



# Assessment of the Wanyu River (China) based on a water, sediment and hydrobiont framework

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## Abstract

Due to the striving for the development of economy and agriculture, anthropogenic activities in many countries dramatically alter natural hydrology. These activities are primarily responsible for river deterioration. Thus, we need to assess the river environment and take measures for remediation. According to the survey data, the study identified the critical factors causing water quality deterioration and evaluated the aquatic biodiversity in the Wanyu River. First, based on the monitoring data of water (dissolved oxygen (DO), chemical oxygen demand (COD), total phosphorus (TP), and ammonia nitrogen (NH<sub>3</sub>-N)), sediment (copper (Cu), zinc (Zn), lead (Pb), arsenic (As), nickel (Ni), mercury (Hg), cadmium (Cd), and chromium (Cr)), and aquatic biodiversity (fish and hydrophyte), the study identified the critical factors causing river quality deterioration. Second, the study provided some recommendations that would consolidate the restoration efforts. Consequently, because of the government's efforts in building the municipal sewage treatment plant, dredging, and other measures, the river environment improved during the 2020–2021 period. The maximum concentrations of COD, NH<sub>3</sub>-N, and TP in water were reduced by 17.76%, 26.17%, and 20.93%, respectively. The sediment had no risk of heavy metal pollution in the past 2 years. And we could utilize sludge as garden soil or compost resource. However, reducing agricultural pollution, internal nutrient loading, and cost-effective restoration and evaluation represent significant challenges in the efforts to recover the river ecosystem.

**Keywords** River Quality Index · Pollution · Restoration · Watershed management

## Introduction

Rivers play an important ecological and economic role, which represent the pathways for mass transport from land to lakes and oceans and are responsible for meeting the societal needs for irrigation, drinking water supply, fisheries, and landscape value (Verhofstad et al. 2017; Hutchins et al. 2009). The river system evolved into a compound ecology system combined with society, economy, and natural design. The river ecosystems contain material flow, energy flow, information flow, and value flow (Nasiri et al. 2007; Zhang et al. 2014). Despite the well-understood significance of rivers, river ecosystems face severe threats during the past century, including non-point source pollution and nutrient

loading. In 2010, nearly 80% of the worldwide population was potentially faced with water security risks (Huang et al. 2021). Especially in developing countries, rivers have been subjected to water quality impairments induced by urbanization, agriculture, and energy-intensive economic development over the past decades (Huang et al. 2021; Wu et al. 2015). To improve surface water quality, the government and organizations have made substantial investments in environmental remediation. For example, the government of China has established a wide range of strict laws and guidelines, including the Water Pollution Control Plan (10-Point Water Plan) in 2015. Restoration programs for polluted rivers are widespread throughout the world, comprising purification and control of watershed uptakes (Hjerpe et al. 2017; Verhofstad et al. 2017). For example, removing a majority of the nitrogen and phosphorus load in water body by harvesting aquatic plants in the Netherlands (Verhofstad et al. 2017), and dredging works in Meiliang Bay of Taihu Lake (Zhong et al. 2018). Furthermore, to identify the characteristics of pollution and optimize the design of restoration practices, addressing the environmental assessment of the

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river is widely recognized as one of the emerging imperatives (Hjerpe et al. 2017; Deng et al. 2021). River water quality has been widely studied, emphasizing some topics, such as eutrophication, microorganisms, nutrient loading, carbon flux, and algae bloom (Sohn and Haggblom 2016; Gillis et al., 2010). To shed light on the water quality assessment and underlying pattern in surface water, numerous indexes and modeling studies were reported, such as Water Quality Index (WQI), Trophic Level Index, Nemerow Pollution Index, and driver characterization modeling (Alothman 2019; Huang et al. 2019). These studies mainly focused on the contents of eutrophication and heavy metals in water. For example, according to Huang et al. (2021), there was a low percentage of heavy metal pollution recorded in Chinese river water (less than 0.3% of sampling sites had severe heavy metal pollution), while the frequency of water quality impairments predominantly displays stronger relationships with total phosphorus for 82.5%, and ammonia nitrogen for 79.5%. Furthermore, we could also focus on sediment during the river restoration. Sediment is a large reservoir for pollutants in the river system. Environmental dredging is a primary remedial option for removing the contaminated material from the river environment (Wu et al. 2017a). Productive reuse of dredged sediments has been discussed in many studies, such as for the fabrication of fired bricks, compost application, and garden soil (Mezencevova et al. 2012). Thus, monitoring heavy metals in sediment is crucial for environmental sustainability and is considered a suitable approach for river system assessment. Hence, this study used River Quality Index (*RQI*), which was an adaptation of the traditional WQI to the five quality class environmental quality standards, to differentiate the river quality conditions. WQI included nutrient enrichment factors and heavy metal variables in water samples, while *RQI* focused on heavy metals in sediments rather than water, except the watersheds with definite sources of heavy metals. Additionally, since the river is the habitat of fish and hydrophytes, we need to investigate the biodiversity (distributions, assemblage attributes, and richness) in river restoration. For instance, the fish community was broadly used to indicate river pollution disturbance and assess the freshwater ecosystem health (Maire et al. 2013; Parker et al. 2018). Hydrophytes were traditionally used to remove the excess nutrients in many freshwater ecosystems (Vukov et al. 2008).

The study took the Wanyu River as an example. The Wanyu River was a polluted river that received little attention in Suzhou City before 2020. Since non-point source pollution from domestic sewage and agriculture was a critical source of nutrients, the government implemented restoration works on the Wanyu River from 2020. For example, completed wastewater treatment plants (commissioning in June 2020 and full operation in August 2020) use the anoxic–oxic system to collect domestic sewage and avoid direct discharge

of sewage around S6–S11 (Fig. 2). Dredging works with a length of approximately 13.6 km (S2–S5) were completed from November to December 2020. Cutter suction dredger, which was important equipment in the dredging engineering, was used to remove about 0.6 m of silt. Artificial floating islands, which are the soilless planting structure constructed with floating mats and aquatic plants (Yeh et al. 2015), were placed along the river in March 2021. These were intended to remove excess nutrients from water bodies. Our study expected to improve the efficiency of monitoring and to assess the restoration of rivers with as few indicators as possible. Therefore, considering environmental sustainability and economic efficiency, the study offered a more comprehensive assessment framework based on twelve environmental quality indicators and the diversity of aquatic organisms in river restoration. This study also aimed to delineate the presence of distinct spatio-temporal river quality trends and pinpoint promising trajectories and crucial problems. Additionally, our analysis provided some recommendations that would consolidate the ongoing remediation efforts of the river environment, including the appropriate sludge disposal and the establishment of strict regulations that can drop the eutrophic level of external stressors on rivers.

