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Study on the phytoplankton community structure and its driving factors in Furong Creek during spring and autumn under the influence of cascade weirs

REN Jiangshan[1], YU Jun[2], LI Jingjuan[1], LYU Jianzhang[1], WANG Xiaogang[1]
(1. Hydraulic Engineering Department, Nanjing Hydraulic Research Institute, Nanjing　210029, Jiangsu, China;
2. Jiangxi Vocational and Technical College of Communications, Nanchang　330013, Jiangxi, China)

Abstract: [Objective] The construction of weirs changes the hydraulic characteristics of rivers and affects the structure of phytoplankton communities and the health of aquatic ecosystems in the river. This study aims to explore the nonlinear response relationship between phytoplankton community structure and its driving factors in spring and autumn in Furong Creek under the construction of cascade weirs. [Methods] The structure of phytoplankton communities and related environmental factors were investigated in Furong Creek from 2023 to 2024. This study focused on the analysis of the changes of nutrient concentrations and biomass of phytoplankton in autumn and spring within the same dry season in Furong Creek. Redundancy analysis was used to identify the key factors influencing the structure of phytoplankton communities. The MIKE 11 model was employed to simulate the hydrodynamic changes in the river. Combined with total nitrogen and permanganate index, a GAM model of phytoplankton diversity index and hydrodynamic factors was developed, and the change of phytoplankton diversity after the optimized layout of the cascade weirs was fitted. [Results] The result showed that the annual average value of Shannon-Wiener diversity index of phytoplankton in Furong Creek was 2. 79, which was in a state of mild pollution. A total of 239 species from 95 genera in 8 phyla were identified. Among the phytoplankton, Chlorophyta was the dominant group throughout the year in Furong Creek, followed by Bacillariophyta and Cyanophyta. The cell abundance of phytoplankton ranged from 3. 11 to 20. 64 mg/L and from 0. 23 to 6. 31 mg/L in spring and autumn, which indicated a clear seasonal succession of phytoplankton community structure. Compared with autumn, the relative abundance of Cyanophyta significantly decreased in spring across the whole river section, while Chrysophyta and Dinophyta showed significant increase at some monitoring sites, leading to water bloom phenomenon and a noticeable decline in the diversity of phytoplankton. The dominant species in the water bodies throughout the year were *Cyclotella catenata*, *Chlorella vulgaris*, *Scenedesmus bijuga*, *Scenedesmus quadricauda*, *Chroomonas acuta*, *Cryptomonas ovata*, and *Cryptomonas erosa*. Redundancy analysis (RDA) showed that hydrodynamic factors (v, h) and water environmental factors (TN, COD_{Mn}) were the main influencing factors of phytoplankton community structure. [Conclusion] The result show that the nutrient

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About the author: REN Jiangshan(2000—), male, postgraduate, mainly engaged in river and lake health management work. E-mail: 2390502236@qq. com
作者简介: 任江山(2000—), 男, 硕士研究生, 主要从事河湖健康治理工作。E-mail: 2390502236@qq. com
Corresponding author: WANG Xiaogang (1980—), male, senior engineer, Deputy Director of Hydraulics Research, Nanjing Institute of Water Conservancy Science, PhD., mainly engaged in research on river and lake health evaluation, fishway hydraulics, navigation hydraulics, dam break hydraulics, etc. E-mail: xgwang@nhri. cn
通信作者: 王晓刚(1980—), 男, 正高级工程师, 南京水利科学研究院水工水力学研究副所长, 博士, 主要从事河湖健康评价、鱼道水力学、通航水力学、溃坝水力学等研究。E-mail: xgwang@nhri. cn

concentration, phytoplankton biomass, and density in Furong Creek in spring are significantly higher than in autumn. The GAM model, constructed by combining hydrodynamic and environmental factors, can effectively reflect the nonlinear relationship between phytoplankton diversity index and its driving factors. In spring, with an increase in nutrient concentration, the habitat conditions of low flow speed and high water depths formed by overflow weirs will lead to a decrease in the Shannon-Wiener index of phytoplankton and an intensified risk of eutrophication. However, a reasonable layout scheme of cascade weirs will improve the diversity of phytoplankton and reduce the risk of eutrophication in the river. The findings of this study can help deepen the understanding of the ecological and environmental effects of cascade weir construction in the river.

Keywords: cascade weirs; MIKE 11 model; redundancy analysis; GAM model; influencing factors

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听语音 聊科研 与作者互动

梯级堰作用下芙蓉溪浮游植物春秋季群落结构及其驱动因素研究

任江山[1], 余　俊[2], 李景娟[1], 吕建璋[1], 王晓刚[1]

(1. 南京水利科学研究院 水工水力学研究所, 江苏 南京　210029;
2. 江西交通职业技术学院, 江西 南昌　330013)

摘　要:【目的】筑堰改变河流水力特性，影响河流浮游植物群落结构以及水生态系统健康水平。为探究梯级堰建设下芙蓉溪浮游植物春秋季群落结构及其驱动因素的非线性响应关系。【方法】于2023—2024年在芙蓉溪开展了浮游植物群落结构及相关环境要素的调研，重点分析了芙蓉溪同一枯水期内秋春两季浮游植物营养物质浓度及生物量变化状况，通过冗余分析筛选影响浮游植物群落结构的关键影响因子，使用MIKE 11模型拟合了河道内水动力变化状况，结合总氮和高猛酸盐指数，构建了浮游植物多样性指数与水动力因子的GAM模型，拟合了梯级堰优化布置后的浮游植物多样性变化状况。【结果】结果显示：芙蓉溪浮游植物Shannon-Wiener多样性指数全年均值为2.79，整体处于轻度污染状态，鉴定出浮游植物8门95属239种：绿藻门是芙蓉溪全年浮游植物的主要构成门类，其次为硅藻门和蓝藻门，浮游植物春秋两季细胞丰度变化范围为3.11～20.64 mg/L和0.23～6.31 mg/L，浮游植物群落结构季节性演替明显，相较于秋季，春季蓝藻门的相对丰度在全河段显著降低，而金藻门和甲藻门在部分点位显著上升，并形成水华现象，造成浮游植物多样性水平显著下降。全年水域优势种为链形小环藻(*Cyclotella catenata*)、小球藻(*Chlorella vulgaris*)、双对栅藻(*Scenedesmus bijuga*)、四尾栅藻(*Scenedesmus quadricauda*)、尖尾蓝隐藻(*Chroomonas acuta*)、卵形隐藻(*Cryptomonas ovata*)和啮蚀隐藻(*Cryptomonas erosa*)。冗余分析(RDA)表明，水动力因子(v、h)和水体环境因子(TN、COD_{Mn})是浮游植物种群结构的显著影响因子。【结论】结果表明：芙蓉溪春季的水环境营养物质浓度、浮游植物生物量和密度远高于秋季，结合水动力因子和环境因子构建的GAM模型可以有效地反应浮游植物多样性指数与驱动因素间的非线性关系，在春季营养物质浓度提升的情况下，溢流堰形成的低流速和高水深的生境条件，会导致浮游植物Shannon-Wiener指数降低，富营养化风险加剧，而合理的梯级堰布设方案将会提高浮游植物多样性水平，降低河流富营养化风险。本研究结果有助于深化理解河流梯级筑堰引发的河流生态环境效应。

关键词：梯级堰；MIKE 11模型；冗余分析；GAM模型；影响因素

0 Introduction

In order to maintain the river landscape, a large number of cascade weirs have been constructed in some water-scarce areas of China. Cascade weirs can effectively change the hydrological situation of the river, realize the goal of "storing water during the abundant period to supplement the water during the depleted period"[1-2], and form artificial wetlands as an ecological landscape in cities[3], but they affect the vertical and horizontal connectivity of the river ecosystem, resulting in a shift in habitat structure, spatial distribution and structural composition[4]. Phytoplankton, as a primary producer, is sensitive to changes in the aquatic environment[5], and different aquatic conditions lead to differences in the composition of phytoplankton species, which have been widely used as important riverine environmental indicator species[6-7].

In recent years, the correlation between phytoplankton community structure and impact factors has been studied by field observation, laboratory incubation and model prediction[8]. Through model calculations and data statistics, it was demonstrated that flow velocity is a key factor impacting the diversity and spatial and temporal changes of phytoplankton community structure[9-10], ZHANG et al[11] established the relationship between phytoplankton and nutrient salts and hydraulic residence time using the generalized additive model (GAM), and LIU[12] explored the optimization of riverine habitats by improving the structure of the rubber dam itself, the filling medium, and the discharge characteristics in conjunction with the habitat suitability model. However, there are fewer studies on the hydrodynamic conditions and phytoplankton changes triggered by the construction of cascade weirs in middle and small rivers, and the relationship between the structural changes of phytoplankton community in Furong Creek and the impact factors has not been completely revealed in terms of seasonal changes. To comprehensively promote the construction of a strong nation with Chinese-style modernization and further promote the high-quality development of water conservancy in the new stage[13-14]. Relying on the National 2023 Happy River and Lake Construction Project, this research launched a river ecological research in Furong Creek watershed in spring and fall, and comparatively analyzed the effects of environmental factors and hydrodynamic factors on the structure of phytoplankton communities by exploring the phytoplankton community structure in different seasons.

