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Research progress on impact of cascade hydropower development in lower Jinsha River on early-life resources of *Coreius guichenoti*

YANG Hongyi, HAN Rui, WU Yihong, ZENG Li, FU Miaoran
(State Key Laboratory of Water Cycle and Water Security in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China)

Abstract: [Objective] To investigate the effects of cascade hydropower development in the lower Jinsha River on the distribution of spawning grounds and early-life resources of *Coreius guichenoti*. [Methods] Based on literature review and field survey data recorded from 1981 to 2023, combined with the progression of hydropower project construction, the spatiotemporal variation characteristics of the spawning scale, early-life resources, and spawning grounds of *C. guichenoti* and their driving factors were analyzed. [Results] The result showed that current spawning activities were primarily distributed in river reaches including Pingdi Town, Yuanmou County, and Jiaopingdu, with only sporadic spawning remaining in areas such as Qiaojia, Huidong, and Wuding, indicating a continuous reduction in overall scale. Following the operation of the second-phase projects, spawning grounds in Qiaojia, Jiaopingdu, and Yuanmou County may further disappear, and the major spawning grounds were projected to shift towards the tributaries and mainstem upstream of the Wudongde Dam. Under the combined influence of environmental factors such as water temperature, discharge, flow velocity, and physical barriers, the age at first sexual maturity of *C. guichenoti* was delayed, the reproductive period was shortened, the spawning frequency decreased, and both spawning quantity and hatching rate declined, leading to a year-by-year decreasing trend in early-life resource abundance. [Conclusion] It is recommended to adopt ecological regulation and habitat substitution technologies to improve spawning habitat conditions. Furthermore, artificial proliferation and release should be enhanced, and fish passage facilities should be constructed to enhance the reproductive population size and genetic diversity, thereby mitigating the negative impact of cascade hydropower development on *C. guichenoti* population resources.

Keywords: Lower Jinsha River; hydropower development; cascade hydropower stations; *Coreius guichenoti*; spawning ground; early-life resources; species protection; influencing factors

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About the author: YANG Hongyi (1997—), male, PhD candidate, mainly engaged in research on ecological and environmental impact of water conservancy projects. E-mail: hongyi_yang1103@hotmail.com
作者简介: 杨红义(1997—), 男, 博士研究生, 主要研究方向为水利工程生态环境影响。E-mail: hongyi_ yang1103@hotmail.com
Corresponding author: HAN Rui (1986—), female, Senior Engineer, PhD, focusing on ecological and environmental impact of water conservancy projects. E-mail: hanrui_first@163.com
通信作者: 韩 瑞(1986—), 女, 正高级工程师, 博士, 主要研究方向为水利工程生态环境影响。E-mail: hanrui_first@163.com

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金沙江下游梯级水电开发对圆口铜鱼早期资源影响研究进展

杨红义，韩　瑞，吴一红，曾　利，付森然

（中国水利水电科学研究院 流域水循环与水安全全国重点实验室，北京　100038）

摘　要：【目的】为探究金沙江梯级水电开发对圆口铜鱼（*Coreius guichenoti*）产卵场分布及其早期资源的影响。【方法】基于文献调研及其中记录的1981年至2023年期间野外调查数据，结合水电工程建设进程，分析了圆口铜鱼产卵规模、早期资源及产卵场的时空变化特征及其驱动因素。【结果】结果表明，现存产卵活动主要分布于平地镇、元谋县及皎平渡等江段，巧家、会东和武定一带仅存零星产卵，总体规模持续缩减。二期工程运行后，巧家、皎平渡和元谋县等产卵场可能进一步消失，产卵区域将向乌东德坝上干支流迁移。受水温、流量、流速及物理阻隔等环境因子的综合影响，圆口铜鱼初次性成熟年龄推迟，繁殖期缩短，产卵次数减少，产卵量和孵化率下降，早期资源量呈逐年衰退趋势。【结论】建议采取生态调度与栖息地替代技术，改善产卵生境条件；加强人工增殖放流与过鱼设施建设，提升繁殖群体数量与遗传多样性，缓解梯级水电开发对圆口铜鱼种群资源的负面影响。

关键词：金沙江下游；水电开发；梯级电站；圆口铜鱼；产卵场；早期资源；物种保护；影响因素

1　Introduction

The Jinsha River Basin is a typical ecologically fragile region in China. Its unique geomorphology, characterized by gorges and rapids, has favored the development of large-scaled cascade dams[1]. The operation of large dams and reservoirs in the lower Jinsha River has significantly altered the natural hydrological regime[2], induced notable "thermal stagnation" effects[3], and obstruction of fish migration routes and habitats[4]. These changes have led to a sharp decline in fish resources[5], pushing some species to the brink of collapse[6]. Consequently, endemic fish species of the upper Yangtze River, such as *Coreius guichenoti*, have been listed in the China Red List of Vertebrates, making fish conservation a critical challenge for the green development of hydropower in the Jinsha River.