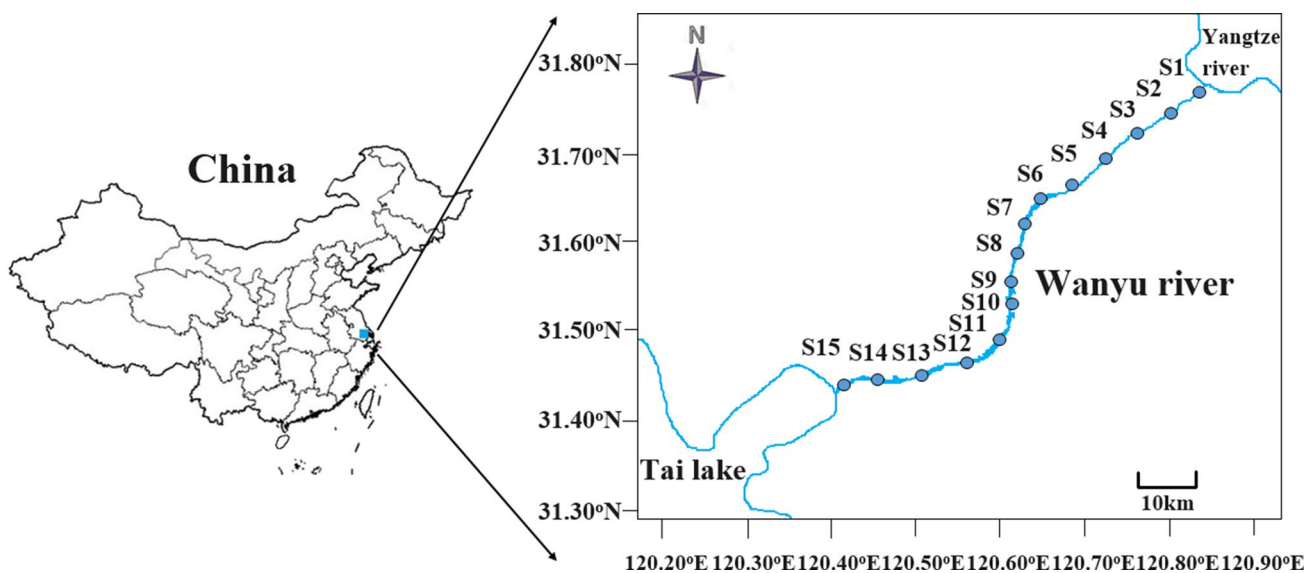
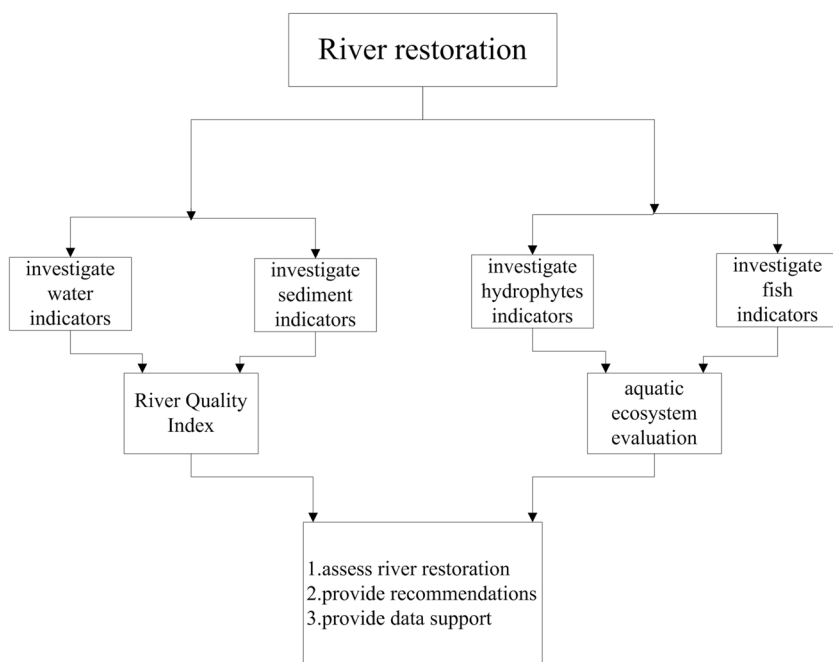
In conclusion, the study established a framework (Fig. 1) to characterize and evaluate the changes in the river ecosystem during the process of restoration. First, based on water and sediment monitoring data, the study identified the critical factors causing river quality deterioration and calculated the *RQI*. Second, according to the diversity of fish and hydrophytes, the study evaluated the stability of the river ecosystem. And the study provided some recommendations that would consolidate the restoration efforts.

## Material and methods

### Study area

The study conducted a thorough investigation of the spatio-temporal pollution in the Wanyu River, the central environmental remediation area in Suzhou City. Suzhou City (30°47′ ~ 32°02′N, 119°55′ ~ 121°20′ E) is located in the lower reaches of the Yangtze River and belongs to the east of China. It is low-lying, with numerous rivers and lakes, known as the Venice of the east. It has a subtropical monsoon marine climate. The average annual precipitation is 1100 mm, and the average yearly temperature is 15.7 °C. Suzhou City is a famous cultural center and an important hub of communication in the eastern areas of China. It has a population of over 12 million, which has put pressure on the ecosystem and environment of the city. Wanyu River (31°26′ ~ 31°47′N, 120°25′ ~ 120°50′E) is located in the north area of Suzhou City. According to the location of

**Fig. 1** Schematic illustration of river restoration evaluation framework



**Fig. 2** Maps of the study area. Map of China, including Wanyu River. Blue circle symbols (1–15) represent sampling sites that were investigated during January, April, July, and October yearly from 2020 to 2021

the pollution source and the actual topography, the fifteen sampling sites (Fig. 2) were separately located along the Wanyu River during the restoration process. To establish the evaluation system, we monitored the variables of water and sediment. We compiled datasets of watershed features (land uses, remedial measures, and the diversity of fish and hydrophytes) from 2020 to 2021.

Considering that the restoration of the river environment requires a sufficient period, water and sediment

sample collections were launched in January, April, July, and October yearly from 2020 to 2021, which had the average temperatures of 5.1 °C, 17.6 °C, 29.7 °C, and 20.8 °C, respectively, and total precipitation of 61 mm, 75 mm, 92 mm, and 63 mm, respectively. Considering the interference of surveys on hydrobionts and the efficiency of monitoring, the investigations of fish and hydrophytes were launched in October 2021.

## Field sampling

According to the technical regulation of the preservation and handling of water samples (HJ493-2009), water samples for chemical measurements were collected and preserved in printed polyethylene bottles. The polyethylene bottles were stored at 4 °C in the dark, temperature-controlled containers while in transit to the laboratory on the same day, which was carried out 7 days or less after sampling. At each sampling point, sediment samples were collected by gravity corer and then using polyvinyl chloride core samplers (about 500 g weight, 10 cm depth). Every sample was transferred into a pre-labeled clean plastic bag, and the transportation was the same as for the water samples (Wu et al., 2017b; Li et al. 2017).

