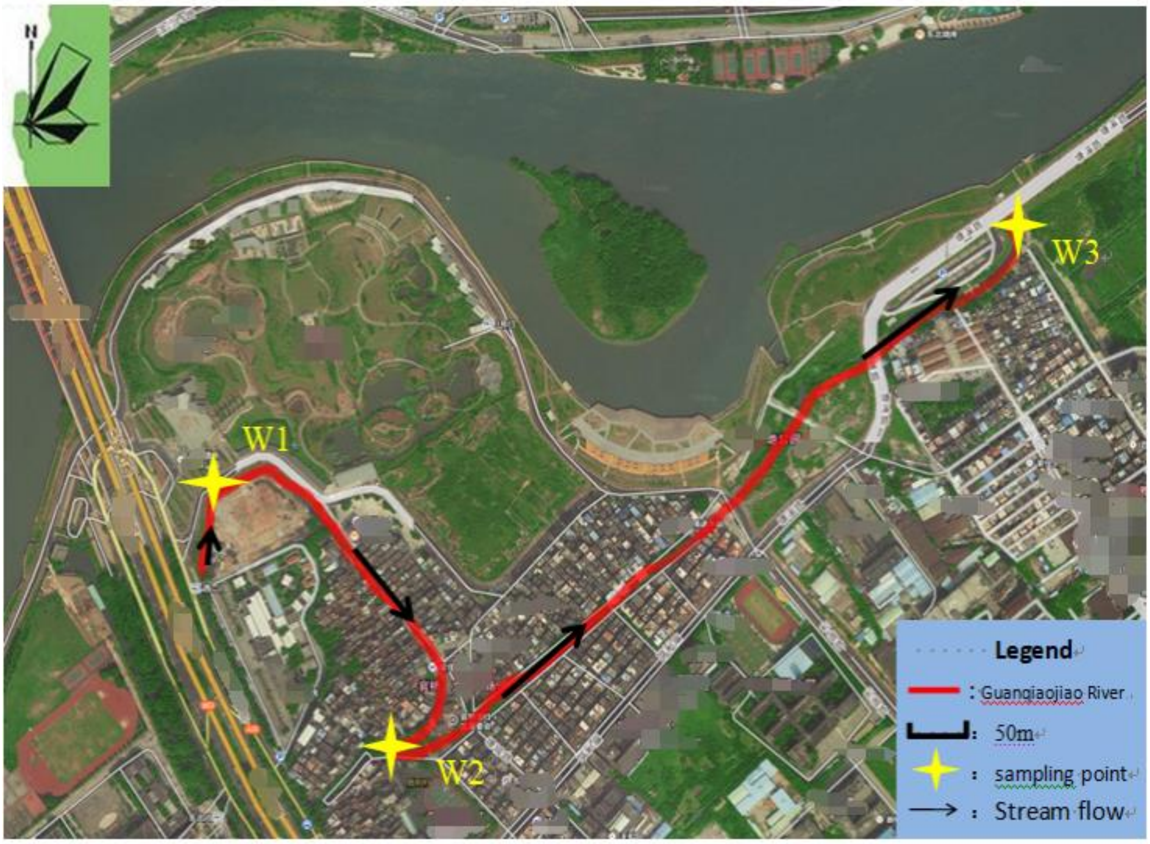

Fig 1: Layout of sampling points of Guanqiaojiao River

3.2 Water Sample Collection and Analysis

The wet season of Guanqiaojiao River is selected as the sampling time, and the specific time is August 2019. Water samples were collected from three sampling points in the river, and immediately stored in an environment below 4℃, with a storage duration of no more than 24 hours. According to the Environmental Quality Standard for Surface Water (GB3838-2002), the test factors of this project are: transparency (SD), dissolved oxygen (DO), 5-day biochemical oxygen demand (BOD5), chemical oxygen demand (CODCr), total nitrogen (TN) and total phosphorus (TP). Sampling and analysis methods were carried out according to the relevant requirements of Environmental Quality Standard for Surface Water (GB3838-2002) and Technical Specifications for Monitoring Surface Water and Sewage, as shown in TABLE II.