C. guichenoti, belonging to the order Cypriniformes, subfamily Gobioninae, and genus *Coreius*, is mainly distributed in the upper Yangtze River and the middle-lower reaches of the Jinsha River. It is an endemic and economically important fish species in the upper Yangtze[7], as well as a key indicator species[8] and one of the priority conservation targets[9-10] in the National Nature Reserve for Rare and Endemic Fish in the Upper Yangtze River (hereinafter referred to as the "Reserve"). In recent years, the population structure of *C. guichenoti* has shifted towards younger ages[11], resources have become smaller in size[12], abundance has decreased[13], biomass has sharply declined[14], and wild spawning grounds have virtually disappeared[15]. Mature individuals are now only found in the middle-lower reaches of the Jinsha River, making reproduction in this area the primary natural source for the species within the Reserve.

C. guichenoti produces drifting eggs, and both its eggs and larvae require flowing water to develop, demonstrating specific demands for flow velocity and hydrological conditions. The dynamics of its early-life resources can effectively reflect the ecological impacts of hydropower development in the Jinsha River[16]. Research on early-life resources is of great significance for the conservation of the species, identification of spawning grounds, and assessment of ecological recovery following hydropower development. Studies in the lower Jinsha River have primarily focused on fish resource abundance and species composition[17-18], while research on *C. guichenoti* has mainly addressed its reproduction[19],

growth and development[20], population dynamics[21], and spawning ground distribution[22-23].

Drawing on a large body of studies regarding cascade hydropower impacts on the early-life resources of *C. guichenoti*, this review consolidates the evidence and situates it along the timeline of hydropower development to provide a comprehensive, system-level perspective. This study examines the development history of major hydropower projects on the mainstream of the upper Yangtze River and the lower reaches of the Jinsha River. Based on field survey data of *C. guichenoti* collected from 1981 to 2023, we analyze the causes and patterns of changes in the spawning scale, early-life resources, and spatiotemporal dynamics of spawning grounds of *C. guichenoti*. The study also predicts the impact of the second phase of hydropower development in the lower Jinsha River on its spawning grounds and early-life resources. The aim is to provide insights for fish resource conservation under hydropower development from the perspective of improving the quality of spawning habitats and restoring the resources of *C. guichenoti* early-life stages.

2 Data Foundation

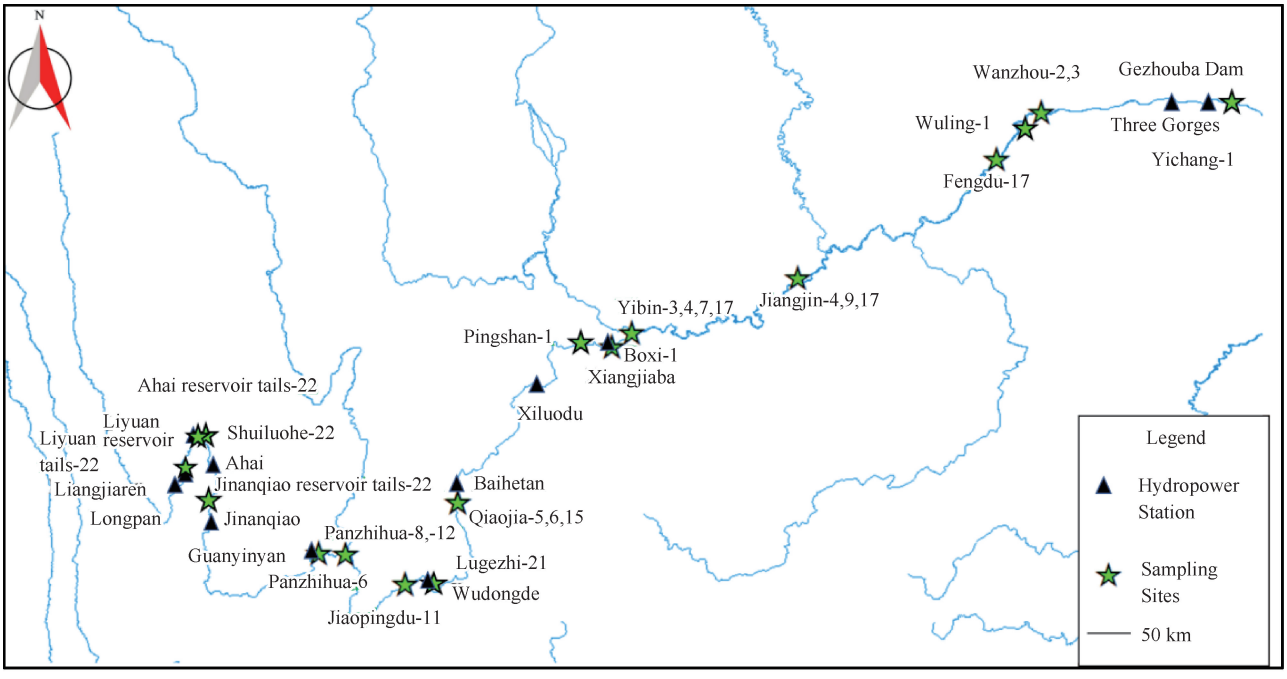
This study is based on investigations of *C. guichenoti* conducted in the mainstream of the upper Yangtze River and the middle-lower reaches of the Jinsha River. The timeline was divided according to the construction and operation phases of major hydropower projects, data were stratified by hydropower development phases. The summary of historical surveys and the distribution of survey areas for *C. guichenoti* are presented in Table 1 and Figure 1. Key milestones in the cascade's development are summarized in Table 2.

