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Specificality, Quality Variation, Assessment and Treatment of Estuarine Water in the Pearl River Delta, South China

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ABSTRACT. The Pearl River Delta (PRD) is a major economic and manufacturing area in South China. Using the comprehensive and authoritative monitoring data, this study conducted a systematic review of the regularity of marine disasters (e.g., storm surges, saltwater intrusions, and red tides), water quality variations, water quality risk assessments and wastewater treatment in seven sections of the Pearl River Estuary (PRE). The total water resources in the PRD have been a decreasing in recent years. Seasonal marine disasters occur frequently, causing loss of life and economic damage. A monitoring and early-warning system was constructed to provide a scientific basis for dealing marine disasters response. Based on the water quality monitoring data from the seven main PRE sections from 2015 to 2020, chemical properties, heavy metal concentrations and comprehensive pollution indices were selected as indicators. The water quality of the seven PRE sections, flowing westward into the South China Sea improved over time. According to a water quality risk assessment, Yamen the estuary nearest the sea is at the highest risk. The PRD had a wastewater treatment rate of 97.37%, which was equal to the average of Guangdong Province. These findings can be used to predict future trends in estuarine water, quality and inform future studies of water quality variations in the PRD.

Keywords: Pearl River Delta, risk assessment, spatial variation trends, wastewater treatment, water quality parameters

1. Introduction

The Pearl River Delta (PRD), Guangdong Province, is a major aquaculture, economic and manufacturing region of South China (Streets et al., 2006; Gong et al., 2011; Geng et al., 2015). The main water resources in the PRD originate from the Pearl River and its multiple tributaries, with the natural conditions ensuring an abundance of water (Liu et al., 2018). The rich water resources and numerous waterways provide water for rural communities and urban residents in the PRD region, and are used for agricultural irrigation, industrial activities and shipping (Fan et al., 2012). Of the total 162.6 billion m^3 of water resources in the river basins of Guangdong Province, the PRD region including the cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing accounted for 16.2% in 2020 (Figure 1). In the PRD region, the volume of total water resources varied by 23.4 ~ 64.4% from 2009 to 2020 (latest data). In 2020, the total water volume was 23.7% lower than that in 2019 (WRDGDP, 2009 ~ 2020). Moreover, despite the large estuary area, the PRD experiences water quality issues. It is therefore important to ensure effective water quality monitoring and treatment (Yang et al., 2017; Zhang et al., 2017).

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Changes in the water pollutant composition in the Pearl River upstream region have significantly affected the downstream water quality (Zhang et al., 2012). In the PRD, water quality has deteriorated due inputs of heavy metals, nitrogen, petroleum and harmful toxic organics (Fu et al., 2003; Ip et al., 2007; Yin et al., 2011; Zhang et al., 2013a). Additionally, the marine environment is increasingly affected by climate change and human activities. Marine disasters have dynamic characteristics and pose serious threats to socioeconomic development. A range of marine disasters, including storm surges, saltwater intrusions, large ocean waves, and red tides, occur frequently and can cause pollution over large areas, the death of marine organisms and huge economic losses in coastal zones and estuaries (Chen et al., 2021; Wang et al., 2021). Therefore, a disaster monitoring and warning system is critical to protect the marine environment, prevent disasters, and further develop the region (Zhang et al., 2014). In 2018, approximately 6.7 billion tons of wastewater was discharged into the PRD Basin, accounting for 58.2% of total wastewater discharged in Guangdong Province (WRDGDP, 2018). Moreover, the water quality compliance rate in the PRD region has decreased (Figure S1). Based on an analysis of 104 river samples in 2018 (the latest data available), the water quality compliance rate was 36.5%, close to the value in 2012. This indicates that the quality of the available water resources is gradually worsening.

Several national water pollution control and treatment projects have been established in China to improve water quality, such as the Major Science and Technology Program for Water Pollution Control and Treatment, and the Water Pollution Control Action Plan by the State Council; these projects have achieved the goals of ensuring that less than 15% of groundwater is of poor quality and approximately 70% of nearshore water samples meet the Chinese water quality standard Class I and Class II (Liu et al., 2019). Studies of the different types of water pollutants and treatment have been conducted in China. In the PRD region, studies have analysed inorganic versus organic water pollutants, but they have not considered the temporal variations in water quality, water quality risk assessments and wastewater treatment in the estuaries that flow westward into the South China Sea. Moreover, studies have not analysed regional pollution systematically, and thus cannot accurately reflect the current statues. Importantly, the data used in previous studies were not collected recently (Cheung et al., 2003; Guo et al., 2009; Yang et al., 2013).

Therefore, the main objective of this study was to comprehensively review the trends of marine disasters, variations in water quality, water quality risk assessments and wastewater treatment from seven sections of the Pearl River Estuary (PRE). In Guangdong Province, water quality monitoring began in 2009, and was gradually systematised, with more comprehensive monitoring since 2015. Meanwhile, the development of water resources in China entered the protection stage in 2013. Therefore, we analyzed the data from 2009 to 2020, which include the most recent statistical data available.

2. Materials and Methods

2.1. Sampling Location

The PRD is located in South China and has a subtropical climate. The region includes the cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing (Figure 1). The water quality monitoring samples used in this study were collected from the seven main PRE sections (113°49′E, 22°49′N to 113°05′E, 22°13′N): Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen and Yamen. The Pearl River flows westward through the large area of the PRD, and drains into the South China Sea. The seven main sections of the PRE are connected to each other via numerous branches, which complicate the predication of changes and the control of inorganic and organic pollutants.

2.2. Statistical Analysis

Water quality monitoring and risk assessments are essential parts of a water resource management program. However, different methods, such as a single assessment method versus multivariate analysis, may yield different results. In this research, multiple-criteria decision analysis (MCDA), including stochastic weight averaging (SWA), the technique for order preference by similarity to an ideal solution (TOPSIS), fuzzy principal component analysis (FPCA) and analytic hierarchy process (AHP), was used for the comprehensive water quality risk assessment of the seven main PRE sections.

