Water quality evaluation based on the water quality index method in Honghu Lake: one of the largest shallow lakes in the Yangtze River Economic Zone

Libin Chen, Zhuo Tian and Kaipeng Zou

ABSTRACT

Honghu Lake is the largest lake-type wetland in Hubei Province, China. It is also one of the largest shallow lakes in the Yangtze River Economic Zone, a key area in the relatively more developed southeast of China. However, the water quality has seen a deterioration tendency in recent decades, mostly owing to unreasonable human activities such as lake enclosure aquaculture following rapid social and economic development. Based on the water quality index (WQI) method, the water quality of Honghu Lake, by the vast amount of data collected from five observation sites monitored over ten years, was analyzed and evaluated. The results show that: (i) the water quality of Honghu Lake is in the 'General' grade as a whole with a WQI value of 43.41 ± 6.66; (ii) the water quality has been improving in the recent two years, reversing its decade-long deterioration; (iii) the water quality sampled at the Lantian site is the worst while that of the Guandun site is the best; (iv) the concentration of Pb and Cd are the key parameters to determine the water quality of Honghu Lake. Therefore, it can be concluded that more attention should be paid to investigate heavy metals in Honghu Lake in the future.

Key words | heavy metal, Honghu Lake, water quality evaluation, water quality index, Yangtze River Economic Zone

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HIGHLIGHTS

- The water quality index (WQI) method is a very effective method to evaluate water quality in lakes.
- Water quality of Honghu Lake, the largest lake wetland in the Hubei Province of China and one of the largest lakes in the Yangtze River Economic Zone as well, was analyzed and evaluated in the past ten years.
- After going through a decade-long increasing deterioration, the water quality has tended to improve in the recent two years in the Honghu Lake.
- The concentrations of Pb and Cd are the key parameters to determine the water quality of the Honghu Lake.

INTRODUCTION

China is a country with abundant water resources including a large number of rivers and lakes. On the other hand, the per capita share of China is small, which makes a shortage of water resources at the country level (Shao *et al.* 2003; Lei & Wu 2007). The water pollution problem is increasingly serious in China as a sacrifice for the fast development of the economy, making China not only a water-lacking country, but also a country with a shortage of quality water (Jiang

2010). Lake pollution is one of the most serious problems that China has ever encountered in its development, for example, the Tai Lake (Gao et al. 2016; Lian et al. 2017), the Dian Lake (Shi et al. 2011; Zhang et al. 2011) and the Chao Lake (Xi et al. 2016; Hu et al. 2018) have all undergone large-scale eutrophication pollution. It is of great urgency to strengthen lake water resources protection to restore ecological system structures and functions that have already been significantly damaged.

Water quality evaluation plays a key role in linking water resources management with water resources protection. The results of water quality evaluation can directly reflect the degree of changes in water quality, which is conducive to the formulation of effective prevention programs and the corresponding water control measures (Xu et al. 2011; Zhang et al. 2012; Zhou et al. 2014; Wu et al. 2017; Sun et al. 2018).

At present, there is a variety of water quality evaluation methods including the Single Factor Evaluation Method (Yin & Xu 2008), Nemero Index Method (Zhou et al. 2014), Grey Correlation Analysis (Hou et al. 2012), Analytic Hierarchy Process (Pang et al. 2008), Grey Clustering (Yang & Yang 2017), Fuzzy Comprehensive Evaluation (Wu et al. 2007; Hao & Jiang 2010), Pair-Comparison Analysis (Qiu et al. 2008), etc. However, most of these evaluation methods can only reflect where a water body is polluted or not, and fail to accurately reflect the pollution degree. So it is hard to take proper prevention and control measures according to the evaluation results (Li & Zhang 2008; Wu et al. 2017). In contrast, the water quality index can effectively overcome the disadvantages of using water quality parameters alone to carry out water quality evaluation. It integrates different water quality parameters into a single value to reflect the water quality level (Sánchez et al. 2007; Li & Zhang 2008; Wu et al. 2017). The water quality index is widely used because of its superiority in water quality evaluation. Li & Zhang (2008) evaluated the water quality of Danjiangkou Reservoir in two seasons using the water quality index and analyzed the main pollution factors of heavy metal pollutants of the Danjiangkou Reservoir. Hou et al. (2016), with the same method, evaluated the water quality of five typical reservoirs in the downstream of the Yellow River, and analyzed the main pollutants based on water quality index (WQI) value. Wu et al. (2017) evaluated the water

quality of Poyang Lake, and concluded that the main contributing factor of WQI value was eutrophic substances.

