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Construction and Application of a Water Quality Risk Sensitive Area Identification System in the Wudongde Reservoir

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Abstract: Numerous water quality risks exist during the initial water storage stage in reservoirs; however, little water quality data is available for this stage. Taking the Wudongde Reservoir as an example, we proposed a water quality risk sensitive area identification system for the initial impoundment stage comprising three modules: water quality assessment, water quality similarity clustering analysis, and sensitive area identification. Temporal and spatial variation in the water quality of the whole reservoir was analyzed, combined with a comprehensive evaluation using the Canadian Council of Ministers of the Environment Water Quality Index. A water quality similar clustering module was used to form similar clusters for monitoring sections in the reservoir area. The water quality risk sensitive areas were then identified and verified through a prototype test. The reservoir water quality was primarily excellent to good, although that of the Madian and Longchuan Rivers was poor. Through cluster analysis, the Madian River and tributaries of the Longchuan River were identified as sensitive areas, and the causes of water quality risk were analyzed. Based on these findings, we suggested focus areas for water environmental protection measures, providing a basis for the protection and restoration of the reservoir water environment.

Keywords: water quality risk; identification system; initial storage; large reservoir; Wudongde Reservoir

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1. Introduction

Most of the planet's major rivers have been dammed since the mid-20th century, when global dam construction reached a high point due to increased hydropower use [1], and reservoirs play a significant strategic role in sustainable energy supply. However, most reservoirs face water degradation owing to pollutants from catchment areas inside the reservoirs [2] and water residence time extension [3].

Water quality degradation not only damages human health but also destroys the ecological environment. Thus, ensuring the safety of water quality is crucial to maintain a balance between human health and ecology [4].

There are two stages from the completion of construction to the normal storage operation of a reservoir: initial storage and periodic storage. From the start of reservoir filling, the water quality will change to different degrees; if the water quality deteriorates, it may affect the health of the surrounding people. This phenomenon has been extensively studied by scholars worldwide, including research on the influence of seasons on water quality parameters, evaluation of water quality monitoring index selection, and water quality evaluation methods.

In terms of the influence of time on water quality parameters, Mishra et al. [5] examined the variation of water quality parameters of the Bidoli Reservoir in India between three different seasons (summer, monsoon, and winter). Fábio et al. [6] analyzed abiotic variables and seasonal variation in water quality in a tropical shall eutrophic reservoir in Recife in northeastern Brazil. In selecting and evaluating water quality monitoring indicators, Soares et al. [7] used multivariable and nonparametric statistical tests to analyze surface water quality in the Vargem das Flores reservoir in Brazil and to evaluate 5415 data items and eight water quality parameters from monitoring stations from 2002 to 2018. Tchounwou and Warren [8] tested the basic physical and chemical parameters of water and evaluated the Ross Barnett Reservoir in the United States using physical and biological assessment methods. Palma et al. [9] found 25 pesticides and several degradation products in the surface water of the Alqueva reservoir in Portugal and conducted risk assessment on the reservoir. Shutiwat et al. [10] calculated the hazard quotient to assess environmental risk by monitoring Mn, Cu, Fe, and other indicators in the Lam Takhong Reservoir in Thailand.

In terms of water quality assessment methods, Pérez et al. [4] used an ecotoxicology test battery to identify the potential toxicity of the Alqueva reservoir water in Portugal. Zotou et al. [11] examined seven different water quality indices (WQIs) using long-term water quality monitoring data from the Polyphytos Reservoir in Greece and found significant variation between the classification results from the different indices. Sunardi et al. [2] assessed the degree of water degradation based on the degree of corrosion of the Cirata Reservoir in Indonesia and examined the impact of this degradation on the hydropower capacity and operation of the reservoir. Habtemariam et al. [12] evaluated the drinking water source of the Legedadi Reservoir in Ethiopia by analyzing collected microcystin samples. Jeznach et al. [13] proposed a framework using hydrodynamic and water quality models to understand the fate and transport of potential pollutants in reservoirs and to develop appropriate emergency response and remedial action, using the Wachusett Reservoir in the United States as an example. Qin et al. [14] combined a principal component/factor analyzation-multiple linear regression model with a Bayesian network to identify water pollution sources and assess water quality risk under different precipitation conditions for the Biliuhe River reservoir. Their findings provide an effective framework for water quality management during the flood season.

Hydrological changes in the process of reservoir impounding are key factors affecting water quality [15]. The Three Gorges Reservoir is a typical example of such changes. The construction of the dam disrupted the continuity of the river, raising the water level, reducing the flow rate, and increasing the deposition time of pollutants [16,17]. Changes in the hydrological regime increase the residence time of pollutants, weaken the self-purification capacity of rivers, and increase the pollution load [18,19]. Therefore, the hydrological regime, flow dynamics, and pollutant load should be considered simultaneously in the analysis of water quality change; however, the coupling of these factors has often been ignored in previous studies. Research on water quality risk assessment has mostly been performed during the later operation stage in storage [20–23], with studies conducted in response to identified water quality problems for which monitoring data is readily available. However, there are few studies on water quality problems that may occur in the initial stage of impoundment, and the lack of monitoring data is a challenge in carrying out research during this stage.

There are potential, sudden, and uncertain water quality risks during the initial stage of water storage that cannot be ignored because of changes in the relative position of pollution sources and water bodies and the inundation of soil samples during the impoundment process, especially for extremely large reservoirs. To reduce the water quality risk during initial reservoir impoundment, it is necessary to establish a water quality risk assessment system for this stage and improve water quality management throughout the reservoir impoundment process. Therefore, using the Wudongde Reservoir of the Jinsha River as an example, this study proposed a set of water quality risk sensitive area identification systems aimed at the initial stage of water storage. Based on water quality monitoring and assessment before impoundment, an in situ reservoir impoundment test was conducted to further analyze water quality changes in the monitored sections during impoundment. In addition, cluster analysis was used to identify and classify sensitive areas for water quality. Finally, we suggested risk prevention measures according to the risk levels. The results of this study will provide a framework for water quality risk assessment during the initial impoundment process in reservoirs, aiding in the mitigation of potential negative health impacts on the surrounding population due to water quality degradation.

2. Materials and Methods

2.1. Study Area

The Jinsha River is an important part of the upper reaches of the Yangtze River. It originates from the southern glacier of Geladan Snow Mountain in the middle section of the Tanggula Mountains [24]. The right bank of the Wudongde dam site belongs to Luquan County in the Yunnan Province, and the left bank belongs to Huidong County in the Sichuan Province. The dam site is located 213.9 km below Panzhihua City, 182.5 km above the Baihetan hydropower station, and 125 km and 470 km from Kunming and Chengdu, respectively [25]. Owing to the construction and storage of the Wudongde hydropower station, a reservoir tail return belt was formed in the Panzhihua section of the Jinsha River [26]. The annual average precipitation at the Wudongde hydropower station site is 825 mm (Qiaojia), mainly distributed from June to October, accounting for 81% of the annual precipitation. The Jinsha River valley area is hot and dry, with a long summer and almost no winter [27]. As the Wudongde reservoir is located in this valley, the annual average evaporation from the water surface (E601) is 2593 mm, while that from the land surface in the reservoir area is 698 mm. The average annual runoff is 3850 m^3/s.

With a total installed capacity of 10.2 million kilowatts, the Wudongde hydropower station is the fourth largest hydropower station in China and the seventh largest hydropower station in the world [28]. The Wudongde hydropower station is the furthest upstream of the four hydropower steps of Wudongde, Baihetan, Xiluodu, and Xiangjiaba in the lower reaches of the Jinsha River (from Panzhihua City to Yibin City). It is a hydropower station project focusing on power generation, considering the comprehensive benefits of flood control, sand containment, and navigation [29]. The dam is a concrete hyperbolic arch dam with a parabolic shape. The elevation of the riverbed foundation plane is 718 m, the elevation of the dam top is 988 m, the maximum dam height is 270 m, the minimum thickness of the dam top is 11.98 m, and the maximum width of the dam top is 49 m. The Wudongde Dam was completed in July 2020. After the completion of the Wudongde reservoir, it will share the flood control task in the middle and lower reaches of the Yangtze River with the Three Gorges Reservoir, reduce the sedimentation in the lower reservoirs, and play a positive role in prolongating the service life of the Baihetan, Xiluodu, Xiangjiaba, and Three Gorges Reservoirs [30]. However, with the completion of the dam, the ecological characteristics of the upstream water changed from a natural river ecosystem to an artificial lake ecosystem [31]. Changes due to impoundment are associated with numerous environmental problems, including hydrodynamic changes [32], continuous deterioration of water quality [31,33], and destruction of habitats [34].