TABLE II. Analysis methods and detection limits of experimental items

No.	Monitoring project	Testing standard	Test method	Instrument	Detection limit (mg/L)
1	Transparency	—	Transparent scale method	Transparent scale	—
2	Dissolved oxygen	—	Oxygen electrode method	Portable dissolved oxygen analyzerJPB-607A	0
3	Chemical oxygen	GB11914-89	Dichromate method	50ml burette	5

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	demand				
4	Biochemical oxygen demand	HJ505-2009	Dilution and inoculation method	Biochemical incubator SPX-250B	0.5
5	Total nitrogen	HJ636-2012	Ultraviolet spectrophotometry with alkaline potassium persulfate digestion	Ultraviolet visible light photometer UV759	0.05
6	Total phosphorus	GB11893-89	Ammonium molybdate spectrophotometry		0.01

3.3 Data Processing

Excel2010 and SPSS16.0 were used for statistical analysis of the water quality data processing of Guanqiaojiao River.

3.4 Research Methods

3.4.1 Comprehensive pollution index method

Pollution index indicates that the discharge of a certain pollutant exceeds the multiple of the discharge of this pollutant in the evaluation standard. Pollution index method is of great significance in practical research, and it is widely used in research evaluation [10]. Pollution index method can be divided into two methods: single factor index method is to calculate the standard pollution index of each index respectively, in which Cio is selected according to the actual situation. When Pi >1, it indicates that the pollution exceeds the standard; the comprehensive pollution index method uses different methods to process the Pi of several indexes to get the comprehensive index P, and then makes evaluation according to the self-made scoring standard to get the result. The calculation formula is as follows:

$$P_i = C_i / C_{io} \quad (1)$$

$$P = \frac{1}{n}\sum_{i=1}^{n} P_i \quad (2)$$

Wherein: Pi -- Pollution index of the i-th pollutant;

C_i --Annual average value of the i-th pollutant;

C_{io}-- Evaluation standard of the i-th pollutant;

P-average pollution index;

n--number of pollutants participating in the evaluation;

As the DO index has the effect opposite to those of other water quality evaluation factors, the smaller its value, the worse the water quality. Therefore, the calculation method of dissolved oxygen pollution

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index is the reciprocal of formula (1) [14]. See formula (3):

$$P_i = \frac{C_{io}}{C_i} \tag{3}$$

According to a certain classification principle, the water quality is classified, and the specific pollution degree classification standard [15] is shown in TABLE III.

TABLE III. Classification standard of pollution degree

Pollution index P	Pollution level
< 0.2	Clean
0.2~0.4	Relatively clean
0.4~0.7	Light pollution
0.7~1.0	Medium pollution
1.0~2.0	Heavy pollution
> 2.0	Serious pollution

3.4.2 Fuzzy mathematics evaluation method

Fuzzy evaluation method is a method based on fuzzy mathematics. It uses the principle of fuzzy relation synthesis to theorize some factors with fuzzy boundaries and difficult quantification, and comprehensively evaluates the subordinate status of the evaluated object from multiple factors [11, 12]. The concept of fuzzy set is the characteristic function of fuzzy mathematics in the intermediate state, and it is represented by membership function. In fuzzy mathematics, let A be a fuzzy set and the membership function be fA, then fA(A) represents the membership degree of X with respect to A, that is, the degree to which X belongs to A. In fuzzy mathematics, membership degree can be used to describe many fuzzy boundaries in objective things. For example, the "pollution degree" in water quality evaluation is a fuzzy concept, so the classification standard of water pollution degree evaluation should also have fuzzy characteristics. It is not reasonable to adopt general evaluation methods, but fuzzy mathematics evaluation method is more in line with objective reality [13].

The evaluation method is to evaluate each parameter at first, and then give appropriate weight to each parameter considering its position in the whole. On this basis, the fuzzy concept is used for reasoning, and the evaluation result is obtained through calculation. Compared with other methods, the advantages of this method are that the membership function is used to describe the boundary line of water quality, and each parameter is evaluated. Considering the difference of each parameter in the overall pollution, different weights are given, so that the evaluation results are closest to the actual situation.