## Laboratory analysis

This study focused on dissolved oxygen (DO), chemical oxygen demand (COD), total phosphorus (TP), and ammonia nitrogen (NH<sub>3</sub>-N) in water, and eight heavy metals, including copper (Cu), zinc (Zn), lead (Pb), arsenic (As), nickel (Ni), mercury (Hg), cadmium (Cd), and chromium (Cr) in sediment. We then calibrated *RQI* to delineate the most significant variables of river quality. DO was measured onsite by a portable hand-held dissolved oxygen meter (Orion Star 120D-01A, USA). The method was from the standard — determination of dissolved oxygen — electrochemical probe method (HJ506-2009). Concentrations of COD were determined using a titrimetric method by acid digestion with potassium permanganate oxidation (determination of permanganate index, GB11892-89). Concentrations of NH<sub>3</sub>-N and TP were determined by persulfate digestion and then spectrophotometrically (with a UV spectrophotometer (uv-1800)), using determination of ammonia nitrogen-Nessler's reagent spectrophotometry (HJ535-2009), and determination of total phosphorus-ammonium molybdate spectrophotometric method (GB11893-89), respectively. For sediments, samples were air-dried, ground, and homogenized using an agate mortar, and oven dried at 50 °C to constant weight. Each sediment sample was digested in acid (HNO<sub>3</sub>:HClO<sub>4</sub>:HF=5:4:1, in volume), and heated in a microwave equipment. The specific heated process was 160 °C for 10 min, 190 °C for 10 min, 220 °C for 10 min, and 270 °C for 15 min. After cooling, the resultant solution was evaporated at 170 to 180 °C to dryness. Next, 2 mL of HCl and 0.2 mL of 0.1 M H<sub>3</sub>BO<sub>3</sub> solution were added, and the solution was evaporated to a volume of approximately 0.7 mL and diluted to a volume of 20 mL with ultrapure water (Kuznetsova et al. 2021; Karandashev et al. 2017). The contents of Cu, Zn, Ni, As, Hg, Cd, Cr, and Pb were determined by inductively coupled plasma mass spectrometry (ICP-MS, PerkinElmer NexION 350X, USA). The atomizer in ICP-MS sends the solution sample to the plasma light source. Ionized gas is dissociated at high temperature and then separated according to charge mass

ratio. The element content is determined by comparing the count of the detector with the standard line (Kuznetsova et al. 2021, 2019; Karandashev et al. 2017; Li et al. 2017).

## River Quality Index

According to the monitoring data, the study used River Quality Index (*RQI*) to evaluate the pollution and remediation of the Wanyu River. *RQI* is an adaptation of the traditional WQI to the five quality class environmental quality standards (GB3838-2002). *RQI* allows differentiating between excellent and bad river quality conditions, i.e.,  $RQI \geq 80$  (excellent, mainly for source of water and national nature protection areas),  $60 \leq RQI < 80$  (good, mainly for centralized potable water source and protection areas for rare fishes),  $40 \leq RQI < 60$  (moderate, mainly for general fish and shrimp migratory passage, aquaculture area, and swimming areas),  $20 \leq RQI < 40$  (poor, mainly for general industrial areas and entertainment areas not directly touched by body) and  $RQI < 20$  (bad, mainly for farmland areas and general landscape requirement). Currently, the *RQI* of Wanyu River is calculated using the following equations.

$$RQI^j = \min(RQI_1^j, RQI_2^j, \dots, RQI_n^j) \quad (1)$$

$$RQI_n^j = 100 - \max\left(0, \frac{c_{nj} - c_n^I}{c_n^V - c_n^I} \times 100\right) \quad (2)$$

where  $RQI_n^j$  is the *RQI* of pollutant *n* at the *j* sampling site.  $C_{nj}$  represents the monitored concentration of the pollutant *n* at the *j* sampling site.  $C_n^I$  and  $C_n^V$  are the concentration of the variable *n* at class I (excellent) and V (bad) (GB3838-2002), respectively. Four water quality variables and eight heavy metals in sediment were used to calculate *RQI*.

Biological data (fish and hydrophytes).

Considering that the restoration of the river ecosystem requires sufficient period and economic efficiency, the surveys of fish and hydrophytes were done at the end of the river restoration. Fish were captured with backpack electro-fisher equipment in sampling sites. Each collection area covered 100 m of stream length. At each sampling site, a one-hundred meter sampling line was established along the river. Prior to sampling, two block nets were placed at each site to prevent the potential immigration. One person conducted the electro fisher while three people help in netting the fish. Fish were identified to the species level, counted, and released alive back into the water. The distributions (information about the number and species of fish surveyed at each sampling site), assemblage attributes (the number of one species of fish at the sampling site/the total number of fish in this sampling site), the richness (the number of fish species), and diversity (Shannon–Wiener Index) were estimated.

## Data analysis

A commonly used biological study index is Shannon–Wiener diversity. As a measure of the amount of variation among abundance values, Shannon–Wiener Index has emphasized the interaction between richness (the number of unique species) and the distribution of abundance (Spellerberg and Peter 2003; Strong 2016; Tucker, et al. 2016; Eriksen, et al. 2021). A high Shannon–Wiener Index indicates high fish abundance and biomass distributed across most species, whereas a low index means low fish abundance. For hydrophyte investigation, 2 quadrants (1 m × 1 m) were set in each sampling site. Hydrophytes in the sampling site were identified to the species level and counted. The distributions, assemblage attributes, and diversity (Shannon–Wiener Index) were estimated.

According to the investigation data of fish and hydrophytes, the Shannon–Wiener Index was employed to evaluate species diversity in the Wanyu River. The following equations were used in the calculation.

$$H' = - \sum_{i=1}^R (P_i)(\ln P_i) \quad (3)$$

where  $p_i$  is the proportion of individuals belonging to the  $i$ th species in the dataset of interest, the Shannon entropy quantifies the uncertainty in predicting the species identity of an individual that is taken at random from the dataset.  $R$  is the total number of species.

## Results

### Monitoring data of pollution indicators

Pollution indicators in river water and sediment sampled along the Wanyu River during January, April, July, and October from 2020 to 2021 were investigated. The monitoring data are shown in Table 1. The variation trend of contaminant contents in water samples declined, while DO

increased in the last 2 years. Before river restoration, the maximum concentrations of COD,  $\text{NH}_3\text{-N}$ , and TP were worse than class V of the national standard (GB3838-2002, China, COD  $15.0 \text{ mg}\cdot\text{L}^{-1}$ ,  $\text{NH}_3\text{-N}$   $2.0 \text{ mg}\cdot\text{L}^{-1}$ , TP  $0.4 \text{ mg}\cdot\text{L}^{-1}$ ). The primary variable responsible for the river water quality characterization was an excess of nutrients (COD,  $\text{NH}_3\text{-N}$ , and TP). But after 2 years of river remediation, the maximum concentrations of COD,  $\text{NH}_3\text{-N}$ , and TP reduced by 17.76%, 26.17%, and 20.93%, respectively, which were all lower than the standard limits of class V. The effect of nitrogen and phosphorus removal in river rehabilitation was notable. Additionally, the average concentrations of DO were 4.59 and  $4.96 \text{ mg}\cdot\text{L}^{-1}$ , respectively, in 2020 and 2021, which belonged to class IV of the national standard (DO  $3.0 \text{ mg}\cdot\text{L}^{-1}$ ).

