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Water Quality Evaluation, Spatial Distribution Characteristics, and Source Analysis of Pollutants in Wanquan River, China

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Abstract: Surface water quality assessment is an important component of environmental protection and sustainable development. In this study, 24 sampling sites were arranged in the Wanquan River area of Hainan Island, China, in 2021, and nine water quality indicators were measured. The water quality of the Wanquan River was assessed using the single factor pollution index method and the Nemerow pollution index method; the spatial distribution characteristics of pollutants were revealed, and the sources of pollution were further analyzed using factor analysis. The results show that the overall water quality of the Wanquan River basin is good, with the average values of all indicators meeting China's Class III water quality standards. The results of the single factor pollution index method showed that 29% of the sampling sites were in the no pollution class, 38% in the slight pollution class, 25% in the light pollution class, and 8% in the moderate pollution class. The results of the Nemerow pollution index showed that 25% of the sampling sites were in the clean category, 17% in the cleaner category, 42% in the light category, and 17% in the moderate category. The results of the factor analysis show that agricultural activities and domestic sewage discharge are the main sources of pollution, with nitrogen and phosphorus being the most important factors affecting water quality. This paper proposes several measures to reduce water pollution in the Wanquan River, including improving agricultural activities, improving wastewater treatment, and strengthening environmental monitoring. The findings have practical implications for reducing water pollution in rivers and lakes and can provide a reference for policy decisions related to water resource management and environmental protection.

Keywords: Wanquan River; water quality assessment; pollution source analysis

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Citation: An, M.; Song, Y.; Jiang, J.; Fu, G.; Wang, Y.; Wan, X. Water Quality Evaluation, Spatial Distribution Characteristics, and Source Analysis of Pollutants in Wanquan River, China. *Appl. Sci.* **2023**, *13*, 7982. https://doi.org/10.3390/app13137982

Academic Editors: Mauro Marini and Oleg S. Pokrovsky

Received: 5 May 2023
Revised: 27 June 2023
Accepted: 5 July 2023
Published: 7 July 2023

1. Introduction

Water is an indispensable resource for the survival and development of human society [1–3]. With the rapid increase in population and rapid economic development in recent decades, the demand for water resources has increased dramatically in a short period of time [4–6]. Water pollution not only destroys the natural ecological landscape but also affects economic development and human health [3,7–10]. Therefore, timely river water quality assessment and pollution source analysis can help to effectively manage and prevent pollution in rivers, which is of great significance to the sustainable development of society, economy, and ecology [11].

Commonly used water quality evaluation methods include the single factor evaluation method, the comprehensive water quality index method, the principal component analysis method, etc. [1,12–18]. In recent years, the water quality index method has also been combined with multivariate statistics [19,20] and GIS technology [21] for water quality assessment to achieve better evaluation results. The above evaluation methods have their own advantages and disadvantages, and their focus is different. The combination of multiple evaluation methods is more scientific and reasonable to evaluate the water quality condition of rivers. The single factor evaluation method is widely used in many regions [18,22] due to its ease of use, and it is the calculation method used in China's Environmental Quality Standards for Surface Water. The Nemerow composite pollution index method also has the advantages of simple calculation and conceptual clarity, as well as better accuracy in the evaluation results, and it is widely used in the field of water quality assessment [12,23]. In this study, the single factor evaluation method and the Nemerow integrated pollution index method were selected to scientifically evaluate the water quality condition of the Wanquan River.

The Wanquan River is the "mother river" of Hainan Island and is an important source of water for local people's livelihoods. Its water quality is directly related to the health and quality of life of the local people. At the same time, the Wanquan River also has an important regulatory role in the local ecosystem, and the deterioration of water quality can lead to the destruction of the local ecosystem, resulting in a reduction in biodiversity. However, little research has been conducted on the pollution status of the Wanquan River, and existing studies mainly focus on the analysis and evaluation of water quality indicators [24,25]. The analysis of pollution sources is still lacking. Therefore, it is important to carry out a water quality assessment of the Wanquan River Basin for local environmental management and ecological protection.

Based on the data from 24 sampling points of the Wanquan River in August 2021, this paper evaluates the water quality condition of the river and analyzes the pollution sources by using the single factor evaluation method, the Nemerow index method, and the factor analysis method. It is worth mentioning that this study introduces geostatistical methods to spatially interpolate the water quality indicators of the Wanquan River to further explore the correlation between water quality indicator data and geographic elements such as towns, traffic, and topography so as to better analyze the spatial distribution characteristics of pollutants and determine the sources of pollution. This is an innovative approach compared to previous studies that focused on the temporal characteristics of river water quality while ignoring the spatial characteristics [1,21,26,27]. This study reveals the water quality status of the Wanquan River, the spatial distribution of pollution, and the speculation of pollution sources, providing a scientific basis for local environmental planning, water pollution prevention, and the management of resources in the Wanquan River.

2. Data and Methods

2.1. Overview of the Study Area

The Wanquan River is the second-largest river in Hainan Province. Originating in Qiongzhong with the Wuzhishan Wind Ridge, the Wanquan River flows eastward through the cities and counties of Liangzhong, Zhongchang, Ding'an, and Wenchang to the port of Bo'ao in Qionghai City and enters the South China Sea. The Wanquan River basin has a tropical and subtropical maritime monsoon climate, influenced by the monsoon, with no distinct seasons, high temperatures, abundant heat, sufficient sunshine, distinct dry and wet seasons, and abundant rainfall. The average annual rainfall is 2385 mm, with an uneven distribution of precipitation within the year, with 5–11 days of precipitation each year accounting for about 84% of the year. The average annual temperature is high, and evaporation is high, with an average annual land evaporation of 870 mm and a water evaporation of 1479 mm. The basin has a high forest cover, mainly natural forests and planted forests such as rubber forests, horse-jammed acacia forests, pressed woods, and betel coconut; the main soil types are red loam, brick red loam, and rice soil. There are important infrastructures such as the Bo'ao Forum for Asia, the Bo'ao Le Cheng International Medical Tourism Advance Zone, and other water sources cited by Gaji downstream of the basin, and the river has a significant role in benefiting the population.

2.2. Sample Collection

In order to ensure the representativeness of the samples, 24 sampling points were set up from the upper reaches of the Wanquan River to the mouth of the lake to collect the overlying water in August 2021, as shown in Figure 1. The water samples were immediately filtered with a 0.45 µm filter membrane, stored in an incubator at 4 °C, protected from light, and then sent to the China Geological Survey Haikou Marine Centre to test the water quality indicators. The indicators measured included the permanganate index (CODMn), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD5), ammonia nitrogen (NH_4^+-N), total phosphorus (TP), total nitrogen (TN), and heavy metals (As, Hg, and Cr(VI)), a total of nine items. The analytical methods refer to *Analytical Methods for Water and Wastewater Monitoring* (4th edition) and follow the requirements of the Environmental Quality Standards for Surface Water (GB3828-2002) [28].