In the Wudongde Reservoir, a total of 18 water quality sampling sections were selected from upstream to downstream (Figure 1), including Luoguo Bridge, Yalong River, Sanduizi, Jinjiang Water Intake, Vanadium Titanium Industrial Park, Madian River, 0.5 km downstream of Madian River, 1 km downstream of Madian River, 3 km downstream of Madian River, Lazha, Shizhuang, Longchuan River, 1 km downstream of Longchuan River, Mengguo River, Chen River, Shenyu River, upriver from the Wudongde Dam, and downstream of the Wudongde Dam.

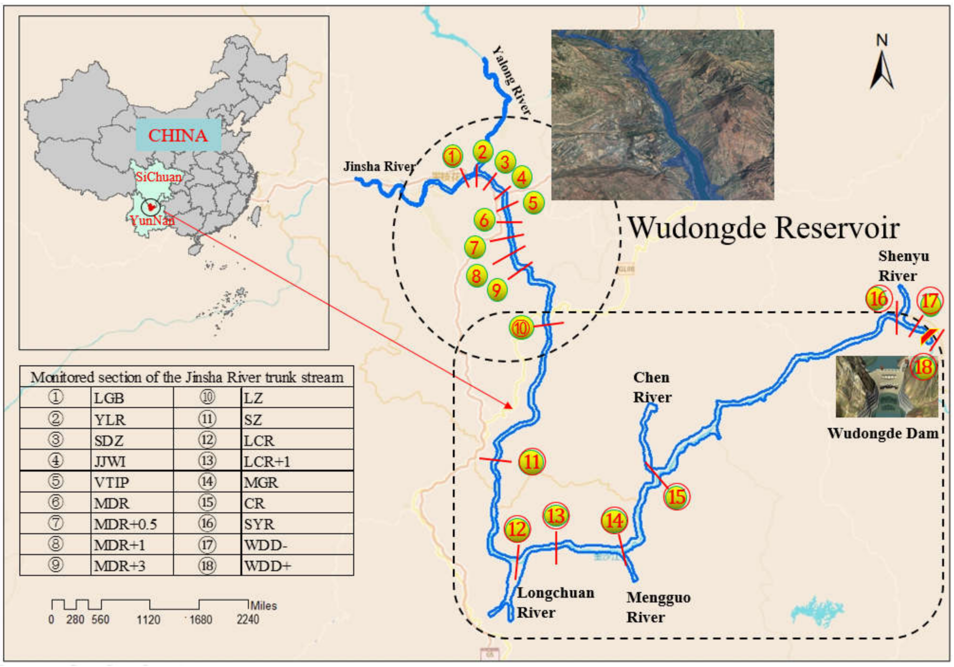


Figure 1. Layout of the monitored section of the main stream in the Wudongde Reservoir. Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; Jinjiang Water Intake, JJWI; Vanadium Titanium Industrial Park, VTIP; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; Lazha, LZ; Shizhuang, SZ; Longchuan River, LCR; 1 km downstream of Longchuan River, LCR + 1; Mengguo River, MGR; Chen River, CR; Shenyu River, SYR; upriver from the Wudongde Dam, WDD-; downstream of the Wudongde Dam, WDD+.

2.2. Sampling and Data Sources

We arranged the vertical lines and sampling points in the monitoring section according to the requirements of "Technical Specifications Requirements for Monitoring Surface Water and Waste Water" (HJ/T91-2002) [35]: three vertical lines on the left, middle, and right, and three sampling points on each vertical line. According to the Water and Wastewater Monitoring and Analysis Method (Fourth Edition), from 2016 to 2021, three water samples (left, middle, and right) were collected in 1 L plastic bottles (three vials per sample) every month and brought back to the laboratory for testing water quality indicators. The parameters and their determination methods are listed in Table 1. Hydrological data were obtained from the Hydrology Bureau of the Yangtze River Water Resources Commission. Pollution load data for 2016–2021 were obtained from the Ministry of Environmental Protection, PRC [36].

The water quality parameters (water temperature and pH), oxygenation parameters (dissolved oxygen, chemical oxygen demand, and biological oxygen demand), nutrient parameters (ammonium-*N*, total nitrogen, and total phosphorus), and photosynthetic pigment content (chlorophyll a) were investigated to monitor the water quality of the Wudongde Reservoir.

Samples were collected from three points below the water surface (0.5 m below the water surface, 0.5 times the depth of the water, and 0.5 m above the river bottom). Water temperature, pH, and dissolved oxygen (DO) were measured on-site at sampling locations using portable electronic instruments (Hach HQ40d™ multi-parameter pH/oximeter (Hach Company, Loveland, CO, USA) and YSI 550A (YSI Inc., Yellow Springs, OH, USA)). Water samples for ammonia nitrogen, nitrate nitrogen, total nitrogen (TN), and total phosphorus (TP) were measured using an DR3900 spectrophotometer (Hach Company, Loveland, CO, USA). The chemical oxygen demand (COD) was analyzed using to the dichromate method. Biological oxygen demand (BOD_5) was analyzed using to the dilution and seeding method. The chlorophyll a concentration was determined spectrophotometrically. All samples were analyzed within the specified time after collection in the Laboratory of Water Environment, China Institute of Water Resources and Hydropower Research. According to government regulations, the water quality of the Wudongde Reservoir should not be worse than that of type III water quality.

2.3. Data Analysis and Water Quality Assessment Methods

2.3.1. Mann–Kendall (MK) Test

The Mann–Kendall trend test is a nonparametric statistical test recommended by the World Meteorological Organization. This method has many advantages, such as a high quantization degree, wide detection range, and convenient calculation, which does not require samples to obey a certain distribution and is not disturbed by a few abnormal values. This non-parametric statistical test can effectively distinguish whether a natural process is in a state of natural fluctuation and whether there is a specific direction trend. Therefore, it has been be widely used to analyze the trends of hydrological series [37,38]. In this study, MATLAB 2019 (The MathWorks Inc., Natick, MA, USA) was used to conduct an MK test to illustrate the time variation trend of water quality parameters in the Wudongde Reservoir.

2.3.2. Canadian Council of Ministers of the Environment Water Quality Index

There are many water quality evaluation methods at home and abroad, among which National Sanitation Foundation Water Quality Index (NSFWQI) [39], Oregon Water Quality Index (OWQI) [40], and Canadian Council of Ministers of the Environment Water Qaulity Index (CCME-WQI) [41] are widely used.

Lumb A. et al. [42] compared and analyzed the evaluation results of the NSFWQI, the OWQI, and the CCME-WQI by using water quality monitoring data of Ontario Lake in Canada. The results show that the CCME WQI is stricter than the NSFWQI and OWQI in grading and classification.

Therefore, the CCME-WQI was selected as the evaluation method to comprehensively evaluate the water quality of Wudongde Reservoir in combination with the China Surface Water Environmental Standard.

Class III of the China Surface Water Environmental Standard (GB3838-2002) [43] was applied in this study to calculate the CCME-WQI of water quality in the Wudongde Reservoir. Table 1 lists the class III criteria, and detailed procedures for calculating the relevant water quality indicators are shown in previous research literature [44,45]. The CCME-WQI values range from 0 to 100, and the corresponding water quality is mainly classified into five categories: excellent (95–100), good (80–94), fair (65–79), marginal (45–64), and poor (0–44).

Table 1. Parameters; their corresponding abbreviations, units, and standard values for China Environmental Quality Standard for Surface Water (GB3838-2002) Class III [43]; and determination methods.

Parameters	Abbreviation	Units	GB Class III Standard Value	Method
pH	pH		6–9	GB6920-86
Dissolved oxygen	DO	mg/L	≥5	GB11913-89
Potassium permanganate index	COD_{Mn}	mg/L	≤6	GB11892-89
Five-day biochemical oxygen demand	BOD_5	mg/L	≤4	GB7488-87
Ammonia nitrogen content index	NH_3-N	mg/L	≤1	GB7479-87
Total nitrogen	TN	mg/L	≤1	GB11894-89
Total phosphorus	TP	mg/L	≤0.05	GB11893-89
Fecal *Escherichia coli*	Fecal *E. coli*	A/L	≤10,000	Water and wastewater monitoring and analysis methods (fourth edition), MEP, 2012
Water temperature	WT	°C		GB13195-91

2.3.3. K-Means Clustering Algorithm

K-means clustering analysis was used to group the sampling points with similar water quality characteristics during the water level period. Wong J.A. and Wong M.A. [46] described this algorithm in detail. The data used in the present study were pre-standardized, and k-means were used for cluster number and calculation in SPSS Statistics 25 (IBM, Armonk, NY, USA).