1 Research Area and Methods

1.1 Overview of the study area

Furong Creek is a tributary of the left bank of Fujiang River, which is called Ride Water in ancient times. Furong Creek has a total channel length of 93 km, narrow and long, with a total watershed area of 592 km^2, and the topography of the watershed is inclined from northeast to southwest, with a natural drop of 235 m and an average specific drop of 2.48‰. Along the longitudinal direction of the river, Furong River is divided into three reaches: upper, middle and lower reaches. In this research, the middle and lower reaches are taken as the research area to carry out water ecological monitoring. Fig. 1 shows the hydrologic conditions of Furong Creek.

There are many tributaries of Furong Creek, among which the larger ones are Jiangjia River, Guanzhong River, Sancha River, Guansi River and so on. Analyzing the historical flood data, it can be seen that there is a large gap in the flow rate of Furong River basin in the rich and dry seasons, the historical maximum flood peak amounted to 3 000 m^3/s, and the multi-year average runoff amounted to 310 million m^3, but the middle reaches of the river can be cut off during the dry period, the minimum flow rate of the downstream channel is 0.4 m^3/s, and the average flow rate of the annual flow rate is only 8 m^3/s. The precipitation in dry period accounts for 25% of the total annual precipitation, and the inter-annual precipitation variance reaches 2 ~ 4 times. Therefore, 13 overflow weirs (Table 1) were constructed on the middle and lower reaches of the main stream of Furong Creek to achieve the function of storing abundance to compensate for dryness and creating scenery.

1.2 Sampling and Processing

1.2.1 *Sampling Period and Sample Collection Points*

For this research, field sampling was conducted in October and November in the autumn of 2023, and in

March and April in the spring of 2024. Watershed boundaries were extracted using the hydrologic analysis module of Arcgis 10. 6. Suitable monitoring locations were determined in conjunction with field exploration, and seven monitoring points were set up in the study area (Table 2). The deployment of monitoring points covered different hydrodynamic characteristic zones upstream and downstream of the weir, Among them, S1 and S2 were set at the tail area of the reservoir 2~3 km upstream of the overflow weir, S5 was set within the reservoir area 1 km upstream of the weir, S4 and S6 were set 50 m upstream of the weir, S3 was set 500 m downstream of the weir, and S7 was set 100 m downstream of the weir.

1. 2. 2 *Sample Processing*

1. 2. 2. 1 Sample Collection and Fixation

Phytoplankton field sampling is done using a quantitative collection method. Three samples of surface, mesopelagic and demersal water were taken in the field, mixed in equal quantities, fixed with Lugol's, labeled with the date of sampling, the sampling point, and the amount of water collected on the sample bottles, and brought back to the chamber for further processing.

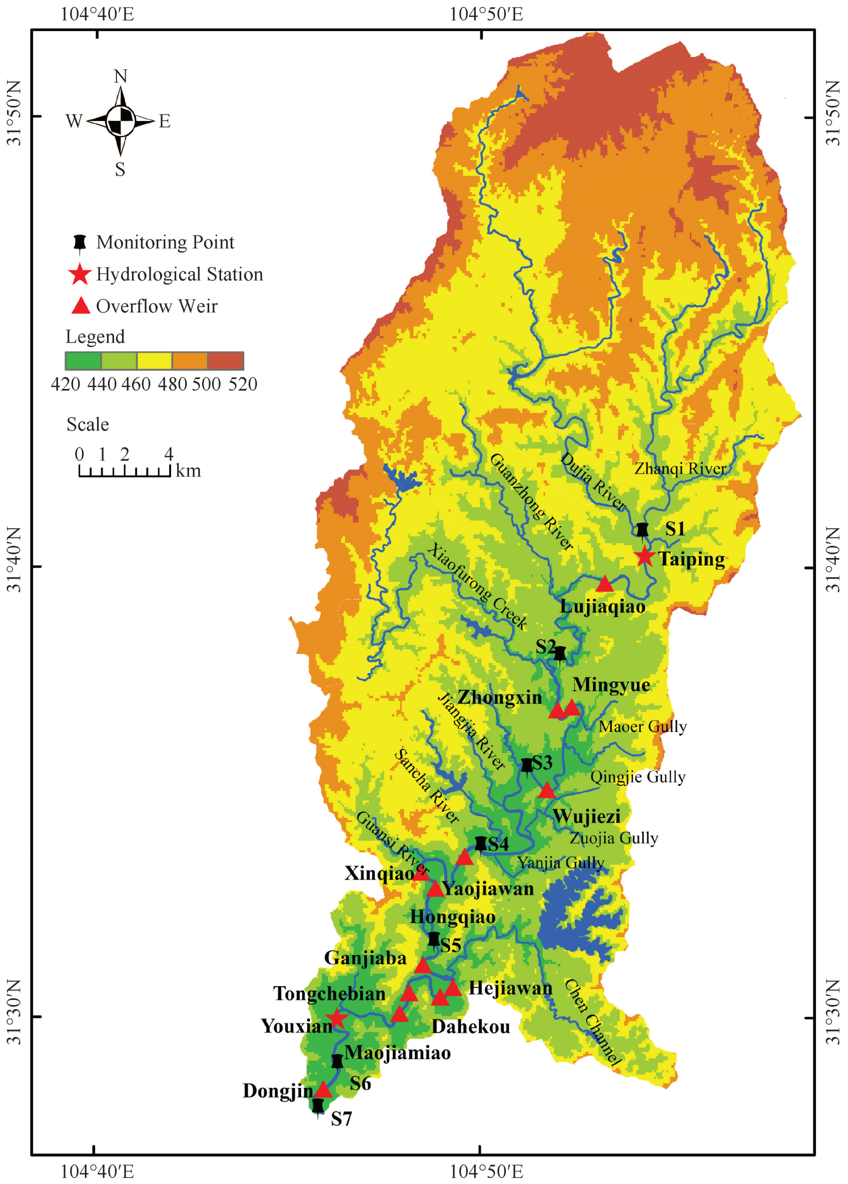


Fig. 1 Hydrological map of Furong Creek wateshed

图 1 芙蓉溪流域水系

Table 1 Basic information of overflow weirs m

表 1 溢流堰基础信息 m

Number	Name	Weir Width	Weir Length	Weir Crest elevation	Weir Height
1	Dongjin	2. 5	70. 0	450. 3	3. 5
2	Maojiamiao	5. 0	63. 0	458. 5	2. 0
3	Tongchebian	1. 5	50. 0	459. 2	1. 5
4	Dahekou	5. 0	45. 0	463. 5	2. 0
5	Hejiawan	1. 0	61. 0	465. 5	3. 5
6	Ganjiaba	3. 0	49. 0	468. 0	1. 2
7	Hongqiao	1. 0	100. 0	477. 2	1. 0
8	Xinqiao	1. 0	67. 0	477. 8	1. 2
9	Yaojiawan	5. 8	75. 0	478. 8	2. 5
10	Wujiezi	1. 5	60. 0	485. 1	2. 5
11	Mingyue	1. 0	55. 0	486. 3	2. 4
12	Zhongxin	3. 0	48. 0	487. 5	2. 5
13	Lujiaqiao	2. 5	35. 0	495. 4	3. 3

Table 2 Layout of monitoring points

表 2 监测点位布设

Points	Subsection of the River	Geographic Coordinates		River Length/km
		Longitude	Latitude	
S1	Middle Reaches	104°54′22. 54″	31°40′36. 78″	37. 5
S2		104°52′04. 53″	31°37′38. 08″	
S3		104°51′36. 75″	31°35′11. 46″	
S4		104°49′52. 49″	31°33′35. 59″	
S5	Lower Reaches	104°48′53. 46″	31°31′36. 44″	19. 0
S6		104°46′22. 67″	31°29′01. 01″	
S7		104°45′52. 36″	31°27′51. 56″	

1. 2. 2. 2 Sample Statistics

The samples were concentrated in the laboratory and counted under the microscope by the visual field method.