In recent years, many scholars have focused on Tai Lake (Gao et al. 2016; Lian et al. 2017), Dian Lake (Shi et al. 2011; Zhang et al. 2011) and Chao Lake (Xi et al. 2016; Hu et al. 2018) in water quality evaluation, but paid less attention to Honghu Lake. Honghu Lake is the largest wetland in Hubei Province, and also an important lake in the Yangtze River economic belt. Plenty of researchers have studied the water quality of Honghu Lake (Pang et al. 2016; Zhang et al. 2016; Zhang et al. 2018; Chen et al. 2019). However, they all focused on eutrophication pollution indicators such as total phosphorus (TP), total nitrogen (TN), and chemical oxygen demand (COD). Based on their research results, this study selected the monthly observation data of 21 kinds of water quality parameters from five observation points of Honghu Lake in the past ten years, and conducted a comprehensive evaluation of the water quality of Honghu Lake with the water quality index. The research results can provide an important scientific basis for protecting the water quality of Honghu Lake.

MATERIALS AND METHODS

Overview of the research area

Honghu Lake is between Honghu City and Jianli County in the southeast region of Hubei Province. North Jing River flows into the lake from the west while East Jing River lies to the north, Yangtze River to the south, and Wuhan borders the lake on the lake's northeast. Honghu Lake is a large shallow lake between the Yangtze River and the East Jing River, a tributary of the Han River. The lake is 23.4 km long from east to west, 20.8 km wide from north to south, and the water surface area is 348.2 km^2. It is the largest natural freshwater lake in Hubei Province. It is also one of the largest lakes in the middle and lower reaches of the Yangtze River (Chen et al. 2002; Huang et al. 2007; Wang et al. 2008), as shown in Figure 1. The region is warm and humid with abundant rainfall and four distinct seasons. In summer, it is hot and rainy. In a year, more than 266.5 days are free from frost. It has typical subtropical humid monsoon climate characteristics, the annual average temperature is 16.6 °C
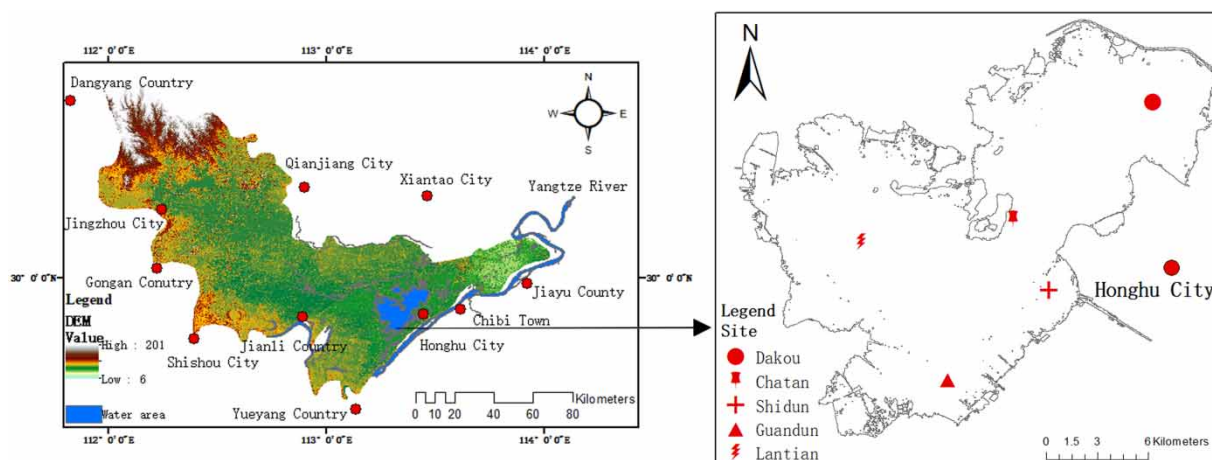
Figure 1 │ Sketch map of the watershed of Honghu Lake and water quality sampling sites.

and the average temperature is 28.9 °C in July (Zhang *et al.* 2009; Ban *et al.* 2014; Zhang *et al.* 2019). Honghu Lake mainly receives surface runoff from the main trunk canals of the four lakes in the upper reaches, and the lake bottom is flat. Its water depth is mainly determined by precipitation in the four-lakes basin (Long Lake, Three Lake, Bailu Lake and Honghu Lake) and incoming water from the upper reaches. The average water depth is 1.34 m, the greatest water depth is 2.30 m, and the least water depth is 0.40 m (Wang *et al.* 2012). Honghu Lake is rich in aquatic animals and plant resources. It is a multi-functional lake for irrigation, shipping, drinking water supply and breeding. It plays an important role in the economic development of the basin (Du *et al.* 2005; Guan *et al.* 2018).