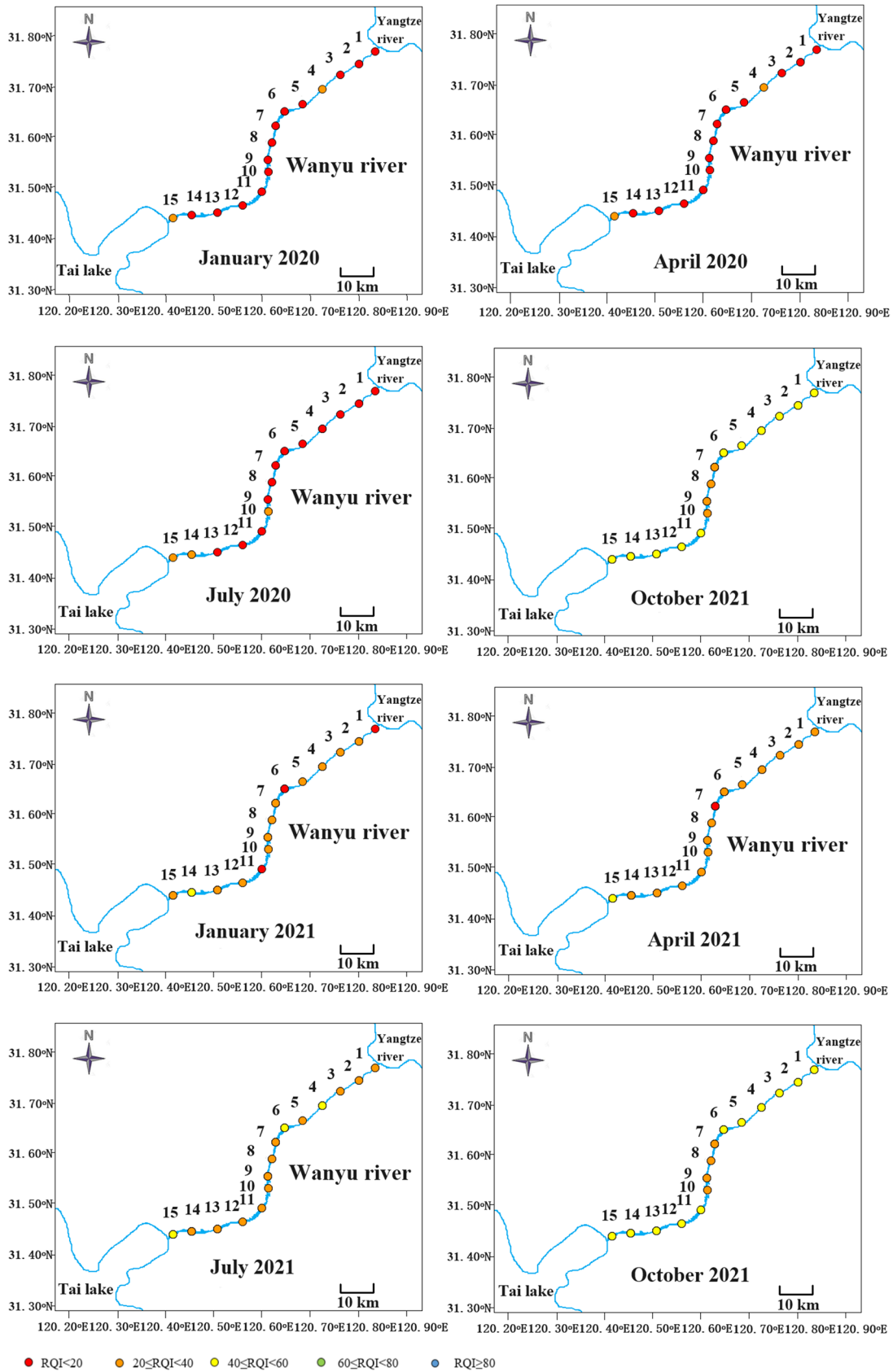
The contents of Cu, Zn, Ni, As, Hg, Cd, Cr, and Pb were in the ranges of 30.17–56.55, 60.76–123.44, 26.09–36.77, 3.81–11.89, 0.03–0.11, 0.01–0.08, 64.31–109.68, and 27.99–62.37  $\text{mg}\cdot\text{kg}^{-1}$ , respectively, during the last 2 years. Compared to the risk limit standards (Cu  $100 \text{ mg}\cdot\text{kg}^{-1}$ , Zn  $250 \text{ mg}\cdot\text{kg}^{-1}$ , Ni  $100 \text{ mg}\cdot\text{kg}^{-1}$ , As  $30 \text{ mg}\cdot\text{kg}^{-1}$ , Hg  $2.4 \text{ mg}\cdot\text{kg}^{-1}$ , Cd  $0.3 \text{ mg}\cdot\text{kg}^{-1}$ , Cr  $200 \text{ mg}\cdot\text{kg}^{-1}$ , and Pb  $120 \text{ mg}\cdot\text{kg}^{-1}$ ), derived from Soil environmental quality – Risk control standard for soil contamination of land GB15618), the contents of the eight heavy metals in this study area were generally lower than the standard limits.

### RQI of Wanyu River

According to the related monitoring data for 2 years, *RQI* was used to analyze pollution and variation characteristics. Several sites, S1, S2, S13, and S14, showed significantly improved water quality from 2020 to 2021 (Fig. 3). Especially, the *RQI* value of S1 increased from 0 to 40 during the restoration period. The investigation results (Fig. 4) showed that Wanyu River quality impairment was due to nutrient enrichment (i.e., high COD and TP). All the polluted sites were caused by excessive nutrients (COD, TP, and  $\text{NH}_3\text{-N}$ ) in January 2020. Still, the critical variables responsible for river impairment in sampling sites with records suggest