The fuzzy evaluation method generally needs the following steps:

3.4.2.1 Establishing the factor set and evaluation set of the evaluation object

Five representative water quality indexes of the river were selected as evaluation factors after screening

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from the six indexes of the original monitoring survey, and the factor set was established:

$$U=\{DO,\ COD_{Cr},\ BOD_5,\ TN,\ TP\}$$

According to the *Environmental Quality Standard for Surface Water* (GB3838-2002), the surface water quality was divided into five categories, and the evaluation set was obtained. The five pollution classes were named clean, relatively clean, light pollution, medium pollution and heavy pollution in turn.

$$V=\{\ ,\ II,\ III,\ IV,\ V\}$$

3.4.2.2 Establishing fuzzy matrix

According to the five category standards of surface water quality, the corresponding membership function of each evaluation factor was established. Assuming that the membership function of water quality is linear, the membership function of the first category of water quality is:

$$f(x)=\begin{cases} 0 & x \ge x_2 \\ \dfrac{x-x_2}{x_1-x_2} & x_1 < x < x_2 \\ 1 & x \le x_1 \end{cases}$$

The membership function of class i (=2, 3, 4) water quality between class I water quality and class V water quality is:

$$f(x)=\begin{cases} 0 & x \le x_{i-1},\ \text{or } x \ge x_{i+1} \\ \dfrac{x-x_{i-1}}{x_i-x_{i-1}} & x_{i-1} < x < x_i \\ \dfrac{x-x_{i+1}}{x_i-x_{i+1}} & x_i < x < x_{i+1} \end{cases}$$

The membership function of class V water quality is:

$$f(x)=\begin{cases} 0 & x \le x_5 \\ \dfrac{x-x_4}{x_5-x_4} & x_4 < x < x_5 \\ 1 & x \ge x_5 \end{cases}$$

Wherein, x in the formula is the actual concentration value of a pollutant, and x with subscript is the standard value of water quality classification corresponding to the subscript number.

After U and V are given, the relation fuzzy matrix can be obtained according to the fuzzy relation among evaluation factors. That is, according to the evaluation principle of fuzzy mathematics, the membership degree matrix R($m \times n$ order) is composed of m evaluation factors belonging to n different

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levels of membership degree:

$$R=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}$$

The calculation method adopted in this study is to first establish a membership degree matrix of m x n order by using the indexes of all pollutants. The number of pollutant items is m=5, and the water quality category standard is n=5, which means to establish a membership degree matrix of 5 x 5.

$$\underline{R}=\begin{bmatrix} f(DO\ \text{I}) & \cdots & f(DO\ \text{V}) \\ f(COD_{Cr}\ \text{I}) & \cdots & f(COD_{Cr}\ \text{V}) \\ f(BOD_5\ \text{I}) & \cdots & f(BOD_5\ \text{V}) \\ f(TN\ \text{I}) & \cdots & f(TN\ \text{V}) \\ f(TP\ \text{I}) & \cdots & f(TP\ \text{V}) \end{bmatrix}$$

Finally, the category corresponding to the maximum membership degree value in each row is used as the single evaluation result of each parameter.

3.4.2.3 Determining fuzzy weight vector.

The greater the weight, the greater the impact of the evaluation factor on water quality. In this evaluation, according to the degree of water pollution by a certain factor, each factor was weighted by exceeding the standard, and then the determined weight distribution of the pollutant was given. The more exceeding the standard, the greater the weight [18].

In the environmental quality evaluation, it is a very important key step to assign the weight of each parameter. At present, there are two commonly used ways. One is to give the weight by experienced experts, and the other is to use the weight initially considered by the water quality classification standard. Because the second method takes into account not only the actual concentration value of each pollutant, but also the calculation method of the standard value of water quality category corresponding to each factor, it is more in line with the actual situation, and thus was adopted in this study. Its calculation formula is:

$$w_i=\frac{x_i/s_i}{\sum_{i=1}^{n} x_i/s_i}\left(\sum_{i=1}^{n} w_i=1\right) \quad (4)$$

Wherein: wi-- Weight value of parameter (pollutant) i;

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s_i-- Average value of the five category standards of the i parameter;

xi-- Actual concentration value of parameter i .