Water quality data sources

The layout of the water quality monitoring sites of Honghu Lake is shown in Figure 1. The five monitoring sites are Shidun estuary (113.38°, 29.83°), Dakou (113.44°, 29.91°), Chatan Island (113.36°, 29.86°), Lantian (113.293°, 29.85°) and Guandun (113.33°, 29.78°) respectively. The sampling frequency was once every month from 2009 to 2017. In order to meet the investigation needs, 21 water quality parameters were selected to evaluate the water quality. Those selected parameters were $\rho(DO)$, pH, $\rho(COD_{Mn})$, $\rho(BOD_5)$, $\rho(TP)$, $\rho(TN)$, $\rho(NH_4\text{-}N)$, $\rho(NO_3\text{-}N)$, $\rho(F^-)$, $\rho(Cl^-)$, $\rho(SO_4^{2-})$, $\rho(As)$, $\rho(Hg)$, $\rho(Cd)$, $\rho(Cr^{6+})$, $\rho(Pb)$, $\rho(Se)$, $\rho(Cu)$, $\rho(Zn)$, $\rho(Fe)$ and $\rho(Mn)$.

The water samples were collected at 0.5 m below the water surface using a 5 L cleaned plexiglass water collector. Water samples of each site were preserved in polyethylene plastic bottles which were rinsed at least three times with distilled water, and then kept at 4 °C in insulation boxes before analyzing water quality parameters. To analyze the heavy metals, 500 mL of the samples were immediately filtered through a 0.45 μm cellulose acetate membrane that had previously been combusted in a muffle furnace at 500 °C for five hours and washed with 0.05 M HNO_3. The filtrates (50 mL) were collected in acid-washed polypropylene bottles and acidified to a pH of 1–2 with ultra-clean HNO_3. All samples were kept in cold storage and transferred from the field to the laboratory using a cooler filled with ice. The dissolved metals were analyzed in the laboratory within two days as described in Wu *et al.* (2017).

The parameters, such as pH and dissolved oxygen (DO), were investigated using a multiparametric probe (YSI Incorporated, Yellow Springs, OH, USA) in the field, and the sensors of the instrument were calibrated before measurement. In the laboratory, COD_{Mn} was analyzed by permanganate titration; BOD_5 was measured by a DO monitor and the reduction of DO in the raw water samples after five days was calculated; TP was determined using potassium persulfate molybdenum antimony spectrophotometry; TN was analyzed by potassium persulfate oxidation spectrophotometry; $NH_4\text{-}N$ was measured by Nessler's reagent spectrophotometry; NO_3-N was determined by ultraviolet spectrophotometry; the concentrations of other inorganic anions, such as F^-, Cl^- and

SO_4^{2-}, were gauged using an ion chromatograph. The dissolved metals, such as As, Hg, Cd, Cr^{6+}, Pb, Se, Cu, Zn, Fe and Mn, were analyzed using inductively coupled plasma atomic emission spectrometry. A detail description of the water quality analysis methods can be found in the book of national standard methods for the examining of freshwater and wastewater in China (State Environmental Protection Administration 2002). All water samples were analyzed in the water quality laboratory of Jingzhou Hydrology and Water Resources Survey Bureau, a CMA (China Metrology Accreditation) laboratory in China.

EVALUATION METHOD

The water quality index is a method to integrate physical and chemical parameters into a single value reflecting the water quality level, thus overcoming the inconsistency problem caused by the different standards on separate use of various parameters in water quality evaluation (Wu *et al.*

2017). In this study, 21 water quality parameters are used to establish a comprehensive evaluation system by referring to the basic items of the surface water quality standards of China (GB3838-2002). The 21 water quality parameters are divided into three categories: refractory toxicity index, easy to purify pollution index and other pollution indexes for comprehensive evaluation and analysis. The evaluation items and evaluation criteria are shown in Table 1.

Calculation of water quality index

The water quality index was calculated at three levels, including single water quality index, classified water quality index and comprehensive water quality index. The single water quality index and classified water quality index were used to discriminate the causes of the water quality pollution. The comprehensive water quality index was used to identify the water quality status and pollution degree (Sánchez *et al.* 2007; Hou *et al.* 2016; Duan *et al.* 2017).

Table 1 | Classification of evaluation parameters and evaluation criteria of water quality