2.3. Data Resources

The data used in the study were collected from Water Resources Department of Guangdong Province (2009 ~ 2020), Department of Natural Resources of Guangdong Province (2013 ~ 2020), Department of Ecology and Environment of Guangdong Province (2014 ~ 2020), Report on the State of Guangdong Provincial Ecology and Environment (2009 ~ 2020) and professional literatures (DEEGDP, 2019, 2020; DNRGDP, 2020; WRDGDP, 2009 ~ 2020).

3. Analysis of Marine Disaster Occurrence and Strategies

3.1. Trends in Marine Disasters

The marine system is complex and usually consists of an economic system, social system and ecosystem (Figure 2a). These subsystems are closely related and influence each other (Sun et al., 2017). Marine disasters have immediate impacts on the social and economic systems. With the rapid development of the marine economy, the risks posed by marine disasters have become increasingly serious and are a crucial environmental issue in coastal areas (Zuo and Li, 2008; Guo et al., 2019). In recent decades, most coastal areas in China have experienced frequent marine disasters (He et al., 2014; Shi et al., 2015). As one of the major coastal provinces in China, Guangdong Province has suffered the most serious marine disasters. This is especially true for the PRD region, which has been threatened by storm surges, saltwater intrusions, ocean waves and other marine disasters (Li and Li, 2010; Wang et al., 2012; Zhou et al., 2012). A 2020 analysis by the Department of Natural Resources of Guangdong Province estimated the direct economic losses caused by marine disasters to be 7.7×10^7 US dollars, lower than the average value over the previous years (2.8×10^8 US dollars); the number of deaths (including missing persons) in 2020 was slightly lower than the average value over the previous years (Figure 2b). From 2013 to 2016, the total direct economic losses caused by marine disasters decreased significantly, but they increased again in 2017, no regularity was evident. This may have been related to differences in the types and frequencies of marine disasters that occurred and the resulting damage (Fang et al., 2017; Sun et al., 2017; Wang et al., 2017). The main marine disasters in the PRD region are summarized in Tables S1 ~ S3; storm surges, saltwater intrusions and red tides occurred yearly in the PRD from 2013 to 2020, and coastal cities such as Shenzhen, Zhuhai and Huizhou were suffered frequently affected.

3.2. Early-Warning System

The frequency of storm surges frequencies is positively correlated with casualties and direct economic losses in coastal areas, with Guangdong Province the most seriously affected compared to the other coastal ones (Shi et al., 2015). The occur-

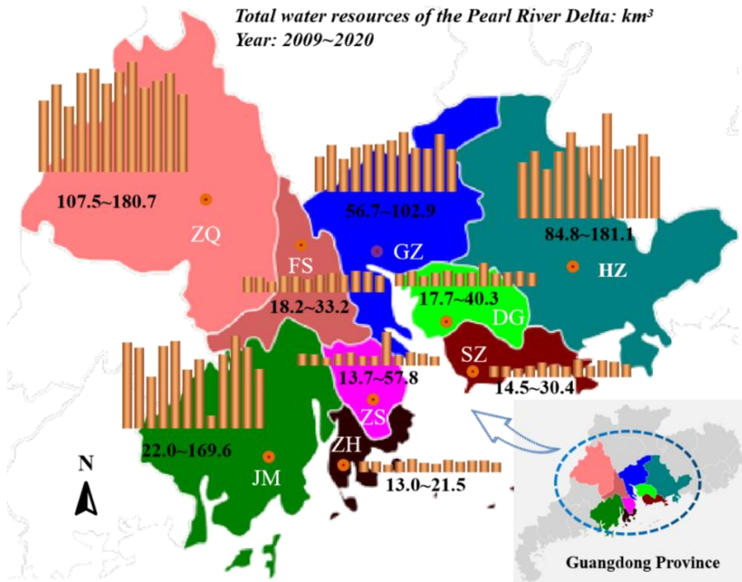

Figure 1. Variation of total water resources in the PRD region (GZ: Guangzhou; SZ: Shenzhen; ZH: Zhuhai; FS: Foshan; HZ: Huizhou; DG: Dongguan; ZS: Zhongshan; JM: Jiangmen; ZQ: Zhaoqing).

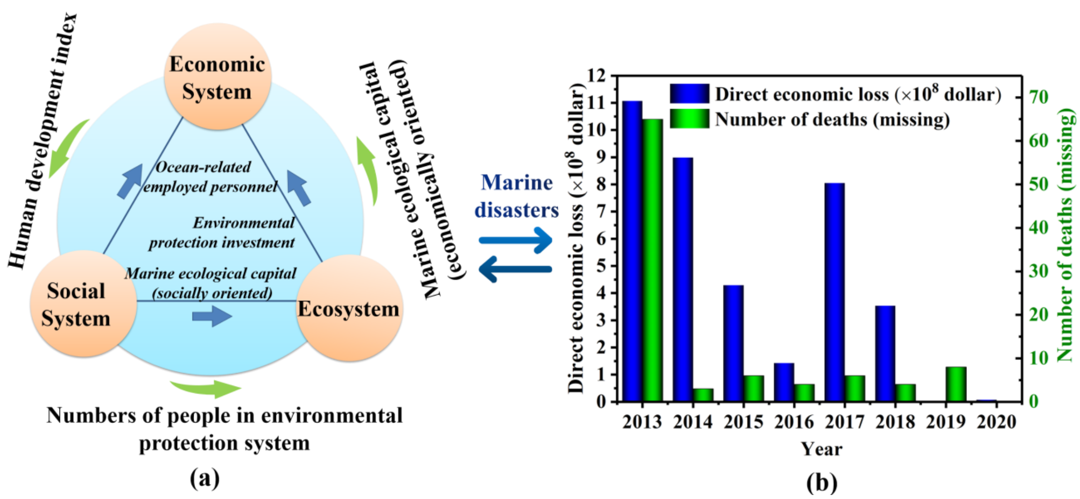

Figure 2. Effect of marine disasters among complex marine system from 2013 to 2020.

rence of marine disasters is seasonal. Table S1 shows the main storm surge disasters in the PRD region from the Marine Disaster Bulletin of Guangdong Province (2013 ~ 2020). The number of cities hit by typhoon has gradually increased in recent years, and with Jiangmen and Huizhou impacted almost every year. Although typhoon surges usually only last for 1 ~ 2 days, it leads a large number of direct economic losses.