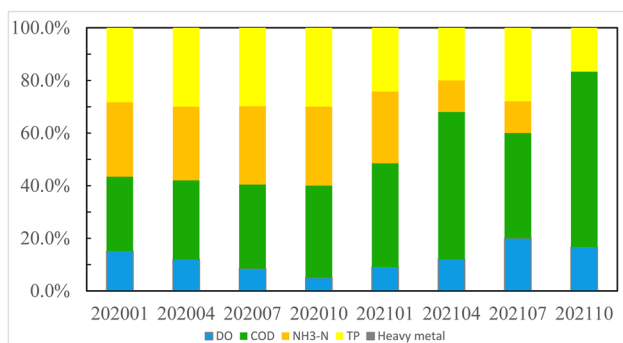
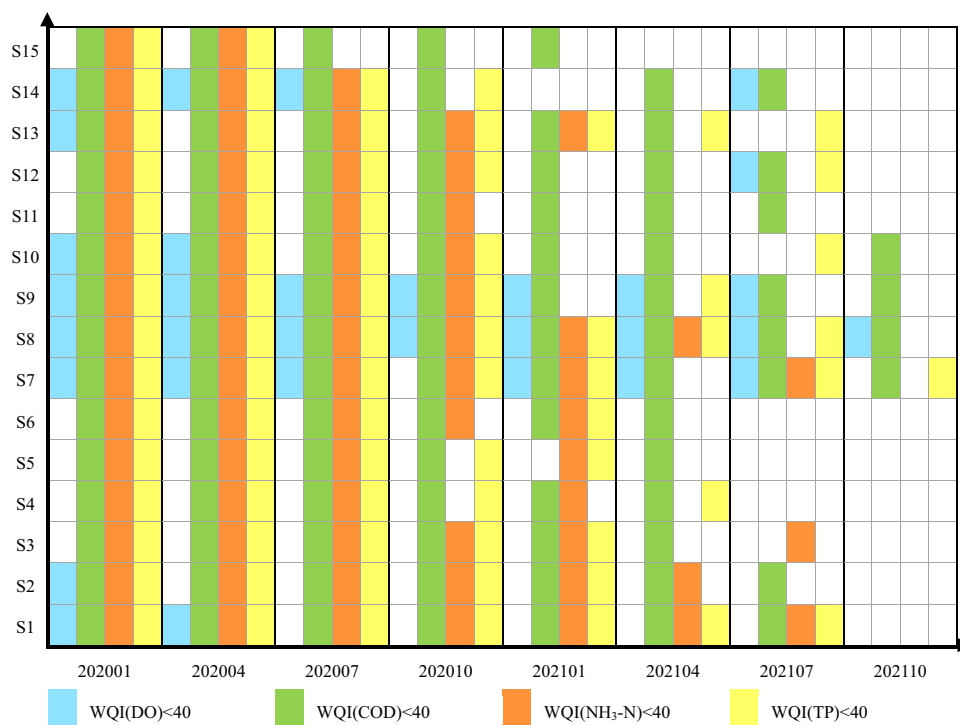
**Table 1** Environmental monitoring data of Wanyu River

		Water ( $\text{mg}\cdot\text{L}^{-1}$ )				Sediment ( $\text{mg}\cdot\text{kg}^{-1}$ )							
		DO	COD	$\text{NH}_3\text{-N}$	TP	Cu	Zn	Ni	As	Hg	Cd	Cr	Pb
2020	Average	4.59	12.97	1.57	0.31	45.87	101.28	31.58	7.77	0.08	0.05	89.98	50.56
	Max	6.85	16.33	2.14	0.43	56.55	123.44	36.77	11.89	0.11	0.08	109.68	62.37
	Min	1.67	9.57	1.16	0.23	31.93	84.37	26.46	4.21	0.03	0.01	72.89	41.73
2021	Average	4.96	10.53	1.11	0.24	38.41	85.26	29.63	6.47	0.07	0.04	78.32	40.68
	Max	6.82	13.43	1.58	0.34	46.22	105.78	33.90	9.89	0.09	0.07	88.08	49.33
	Min	3.08	7.76	0.48	0.17	30.17	60.76	26.09	3.82	0.03	0.01	64.31	27.99
Risk thresholds		2.00	15.00	2.00	0.40	100.00	250.00	100.00	30.00	2.40	0.30	200.00	120.00



**Fig. 3** Spatial and temporal information of *RQI* in Wanyu River during January, April, July, and October yearly from 2020 to 2021

**Fig. 4** Critical variables (The *RQI* of DO, COD, NH<sub>3</sub>-N, TP, and heavy metals were less than 40) responsible for impairment in Wanyu River during the 2020–2021 period



**Fig. 5** Contribution of critical variables to river quality impairment in Wanyu River during the 2020–2021 period

that nutrient enrichment has been alleviated from 2021. For example, 73.3% of the sampling sites showed moderate quality ( $RQI > 40$ ) in October 2021. However, the eutrophication was not fully eliminated, and the  $RQI$  of COD in four sites (S7, S8, S9, and S10) was less than 40, which showed poor water quality. Additionally, the study used the relative frequency that each variable resulted in negative  $RQI$  values to identify the most sensitive indicators of river quality impairment in the Wanyu River. The results (Fig. 5) revealed a decreasing contribution of variables, such as NH<sub>3</sub>-N and TP, but the increasing contributions of COD and DO to river water impairment. During the 2020–2021 period, the proportion of NH<sub>3</sub>-N decreased from 28.3 to 0%, and the proportion of TP decreased from 28.3 to 16.7%.

## Investigation of fish and hydrophytes

The results (Table 2 and Fig. 6) clearly showed the fish survey results (distributions, assemblage attributes, richness, and Shannon–Wiener Index) for each sampling site. In total, 31 fish species were recorded. The dominant species were *Cyprinus carpio*, *Carassius auratus*, *Ctenopharyngodon Idella*, and *Hypophthalmichthys molitrix*, which represented about 11.5%, 6.5%, 6.7%, and 4.7%, respectively, while *Lateolabrax maculatus* and *Pelteobagrus vachelli*, only represented less than 2%. Concerning the diversity of fish species, the river showed two distinct regions. The northeast region was characterized by broad high species diversity and Shannon–Wiener Index. In contrast, the southwest region showed a much lower species diversity, with many species occurring continuously in low abundance. For example, S1 and S2 showed the highest values of fish abundance, and the Shannon–Wiener Index of these two sites was 3.19 and 3.13, while S11 and S12 presented the lower values, and the Shannon–Wiener Index of these two sites were 2.78 and 2.84.

Our study showed some differences among sampling sites in the analyzed hydrophytes parameters (distributions, assemblage attributes, richness in Table 3, and Shannon–Wiener Index in Fig. 7). Along the Wanyu River, 16 aquatic plant species were found. And the dominant species were *Phragmites australis*, *Acorus calamus*, and *Typha orientalis*, which presented about 29.7%, 26.6%, and 15.4%, respectively, while *Hydrilla verticillata* and *Potamogeton*