The number of phytoplankton per liter of water sample was calculated as in equation 1).

$$N = \frac{C_s}{F_s \times F_n} \times \frac{V}{v} \times P_n \qquad (1)$$

In Eq. (1), N is the number of phytoplankton per liter of water (cells/L); C_s is the area of the counting chamber (mm^2); F_s is the field of view area (mm^2); F_n is the number of fields of view counted per slide; V is the volume of the concentrated 1 L water sample (mL); v is the volume of the counting chamber (mL); P_n is the number of individuals counted (ind.).

1.2.2.3 Data Processing

In this paper, phytoplankton diversity was analyzed using the Shannon-Wiener index (H'), which is often used to analyze the health of phytoplankton communities[15], which takes into account both species abundance and diversity and is widely used in ecology. Its calculation formula is shown in equation 2. The Shannon-Wiener index (H') was utilized to evaluate the water quality status of the water body, which was evaluated as non-polluted or clean when $H'>3.0$, mildly polluted when $2 < H' < 3$, moderately polluted when $1 \leqslant H' < 2$, and heavily polluted when $H'<1$[16].

$$H' = -\sum_{i=1}^{s} \left(\frac{n_i}{N}\right) \log_2 \left(\frac{n_i}{N}\right) \qquad (2)$$

In Eq. (2), n_i is the total number of individuals of the i^{th} species of phytoplankton; i is the total number of individuals of all species of phytoplankton; S is the total number of species in the phytoplankton sample.

The dominance index (Y) can reflect the relative abundance status of the species in the population. Y was calculated according to Equation 3, and the species with $Y>0.02$ were regarded as the dominant species.

$$Y_i = \frac{n_i}{N} \times f_i \qquad (3)$$

In Eq. (3), Y_i is the dominance of phytoplankton species i; n_i is the total number of individuals of phytoplankton species i; N is the total number of individuals of all species in the sample; f_i is the frequency of occurrence of species i in each sample.

1.3 Hydraulic Model

By simulating the water velocity, water depth and flow rate under different conditions in the river channel, the hydraulic model can predict floods, assess the stability of the river channel, optimize the use of water resources, and study the role of ecological environment changes. The one-dimensional model mainly studies the evolution of the water surface line in the river channel, with small computational volume and high efficiency, which is suitable for the simulation of water movement in long river sections or complex river networks[17]. The MIKE 11 model developed by the Danish Hydraulics Institute using the difference method has become one of the mainstream software for the study of water ecological environment in China[18-20].

Since the longitudinal scale of the study reach of Furong Creek is much larger than the transverse scale, the hydrodynamic modeling in this research will be based on the HD module of MIKE 11 software. The computational principle of the model is based on the Saint-Venant equation. The computational grid of the model consists of the intersection of water depth points and flow points. The modeling parameters of the model include river cross-section vector, water depth and flow data.

1.4 Redundancy Analysis

Redundancy analysis (RDA) is a technique used in the analysis of multivariate data in ecology and environmental science. It is a form of regression analysis used to interpret and visualize the relationship between the response matrix and the explanatory matrix. In R, performing RDA analyses is usually done using the vegan package, which is a specialized package for ecological data analysis and diversity assessment.

Firstly, the species were subjected to Decision Curve Analysis (DCA), and the phytoplankton abundance of each phyla of phytoplankton was analyzed by ranking the phytoplankton abundance and drivers, and we obtained that the maximum value of the length of the gradient in the four ranking axes was less than 3. The RDA was used to screen the impact factors affecting the phytoplankton community structure in the study area.

1.5 GAM Model

Generalized Additive Models (GAM), proposed by Trevor Hastie and Robert Tibshirani in 1986, is a nonparametric extension of the generalized linear model, which assumes that the functions of the variables are additive and smooth, and can effectively deal with highly nonlinear and nonmonotonic response relationships[21]. The GAM model is highly flexible and can be used to establish long-term dynamic trend analysis of phytoplankton, and has been widely used in the fields of biohabitat simulation and exploring the response relationship between species distribution and environmental factors[11-24]. The general expression of the GAM model is shown in equation 4.

$$g(E(Y)) = \beta_0 + f_1(x_1) + f_1(x_1) + \cdots + f_i(x_i) + \cdots + f_m(x_m) \tag{4}$$

In Eq. (4), Y represents the diversity index of aquatic organisms; $E(Y)$ is the expected value of the response variable; $g(\cdot)$ is the link function; x_i are the explanatory variables, corresponding to environmental factors; β_0 is the intercept; and $f_i(\cdot)$ denotes the smoothing function.

The GAM model was implemented using the "mgcv" toolkit in R 4.3.0 software. The optimal nonlinear fitting equation was determined by analyzing the P-value (P), the Coefficient of Determination (R^2), and Root Mean Square Error ($RMSE$). $RMSE$ is used to measure the difference between the simulation value of the model and the measured value. The smaller $RMSE$ is, the better the model fits the data; R^2 reflects the explanatory rate of the dependent variable for the independent variable, and its value ranges from 0 to 1. The closer the R^2 is to 1, the better the model fits the data; and the smaller the P is, the smaller the likelihood of the null hypothesis being set up is, and the more significant the results are.; P represents the significance of the statistical results, and the lower the P, the more significant the results are. When $P<0.05$, it means the model has a good fit[25]. In this paper, the GAM model will be used to establish the response relationship between phytoplankton diversity index and factors.

2 Results

2.1 Analysis of phytoplankton results

A total of 95 genera and 239 species of phytoplankton from 8 phyla were identified in Furong Creek. Among them, Chlorophyta have the most species, with 36 genera and 81 species, accounting for 33.89%, followed by Bacillariophyta, with 20 genera and 74 species, accounting for 30.96%; Cyanophyta, with 14 genera and 24 species, accounting for 10.04%; Euglenophyta, with 7 genera and 24 species, accounting for 10.04%; Chrysophyta, with 8 genera and 12 species, accounting for 5.02%; Dinophyta, with 4 genera and 12 species, accounting for 5.02%; Xanthophyta, with 4 genera and 8 species, accounting for 3.35%; Cryptophyta, with 2 genera and 4 species, accounting for 1.67%. The genus Oscillatoria had the highest abundance value of 1.63×10^7 Cells/L in Chlorophyta, followed by the genus Chrysochromulina spp. with 1.549×10^7 Cells/L.

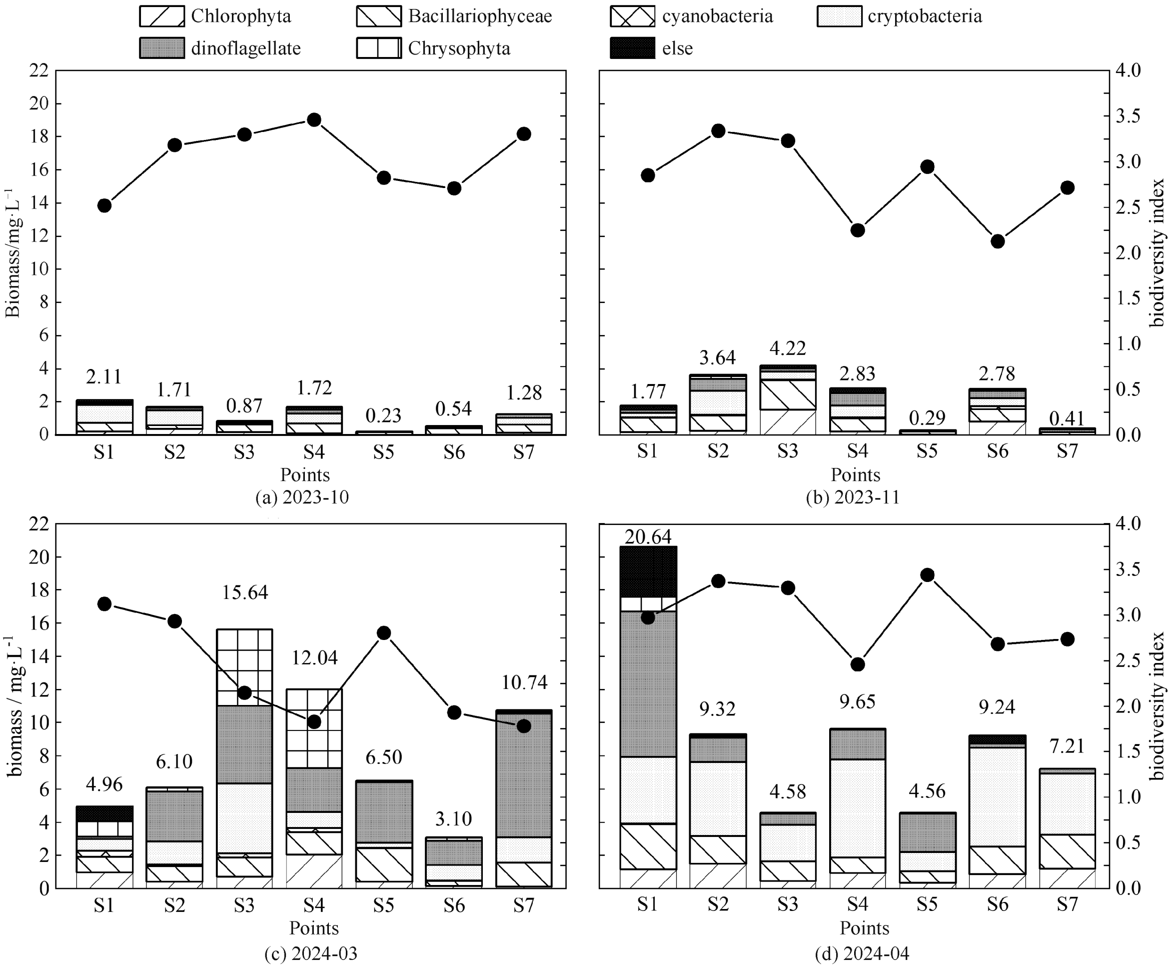
Observing the changes of phytoplankton biomass and Shannon-Wiener index in the study reaches (Fig. 2), Chlorophyta, Bacillariophyta and Cyanophyta were the most dominant phytoplankton in Furong Creek. The mean values of phytoplankton biomass in spring and autumn were 8.88 mg/L and 1.74 mg/L, and the ranges of biomass variation were 3.11 ~ 20.64 mg/L and 0.23 ~ 6.31 mg/L, while the total biomass in spring was ten times higher compared to that in autumn. Among them, *Chroomonas acuta*, *Cryptomonas ovata* and *Cryptomonas erosa* continued to grow in abundance and remained dominant, while *Peridiniopsis cunningtonii* and *Chrysochromulina parva* increased their biomass significantly and became the new dominant species.