In recent years, saltwater intrusions have become more frequent and severe, especially in winter (Huang et al., 2004; Becker et al., 2010; Cui, 2010; Wang et al., 2012). Table S2 shows the occurrence of saltwater intrusion disaster from 2013 to 2020. Saltwater intrusions commonly occur in spring and winter, with the longest lasting for nearly 3 months in the PRD. During these periods, salinity and chloride concentrations increase, causing drinking water, and industrial and agricultural water to become salty. According to the Water Quality Standard for Drinking Water Sources (CJ3020-93) and the Sanitary Standard for Drinking Water (GB5749-2006) (NHCPRC, 2006), the maximum chloride concentration of estuarine in the PRD was about 20 times higher than the standard value (< 250 mg/L). High chloride contents in drinking water have adverse health effects (Wang et al., 2019; Zeng et al., 2020; Ekundayo et al., 2021).

The monitoring data also identified multiple red tides events, with wide-ranging losses in recent years (Guan and Zhen, 2003; Wei et al., 2008). Shenzhen, Zhuhai, and Huizhou were affected by red tides almost every year (Table S3). The maximum area affected reached 100 km^3, and the events lasted more than 10 days. Although sudden red tides have become normalized, the monitoring of eutrophication sources, invasive species con-

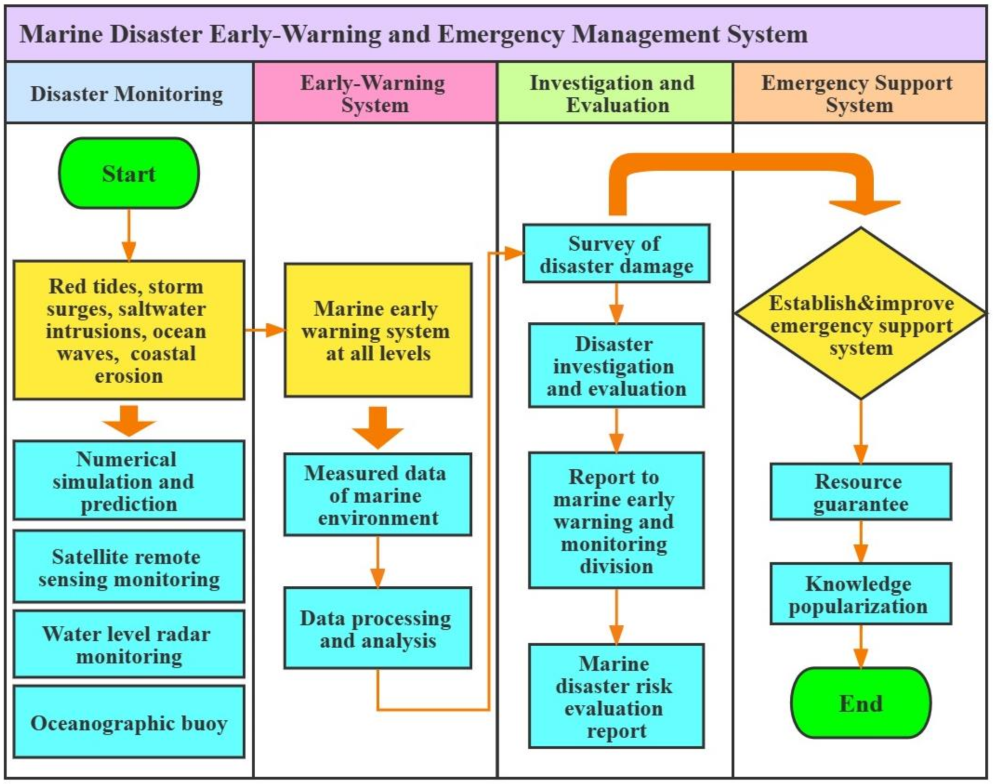

Figure 3. Marine disaster early-warning and emergency management system.

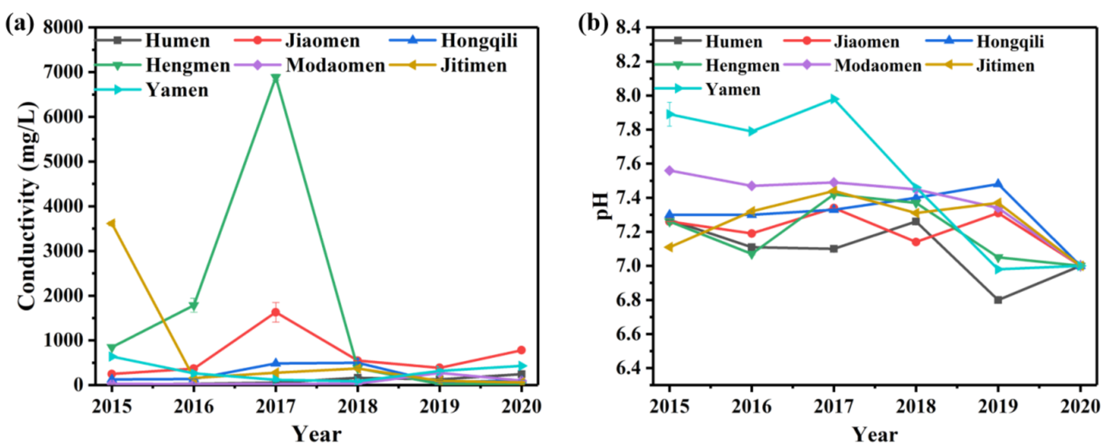

Figure 4. Chemical properties of (a) conductivity and (b) pH in the seven PRE sections.

trol and water quality improvements are important (Chen et al., 2021).

