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Innovative approach for the development of a water quality identification index—a case study from the Wen-Rui Tang River watershed, China

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ABSTRACT

Many different approaches have been suggested for the assessment of organic pollution and related water quality variables. However, many methods used to assess organic pollution cannot qualitatively estimate the degree of importance of each pollutant. Water quality identification indices can provide comprehensive water quality information, which is both qualitative and quantitative, especially for areas worse than Grade V of the National Surface Water Quality Standard of China. However, this method considers every indicator equally, without considering the degree of importance of each parameter. Consequently, in this study, the entropy weight method was combined with the water quality identification index method. The improved comprehensive water quality identification index was applied to a water quality data-set for the Wen-Rui Tang River in China, which was generated in 2009 during six months of monitoring at 16 different sites and included seven parameters. The results indicated that the improved comprehensive water quality identification index provided an objective evaluation of each water quality indicator. Understanding the significance of each water quality parameter will help to implement more effective water quality improvement plans.

Keywords: Organic pollution; Water quality assessment; Entropy weight methods; Water quality identification index method

1. Introduction

Different regions of the world experience different types of water problems. Areas with a shortage of water resources may experience both increased water scarcity and decreased water quality [1,2]. Anthropogenic influences (urban, industrial, and agriculture activities) can degrade water quality and cause organic pollution (Dissolved oxygen, Chemical oxygen demand, and Five-day biochemical oxygen demand) [3,4]. Organic pollution is a serious water quality issue. Organic pollutants can have an important role in evaluating levels of water contamination due to natural or anthropogenic inputs to surface water sources. Many approaches to the assessment of organic pollution and related water

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quality variables have been suggested. However, many methods are only able to evaluate water quality if it is better than Grade V, and are therefore not suitable for seriously polluted (worse than Grade V) areas. Furthermore, few methods can simultaneously evaluate water quality both qualitatively and quantitatively.

The Wen-Rui Tang River flows through a large urban center, Wenzhou city, which is situated in the eastern part of Zhejiang province, China. The water quality of the river is classified as worse than Grade V, which is the lowest water quality classification in China (Wenzhou State of the Environment, 2008). The Water Quality Identification Index is a water quality assessment method that is capable of determining water quality that is inferior to Grade V, and quantitatively estimating the relative diversity of the water quality in the same water quality grade [5]. However, this method treats every water quality indicator with equal importance. It is difficult to stress the importance of each individual water quality indicator in a water quality assessment. To solve this problem, the entropy weight method can be used in conjunction with the water quality identification index to provide a comprehensive evaluation of each water quality indicator, which could then overcome the subjectivity of using the arithmetic mean of all indicators. This study proposes the use of this improved comprehensive water quality identification index.

The aim of the this study was to analyze seven organic pollution parameters, which were collected bimonthly in 2009 at 16 monitoring sites in the Wen-Rui Tang River watershed, using the entropy weight method combined with the water quality identification index. Furthermore, we (1) analyzed the feasibility of the improved water quality identification index method, (2) identified the main impact factor when using the entropy weight method, and (3) used the improved water quality identification index to analyze the bimonthly variation and spatial characteristics of organic pollution.

2. Materials and methods

2.1. Study area

The Wen-Rui Tang River watershed flows through a densely populated area on the east coast of China (Fig. 1). Since the rapid economic development in the 1980s and the subsequent significant population increase, water quality in the Wen-Rui Tang River has deteriorated. Due to the direct discharge of large amounts of industrial, agricultural, and domestic wastewater into the river, the water quality has degraded dramatically [6–8]. In a previous study, concentrations of NH_4^+-N and TN in all samples exceeded the Grade V national water quality standard, and one-

