, regulate other anthropogenic perturbations and restore destroyed fish habitats. According to our previous surveys, hydropower development on tributaries, water pollution and other human activities are important contributors to the decrease in fish resources in the Chishui River, in addition to overfishing (Li et al. 2015; Liu et al. 2020). Even though no dams have been built in the mainstem Chishui River, 373 dams have been built in its tributaries. The high-intensity hydropower development on tributaries blocked the migration route of migratory species, destroyed the natural running habitat of lotic species and altered the hydrological rhythm (Li et al. 2015). These factors seriously affected the survival and development of fish resources in the Chishui River (Li et al. 2015; Liu et al. 2020). In addition, the Chishui River is famous for white wine and tours. The rapid expansion of wine production and the tourist industry in recent years impose increasing pressure on the conservation of fish resources (An et al. 2014). In this situation, habitat restoration programs should be implemented, including removing the small hydropower stations on the tributaries and strengthening the water pollution treatment.

Finally, enhance the monitoring and assessment of the effects of the fishing ban. Such results are important in developing adaptive management strategies (Chen et al. 2020; Tuset et al. 2021). This study demonstrated initial changes in fish resources, including species composition, diversity indices, the occurrence rates of rare species, the structure of fish assemblages, population structure of dominant species and catch per unit effort (CPUE), by comparing data collected 5 years before and 5 years after the fishing ban in four typical reaches. Numerous studies have demonstrated that a complete recovery of an ecosystem requires long periods of time (Mak et al. 2021; Tuset et al. 2021). Therefore, long-term and systematic monitoring programs should be implemented, to confirm the effectiveness of this full 10-year fishing ban in the Chishui River. Large tributaries, such as the Tongzi River, the Xishui River and the Erdao River, should be also incorporated in the monitoring, as a supplement to the mainstream, to monitor fish resource changes in the whole Chishui River, especially changes in the distribution range and population size of key protected fish species. In addition, the evaluation aspect of the fishing ban should be expanded to ecosystem structure and service function (Liu et al. 2021a).

Conclusion

The present study showed that fish resources in the Chishui River have been restored remarkably in several aspects, including species composition, assemblage structure, population composition and fish density, after 5 years of the implementation of the complete fishing ban. The results were basically consistent with our hypotheses. However, the species diversity and the population size of some key protected species still showed no increasing trends. Comprehensive protection measures are recommended, to further promote the fish resources recovery in this ecologically important tributary. Benefiting from the demonstration of positive effects on the Chishui River, the 10-year fishing ban policy has been extended to the entire mainstream of the Yangtze River as well as its major tributaries (including Min River, Tuo River, Jialing Rive, Wu River, Han River and Dadu River) and attached lakes (including Poyang Lake and Dongting Lake) (Ministry of Agriculture and Rural Affairs of China 2019). This initiative can doubtless facilitate fish resources recovery in these water bodies and provides a good opportunity to restore the aquatic biodiversity of the entire Yangtze River Basin, based on experiences obtained from the Chishui River. Meanwhile, we must realize that the depression of fish resources in the Yangtze River has resulted from the long-term and combined effects of many kinds of human activities, such as overfishing, hydropower development, water pollution, waterway regulation, lake reclamation and river–lake isolation (Liu et al. 2019; Chen et al. 2020; Zhang et al. 2020; Wange et al. 2022). Compared to the Chishui River, these rivers and lakes are being faced with more frequent, more complicated and more intense human activities. Fishing bans can effectively compensate for the impacts of overfishing. However, the impacts caused by habitat loss and fragmentation cannot be neutralized by fishing bans (Chen et al. 2020 Liu et al. 2021a; Jin et al. 2022). Therefore, comprehensive protection plans that consider all kinds of human activities based on the whole watershed perspective should be implemented, in addition to fishing closure (Chen et al. 2020; Zhang et al. 2020; Liu et al. 2021a; Jin et al. 2022).

Acknowledgements
This study is a result of long-term field monitoring. We thank Pengcheng Lin, Jinmin Wu, Futie Zhang, Jun Wang, Fubin Zhang, Zhang Zhi, Wang Xue, Shengguo Dan, Qiu Ning, Fandong Yu, Qiang Qin, Chunsen Xu, Zhiheng Wu, Ting Zhou, Shaowu Xu, Qin Wang, Pengcheng Hu, Zhongyuan Huang, Yanling Liu and other colleagues for their assistance in field sampling. This study was supported by grants from the National Key Research & Development Program of China (2022FY100400, 2022YFB3206905), the National Key Research & Development Program of Yunnan Province (202203AC100001) and the China Three Gorges Corporation (BHQ202305).

Author contributions
FL, HL and JW conceived and designed the investigation. FL and ZX performed the field work. FL and ZW analyzed the data and wrote the paper. All authors read and approved the final manuscript.

Funding
This work was supported by Grants from the National Key Research & Development Program of China (2022FY100400, 2022YFB3206905), the National Key Research & Development Program of Yunnan Province (202203AC100001) and the China Three Gorges Corporation (BHQ202305).

Availability of data and materials
The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The fish samplings comply with relevant laws and regulations in China.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Received: 30 April 2023 Accepted: 16 October 2023
Published online: 30 October 2023

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