In addition to the marine disasters mentioned above, large ocean waves, sea level changes, coastal erosion and tsunamis may occur in the PRD region. Because disaster loss is an important factor when determining the disaster level, preventative measures should be taken to minimize the losses resulting from marine disasters (Sun et al., 2020). An effective early-warning system should consider a series of external factors, such as the type of marine disaster, and its time of occurrence and duration. Several studies have reported the establishment of interactive early-warning or emergency management systems for marine disasters (Sun et al., 2013; Zeng et al., 2018; Wang et al., 2019; WRDGDP, 2020). Due to the geographical location of the PRD region, complex and variable marine disasters occur in the region almost every year, therefore, an adaptive and systematic early-warning and emergency management system is required. In view of the current situation and based on the main marine disaster data in the PRD region, a monitoring and early-warning system was proposed (Figure 3). The system includes disaster monitoring, an early-warning system, investigations and an evaluation and emergency support system that was mainly directed

Table 1. Summary of Statistical Analysis for Heavy Metals in the Seven PRE Sections from 2015 to 2020 (Unit: μg/L)

City	Estuary	Aggregation	Cu	Zn	Se	As	Hg	Cd	Cr^{6+}	Pb
Dongguan	Humen	Min	1.06	1.80	0.20	0.20	0.010	0.02	2.00	0.04
		Max	66.00	59.00	2.60	4.70	0.850	0.05	2.00	0.57
		Mean	5.88	6.71	0.50	2.19	0.050	0.03	2.00	0.18
		SD	9.35	7.29	0.51	0.96	0.140	0.01	0.00	0.12
Guangzhou	Jiaomen	Min	1.20	3.10	0.20	1.50	0.020	0.02	2.00	0.04
		Max	2.00	43.30	2.40	4.90	0.310	0.10	2.00	0.70
		Mean	2.72	4.55	0.77	2.46	0.130	0.03	2.00	0.24
		SD	2.10	6.39	0.95	1.34	0.010	0.03	0.00	0.30
Guangzhou	Hongqili	Min	2.00	2.30	0.20	1.80	0.002	0.02	2.00	0.04
		Max	9.90	22.00	1.00	3.10	0.050	0.10	13.00	1.00
		Mean	2.79	4.01	0.53	2.03	0.010	0.03	2.33	0.25
		SD	2.12	3.75	0.74	0.86	0.010	0.02	1.91	0.30
Zhongshan	Hengmen	Min	1.09	2.40	0.20	0.20	0.040	0.02	2.00	0.04
		Max	18.00	63.00	0.80	1.90	0.030	0.03	4.00	1.00
		Mean	3.81	7.95	0.22	1.70	0.020	0.02	2.06	0.17
		SD	5.29	14.91	0.08	1.00	0.010	0.00	0.34	0.19
Zhuhai	Modaomen	Min	2.00	1.00	0.20	0.20	0.001	0.02	2.00	0.10
		Max	6.00	37.5	0.30	4.40	0.030	0.04	10.00	1.00
		Mean	4.60	3.62	0.21	1.56	0.010	0.03	5.98	0.15
		SD	9.36	6.51	0.03	0.84	0.010	0.02	6.72	0.10
Zhuhai	Jitimen	Min	2.00	2.00	0.20	0.10	0.010	0.02	2.00	0.04
		Max	4.00	8.00	7.20	5.40	1.410	0.03	20.00	1.00
		Mean	2.46	2.43	0.39	1.60	0.050	0.03	7.37	0.15
		SD	1.95	2.67	1.15	0.92	0.220	0.01	5.82	0.24
Jiangmen	Yamen	Min	0.71	2.00	0.20	0.70	0.002	0.02	5.00	0.04
		Max	8.00	11.60	0.50	8.20	0.020	0.40	23.00	2.00
		Mean	3.39	6.45	0.37	1.53	0.020	0.03	5.79	0.71
		SD	5.25	7.07	0.28	1.15	0.010	0.15	7.10	0.90

Note: SD denotes Standard Deviation.

towards the red tides, storm surges, saltwater intrusions, ocean waves and coastal erosion. This marine disaster early-warning and emergency management system has a scientific basis and represents an opportunity to better manage marine disasters in the coastal areas of China.

4. Water Quality Variation Trend in Seven Estuaries

In the PRD region, the seven main sections of the PRE (Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen and Yamen) flow westward into the South China Sea. To identify the variations in estuarine water quality in recent years and make future predictions, the chemical properties, concentrations of eight heavy metals and nine comprehensive pollution indices were selected as index parameters. The water quality data were processed, including complementary data and null values, and expressed as monthly, seasonal and annual averages.

4.1. Chemical Properties

The main chemical properties, including conductivity and pH, have been measured in recent years. Conductivity is a measure of the electric current in flowing water, and pH is a measure of the acidity and alkalinity of water (Thirumdas et al., 2018). Conductivity and pH are important factors in water quality monitoring (Wenner and Geist, 2001; Mosley and Liss, 2019).

Using data from the DEEGDP for the period 2015 ~ 2020, variations in the spatial distributions of conductivity and pH were analyzed. Conductivity tended to increase in Humen, Jiaomen and Yamen after 2019 (Figure 4a). Increases in conductivity are related to organic matter decomposition and mineralization (Srivastava and Srivastava, 2011), which could be explained by the higher pollutant discharges in these sections. The linear fit is shown in Figure S2. The first-order kinetic model fitted relatively well (R^2 > 0.86) with a slope of 44.35 for Humen. The maximum and minimum slopes of the fitted equations were 46.25, and −510, respectively. Moreover, conductivity tended to increase in Humen and decrease in Jitimen. The kinetic model could be used to predict the conductivity trend of the seven PRE sections. The data revealed no significant difference in pH among the seven sections (Figure 4b); all pH values fluctuated within a range of 7 ~ 8.