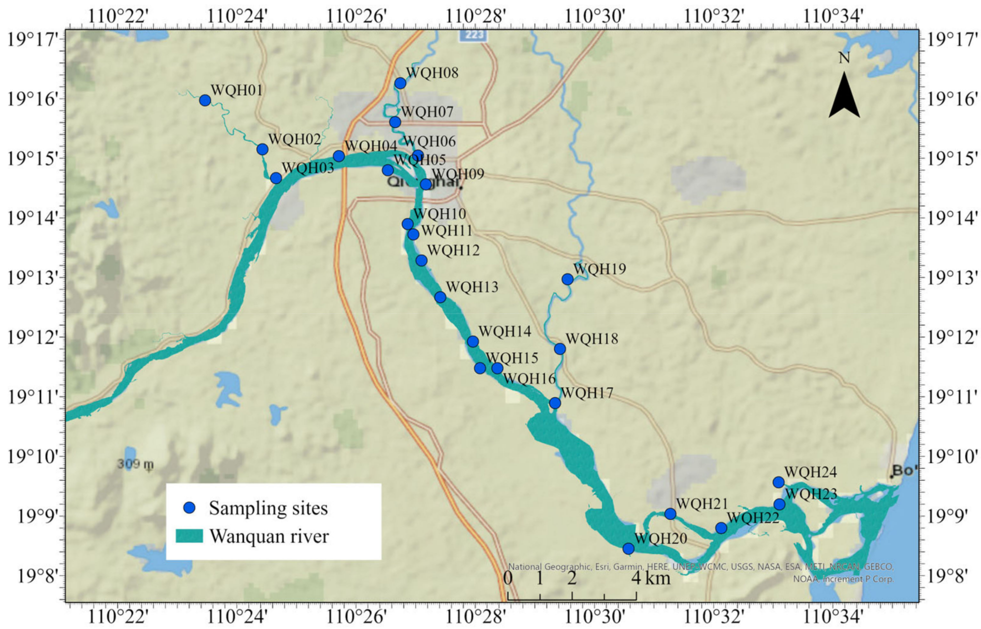

Figure 1. Distribution of sampling sites in the Wanquan River.

2.3. Chemical Analysis and Quality Assurance of the Data

In order to comprehensively consider the water quality in the eastern coastal zone of Hainan Island, a total of 112 surface water and groundwater samples were taken in three batches from 11 to 13 August 2021, with reference to the "1:50,000 Regional Hydrogeological Survey Specification" and "Surface Water and Wastewater Monitoring Specification" for the point layout and sampling standards. An amount of 5 L of water samples were collected, and the water samples were filtered with a 0.45 µm filter membrane immediately after collection and stored in a thermal chamber at 4 °C, protected from light, total phosphorus (TP), total nitrogen (TN), heavy metals (As, Hg, and Cr (VI)), for a total of nine.

Among them, CODMn index refers to the "determination of permanganate index GB/T 11892-1989" [29], using a 50 mL buret for determination; the detection limit is 0.5 mg/lL; COD determination using the rapid closed catalytic digestion method; BOD5 determination using rapid closed catalytic digestion method, refer to the "Water and wastewater monitoring and analysis methods (fourth edition) Supplement" State Environmental Protection Administration (2002); NH_4^+-N using nano-reagent spectrophotometry (HJ 535-2009) [30]; TP determination using ammonium molybdate spectrophotometry; TN determination using alkaline potassium persulfate ablation—UV spectrophotometry; heavy metals (As, Hg, and Cr(VI)) using diphenylcarbonyl dihydrazide spectrophotometry (Cr(VI)) and atomic fluorescence hair (As, Hg), test The results meet the quality requirements. These nine ions were tested and analyzed with the following information (using NH_4^+ as an example):

Principle of method: Ammonia nitrogen in the form of free ammonia or ammonia ions reacts with the nanoreagent to form a light reddish-brown complex. The absorbance of this complex is proportional to the ammonia-ammonia content. The absorbance of the complex can be measured at a wavelength of 420 nm. Apparatus and equipment: (1) Visible spectrophotometer with a 20 mm cuvette; (2) ammonia distillation apparatus with a 500 mL distillation flask. Chemical samples used: MgO; HCl; $HgCl_2 - KI - KOH$; $HgI_2 - KI - NaOH$; $KNaC_4H_6O_6{\cdot}4H_2O$; $Na_2S_3O_3$; Na_2CO_3; $ZnSO_4{\cdot}7H_2O$; $NaOH$; H_3BO_3; NH_4Cl; *bromthymol blue*. Calculated as:

$$\rho_N = \frac{A_s - A_b - a}{b \times V} \tag{1}$$

where ρ_N is the mass concentration of ammonia nitrogen in the water sample, calculated as nitrogen, mg/L; A_s is the absorbance of the water sample; A_b is the absorbance of the blank test; a is the intercept of the calibration curve; b is the slope of the curve; V is the volume of the test material, mL.

Accuracy and precision: For the standard solution of 1.21 mg/L ammonia, the repeatability limit was 0.028 mg/L, the reproducibility limit was 0.075 mg/L, and the recoveries ranged from 94% to 104%. Quality assurance and quality control were carried out through the following measures: absorbance of the reagent blank should not exceed 0.030 (10 mm cuvette); preparation of Nessler; preparation of potassium sodium tartrate; flocculation and precipitation processes; pre-distillation of the water sample; cleaning of the distillator.

2.4. Spatial Interpolation Methods

The Kriging interpolation method is used for spatial analysis. The Kriging method is the basis for the creation of geostatistics and is an effective tool for investigating phenomena related to spatial correlation in nature. The weight of each sample is calculated as a weighted average of the attributes of the samples to be measured.

There are many types of kriging interpolation methods, and ordinary kriging interpolation is one of the most common and commonly used methods, with the formula

$$\hat{Z}_{(x_0)} = \sum_{i=1}^{n} \lambda_i Z_{(x_i)} \tag{2}$$

where $\hat{Z}_{(x_0)}$ is the predicted value. $Z_{(x_i)}$ is the sampled value, determined by the semivariance function model. λ_i is the weight to be assigned to each unsampled location.

2.5. Water Quality Assessment Methods

2.5.1. Single Factor Pollution Index Method

The single factor pollution index method is used to determine the overall water quality category of a water body by calculating the worst single water quality indicator among all the indicators used for water quality assessment and then determining the category to which this indicator belongs. The single factor pollution index method is one of the most widely used evaluation methods for water quality assessment, which effectively avoids the subjective arbitrariness of determining the weight of indicators.