The mean value of Shannon-Wiener index for the

Table 3 Number of phytoplankton species in Furong Creek

表 3 芙蓉溪浮游植物种类数

Time	Number of species/Species							
	Bacillariophyta	Xanthophyta	Dinophyta	Chrysophyta	Cyanophyta	Euglenophyta	Chlorophyta	Cryptophyta
Oct-23	31	4	5	5	13	13	36	3
Nov-23	35	5	4	5	13	6	38	4
Mar-24	43	2	9	8	5	8	34	4
Apr-24	26	1	7	3	3	8	43	4



(a) 2023-10 (b) 2023-11

(c) 2024-03 (d) 2024-04

Fig. 2 Biomass and diversity index status

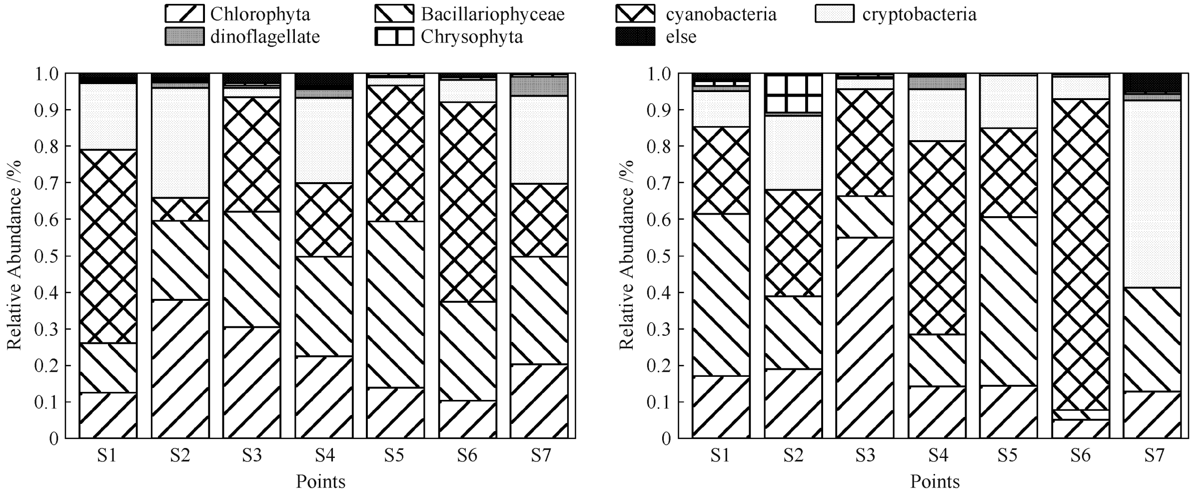
图2 生物量与多样性指数状况

four monitoring data was 2.79, which means that the phytoplankton in the Furong Creek watershed is in a mildly polluted condition. The mean values of Shannon-Wiener index in spring and autumn were 2.68 and 2.91, with a range of 1.78～3.44 and 2.12～3.46. The mean value of Shannon-Wiener index for phytoplankton was 2.36 in March in spring. Among them, S4, S6 and S7 were 1.83, 1.93 and 1.78 which meant that the phytoplankton was in a moderately polluted state, and the field sampling revealed that the river produced an odor accompanied by algal bloom.

The changes in relative abundance of phytoplankton in Furong Creek are shown in Fig. 3. Among them, Chlorophyta, Bacillariophyta and Cryptophyta occupied a large proportion in all four detections, indicating that these three phytoplankton groups are dominant in the region. Cryptophyta, as an indicator species of water quality pollution, was found at all points, which indicates that the risk of eutrophication in the water body of Furong Creek is high, and this risk is more prominent in spring. While the relative abundance of Cyanophyta, Chrysophyta and Dinophyta was seasonally and spatially variable. The relative abundance of phytoplankton at each sampling site differed significantly in different sampling periods. In autumn, various algae were in a balanced community structure, while in spring, phytoplankton reproduced in large quantities, the community density increased, and some of them reproduced rapidly to become absolutely dominant species. The monitoring results showed that the balanced community structure of phytoplankton in autumn was destroyed and the level of Shannon-Wiener index declined after the spring-autumn turnover in the study reach of Furong Creek.

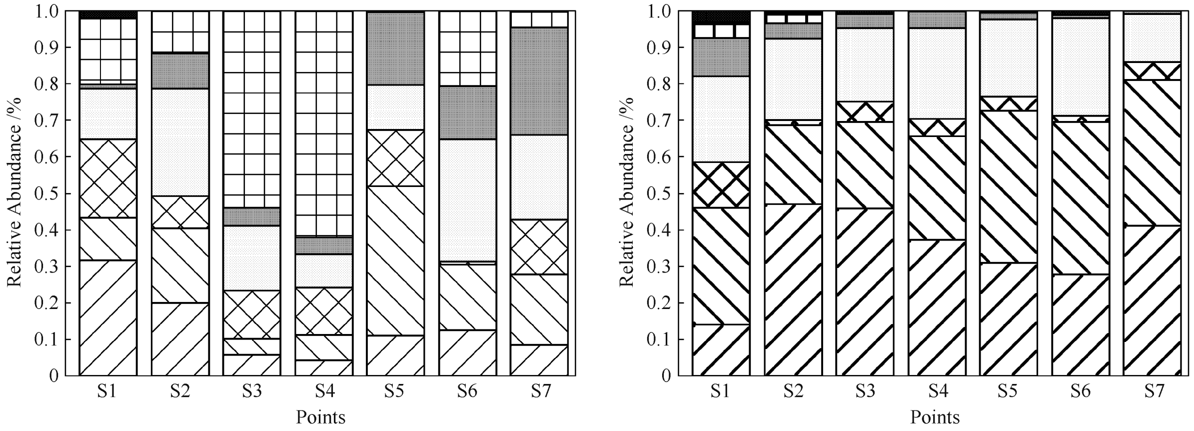
2.2 Redundancy Analysis

The total nitrogen (*TN*), peroxynitrite index (COD_{Mn}), chemical oxygen demand (*COD*), ammonia nitrogen (NH_4^+-N), total phosphorus (*TP*) and water temperature of the four data in the study area of Furong



(a) 2023-10

(b) 2023-11



(c) 2024-03

(d) 2024-04

Fig. 3 Relative abundance status

图 3 相对丰度状况

Creek respectively ranged from 0.63 to 1.56 mg/L, 2.96 to 7.10 mg/L, 6.67 to 8.33 mg/L, 0.040 to 0.584 mg/L, 0.04 to 0.16 mg/L and 14.3~17.8 ℃. The pH ranged from 7.2 to 8.0 and was generally weakly alkaline (Table 4). The mean values of environmental factors were significantly higher in spring than in autumn.