That is to say, in a weight matrix of l x n (n=5), that is, in a weight matrix of l x 5.

$$\underline{W} = [w_1 \quad w_2 \quad w_3 \quad w_4 \quad w_5]$$

Note: because the DO index has the opposite meaning to other indexes, the larger the value of this index, the better the water quality of the river. Then, the weighted value wi of dissolved oxygen is the inverse of the above formula.

3.4.2.4 Making comprehensive evaluation by fuzzy matrix compound operation

The fuzzy comprehensive evaluation vector B is obtained by the compound operation of the fuzzy matrixes W and R, which means that: the 1st-5th columns in R are the membership degrees of five single indexes on f(x) to I-V water; The five values in W are the weight of five single water pollution indexes in f(x) on the overall pollution. When considering the overall membership degree of several types of water, we must take into account of the membership degree of each classification index to several types and their weights, which is the purpose of the compound operation of the first row in W and the first column in R. It is the membership degree of the evaluation object to the j-th element in the evaluation set when all factors are considered comprehensively. Finally, according to the principle of maximum membership degree, the pollution level of each river water body is determined.

$$B = \underline{W} \times \underline{R} = [w_1 \quad w_2 \quad w_3 \quad w_4 \quad w_5] \times \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = [\mathrm{b}_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5]$$

IV. RESULTS AND ANALYSIS

4.1 Water Quality Factor Characteristics of Single Factor Index Evaluation

According to the water pollution characteristics of Guanqiaojiao River, combined with the integrity and practicability of the collected data, five indexes including DO, CODCr, BOD5, TN and TP were selected as the water quality evaluation factors. Based on the functional categories of water environment, the use purpose of Guanqiaojiao River and its environmental protection objectives, the class IV standard in Environmental Quality Standard for Surface Water (GB3838-2002) was adopted as the evaluation standard of river water quality. See TABLE IV for details.

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TABLE IV. Evaluation criteria (unit: mg/L)

Water quality param	Water quality category				
	I	II	III	IV	V
DO	7.5	6	5	3	2
COD_{Cr}	15	15	20	30	40
BOD_5	3	3	4	6	10
TN	0.2	0.5	1.0	1.5	2.0
TP	0.02	0.1	0.2	0.3	0.4

After a series of experimental tests and analysis, the water quality monitoring data of Guanqiaojiao River in the wet season are statistically processed, and the monitoring results are shown in TABLE V.

TABLE V. Data sheet of river water quality monitoring

Monitoring project	SD/(cm)	DO/(mg/L)	COD_{Cr}/(mg/L)	BOD_5/(mg/L)	TN/(mg/L)	TP/(mg/L)
W1	48	0.1	15.0	3.5	5.10	0.661
W2	36	0.1	15.0	3.4	6.04	0.64
W3	35	0.4	37.6	8.7	9.80	1.08

Compared with the monitoring results, the single factor index evaluation method shows that the transparency of each sampling point is less than 0.5 m, which is inferior to class V water standard. The chemical oxygen demand (CODCr) of sampling points W1 and W2 met the class II standard, while the water quality of sampling point W3 reached class V water. The 5-day biochemical oxygen demand (BOD5) of sampling points W1 and W2 met the class III standard, but the water quality of W3 reached class V, but not class IV. Total nitrogen (TN) content in the three sampling points is more than 2.0 mg/L, reaching the standard of inferior grade V water. Among them, the total nitrogen content at the sampling point W3, where the river flows into Dongguan City Waterway, is as high as 8.7mg/L, and according to the field investigation, it is observed that the water body is seriously black and smelly from the sensory point. The total phosphorus (TP) content in each sampling point has exceeded the class V standard and reached the inferior class V water quality standard, which indicates that the water quality is extremely poor.