The single-factor pollution index method is calculated using the formula

$$P_i = \frac{C_i}{S_i} \tag{3}$$

$$P = MAX(P_i) \tag{4}$$

where C_i is the water quality indicator and i the measured concentration of the water quality indicator (mg/L); S_i is the water quality indicator and i is the evaluation standard value (mg/L) of the water quality indicator (taken from the water quality standard of category III in the Surface Water Environmental Quality Standard); and P_i is the single factor index evaluation results. Finally, the worst water quality category shows the results of the comprehensive evaluation of water quality. For the grading standards of the single factor pollution index method of environmental quality assessment, see Table 1.

Table 1. Environmental quality assessment grading criteria for the single factor pollution index method.

Grade	P_i	Pollution Assessment
I	≤ 1	Non-polluting
II	(1, 2]	Light pollution
III	(2, 3]	Light pollution
IV	(3, 5]	Moderate pollution
V	>5	Heavy pollution

2.5.2. Nemerow Pollution Index Method

The Nemerow pollution index was first proposed by Professor N.L. Nemerow of Syracuse University in his book "Scientific Analysis of River Pollution". Compared with the single factor pollution index method, the Nemerow pollution index method takes into account the contribution of other factors in the evaluation system while highlighting the most polluting factors, and it is a more comprehensive evaluation method.

The Nemerow pollution index method is calculated using the formula

$$P_{\text{Nemerow}} = \sqrt[2]{\frac{\overline{P}^2 + {P_{max}}^2}{2}} \quad (5)$$

where P_{Nemerow} is the combined pollution index of the sampling point. P_{max} is the maximum value of the single-factor pollution index for each pollutant at the sampling point. $\overline{P} = \frac{1}{n}\sum_1^n P_i$ is the average value of the single-factor pollution index. The environmental quality assessment criteria of the Nemerow pollution index method are shown in Table 2.

Table 2. Environmental quality assessment grading criteria for the Nemerow pollution index method.

Grade	P_i	Pollution Assessment
I	≤ 0.7	Cleaning
II	(0.7, 1.0]	Cleaner
III	(1.0, 2.0]	Light pollution
IV	(2.0, 3.0]	Moderate pollution
V	>3.0	Heavy pollution

2.6. Source Analysis Methods

Factor analysis is used in the analysis of pollution sources. Factor analysis is a method of variable dimensionality reduction that assumes the existence of multiple unobservable hidden factors behind the original variables. It starts with the study of the correlation matrix of the original variables and reduces the number of original variables into a few composite factors by means of dimensionality reduction, which usually reveals the internal links and important information hidden between the original variables, especially the causal (pollution source) links. The KMO (Kaiser–Meyer–Olkin) test and Bartlett's sphericity test are used to determine the correlation between indicators before factor analysis to determine whether the original variables are suitable for principal component analysis, and the specific evaluation methods are established as follows:

1. Min-max normalization: eliminate the effects of dimensions and orders of magnitude by subtracting the mean of all variables and dividing by the standard deviation of each variable;
2. Calculate the correlation coefficient matrix: use the standardized data matrix to calculate its corresponding correlation coefficient matrix, R, and calculate the eigenvalue and eigenvector of R;
3. Determine the number of principal components: determine the number of principal components m according to the principle that the eigenvalue is greater than 1 or the cumulative contribution rate of principal component variance is greater than 85%;

4. Calculate the factor score: calculate the score of the top m principal components of each sample and plot the spatial distribution of the factor score.

3. Results and Discussion

3.1. Statistical Characteristics of Water Quality in the Wanquan River

The statistical results of water quality indicators at each sampling point of the Wanquan River are shown in Table 3 and Figure 2. The average value of each water quality indicator in Table 3 is used to characterize the overall level of each water quality indicator in the water, and the coefficient of variation is mainly used to reflect the degree of variation of the indicators and reveal the spatial differences of the indicators in the water.

Table 3. Statistical results of water quality indicators for the Wanquan River.

Indicator (mg/L)	Maximum Value	Minimum Value	Average	Standard Deviation	Coefficient of Variation	Class II Water Standard	Class III Water Standard	Exceedance Rate
NH_4^+-N	2.60	0.12	0.56	0.59	107%	0.50	1.00	13%
TN	2.82	0.33	0.85	0.61	72%	0.50	1.00	17%
TP	0.34	0.06	0.13	0.08	62%	0.10	0.20	17%
COD_{Mn}	7.30	3.70	5.49	0.72	13%	4.00	6.00	13%
COD	16.00	2.50	7.81	3.54	45%	15.00	20.00	0%
BOD5	3.60	0.25	1.66	0.94	56%	3.00	4.00	0%
Cr^{6+}	0.14	2.00×10^{-3}	0.02	0.02	113%	0.05	0.05	4%
As	4.00×10^{-3}	1.50×10^{-4}	1.03×10^{-3}	1.04×10^{-3}	101%	0.05	0.05	0%
Hg	3.40×10^{-4}	2.00×10^{-5}	1.30×10^{-4}	1.05×10^{-4}	81%	5.00×10^{-5}	1.00×10^{-4}	54%

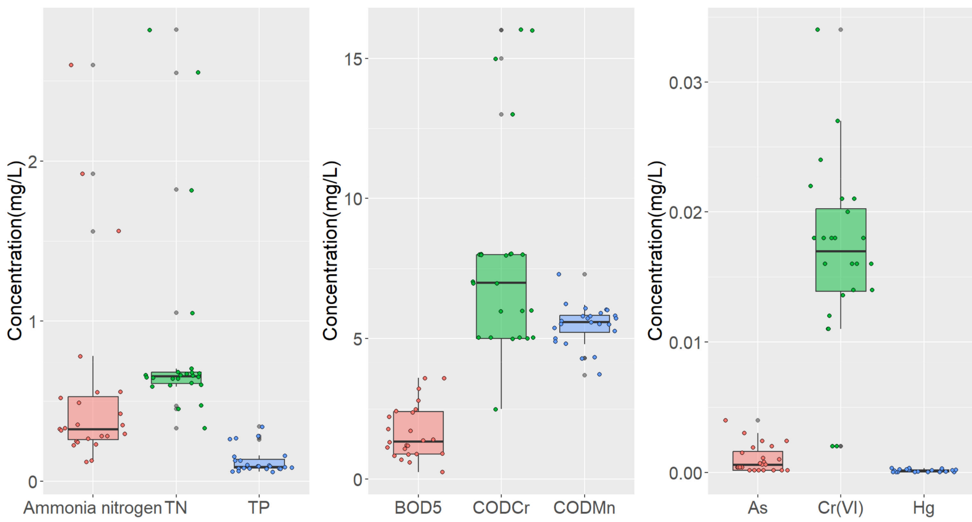

Figure 2. Distribution of various water quality indicators in the Wanquan River.