4.2. Estuarine Water Quality Monitoring

Heavy metal concentrations. Heavy metals do not decompose in the environment and present serious problems due to the toxicity, persistence, and tendency to bioaccumulate (Yang et

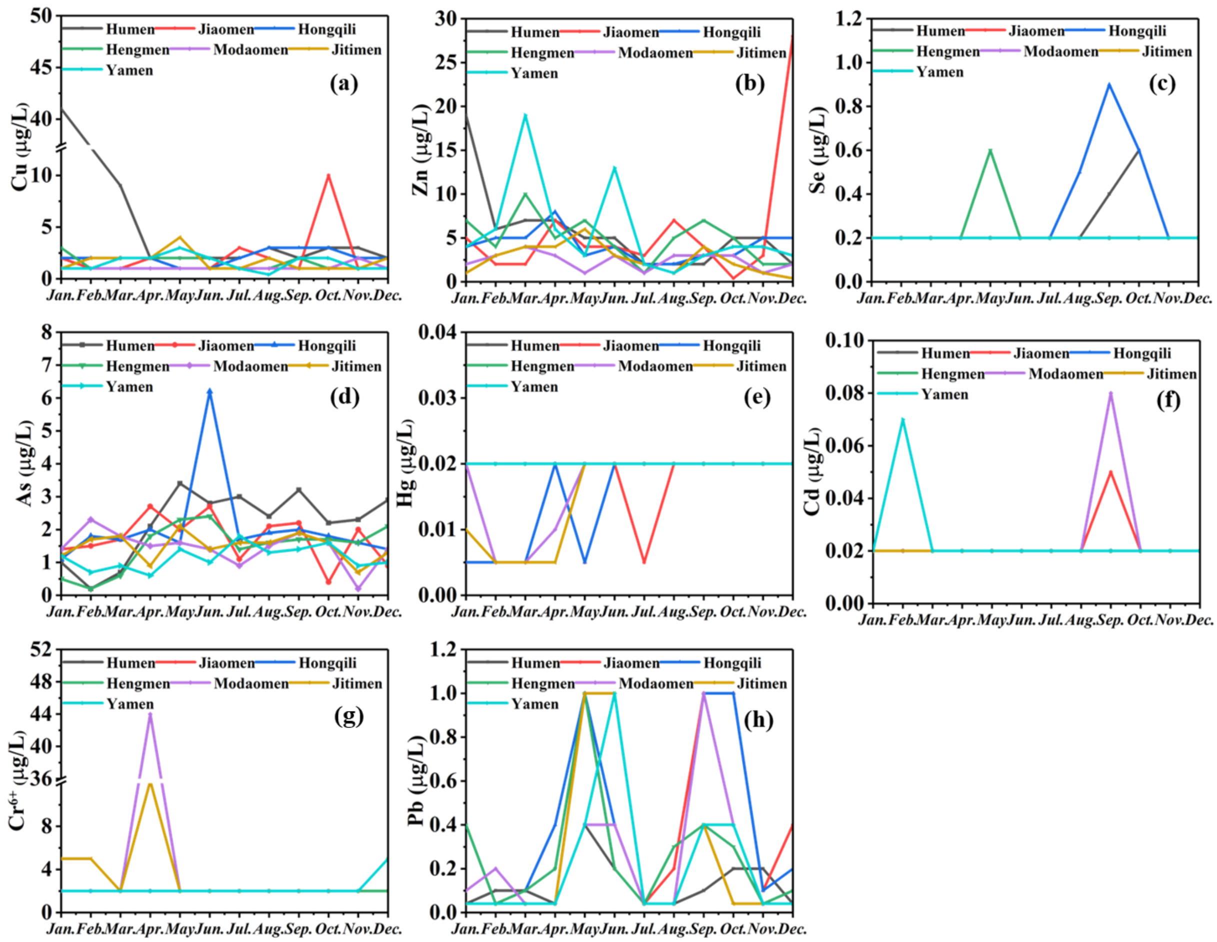

Figure 5. Monthly changes of heavy metal concentrations in the seven PRE sections (2020 data).

al., 2012; Sun et al., 2015). Arsenic (As), cadmium (Cd) and lead (Pb) have been classified as priority pollutants (Ip et al., 2005; Ye et al., 2012). With the rapid development of leisure-orientated industries in coastal areas, heavy metal pollution has become a serious problem in estuarine waters (He and Fan, 2006; Chen et al., 2012). In recent decades, heavy metal concentrations higher than the relevant seafood standards have been detected in the PRD (Wei et al., 2002). Figure 5 shows the monthly changes in the concentrations and spatial distributions of heavy metals in the seven PRE sections (2020 data). The concentrations of most metals varied throughout the year. However, there were no monthly changes in the selenium (Se), mercury (Hg) and hexavalent chromium (Cr^{6+}) concentrations in Yamen. In general, total heavy metal concentrations were lower in the west than in the east. In particular, the copper (Cu) and As concentrations gradually decreased from Humen in the east to Yamen in the west.

Table 1 shows the descriptive statistics of the heavy metals in the seven PRE sections from 2015 to 2020. The mean heavy metal concentrations followed the order of zinc (Zn) > Cr^{6+} > Cu > As > Se > Pb > Hg > Cd. Yamen had the highest heavy metal concentrations. The heavy metal concentrations declined significantly in all seven sections from January 2015 to December 2020 (Figure S3), indicating the efficacy of heavy metal control in the region. However, Zn, Cu, As, and Cr^{6+} concentrations were enriched in all seven sections.