Redundancy analysis of phytoplankton abundance and impact factors for each phylum in Furong Creek showed that hydrodynamic factors (v, h) and environmental factors (TN, COD_{Mn}) were significant impact factors of phytoplankton community structure ($P<0.05$), and the cumulative explanation of the first two axes was 66.47%. The first sorting axis was positively correlated with T and TP, and negatively correlated with NH_4^+-N and TN; the second sorting axis was positively correlated with h, and negatively correlated with COD and v. Among them, v was significantly and positively correlated with Chlorophyta and Bacillariophyta; COD_{Mn} was significantly and positively correlated with Cryptophyta, Dinophyta and Chrysophyta, and significantly and negatively correlated with Euglenophyta; TN was significantly negatively correlated with Xanthophyta (Fig. 4).

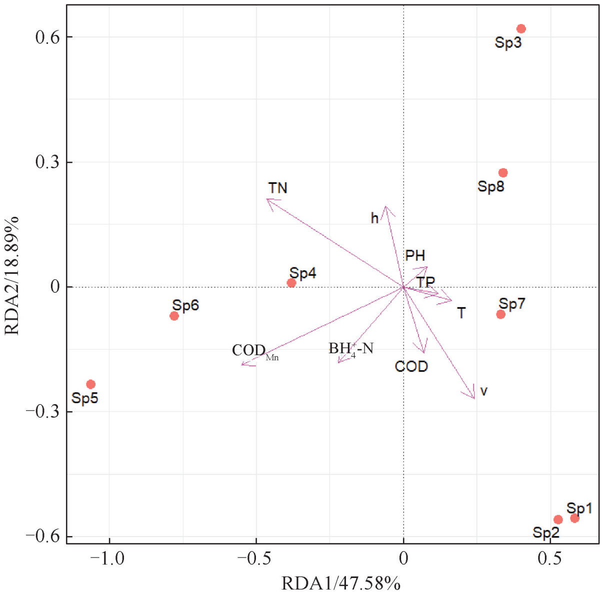
2.3 Analysis of impact environmental factors

COD_{Mn} and TN are one of the commonly used indicators in water quality monitoring (GB 3838—2002, China), which are used as indicator factors in river eutrophication problem for river health assessment and can reflect the pollution level of the river. COD_{Mn} is the total amount of reducing substances in the sample, including organic matter and some inorganic reducing substances, such as sulfide and nitrite; Nitrogen is a nutrient element required for biological growth, and excessive TN will lead to eutrophication of the river, which in turn will trigger problems such as algal bloom and water quality deterioration. According to the concentration, COD_{Mn} and TN are divided into five

Table 4 Variation of environmental factors in water bodies

表 4 水体环境因子的变化

Time	$\rho(TN)/\mathrm{mg\cdot L^{-1}}$		$\rho(COD_{Mn})/\mathrm{mg\cdot L^{-1}}$		$\rho(COD)/\mathrm{mg\cdot L^{-1}}$		$\rho(\mathrm{NH_4^+\text{-}N})/\mathrm{mg\cdot L^{-1}}$	
	mean	range	mean	range	mean	range	mean	range
23-Oct	0. 957	0. 78~1. 12	3. 857	2. 96~3. 72	7. 075	8. 33~8. 33	0. 131	0. 040~0. 040
23-Dec	0. 957	0. 81~1. 11	3. 857	3. 50~4. 20	7. 075	6. 67~8. 33	0. 131	0. 083~0. 372
24-Mar	1. 174	0. 89~1. 56	5. 614	4. 40~7. 10	7. 613	7. 05~7. 95	0. 184	0. 138~0. 312
24-Apr	0. 840	0. 63~1. 07	4. 343	4. 10~4. 80	7. 796	7. 67~8. 03	0. 229	0. 051~0. 584
Time	$\rho(TP)/\mathrm{mg\cdot L^{-1}}$		PH		T/℃		—	
	mean	range	mean	range	mean	range	—	—
23-Oct	0. 06	0. 10~0. 10	7. 886	7. 5~7. 5	17. 4	14. 5~20. 0	—	—
23-Dec	0. 06	0. 04~0. 07	7. 886	7. 2~8. 0	14. 3	13. 5~17. 5	—	—
24-Mar	0. 061	0. 04~0. 1	7. 264	7. 2~7. 5	16. 1	13. 5~20. 0	—	—
24-Apr	0. 10	0. 08~0. 16	7. 329	7. 2~7. 5	17. 8	15. 0~21. 0	—	—



Sp1-Chlorophyta; Sp2-Bacillariophyta; Sp3-Cyanophyta; Sp4-Cryptophyta; Sp5-Dinophyta; Sp6-Chrysophyta; Sp7-Xanthophyta; Sp8-Euglenophyta

Fig. 4 Redundancy analysis of Furong Creek

图 4 芙蓉溪冗余分析

categories of water bodies with different functional zones. In general, the lower the concen-tration, the higher the water quality category.

The interannual variation of COD_{Mn} from December 2020 to March 2023 at Youxian Hydrological Station was analyzed (Fig. 5). It was found that the high COD_{Mn} at this monitoring section is in the category II or III all year round, which is a mild to moderate health condition; COD_{Mn} showed annual cyclic changes, with significantly higher values in spring compared to autumn, transforming from Class II to Class III.

Comparison of the results of the stream environmental factors at different monitoring points during the four monitoring periods in Furong Creek (Fig. 6). The COD_{Mn} and TN concentrations at each point location in March 2024 were at higher values, reaching a moderately heavy pollution state. Points near the overflow weir (S4, S6, S7) had the highest COD_{Mn} and TN concentrations, which are prone to phytoplankton blooms, leading to a shift of the original community structure towards a single species and algal blooms.

Rainfall and agrochemical pollution are the main impact factors on changes in river water quality[26-27]. Observation of the flow change process in the dry period of Furong Creek watershed reveals that the intensity of rainfall is weak, and agricultural nonpoint source pollution in spring should be considered as the main factor of water quality change in Furong Creek watershed.