3 Analysis of the Impact of Hydropower Project Construction on Early-Life Resources of *C. guichenoti*

3.1 Impact Analysis of Hydropower Projects on the Mainstream of the Upper Yangtze River

In the 1970 s, the mainstream sections of the upper Yangtze River were primarily fished for species such as *C. guichenoti*[7]. The spawning grounds of *C. guichenoti* were mainly distributed in the upper Yangtze, where the eggs drift with the current to hatch, and some larvae may reach sections as far as the middle reaches, gradually migrating upstream as they grow.

After the construction of the Gezhouba Dam on the mainstem of the upper Yangtze River, the migration route



Green labels indicate sampling sites; the numbers correspond to the identifiers in Table 1

Fig. 1 Distribution map of *C. guichenoti* survey areas

图 1 圆口铜鱼调查区域分布示意

Table 1 Statistics of *C. guichenoti* surveys

表 1 圆口铜鱼调查情况统计

No.	Life stage/ Species	Survey Period	Survey Area	Overview of hydropower development near the surveyed resources	Data Source
1	Eggs and Juvenile adult	1981—1986	Yichang and the Wuling downstream of Gezhouba River reach; Baixi and Pingshan, lower Jinsha River reaches	After the impoundment of Gezhouba	LIU et al.[7]
2	Juvenile adult	2000—2004	Wanzhou reach of the upper Yangtze	Three Gorges impoundment in 2003	YAN[24]
3	Juvenile adult	February—April 2000—2005	Yibin, Banan, and Wanzhou reaches of the upper Yangtze	Three Gorges impoundment in 2003	DUAN et al.[22]
4	Juvenile adult	May—July & September—November 2007—2009	Jiangjin and Yibin reaches of the upper Yangtze	Xiangjiaba river closure in 2008	XIONG et al.[12]
5	Eggs	2007—2008; May—July 2012—2014	Qiaojia reach of the lower Jinsha River (102°54′E, 26°54′N)	Impoundment of the Guanyinyan Hydropower Station in 2014	XIAO[25]
6	Eggs	2007—2008	Panzhihua and Qiaojia reaches of the Jinsha River (101°31′E, 26°35′N)、(102°54′E, 26°54′N)	After the river closure at Jin'anqiao	ZHANG[26]
7	Eggs	May—July 2008; May—July 2010—2013	Shuifu reach of the lower Jinsha River (104°25′E, 28°37′N)	Xiangjiaba river closure in 2008; impoundment in 2012	GAO et al.[10]
8	Eggs	June—July 2010	Panzhihua reach of the Jinsha River (101°31′E, 26°35′N)	After the river closures at Jin'anqiao and Ludila	TANG et al.[23]
9	Eggs	May—July 2010—2012	Jiangjin reach of the upper Yangtze main stem (106°15′E, 29°18′N)	After the river closure at Xiangjiaba	DUAN et al.[27]
10	Juvenile adult	2012—2021	Upper Yangtze main stem and tributaries at sections including Yunyang, Fuling, Jiangjin, Hejiang, Yibin, Suijiang, Yongshan, Qiaojia, Dongchuan Ferry, Jiaopingdu, Panzhihua, Jinhe on the Yalong River	Covering multiple stages of hydropower development	XIONG et al.[28]
11	Eggs	May—July 2016—2018	Jiaopingdu reach of the lower Jinsha River (102°23′E, 26°17′N)	After the river closures at Wudongde and Baihetan	HU et al.[29]
12	Eggs	June—July 2016—2018	Panzhihua reach of the Jinsha River (101°48′E, 26°35′N)	After the impoundment of Liyuan, Ahai, Jin'anqiao, and Guanyinyan	WANG et al.[30]
13	Juvenile adult	2016—2018	Xiangjiaba Reservoir area	After the impoundment of Xiangjiaba	XIONG et al.[31]
14	*C. guichenoti*	2017—2021	Yibin-Jiangjin reach of the upper Yangtze	After the impoundment of Xiangjiaba	TANG et al.[32]
15	Eggs	May—July 2017—2018	Qiaojia reach of the lower Jinsha River (26°54′N, 102°54′E)	After the river closures at Wudongde and Baihetan	ZHOU et al.[33]
16	Juvenile adult	2018—2022	Yibin reach of the upper Yangtze	After the impoundment of Xiangjiaba	LU et al.[34]
17	Eggs	June—July 2019	Yibin-Jiangjin and Fuling-Fengdu reaches of the upper Yangtze	After the impoundment of Xiangjiaba	ZHANG et al.[35]
18	Juvenile adult	2020—2021	Middle-upper Yangtze reaches	After the impoundment of Xiangjiaba	WANG et al.[36]
19	Juvenile adult	2021—2023	Shuifu-Yibin reach of the lower Jinsha main stem	After the impoundment of Xiangjiaba and Xiluodu	DAO et al.[37]
20	Juvenile adult	2021—2022	Liyuan-Yinjiang reach of the middle Jinsha River	After the impoundment of Liyuan, Ahai, Jin'anqiao, and Guanyinyan	WANG et al.[38]
21	Eggs	April—June 2021—2022	Luoga tributary reach of the below Wudongde Dam	After the impoundment of Wudongde	HU et al.[39]
22	Eggs and Juvenile adult	June—July 2023	Liyuan, Ahai, and Jin'anqiao, Shuiluo River site of the middle Jinsha River	After the impoundment of Liyuan, Ahai, Jin'anqiao, and Guanyinyan	CHEN et al.[40]

of *C. guichenoti* in the Yangtze mainstream was blocked. The recruitment of *C. guichenoti* resources since then has primarily relied on the river sections upstream of Gezhouba.