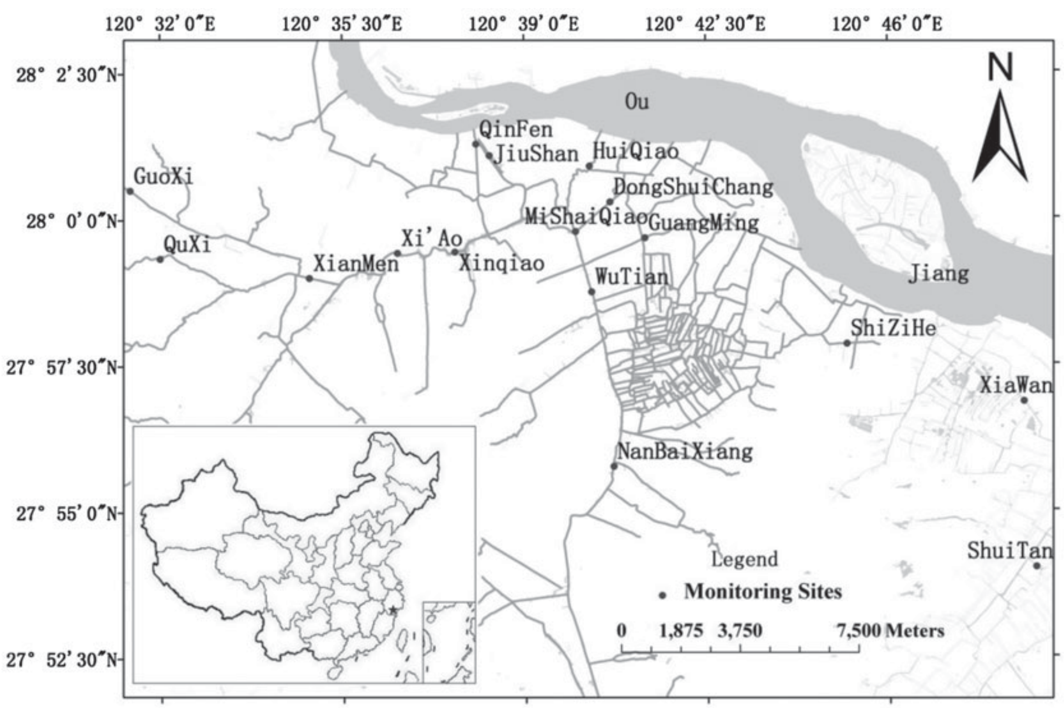

Fig. 1. Study area and monitoring sites.

third of all samples exceeded the Grade V national water quality standard for BOD_5 [9]. Many of the urban waterways are considered dead zones due to persistent hypoxia (Asian Info Services, 2004).

2.2. Parameters monitored and sampling dates

Water quality data were obtained from the Wenzhou Environmental Protection Bureau. The data included seven water quality parameters that were measured bimonthly at 16 water quality monitoring sites in 2009. The seven parameters selected as indicators of organic pollution were dissolved oxygen (DO), five-day biochemical oxygen demand (BOD_5), cadmium-chemical oxygen demand index (COD_{Cr}), petroleum, ammonia nitrogen (NH_4^+-N), volatile phenol, and the potassium permanganate-chemical oxygen demand index (COD_{Mn}). The sampling, preservation, transportation, and analysis of the water samples followed standard methods (China 2002b). Water samples from the 16 sites were collected at a depth of 0.5 m. The samples were kept in 1 L polyethylene plastic bottles, which had been previously cleaned. All samples were maintained at 4℃ during transportation to the laboratory and during the later processing and analysis. The specific method used is given in Table 1.

Where variables were below the detection limit in samples, the values were replaced by the method detection limit. We ignored the measured values of volatile phenol in May and July of 2009, because all values were <0.002 during these two months.

2.3. Multivariate analysis methods

2.3.1. Organic pollution index A

Organic pollution index (A) is a comprehensive method for the evaluation of organic pollution according to the sum of the equivalent standard pollution concentrations of ammonia nitrogen, dissolved oxygen, biochemical oxygen demand, and cadmium-chemical oxygen demand. The method can be used to determine the comprehensive index of water quality proposed by Shanghai environmental protection workers. Organic pollution index (A) [10] is defined by:

$$A = \frac{BOD_i}{BOD_0} + \frac{COD_i}{COD_0} + \frac{NH_3\text{-}N_i}{NH_3\text{-}N_0} + \frac{DO_i}{DO_0} \qquad (1)$$

where COD_i, NH_3-N_i, BOD_i, and DO_i are the measured concentrations, and COD_0, DO_0, BOD_0, and NH_3-N_0 are the standard concentrations, as defined in the water quality standards of China, GB3838-2002 (Table 4). In this study, considering the poor water quality and to be consistent for all the samples, COD_0, DO_0, BOD_0, and NH_3-N_0 were set to a concentration that represented Grade V of the Environmental Quality Standards for Surface Water (State Bureau of Environmental Protection, 2002).

Based on previous research [11], if $A < 0$, the water quality is excellent; if $0 < A < 1$, the water quality is good; if $1 < A < 2$, water is slightly contaminated; if $2 < A < 3$, water is lightly polluted; if $3 < A < 4$, water is moderately polluted; and if $A > 4$, water is heavily polluted.