2.4. Identification System Framework for Determining Sensitive Areas of the Wudongde Reservoir

The proposed sensitive area identification scheme combined the overall water quality evaluation of the reservoir with the water quality evaluation of the local sections, used the clustering method to cluster the sections with similar water quality changes, and analyzed the sensitive areas according to the clustering results. The sensitive area was presented according to the sensitive area identification scheme recognition framework, which included three modules (as shown in Figure 2). Module I was the reservoir overall assessment module, emphasized from the perspective of the whole reservoir. This module analyzed how each water quality index success rate compares with the class III standard (Table 1), using the CCME-WQI to evaluate the overall water quality. Module II was mainly used to complete the cluster analysis of the original sections and find the section groups with similar water quality characteristics. In module III, a prototype experiment was conducted to verify the water quality in the sensitive areas and analyze and investigate the causes of water quality risks in these areas.

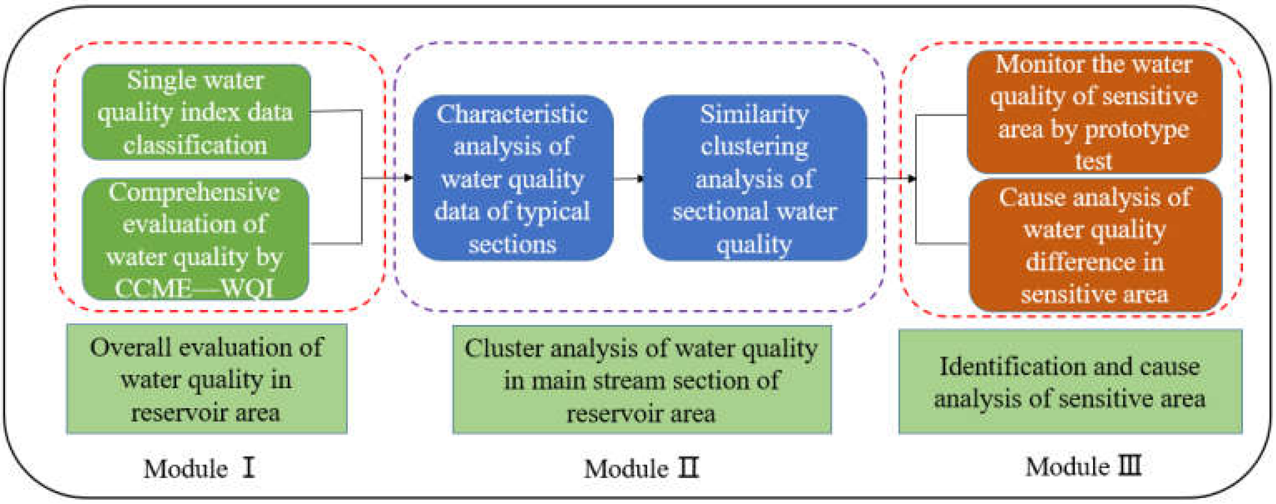


Figure 2. Frame diagram of identification of sensitive areas in relation to water quality concerns. CCME-WQI, Canadian Council of Ministers of the Environment Water Quality Index.

Based on the analysis of the characteristics of water quality change, the framework aimed to identify sensitive areas and analyze the causes of the reduced water quality in these areas, find the key points of water quality deterioration in the reservoir area, and provide a basis for determining future research goals.

3. Results and Discussion

3.1. Comprehensive Assessment of Water Quality in the Whole Reservoir Area

3.1.1. Single Water Quality Index Data Classification in the Whole Reservoir Area

The water quality monitoring indices for the Wudongde Reservoir area included the potassium permanganate index (COD_{Mn}), five-day biochemical oxygen demand (BOD_5), ammonia nitrogen content index (NH_3-N), TN, TP, and fecal *Escherichia coli*. The monitoring cross-section data for all indicators in the Wudongde Reservoir area from 2016 to 2020 were classified according to the classification method of the China Surface Water Environmental

Quality Standard (GB3838-2002) (as shown in Figure 3). The proportions of the monitoring data varied between the indicators, as shown in Table 2. For COD_{Mn}, BOD_5, and NH_3-N, 2.54%, 3.38%, and 6.04% of the monitoring data were lower than the class II standard, and 92.87%, 94.84%, and 93.71% of the monitoring data were within the class I–II standard, respectively. The amount of monitoring data for TP and TN that was lower than the class III standard was slightly higher than that for the previous three indicators, accounting for 26.18% and 18.87% of the data, respectively. Fecal *E. coli* had the highest amount of data below the class III standard, with 49.67% below the standard.

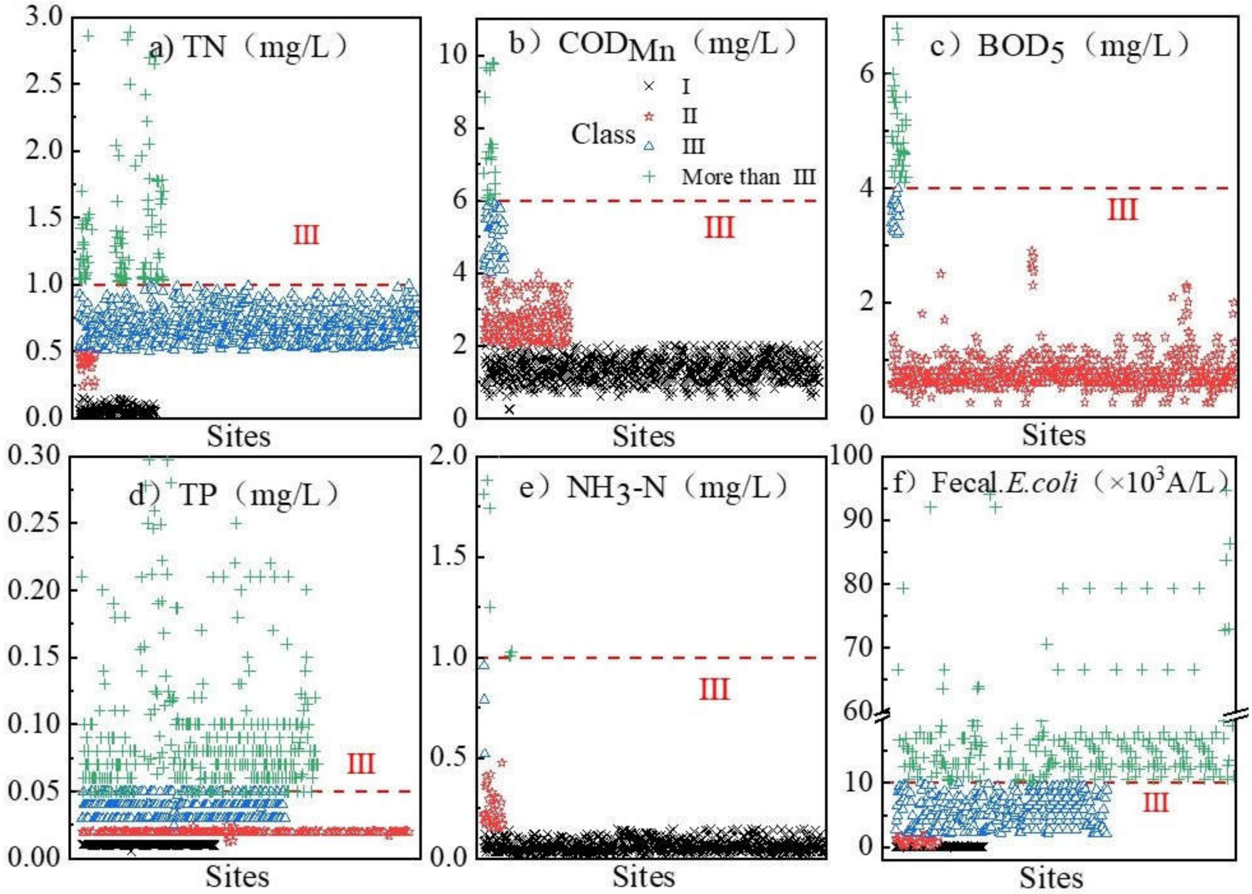


Figure 3. (**a**) TN, total nitrogen; (**b**) COD_{Mn}, potassium permanganate index; (**c**) BOD_5, five-day biochemical oxygen demand; (**d**) TP, total phosphorus; (**e**) NH_3-N, ammonia nitrogen content index; (**f**) Fecal *E.coli*, fecal *Escherichia coli*. Classification of water quality parameters of the Wudongde main stream between 2016 and 2020 based on the China Environmental Quality Standard for Surface Water (MEP, 2002) [43]. The Class III standard for surface water is marked with a red dotted line.

Table 2. Proportion of water quality indicator monitoring data within the different classes of China Surface Water Environmental Standards (%).