Comparing the average values of the indicators of the Wanquan River water quality with the Class III water quality standard in the Environmental Quality Standard for Surface Water (GB3838-2002) [28], we found that the overall water quality of the Wanquan River basin is good, with the average values of all indicators meeting the Class III water quality standard. Compared with Ma's research on the water quality of Wanquan River in 2012–2015, the water quality of Wanquan River decreased from Class II to Class III in 2021, which may be closely related to the development of tourism in this area [31]. In terms of the exceedance rate, Hg was the most serious element, reaching 54%, followed by TN and TP (both 17%) and NH_4^+-N and COD_{Mn} (both 13%). In terms of coefficient of variation, NH_4^+-N (107%), Cr^{6+} (113%), and As (101%) had large coefficients of variation, indicating a large degree of dispersion and an uneven spatial distribution for these three indicators.

3.2. Spatial Distribution

In order to explore the spatial distribution characteristics of each water quality indicator, the nine indicators were subjected to kriging interpolation, and the water quality status corresponding to each indicator was graded according to the Environmental Quality Standard for Surface Water (GB3838-2002) (Figure 3).

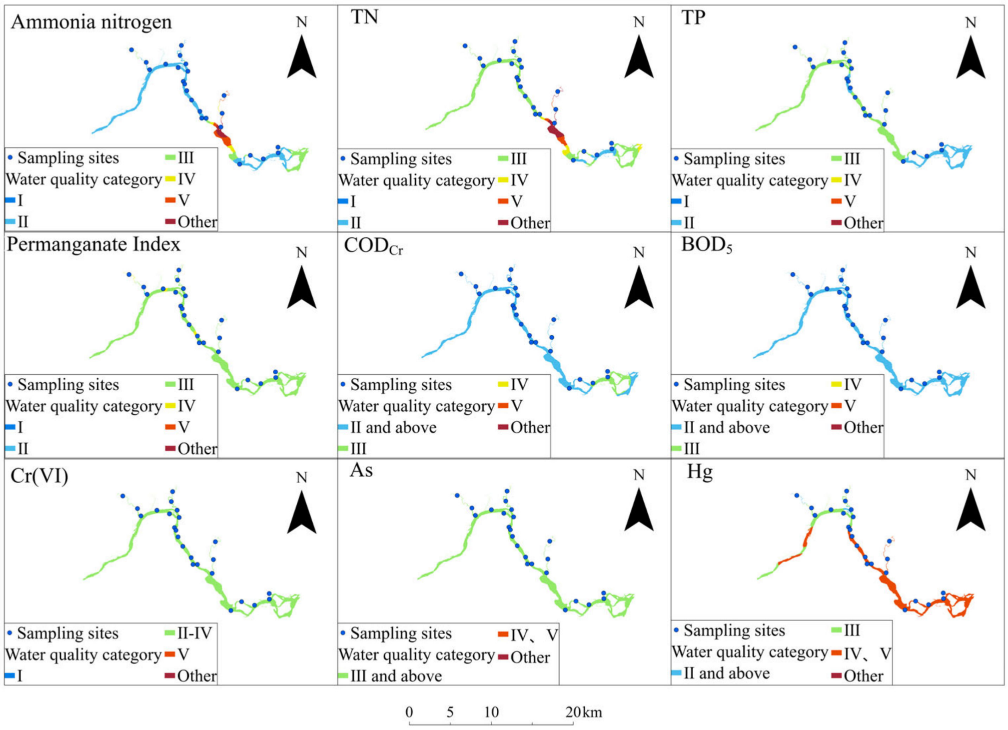

Figure 3. Spatial distribution of various water quality indicators in the Wanquan River.

Among them, $NH_4{}^+$-N and TN show a similar spatial distribution pattern, with concentrations in the Tayang River, a tributary of the Wanquan River, and at the confluence of the two rivers at V water quality level or even worse, both of them reaching Class III water quality in most areas, with $NH_4{}^+$-N concentrations meeting Class II water quality requirements in most areas; TP concentrations meeting Class III water quality requirements and Class II water quality in the vicinity of the downstream mouth of the Wanquan River and the southern part of Qionghai City; COD, Cr and As reaching Class II water quality requirements in most areas; and COD and BOD meeting Class II water quality requirements in most areas. With $Hg_{Mn}{}^{6+}{}_5$, the spatial distribution pattern of Hg is the most special, corresponding to water quality class IV or worse in most areas and only in the northernmost part of the river west of Qionghai city.

3.3. Single Factor Pollution Index Evaluation

3.3.1. Single Factor Pollution Index Evaluation Results

Nine water quality indicators were calculated for twenty-four sampling points in the Wanquan River basin, using Class III water as the target water quality to obtain the single factor pollution index for each sampling point in the Wanquan River basin (Table 4 and Figure 4).

Of the 24 sampling points, 7 (29%) were in the no pollution class, 9 (38%) in the slight pollution class, 6 (25%) in the light pollution class, and 2 (8%) in the moderate pollution class (Table 4).

Table 4. Evaluation results of the single factor pollution index method for each sampling point in the Wanquan River.

Sampling Sites	NH_4^+-N	TN	TP	COD	BOD_5	COD_{Mn}	Cr^{6+}	As	Hg	One-Factor Evaluation Rating
WQH01	0.78	1.05	1.70	0.35	0.63	1.22	0.54	0.02	0.20	Light pollution
WQH02	0.33	0.67	0.65	0.35	0.35	0.72	0.04	0.01	0.20	Non-polluting
WQH03	0.35	0.64	0.50	0.35	0.60	0.62	0.04	0.01	1.50	Light pollution
WQH04	0.32	0.64	0.40	0.13	0.20	1.02	0.36	0.00	0.20	Light pollution
WQH05	0.28	0.60	0.40	0.25	0.43	0.93	0.24	0.05	0.50	Non-polluting
WQH06	0.52	0.66	0.65	0.40	0.70	0.83	0.36	0.01	0.20	Non-polluting
WQH07	0.49	0.66	0.75	0.40	0.90	0.90	0.36	0.00	0.40	Non-polluting
WQH08	0.42	0.65	0.80	0.25	0.60	0.97	0.32	0.01	1.40	Light pollution
WQH09	0.29	0.59	0.45	0.30	0.55	0.72	0.32	0.03	0.20	Non-polluting
WQH10	0.25	0.60	0.50	0.25	0.28	1.00	0.22	0.00	0.70	Light pollution
WQH11	0.35	0.65	0.45	0.25	0.45	0.88	0.28	0.04	1.60	Light pollution
WQH12	0.32	0.68	0.45	0.25	0.33	0.93	0.28	0.00	2.10	Light pollution
WQH13	0.26	0.64	0.40	0.25	0.35	0.92	0.42	0.00	1.50	Light pollution
WQH14	0.24	0.67	0.40	0.30	0.30	1.03	0.32	0.02	0.20	Light pollution
WQH15	0.22	0.61	0.40	0.40	0.23	0.80	0.42	0.01	2.60	Light pollution
WQH16	0.23	0.66	0.45	0.40	0.18	0.82	2.72	0.06	1.60	Light pollution
WQH17	2.60	2.82	1.40	0.40	0.80	0.95	0.68	0.02	2.00	Light pollution
WQH18	1.56	1.82	1.30	0.40	0.28	0.92	0.48	0.05	2.80	Light pollution
WQH19	1.92	2.55	1.35	0.40	0.90	0.97	0.36	0.01	3.40	Moderate pollution
WQH20	0.12	0.45	0.40	0.30	0.30	0.95	0.32	0.00	0.20	Non-polluting
WQH21	0.56	0.70	0.40	0.65	0.23	1.00	0.44	0.04	1.80	Light pollution
WQH22	0.28	0.47	0.30	0.80	0.23	0.97	0.22	0.01	3.20	Moderate pollution
WQH23	0.13	0.33	0.30	0.80	0.15	0.98	0.36	0.08	0.20	Non-polluting
WQH24	0.55	0.68	0.30	0.75	0.06	0.92	0.40	0.00	2.40	Light pollution