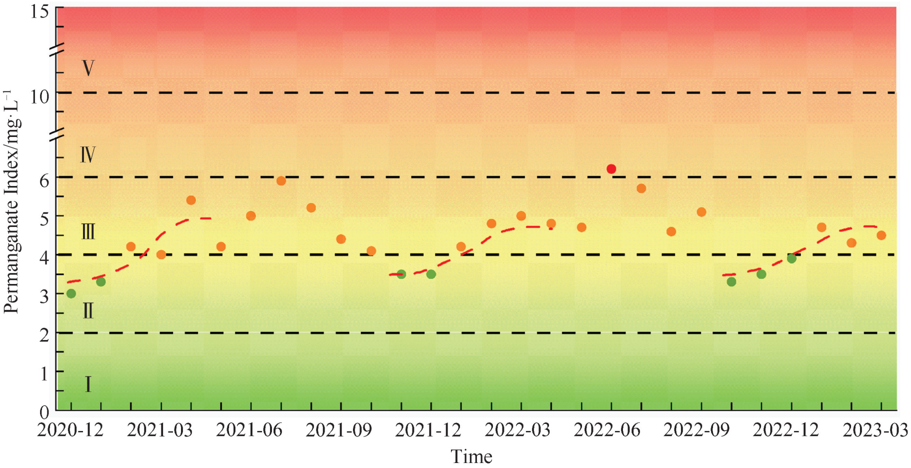


Fig. 5 Interannual variation of permanganate index

图 5 高锰酸盐指数年际变化

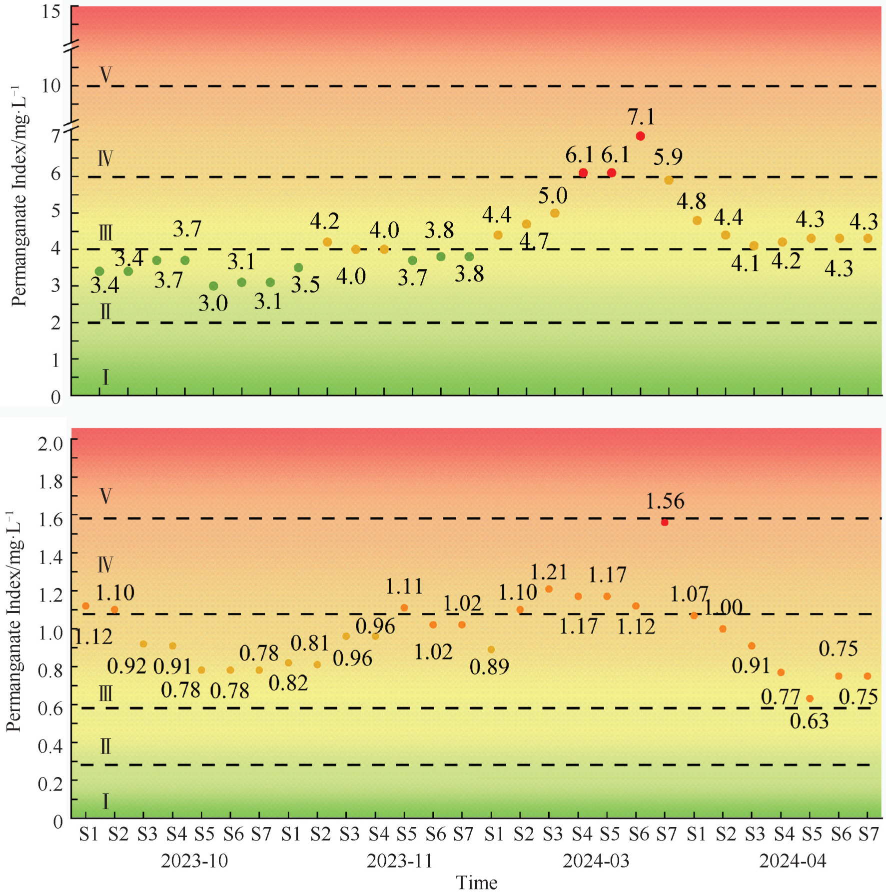


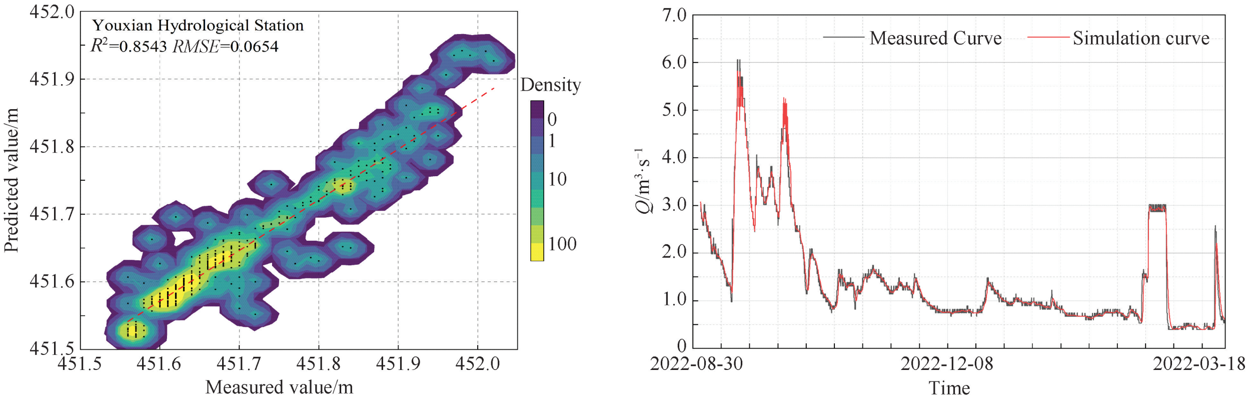
Fig. 6 Total nitrogen and permanganate index status

图 6 总氮、高锰酸盐指数状况

2.4 Hydrodynamic Modeling

Furong Creek is a seasonal stream, and the flow process in spring and autumn within a single dry period is basically the same. In this research, the MIKE 11 model was used to simulate the hydrodynamics. From August 28, 2022 to March 28, 2023 as the simulation time period, the flow process line of Taiping Hydrological Station was taken as the boundary condition in the upstream, and the water depth process line of Furong Creek into the mouth of Fujiang River was taken as the boundary condition in the downstream to establish a one-dimensional hydrodynamic model. The parameters of the MIKE 11 model are calibrated by the water depth and flow parameters of the monitoring section at Youxian Hydrological Station. The simulated values of water depth and flow were fitted to the measured values to assess the representativeness and reliability of the simulation (Fig. 7). An R^2 of 0.854 3 and an *RMSE* of 0.065 4 were obtained for the water depth, and an R^2 of 0.978 3 and an *RMSE* of 0.157 1 were obtained for the flow rate. The results show that the hydrodynamic model with reasonable parameter settings and high accuracy can effectively simulate the hydrodynamic characteristics of Furong Creek.

Hydrodynamic conditions were simulated for the four sampling time periods, in which the four sampling times corresponded to five-day average flow rates of 2.15 m^3/s, 1.50 m^3/s, 0.61 m^3/s and 1.90 m^3/s. The simulation results showed that the average flow velocity in the river was 0.13 m/s, with a range of variation in flow velocity



(a) Calibration of bathymetric regression analysis

(b) Water flow velocity fitting

Fig. 7 Simulation results of hydraulic model

图 7 水动力模型模拟效果

from 0.004 to 0.52 m/s, and the average water depth was 1.25 m, with a range of variation in water depth from 0.16 to 4.12 m. Analyze the distribution of flow velocity and water depth along the course in March 2024 (Fig. 8). The overall flow velocity in the overflow weir reservoir section is small, generally below 0.05 m/s, while the water depth is large, and the overall flow pattern changes from a river type with high flow velocity and low water depth to a lake type with low flow velocity and high water depth. The flow velocity at the reservoir area formed by the overflow weir is slower, generally maintained below 0.05 m/s, while the water depth is larger, and the flow pattern changes from a river type with high flow velocity and low water depth to a lake type with low flow velocity and high water depth.

Phytoplankton is characterized by small size, short growth cycle, frequent species succession, etc. It is sensitive to environmental changes and has a certain degree of mobility, so the mean value of the cross-section at the sampling site cannot well respond to the influence of hydrodynamic factors on phytoplankton. Therefore, the five-day average value of the river section in a certain interval upstream of the sampling point is chosen as the calculation of flow rate and water depth later.

2.5 Generalized Additive Model (GAM) Construction

The phytoplankton Shannon-Wiener index and impact factors were simulated using the "mgcv" toolkit in R 4.3.0 software. The multi-model fitting conditions (Table 5) showed that the GAM model, which was constructed by combining hydrodynamic and environmental factors, could effectively respond to the nonlinear relationship between the Shannon-Wiener index and the impact factors of phytoplankton. Model 1 contains only a single hydrodynamic factor (v), and the performance of the GAM model gradually improves with the introduction of other hydrodynamic and environmental factors.

Among them, the GAM model containing only a single hydrodynamic factor has the relatively worst simulation effect, indicating that a single hydrodynamic factor does not effectively improve the model performance. Introducing the interaction term between h and v, it was found that $RMSE$ and R^2 were significantly improved, but the P-value increased. The interaction term of environmental factors (TN, COD_{MN}) was added to the model. It was found that the $RMSE$ of the model decreased to 0.36 and the adjusted R^2 increased to 0.91 with a P-value less than 0.05. Comprehensively comparing multiple sets of models, the optimal model was determined to be Model 6: $H' \sim \mathrm{s}(v) + \mathrm{te}(h, v) + \mathrm{te}(\mathrm{Mn}, TN)$. The model explained 95.3% of the bias of the data and could effectively fit the Shannon-Wiener index of phytoplankton in Furong Creek.

Using Model 6, the health status of phytoplankton in the studied river section was simulated for October 2023 and March 2024. The measured and simulated values of phytoplankton Shannon-Wiener index were presented in geospatial by ArcGIS software (Fig. 8). The map of phytoplankton Shannon-Wiener index distribution status rendered from the model-fit values can be a good representation of the measured values. The spatial distribution characteristics of species diversity in Furong Creek can be simulated by the model.

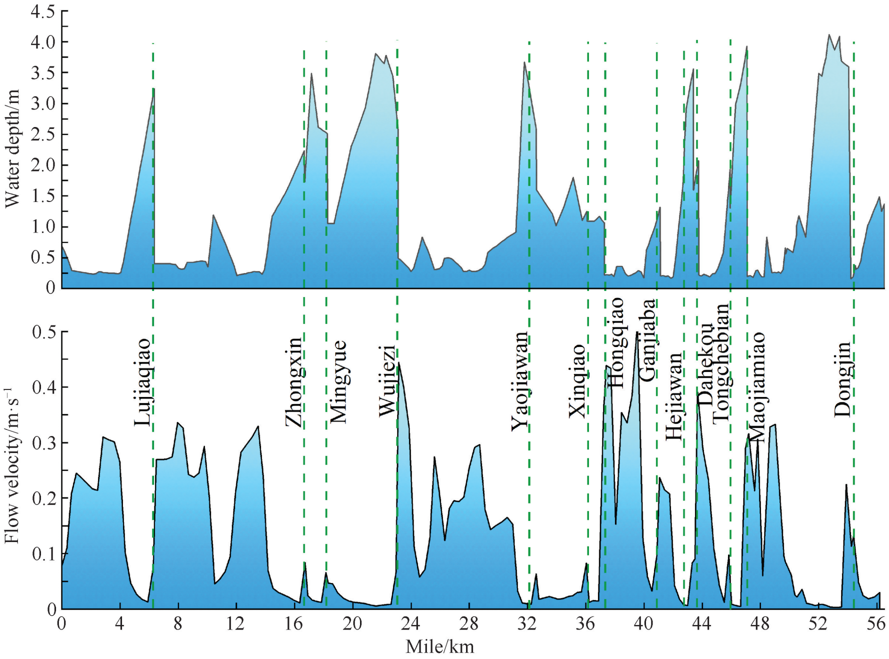


Fig. 8 Flow velocity and water depth distribution in March 2024

图 8 2024 年 3 月流速、水深分布状况

Table 5 Comparison of GAM models

表 5 GAM 模型比选

Number	Model Structure	Residual Deviation	Adjusted R^2	P-value
1	$H' \sim s(v)$	4.65	0.36	<0.05
2	$H' \sim s(h)$	2.64	0.57	<0.05
3	$H' \sim s(v)+te(h,\ v)$	2.12	0.67	0.59
4	$H' \sim s(v)+s(h)+te(h,\ v)$	1.52	0.74	<0.05
5	$H' \sim te(Mn,\ TN)$	4.82	0.31	<0.05
6	$H' \sim s(v)+te(h,\ v)+te(Mn,\ TN)$	0.36	0.91	<0.05