After the commissioning of the Gezhouba Dam in 1981, mature individuals of *C. guichenoti* were only

Table 2 Key timelines for hydropower development

表 2 水电开发的关键时间节点

Dam	Event	Date
Three Gorges	Began impoundment and power generation	June 2003
Jin'anqiao	River closure	December 2005
Xiangjiaba	River closure	December 2008
Ludila	River closure	January 2009
Jin'anqiao	Impoundment	November 2011
Ahai	Impoundment	December 2011
Xiangjiaba	Impoundment	October 2012
Longkaikou	Impoundment	November 2012
Ludila	Impoundment	April 2013
Xiluodu	First-stage gate closure & start of impoundment	May 4, 2013
Xiluodu	Water level reached 600 m	May 27, 2014
Guanyinyan	Impoundment	October 2014
Liyuan	Impoundment	November 2014
Baihetan	Main-river closure	November 2015
Wudongde	River closure	June 1, 2016
Wudongde	Began impoundment	2020
Baihetan	Began impoundment	April 7, 2021

collected in sections above Yibin. Its spawning grounds were mainly distributed from the middle-lower reaches of the Jinsha River to the Yibin section. Those in the lower Jinsha River included: Niulanjiangkou, Dashibao, Meiguhekou, Leibo, Ganjiaba, Xinshi Town, Suijiang, Pingshan, Anbian, and Jiulongpo, among others. The Ganjiaba spawning ground had the largest distribution range (approximately 39 km) and the highest spawning intensity, followed by the Leibo and Pingshan spawning grounds, each with a range of about 27 km. Some spawning grounds existed in the section from Yibin to Chongqing, while the section from Chongqing to Yichang primarily served as spawning grounds for *Coreius heterodon* (Copper Fish). After the impoundment of Gezhouba, the backwater area reached between Badong and Fengjie, which had relatively little direct impact on the spawning grounds of *C. guichenoti* above the dam. No spawning grounds for *C. guichenoti* were found in the sections below the dam during years of surveys.

After the impoundment of the Three Gorges Dam in 2003, the backwater extended to Chongqing, causing the gradual disappearance of *C. guichenoti* spawning grounds near Chongqing due to altered hydrological conditions[41-42]. Endemic fish species originally inhabiting this area were forced to shift upstream[41-42]. *C. guichenoti* moved from the reservoir section to the Jiangjin section above the reservoir tail. From 2007 to 2009, the resource abundance of *C. guichenoti* increased in this section[12]. However, after the Three Gorges Reservoir reached its full impoundment level of 175 m in 2010, the habitat of *C. guichenoti* shrank further. No specimens of *C. guichenoti* were collected in the Jiangjin section between 2010 and 2012[22]. To date, no mature individuals of *C. guichenoti* have been found in the middle reaches of the Yangtze mainstream or the upper mainstream sections above Yichang[19]. No spawning grounds for *C. guichenoti* exist below the Yibin section of the Yangtze mainstream[10], making the middle and lower reaches of the Jinsha River a key area for the conservation of its early-life resources.

3.2 Analysis of the Impact of the First Phase of Jinsha River Hydropower Development

The middle reaches of the Jinsha River historically contained five spawning grounds for *C. guichenoti*, including Jin'anqiao, Duomei, Pilahai, Huilagu, and Guanyinyan[23]. Among these, the Jin'anqiao spawning ground had the largest distribution, spanning approximately 28 km. Downstream, spawning grounds were located in Qiaojia, Pingshan, Xinshi, and Fotan[10,25].

Following the impoundment of the Xiangjiaba and Xiluodu reservoirs in October 2012 and May 2013, respectively, new spawning grounds emerged in areas such as Jiaopingdu, Yuanmou, and Panzhihua during 2012—2014. Meanwhile, traditional spawning grounds including Jin'anqiao, Guanyinyan, Pingshan, Xinshi, and Fotan gradually disappeared[10,25].

A significant decline in the spawning scale of *C. guichenoti* has been observed in the middle and lower Jinsha River[27]. For example, the estimated egg production at the Qiaojia section in the lower reaches decreased from 203 million eggs in 2007 to 3.817 million eggs in 2014[25].

The first phase of hydropower development on the Jinsha River has already impacted the recruitment of early-life resources of *C. guichenoti* to the upper Yangtze mainstream. From 2010 to 2012, the collection of eggs

and larvae in the Yibin section accounted for less than 2% of the total catch. Based on this, the estimated egg supplementation was approximately 136 million eggs. By 2013, no eggs or larvae of *C. guichenoti* were collected[10]. This sharp decline in early-life resources is closely associated with alterations in hydrological conditions, reduction in size, or complete loss of spawning grounds[7,23].