**Table 2** Distributions, assemblage attributes, and richness of fish collected at each sampling site along Wanyu River

Fish species	Assemblage attributes	Sampling sites														
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Cypriniformes																
Cyprinidae	<i>Cyprinus carpio</i>	0.14	0.09	0.08	0.12	0.13	0.12	0.12	0.1	0.17	0.13	0.09	0.12	0.16	0.07	0.08
	<i>Carassius auratus</i>	0.08	0.02	0.10	0.07	0.07	0.05	0.04	0.06	0.08	0.08	0.09	0.05	0.07	0.10	0.11
	<i>Ctenopharyngodon idella</i>	0.05	0.05	0.08	0.06	0.04	0.07	0.07	0.11	0.12	0.11	0.09	0.06	0.05	0	0.05
	<i>Hypophthalmichthys molitrix</i>	0.05	0.03	0.05	0.05	0.05	0.05	0.03	0.05	0.04	0.08	0.06	0.02	0.04	0.06	0.05
	<i>Mylopharyngodon piceus</i>	0.03	0.01	0.05	0.02	0.06	0.01	0.05	0.04	0.01	0	0.04	0.06	0.04	0	0.05
	<i>Abbottina rivularis</i>	0.03	0.05	0.03	0.01	0.05	0	0.02	0.09	0.04	0.04	0	0.05	0.02	0.04	0
	<i>Gobio rivuloides</i>	0.01	0.07	0.04	0	0.02	0.04	0.04	0	0	0	0	0	0.03	0.08	0.04
	<i>Pseudorasbora parva</i>	0.02	0.03	0.02	0.05	0.03	0	0	0	0	0.06	0	0.05	0.01	0.09	0.05
	<i>Opsariichthys bidens</i>	0.03	0.02	0	0	0	0.01	0.04	0.04	0.07	0.03	0.05	0.02	0	0	0
	<i>Acheilognathus chankaensis</i>	0	0	0.05	0	0.05	0.06	0	0.06	0	0.04	0.10	0	0.03	0	0.02
	<i>Acheilognathus taenianalis</i>	0.03	0	0.03	0.04	0	0	0.02	0	0.03	0.02	0.05	0	0.01	0.07	0
	<i>Cultrichthys erythropterus</i>	0.02	0.03	0	0.01	0.05	0.07	0	0.03	0.04	0	0	0.06	0.03	0.07	0
	<i>Sarcocheilichthys nigripinnis</i>	0.04	0.07	0.04	0.04	0	0	0.06	0.01	0	0.02	0.01	0	0	0.04	0.03
	<i>Squalidus wolterstorffi</i>	0.03	0.01	0.04	0	0.05	0.01	0.01	0	0.02	0	0.03	0.05	0	0.04	0
	<i>Coreius heterodon</i>	0.03	0.03	0	0.03	0	0	0	0.04	0.03	0.04	0	0.02	0	0.03	0.02
	<i>Hemiculter leucisculus</i>	0.03	0.04	0.07	0.02	0.04	0	0.06	0.04	0.04	0.04	0.05	0	0.05	0	0.06
	<i>Squaliobarbus curriculus</i>	0.02	0.07	0.01	0	0.02	0	0	0.03	0	0.03	0.02	0.02	0.10	0.04	0.05
<i>Rhinogobio typus</i>	0.02	0.04	0.02	0	0	0.04	0	0	0.04	0	0	0.04	0.06	0.04	0	
<i>Parabramis pekinensis</i>	0.06	0	0.03	0.04	0.05	0	0	0	0	0.06	0	0.06	0	0	0.07	
<i>Squaliobarbus curriculus</i>	0.03	0	0	0.03	0.03	0.04	0.05	0.02	0	0.03	0.04	0	0.03	0.01	0	
Cobitidae	<i>Misgurnus anguillicaudatus</i>	0.01	0.04	0	0.03	0	0.04	0.04	0	0	0.02	0	0	0.03	0.01	0.03
Perciformes																
Serranidae	<i>Siniperca chuatsi</i>	0.03	0.04	0.05	0.06	0.04	0	0.02	0.01	0.04	0	0.06	0.09	0.03	0	0.06
	<i>Lateolabrax japonicus</i>	0.03	0.06	0.03	0.07	0.03	0.04	0	0	0	0.04	0	0.06	0	0	0.04
Moronidae	<i>Lateolabrax maculatus</i>	0.01	0	0	0	0	0	0	0	0.03	0	0	0	0.05	0.03	0
Channidae	<i>Channa argus</i>	0.03	0.01	0	0.03	0	0.07	0	0	0	0.03	0.04	0	0.05	0.08	0
Siluriformes																
Siluridae	<i>Silurus asotus</i>	0.03	0.03	0.05	0.06	0.03	0.04	0.07	0.05	0.03	0.06	0.07	0.08	0	0	0.05
Bagridae	<i>Pelteobagrus fulvidraco</i>	0	0.02	0	0.03	0.04	0.05	0	0.04	0.04	0	0.07	0	0	0.01	0
	<i>Pelteobagrus vachelli</i>	0.02	0.02	0	0	0.05	0.02	0.04	0	0	0	0	0.05	0.01	0	0
	<i>Leiocassis longirostris</i>	0.03	0.03	0.03	0.04	0	0	0	0	0.04	0.01	0.02	0	0	0.04	0.09
Anguilliformes																
Anguillidae	<i>Anguilla japonica</i>	0.03	0.03	0.03	0.04	0.02	0.12	0.08	0.02	0.04	0.03	0	0.06	0.04	0	0.01
Mugiliformes																
Mugilidae	<i>Mugil cephalus</i>	0.04	0.04	0.02	0.06	0.05	0.04	0.04	0.06	0.04	0	0	0	0.04	0.05	0.03
Fish richness		29	26	22	23	22	20	19	19	20	21	17	19	22	20	20

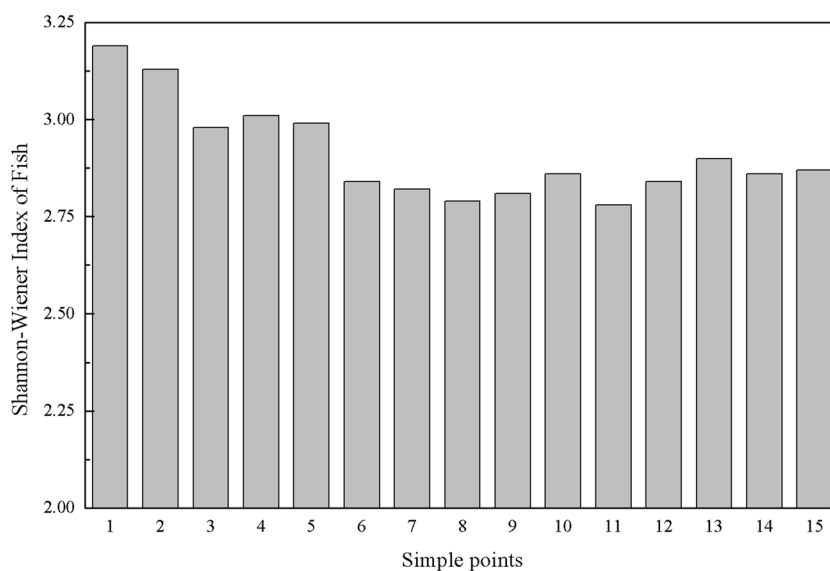
*distinctus* rarely occurred, which offered less than 10%. Regarding the abundance of hydrophyte species, the river showed little difference in distinct regions. The richness of hydrophytes in the Southwest region was slightly higher than that in the Northeast region. For example, S14 and S5 showed the highest values of hydrophyte abundance, and the Shannon–Wiener Index of these two sites was 2.33 and 2.37, while S1 and S1 presented relatively low values. The Shannon–Wiener Indexes of these two sites were 2.28 and 2.26.

