

Original Articles

Estimation and evaluation of aquaculture mass load based on inventory and improved entropy weight: The case of Zhuhai City, China

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ABSTRACT

China's rapid development of aquaculture has focused attention on its environmental impacts and the need for a comprehensive method that will enable environmental managers to estimate and evaluate aquaculture pollutant emissions. Few reports have estimated the environmental quality load of aquaculture conducted under different culture modes at the township level, and even fewer have studied the methods used to evaluate pollutant emissions. Here, we present a novel joint method based on an inventory analysis and an improved entropy weight method supplemented by remote sensing and an analysis of emission intensity. The method was applied to estimate and evaluate the environmental mass load of aquaculture in Zhuhai, Guangdong Province, China. The results showed that the main pollutant in areas dominated by freshwater aquaculture was chemical oxygen demand, whereas in areas dominated by mariculture the main pollutant was total nitrogen. Negative emissions occurred in Jinwan and Gaolan Port Districts, whereas the highest environmental quality load under different aquaculture modes was found in Baijiao Town, located in Doumen District. This study identified the excessive aquaculture density in Zhuhai. More generally, it provides a reference method for the environmental management of aquaculture in coastal cities.

1. Introduction

The rapid development of aquaculture worldwide has caused serious environmental problems (Yang et al., 2021). Feed, antibiotics, and the excreta produced by aquaculture organisms are important factors that exacerbate water pollution. Since 1989 and for > 30 consecutive years, China's aquatic product yield has ranked first worldwide (FAO, 2022), such that the country is the world's largest supplier of high-quality protein. In 2010–2020, an average of 75% of China's aquatic products came from aquaculture (Editorial Board of China Fishery Statistical Yearbook, 2020). However, according to the results of the Second National Census of Pollution Source (Ministry of Ecology and Environment, National Bureau of Statistics, Ministry of Agriculture and Rural Affairs, 2020), emissions of total nitrogen (TN), total phosphorus (TP), ammonia

nitrogen (NH₃-N), and chemical oxygen demand (COD) from aquaculture accounted for 3%, 5%, 2%, and 3%, respectively, of discharged pollutants from various pollution sources in 2017. Compared with 2007, the emission intensity per unit yield of TN, TP, and COD decreased by 20%, 23.8%, and 30.7% in 2017 (Mu et al., 2021). However, in recent years, the Bulletin of China's Ecological Environment (Ministry of Ecology and Environment of the PRC, 2019–2021) identified TN and TP in the fishery waters of rivers and inorganic nitrogen in seawater as the main pollutants. The discharge of nitrogen and phosphorus, as key components of feed and excreta, into offshore waters could lead to eutrophication (Nhan et al., 2007; Nhan et al., 2008; Rosendorf et al., 2016). Therefore, although emissions of aquaculture pollutants have declined in recent years, their potential environmental risks have not abated.

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The identification of environmental risk is an important aspect of environmental quality assessments. Accurate estimation of the aquaculture mass load is an essential aspect of environmental quality assessments. The main methods used to estimate the pollution load include modeling methods and inventory analysis (IA); the former generally includes empirical and mechanistic models (Zou et al., 2020). However, while a large number of parameters, input data, and other information can ensure the accuracy of a model, they can also lead to difficulty in model verification. IA is a low-input, manageable method and the production factors that determine inputs based on this method are relatively easy to obtain from statistical data (Chen et al., 2006). Moreover, this approach greatly reduces the need to consider complex pollution processes and mechanisms, while also reducing the cost of the analysis. IA has been widely used to estimate rural non-point-source pollution (Chen et al., 2018) and air-pollutant emissions (Banerjee et al., 2021; Liang et al., 2022). In an IA, pollutant emissions are calculated based on the activity level and the pollutant emission coefficient. While the method can be used to estimate the environmental quality load of aquaculture (Chen et al., 2016; Shen et al., 2018), it has not been applied to obtain refined estimations, including in the region of this study.

Water environmental quality assessments are the basis for water-related environmental planning, decision-making, and management (Rao et al., 2019). Commonly used evaluation methods include those based on a single factor (Tripathi and Singal, 2019), water-quality indices (Ma et al., 2020), and multivariate statistical methods (including principal component analysis, hierarchical analysis, cluster analysis, etc.) (Zhang et al., 2020). However, all of these rely on water-quality-monitoring databases (i.e., concentration values), which are not applicable to pollutant emission evaluations. The latter can be achieved using the equivalent pollution load (EPL) method, which evaluates and compares the potential pollution capacity of different pollutants or pollution sources on the same scale according to the percentage of the respective EPL, thus identifying major pollution sources and major pollutants (Committee for the Compilation Data of the First Census of Pollution Sources, 2011). The EPL method is based on national standards, but for seawater environments (GB 3097, 1997) standard values for TN, TP and NH₃-N corresponding to surface water quality are lacking (GB 3838, 2002). The entropy weight method (EWM) has been used to evaluate pollutant emissions and has supported the realization of reduction targets for major pollutant emissions within our study region (Wu et al., 2016; Zheng and Wei, 2013). However, while both the EPL method and the EWM are commonly applied in the case of positive pollutant emissions (Peng et al., 2023; Han et al., 2023), emissions from mariculture may be negative. Therefore, it is necessary to improve EWM so that it is suitable for both cases.

Aquaculture in coastal prefecture-level cities is generally divided into three levels for management according to administrative units. The IA, based on statistical and survey data, can only estimate emissions at the district level. The commonly used EWM cannot accurately evaluate negative emissions. Thus, a joint method to systematically and comprehensively estimate and evaluate the environmental quality load of different aquaculture modes at the same scale would facilitate environmental management in coastal cities. In this study, we present a newly developed joint method based on an IA and an improved entropy weight method (IEWM), supplemented by remote sensing and analyses of emission intensity. The joint method can localize emissions to the smallest environmental management unit while evaluating environmental mass loads with positive and negative emissions. It therefore provides researchers and environmental management agencies in coastal cities with a methodological tool to help them refine environmental management policies and formulate effective measures to promote the green and sustainable development of aquaculture.

2. Materials and methods

2.1. Study area

The study area was Zhuhai City, a prefecture-level city and a provincial sub-central city in Guangdong Province, China, that is a special economic zone approved by the State Council. Zhuhai is a core city on the west bank of the Pearl River Estuary and an important node city in the Guangdong–Hong Kong–Macao Greater Bay Area (Fig. 1). It has the largest ocean area, the largest number of islands, and the longest coastline in the Pearl River Delta. Given its geographical advantages, Zhuhai provides a large number of high-quality aquatic products for the Guangdong–Hong Kong–Macao Greater Bay Area and even for Guangdong Province.