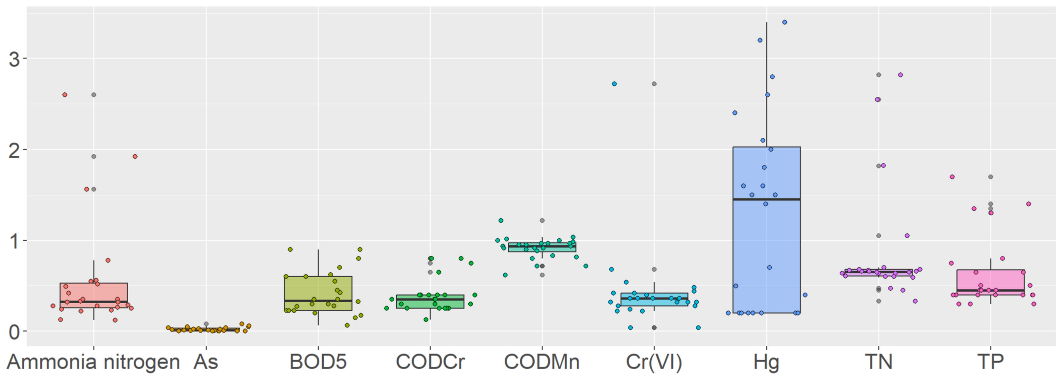

Figure 4. Single factor pollution index for each water quality indicator of the Wanquan River.

For the nine water quality indicators, Hg has the highest average single factor index of 1.3 and is the most significant source of pollution. The average single factor index for the remaining eight indicators is less than 1. Among them, the average single factor index values for COD_{Mn} and TN are 0.91 and 0.85, respectively, which are close to the lower limit of Class III water, and the relevant departments need to pay attention to them.

3.3.2. Characteristics of the Spatial Distribution of Single-Factor Evaluation Results

(1) Water quality class evaluation

The method of single-factor evaluation of water quality grades is to take the worst grade of each point as the final water quality grade of the point. The results of the single factor evaluation of the water quality grade at each point were plotted (Figure 5) for the spatial distribution characteristics of water quality.

Among the 24 sites in the Wanquan River, most of them meet the surface water quality standard of V and above (Figure 5), while only three sites near the Tayang River, WQH17, WQH18, and WQH19, are of poor V quality, in addition to the sample sites in the northern section of the Wanquan River, where the water quality reaches IV or above. This indicates that the overall water quality of the Wanquan River is currently good, but water quality monitoring and management need to be strengthened near the Tayang River.

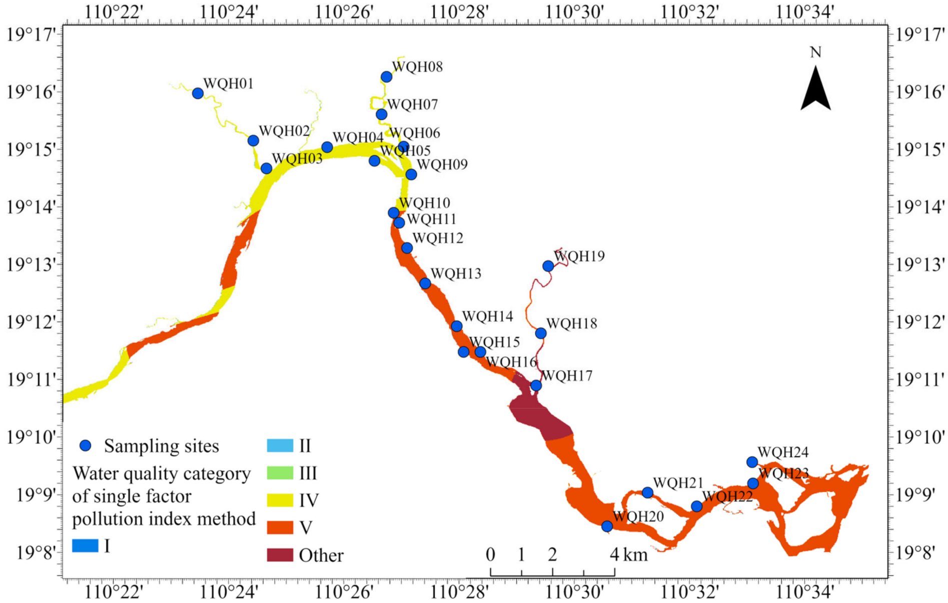

Figure 5. Spatial distribution of water quality level evaluation results by the single-factor pollution index method.

(2) Evaluation of pollution levels

Using Class III water as the target water quality, the results of the single factor pollution level evaluation are shown in Figure 6. The overall pollution level of the 24 loci of the Wanquan River is above light pollution, with very few areas (WQH19, near Tayang River) showing moderate pollution, reaching a pollution-free level in the northern part of the river near the western part of Qionghai city, which may be related to the good urban sewage treatment system.