2.3.2. Comprehensive water quality identification index (Iwq)

The comprehensive water quality identification index (Iwq) is a tool used for general water quality assessments of surface water, which can fully depict the general water quality of surface water. The comprehensive water quality identification index consists of a whole number (*X*) and a decimal fraction (*YMN*). Pollution categories are classified as a whole number and the difference in the degree of pollution in the

Table 1
Analytical methods for the variables of water quality

Variables	Abbreviations	Units	Analytical methods
pH	pH	pH-unit	pH-meter
Water temperature	T	℃	Mercury thermometer
Five-day biochemical oxygen demand	BOD_5	mg/L	Dilution and inoculation test
Volatile phenol	Volatile phenol	mg/L	Spectrophotometric determination with 4-Amino-Antipyrin
Dissolved oxygen	DO	mg/L	Probe method iodometric method
Petroleum	Petrol	mg/L	Infrared spectrophotometry
Potassium permanganate index	COD_{mn}	mg/L	Permanganimetric method
Chemical oxygen demand	COD	mg/L	Dichromate method
Ammonia nitrogen	NH_4^+-N	mg/L	Nessler'reagent-colorimetry

same category is determined by the decimal fraction [5,12] (Table 3). The Iwq is then expressed by the following formula:

$$\mathrm{Iwq} = X \cdot YMN \tag{2}$$

where X is the comprehensive water quality classification; Y is the position of a Grade X water quality interval; M is the number of individual water quality indicators considered that are worse than the desired water quality of the surface water environment function areas (e.g. if $M = 0$, all of the water quality evaluation indicators under consideration have reached the desired water quality, whereas if $M = 1$, one of the water quality evaluation indicators has failed to reach the desired water quality); and N is the result of a comparison of the water quality categories and the desired water quality of the surface water. Additionally,

$$X \cdot Y = \frac{1}{m}\sum_{m}^{1}(X_i \cdot Y_i) \tag{3}$$

where m is the number of the water quality index. The formula describing $X_i \cdot Y_i$ is also called the single factor water quality identification index. Different water quality classifications are calculated in different ways.

If the water quality grade is between I and V, $X_i \cdot Y_i$ can be calculated using the following formula:

$$X_iY_i = \alpha + \frac{C_i - C_{iko}}{C_{iuk}} - C_{iko} \quad \text{general indicators} \tag{4}$$

$$X_iY_i = \alpha + 1\frac{C_i - C_{iko}}{C_{iuk}} - C_{iko} \quad \text{dissolved oxygen (DO)} \tag{5}$$

where C_i is the measured concentration of the ith water quality index; C_{iuk} is the upper limit value of the Grade X_i water quality standard for the ith water quality index, $K = \alpha = X_i$; C_{iko} is the lower limit value of the Grade X_i water quality standard for the ith water quality index; and α = Grade I, II, III, IV, or V, which is determined by comparing the monitoring data with national standards.

If the water quality is worse than or equal to Grade V, $X_i \cdot Y_i$ can be calculated using the following formula:

$$X_iY_i = 6 + \frac{C_i - C_{iu}}{C_{iu}} \quad \text{general indicators} \tag{6}$$

$$X_iY_i = 6 + \frac{C_{io} - C_i}{C_{io}} \cdot m \quad \text{dissolved oxygen} \tag{7}$$

where C_{iu} is the upper limit value of the Grade V water quality standard for the ith water quality index; C_{io} is the lower limit value of the Grade V water quality standard for the DO; and m is a correction coefficient. In this study, $m = 4$.

Based on previous research, if $1 \le X \cdot Y \le 2$, water samples comply with Grade I water quality; if $2 \le X \cdot Y \le 3$, water samples comply with Grade II water quality; if $3 \le X \cdot Y \le 4$, water samples comply with Grade III water quality; if $4 \le X \cdot Y \le 5$, water samples comply with Grade IV water quality; if $5 \le X \cdot Y \le 6$, water samples comply with Grade V water quality; if $6 \le X \cdot Y \le 7$, water samples exceeded Grade V water quality but not malodorous black; and if $X \cdot Y > 7$, water samples exceed Grade V water quality and malodorous black.

2.3.3. Improved comprehensive water quality identification index (IIwq)

The comprehensive water quality identification index is a good method for the assessment of water quality that is worse than Grade V. However, weighting for each indicator is not calculated in this method. Instead, the entropy weight method is used as an objective method for fixed weightings, which can eliminate anthropogenic disturbances and produce results that are more realistic. Consequently, the improved comprehensive water quality identification index combines both the comprehensive water quality identification index and the entropy weight method. The IIwq can be expressed by the following formula:

$$\mathrm{IIwq} = X''Y''MN \tag{8}$$

$$\text{where } X''Y'' = \left(\sum_{i=1}^{m}[(X_i \cdot Y_i) * \lambda_i]\right) \tag{9}$$

$\lambda_1, \lambda_2, \ldots, \lambda_m$ are the index's entropy weightings. The other indicators are the same as those mentioned above.