2.2. Data sources

Aquaculture yield and area in the study region were derived from the results of local agricultural and rural sector surveys as well as from the Guangdong Rural Statistical Yearbook 2020 (Editorial Board of Guangdong Rural Statistical Yearbook, 2020) and the Zhuhai Statistical Yearbook 2020 (Zhuhai Bureau of Statistics, National Bureau of Statistics in Zhuhai investigation team, 2020). Emission factors were derived from the Manual of Emission Coefficient for the Second National Census of Pollution Source (Second National Census of Pollution Source Office of the Ministry of Ecology and Environment, 2020), as shown in Table S1. The main pollutant indicators were TN, TP, NH₃-N, and COD. Remote-sensing data were obtained from the French satellite Pléiades. The satellite data used in this study were acquired in February 2020, comprised panchromatic band data with a spatial resolution of 0.5 m, and covered the Zhuhai administrative region.

3. Research method

In this study, an IA was used to estimate the emissions of aquaculture pollutants in Zhuhai in 2019. Aquaculture in the study region consists of freshwater aquaculture (FA) and mariculture. In this study, the emission coefficients were selected according to the main breeding methods and aquaculture species in Zhuhai. Both culture modes are mainly pond culture, but mariculture also includes cage culture and shallow sea rafts.

In the remote-sensing imagery, FA areas were identified as rectangular ponds and mariculture areas as offshore strip cages. The proportion of aquaculture area determined by remote-sensing data interpretation (Walaiporn et al., 2018) together with statistical data verification defined the aquaculture areas devoted to FA and mariculture at the three administrative levels. Aquaculture yield correlates significantly with area, as evidenced by a Spearman's correlation coefficient (r) of 0.918. Therefore, based on the data extracted from the remote-sensing area, the percentage of aquaculture area in each township was calculated and then matched with the proportion of pollutant emissions in each township. As there was no aquaculture in Xiangzhou District or Chibi Island, neither was included in the comprehensive evaluation.

In the joint method, the EWM was improved using an exponential function, and the accuracy was enhanced using the EPL method and emission ranking verification. The resulting IEWM-based comprehensive evaluation was applied to evaluate the aquaculture mass loads of the secondary and tertiary administrative units, and identify key management areas. Finally, based on the emission intensity per unit yield and the emission intensity per unit aquaculture area, the current aquaculture-related conditions and environmental problems were compared and highlighted, and appropriate management suggestions were then proposed.

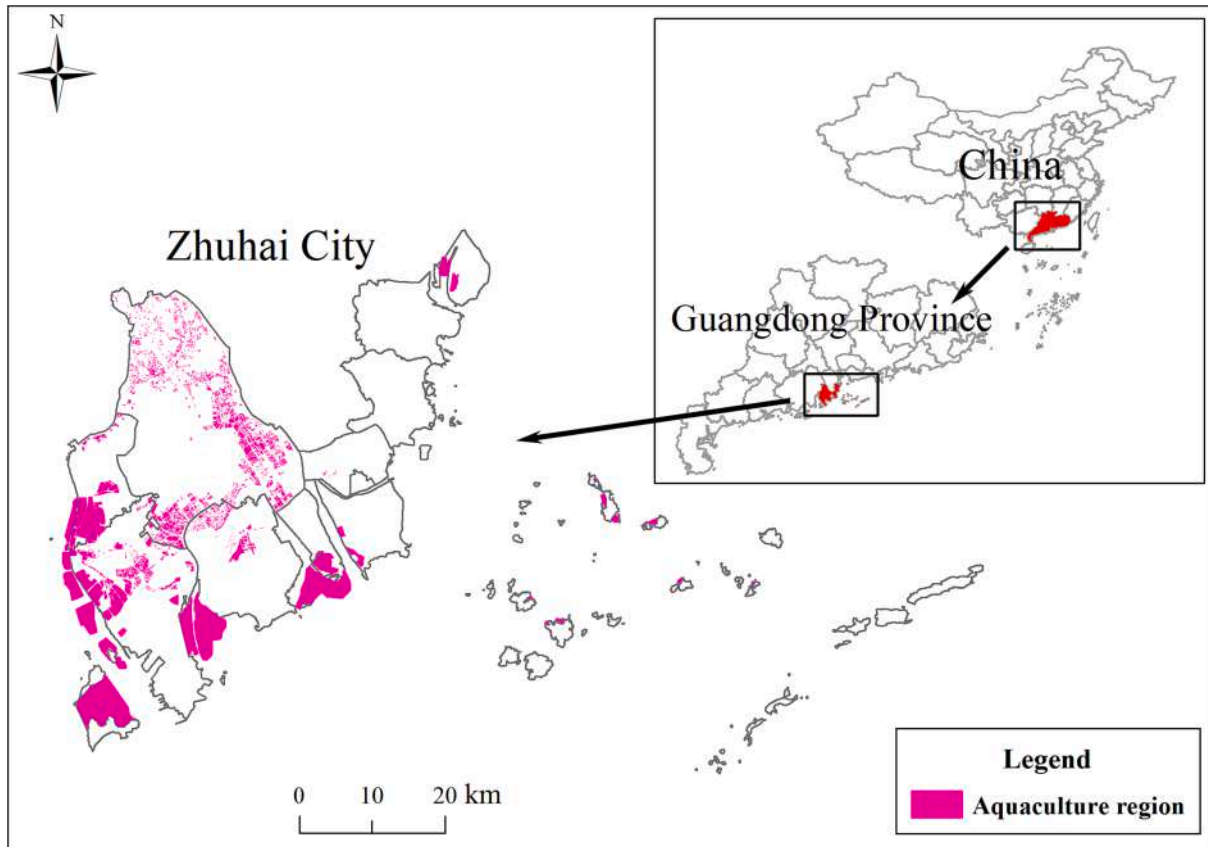


Fig. 1. Location and aquaculture-distribution map of Zhuhai, Guangdong, China.

3.1. IA-based calculation of mass load

Based on the IA, an emissions list of aquaculture pollutants in each district and county was established (Committee for the Compilation Data of the First Census of Pollution Sources, 2011). The calculation method is shown in Eq. (1):

$$Q_{ai} = YZ_m \times \delta_{i,m} \quad (1)$$

where Q_{ai} is the emission of aquaculture pollutant i , YZ_m is the increased yield of aquaculture type m (kg or t), defined as the difference in value of the yield and seedling quantity, and $\delta_{i,m}$ is the emission coefficient of pollutant i of aquatic product type m ($g \cdot kg^{-1}$).

3.2. IEWM-based comprehensive evaluation

In the entropy method, the weight of each index is determined according to the dispersion degree of the data (Zhe et al., 2021). In this study, the method was used to determine the weights of TN, TP, NH_3-N , and COD emissions and then rank them in a comprehensive index reflecting the aquaculture mass load of the tertiary administrative units under the jurisdiction of Zhuhai (Tian et al., 2020). Indicators with greater degrees of variation provide more information (Sahoo et al., 2017; Zhe et al., 2021) and thus have larger roles in the comprehensive evaluation, in which they are given greater weights (Wu et al., 2022). The calculation is presented in Eqs. (2)–(7):

Step 1: Construct the decision matrix R , composed of n evaluation indicators of m evaluation objects:

$$R = (x_{ij}) (i = 1, 2, \dots, n; j = 1, 2, \dots, m) \quad (2)$$

Step 2: Transform the original data into a non-zero continuous data set using an exponential function:

$$r_{ij} = a^{x_{ij}} \quad (3)$$

where r_{ij} is the processed value and x_{ij} is the initial value of the matrix. The data set should not be too large or too small, to facilitate analysis and comparison; in this study a was 1.01.