Comprehensive pollution indices. The estuarine waters pollution levels in the seven PRE sections were also assessed based on comprehensive pollution indices, including dissolved oxygen (DO), biochemical oxygen demand (BOD), potassium permanganate index (CODMn), total phosphorus (TP), total nitrogen (TN) and ammonia nitrogen (NH_3-N).

Figure 6 shows the changes in the comprehensive pollution indices from 2015 to 2020. Over this period, the concentrations of NH_3-N, BOD, volatile phenols, petroleum, TP, CODMn, and anionic surfactant displayed significant reduction of 70.0, 66.4, 54.1 53.6, 49.8, 28.4, and 11.7%, respectively. In contrast, DO increased by 42.0%, and TN remained stable. Overall, the water quality improved after 2015. The success of pollutant reduction measures could be attributed to industrial upgrading and relocation, as well as improvements to sewage treatment systems in the PRD region. Nitrogen, phosphorus, and organic pollutants in the estuarine waters were most likely due to industrial wastewater discharges, faecal pollution or agricultural irrigation from upstream areas. Therefore, effective approaches to reduce the levels of nitrogen, phosphorus and organic pollutants should be implemented (Li et al., 2019a).

As shown in Figures 7a ~ 7e, the comprehensive pollution indices using 2020 data followed the order of DO > CODMn > BOD, TN > NH_3-N > TP. The DO concentration was lower in humen than in other estuary sections, whereas the BOD, CODMn, TN and NH_3-N concentrations were higher, in all months (January ~ December). Our data (Figures 7d ~ 7e) were consistent with previous findings that phosphorus and nitrogen were the dominant pollutants in China's coastal seas, especially in the late spring and early summer (Zhang et al., 2007; Zhang et al., 2013b; Yuan et al., 2018). As shown in Figures 7g ~ 7i, the volatile phenols, petroleum and anionic surfactant concentration

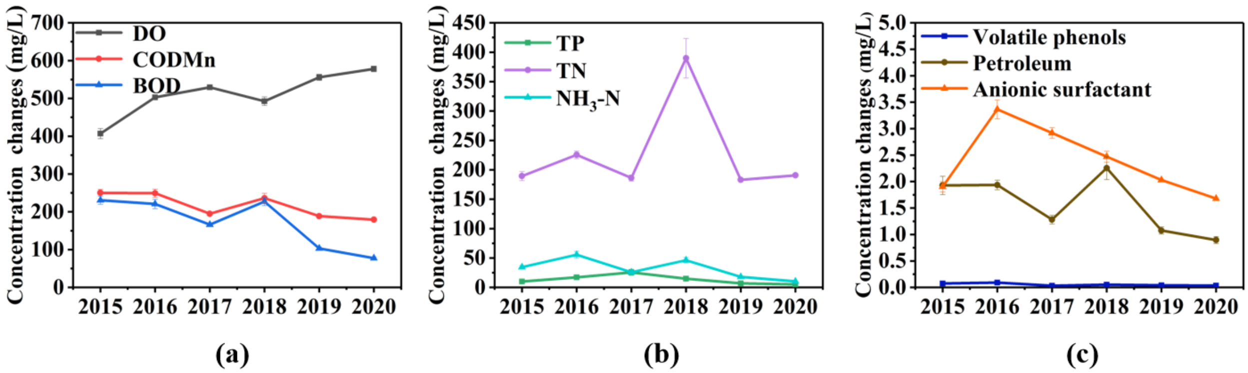

Figure 6. Concentration changes of comprehensive pollution indices from 2015 to 2020.