	I	II	III	More than III
COD_{Mn}	74.02%	18.85%	4.59%	2.54%
BOD_5	0.00%	94.84%	1.78%	3.38%
NH_3-N	89.55%	4.16%	0.24%	6.04%
TP	14.76%	36.43%	22.62%	26.18%
TN	1.66%	3.64%	75.83%	18.87%
Fecal *Escherichia coli*	12.91%	6.41%	31.01%	49.67%

COD_{Mn}, potassium permanganate index; BOD_5, five-day biochemical oxygen demand; NH_3-N, ammonia nitrogen content index; TP, total phosphorus; TN, total nitrogen.

Overall, except for fecal *E. coli*, most of the indicator values were above the class III standard (as shown in Figure 3). However, for TP and fecal *E. coli*, the data below the class III standard accounted for a large proportion of the monitoring data. Thus, although the level of a single water quality index in the entire reservoir area may be known, the evaluation level of different indices varies to some extent, and the comprehensive water quality status cannot be reflected using only a single indicator.

3.1.2. Comprehensive Evaluation of Water Quality by CCME-WQI

The annual CCME-WQI of 18 monitoring sections in the Wudongde Reservoir area was calculated using water quality monitoring data from 2016 to 2020, and Origin 18 was used to draw a heat map (Figure 4). The CCME-WQI values were above 80 for most of the spatial and temporal distribution, meaning that the water quality was at excellent to good levels. However, the CCME-WQI values for the MDR section were consistently below 79, remaining in a medium deviation state.

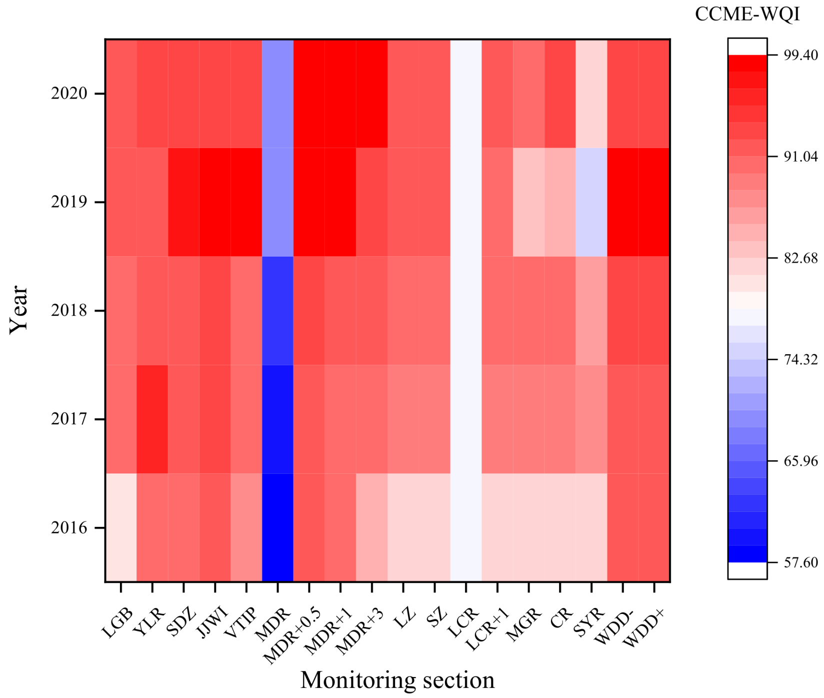


Figure 4. Spatial and temporal variation in Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) values in the Wudongde Dam from 2016 to 2020. Excellent (95–100), good (80–94), fair (65–79), marginal (45–64), and poor (0–44). Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; Jinjiang Water Intake, JJWI; Vanadium Titanium Industrial Park, VTIP; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; Lazha, LZ; Shizhuang, SZ; Longchuan River, LCR; 1 km downstream of Longchuan River, LCR + 1; Mengguo River, MGR; Chen River, CR; Shenyu River, SYR; upriver from the Wudongde Dam, WDD-; downstream of the Wudongde Dam, WDD+.

According to the time series analysis, from 2016 to 2020, the entire reservoir area exhibited a positive trend. In 2016, the sections of water quality below the medium level accounted for 50% of all sections, while in 2020, the sections of water quality below the medium level accounted for only 16.7%. This change has a strong relationship with the transformation of environmental protection measures in the entire reservoir area during the construction of the Wudongde hydropower station.

The water quality of the MDR, LCR, and their tributaries are worth noting. The reason for the poor water quality of the MCR lies in the sewage discharge of the Madian River sewage outlet. Owing to the requirements of environmental protection, the water quality discharged to the Jinsha River after the completion of the sewage treatment plant has improved as a whole, and the water quality has gradually improved.

The water quality of the LCR remained relatively stable at a medium state from 2016 to 2020. The Longchuan River is located in a subtropical zone and can grow double crops. The Longchuan River Basin has a total area of 92 km^2. With rapid economic development, land use types have changed, with the proportion of dry land decreasing from 13.47% in 2017 to 10.55% in 2020, and the proportion of paddy land increasing from 8.74% in 2017 to 8.76% in 2020 (as shown in Figure 5). There has been little change in cultivated land, but the annual use of nitrogen and phosphorus fertilizers in paddy fields increases non-point source pollution, resulting in a high nutrient content in water bodies.

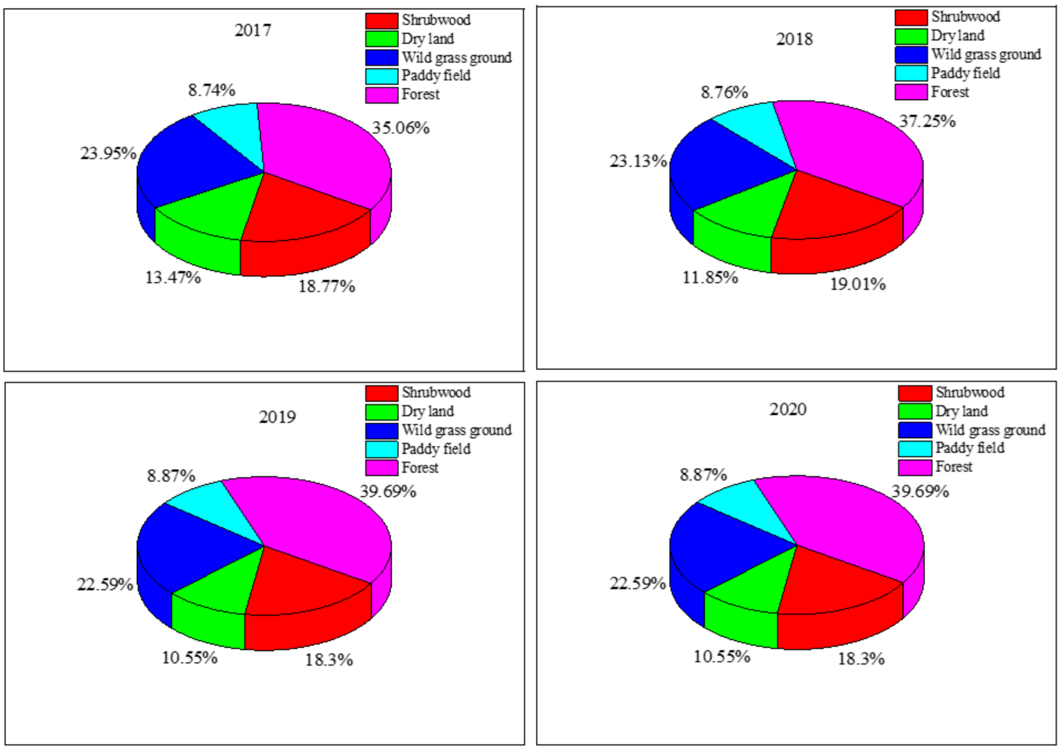


Figure 5. Proportion of land types in the Longchuan river basin.

The water quality of the Mengguo, Chen, and Shenyu Rivers fluctuated considerably, generally above medium levels. This is due to the discharge of wastewater by rural enterprises in the tributaries. The Shenyu River receives pollutants from Huili and Huidong Counties, the Chen River receives pollutants from Huili County, and the Mengguo River receives pollutants from Wuding County. The water quality of the tributaries fluctuates due to the irregular discharge of domestic and industrial sewage in the sewage collection area, the lack of environmental protection facilities, and changes in hydrological and climatic factors.

3.2. Cluster Analysis of Water Quality in the Main Stream Section of the Reservoir Area

3.2.1. Characteristic Analysis of Water Quality Data of Typical Sections

According to the data analysis results shown in Figure 6, from 2016 to 2020, the average values of COD_{Mn}, BOD_5, NH_3-N, TN, and TP were the highest in the Madian River section, at 6.73, 4.01, 4.63, 13.93, and 0.45 mg/L, respectively. Longchuan River followed with 2.9, 1.08, 0.12, 4.16, and 0.13 mg/L, respectively. In the other monitoring sections, the average values of each index were essentially the same without much change. The fecal *E. coli* index in the Madian River was 30.94 ($\times 10^3$ A/L). However, the average values for Luoguo Bridge, Lazha, Shizhuang, 1 km downstream of Longchuan River, Mengguo River, Chen

River, and Shenyu River were approximately 18.91 ($\times 10^3$ A/L) for fecal *E. coli*, with little difference between the sections.