Step 3: Compute the weight:

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^m (P_{ij} \ln P_{ij}), 0 \leq H_j \leq 1 \quad (4)$$

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \quad (5)$$

$$w_j = \frac{1 - H_j}{n - \sum_{j=1}^n H_j} \quad (6)$$

where H_j is the entropy value of the j^{th} indicator and P_{ij} is the contribution degree of the i^{th} evaluation object under the j^{th} indicator. The entropy weight w_j of the j^{th} factor is calculated using Eq. (6).

Step 4: Calculate the comprehensive evaluation score, S :

$$S = \sum_{j=1}^n w_j \times P_{ij} \times 100 \quad (7)$$

3.3. Estimation of mass load and EPL

3.3.1. Mass load

To convert pollutant emission intensities into uniform, measurable amounts, the mass loads of the area ($kg \cdot ha^{-1} \cdot a^{-1}$) and yield (a^{-1}) were used, as they represent the contaminant mass discharged from one unit of area within one unit of time in units of mass (Liu et al., 2020; Wu et al., 2021). The calculation was performed as shown in Eq. (8):

$$I_i = \frac{Q_i}{A} \tag{8}$$

where I_i is the mass load of the area ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{a}^{-1}$); Q_i is the emission of pollutant i ($\text{t}\cdot\text{a}^{-1}$); and A is the aquaculture area of an administrative unit (ha). Similarly, the mass load of the yield was defined as the ratio of the emission of major pollutants (t) to the aquaculture yield (t).

3.3.2. EPL method

The EPL method was introduced to reflect the pollution potential of different pollutants or pollution sources. In this method, emissions are expressed as the volume of water required to dilute the pollutant to the evaluation standard (Qu et al., 2022), calculated as shown in Eqs. (9) and (10):

$$M_i = \frac{I_i}{C_o} \tag{9}$$

$$K = \frac{M_i}{M} \times 100\% \tag{10}$$

where M_i is the EPL of the pollutant i ($10^6 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{a}^{-1}$); I_i is the release of pollutant i ($\text{t}\cdot\text{a}^{-1}$); and C_o is the standard value of the target control category based on the functional partition of the water environment for pollutant i ($\text{mg}\cdot\text{L}^{-1}$). In Eq. (10), K is the ratio of EPL, M (M_n , $10^6 \text{ m}^3\cdot\text{ha}^{-1}\cdot\text{a}^{-1}$, where n is the number of pollutants) is the sum of the EPL of all pollutants in the region. For FA, C_o is the pollutant concentration according to GB 3838–2002, in which TN is $1 \text{ mg}\cdot\text{L}^{-1}$, TP $0.2 \text{ mg}\cdot\text{L}^{-1}$, $\text{NH}_3\text{-N}$ $1 \text{ mg}\cdot\text{L}^{-1}$, and COD $20 \text{ mg}\cdot\text{L}^{-1}$.

4. Results and discussion

4.1. Analysis of aquaculture emissions

The emissions of major pollutants in FA and mariculture in Zhuhai and tertiary administrative units, as well as total aquaculture emissions, were estimated according to Eq. (1); the results are shown in Fig. 2 and Fig. 3. The structure of the emissions of major pollutants under the two aquaculture methods in Zhuhai and in the secondary administrative unit is shown in Fig. 4.

The emissions from FA in the towns of Baijiao, Qianwu, and Lianzhou accounted for 68.0% of total major pollutant emissions from FA in Zhuhai (Fig. 2(a)). Emissions of TN, TP, and COD followed the order Baijiao > Qianwu > Lianzhou, and $\text{NH}_3\text{-N}$ emissions the order Baijiao > Pingsha > Qianwu. The COD of districts and counties dominated by FA, such as Doumen and Jinwan, accounted for > 60% of total major pollutant emissions from aquaculture (Fig. 3(a)).

The main pollutant emissions of Guishan, Baijiao, and Wanshan towns accounted for 65.1% of the major pollutants emissions from

mariculture in Zhuhai (Fig. 2(b)). TN emissions followed the order Guishan > Wanshan > Dangan, TP emissions the order Guishan > Wanshan > Baijiao, and $\text{NH}_3\text{-N}$ and COD emissions the order Baijiao > Qianwu > Lianzhou. In Wanshan District, where only mariculture was carried out, TN had the largest contribution (80.4%) to total major pollutant emissions (Fig. 3(b) and Fig. 4). Negative emissions of TN, $\text{NH}_3\text{-N}$, and COD occurred in Jinwan District and Gaolan Port District and may have been associated with the aquaculture species.

A comparison of the estimates from 2019 with the results of the second pollution source census conducted in Zhuhai in 2017 is shown in Fig. 5. An overall decrease of 46.9% compared to 2017 was determined, with TN, TP, $\text{NH}_3\text{-N}$, and COD decreasing by 35.9%, 38.6%, 72.8%, and 48.2%, respectively (Zhuhai Ecological Environment Bureau, 2021). Compared to 2017, FA and mariculture yields in 2019 increased by 7.5% and 7.3%, respectively, while the area of FA and mariculture decreased by 7.2% and 1.7% respectively, based on an analysis of the aquaculture area in Zhuhai (Table S2). The green transformation of aquaculture methods and the optimization and upgrading of the related infrastructure likely accounted for the reduced emissions of major pollutants from aquaculture. Production from deep-water cage culture was 35% higher in 2019 than in 2017, and the area under cultivation increased by 33%. Mariculture crustacean aquatic production increased by 27% in 2019 compared to 2017. The ability of some filtering shellfish to use the natural bait in water has led to water purification and contributed to negative emissions (Huang et al., 2021). In 2019, Zhuhai built the “Dehai No. 1” semi-submersible intelligent fishery and the “Penghu” semi-submersible wave energy deep-water cage aquaculture platform, both of which offered economic, social, and ecological benefits (Editorial Board of Guangdong Statistical Yearbook, 2020).

4.2. Environmental mass load evaluation

4.2.1. Indicator method data preprocessing

Evaluation of the aquaculture emission load in Zhuhai and secondary administrative units based on the EWM was calculated using Eqs. (4)–(7). The results are shown in Table 1. To eliminate the influence of the dimension and magnitude of different indicators in the EWM, the original data must first be standardized, such as by using the normalization method, which compresses the data in the [0, 1] interval. It is then necessary to evaluate the positive or negative normalization treatment according to the characteristics and meaning of the data. Since smaller pollutant emissions equate to better environmental quality, reverse normalization ($r_{ij} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}}$) is needed.