3.3 Analysis of the Impact of Guanyinyan Hydropower Project Construction

Following the damming of the Guanyinyan Hydropower Project in January 2013, a spawning ground for *C. guichenoti* formed downstream of the dam. After the reservoir impoundment, the location of this spawning ground shifted downstream to the Panzhihua West District, where it merged with existing spawning grounds in that area[30,33]. The Panzhihua river section hosts four spawning grounds: Panzhihua East District, Panzhihua West District, Geliping Town, and Guanyinyan. Among these, the Panzhihua East District spawning ground has the largest distribution, spanning approximately 13 km and accounting for 76% of the total spawning scale[33]. The spawning scales at Geliping Town and Guanyinyan are relatively small.

After the stable operation of mid-reach hydropower projects, including Guanyinyan, spawning activities of *C. guichenoti* in 2017 were mainly concentrated in Huize and Jiaopingdu within the Qiaojia and Panzhihua sections. Spawning was scattered and occurred on a small scale[30]. In 2018, spawning was primarily observed in the Panzhihua West District, Qiaojia, Huidong, and Wuding sections, yet the scale remained limited. For example, the egg production in the Panzhihua West District was only 230, 000 eggs[30].

Following the construction of the Liyuan, Ahai, and Jin'anqiao dams in the middle Jinsha River, the original *C. guichenoti* spawning ground documented at Jin'anqiao in 2010 has progressively fragmented into several small sites distributed at the reservoir tails of Liyuan, Ahai, and Jin'anqiao, indicating a gradual reduction in suitable spawning habitat[23,40].

3.4 Analysis of the Impact of the Second Phase of Jinsha River Hydropower Projects

Before the operation of the second phase of the Jinsha River hydropower projects, the main spawning grounds of *C. guichenoti* in the middle and lower reaches were distributed in the following areas: Duomei, Pilahai, Huilagu, Panzhihua East District, Panzhihua West District, Geliping Town, Jiaopingdu, Wuding County, Yuanmou County, Pingdi Town, and Jinjiang Town[27,33]. The locations, sizes, and overall distribution of the major spawning grounds are shown in Table 3 and Figure 2.

After impoundment at Xiangjiaba, portions of upstream spawning habitat were inundated and several historical spawning grounds disappeared. In general, when the perennial backwater zone overlaps a historical spawning site, that site ceases to function as a spawning ground. After the operation of the second phase of the Jinsha River hydropower projects, the perennial backwater zones of the Baihetan and Wudongde reservoir areas extend 149 km and 153 km, respectively. These changes are expected to alter the spawning grounds of *C. guichenoti*: spawning grounds located 41 km upstream of the Baihetan dam (Qiaojia), 30 km upstream of the Wudongde dam (Jiaopingdu), and 100 km upstream (Yuanmou County) will be submerged. Affected populations may migrate to suitable habitats in tributaries, leading to a spatial shift in spawning locations[23,43]. The spawning grounds near Pingdi Town (180 km upstream of Wudongde) and Jinjiang Town are projected to gradually decline in scale during the initial impoundment period, with their locations and sizes expected to stabilize within 2~3 years.

4 Response of *C. guichenoti* Spawning to Changes in Environmental Factors

4.1 Correlation analysis

Using Pearson's correlation, the spawning output shows a moderate positive correlation with transparency ($r \approx +0.33$). All other hydrologic metrics exhibit weak negative correlations, led by water temperature ($r \approx -0.19$), flow velocity ($r \approx -0.18$), rate of water-depth change ($r \approx -0.16$), water-depth range ($r \approx -0.15$), effective days of rising discharge ($r \approx -0.13$), and discharge change rate ($r \approx -0.13$). Discharge, depth, discharge range, accumulated temperature, and suspended sediment also correlate negatively but with

Table 3 Distribution statistics of *C. guichenoti* spawning grounds in middle and lower reaches of Jinsha River