Information entropy was first introduced by Shannon [13]. Since then, the concept has been widely used in management science [14,15], engineering technology [16,17], environmental assessment [18,19], and sociological economics [20,21]. According to the concept of information entropy, the amount or quality of information acquired from decision-making is one of the determinants of the accuracy and reliability of any decision-making problem [22]. This method is based on the amount of information required to determine the objective weighting of the index. Entropy can be used to measure the quantity of useful information provided by the data itself. It can eliminate human disturbances and make the results more genuine and believable [22–24]. The specific equation for the index's entropy weight is as follows:

(1) Standardization of value:
If there are n sampling points and m water quality indicators in the index system, X_{ij} is the ith index value in the jth water sample, $\gamma \in [0,1]$.

$$\gamma_{ij} = \frac{X_{ij} - \min X_{ij}}{\mathrm{Max}(X_{ij}) - \mathrm{Min}(X_{ij})} \quad \text{positive indicators} \tag{10}$$

$$\gamma_{ij} = \frac{\mathrm{Max}X_{ij} - X_{ij}}{\mathrm{Max}(X_{ij}) - \mathrm{Min}(X_{ij})} \quad \text{negative indicators} \tag{11}$$

(2) Calculation of the index's entropy:
According to the definition of information entropy, the entropy of the ith indicator can be determined from the following equation:

$$P_i = -\mathrm{k}\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{f}_{ij} \ln f_{ij} \tag{12}$$

$$\text{where } f_{ij} = \frac{y_{ij}}{\sum_{j=1}^{n} y_{ij}}, k = \frac{1}{\ln n}, \quad i = 1, 2, \ldots, m \tag{13}$$

Assuming that $f_{ij} = 0$ then f_{ij} ln $f_{ij} = 0$. If $f_{ij}(j = 1, 2, \ldots, n)$ are all the same, the entropy of the ith criterion is the maximum and is insignificant, i.e. $P_i = 1$. This index will then be eliminated.

(3) Calculation of the index's entropy weight:
The entropy weight of the ith index is determined by the following equation:

$$\lambda_i = \frac{1 - p_i}{m - \sum_{i=1}^{m} p_i} \tag{14}$$

$$\text{where } 0 \le \lambda_i \le 1, \sum_{i=1}^{m} \lambda_i = 1 \tag{15}$$

3. Results

3.1. Concentration patterns throughout the watershed

The surface water quality standard is an authorized guideline in China (GB3838-2002), where Grade I water quality standard refers to the source water or national nature reserve water. Grades II and III refer to protected zones, where surface water is used as a source of drinking water. Water quality below Grade III is no longer suitable for drinking, and Grade IV and V water quality standards refer to water suitable for industrial and agricultural purposes, respectively. Water quality worse than Grade V can barely support aquatic ecosystem health (China 2002a) (Table 2).

The average concentration of various water quality parameters at each sampling point are shown in Table 3. The pH range was 6.58–7.64, which complies with the surface water guidelines for pH (6–9). Because pH values within this range do not affect water quality, pH was not included in the subsequent analysis. For DO, more than half of the samples (56.3%) exceeded the Grade V water quality standard. The lowest concentration of DO was 50 times lower than the minimum Grade V water quality standard. The DO in Huiqiao and Qinfen was lower than at other sampling sites, while the DO in Guoxi, Quxi, and Jiushan was higher than at other sampling sites. Nitrogen pollution was the most serious pollution problem in the Wen-Rui Tang River watershed, with mean values of NH_4^+-N that exceeded the Grade V water quality standard. About 81.3% of the samples had NH_4^+-N concentrations that

Table 2
National surface water quality standard (GB 3838-2002)

Grade	pH	DO (mg/L)	COD (mg/L)	COD_{Mn} (mg/L)	NH_4^+-N (mg/L)	Volatile phenol (mg/L)	Petroleum (mg/L)	BOD_5 (mg/L)
		≥	≤	≤	≤	≤	≤	≤
I	6–9	7.5	15	2	0.15	0.002	0.05	3
II	6–9	6	15	4	0.5	0.002	0.05	3
III	6–9	5	20	6	1	0.005	0.05	4
IV	6–9	3	30	10	1.5	0.01	0.5	6
V	6–9	2	40	15	2	0.1	1	10