However, when emissions rankings were used to verify the EWM results for mariculture, the latter were found to be inconsistent with the actual data, perhaps because, during normalization, the data set with negative numbers shifts the assumed reverse direction. A comparison of Table 1 and Table 2 shows that if the original data are positive, the

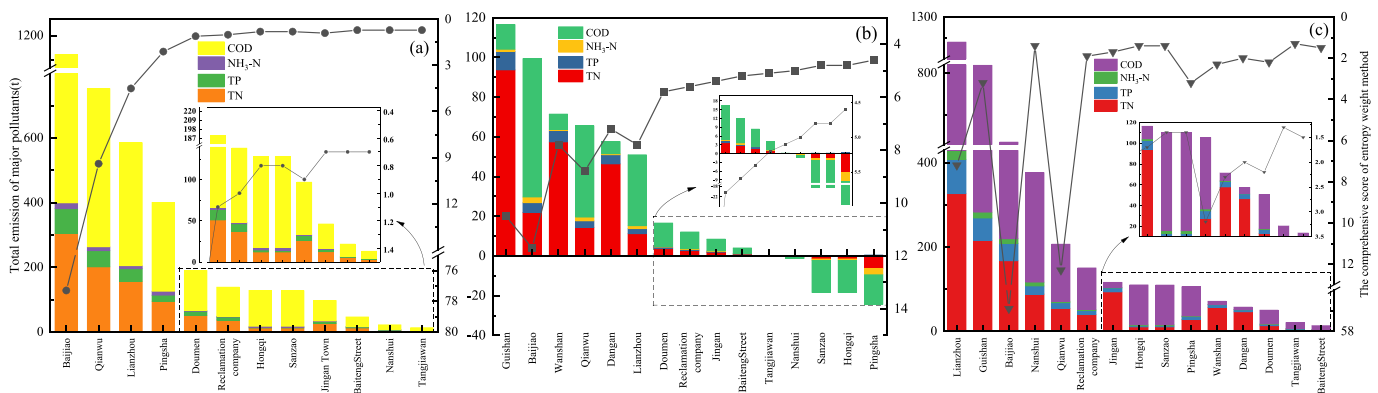


Fig. 2. Emission structure of major pollutants under different aquaculture modes in Zhuhai's tertiary administrative units: (a) freshwater aquaculture, (b) mariculture, and (c) aquaculture. COD, chemical oxygen demand; $\text{NH}_3\text{-N}$, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus.

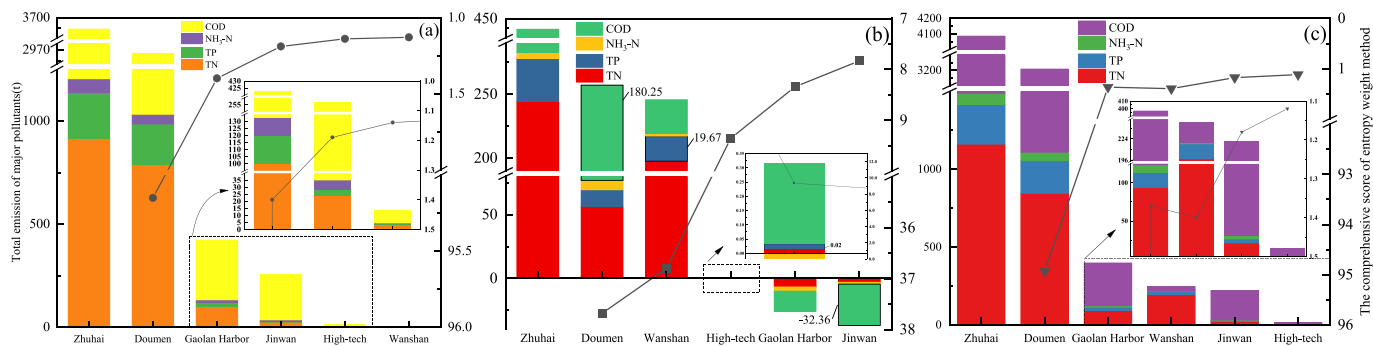


Fig. 3. Emission structure of major pollutants under different aquaculture modes in Zhuhai and its sub-districts: (a) freshwater aquaculture, (b) mariculture, and (c) total aquaculture. COD, chemical oxygen demand; NH₃-N, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus.

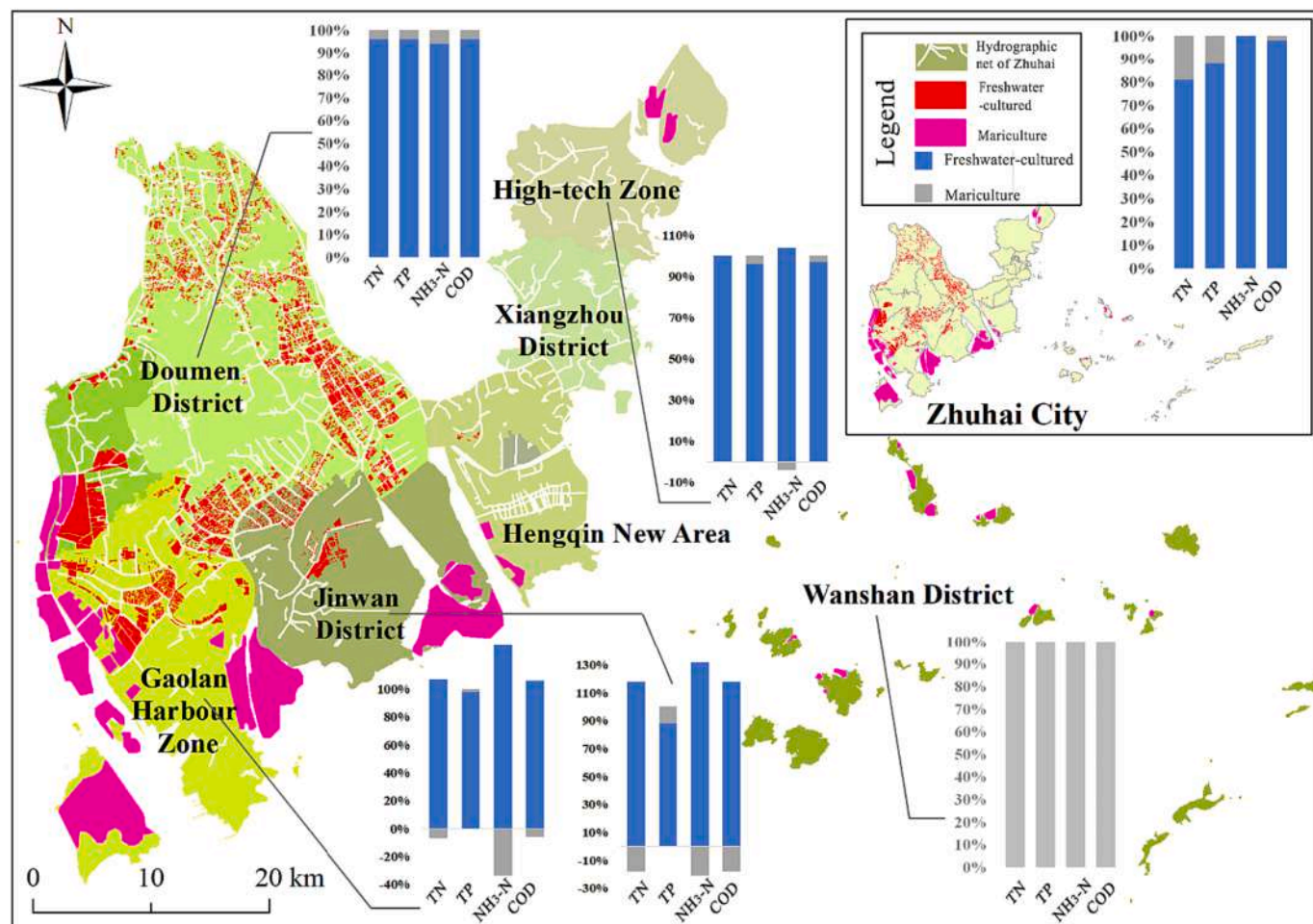


Fig. 4. Aquaculture areas and main pollutant emissions in Zhuhai. COD, chemical oxygen demand; FA, freshwater aquaculture; NH₃-N, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus.