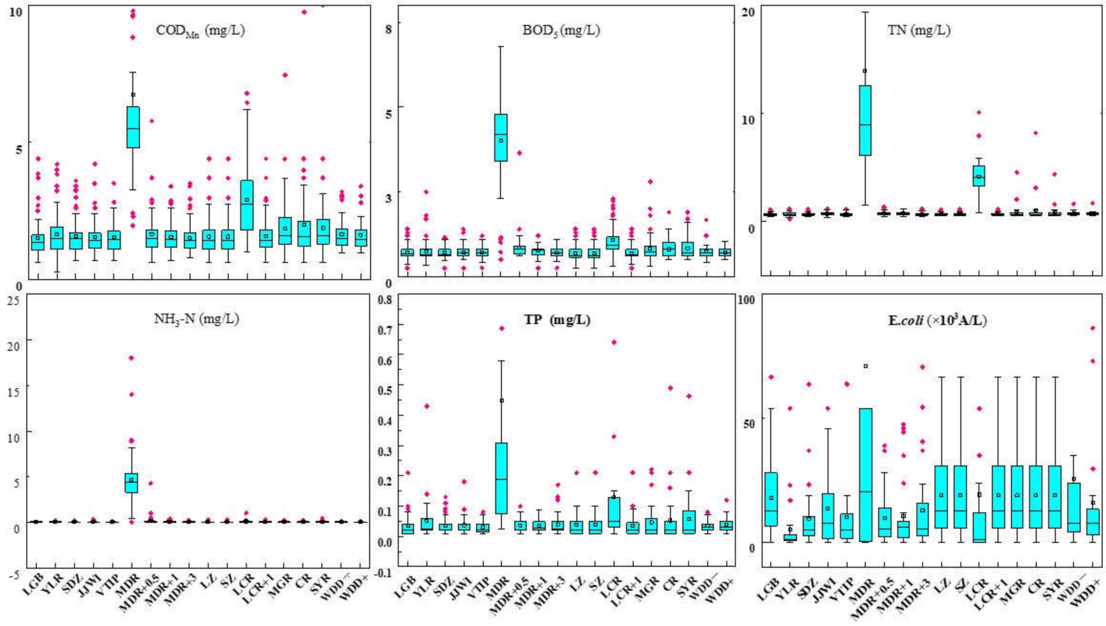


Figure 6. Water quality parameters at each sampling site from 2016 to 2020. Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; Jinjiang Water Intake, JJWI; Vanadium Titanium Industrial Park, VTIP; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; Lazha, LZ; Shizhuang, SZ; Longchuan River, LCR; 1 km downstream of Longchuan River, LCR + 1; Mengguo River, MGR; Chen River, CR; Shenyu River, SYR; upriver from the Wudongde Dam, WDD-; downstream of the Wudongde Dam, WDD +.

Before the construction of the Madian River sewage treatment plant, the sewage discharge was mainly industrial wastewater. Under the premise of environmental protection measures, the total amount of sewage discharged annually is 21.9 million tons per year, among which COD_{Mn}, NH_3-N, TP, TN comprise 1095, 109.5, 2.6, and 212.4 tons per year. The Madian River section is where the sewage outlet is located. Thus, the higher values of each pollutant compared with those in the other sections is likely related to sewage discharge. The higher index of the Longchuan River is likely related to the use of pesticides and nitrogen and phosphorus fertilizers in the farming process of upstream farmland. High levels of *E. coli* and untreated urban sewage were directly related to discharge. Restricted by the geographical location of the urban core area, sewage outlet, and tributaries, urban domestic sewage is directly discharged into rivers, which is the main reason for the high standard of fecal *E. coli*.

3.2.2. Similarity Clustering Analysis of Water Quality in Typical Sections

As shown in the cluster analysis (Tables 3 and 4), during the early stage of water storage (2016–2019), in 2016, the Madian River belonged to the first category, Yalong River, Sanduizi, Jinjiang Huikou, Vanadium, and Titanium Industrial Park belonged to the second category, and the other sections belonged to the third and fourth categories. In 2017, the Madian River belonged to the first category, the sections along the Yalong River, Sanduizi, and Madian River belonged to the second category, and the rest belonged to the third and fourth categories. In 2018, the Madian River belonged to the first category, 1 and 3 km downstream of the Madian River and sections in front of and behind Wudongde Dam belonged to the second category, and the rest belonged to the third and fourth categories. In 2019, the Madian and Longchuan Rivers belonged to the first category, Jinjiang Huikou and sections near the Madian River belonged to the second category, and the other sections belonged to the third and fourth categories. However, in the experimental stage of water storage (2020–2021), all sections from Vanadium and Titanium Industrial Park to Shizhuang in 2020 belonged to the first category, and the remaining sections belonged to the second, third, and fourth categories.

Table 3. Cluster analysis of each monitoring section in the Wudongde Reservoir area from 2016 to 2021.

Monitoring Section	Before Impoundment				First Impoundment Stage	
	2016	2017	2018	2019	2020	2021
LGB	■	■	■	■	▲	▲
YLR	•	•	■	■	▲	■
SDZ	•	•	▲	▲	■	▲
JJWI	•	■	▲	•	■	–
VTIP	•	■	▲	▲	★	–
MDR	★	★	★	★	★	★
MDR + 0.5	•	•	▲	•	★	•
MDR + 1	•	•	•	▲	★	•
MDR + 3	•	■	•	•	★	•
LZ	■	■	■	■	★	▲
SZ	■	■	■	■	★	–
LCR	▲	■	▲	★	■	–
LCR + 1	■	■	■	■	•	–
MGR	■	■	■	■	•	–
CR	■	■	■	■	•	–
SYR	■	■	■	■	■	–
WDD-	■	▲	•	▲	■	–
WDD+	•	▲	•	▲	■	–

First category: ★ second category: • third category: ■ Fourth category: ▲. Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; Jinjiang Water Intake, JJWI; Vanadium Titanium Industrial Park, VTIP; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; La Zha, LZ; Shi Zhuang, SZ; Longchuan River, LCR; 1 km downstream of Longchuan River, LCR + 1; Meng Guo River, MGR; Chen River, CR; Shen Yu River, SYR; upriver from the Wudongde Dam, WDD-; downstream of the Wudongde Dam, WDD+.

Table 4. Water quality clustering and monitoring indicators in the Wudongde Reservoir from 2016 to 2021.

	Cluster Analysis			
	1 (★)	2 (•)	3 (■)	4 (▲)
DO (mg/L)	7.46	8.82	8.92	8.98
COD_{Mn} (mg/L)	4.48	2.13	1.93	1.55
BOD_5 (mg/L)	2.34	0.89	0.8	0.73
NH_3-N (mg/L)	2.23	0.07	0.06	0.06
TN (mg/L)	3.26	1.57	1.42	0.7
TP (mg/L)	0.15	0.05	0.04	0.03
Escherichia coli (A/L)	13,943.36	15,757.01	9932.91	7247.65
pH	7.78	8.1	8.04	8.05

First category: ★ second category: • third category: ■ Fourth category: ▲. Luoguo Bridge, DO, dissolved oxygen; COD_{Mn}, potassium permanganate index; BOD_5, five-day biochemical oxygen demand; NH_3-N, ammonia nitrogen content index; TP, total phosphorus; TN, total nitrogen.

In whole cluster analysis, the different clusters of each section are beneficial to the analysis of the differences in water quality in different regions. With the beginning of water storage, the water quality gap around the Madian River became increasingly smaller, and all sections from Vanadium and Titanium Industrial Park to Shizhuang could be grouped into one category, which indicates that water storage reduced the difference between the sections around the Madian River. Based on the results of the cluster analysis, the area around the Madian River could be considered as the focus of research in the later stage.

3.3. Water Quality Monitoring of Sensitive Areas Using a Prototype Test

Based on a comprehensive assessment of the entire reservoir area of the Wudongde Reservoir and the water quality monitoring data of 18 sections from 2016 to 2020, a similarity cluster analysis of the water quality of typical sections was conducted. It was preliminarily determined that the Madian River section belonged to the key sensitive area and should be further monitored, while the other sections belonged to the sub-sensitive or non-sensitive areas. To further verify the accuracy of the identified sensitive areas, a prototype reservoir storage test was carried out, and the hydrology and water quality of nine sections selected at the end of the reservoir were monitored to analyze the hydrology and water quality change trends. Figure 7 shows the variation in the water level in front of the Wudongde Dam, and Figure 8 shows the variation in the water level in different sections of the reservoir tail.