### Discussion

Environmental degradation, food security, and climate change are significant challenges that face the developing country this century. Almost all the developing countries strive for the development of economy and agriculture, which has caused adverse environmental impacts (i.e., nutrient loading, algae pollution, and unreasonable carbon flux) and extensive degradation of the river ecosystem. The identification and control of the environmental contaminants



**Fig. 6** Shannon–Wiener Index of fish



generated by point sources (sewage discharges and industrial emissions) and non-point sources (urban runoff, livestock discharges, and agricultural fertilizer) pose many threats to the surface water ecosystem (Stephenson et al. 2010; Beristain et al. 2013). To alleviate the pressure exerted by pollution, many countries have taken remedial measures to restore their freshwater sources, such as the construction of wastewater treatment plants, dredging, artificial floating island, and replacement of management measures. During the restoration, many studies only focused on surface water health in general, like hydrology regime (Wu et al. 2015), water quality (Huang et al. 2019), and fish assemblages (Lamprey and Ofori-Danson 2014). Moreover, few studies had focused on the water quality, sediment and biodiversity simultaneously. Therefore, during the restoration of the Wanyu River, this study used the evaluation system (based on twelve environmental quality indicators and the diversity of aquatic organisms) to characterize the watershed quality.

### Improvement of the river environment

Since non-point source pollution from domestic sewage and agriculture was a critical source of nutrients in surface water, the environment of the Wanyu River had pollution problems before January 2020. Nitrogen, phosphorus, and organic matter in domestic sewage contributed to high levels of  $\text{NH}_3\text{-N}$ , TP, and COD. And unreasonable use of chemical fertilizers in agricultural production leads to excessive loading of nitrogen and phosphorus (Sun et al. 2020). Excess nutrients entering water bodies could alter the ecological balance, affecting the growth of aquatic organisms and reducing DO levels in the water. Therefore, the government was implementing restoration works on the Wanyu River from 2020. During the restoration period, the values of *RQI*

(Figs. 3 and 4) showed that the quality of the Wanyu River displayed significant spatio-temporal variation. Quarter *RQI* trends provide evidence of improved water quality in 15 sampling sites with long-term records (Fig. 3). The *RQI* of the Wanyu River showed an increasing trend during the 2020–2021 period, suggestive of a quality improvement. For example, 86.7% of the sampling sites showed bad river quality in January 2020, compared with 0% in October 2021. Suzhou City had made considerable progress in improving the environmental quality of the Wanyu River, especially in alleviating nutrient enrichment. Clear evidence for the conclusion was provided by the significant decline in the concentrations of both TP and  $\text{NH}_3\text{-N}$  (Table 1, Figs. 4 and 5). This change was mainly due to the restoration plans and considerable efforts in mitigating nutrient enrichment, especially the wastewater treatment plant and dredging work in 2020. The primary strategy to control water pollution was based on the construction of wastewater treatment plants (use the anoxic–oxic system to collect domestic sewage and avoid direct discharge of sewage around S6, S7, and S11) that can effectively remove the pollutants ( $\text{NH}_3\text{-N}$ , TP, and COD) from sewage. DO was an indicator factor for water pollution and aquatic biota. Temperature crucially affected the oxygen concentration, which was lower at higher temperatures in summer. From 2020 to 2021, the oxygen concentration in the river has increased, which means the river could provide more suitable environmental conditions for aquatic organisms. Moreover, dredging works reduced the nutrient loading from river sediments, and artificial floating islands along the river maintained the stability of the river ecosystem. Additionally, as the river was flowing, the ecological protection of the Yangtze River and Tai Lake was receiving increasing attention, and this was partly leading to an improvement of environmental quality in the Wanyu River.

**Table 3** Distributions, assemblage attributes, and richness of hydrophytes collected at each sampling site along Wanyu River

Hydrophyte species	Assemblage attributes	Sampling sites														
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Poaceae																
Phragmites	<i>Phragmites australis</i>	0.2	0.11	0.21	0.11	0.22	0.12	0.15	0.16	0.1	0.26	0.21	0.22	0.18	0.16	0.18
Araceae																
Acorus	<i>Acorus calamus</i>	0.13	0.03	0.21	0.16	0.14	0.12	0.11	0.16	0.18	0.28	0.19	0.09	0.13	0.09	0.11
Typhaceae																
Typha	<i>Typha orientalis</i>	0.06	0.03	0.04	0.06	0.04	0.06	0.11	0	0.06	0	0.14	0.09	0.03	0.11	0.07
Iridaceae																
Iris	<i>Iris pseudacorus</i>	0.07	0.08	0.07	0	0.06	0.22	0.09	0.1	0	0	0	0.11	0.1	0.09	0.14
Pontederiaceae																
Pontederia	<i>Pontederia cordata</i>	0.05	0	0	0.03	0	0.12	0	0	0	0	0	0.07	0.11	0	0.03
Eichhornia	<i>Eichhornia crassipes</i>	0	0.04	0.07	0.09	0	0.04	0	0.12	0	0.05	0	0	0.1	0.13	0.04
Marantaceae																
Thalia	<i>Thalia dealbata</i>	0.14	0.08	0	0.03	0.02	0.04	0	0	0.12	0.05	0.17	0.17	0.03	0	0.03
Nymphaeaceae																
Nelumbo	<i>Nelumbo nucifera</i>	0	0.03	0.01	0.04	0.08	0	0.07	0.04	0.06	0.07	0.12	0	0	0	0
Menyanthaceae																
Nymphoides	<i>Nymphoides peltatum</i>	0.08	0.09	0.08	0.1	0.06	0	0.04	0.12	0.12	0.09	0	0	0	0.03	0.08
Lemnaceae																
Lemna	<i>Lemna minor</i>	0	0	0	0.06	0	0.1	0.09	0.12	0	0.09	0	0	0.03	0.06	0
Potamogetonaceae																
Potamogeton	<i>Potamogeton crispus</i>	0.1	0.09	0.07	0.08	0.12	0.04	0.15	0	0	0	0	0	0.03	0.06	0.03
	<i>Potamogeton distinctus</i>	0	0	0.1	0	0.06	0	0	0	0.12	0	0	0.15	0.05	0	0
Ceratophyllaceae																
Ceratophyllum	<i>Ceratophyllum demersum</i>	0.07	0.24	0.06	0	0	0.06	0.13	0.06	0.06	0	0.05	0	0	0	0.04
Gramineae																
Hydrilla	<i>Hydrilla verticillata</i>	0	0	0.03	0.18	0.1	0	0.04	0	0	0	0.07	0	0	0.09	0.11
Cyperaceae																
Eleocharis	<i>Eleocharis tuberosa</i>	0.08	0.04	0	0	0	0.08	0	0.12	0.1	0.07	0.05	0.04	0.1	0.06	0.1
Alismataceae																
Sagittaria	<i>Sagittaria potamogetifolia</i>	0.03	0.14	0.04	0.08	0.12	0	0.02	0	0.06	0.05	0	0.07	0.1	0.11	0.03
Hydrophyte richness		11	12	12	12	11	11	11	9	10	9	8	9	12	11	13