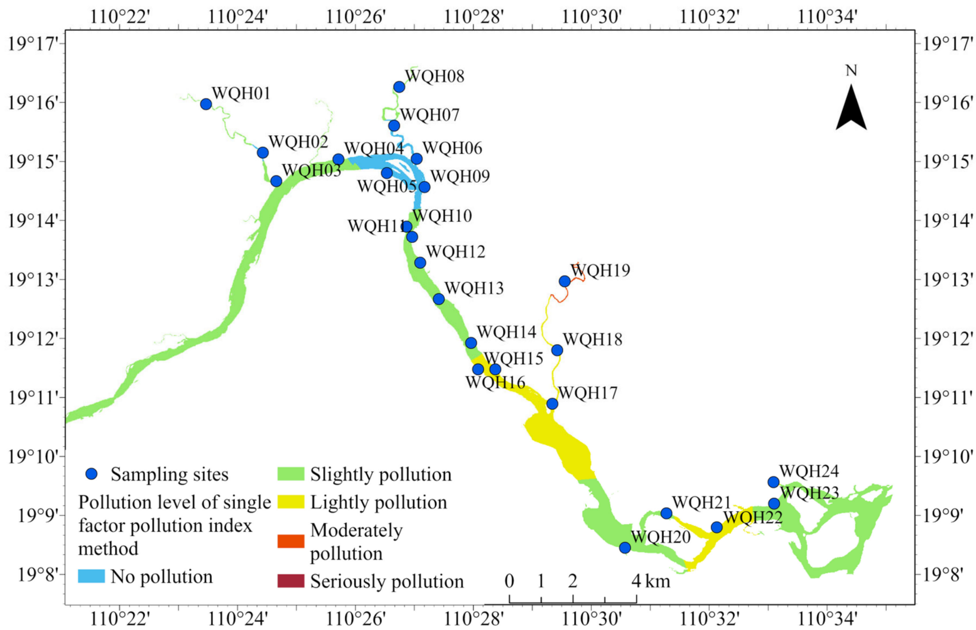

Figure 6. Spatial distribution of pollution level evaluation results by the single-factor pollution index method.

3.4. Evaluation of the Nemerow Composite Pollution Index

3.4.1. Results of the Evaluation of the Nemerow Composite Pollution Index

The Nemerow pollution index was calculated for 24 sampling points in the Wanquan River basin to obtain the pollution level of each sampling point in the Wanquan River basin (Table 5). Of the 24 sampling sites, 6 (25%) were in the clean class, 4 (17%) in the cleaner class, 10 (42%) in the light pollution class, and 4 (17%) in the moderate pollution class (Table 4). Compared to the single factor pollution index method, the proportion of the first two classes of the Nemerow pollution index method decreased while the proportion of the third and fourth classes increased, resulting in a more stringent evaluation than the single factor index method.

Table 5. Evaluation results of the Nemerow integrated pollution index method for each sampling point in the Wanquan River.

Sampling Sites	Nemerow Pollution Index	Pollution Level
WQH01	1.27	Light pollution
WQH02	0.56	Cleaning
WQH03	1.10	Light pollution
WQH04	0.75	Cleaner
WQH05	0.69	Cleaning
WQH06	0.64	Cleaning
WQH07	0.70	Cleaning
WQH08	1.04	Light pollution
WQH09	0.55	Cleaning
WQH10	0.74	Cleaner
WQH11	1.17	Light pollution
WQH12	1.52	Light pollution
WQH13	1.10	Light pollution
WQH14	0.76	Cleaner
WQH15	1.87	Light pollution
WQH16	1.97	Light pollution
WQH17	2.11	Moderate pollution
WQH18	2.06	Moderate pollution
WQH19	2.50	Moderate pollution
WQH20	0.70	Cleaning
WQH21	1.32	Light pollution
WQH22	2.29	Moderate pollution
WQH23	0.73	Cleaner
WQH24	1.74	Light pollution

3.4.2. Spatial Distribution of the Results of the Evaluation of the Nemerow Composite Pollution Index

The spatial distribution of the results of the Nemerow integrated pollution index evaluation is shown in Figure 7. Spatially, the entire Wanquan River is predominantly lightly polluted, reaching the clean (WQH05, WQH06, and WQH09) and cleaner grades (WQH02, WQH03, WQH04, and WQH07) in the northern section of the river. The loci near the Tayang River reach moderate pollution levels (WQH17, WQH18, and WQH19).

Comparing the evaluation results of the single factor pollution index method (Figure 6), it can be seen that the overall distribution trends of both are similar, with the low and high values of pollution occurring in the western part of Qionghai city and the Tayang River, respectively. The difference lies in the fact that the results of the single-factor pollution index method are dominated by minor pollution at the second level, while the Nemerow pollution index method is dominated by light pollution at the third level.

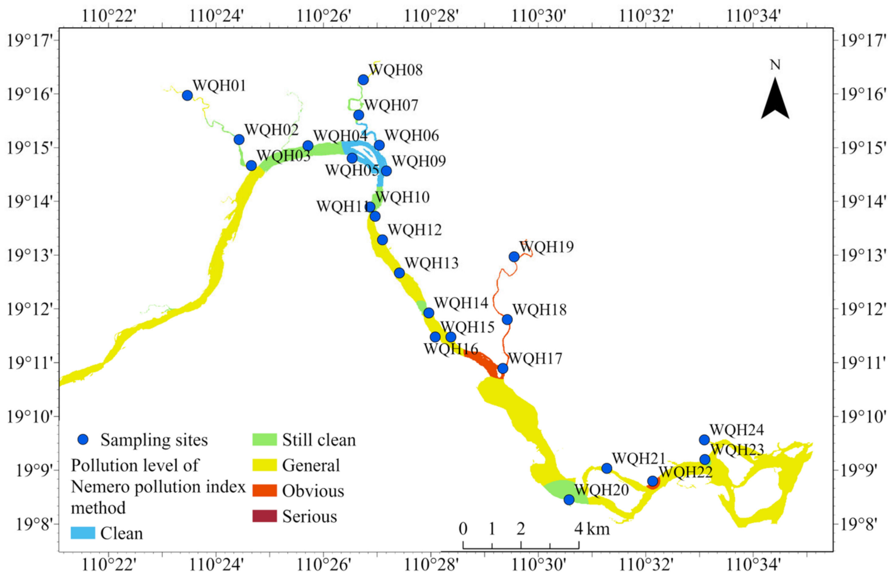

Figure 7. Spatial distribution of pollution levels in the Nemerow composite pollution index.

3.5. Analysis of Pollutant Sources

3.5.1. Correlation Analysis

The results of the correlation analysis of the indicators in the Wanquan River samples are shown in Figure 8. NH_4^+-N was significantly correlated with TN and TP, with a significant positive correlation at the 0.01 level, indicating that these three groups of indicators may have the same source. In addition, BOD_5 was significantly and positively correlated with NH_4^+-N, TN, and TP at the 0.05 level, and As was significantly and positively correlated with Cr^{6+} and Hg with NH_4^+-N and TN at the 0.1 level. The presence of significant correlations between multiple groups of indicators suggests that factor analysis can be performed.