		Evaluation criteria					
		Ii,k = 0	*Ii,k* = 20	*Ii,k* = 40	*Ii,k* = 60	*Ii,k* = 80	*Ii,k* = 100
		Water quality standards of China (GB3838–2002)					
Classification parameters		Not detected	I	II	III	IV	V
Refractory toxicity index	As (mg/L) $\leq$	0	0.05	0.05	0.05	0.1	0.1
	Hg (mg/L) $\leq$	0	0.00005	0.00005	0.0001	0.001	0.001
	Cd (mg/L) $\leq$	0	0.001	0.005	0.005	0.005	0.005
	Cr^{6+} (mg/L) $\leq$	0	0.01	0.05	0.05	0.05	0.1
	Pb (mg/L) $\leq$	0	0.01	0.01	0.05	0.05	0.1
	Se (mg/L) $\leq$	0	0.01	0.01	0.01	0.02	0.02
Easy to purify pollution index	pH						
	DO (mg/L) $\geq$		7.5	6	5	3	2
	I_{Mn} (mg/L) $\leq$	0	2	4	6	10	15
	BOD_5 (mg/L) $\leq$	0	3	3	4	6	10
	NH_3-N (mg/L) $\leq$	0	0.15	0.5	1.0	1.5	1.5
Other pollution indexes	TP (mg/L) $\leq$	0	0.01	0.025	0.05	0.1	0.2
	TN (mg/L) $\leq$	0	0.2	0.5	1.0	1.5	2.0
	F^- (mg/L) $\leq$	0	1.0	1.0	1.0	1.5	1.5
	CI^- (mg/L) $\leq$	0			250		
	SO_4^{2-} (mg/L) $\leq$	0			250		
	NO_3-N (mg/L) $\leq$	0			10		
	Cu (mg/L) $\leq$	0	0.01	1.0	1.0	1.0	1.0
	Zn (mg/L) $\leq$	0	0.05	1.0	1.0	2.0	2.0
	Fe (mg/L) $\leq$	0			0.3		
	Mn (mg/L) $\leq$	0			0.1		

Single index

Compare the measured concentration Ci of each water quality parameter with the corresponding criteria in the water quality standards of China (GB3838-2002) as listed in Table 1. When the measured concentration Ci meets $Ci,k \leq Ci < Ci,k + 1$:

$$Ii = \frac{Ci - Ci,k}{Ci,k + n - Ci,k} \times 20n + Ii,k$$

wherein: Ii is the evaluation index of the ith water quality parameter; Ci is the measured concentration of the ith water quality parameter; Ci,k is the k-level standard limit of the ith water quality parameter according the water quality standards of China (GB3838-2002); $Ci,k + 1$ is the level $k + 1$ standard limit of the ith water quality parameter according the water quality standards of China (GB3838-2002); n is the same number of $k + 1$ standard limits of the ith water quality parameter ($n = 1$ when none is the same), e.g. when the investigated concentration of Hg is between 0.0001 mg/L and 0.001 mg/L, n is 2, because the corresponding class IV and class V of the water quality standards of China (GB3838-2002) are also 0.001 mg/L; $Ci,k + n$ is the standard limit of level $k + n$ of the ith water quality parameter according the water quality standards of China (GB3838-2002); Ii,k is the k-level index of the ith water quality parameter, listed in Table 1. If the concentration of Ci is 0 (not detected), Ii,k is 0.

Sub-index

For the first category of evaluation items:

$$CI(I) = max(Ii)$$

For the second evaluation index:

$$CI(II) = \frac{1}{n}\sum_{i=1}^{n} Ii$$

For the third category of evaluation items:

$$CI(III) = \frac{1}{n}\sum_{i=1}^{n} Ii$$

In the formulas, CI(I), CI(II) and CI(III) respectively represent the classification indexes of the first category of refractory toxicity indexes, the second category of easily purified pollution indexes and the third category of other pollution indexes.

Comprehensive water quality index

$$WQI = max[CI(I), CI(II), CI(III)]$$

For special parameter processing:

There is only one standard limit for Cl^-, SO_4^{2-}, NO_3-N, Fe and Mn calculated as:

$$Ii = \frac{Ci}{Ci,3} \times 60$$

For pH, $I = 0$; when $6 \leq pH \leq 9$, or else, $I = 100$.
For DO, $I = 0$; when $Ci \geq 7.5$, or else,
when $Ci,k + 1 \leq Ci < Ci,k$:
$Ii = [(Ci - Ci,k)/(Ci,k + n - Ci,k)] \times 20n + Ii,k$.

Final water quality evaluation

The WQI value of the comprehensive water quality index was divided into seven grades: excellent, very good, good, relatively poor, poor, extremely poor and threatening water safety and human beings. As shown in Table 2, the comprehensive evaluation of water quality was carried out.

RESULTS AND DISCUSSION

Water quality evaluation of Honghu Lake based on WQI

The average multi-year WQI of Honghu Lake water is 43.41 ± 6.66. According to the comprehensive evaluation standard of the water quality index, the water quality of Honghu Lake is 'good', and the average value is close to 'very good'. In addition, Honghu Lake water quality is mainly of 'very good' and 'good' grades most of the time, that is, Honghu Lake water basically meets the requirements of Honghu Lake water quality during the evaluation period.