表 3 金沙江中下游圆口铜鱼产卵场分布统计

Spawning Ground Name	Spawning Ground Range	Spawning Ground Length/km	Spawning Scale /$\times 10^4$ eggs	Survey Year	Data Source
Duomei	Duomei Township—Taoyuan Township	17.0	98.4	2010	TANG et al. [23]
Pilahai	Pilahai—Qikeshu	11.0	187.8	2010	TANG et al. [23]
Huilagu	Wanbi Dai-Lisu Township—Huilagu	8.0	251.6	2010	TANG et al. [23]
Geliping Town	Zhuangshang Jinsha River Bridge—Baoding Bridge	8.0	—	2016—2018	WANG et al. [30]
Panzhihua West District	Taojiadu Bridge—Xinzhuang Bridge	5.0	23.0	2016—2018	WANG et al. [30]
Panzhihua East District	Xinzhuang Village—Midi Bridge	13.0	—	2016—2018	WANG et al. [30]
Jinjiang Town	Tuanshan—Jinjiang Interchange	3.0	9.3	2016—2018	HU et al. [27]
Pingdi Town	Yibuku—Lazha Village	30.0	55.9	2016—2018	HU et al. [27]
Yuanmou County	Jiyi Township—Huanzhou Township, Yuanmou County	35.0	23.3	2016—2018	HU et al. [27]
Jiaopingdu	10~40 km upstream of Jiaopingdu Bridge	30.0	229.8	2012—2014	XIAO [25]
Qiaojia Section	Scattered in Wuding, Qiaojia, Huidong, etc.	—	524.2	2017—2018	ZHOU et al. [29]
Downstream of Wudongde Dam	5.4~11.1 km downstream of Wudongde Dam	5.7	15.1	2021—2022	HU et al. [39]
Tail of Liyuan Reservoir	—	—	199.0	2023	CHEN et al. [40]
Tail of Ahai Reservoir	—	—	546.0	2023	CHEN et al. [40]
Tail of Jin'anqiao Reservoir	—	—	106.0	2023	CHEN et al. [40]

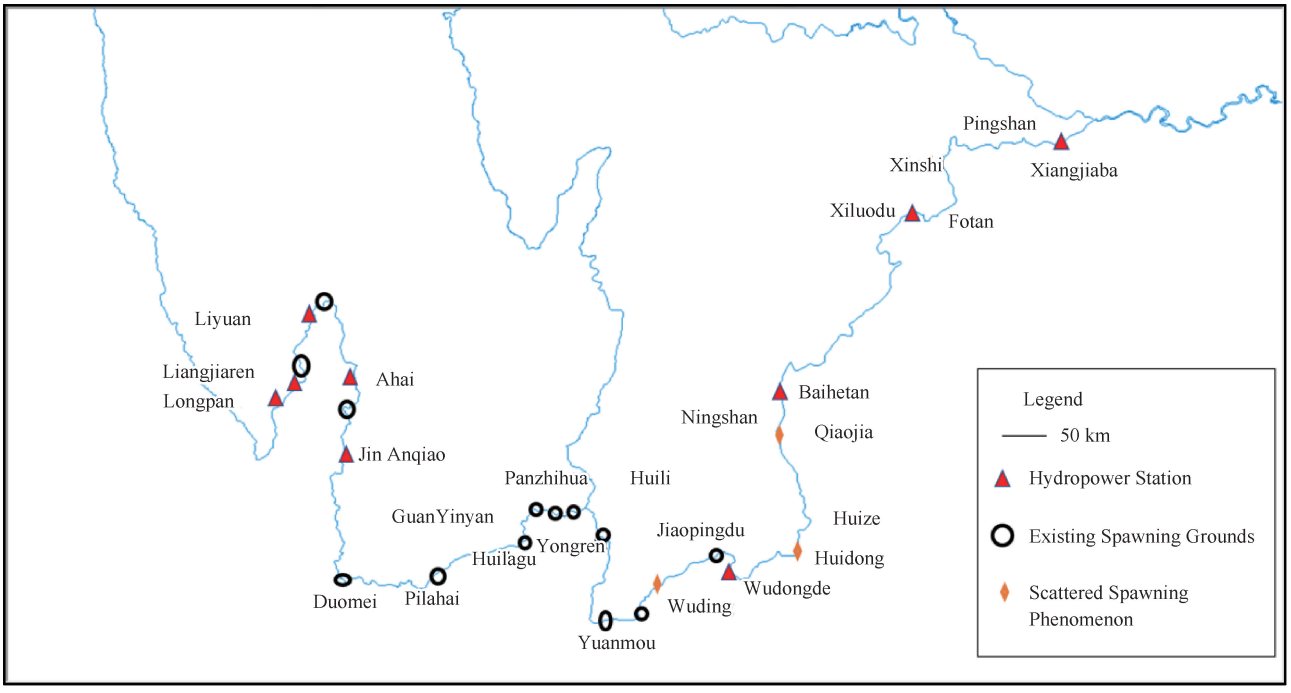


Fig. 2 Distribution dynamics of *C. guichenoti* spawning grounds

图 2 圆口铜鱼产卵场分布动态

small magnitudes ($|r|<0.13$). Overall, clearer water is associated with higher spawning output, whereas stronger currents and greater hydraulic variability tend to coincide with lower output.

4.2 Water Temperature

Water temperature is a key environmental factor influencing the reproduction of *C. guichenoti*. Its spawning season occurs from April to July each year. The

Table 4 Correlation coefficients between environmental factors and spawning quantity