Table 3
Average concentration of the water quality parameters at each sampling point considered in this study

Site	DO (mg/L)	COD_{Mn} (mg/L)	BOD_5 (mg/L)	NH_4^+-N (mg/L)	COD_{Cr} (mg/L)	Volatile phenol (mg/L)	Petroleum (mg/L)
DongShuiChang	1.395	5.117	4.083	6.690	20.000	0.003	0.060
GuangMing	1.360	5.717	5.583	8.778	20.500	0.003	0.068
GuoXi	7.515	3.133	2.650	0.767	11.833	0.002	0.115
HuiQiao	0.990	7.583	8.917	11.780	31.617	0.006	0.222
JiuShan	6.198	5.400	2.883	0.505	20.533	0.004	0.050
QuXi	6.647	2.900	3.267	0.827	13.767	0.003	0.070
MiShaiQiao	1.263	5.217	3.233	6.873	18.883	0.003	0.077
NanBaiXiang	1.302	6.250	5.617	9.402	22.183	0.004	0.057
QinFen	1.000	9.383	14.850	13.763	38.733	0.007	0.408
ShiZiHe	2.170	7.983	9.267	14.295	29.483	0.005	0.175
WuTian	1.580	5.467	4.833	7.660	21.933	0.003	0.073
Xi'Ao	2.725	5.167	5.433	5.262	18.317	0.004	0.078
XianMen	2.355	7.400	12.400	8.773	27.367	0.005	0.067
XinQiao	1.568	5.633	5.650	5.740	19.917	0.003	0.065
XiaWan	2.015	8.500	12.883	14.835	34.800	0.005	0.082
ShuiTan	2.103	8.883	10.533	19.202	36.850	0.004	0.128

Note: All data were collected from the Environmental Quality Standards for Surface Water of China (State Environmental Protection Administration, 2002).

exceeded the Grade V water quality standard. The concentration of NH_4^+-N was highest in Shuitan, which was 14.5 times higher than the Grade V water quality standard. The concentration of NH_4^+-N in Huiqiao, Xiawan, Shizihe, and Qinfen was 10 times higher than the Grade V water quality standard. For COD, 18.7% of samples exceeded the Grade V water quality standard. The highest COD_{Cr} (57 mg/L) was 1.525 times higher than the Grade V water quality standard. The COD_{Cr} in Huiqiao, Xiawan, Shuitan, and Qinfen was higher than at the other sampling sites. The average BOD_5 was 7.0 mg/L, with 32.3% of all samples exceeding the Grade V water quality standard. The BOD_5 in Xianmen, Xiawan, Shuitan, and Qinfen was higher than at the other sampling sites. The highest BOD_5 (34.8 mg/L) was 3.48 times higher than the Grade V water quality standard. The average COD_{Mn} was 6.2 mg/L, with most samples complying with the Grade V water quality standard (8.3% of all samples exceeded the Grade IV water quality standard and no samples exceeded the Grade V water quality standard). For volatile phenol and petroleum, almost all samples complied with the Grade III and IV water quality standard.

3.2. Comparison of the proposed IIwq with conventional Iwq indices

A data matrix with columns corresponding to the average annual value of every measured parameter and rows representing the average annual value at every sampling site was constructed. This data matrix was assessed according to A, Iwq, and IIwq (Table 4). As can be seen from Table 4, trends within the results are consistent among these three methods. The three methods are not only qualitative and quantitative evaluations of water quality, but they also reflect the same relative pollution trend: the water quality in GuoXi, QuXi, and JiuShan is better than in HuiQiao, XiaWan, QinFen, and ShuiTan. There were some differences between the three methods. Organic pollution indices cannot determine the water quality at a particular time [25]. We can only conclude that the various water quality parameters measured in GuoXi, QuXi, and JiuShan were better than the Grade V water quality standard. If we want to determine water quality more precisely, we need to use a lower concentration as a water quality standard. Consequently, BOD_0, COD_0, NH_4^+-N_0, and DO_0 were set as the Grade V water quality standard of the Environmental Quality Standards for Surface Water (GB3838-2002). If we could not identify water quality categories, then BOD_0, COD_0, NH_4^+-N_0, and DO_0 were sequentially set as the Grade IV, Grade III, or Grade II standard until the grade of water pollution was determined. After this assessment, the water quality categories in GuoXi, QuXi, and JiuShan were identified as Grade II, III, and III, respectively. However, Iwq and IIwq cannot only identify water quality categories at one particular time, but can also be used to detect water quality