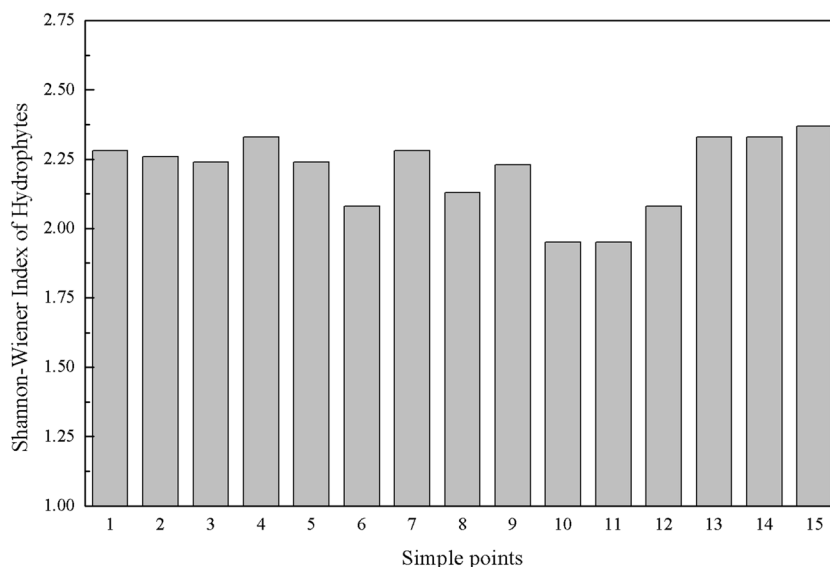
According to the study, all the *RQI* of eight heavy metals were higher than 80, which meant Wanyu River had no risk of heavy metal pollution in the past 2 years. This result was because there were no heavy industrial factories in the surrounding area, and human activities were relatively simple.

Characteristics of fish and hydrophytes.

This study showed that the Shannon–Wiener Indexes of fish and hydrophytes were generally higher than 2.0. Compared with the survey from Spellerberg and Peter (2003) and Lamptey and Ofori-Danson (2014), this result collectively offered an optimistic perspective regarding the habitat suitability for a diverse range of biotic communities. Fish assemblage structure changed with different sites, showing a relatively more straightforward design in the polluted area (S7 and S8), where few fish found suitable conditions for their establishment in degraded regions. Similar

to the results reported by Parker et al. (2018), our study showed that the species richness and diversity were lower in the sites after the domestic sewage plant. Also, since the upstream area was close to the estuary of the Yangtze River and diverse hydrological environments provided different habitats, the abundance and diversity of fish species in the upstream region were higher. Additionally, in contrast to the upstream area, the species diversity and many hydrophytes in the downstream area were higher (Fig. 7). The high species diversity and Shannon–Wiener Index of the hydrophytes in the region (S13, S14, and S15) of the Wanyu River were caused by the hydrological factors, such as the decreased flow velocity and larger riparian areas. Water flow changes the habitat, distribution, and abundance of aquatic communities. Flow velocity is one of the decisive factors of biological composition (Magoulick et al. 2021). The water

**Fig. 7** Shannon–Wiener Index of hydrophytes



flow velocity in the downstream area is slow, which is conducive to the rooting of hydrophytes.

#### Management recommendations.

Based on the variation of *RQI*, we found that the assessment framework of the river quality status revolved around extreme pollutant levels and had the advantage of tracking the actual changes in river quality directly but also connected with the ecosystem environment. The *RQI* values in 86.7% of the sampling sites were less than 20, which showed bad river quality at the beginning of 2020. The lower *RQI* values could reflect the influence of a suite of factors associated with environmental management, such as inefficient surface water management and underdeveloped sewers. Nutrient load reduction and ecological restoration are the most widely used remediation strategies to restore the damaged ecosystem. Building a wastewater treatment plant could reduce the amount of sewage pollution and thus significantly decrease the degree of nutrient loading from non-point sources. After 2 years, the river was eliminated as the sampling sites were of bad quality. The improvement reflected the government's efforts in building the municipal sewage treatment plant, dredging, using the artificial floating islands and other measures during the past 2 years. To optimize the broad impact of the ongoing development process, the government could establish a national initiative termed sponge cities as a comprehensive strategy, which combines creative technologies, effective governance, and sustainable development to promote harmony between humans and surrounding ecosystems. Although the river recovery had made significant progress, four sites in the midstream areas displayed low *RQI* values due to the relatively high COD concentration. Considering *S7* is closed to the sewage outlet of the treatment plant, the government could take practical

approaches, such as strict regulations and meticulous control of the sewerage plant, especially the improvement of effluent standards.

Another note of consideration was the recycling of sludge from river sediment. The interplay between water and sediment, such as flow regimes, adsorption, desorption, and microbial decomposition, can profoundly modulate the ambient levels of nutrients and heavy metals. In particular, sediment–water interfaces had been the focus of the nutrient cycling in rivers (Huang et al. 2021). Thus, according to the result that the Wanyu River had no risk of heavy metal pollution in the past 2 years, we could utilize sludge as garden soil and compost resource.

In the river ecosystem, where the external nutrient loading was the crucial factor that decided the nutrient enrichment, the control of non-point source pollution (e.g., agricultural and urban sources) was widely recognized as the most effective measure (Durand et al. 2015). We could control the pollution of urban domestic sewage by building treatment plants. However, we could not quantify the effect of fertilization on nutrient enrichment in river. The practical application of fertilizer was challenging to control in the process of actual cultivation. Thus, finding the method of rational fertilization was the key to restoration in the future.

Additionally, the dataset used includes twelve variables for monitoring samples but did not provide other information for the other contaminants, such as pesticides, antibiotics, and persistent organic pollutants. These contaminants lead to polluted bodies of water and health problems for consumers, especially the high risk for children and teenagers (Rrka et al. 2021; Zhao et al. 2021). Therefore, an assessment exercise with more environmental variables could present another spatiotemporal trend of river quality. And the concentration of persistent

organic pollutants in the river water might be concerning. Selling and using antibiotics and pesticides, especially the banned ones, should be more regulated.

## Conclusions

The establishment of a river evaluation system represented a critical step in advancing the restoration of the environment. The evaluation information could help us identify the characteristics of pollution and optimize the design of restoration practices. In 2020, the government released many plans and guidelines to ensure that the appropriate remedial measures were taken to improve the total environmental quality of the Wanyu River, especially to control phosphorus and nitrogen loading. Our results suggested that implementation measures successfully improved environment quality during the 2020–2021 period. Although the mitigation of eutrophication in the water had been successful, there was still some space for improving societal and ecological significance. Reduction of agricultural pollution, internal nutrient loading of sediment, and cost-effective restoration and evaluation represent significant challenges in our efforts to recover the river ecosystem. Hence, it is imperative to devise long-term management and conservation plans for ecological improvement focusing on sustainable livelihood. In the subsequent regulation of the river, the government could conduct continuous biomonitoring studies to account for temporal variability and ensure comprehensiveness.

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**Author contribution** Liu Jing designed and investigated the ecological environment of Wanyu River and completed the paper.

**Data Availability** The data that support the findings of this study are available from the corresponding author, upon reasonable request.

## Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interest** The author declares no competing interests.

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