evaluation objects of the two data preprocessing methods are ranked consistently. However, if there are negative numbers in the data set, the normalized results show unexpected values. The standardized treatment of TN emissions from mariculture serves as an example. For TN and other pollutant emissions, smaller values are better. As shown in Fig. 3, TN emissions by secondary administrative unit were ranked in the order Wanshan > Doumen > High-tech > Jinwan > Gaolan Port. Table 2 shows the standardized results, with TN emissions in the order Gaolan Port > Jinwan > High-tech > Doumen > Wanshan. Therefore, when the data set has positive and negative numbers, standardization may distort the results.

Another reason for the inconsistent results is that standardization changes the differentiation of raw data. As shown in Fig. 3, in the assessment of the mass load of mariculture in secondary administrative units, TP emissions were concentrated in the range of 0.02–19.67 t, representing a difference of 19.65 t. COD emissions were distributed in the range of –32.36–180.25 t, representing a difference of 212.61 t. The coefficient of variation (Wu and Huang, 2023) reflects the degree of dispersion of a set of data; larger coefficients indicate a greater degree of dispersion. For COD, the coefficient of variation was twice that of TP (Table 2). The degree of differentiation of COD was also higher than that of TP, such that COD should be assigned a higher weight. However,

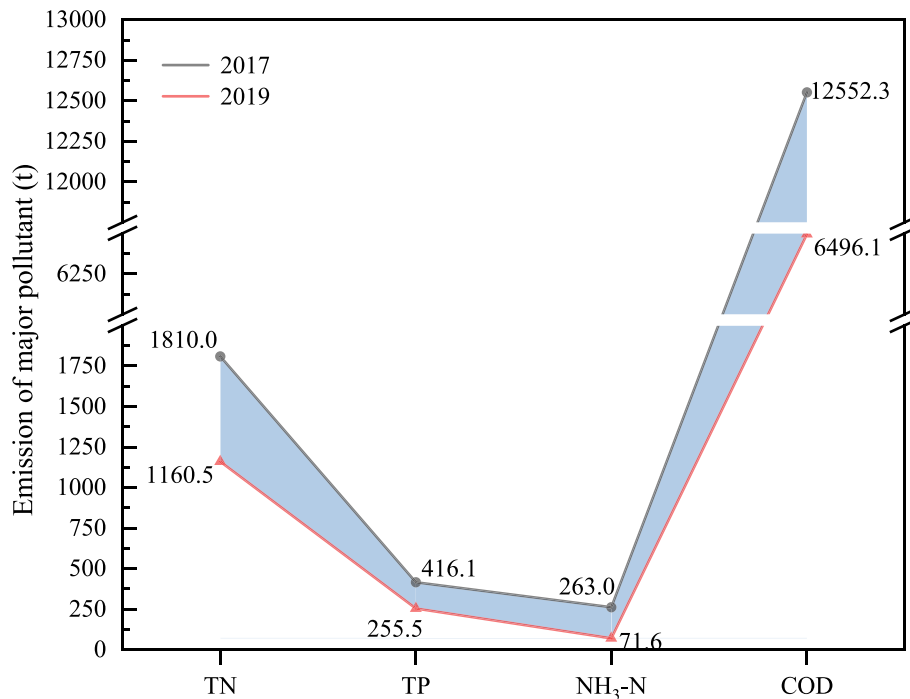


Fig. 5. Comparison between the estimated levels of major pollutants in aquaculture in Zhuhai in 2019 and the results of the second pollution source census in 2017. COD, chemical oxygen demand; NH₃-N, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus.

Table 1
Entropy weight comprehensive evaluation scores based on two data preprocessing methods.

Secondary administrative unit	Exponential preprocessing			Standardization preprocessing		
	Freshwater aquaculture	Mariculture	Aquaculture	Freshwater aquaculture	Mariculture	Aquaculture
Doumen District	95.15	37.68	94.93	0.00	7.41	0.00
Jinwan District	1.19	7.83	1.18	24.55	28.21	25.37
Wanshan District	1.13	36.80	1.40	26.68	8.86	24.35
High-tech Zone	1.14	9.35	1.12	26.53	26.25	26.81
Gaolan Harbor Zone	1.40	8.34	1.37	22.24	29.27	23.47

Table 2
Empowerment process and coefficients of variation according to the entropy weight method applied to the mariculture mass load evaluation performed using the standardization preprocessing method.

Index		TN	TP	NH ₃ -N	COD
Normalized processing result	Doumen District	0.69	0.34	0.00	0.00
	Jinwan District	0.98	0.97	0.83	1.00
	Wanshan District	0.00	0.00	0.49	0.72
	High-tech Zone	0.97	1.00	0.70	0.85
	Gaolan Harbor Zone	1.00	0.97	1.00	0.92
Entropy Weight		0.86	0.82	0.84	0.86
Coefficient of variation		0.232	0.289	0.252	0.228
		1.59	1.20	3.82	2.42

Abbreviations: TN, total nitrogen; TP, total phosphorus; NH₃-N, ammonia nitrogen; COD, chemical oxygen demand.

according to the entropy weight model calculations (Table 4), the weights of COD and TP were 0.23 and 0.29, respectively, representing a 1.3-fold difference. Therefore, entropy weight empowerment results may not truly reflect the degree of differentiation of the chosen indicators. The root cause of this problem is that, after the standardization of TP, the standardized data have a 0–1 distribution and thus a high degree of differentiation. Yan et al. (2019) and Zhu et al. (2020) noted that, in water quality assessments, the EWM focuses only on the

statistical characteristics of the data set, not on its true significance. Bao et al. (2020) attributed the distortion of the entropy weight results to the change in data dispersion caused by the standardization and ranging processes, which in turn changed the weight. Therefore, standardization may increase the weight of less-polluting indicators, such that the results do not objectively reflect the information value of those indicators.

To avoid distortion of the evaluation results, we used the exponential method shown in Eq. (3) for data preprocessing, as it can maintain and reflect the relative relationship between data sets, by ensuring that the positive or negative direction of the data set is consistent in meaning while meeting the prerequisites of the EWM. As shown in Table 1, if the values in the data sets are all positive, the EWM results using the pre-processed data sets will be sorted consistently. In the case of negative numbers, the ranking of the EWM results preprocessed using the exponential function will be consistent with the ranking of major pollutant emissions. Thus, in the case of mariculture (Table 2), the evaluation results followed the order Jinwan > Gaolan Port > High-tech > Wanshan > Doumen.