Table 4
Results using three different water quality assessments

Site	A (V class)	Iwq	IIwq
DongShuiChang	3.556 (Worse than V)	4.92 (IV)	5.72 (V)
GuangMing	4.78 (Worse than V)	5.32 (V)	6.02 (Worse than V, not malodorous black)
GuoXi	−2.813 (Better than V)	3.061 (III)	2.6619 (II)
HuiQiao	7.077 (Worse than V)	6.131 (Worse than V, not malodorous black)	6.8319 (Worse than V, not malodorous black)
JiuShan	−2.045 (Better than V)	3.52 (III)	3.32 (III)
MiShaiQiao	3.6 (Worse than V)	4.872 (IV)	5.772 (V)
NanBaiXiang	5.166 (Inferior to V)	5.42 (V)	6.12 (Worse than V, not malodorous black)
QinFen	8.835 (Worse than V)	6.631 (Worse than V, not malodorous black)	7.131 (Worse than V, and malodorous black)
QuXi	−2.239 (Better than V)	3.272 (III)	2.972 (II)
ShiZiHe	7.726 (Worse than V)	5.931 (V)	5.9319 (V)
WuTian	4.072 (Worse than V)	5.129 (V)	5.62 (V)
Xi’Ao	2.27 (Worse than V)	4.772 (IV)	4.972 (IV)
XianMen	5.133 (Worse than V)	5.531 (V)	5.631 (V)
XinQiao	3.149 (Worse than V)	4.941 (IV)	5.641 (V)
XiaWan	8.568 (Worse than V)	6.142 (Worse than V, not malodorous black)	6.242 (Worse than V, not malodorous black)
ShuiTan	10.524 (Worse than V)	6.421 (Worse than V, not malodorous black)	6.421 (Worse than V, not malodorous black)

worse than Grade V and determine whether the river contains malodorous black water. The water quality in HuiQiao, XiaWan, and ShuiTan was worse than the Grade V water quality standard but did not contain malodorous black water.

We identified some subtle differences between Iwq and IIwq. When water is not contaminated, the quantitative results of the IIwq were more conservative than those of the Iwq. The water quality classification in Guoxi and Quxiis was Grade III according to Iwq, while it was Grade II according to IIwq. Furthermore, the water quality categories in GuoXi and QuXi were classified as Grades II and III, respectively, according to the A method. Therefore, we cannot precisely determine the water quality category using these indices. However, from the data in Tables 3 and 4, we can state that the water quality in GuoXi is better than that in QuXi. When water was seriously polluted, the quantitative evaluation of Iwq was more conservative than that of IIwq. The water quality classification in DongShuiChang and MiShaQiao was classified as Grade IV according to Iwq, whereas it was Grade V according to IIwq. As shown in Table 3, the concentration of DO exceeded the Grade V water quality standard in both of these sampling sites, and the concentration of NH_4^+-N was three times higher than the Grade V water quality standard. Consequently, the water quality classification in DongShuiChang and MiShaiQiao should be set to Grade V. In consideration of this, we conclude that IIwq is a better method to assess poor-quality water.

3.3. Evaluation of the water quality status in the study area with the proposed IIwq

3.3.1. Entropy weight analysis

The entropy weight has particular significance. Entropy weights of indices are determined by the contrast in intensity of the objects’ performance ratings with respect to each criterion [10]. Smaller entropy values indicate a decreased degree of disorder in the system. The entropy weight method is based on the amount of information available to determine the index’s weight, which is part of the objective fixed weight method [26]. The entropy weight method was used to calculate the weighting of each index factor in January, March, May, July, September, and November. The results indicated that the weightings of DO, COD_{Cr}, and NH_4^+-N were larger than the other parameters (Table 5), with DO in July having a particularly large weighting. The DO is inversely proportional to the temperature of the Wen-Rui Tang River [27]. Organic matter is partially oxidized by oxygen, while nutrients are responsible for the eutrophication of freshwater, causing a further increase in the concentration of