In terms of time scale, as shown in Figure 2, the annual average WQI of Honghu Lake is between 35 and 55 from

**Table 2** │ WQI value and corresponding water quality grade

WQI	≤ 20	>20 and ≤40	>40 and ≤60	>60 and ≤80	>80 and ≤100	>100 and ≤120	>120 and ≤200
Evaluation results	Excellent	Very good	Good	Relatively poor	Poor	Extremely poor	Threatening water safety and human beings

2009 to 2017. There are four years that the annual average of WQI was lower than 40. The four years are 2010, 2011, 2012 and 2013 with the annual average WQI being 36.75 ± 0.59, 36.81 ± 0.60, 36.78 ± 0.65 and 39.93 ± 2.47, respectively. The low WQI values indicate the water quality was 'very good'. There are five years that the average annual WQI was between 40 and 60. The five years are 2009, 2014, 2015, 2016 and 2017 with the annual average WQI being 41.95 ± 2.57, 42.51 ± 2.05, 54.61 ± 5.51, 53.97 ± 4.98 and 47.37 ± 1.77, respectively. The low WQI values indicate the water quality was 'good'.

On annual changes, the lowest WQI value appeared in 2010 and the highest WQI value appeared in 2015. In addition, the water quality of Honghu Lake began to deteriorate in 2013 and was worst in 2015. After 2015, there was a tendency to restore, and the average WQI in 2017 dropped to 47.37 ± 1.77, close to the 'very good' grade. The reasons for this situation may be related to the seine dismantling action carried out in 2014 and heavy rains in 2016 in the lake. When the purse seining was removed in 2014, the release of pollutants in the bottom sludge increased, resulting in an increase of the concentration of pollutants in the water body, showing the deterioration of the water body. In 2016, Honghu Lake was hit by continuous heavy rains. The water

level continued to exceed the guaranteed water level, which reduced the concentration of pollutants in the lake by dilution. Zhou *et al.* (2019) pointed out that Honghu Lake's water quality improved from 2009 to 2011, and deteriorated from 2012 to 2017. This research result is quite different from those of this paper, which is mainly reflected in the worst water quality years and the trend of water quality change in the last two years. The reasons for the difference may be that previous studies on Honghu Lake water quality mainly considered water quality parameters as its factors, such as ammonia nitrogen, chemical oxygen demand and dissolved oxygen, but did not take in heavy metal pollutants. In terms of spatial scale, as shown in Figure 3, the multi-year mean value of WQI of the five water quality monitoring stations, that is, the water pollution degree, is in the following order: Lantian > Dakou > Shidun estuary > Chatan Island > Guandun Island.

The multi-year mean value of WQI in Guandun was the smallest, 41.71 ± 5.38, that is, the water quality was relatively the best, showing a 'good' grade but close to 'very good' grade. The annual mean value of WQI at Lantian is the largest, which is 46.09 ± 9.21, that is, the water quality is relatively poor, showing a 'good' grade. The poor water quality at Lantian is mainly due to the inflow of incoming
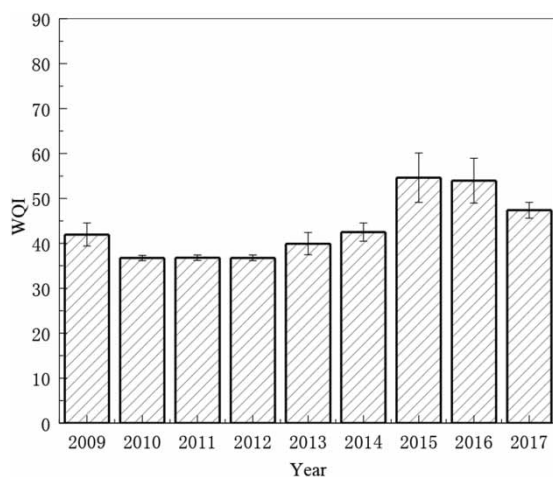
Figure 2 │ WQI variation of Honghu Lake in the past ten years.
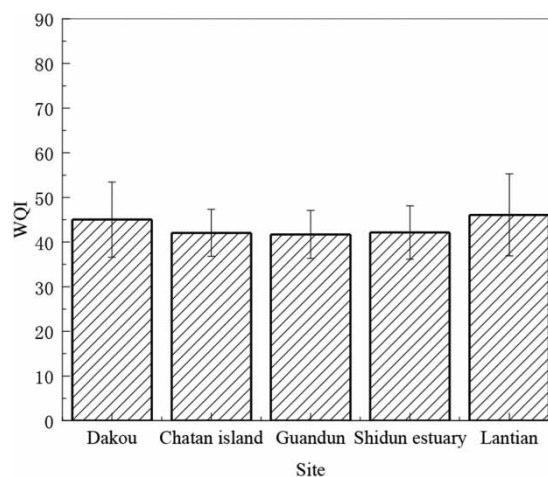
Figure 3 │ WQI variation of sampling sites in Honghu Lake in the past ten years.

water and pollutants from the upper reaches of Honghu Lake basin into Honghu Lake. This is basically consistent with the results of Wang Simeng's research on the spatial–temporal variation characteristics of Honghu Lake water quality, that is, the water quality of Honghu Lake generally becomes better from northwest to southeast (Wang 2018).