3 Discussion

3.1 The Mechanism of The Phytoplankton Shannon-Wiener Index of Cascade Weirs

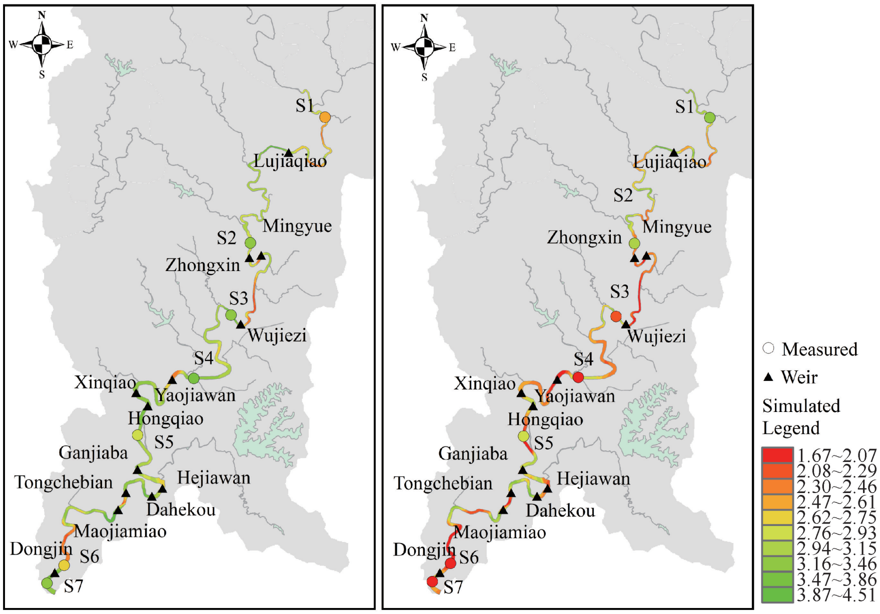
The 13 overflow weirs distributed along the study reach of Furong Creek caused changes in the hydrodynamic conditions within the reach. Hydrodynamic conditions are impact factor that influence phytoplankton species diversity[28]. Appropriate flow rate stimulation leads to elevated nutrient diffusion and reoxygenation capacity in rivers, and the river environment is more suitable for algal growth, causing an increase in phytoplankton density and biomass[29-30]. However, too high flow velocity can lead to too much turbulence in the water, and the shear force formed by the water flow can lead to the death of algae due to cell wall breakage. At the same time, high flow velocities can also lead to impaired nutrient uptake and photosynthesis by algae, thus inhibiting algal growth[31]. Therefore, the stabilization of phytoplankton community structure requires a suitable turbulence zone and water depth to maintain its dynamic balance.

The spatial distribution of the Shannon-Wiener index of phytoplankton in Furong Creek was observed on both occasions (Fig. 9). It was found that the index increased significantly in all reaches of the river in March in spring. Among them, the river section near the overflow weir produced the most significant variation. A lake-type environment with low flow velocities and high water depths increases the residence time of water and nutrients[32], resulting in increased nutrient content as well as changes in proportions and a dramatic increase in phytoplankton abundance[33]. Lower current turbulence intensity shifted the phytoplankton community structure to homogenization[34], leading to a decrease in the Shannon-Wiener index of phytoplankton and outbreaks of algal blooms.

3.2 Prediction of Shannon-Wiener index of phytoplankton after the modification of Cascade weirs

In order to create an urban ecological wetland, Mianyang government built three new overflow weirs at the Forest Park in Fisherman's Village at the beginning of 2024, which together with the existing 13 overflow weirs in Furong Creek form a dense and continuous lake-type river environment. This creates a higher risk of eutrophication in Furong Creek in the spring. The overflow weirs should be engineered for ecological purposes to avoid algal blooms.

Observing the distribution of phytoplankton Shannon-Wiener index in Furong Creek in March 2024, it was found that the phytoplankton Shannon-Wiener index at the three overflow weirs of Wujiezi, Yaojiawan, and Dongjin showed a poor condition. In order to investigate the influence of the three new overflow weirs on the



(a) 2023-10

(b) 2024-03

Fig. 9 Longitudinal distribution of species diversity

图 9 物种多样性沿程分布状况

phytoplankton community structure and to cope with the decline of the phytoplankton Shannon-Wiener index in Furong Creek in spring, the weir heights of the three overflow weirs at Wujiezi, Yaojiawan and Dongjin were adjusted (Table 6).

Table 6 Optimization information of overflow weirs m

表 6 溢流堰优化信息 m

Number	Name	Weir Height		Weir Crest Elevation	
		Before	After	Before	After
1	Dongjin	3. 5	1. 5	450. 3	448. 3
2	Hejiawan	3. 5	2. 4	465. 5	464. 4
3	Wujiezi	2. 5	1. 2	485. 1	483. 8
4	Xiantong	—	1. 0	—	450. 0
5	Yufu	—	2. 2	—	452. 3
6	Yuqiao	—	2. 0	—	452. 5

Analyzing the distribution of phytoplankton Shannon-Wiener index in March 2024 after the cascade weirs modification (Fig. 10), it was found that the phytoplankton Shannon-Wiener index in the study area of Furong Creek increased from 2. 54 to 2. 73. Then, the simulated values were mapped in geospatial space using ArcGIS software, and four reaches, A1 - A4, were selected to show the distribution of phytoplankton Shannon-Wiener index after the modification. The results showed that the corresponding phytoplankton Shannon-Wiener indices of the four river sections A1−A4 increased by 21%, 13%, 5% and 35%, respectively, and that the reasonable deployment of the Cascade weirs can reduce the eutrophication risk of the river.

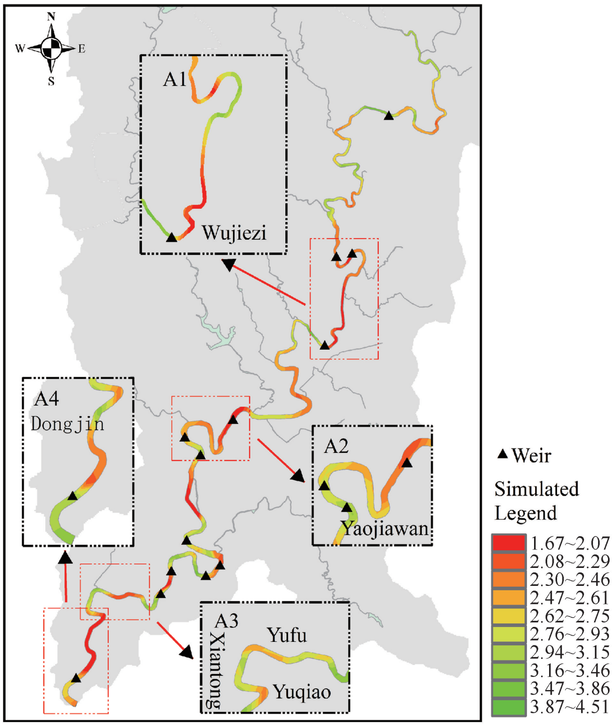


Fig. 10 Distribution of species diversity after cascade weir reconstruction

图 10 梯级堰改造后物种多样性分布状况

4 Conclusion

Research was conducted in Furong Creek in order to investigate the nonlinear response relationship between spring and autumn phytoplankton community structure and its impact factors in Furong Creek under the construction of cascade weirs. The main conclusions of this paper are as follows.