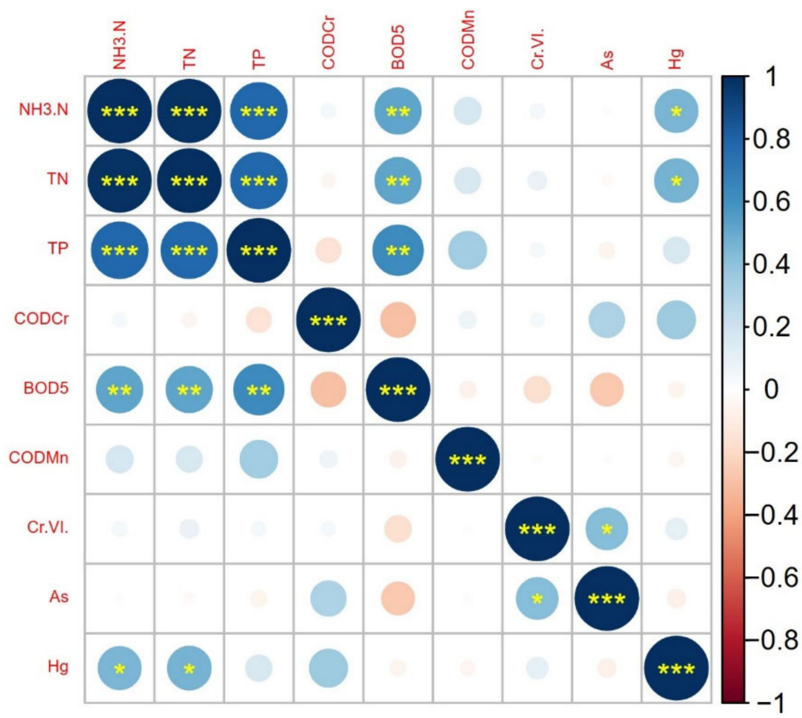

Figure 8. Results of the correlation analysis of the indicators. * denotes $p < 0.05$, ** denotes $p < 0.01$, *** denotes $p < 0.001$.

3.5.2. Principal Component Analysis

The KMO test and Bartlett's sphericity test were performed to determine the suitability of the data for factor analysis before the factor analysis was conducted. In this study, the KMO statistic was 0.57, which is generally considered to be a KMO value greater than 0.5, indicating that the data are suitable for factor analysis.

The factors were extracted using the principal component analysis method, and orthogonal rotation was performed using the maximum variance method. The factors were extracted according to the principles of a cumulative contribution rate of 80% or more and an initial eigenvalue greater than 1, and four common factors were obtained (Table 6). The cumulative variance contribution rates before and after rotation did not change, indicating that these four common factors can be used to explain the basic information of the nine original variables of the Wanquan River. The factor loading matrices and the main control indicators of water quality for each common factor after rotation are shown in Tables 6 and 7.

Table 6. Rotated factor loading matrix.

Indicators	F_1	F_2	F_3	F_4
NH_4^+-N	**0.941**	0.222	0.030	0.060
TN	**0.951**	0.181	0.041	0.025
TP	**0.890**	−0.123	0.019	0.273
COD_{Mn}	0.146	0.021	−0.013	**0.954**
COD	−0.158	**0.798**	0.151	0.169
BOD_5	**0.713**	−0.390	−0.244	−0.158
Cr^{6+}	0.081	0.007	**0.844**	−0.117
As	−0.101	0.111	**0.834**	0.115
Hg	0.370	**0.795**	−0.052	−0.218

Note: Values in bold in the table represent higher factor loadings.

Table 7. Extracted common factors.

Common Factor	Eigenvalue	Percentage of Variance	Cumulative Contribution of Variance	Main Control Indicators
F_1	3.33	37.04	37.04	NH_4^+-N, TN, TP, BOD_5
F_2	1.80	20.05	57.09	COD
F_3	1.22	13.57	70.66	Cr^{6+}, As
F_4	1.07	11.92	82.58	COD_{Mn}

The contribution of the first principal component (F_1) was 36.556%. NH_4^+-N, TN, TP, and BOD_5 had high factor loadings, indicating organic pollution sources, among which the factor loadings of TP and TN were 0.890 and 0.951, respectively, indicating the presence of nitrogen and phosphorus pollution in the water body, whereas the factor loading of NH_4^+-N was 0.941, whose main source was the decomposition of organic nitrogen compounds entering the water body by microorganisms [32]. Its content can reflect the degree of pollution and self-purification ability of the water body.

The contribution of the second principal component (F_2) is 17.007%. COD has a high factor loading, indicating the source of organic pollution. COD can reflect the amount of organic substances in the water body and, to some extent, can characterize the degree of pollution of the water body by organic substances.

The third principal component (F_3) has a contribution of 16.611%, with Cr^{6+} and As having high factor loadings, indicating metallurgical and chemical pollution sources, which are mainly from the mining, smelting, and foundry industries of chromium ore and the application of chromium compounds in electroplating, alloying, printing, and dyeing, as well as in agriculture [33].

The fourth principal component (F_4) has a contribution of 12.410%, and COD_{Mn} has a high factor loading. COD_{Mn} reflects the concentration of organic matter by measuring the oxidation capacity of organic matter in a water sample and is not fundamentally different from what COD represents. Therefore, the fourth principal component, like the second principal component, indicates organic pollution sources.

The sampling points with high scores on Factor 1 were WQH17, WQH18, and WQH19 (Table 8 and Figure 9), indicating that these three sampling points contributed more to the variance of Factor 1, and the pollutants were mainly TN, TP, and NH_4^+-N. These three sampling points were all located near the Tayang River, which may be related to the wastewater treatment plants distributed around the Tayang River.

Table 8. Rotated factor score matrix for sampling points.

Sampling Sites	F_1	F_2	F_3	F_4
WQH01	1.01	−1.17	0.10	**2.66**
WQH02	−0.35	−0.57	−0.60	−1.03
WQH03	−0.07	−0.14	−0.80	−2.26
WQH04	−0.57	−1.05	−0.44	0.77
WQH05	−0.44	−0.83	0.52	0.21
WQH06	0.09	−0.84	−0.27	−0.55
WQH07	0.35	−0.98	−0.62	−0.23
WQH08	0.19	−0.63	−0.39	0.22
WQH09	−0.29	−0.98	0.22	−1.32
WQH10	−0.51	−0.53	−0.68	0.67
WQH11	−0.21	−0.30	0.21	−0.42
WQH12	−0.28	0.14	−0.75	−0.20
WQH13	−0.37	−0.22	−0.53	−0.23
WQH14	−0.59	−0.68	−0.04	0.99
WQH15	−0.48	0.88	−0.34	−1.06
WQH16	−0.28	−0.15	**3.78**	−1.17
WQH17	**2.84**	0.31	0.38	−0.03
WQH18	**1.35**	0.99	0.86	0.16
WQH19	**2.55**	0.85	−0.57	−0.20
WQH20	−0.73	−0.70	−0.53	0.38
WQH21	−0.51	**1.24**	0.43	0.81
WQH22	−0.76	**2.43**	−0.87	0.35
WQH23	−1.26	0.82	**1.53**	1.33
WQH24	−0.72	**2.10**	−0.59	0.16

Note: Values in bold in the table represent higher factor scores.