Table 5
The weighting of each water quality parameter in different months

	DO	COD_{mn}	BOD_5	NH_4^+-N	COD_{cr}	Volatile phenol	Petroleum
January	0.333	0.163	0.102	0.096	0.125	0.095	0.086
March	0.41	0.186	0.11	0.086	0.088	0.072	0.048
May	0.346	0.204	0.05	0.129	0.212	Null	0.059
July	0.483	0.11	0.099	0.105	0.098	Null	0.104
September	0.244	0.101	0.083	0.172	0.131	0.1963	0.07
November	0.378	0.102	0.105	0.101	0.17	0.071	0.073

organic matter and a decrease in water quality [28]. In July, the higher water temperature reduces the DO saturation, while aquatic algae and micro-organisms breed excessively. This results in increased consumption by chemical reactions and increased microbial degradation of organic matter, which decreases the DO [29]. Furthermore, the change in the DO levels at the monitoring points with better water quality was smaller than in the polluted river. The different values recorded at the individual monitoring stations resulted in changes of the DO weighting. The weighting of DO, NH_4^+-N, and COD_{Cr} displayed the opposite characteristics in terms of monthly variations. NH_4^+-N and COD_{Cr} are important indicators of organic pollution in water, and can reflect the degree of contamination of a water body. The concentrations of NH_4^+-N and COD_{Cr} were high, while the concentration of DO was relatively low in severely polluted water [30,31].

3.3.2. Temporal and spatial variations

Box and whisker plots of the discriminating water quality parameters identified by the improved water quality identification index and displaying bimonthly variations are given in Table 6. Organic pollution is most severe in July and least severe in November. This is mainly because higher temperatures promote the growth and activity of micro-organisms in summer, increasing the degradation of organic matter; conversely, lower temperatures restrain the growth of micro-organisms in winter, reducing the degradation of organic matter.

The spatial variation of organic pollution was assessed by IIwq in 2009. The spatial variation of organic pollution is shown in Fig. 2 and followed the order of QinFen > HuiQiao > ShuiTan > XiaWan > NanBaiXiang > GuangMing > ShiZiHe > MiShaiQiao > DongShuiChang > XinQiao > XianMen > WuTian > Xi'Ao > JiuShan > QuXi > GuoXi. The sites at GuoXi and QuXi are the origin of the Wen-Rui Tang River. The organic pollution at GuoXi and QuXi is mainly derived from agricultural non-point pollution sources, with fewer industrial wastewater and domestic sewage discharges. The JiuShan River is well protected and can be used for swimming. HuiQiao and QinFen are located in the Wenzhou main city zone, where

Table 6
Result of the water quality identification index assessment for different months

Site	January	March	May	July	September	November
DongShuiChang	5.12	5.52	5.12	5.82	4.81	4.92
GuangMing	5.42	5.52	6.321	5.21	5.33	4.92
GuoXi	2.961	2.661	2.141	2.261	3.262	2.441
HuiQiao	6.341	5.11	6.421	6.831	5.72	5.72
JiuShan	3.51	2.52	3.4	4.321	3.4	2.91
MiShaiQiao	5.072	5.263	5.042	5.963	4.852	5.153
NanBaiXiang	5.62	6.03	6.02	5.62	4.72	5.11
QinFen	6.641	6.241	5.92	7.242	5.21	6.621
QuXi	3.572	2.361	3.162	2.971	3.672	2.861
ShiZiHe	5.531	6.03	6.422	4.71	5.841	6.552
WuTian	5.32	5.92	5.42	5.62	4.61	4.71
Xi'Ao	4.152	5.463	4.122	5.563	4.842	4.66
XianMen	6.862	4.62	6.632	5.621	4.92	3.6
XinQiao	4.631	5.862	4.921	5.842	4.621	4.741
XiaWan	7.353	5.841	6.822	6.122	6.222	4.02
ShuiTan	7.222	5.33	6.821	6.01	5.81	6.711

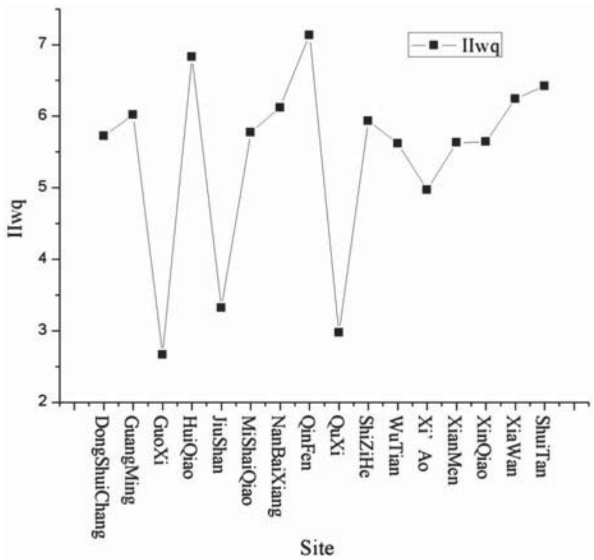

Fig. 2. Spatial variations of the indicators of surface water quality.

drainage outlets are widely distributed, and both sites are consequently affected by various pollution sources. The narrow and relatively weak channels that slow the water can accommodate pollutants easily, which eventually decreases their ability to self-purify. Pollution is severe in XiaWan and ShuiTan, as these two sites are located in the LongWan industrial zone, where water quality is affected by several sources of industrial pollution. In summary, it can be concluded that the most heavily polluted regions are located in industrial and residential zones.