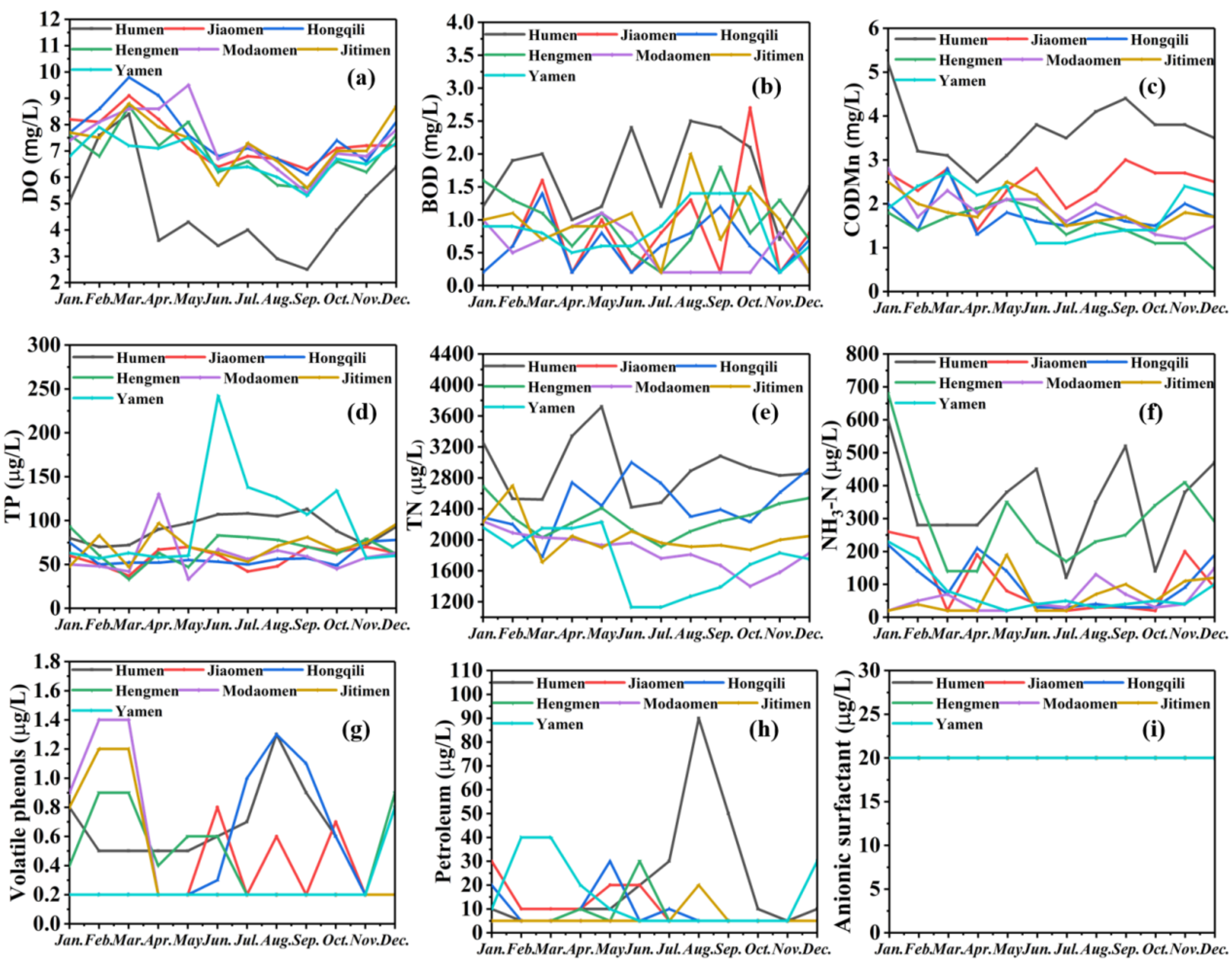

Figure 7. Monthly changes of comprehensive pollution indices in the seven PRE sections (2020 data).

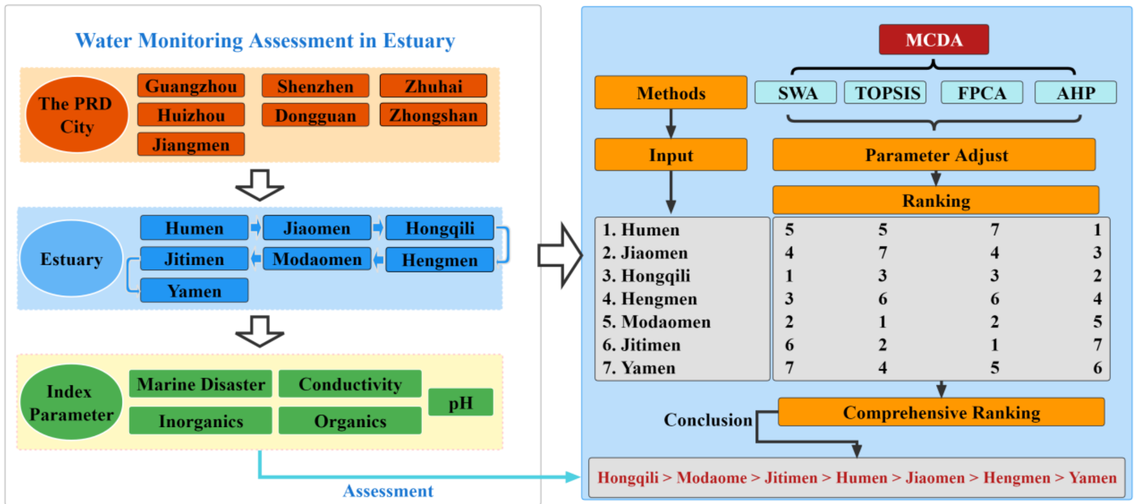

Figure 8. Flow chart of water monitoring assessment in the seven PRE sections.

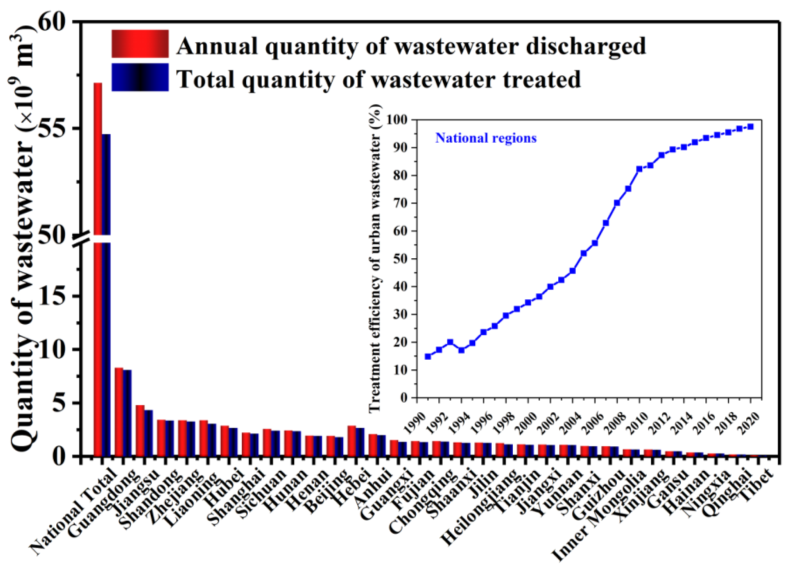

Figure 9. Quantities of treated wastewater in each province of China by 2020 data (Insert figure: wastewater treatment rate from 1991 to 2020).

remained at stable in Yamen, although anionic surfactant concentrations were higher than that of petroleum and volatile phenols. The concentration of volatile phenols and petroleum increased significantly in Humen from August to September, with the lowest DO concentrations recorded during the same period. This could be related to the occurrence of storm surges from August to October (Table S1). Finally, the anionic surfactant concentration remained relatively stable each month in all estuaries due to high chemical stability and minimal effects by DO.

According to the Integrated Wastewater Discharge Standard (GB-8978-1996) (MEEPRC, 1996), Discharge Limits of Water Pollutants Standards (DB44/66-2001) (DEEGDP, 2002) and Environmental Quality Standards for Surface Water (GB 3838-2002) (MEEPRC, 2002), the water quality in the seven PRE sections met Class II ~ IV quality standards.