4.2 Evaluation Results of Comprehensive Pollution Index Method

According to the functional categories of water environment, the actual situation of Guanqiaojiao River, the use purpose of the local waters and its environmental protection objectives, the water quality evaluation standard of Guanqiaojiao River adopts class IV standard in the national Environmental Quality Standard for Surface Water (GB3838-2002). The evaluation results of river water quality by comprehensive pollution index method are shown in TABLE VI.

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TABLE VI. Water quality evaluation results of Guanqiaojiao River (comprehensive pollution index method)

Evaluation project	DO/(mg/L)	COD_{Cr}/(mg/L)	BOD_5/(mg/L)	TN/(mg/L)	TP/(mg/L)
W1	0.1	15.0	3.5	5.10	0.661
W2	0.1	15.0	3.4	6.04	0.64
W3	0.4	37.6	8.7	9.80	1.08
C_i (average pollutant concentration)	0.11	30.98	7.17	8.51	0.95
C_{io}	3	30	6	1.5	0.3
P_i	27.27	1.03	1.20	5.67	3.17
Pollution level of major pollutants	Serious pollution	Heavy pollution	Heavy pollution	Serious pollution	Serious pollution
Single factor water quality category	Inferior class V	class V	class V	Inferior class V	Inferior class V
P	7.67				
Comprehensive pollution index evaluation	Serious pollution				
Comprehensive water quality category	Inferior class V				

The comprehensive pollution index of river water quality was 7.67, which was much higher than 2.00. According to the discrimination standard of water quality pollution, it has been classified as serious pollution, reaching the inferior V water standard. It can be seen from Table 6 that the average pollution index of DO was the highest among the main pollution indexes, which was 27.27, far more than 2.00. It indicates a serious pollution. The average pollution index of TN was 5.67, which was a serious pollution. The average pollution index of TP was 3.17, more than 2.00, which was also a serious pollution. CODCr and BOD5 were mild pollution. Their average pollution indexes exceeded 1.00, but did not exceed 2.00. The results showed that nutrients such as N and P led to the serious pollution of Guanqiaojiao River. The average pollution index of dissolved oxygen was the highest among all pollution indexes, so the phenomenon of anoxia was the most serious, showing a strong eutrophication of domestic pollution. The organic pollution was mild. At present, the main task to improve the water quality of the river is to remove nitrogen and phosphorus.

4.3 Evaluation Results of Fuzzy Mathematics Evaluation Method

4.3.1 Establishing water quality membership function

Taking the membership function of DO as an example (because the meaning of DO is opposite to other indexes, its interval range is also opposite), and so on.

$$\text{class I water} \quad X_1 = \begin{cases} 0 & 6 < x < 7.5 \\ \dfrac{x\text{-}6}{1.5} & 0 \le x \le 6 \\ 1 & 7.5 \le x \le 10.9 \end{cases}$$

Note: 10.9 is the content of saturated dissolved oxygen in water at 10°C)

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$$\text{class II water} \quad X_2 = \begin{cases} 0 & x \geq 7.5, \text{or } x \leq 5 \\ \dfrac{7.5\text{-}x}{1.5} & 6 < x < 7.5 \\ x\text{-}5 & 5 < x < 6 \end{cases}$$

$$\text{class III water} \quad X_3 = \begin{cases} 0 & x \geq 6, \text{or } x \leq 3 \\ 6\text{-}x & 5 < x < 6 \\ \dfrac{x\text{-}3}{2} & 3 < x < 5 \end{cases}$$

$$\text{class IV water} \quad X_4 = \begin{cases} 0 & x \geq 5, \text{or } x \leq 2 \\ \dfrac{x\text{-}5}{2} & 3 < x < 5 \\ x\text{-}2 & 2 < x < 3 \end{cases}$$

$$\text{class V water} \quad X_5 = \begin{cases} 0 & x \geq 3 \\ x - 2 & 2 < x < 3 \\ 1 & x \leq 2 \end{cases}$$