4.2.2. EWM results

Tables 1 and 3 summarize the results of the evaluation of the aquaculture entropy weights processed using the exponential function conversion. Higher comprehensive evaluation scores indicated greater environmental quality loads. In the analysis, Doumen District had the highest scores for FA, mariculture, and total aquaculture.

The comprehensive evaluation score for FA followed the order

Table 3

Comprehensive evaluation scores of the aquaculture mass load evaluations for the tertiary administrative units in Zhuhai.

Secondary administrative unit	Tertiary administrative unit	Freshwater aquaculture	Mariculture	Aquaculture
Doumen District	Lianzhou Town	4.47	7.75	7.17
	Doumen Town	1.13	5.80	2.22
	Baijiao Town	77.25	11.73	56.93
	Jingan Town	0.86	5.42	1.70
	Baiteng Street	0.75	5.22	1.47
	Leizhu	0.97	5.58	1.91
	Reclamation Area of reclamation company			
Jinwan District	Qianwu Town	9.45	8.78	12.33
	Hongqi Town	0.82	4.76	1.44
	Sanzao Town	0.81	4.76	1.44
Wanshan District ^a	Guishan Town	/	10.54	3.23
	Wanshan Town	/	7.82	2.26
	Dangan Town	/	7.16	2.03
High-tech Zone	Tangjiawan Town	0.69	5.05	1.34
Gaolan Harbor Zone	Pingsha Town	2.11	4.62	3.16
	Nanshui Town	0.70	5.02	1.35

^a There is no freshwater aquaculture in Wanshan District.

Doumen > Gaolan Port > Jinwan > High-tech, which was consistent with the order of FA emissions. The ranking was verified by calculating the EPL according to Eqs. (9) and (10); the results are shown in Table 4. The EPL (%) ranking followed the order Doumen > Gaolan Port > Jinwan > High-tech. The evaluation of the entropy weight largely agreed with the EPL evaluation.

4.2.3. Analysis of the EWM results

The comprehensive evaluation scores of the mass load evaluation of aquaculture in Zhuhai's tertiary administrative units are shown in Table 3. For total aquaculture and FA, the highest scores followed the order Baijiao > Qianwu > Lianzhou. These results are consistent with the ranking of emissions. For mariculture, the highest comprehensive evaluation scores followed the order Baijiao > Guishan > Qianwu. It should be noted that, among the towns included in this study, only Guishan belongs to Wanshan District; the other towns belong to Doumen District. For FA, the score at Baijiao was 67.8 higher than that at Qianwu; for total aquaculture, the score at Baijiao was 44.6 higher than that at Qianwu. As a result, Baijiao Town should be the top priority for aquaculture control in Zhuhai.

In the preprocessing of raw data using the exponential function, there was a slight discrepancy between the entropy-corrected evaluation results for mariculture in the tertiary administrative units involved and the emissions ranking. For example, the comprehensive evaluation scores for mariculture ranked the top four sites as Baijiao > Guishan > Qianwu > Wanshan, whereas emissions followed the order Guishan > Baijiao > Wanshan > Qianwu. The empowerment procedure and the coefficients of variation of the EWM are shown in Table S3. The raw data

Table 4

Equivalent pollution load ratios in freshwater aquaculture.

Administrative unit	TN (%)	TP (%)	NH ₃ -N (%)	COD (%)	Total load ratio (%)
Zhuhai City	43.05	45.60	4.78	6.57	100.00
Doumen District	17.46	21.81	1.04	2.13	42.43
Jinwan District	2.62	2.44	0.72	1.21	6.99
High-tech Zone	0.00	0.00	0.00	0.00	0.00
Gaolan Harbor Zone	4.72	3.26	0.68	0.60	9.26

Abbreviations: TN, total nitrogen; TP, total phosphorus; NH₃-N, ammonia nitrogen; COD, chemical oxygen demand.

were forward-processed using the exponential function; the results were consistent with the relative emissions. The weights were consistent with the degree of dispersion of the data, represented by the coefficient of variation. Therefore, the reason for the inconsistency between the EWM results and the ranking of emissions is that the exponential method changed the relative size of the original data. For example, the emission of major pollutants from mariculture was in the range of 94.5–6.4 t. After exponential treatment, TN emissions ranged from 2.56 to 0.98 (dimensionless). Thus, although the exponential function of the IEWM changed the relative size of the original data, the evaluation results reflected the actual situation.

4.3. Emission intensity analysis

The most important indicator of pollutant emission in aquaculture is the emission intensity of major pollutants per unit yield (Mu et al., 2021) or, in this case, per unit aquaculture area, calculated using Eq. (8). The results are shown in Fig. 6. The intensities of TN, TP, NH₃-N, and COD emissions per unit aquaculture yield in Zhuhai in 2017 were 2.13-, 3.4-, 1.04-, and 2.22-fold higher than those at the national level, respectively. In 2019, the yield increased slightly (by 7%) compared to 2017, but the emission intensities of major pollutants per unit aquaculture yield in Zhuhai decreased, with the emission intensities of TN, TP, NH₃-N, and COD decreasing by 40%, 43%, 75%, and 52%, respectively. Compared with the emission intensities of major pollutants per unit yield in 2017, the emission intensities of the major pollutants other than NH₃-N remained higher than those at the national level. Therefore, it is important to better prevent and control aquaculture pollution in Zhuhai, for instance by improving aquaculture tailwater treatment methods, introducing ecologically healthy breeding models, reducing the use of pharmaceuticals in aquaculture, and continuing emission reduction efforts.

The emission intensities of major pollutants per unit aquaculture area in Zhuhai and in the secondary administrative units are shown in Fig. 7. The analysis was performed using the data in Table S4. For FA, the yield in Gaolan Port District was 0.09 times that of Doumen District, and the emission intensities per unit yield of NH₃-N and COD were 2.12- and 1.31-fold higher than those of Doumen District, respectively. As shown in Table 5, from the perspective of yield, the structure of aquaculture in Gaolan Port District and Doumen District was similar, with FA and mariculture yields accounting for ~ 30% and ~ 70% of the total aquaculture yield, respectively. However, the pollutant emission intensity was higher in Gaolan Port District than in Doumen District. Previous studies (Edwards, 2015; Zhang et al., 2022) showed that most aquaculture in China has a low level of intensification, such that the yield potential of the existing aquaculture area, and thus the yield per unit area, can be increased. These results show that ecologically sound aquaculture techniques must be improved, with a focus on preventing NH₃-N contamination, in Gaolan Port District.

For mariculture, Wanshan District had the highest emissions of TN and TP per yield. The yield of mariculture in Wanshan District was 0.29-fold higher than that in Doumen District, but the TN and TP emission intensities per unit yield were 12.2- and 5.31-fold higher, respectively. Wanshan is the only district in Zhuhai in which only mariculture is conducted, and it is also the main area for deep-water cage culture. According to remote-sensing images, pond culture is the main aquaculture method in Doumen District. The difference in the emission intensity per unit yield can thus be directly attributed to the aquaculture method. Accordingly, Wanshan District should adopt not only ecologically sound aquaculture techniques but also pollution control measures.