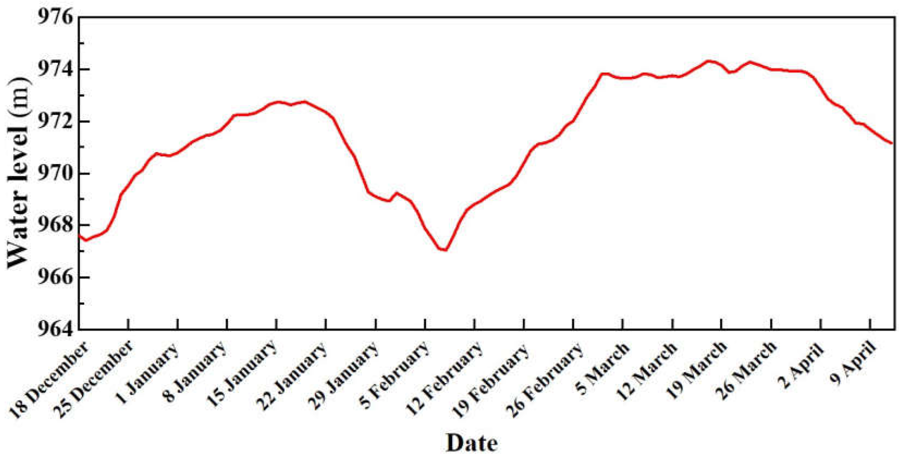


Figure 7. Water level in front of the Wudongde Dam.

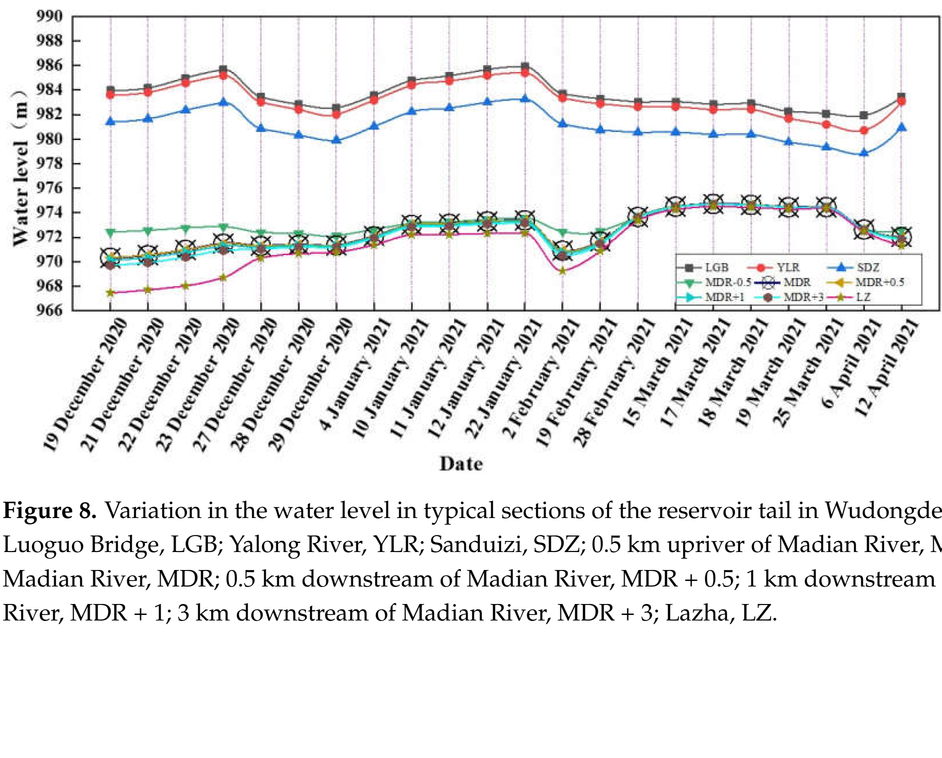


Figure 8. Variation in the water level in typical sections of the reservoir tail in Wudongde Reservoir. Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; 0.5 km upriver of Madian River, MDR − 0.5; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; Lazha, LZ.

During the impoundment test stage (December 2020–April 2021), the water level of the Wudongde Reservoir area rose from 965 to 975 m, and then fell back to approximately 971 m (as shown in Figure 8). During the entire process of water storage, except for the Madian River section, the changes in oxidation parameters (BOD_5, COD_{Mn}, and DO) and nutrient parameters (NH_3-N, TN, and TP) were small. The index fluctuation of the Madian River section was the most prominent (as shown in Figures 9 and 10). Although the index values fluctuated continuously, there was an obvious trend of initially declining and then improving.

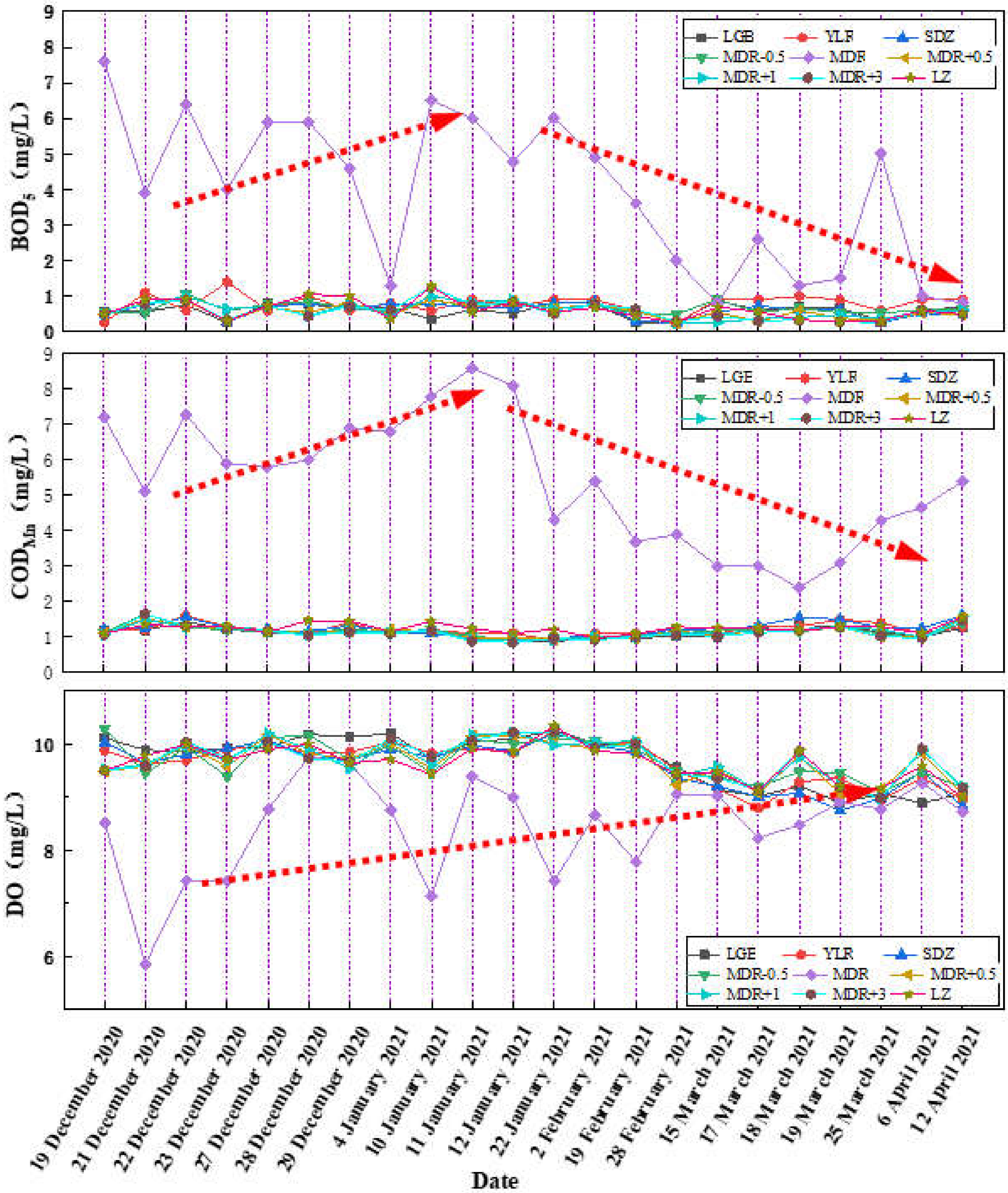


Figure 9. Changes in oxidation parameters at each monitoring point during the impoundment test stage (2020–2021). Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; 0.5 km upriver of Madian River, MDR − 0.5; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; Lazha, LZ.