(1) A total of 8 phytoplankton genera, 95 genera and 239 species of phytoplankton were identified in Furong Creek. The annual average value of Shannon-Wiener index was 2. 79, which was in a mildly polluted state. The dominant phytoplankton species in Furong Creek were identified from 6 phyla and 12 genera based on the criterion of dominance $Y > 0.02$. The mean phytoplankton abundance in spring was 1.344×10^7 Cells/L, and the dominant species were Cyanophyta, Bacillariophyta and Chlorophyta; The mean phytoplankton abundance in spring was 1.344×10^7 Cells/L, and the dominant species were Cyanophyta, Bacillariophyta and Chlorophyta, while Chrysophyta and Dinophyta showed significant dominance in some points.

(2) Redundancy analysis showed that hydrodynamic factors (v, h) and environmental factors (TN, COD_{Mn}) were significant influences on phytoplankton community structure. The environmental factors (TN, COD_{Mn}) had seasonal characteristics, and the concentrations of the environmental factors in the spring were elevated compared to the autumn, reaching a state of medium-heavy pollution. A GAM model combining hydrodynamic and environmental factors can effectively respond to the nonlinear relationship between phytoplankton Shannon-Wiener index and the impact factors.

(3) Lower current turbulence intensity homogenized the phytoplankton community structure during the spring when nutrient concentrations increased, leading to a decrease in the Shannon-Wiener index of phytoplankton and algal bloom outbreaks. In this paper, by adjusting the weir height of overflow weirs, the phytoplankton

Shannon-Wiener index of four local river sections (A1-A4) were increased by 21%, 13%, 5%, and 35%, respectively, which reduced the eutrophication risk of the river.

References:

[1] HU W W, WANG G X, DENG W, et al. The influence of dams on ecohydrological conditions in the Huaihe river basin[J]. Ecological Engineering, 2008, 33(3-4): 233-241.

[2] ZHAO Q H, LIU S L, DENG L, et al. The effects of dam construction and precipitation variability on hydrologic alteration in the Lancang River Basin of southwest China [J]. Stochastic Environmental Research and Risk Assessment, 2012, 26(7): 993-1011.

[3] XU J J, JING H. Research progress of river ecological restoration concept and technology[J]. Research of Agricultural Modernization, 2022, 43: 691-701.

[4] WOZNEY K M, HAXTON T J, KJARTANSON S, et al. Genetic assessment of lake sturgeon (<i>Acipenser fulvescens</i>) community structure in the Ottawa River[J]. Environmental Biology of Fishes, 2011, 90(2): 183-195.

[5] O' FARRELL I, DE TEZANOS PINTO P, IZAGUIRRE I. Phytoplankton morphological response to the underwater light conditions in a vegetated wetland[J]. Hydrobiologia, 2007, 578: 65-77.

[6] LESKA S, GRAFE C. Using diatoms to assess the biological condition of large rivers in Idaho (USA)[J]. Freshwater Biology, 2002, 47(10): 2015-2037.

[7] SUN C M, FAN Y W. Canonical correspondence analysis of the relationship between algal community and environment variables of Heilongjiang river in Heihe[J]. Journal of Lake Science, 2009, 21(6): 839-844.

[8] WU F C. Effectiveness, scientific and technological support, and prospects for water pollution control and management in China[J]. Water Resources Development Research, 2023, 23(12): 1-8.

[9] SONG Y, ZHANG L L, CHEN W. Study on the effect of flow velocity on the growth of Microcystis aeruginosa, a dominant species in reservoir hydrography[J]. Advanced Engineering Sciences, 2016, 48(S1): 25-32.

[10] LI P F, GAO Y, ZHANG H P. Simulation of the effect of flow velocity on the growth and population changes of planktonic algae[J]. Journal of Lake Sciences, 2015, 27(1): 44-49.

[11] ZHANG Q, CHEN Y C, LIN Y Q. Characteristic of phytoplankton community structure and its driving factors along the cascade reservoirs in the Lancang River[J]. Journal of Lake Sciences, 2023, 35(2): 530-539.

[12] LIU S F. Study on Rubber Dam Ccheduling Based on Habitat Simulation of Aquatic Organisms [D]. Zhengzhou: Zhengzhou University, 2022.

[13] LI G Y. Improved water security for China's efforts to build itself into a stronger country and rejuvenate the Chinese nation on all fronts by pursuing Chinese modernization: Speech at the 2024 National Water Conservancy Work Conference[J]. Water Resources Development Research, 2024, 24(1): 1-10.

[14] LI G Y. Thoroughly implement the spirit of the 20th National Congress of the Communist Party of China and solidly promote the high-quality development of water conservancy in the new stage: Speech at the National Water Conservancy Work Conference in 2023[J]. Water Resources Development Research, 2023, 23(1): 1-11.

[15] ZHANG Q, CHEN Y C, LIN Y Q. Spatial distribution patterns of phytoplankton community during different water periods along cascade reservoirs in the Lancang River[J]. Acta Scientiae Circumstantiae, 2022, 42(12): 392-401.

[16] QIN J J, WANG Y. Application and evaluation of phytoplankton diversity index[J]. Journal of Shenyang Normal University, 2014, 32(4): 502-505.

[17] GENG Y F. A Coupled Hydraulic Numerical Models on the Urban Rain Flood[D]. Dalian, Dalian University of Technology, 2006.

[18] DANG X G, WANG S Y, CHANG L, et al. Ecological flow guarantee simulation based on Mike11 in north canal gate dams joint regulation[J]. China Rural Water Hydropower, 2021, 7: 94-100.

[19] HU W. Study on Hydrodynamic Characteristics and Ecological Flow in the Middle and Lower Reaches of Hanjiang River Based on Bloom Control [D]. Yichang: China Three Gorges University, 2021.

[20] MENG D. Study on Ecological Water Demand of Artificial River in Plain Area-take Yangzhou Jiangdu as an Example[D]. Yangzhou: Yangzhou University, 2021.

[21] DENG J M, QIN B Q, WANG B W. Quick implementing of generalized additive models using R and its application in blue-green algal bloom forecasting[J]. Chinese Journal of Ecology, 2015, 34(3): 835.

[22] XIONG P L, XU S N, CHEN Z Z, et al. Spatiotemporal distribution of Collichthy lucidus in the Pearl River Estuary and its relationship with environmental factors[J]. Marine Science, 2022, 46: 79-87.

[23] FENG Q Y, WANG S R, LIU X Q, et al. Seasonal and spatial variations of phytoplankton communities and correlations with environmental factors in Lake Dianchi[J]. Beijing Da Xue Xue Bao, 2020, 56(1): 184-192.

[24] ZHANG J P, ZHI M M, ZHANG Y. Combined generalized additive model and random forest to evaluate the influence of environmental factors on phytoplankton biomass in a large eutrophic lake [J]. Ecological Indicators, 2021, 130: 108082.

[25] YUAN W H, WANG H, XIA Y B, et al. Relationship of chlorophyll a and water quality factors in Poyang lake based on GAM model[J].

Ecology Environment, 2021, 30(8): 1716.

[26] WANG Y, WANG J, XIE B H, et al. Research on surface source pollution pattern of typical watersheds in hilly mountainous area and plain river network area of China[J]. Environmental Engineering, 2024, 42(10): 33-40.

[27] LI J, MIN Q W, LI Z J. Analysis of agricultural pollution pressure in the lake Tai basin[J]. Chinese Journal of Eco-Agriculture, 2012, 20(3): 348-355.

[28] LIANG P, WANG X, MA F. Effect of hydrodynamic conditions on water eutrophication: A review[J]. Lake Science, 2013, 25(4): 455-462.

[29] WANG H P, QIAN J, XIE P, et al. Mechanisms for hydrological factors causing algal blooms in Hanjiang river: Based on kinetics of algae growth[J]. Resources Environment in the Yangtze Valley, 2004, 13(3): 282-285.

[30] HUANG C, ZHONG C H, DENG C G, et al. Preliminary study on correlation between flow velocity and algae along Daning River's backwater region at sluice initial stages in the three gorges reservoir[J]. Journal of Agro-Environment Science, 2006, 25(2): 453-457.

[31] GHOSAL S, ROGERS M, WRAY A. The Ecology of Phytoplankton[M]. Cambridge: Cambridge University Press, 2006.

[32] MAAVARA T, CHEN Q W, VAN M, et al. River dam impacts on biogeochemical cycling[J]. Nature Reviews Earth Environment Australia, 2020, 1(2): 103-116.

[33] CHEN Q W, SHI W Q, HUISMAN J, et al. Hydropower reservoirs on the upper Mekong river modify nutrient bioavailability downstream[J]. National Science Review, 2020, 7(9): 1449-1457.

[34] SYVITSKI J P M, VÖRÖSMARTY C J, KETTNER A J, et al. Impact of humans on the flux of terrestrial sediment to the global coastal ocean[J]. Science, 2005, 308(5720): 376-380.

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