The lowest WQI values of the five water quality monitoring sites all occurred in 2010, 2011 and 2012, and the highest WQI values all occurred in 2015 and 2016, as shown in Figures 4–8. The annual variation trend is similar to the overall water quality variation trend of Honghu Lake, but slightly lags behind in time, which may be affected by the water fluidity of Honghu Lake.

The following are the detailed variations of the five water quality monitoring stations. There are five years that the average annual WQIs of Guandun were below 40, as shown in Figure 4, which are 2009–2013, the water quality was rated 'very good', accounting for 55.56% of the total years, and in the other four years the average WQIs were between 40 and 60, the water quality had a 'good' rating, accounting for 44.44% of the total years, including a lowest WQI of 36.54 ± 1.52 that appeared in 2011, and the largest WQI of 50.47 ± 15.16 was in 2016. There are four years that the average annual WQIs of Chatan Island were below 40, as shown in Figure 5, which are 2010–2013, the water quality was rated 'very good', accounting for 44.44% of the total years, and in the other five years the average WQIs were between 40 and 60, the water quality had a 'good' rating, accounting for 55.56% of the total years,
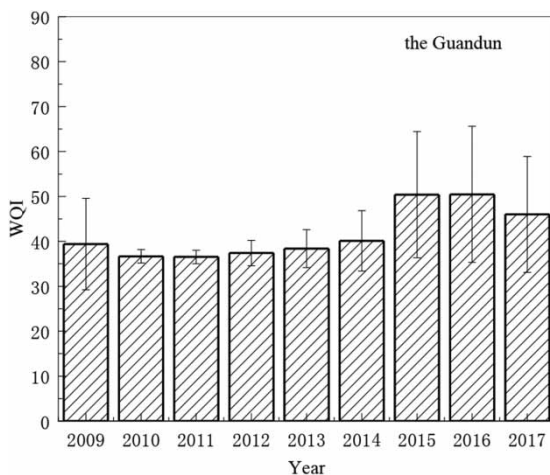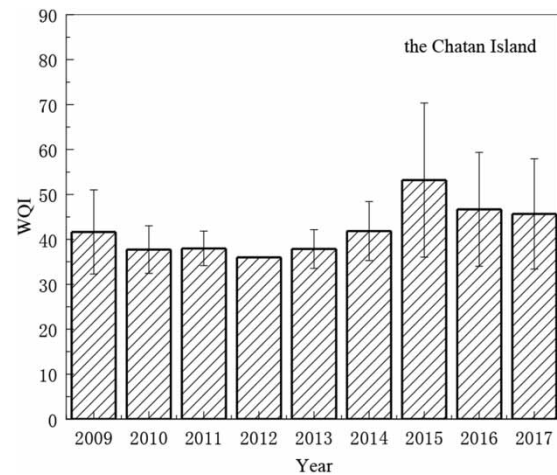
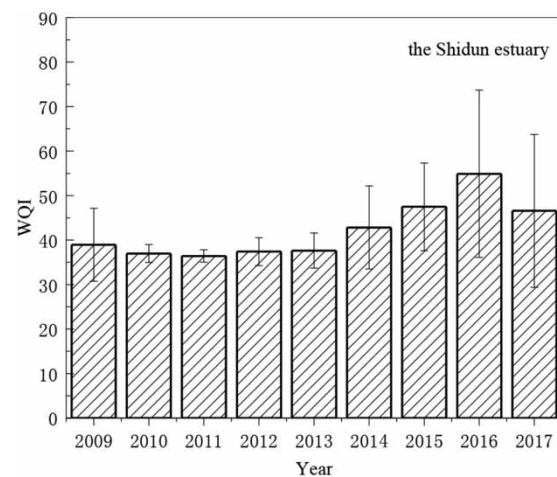**Figure 5** | Annual variation of the WQI in the Chatan Island.

Figure 6 | Annual variation of the WQI in the Shidun Estuary.

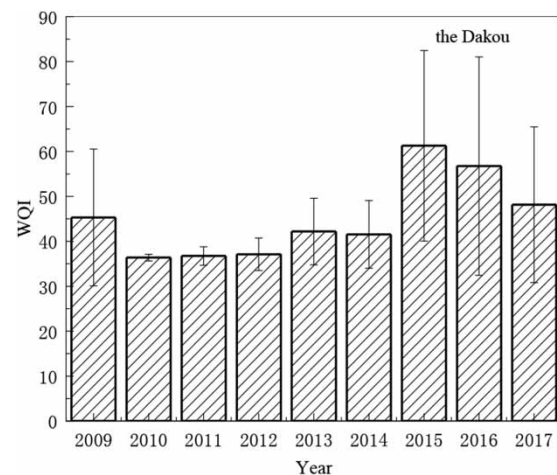**Figure 4** | Annual variation of the WQI in the Guandun.