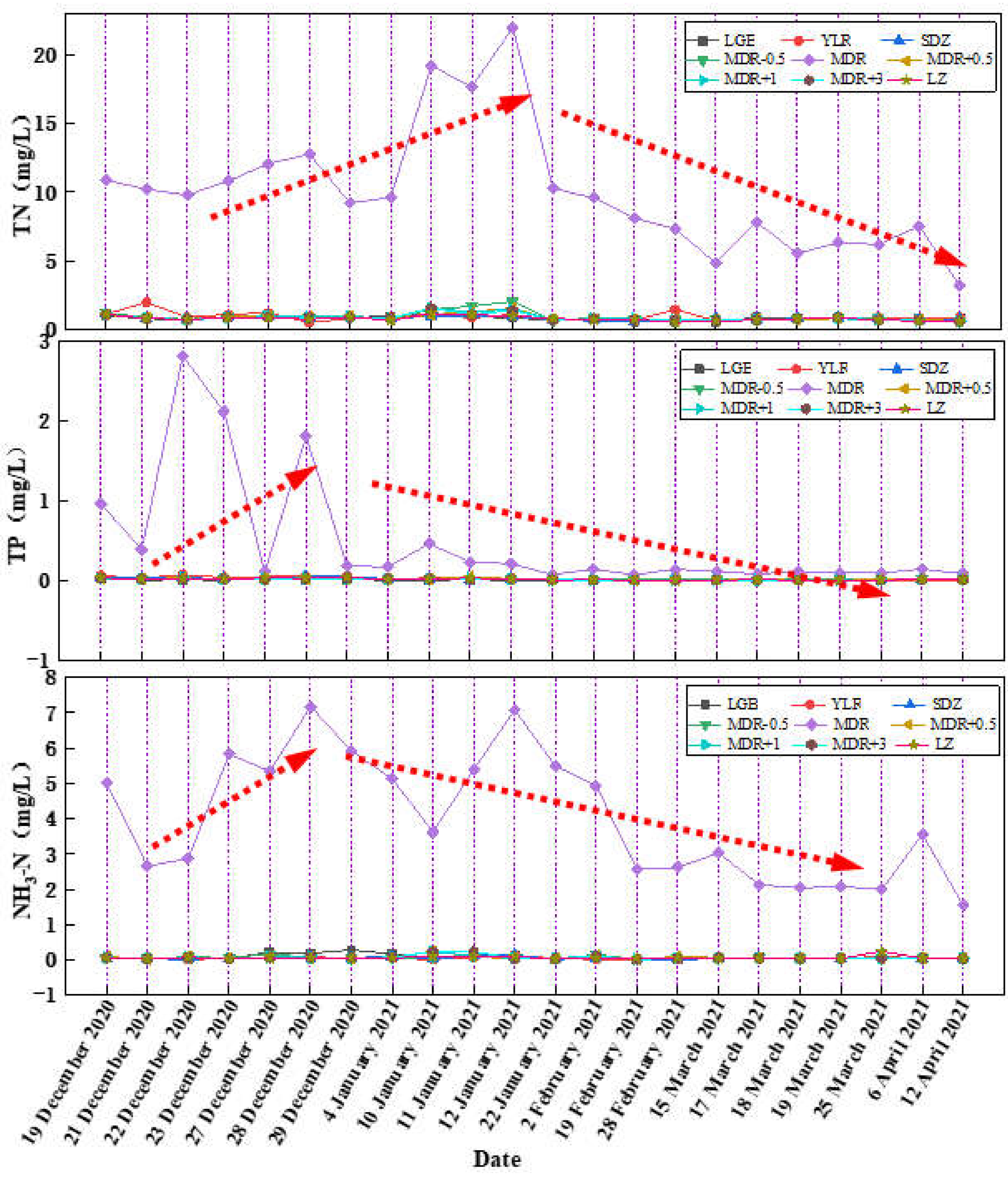


Figure 10. Changes in nutritional parameters at each monitoring point during the impoundment test stage (2020–2021). Luoguo Bridge, LGB; Yalong River, YLR; Sanduizi, SDZ; 0.5 km upriver of Madian River, MDR − 0.5; Madian River, MDR; 0.5 km downstream of Madian River, MDR + 0.5; 1 km downstream of Madian River, MDR + 1; 3 km downstream of Madian River, MDR + 3; Lazha, LZ.

As shown in the statistical data in Table 5, the minimum, maximum, and mean values of each index monitored in the Madian River section were much larger than those of the other sections. Comparatively speaking, the fluctuation range of each parameter index in the other sections, except the Madian River section, was small. For the oxidation parameters, BOD_5, COD_{Mn}, and DO ranged from 0.25–1.4, 0.84–1.656, and 8.75–10.34 mg/L, respectively. For the nutritional parameters, NH_3-N, TN, and TP ranged from 0.0125–0.282, 0.49–2.03, and 0.005–0.07 mg/L, respectively.

Table 5. Monitoring data of various indicators for Madian River and all other sections.

Water Quality Index	Monitoring Section	Minimum Value (mg/L)	Maximum Value (mg/L)	Mean Value (mg/L)
BOD_5	MDR	0.8000	7.6000	3.9300
	Other sections	0.2500	1.4000	0.6300
NH_3-N	MDR	1.5440	7.1790	4.0000
	Other sections	0.0125	0.2820	0.0630
COD_{Mn}	MDR	2.4000	8.6000	5.3900
	Other sections	0.8400	1.6560	1.1740
TN	MDR	3.1700	22.0000	10.0400
	Other sections	0.4900	2.0300	0.8460
DO	MDR	5.8600	9.7600	8.4600
	Other sections	8.7500	10.3400	9.6700
TP	MDR	0.0700	2.8200	0.4810
	Other sections	0.0050	0.0700	0.0160
pH	MDR	7.8000	8.6000	8.1500
	Other sections	7.9500	8.9200	8.4000

MDR, Madian River; Other sections, all sections other than the Madian River; BOD_5, five-day biochemical oxygen demand; NH_3-N, ammonia nitrogen content index; COD_{Mn}, potassium permanganate index; TN, total nitrogen; DO, dissolved oxygen; TP, total phosphorus.

In the process of water storage, the water level rises, and the river changes from its original river state to a lake state. In addition, the flow rate slows down, and the natural purification capacity of the water weakens, while the sewage carrying capacity of the water increases. The process of water storage affects the water quality of each monitoring section, but the relationship between the water level changes and water quality changes is very uncertain. However, from the monitoring data, compared with that for the other sections, the water quality of the Madian River section was quite different. This was consistent with the results from the sensitive area identification framework. According to the results of the field investigation, the sewage outlet of the Madian River section is the main reason for the water quality change. The water quality of the other sections was more stable.

The water quality change of the Madian river section should be influenced by upstream inflow and water level increase in terms of hydrodynamic force. With an increase in the water level, the water depth and water capacity of the beaches around the Sewage outlet of the Madian River increased, and the pollution indices gradually decreased, while the concentration of dissolved oxygen gradually increased. In the later period, as the water level began to decrease (Figure 8), the flow rate began to increase (Figure 11), and the index values showed a strong trend of either decline or rise. The pollutant index of the Madian River section was affected by the rise in water level and the change in discharge, which was mainly reflected in two aspects: the pollutant carrying capacity and diffusion capacity.

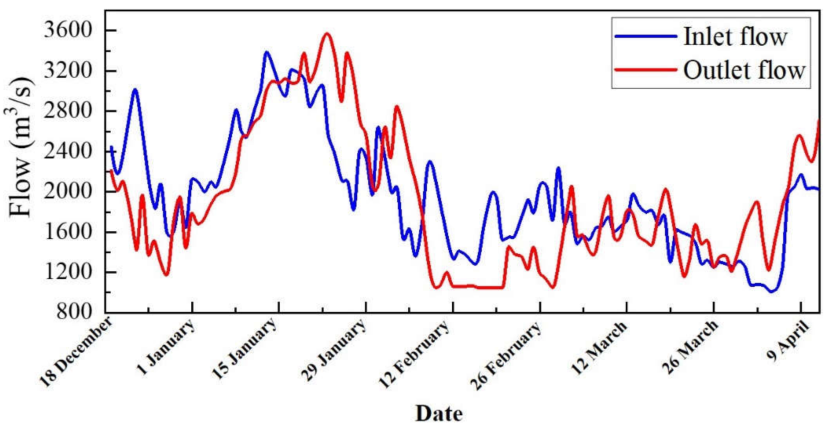


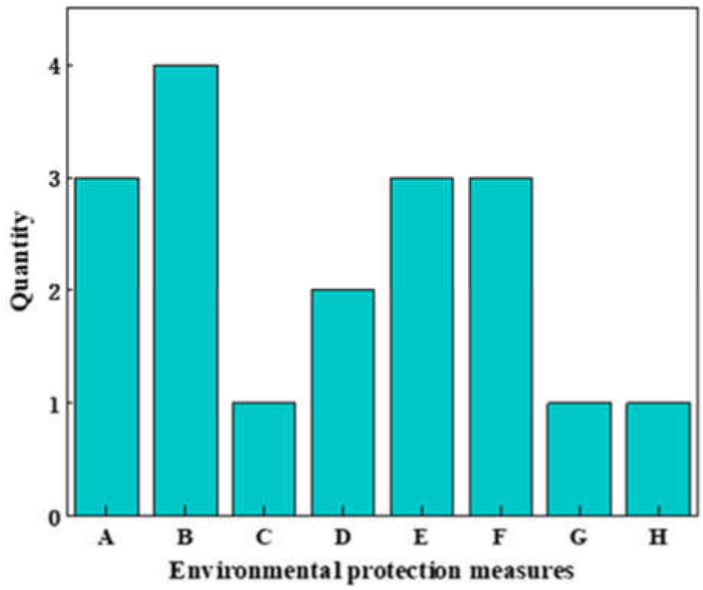
Figure 11. Changes in the inlet and outlet flow during the water storage test.