The emission intensities of major pollutants per unit aquaculture area were calculated according to Eq. (8), and the results are shown in Fig. 7. For FA, Doumen District had the highest TP emission intensity per unit aquaculture area, while Gaolan Port District had the highest TN, NH₃-N, and COD emission intensities per unit aquaculture area. The EPL results indicated that TP and TN were the most important FA pollutants

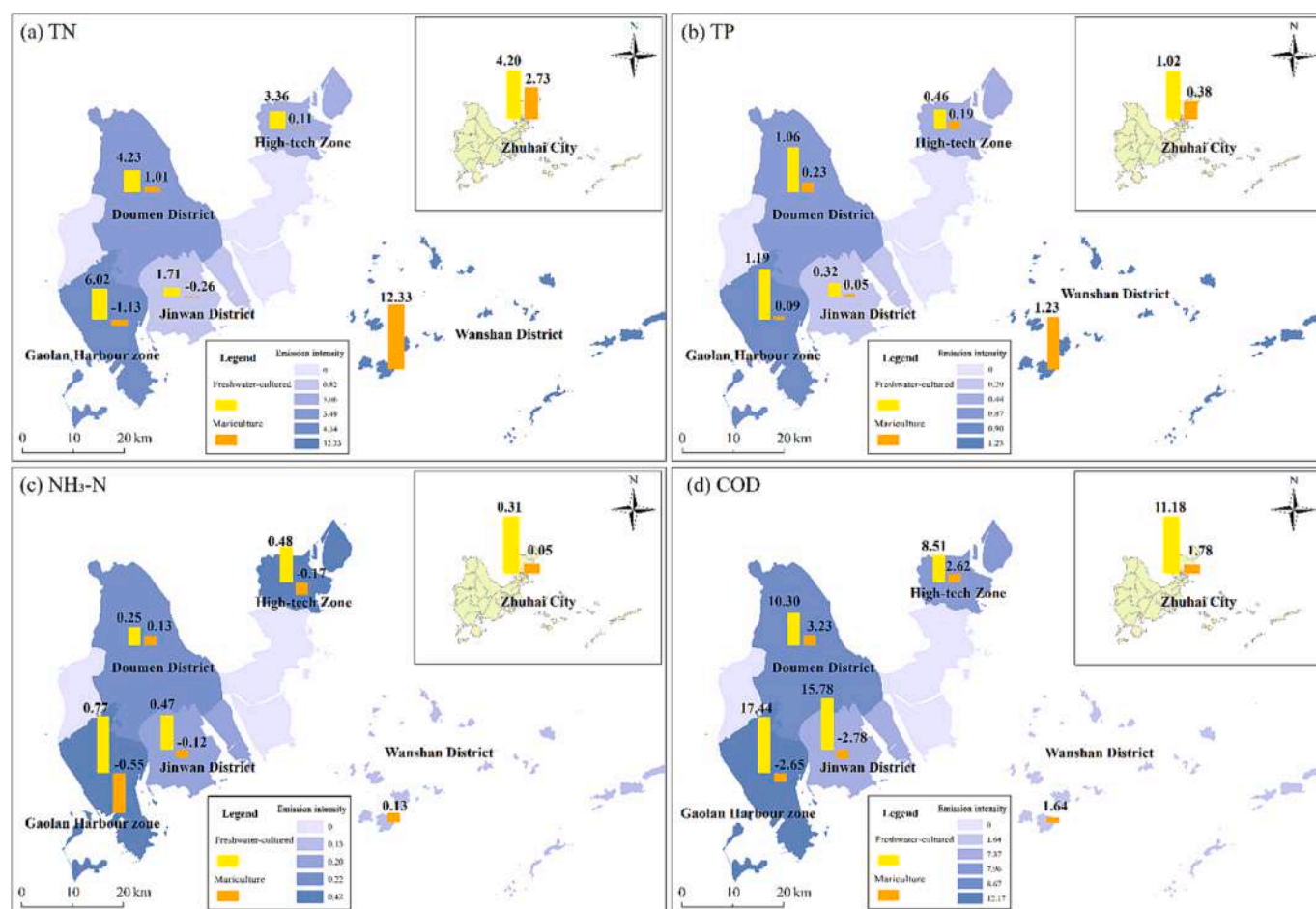


Fig. 6. The mass loads (kg·t⁻¹·a⁻¹) of freshwater aquaculture (FA) and mariculture per unit yield in Zhuhai and the secondary administrative units: (a) total nitrogen (TN), (b) total phosphorus (TP), (c) ammonia nitrogen (NH₃-N), and (d) chemical oxygen demand (COD).

(Table 5). In terms of pollutant contribution, Doumen District had the highest percentage EPL for all major pollutants.

According to the findings presented in Table 5, the TN, TP, NH₃-N, and COD emissions from aquaculture per unit aquaculture area in Zhuhai in 2017 were 5.18-, 7.32-, 3.34-, and 5.35-fold higher than those at the national level, respectively. In 2019, emissions improved slightly, except for NH₃-N. The emission intensities of the other major pollutants per unit aquaculture area were 2.91- to 4.72-fold higher than those at the national level. Among them, the TP emission intensity per unit aquaculture area was highest in Doumen District, whereas the emission intensities of TN, NH₃-N, and COD per unit aquaculture area were highest in Gaolan Port District. In 2017, the yield per unit aquaculture area was 6.59 t·ha⁻¹ nationally and 10.92 t·ha⁻¹ in Zhuhai (Editorial Board of China Fishery Statistical Yearbook, 2018). The respective values for 2019 were 7.15 t·ha⁻¹ and 12.31 t·ha⁻¹ (Editorial Board of China Fishery Statistical Yearbook, 2020). The high emission intensity of major pollutants per unit area in Zhuhai is due to the high aquaculture density. Unustainable production practices, such as excessive farming density, excessive bait stocking, and excessive use of antibiotics, cause regional environmental problems and threaten the ecological health of the surrounding water bodies (Edwards, 2015; Zhang et al., 2015). Therefore, in addition to gradually reducing the aquaculture area and improving production capacity, the use of ecologically aquaculture techniques should be enhanced and aquaculture pollution control should be improved in Zhuhai.

In districts and counties dominated by FA, COD emissions accounted for > 60% of total major pollutant emissions from FA. For example,

Gaolan Port District had the highest NH₃-N and COD emission intensities. In districts and counties dominated by mariculture, TN emissions accounted for ~ 80% of the total major pollutant emissions. In Jinwan and Gaolan Port Districts, mariculture TN, NH₃-N, and COD emissions were negative. Wanshan District had the highest TN and TP emission intensities per unit yield. The results of the EWM showed that Doumen District had the highest mass loads from FA and mariculture, while Baijiao Town had the highest mass loads from FA, mariculture, and total aquaculture. With the exception of NH₃-N, the emission intensities of major pollutants in Zhuhai exceeded the national average in 2017, with the largest excess that of TP.