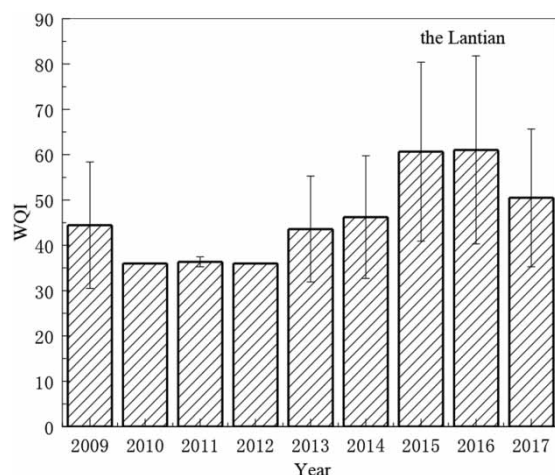**Figure 7** | Annual variation of the WQI in the Dakou.

Figure 8 | Annual variation of the WQI in the Lantian.

including a lowest WQI value of 36 that appeared in 2012, and the largest WQI of 53.21 ± 17.16 was in 2015. There are five years that the average annual WQIs of Shidun estuary were below 40, as shown in Figure 6, which are 2009–2013, the water quality was rated 'very good', accounting for 55.56% of the total years, and in the other four years the average WQIs were between 40 and 60, the water quality was in a 'good' rating, accounting for 44.44% of the total years, including a lowest WQI of 36.42 ± 1.38 that appeared in 2011, and the largest WQI of 54.89 ± 18.79 was in 2016. There are three years that the average annual WQIs of Dakou were below 40, as shown in Figure 7, which are 2010–2012, the water quality was rated 'very good', accounting for 33.33% of the total years, and there was one year the WQI was more than 60, the water quality was rated 'relatively poor', and in the other five years the water quality had a 'good' rating, accounting for 55.56% of the total years, including a lowest WQI of 36.38 ± 0.74 that appeared in 2010, and the largest WQI of 61.26 ± 21.20 was in 2015. There are three years that the average annual WQIs of Lantian were below 40, as shown in Figure 8, which are 2010–2012, the water quality was rated 'very good', accounting for 33.33% of the total years, and there are two years the WQIs were more than 60 (2015 and 2016), the water quality was rated 'relatively poor', and in the other four years the water quality had a 'good' rating, accounting for 44.44% of the total years, including a lowest WQI of 36.00 that appeared in 2010 and 2012, and the largest WQI of 61.05 ± 20.76 was in 2016.

Major contributors of Honghu Lake WQI value

In three types of evaluation project, As, Hg, Cd, Cr, Pb and Se are used to determine the refractory toxicity index of the major categories of WQI. They play a leading role, especially Pb and Cd as major contributors of Honghu Lake WQI values. The indexes of easy purification and other pollution meet the basic requirements of Honghu Lake water quality.

In terms of time scale, as shown in Table 3, the WQI perennial mean value of refractory toxicity index is 42.66 ± 6.73, almost equivalent to the WQI perennial mean value of Honghu Lake, which is 43.41 ± 6.66, and the WQI perennial mean value of the easy-to-purify pollution index and other pollution indexes are 26.18 ± 2.42 and 26.67 ± 6.70 respectively, both far lower than the WQI perennial mean value of Honghu Lake.

In terms of spatial scale, as shown in Table 4, the WQI perennial mean value of the refractory toxicity index of the five water quality monitoring stations is 42.88 ± 1.61, which is also almost equivalent to the WQI perennial mean value of Honghu Lake at 43.41 ± 1.80, while the WQI perennial mean values of the easy-to-purify pollution index and other pollution indexes are 26.29 ± 0.50 and 26.96 ± 1.90 respectively, which are also far lower than the WQI perennial mean value of Honghu Lake.

Secondly, Pb and Cd in the refractory toxicity index are almost the highest in the single index calculation, which is the main reason why the refractory toxicity index plays a leading role in the WQI value. From 2009 to 2014, the single

Table 3 | Interannual variation of the WQI values of the three types of pollution indicators