4. Discussion

Although multiple statistical analyses (e.g. multivariate linear regression (MLR), principal component analysis, canonical correlation analysis, cluster analysis, and factor analysis) have been used in many previous studies to identify possible factors/sources that influence water quality and evaluate spatial and temporal variations in surface water and freshwater, they cannot qualitatively estimate the degree of pollution [32–38]. The degree of water pollution has been assessed using the organic pollution index, fuzzy comprehensive evaluation method, single-factor assessment method, comprehensive pollution index, and water quality identification index [39–42]. However, it is not clear for which grade of contaminated water source these methods are best suited. Although some methods are better for Grade I–V water quality, they may not be able to evaluate the degree of pollution where water quality is worse than Grade V (e.g. a single-factor evaluation method). Some evaluation methods do not provide ideal results for evaluating water quality that is worse than Grade V (e.g. the fuzzy comprehensive index method). Consequently, the selection of an appropriate evaluation method should be based on actual water pollution. The organic pollution index is a simple but effective way to assess the organic pollution of a water system. It uses a simple digital indicator to set boundaries that determine the grades of pollution, where both sides of the boundary are divided into distinct grades. However, the organic pollution index method cannot determine the grade of water quality at one particular time, so it must be repeatedly used to determine the limits of a water quality standard and assess pollution levels [25]. Alternatively, Iwq cannot only determine the grade of water quality at a time but can also evaluate water quality both qualitatively and quantitatively. The greatest advantage of this method is its ability to evaluate water quality that is worse than Grade V and to determine whether it meets the criteria for classification as a malodorous black river. However, the shortcoming of Iwq is the use of a single arithmetic mean for all parameters in the water quality identification index, without considering the different effects of each parameter. Water quality is not determined by the average state of all water quality parameters, but is controlled by each of the water quality parameters, which determine the optimum state of each water quality index. Therefore, a weighting of each parameter should be taken into consideration when the water quality is evaluated. The entropy method, which was used to calculate weighting for each parameter based on the measured data, was combined with the Iwq method, enabling a comprehensive evaluation of water quality. The results not only highlighted the influences of different water quality parameters but also overcame the shortcomings caused by the use of the arithmetic mean in Iwq. IIwq can be used to provide comprehensive water quality information. At the same time, the results obtained from IIwq can determine whether the water quality meets the required standard and indicate the effectiveness of water environment improvements.

In summary, the existing water quality assessment methods have several advantages and disadvantages. The selection of the correct evaluation method for a particular purpose and specific watershed is a topic that requires further research.

5. Conclusions

In this study, Iwq combined with the entropy weight method was used to produce the improved comprehensive water quality identification index (IIwq). This study considered the temporal and spatial distribution of water pollution through the analysis of major pollutants (e.g. BOD_5 and COD_{Mn}) using IIwq in the Wen-Rui Tang River watershed (China). Several conclusions may be drawn from this study, but the results must be interpreted with caution because they are based on a limited data-set:

(1) The organic pollution index A, Iwq, and IIwq produce the same results in the Wen-Rui Tang Watershed. However, we concluded that the use of IIwq enables the evaluation of organic pollution to be undertaken more accurately through the analysis of major pollutants (e.g. BOD_5, COD_{Mn}, and COD_{Cr}).

(2) Organic pollution is a very serious issue in the Wen-Rui Tang River Watershed. The water quality classification of most samples was Grade V. DO, NH_4^+-N, and COD_{Cr} contribute the largest proportion of the organic pollution load in a seriously polluted watershed.

(3) The same water quality parameters have different weightings and different pollution characteristics in different months. The weightings of DO, NH_4^+-N, and COD_{Cr} vary inversely. Temporal effects, associated with monthly variations, resulted in fluctuations in water quality. Organic pollution is most serious in July and least serious in November.

(4) Spatial effects were associated with human activity. The water quality is less polluted in QuXi and GuoXi than in HuiQiao, QinFen, XiaWan, and ShuiTan. The poor water was attributed to local pollutant inputs from industrial, agricultural, and domestic wastewater.

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