The membership degree matrix of each parameter is obtained:

$$\text{Membership matrix } \underline{R} = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.902 & 0.098 \\ 0 & 0 & 0 & 0.7075 & 0.2925 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} \text{DO} \\ \text{COD}_{Cr} \\ \text{BOD}_5 \\ \text{TN} \\ \text{TP} \end{matrix}$$

Digital category I II III IV V

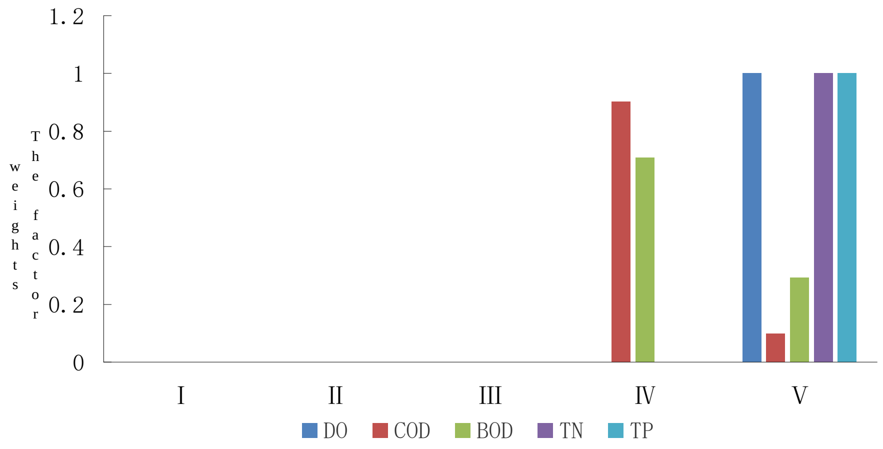

Fig 2: Weight of evaluation factors of Guanqiaojiao River

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It can be seen that DO, TN and TP in rivers belonged to water quality V, all reaching 100%. CODCr belonged to water quality IV, reaching 90.2%; BOD5 belonged to water quality IV, reaching 70.75%. According to the weight calculation results (see Figure 2), the surface layer of the river was in serious short of oxygen. The pollution factors with the largest weight were TN and TP, with weights far exceeding other indexes, followed by CODCr and BOD5. It shows that the main pollutants of Guanqiaojiao River are TN and TP, that is, nitrogen and phosphorus nutrients.

4.3.2 Listing and calculating the weight of each parameter.

Based on the monitoring data of Guanqiaojiao River in August, 2019, the weight of each water quality monitoring item was calculated. See Table 7 for the calculation table.

TABLE VII. Weight Calculation Table of Guanqiaojiao River Water Quality Project

Item	I	II	III	IV	V	x_i	s_i	x_i/s_i	w_i
DO	7.5	6	5	3	2	0.11	4.7	0.023	0.001
COD_{Cr}	15	15	20	30	40	30.98	24	1.291	0.083
BOD_5	3	3	4	6	10	7.17	5.2	1.379	0.089
TN	0.2	0.5	1.0	1.5	2.0	8.51	1.04	8.183	0.527
TP	0.02	0.1	0.2	0.3	0.4	0.95	0.204	4.657	0.300

As can be seen from Table 7, the weight $\underline{W} = [0.001 \quad 0.083 \quad 0.089 \quad 0.527 \quad 0.300]$

4.3.3 Fuzzy matrix compound operation

$$B = \underline{W} \times \underline{R} = [0.001 \quad 0.083 \quad 0.089 \quad 0.527 \quad 0.300] \times \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.902 & 0.098 \\ 0 & 0 & 0 & 0.7075 & 0.2925 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= [0 \quad 0 \quad 0 \quad 0.1378 \quad 0.8622]$$

Seen from the above fuzzy comprehensive evaluation results, the evaluation grades of Guanqiaojiao River in wet season are as follows: the membership degree of class I water is 0, that of class II water is 0; that of class III water is 0; that of class IV water is 0.1378, and that of class V water is 0.8622 at the maximum. Therefore, according to the evaluation method and principle, the greater the degree of membership degree to which kind of water level is, the more it belongs to which level. From the comprehensive evaluation results, it can be judged that the water body of the river is classified as class V water.