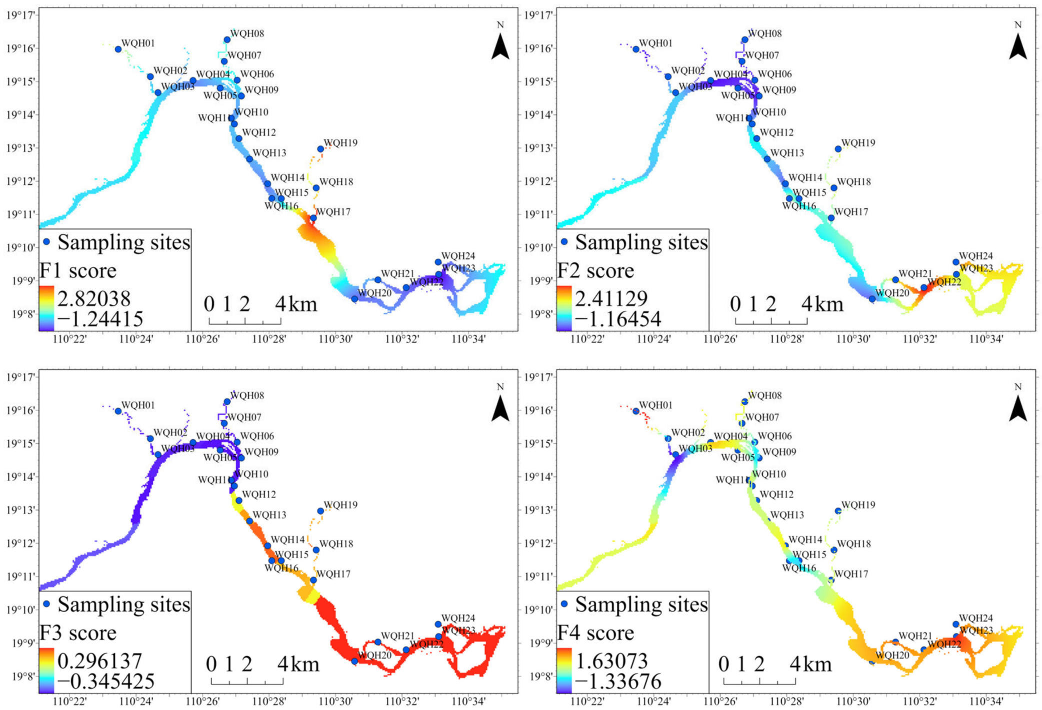

Figure 9. Spatial distribution of factor scores at sampling points.

The sampling sites with high scores on Factor 2 were WQH21, WQH22, and WQH24, where the pollutant was mainly COD. All three sampling sites were located at the downstream mouth of the Wanquan River, and it is generally assumed that COD_{Mn} and COD are associated with domestic sewage discharges due to urbanization. The lower reaches of the Wanquan River are located in the center of Bo'ao town, and in recent years, due to the rapid development of the construction of the Asia International Forum, the high rate of urbanization may have placed a burden on the sewage treatment system that has not yet been formed to support it, and it is presumed that the high COD at these points is mainly related to some untreated sewage.

The sampling sites with high scores on factor 3 are WQH16 and WQH23, where the pollutants are mainly Cr^{6+} and As. Both sampling sites are located near traffic arteries, and some studies have shown that elemental Cr is closely related to traffic. It is assumed that the high Cr^{6+} values at these sites may be related to the migration of chromium from the plating of car wheels [34,35].

The sampling site with a high score on factor 4 is WQH01, located in the upper reaches of the Wenqu River, where the pollutant is mainly COD_{Mn}, the cause of which is similar to COD and presumably due to inadequate sewage treatment.

3.6. Recommendations for Water Pollution Prevention and Control

1. Strengthen sewage treatment: Ensure that industrial, agricultural, and urban wastewater are all treated properly and discharged to environmental standards by building and improving sewage treatment facilities and using appropriate technologies and methods to effectively remove harmful substances and pollutants;
2. Improve agricultural practices: Promote sustainable agricultural practices in the area around the Wanquan River and call on farmers to reduce the use of chemical fertilizers and pesticides. Promote and popularize more scientific irrigation methods to reduce soil erosion and nutrient loss and prevent agricultural surface pollution from entering the river;
3. Sound water quality monitoring and assessment system: Establish a comprehensive water quality monitoring network to regularly monitor and assess the water quality of the Wanquan River. Ensure that problems can be identified in a timely manner and that appropriate measures can be taken quickly to treat and improve the situation;
4. Transboundary cooperation and policy coordination: Water pollution is a transboundary issue that requires cooperation and coordination between all relevant sectors and stakeholders. Strengthen the integration of policies to promote the unified management of river basins and achieve integrated water resource management and protection.

4. Conclusions

(1) The mean values of water quality indicators in the Wanquan River basin all meet the requirements for Class III water in China's surface waters; Hg exceeds the standard most seriously, at 54%, while TN (17%), TP (17%), NH_4^+-N (13%), and CODMn (both 13%) also exceed the standard to a small extent;

(2) Spatially, NH_4^+-N and TN correspond to Class V water and below near the Tayang River in the south-eastern part of Qionghai, while Hg corresponds to Class III water in the western part of Qionghai and Class IV water and below in most other areas. The other six pollution indicators correspond to Class III water and above in most areas;

(3) The single factor pollution index method shows that Hg has the highest average single factor index (1.3) and is the most important source of pollution. In total, 87.5% of the sample sites meet the surface water quality standard of Class V and above. With Class III water as the target water quality, 92% of the sample sites were at the mild pollution level or above. Spatially, the lightest level of pollution was found in the western part of Qionghai City and the heaviest in the Tayang River area;

(4) The results for the Nemerow pollution index method show that 83% of the sample points are at the light pollution level or above. Spatially, the water pollution is better in the southwest of Qionghai, and the pollution level is worst in the Tayang River basin;
(5) The results of the pollution source analysis indicate that the possible sources of pollution in the Wanquan River include organic and chemical pollution, which may be related to the city's sewage treatment system and industrial and agricultural activities.

Author Contributions: Methodology, Y.W. and M.A.; Software, M.A. and Y.W.; Validation, M.A. and J.J.; Formal analysis, G.F.; Investigation, J.J. and Y.S.; Resources, X.W.; Data curation, M.A.; Writing—original draft, M.A.; Writing—review and editing, M.A., Y.S. and X.W.; Visualization, G.F.; Supervision, Y.S. and M.A.; Project administration, J.J. and Y.S.; Funding acquisition, J.J. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Comprehensive Survey of Natural Resources in Haichengwen Coastal Zone: DD20230414.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are unavailable due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

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