表 4 环境因子与产卵量的相关性系数

Environmental factors	Pearson *r*	Pearson *p*
Discharge	−0.125 9	0.150 2
Depth	−0.051 5	0.557 5
Discharge range	−0.104 5	0.233 1
Water-depth range	−0.153 2	0.079 0
Rate of discharge change	−0.131 8	0.131 8
Rate of water-depth change	−0.159 3	0.068 0
Effective days of rising discharge	−0.134 8	0.123 1
Flow velocity	−0.184 6	0.034 0
Transparency	0.331 7	0.000 1
Water temperature	−0.191 1	0.028 0
Accumulated temperature	−0.092 1	0.293 1
Suspended sediment	−0.107 6	0.219 2

minimum accumulated temperature threshold for gonad maturation is 1 728.1 ℃ · d[44], and the critical water temperature threshold for spawning is 18℃, with an optimal range of 20 ~ 25.2℃[45]. After the operation of the cascade hydropower stations on the Jinsha River, a significant delay in the warming period of water temperature below the dams has been observed[46]. The time required to reach both the minimum accumulated temperature threshold and the critical water temperature threshold for spawning is delayed. For example, under the joint operation of the four reservoirs in the lower Jinsha River, the time to reach the critical spawning temperature at the Xiluodu dam site is delayed by 45 days[47], and the time to reach the minimum accumulated temperature threshold is delayed by 17 days. The overlapping period during which both temperature thresholds are simultaneously met is shortened. As a result, the reproductive period of *C. guichenoti* has been reduced to only 51.1% of its pre-dam duration[46], leading to a decline in egg production. Additionally, the age at first sexual maturity of *C. guichenoti*, influenced by long-term factors such as water temperature and genetics[48-49], has increased from 2 ~ 3 years[50] to 4 years[14,19], further affecting its spawning and reproduction.

4.3 Flow Discharge

The frequency, intensity, and duration of flow pulses can directly affect the spawning of *C. guichenoti*[30]. The regulation strategy of "flood peak reduction and dry season flow supplementation" implemented by the cascade hydropower stations in the lower Jinsha River has resulted in flow pulses exhibiting a "stepped" pattern (where flow remains constant for extended periods after rise and fall) or a "sawtooth" pattern (frequent but short-lived and low-peak fluctuations). Both patterns are unfavorable for the spawning of *C. guichenoti*. After the operation of the first phase of the Jinsha River projects, the number of high-flow pulses decreased from 9 to 3, the peak flow discharge dropped from 13, 926 m^3/s to 7, 781 m^3/s, and the duration of peak flow decreased from 14.6 days to 6.3 days[51]. Due to these changes in flow pulses, the frequency of concentrated spawning events declined from 4 ~ 5 times in 2008[23] to 1 ~ 3 times between 2016 and 2018[27,33], and peak spawning intensity decreased.

4.4 Flow Velocity

The reservoirs of the Wudongde, Baihetan, Xiluodu, and Xiangjiaba dams are connected end-to-end, forming an alternating distribution of riverine segments (flow velocity > 0.5 m/s) at the reservoir tails and lacustrine segments (flow velocity < 0.2 m/s) in the central reservoir areas. Only one-third of the riverine habitats remain in the lower Jinsha River, leading to a reduced proportion of rheophilic fish species such as *C. guichenoti*[18]. During spawning, when flow velocity meets the requirements for egg release, the fertilized eggs absorb water, expand, and become slightly denser than water. A certain flow velocity is necessary to keep them suspended for drifting incubation. Insufficient flow velocity causes fertilized eggs to sink to the reservoir bottom due to inadequate drifting distance, resulting in death from hypoxia[45]. Moreover, when the flow velocity drops below 0.5 m/s, spawning behavior ceases entirely[46].

4.5 Physical Barriers

The construction of cascade hydropower projects in the lower Jinsha River has blocked the migration routes of *C. guichenoti*, fragmenting the once continuous river ecosystem into isolated segments[52]. On one hand, upstream migrating populations are obstructed below the dams; on the other hand, eggs and larvae produced by resident spawners above the dams are trapped within the reservoirs. Currently, due to these high dam barriers, low but significant genetic differentiation has already

occurred among different geographical groups of *C. guichenoti*, such as the Jin'anqiao, Longkaikou, Qiaojia, and Pingshan populations[53]. The cumulative effect of this differentiation over generations could influence evolutionary trajectories, potentially leading to reproductive isolation. If the population size becomes too small to support free intra-species mating, the evolutionary trajectory of *C. guichenoti* may fail to stabilize, compromising species sustainability and leading to genetic degradation[54].

5 Conservation Strategies

5.1 Water Temperature Regulation Measures

5.1.1 *Selective Water Withdrawal*

Selective water withdrawal technologies comprise stop-log gates, multi-level intake structures, frontal barrier-type intakes, and control curtains[55]. Such structures, particularly multi-level and selective withdrawal systems, have been increasingly applied in deep stratified reservoirs worldwide to mitigate downstream thermal alteration and improve habitat conditions for temperature-sensitive fishes. Among these, stop-log gate systems demonstrate high adaptability to substantial withdrawal depths and fluctuating water levels, and have been established as a primary mitigation strategy in China to reduce the discharge of low-temperature water. At present, the Wudongde, Baihetan, and Xiluodu dams are outfitted with stop-log gate intake installations. Operational trials at Xiluodu have indicated that the temperature of released water can be elevated by 0.4℃. During coordinated operation of the four reservoirs, the implementation of layered water withdrawal via stop-log gates can advance the attainment of the spawning temperature threshold for *C. guichenoti* by approximately 10 days[56]. This is consistent with recent eco-hydrothermal modelling and optimization studies showing that joint selective withdrawal in cascade systems can effectively fine-tune downstream thermal cues for fish reproduction while balancing power generation and water-quality objectives[57-60].