This study provides a detailed description of aquaculture emissions to the township level. The use of an exponential preprocessing method improved the EWM while the positive transformation of natural data sets avoided the anomalous effects of the standardization of data sets with negative numbers. Our results suggest both a theoretical and a scientific framework for the evaluation of aquaculture in coastal cities as currently practiced, in addition to highlighting the need for various pollution control measures. However, the limitations of this study must be noted. First, the auxiliary method of identifying problems through comparative evaluation is not concise, and the EWM index is relatively limited. Moreover, the exponential function preprocessing method changes the relative relationships among the raw data, which may affect the accuracy of the EWM.

5. Conclusion and prospects

In this study, a joint method was used to estimate and evaluate the

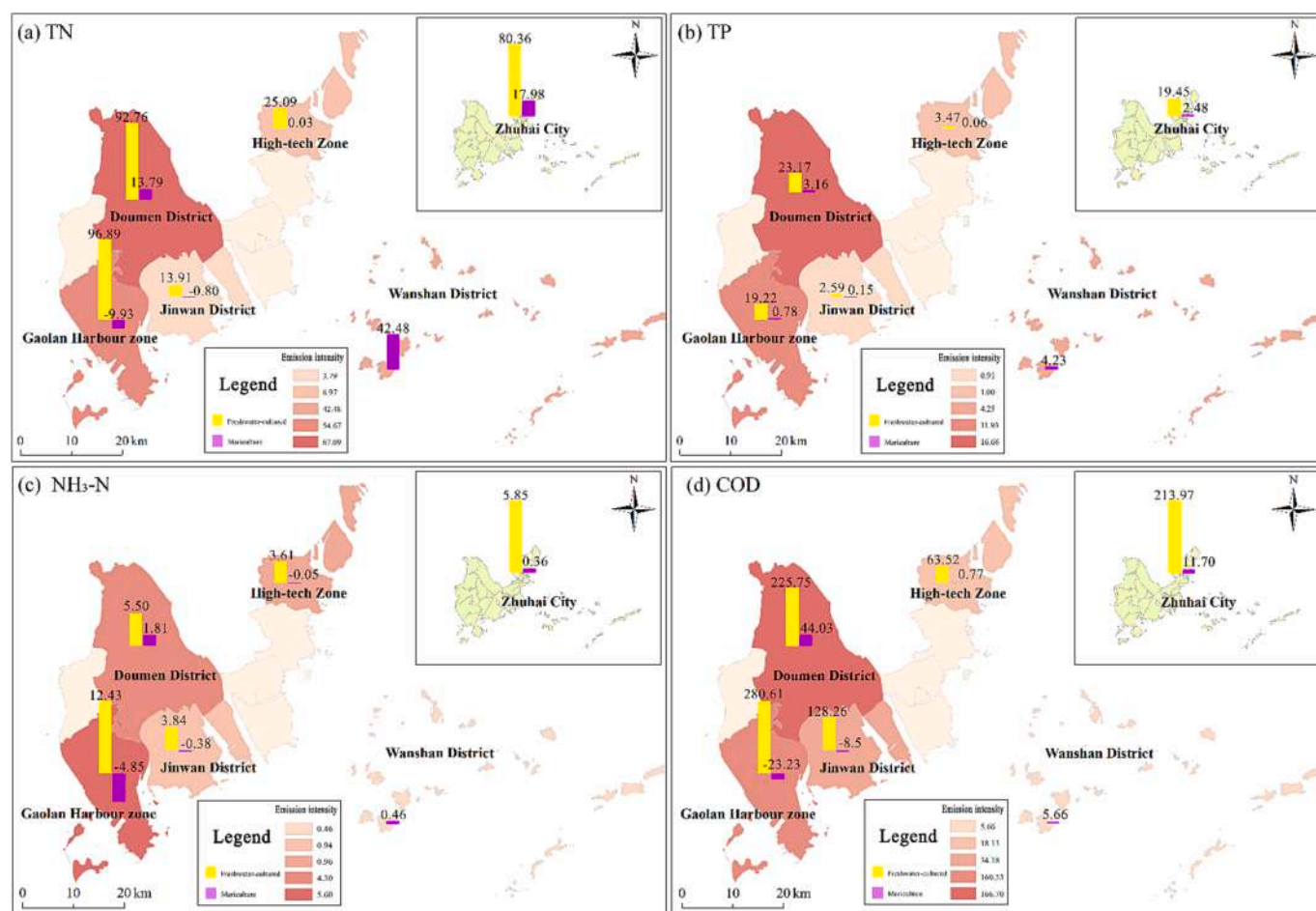


Fig. 7. The mass loads (kg·ha⁻¹) of freshwater aquaculture (FA) and mariculture areas per unit in Zhuhai City and the secondary administrative units: (a) total nitrogen (TN), (b) total phosphorus (TP), (c) ammonia nitrogen (NH₃-N), and (d) chemical oxygen demand (COD).

Table 5

Comparison of the aquaculture emission intensity and aquaculture intensity in China and in Zhuhai.

Year	Administrative unit	Emission intensity per unit yield (kg·t ⁻¹ ·a ⁻¹)				Emission intensity per aquaculture area (kg·ha ⁻¹ ·a ⁻¹)				Yield per unit aquaculture area (t·ha ⁻¹)
		TN	TP	NH ₃ -N	COD	TN	TP	NH ₃ -N	COD	
2017	Zhuhai City	6.31	1.45	0.92	43.79	68.96	15.85	10.02	478.20	10.92
2019	Zhuhai City	3.77	0.83	0.23	21.12	46.43	10.22	2.86	259.92	12.31
2017	China	2.02	0.33	0.46	13.58	13.31	2.17	3.00	89.41	6.59

Abbreviations: TN, total nitrogen; TP, total phosphorus; NH₃-N, ammonia nitrogen; COD, chemical oxygen demand.

emissions of major pollutants from FA and mariculture in Zhuhai City and its tertiary administrative units. According to the analysis, emissions of TN, TP, NH₃-N, and COD from FA were 916.26 t, 221.77 t, 66.73 t, and 2439.63 t, while from mariculture they were 244.31 t, 33.71 t, 4.84 t, and 159.01 t, respectively. The joint method allowed for a more accurate estimation and evaluation of the aquaculture mass load. The results showed that FA in Gaolan Port District must include measures to prevent NH₃-N and COD pollution, and mariculture in Wanshan District requires measures to better control TN and TP emissions. The negative emissions from mariculture in Jinwan and Gaolan Port Districts may be related to the species and to the aquaculture methods. Aquaculture in Zhuhai is intensive, and the high aquaculture density and high pollutant emission intensities remain problematic. To more accurately evaluate the aquaculture load in coastal cities, the EWM index requires further improvement.

6. Authorship contribution statement

Yu Xing: Study conceptualization and design, manuscript drafting, manuscript approval for publication; Zhou Zhang: GIS mapping, visualization; Wenjing Zhao: Supervision, writing—review & editing. Yan Liao: Writing—review, manuscript approval for publication; Zhuangming Zhao: Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2023.111205>.

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