The water level processes of the Luoguo Bridge, Yalong River, and Sanduizi sections in the upper reaches were not affected by the impounding, and the water quality indices of these sections did not vary from those of the other evaluated sections in the reservoir area (except the Madian River).

3.4. Cause Analysis of Water Quality Differences in Sensitive Areas

Reservoir operation can change the flow state of the water body to enhance the self-purification capacity of the water body. Furthermore, pollution control can be achieved through the rectification of environmental protection measures. A combination of the two can improve the water quality of the Wudongde Reservoir.

After the Environmental Impact Assessment was approved in 2014, a total of 1.297 billion yuan was spent on the optimization and adjustment of water environmental protection measures of the Wudongde Reservoir, and related projects were reformed (as shown in Figure 12) to ensure that the sewage discharge from all sewage treatment plants met the first-class A standard (GB18918-2002) [47].



Code	Environmental protection measures
A	New Sewage Treatment Plant
B	Upgrading and expanding sewage treatment plants
C	Remodel the drain
D	Minor drainage basin management
E	Rural environment improvement area
F	Construction of automatic water quality monitoring station
G	Establish emergency monitoring laboratories
H	Emergency water pollution information system

Figure 12. Optimization and adjustment measures for water environmental protection. (A–H) Code of optimization measures. Code notes are shown in the table on the right [48].

To ensure that the water intake along the Jinsha River is not polluted, the water diversion pipe in the park was rebuilt to take water from the Guanyinyan water protection zone [49]. Intervention measures such as water diversion are needed to address the issues such as land use, soil erosion, sewage treatment, garbage treatment, point source, and non-point source pollution in small river basins at risk of pollution, and land sources of pollution. These measures can ensure the safety of drinking water and reduce the risk of water pollution from land sources. The purpose of rural environmental governance in this area is similar to that of small watershed governance.

The construction of a water quality automatic monitoring station and emergency monitoring laboratory can be used for real-time monitoring of water quality data, providing for sudden water pollution information system evaluation data. Measures to reduce pollution of the water body from land include cutting off the pollution sources and paths. Sudden water pollution forecast aspects can be factored into the design of mitigation pollution to maintain basic water environmental functions.

Another important method for protecting the water environment is to determine the optimal hydrodynamic conditions for the self-purification of pollutants in the reservoir area by optimizing the reservoir operation scheme. This is an effective way of controlling the source of pollutants and improving the self-purification conditions.

By comparing the changes in the oxidation (DO, COD_{Mn}, and BOD_5) and eutrophication indices (TN, NH_3-N, and TP) from 2016 to 2021, it was found that the concentration of DO had increased year by year, reaching 9.3 mg/L in 2021. The concentrations of COD_{Mn} and BOD5 were higher before 2020, and the 2021 values were as low as 1.2 and 0.5 mg/L, respectively. The concentrations of the eutrophication indices TN, NH_3-N, and TP gradually decreased to 0.8, 0.6, and 0.2 mg/L in 2021, respectively (Figure 13). Compared with the environmental quality standard for surface water (GB3838-2002), the oxidation indices reached the standard of class I water, while the eutrophication indices were above the standard for class III water. By comparing the water environment before (2016–2020) and after impoundment (2021), it was found that the water environment has been greatly improved, which is related to the implementation of optimization and adjustment measures for water environment protection (as shown in Figure 12).

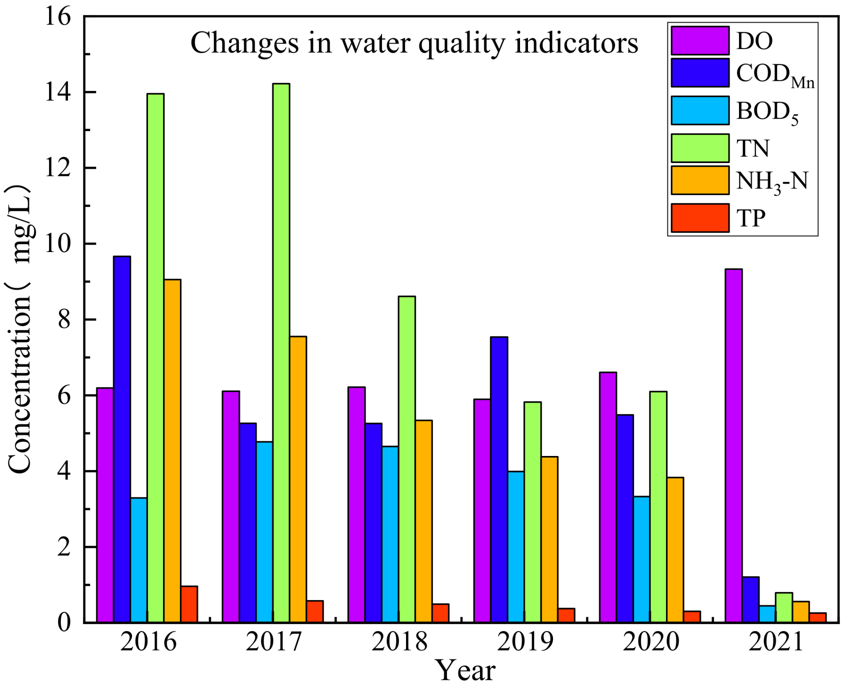


Figure 13. Changes in water quality monitoring indices from 2016–2021. DO, dissolved oxygen; COD_{Mn}, potassium permanganate index; BOD_5, five-day biochemical oxygen demand; TN, total nitrogen; NH_3-N, ammonia nitrogen content index; TP, total phosphorus.

4. Conclusions

Considering the Wudongde Reservoir of the Jinsha River as an example, this study proposed a system to identify areas sensitive to water quality risks in the initial stage of reservoir impoundment. In the process of identifying water quality risk sensitive areas, a comprehensive evaluation of the water quality of the entire reservoir area was conducted, a similar cluster analysis of water quality was completed for the complicated river and lake conversion section at the end of the reservoir, and a prototype storage test was used to verify the identification of sensitive areas. The following conclusions were drawn from the study findings:

(1) The temporal and spatial variation of water quality parameters in the main stream of the Wudongde Reservoir area was studied, and CCME-WQI was used to evaluate the water quality in this area. For the overall spatial and temporal distribution, the water quality primarily remained within excellent and good levels. However, the Madian River section consistently exhibited a medium-deviation state.

(2) Based on the combination of overall and local section water quality assessment, an identification system for sensitive areas of the Wudongde Reservoir was constructed. The sections with similar water quality changes were clustered using the clustering

method, and the Madian River section was identified as a sensitive area with high pollution levels.

(3) Comparing the water quality of the Wudongde Reservoir before and after impoundment, the water quality of the monitoring section after impoundment was better than that before impoundment because of the increase in the water environmental capacity. The nutritive index value was slightly larger, especially in the vicinity of the Madian River sewage outlet; however, this did not affect the overall water environmental quality of the Wudongde Reservoir.

The results of this study will provide a framework for water quality risk assessment during the initial impoundment process in reservoirs. The water quality sensitive area identification system enables managers to monitor water quality in a more targeted and standardized manner, which helps mitigate the potential negative impact of water quality degradation on the health of the surrounding population. Simultaneously, to monitor and control sensitive areas more efficiently and in real-time by managers, a real time monitoring system integrating climate, hydrology, topography, pollution sources, and other factors will be developed based on the theory of the existing identification system in the future. It will offset the limitation of the initial identification of water quality risks and reduce the management costs and the probability of risk occurrence.

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