5.1.2 *Ecological Regulation*

Optimizing reservoir operation timing directly influences the temperature of released water. For example, comparing three operational scenarios at Xiluodu where the reservoir water level is lowered to 540 m in March, April, and May, the temperature of released water increased by 0.11℃, 0.21℃, and 0.11℃, respectively, and the time to reach the spawning temperature threshold at the dam site was advanced by 7 days, 6 days, and 2 days, respectively[61]. Adjusting the winter operation schedule at Xiluodu[62] can raise the average temperature of released water in April and May by 0.9℃ and 1.0℃, respectively. Large-scale analyses of eco-hydrothermal regimes in the upper Yangtze River further highlight that reservoir impoundment is a dominant driver of thermal regime change, and that adaptive operating rules are needed to restore suitable thermal windows for rare and endemic fishes in the Reserve under ongoing climate change[63].

5.2 Flow Regulation Measures

To alleviate the adverse effects of reduced high-flow pulses on the spawning of *C. guichenoti*, measures such as maintaining base flow power generation, creating artificial flood peaks, and adjusting the timing of peak flows during the fish reproductive period can be implemented[64]. These measures stimulate spawning and drifting incubation processes for rheophilic spawners like *C. guichenoti*. The ecological flow regulation plan at Xiangjiaba involves gradually increasing discharge to simulate natural rising hydrographs, thereby inducing spawning in downstream sections. Monitoring confirmed spawning peaks in the Yibin and Jiangjin sections downstream of Xiangjiaba during the regulation period[65]. in line with broader evidence that adaptive environmental-flow releases can partially offset the impacts of cascade regulation on fish recruitment[66-68].

5.3 Fish Passage Facilities

Migratory fish such as *C. guichenoti* are obstructed by dams and unable to complete their spawning migrations. Suitable fish passage facilities can be constructed to restore connectivity between upstream and downstream sections. The Wudongde Hydropower Station has implemented a fish collection and transportation system[69], targeting *C. guichenoti* as a primary species. The system employs a strategy of "tailwater fish collection, bionic transportation, and release into flowing water", significantly improving passage efficiency and providing technical support for the upstream migration of

broodstock and genetic exchange. Juvenile *C. guichenoti* have weak swimming ability and typically descend via spillways or turbines[70], both of which can cause significant physical damage. Further research on downstream fish passage facilities is needed.

5.4 Ecological Restoration

Ecological restoration measures include establishing protected areas, restoring spawning grounds, and implementing tributary habitat replacement techniques. The establishment of the National Nature Reserve for Rare and Endemic Fish in the Upper Yangtze River has partially mitigated the ecological impacts of the Three Gorges and the first phase of Jinsha River projects, conserving fish resources and population richness. The construction of artificial spawning grounds and fish nests helps enhance early-life resource abundance[71]. The tributary habitat replacement technique, which uses tributaries with similar "hydrological regimes, water quality, biological communities, and physical structures" to replace original habitats, has shown positive results in the Heishui River of the Jinsha River[72-73].

5.5 Stock Enhancement

To mitigate the impacts of cascade hydropower operation in the lower Jinsha River on the early-life resources and populations of *C. guichenoti*, China Three Gorges Corporation conducted large-scale juvenile stock enhancement from 2020 to 2022, releasing over 100,000 individuals each year. This effort has positively contributed to the recruitment of endemic fish resources. Scaling up broodstock cultivation[74], research on gonad stimulation, and germplasm resource management can further improve the quantity and survival rates of released *C. guichenoti*. in alignment with the national agenda for high-quality water governance, ecological restoration, and water security in the context of Chinese modernization. Experiences from stock-enhancement programs for rare and migratory fishes in the upper Yangtze, including sturgeons and other large rheophilic species, indicate that release strategies (size, timing and location), post-release habitat quality and connectivity, and long-term genetic management jointly determine the effectiveness of stocking at the population level[75]. Therefore, stock enhancement for *C. guichenoti* should be implemented in concert with habitat restoration, environmental-flow regulation and basin-scale connectivity protection to avoid dependence on hatchery production alone.

6 Conclusions

Based on long-term survey data of *C. guichenoti* and the development process of major hydropower projects in the mainstream of the upper Yangtze River and the middle-lower reaches of the Jinsha River, this study analyzed the distribution of spawning grounds and dynamics of early-life resources of *C. guichenoti* in the lower Jinsha River. The following conclusions are drawn.

(1) The cumulative effects of cascade dam development led to a significant contraction and fragmentation of *C. guichenoti* spawning grounds. The remaining spawning activities are concentrated in a few vulnerable locations (Pingdi Town, Yuanmou County, Jiaopingdu), which are projected to face further threats from the second-phase projects, likely forcing a shift to tributaries and areas above the Wudongde Dam.

(2) Cascade hydropower operation delayed water temperature thresholds for spawning, shortening the reproductive period and reducing flow pulse requirements, which led to fewer and weaker spawning events. Inadequate egg drifting further reduced hatching success and early-life abundance. Mitigation measures include ecological regulation, habitat enhancement, selective water withdrawal, fish passages, and stock enhancement.

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