Years	Refractory toxicity index	Easy-to-purify pollution index	Other pollution indexes	WQI
2009	41.67 ± 11.97	25.65 ± 7.32	20.61 ± 5.95	41.95 ± 2.57
2010	36.49 ± 2.46	25.57 ± 5.93	17.98 ± 4.09	36.75 ± 0.59
2011	36.10 ± 0.71	21.75 ± 8.57	22.12 ± 3.32	36.81 ± 0.60
2012	36.14 ± 1.04	24.76 ± 8.23	19.60 ± 3.05	36.78 ± 0.65
2013	37.66 ± 5.76	30.81 ± 10.29	24.17 ± 5.03	39.93 ± 2.47
2014	41.84 ± 8.82	24.72 ± 6.79	32.84 ± 7.52	42.51 ± 2.05
2015	53.64 ± 18.40	27.99 ± 6.08	35.77 ± 7.17	54.61 ± 5.51
2016	53.60 ± 19.69	28.11 ± 5.78	34.10 ± 5.75	53.97 ± 4.98
2017	46.80 ± 15.48	26.26 ± 6.60	32.85 ± 5.55	47.37 ± 1.77
Mean	42.66 ± 6.73	26.18 ± 2.42	26.67 ± 6.70	43.41 ± 6.66

Table 4 | Spatial variation of the WQI values of the three types of pollution indicators

Sampling sites	Refractory toxicity index	Easy-to-purify pollution index	Other pollution indexes	WQI
Shidun estuary	41.46 ± 11.88	26.17 ± 7.17	26.37 ± 8.44	42.13 ± 6.00
Dakou	44.41 ± 16.44	26.46 ± 8.20	27.42 ± 7.60	45.04 ± 8.42
Chatan Island	41.94 ± 11.06	25.69 ± 7.02	26.41 ± 7.40	42.07 ± 5.26
Lantian	45.22 ± 16.27	27.16 ± 7.96	30.20 ± 10.70	46.09 ± 9.21
Guandun Island	41.37 ± 10.99	25.97 ± 8.38	24.37 ± 7.86	41.71 ± 5.38
Mean value	42.88 ± 1.61	26.29 ± 0.50	26.96 ± 1.90	43.41 ± 1.80

indexes of Pb were almost the largest; from 2015 to 2017, the single indexes of Cd were almost the largest. This is consistent with the economic and industrial development of Honghu Lake basin in recent years, and has also been an important reason for Jingzhou Municipal Environmental Protection Bureau to compile the *Comprehensive Prevention and Control Plan of Heavy Metal Pollution*. However, Wu *et al.* (2013), Wu *et al.* (2015), Zhou *et al.* (2019) and Li *et al.* (2019) still focused on eutrophication pollution indicators such as TP, TN, COD and chlorophyll when studying Honghu Lake water, rather than the refractory toxicity index, such as Pb and Cd, and these heavy metal pollutants in the refractory toxicity index have been exactly the main pollution factors in Honghu Lake in recent years. Hu *et al.* (2012) in the Honghu Lake studies also show that Honghu Lake was polluted by heavy metals such as Cr, As, and Pb, and point out that most of the heavy metals may mainly come from fertilizers, industrial wastewater and surrounding domestic sewage. Some scholars have studied the heavy metal pollution in Honghu Lake sediments and pointed out the potential risk of heavy metals in Honghu Lake sediment (Makokha *et al.* 2016; Li *et al.* 2018).

Suggestions for Honghu Lake water quality monitoring and management

Based on the research results of this paper, suggestions for Honghu Lake water quality monitoring and management are put forward as follows:

(1) It is suggested to increase the frequency of water quality monitoring to once every ten days or a week, so as to ensure that the change rule of Honghu Lake water quality can be accurately judged. This paper only has the

monthly monitoring data, which does not accurately reflect the change of Honghu Lake water quality.

(2) It is suggested to analyze the flow field law of the lake and determine the key water quality monitoring stations of Honghu Lake according to the distribution law of the flow field. The determination of the five water quality monitoring stations in this paper is based on the pollution degree and spatial representation of the water body, which does not reflect the migration and transformation law of the pollutants.

(3) It is suggested to strengthen the monitoring and prevention of heavy metal pollutants to curb the further concentration of heavy metal pollution. The research results of this paper reflect the occurrence of heavy metal pollution in Honghu Lake, but there is no in-depth analysis of the source of heavy metals.

(4) It is suggested to focus on the areas with relatively serious pollution near the Lantian water quality monitoring station, and focus on monitoring the flow of pollutants into the lake and the types of pollutants.

CONCLUSIONS

(1) The overall water quality of Honghu Lake in the past ten years was 'good', close to 'very good', and most of the time was 'very good' and 'good'.

(2) In terms of annual changes, Honghu Lake water quality began to deteriorate in 2013, and was the most polluted in 2015, however, it showed a recovery trend in the past two years.

(3) Refractory toxicity indicators such as Pb and Cd have been the most important pollution factors in Honghu

Lake in the past ten years, among which Pb pollution was the most serious from 2009 to 2014. Cd pollution was worst from 2015 to 2017.

(4) Among the five Honghu Lake water quality monitoring stations, Guandun has the best multi-year average water quality, while Lantian has the worst multi-year average water quality.

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