4.4 Comprehensive Evaluation and Analysis

From Table 5, it can be seen that the comprehensive result of single factor index method and comprehensive index evaluation was inferior to class V water, which belonged to serious pollution.

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However, from the results of fuzzy comprehensive evaluation, the water quality of Guanqiaojiao River belonged to class V water, which was judged as heavy pollution.

In the evaluation of water environment quality, the single factor index method can determine the water quality category of each factor and find the main pollution factors, while the calculation of comprehensive pollution index method is based on the single factor pollution index evaluation. Therefore, the evaluation can judge the water quality through quantitative data, which can not only intuitively judge whether the comprehensive water quality reaches the functional area goal and its water quality category, but also judge the comprehensive water quality category [14].

From the analysis process, it can be seen that: fuzzy mathematics evaluation method can well transform qualitative water quality into quantitative evaluation by calculating the membership degree of each factor, which is reasonable and scientific in theory. Using this method, we can get the water quality reflected by the interaction of various factors, and determine the main pollution factors and main pollution types [15]. In this study, the weights of TN and TP are obviously far higher than other indexes, which indicates that nitrogen and phosphorus are the main factors of the serious pollution in the river.

Fuzzy mathematics method was used to calculate the membership degree of evaluation factors to evaluation criteria, which avoided the generation of a large number of uncertain factors in urban environment. In the water quality evaluation, the fuzzy mathematics evaluation results had the most serious grade V. But when the comprehensive water quality was inferior grade V, the evaluation of inferior grade V water quality was lacking, which led to the conservative evaluation conclusion of this study [16]. Therefore, to make the evaluation results more in line with the actual situation, we should take the actual situation as the basis, and quantify the upper limit of pollutants corresponding to the inferior V water quality standard when using fuzzy evaluation method to evaluate water quality, so as to provide a basis for the practical application in water environment [17].

From the comparison of the evaluation results of the three methods, the single factor pollution index method is more suitable for the actual situation of Guanqiaojiao River. This method only classifies the water quality with a deterministic index, and it cannot reflect the true pollution degree of water body. So, the method itself has certain limitations. To ensure the rationality and scientificity of the research, we should combine the pollution index method and fuzzy mathematics method to evaluate the river, thus providing a scientific basis for the regulation of Guanqiaojiao River [18,19].

V. CONCLUSION

(1) By monitoring and investigating some water quality indexes of Guanqiaojiao River, and analyzing and evaluating the monitoring data of major pollutants, it is found that there were different levels of pollution in the river and the river body did not meet the IV water quality standard of the river section. Among it, TN and TP were the main pollution factors, which had strong characteristics of domestic pollution and eutrophication and relatively small organic pollution.

(2) According to the comprehensive pollution index method, the water quality of Guanqiaojiao River was inferior grade V, indicating that the water had been seriously pollute and should be treated urgently. This method can synthesize the pollution degree of each water quality index, intuitively judge the water quality status, and improve the defect of imperfect evaluation of the water quality pollution by single index. The difference between the evaluation result and the standard of the actual water body was small. Thus, this method is more in line with the real situation.

(3) When using the fuzzy comprehensive evaluation method, if the evaluation index was inferior V, the expression would be {0,0,0,0,1}, regardless of the concentration. This method underestimated the contribution of inferior V, thus making the evaluation conclusion conservative. It can comprehensively consider various pollution factors and their relations, and can reflect the water quality objectively. Besides, the theory and method of environmental evaluation can be established on the basis of a rigorous mathematical model. Through weight calculation, when the concentration of individual pollutants in water exceeded the standard, the evaluation results tended to be biased because of the relatively large weight.

(4) By comparing the evaluation results with the objective facts, among the three methods, the evaluation results of pollution index method were more in line with the actual water environment of Guanqiaojiao River in this study. The selection of different evaluation methods should be based on the objective situation and cannot be generalized; in the water quality evaluation of Guanqiaojiao River, comprehensive pollution index method and fuzzy mathematics evaluation method can be combined to make a more comprehensive and objective evaluation.

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