4.3. Estuarine Water Quality Risk Assessment

Water quality risk assessment of the PRE sections could be used to evaluate the potential for loss of life, injury, destruction or damage. A systematic and quantitative risk assessment model would identify hotspots and trends in marine disaster risk management (Shi et al., 2013; Sun et al., 2020). The Water Quality Index (WQI) is an effective tool for assessing water quality and has been used widely in water management. We selected 20 parameters including marine disasters, conductivity, pH, heavy metals and comprehensive pollution indices for the water quality risk assessment in the seven PRE sections. To reduce the uncertainty of a single assessment method, and obtain optimal assessment results, MCDA, which included the SWA, TOPSIS, FPCA and AHP was applied for a comprehensive water quality risk assessment (Vaalgamaa and Conley, 2008; Zhao

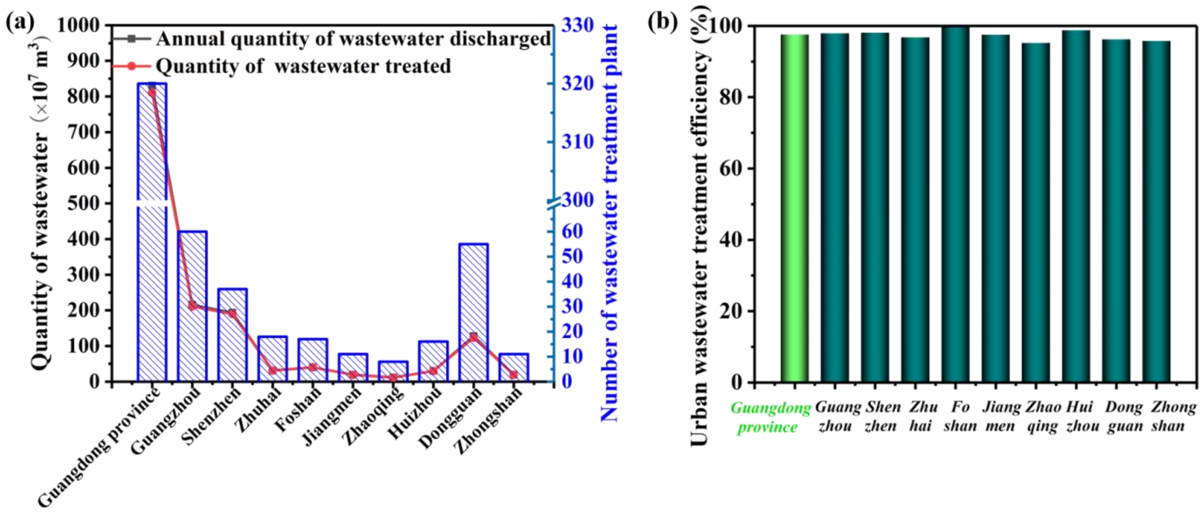

Figure 10. (a) Wastewater quantity and (b) treatment efficiency in the PRD region.

et al., 2020; Akhtar et al., 2021). The overall credibility of an index can be improved by quantifying uncertainty and using a fixed set of parameters (Akhtar et al., 2021). The calculation processes used in the four risk assessment methods are presented in Text S1.

The comprehensive water quality risk assessment ranked the risk presented in the PRE sections in the order of follows: Hongqili < Modaome < Jitimen < Humen < Jiaomen < Hengmen < Yamen (Figure 8). Yamen, in Jiangmen city, had the highest risk associated with water quality, whereas Hongqili had the lowest risk. Based on these findings, we suggest two risk management actions. First, the estuarine water quality in Jiangmen should be improved by controlling phosphorus and nitrogen emissions, which would reduce the risk of red tide occurrence. Second, breakwaters should be built to prevent storm surges in Jiangmen.

5. Current State of Wastewater Treatment

Marine disasters, conductivity, pH, and heavy metal and organic pollution substantially affect estuarine water quality. The effectiveness of wastewater treatment in the PRD region, especially the treatment of urban wastewater determines estuarine water quality. The construction of wastewater treatment plants in China has accelerated in recent years. According to 2020 data from Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURDPRC, 2018), the 286 wastewater treatment plants in Guangdong Province have achieved a capacity of 2.3×10^7 m^3/day. The annual quantity of wastewater discharged in Guangdong Province is 7.6×10^9 m^3, accounting for 14.5% of the national discharge. As shown in Figure 9, a total of 7.2×10^9 m^3 of wastewater was treated in Guangdong Province, accounting for 14.4% of the national total treated wastewater. The amount of wastewater treated in Guangdong Province in 2020 was higher than that in any other province of China, although the national wastewater treatment rate in China has rapidly increased from 14.86% in 1991 to 97.53% in 2020 (inset, Figure 9).

In the PRD, the wastewater treatment capacity and efficiency have improved rapidly. As the most developed city in the PRD region, Shenzhen city has 37 wastewater treatment plants, fewer than Guangzhou (the capital city) and Dongguan. The average daily treatment capacity was 5.7×10^4 m^3/ plant in 684 Chinese cities, but 1.4×10^5 m^3/ plant in Shenzhen (GZSB, 2019). As shown in Figure 10b, the wastewater treatment efficiency in the PRD region exceeded 95%, higher than the average treatment efficiency of Guangdong Province. To help accommodate the population of 1.4 billion in China, more than 10 wastewater treatment plants have been constructed in each of the large- and medium-sized cities. However, even a small city in China might discharge more than 1.0×10^7 m^3 of wastewater every year; therefore, the construction of additional wastewater treatment plants in small cities should be considered.

In the PRD region, secondary and secondary reinforcement treatments are the main processes used to treat wastewater (GDPDHURD and DEEGDP, 2003). The anaerobic-anoxic-oxic (A_2/O) and improved A_2/O processes are the most widely employed treatment (Huang et al., 2018). Research reported that (Li et al., 2019b) the proportion of total wastewater treated using the A_2/O, improved A_2/O, and DO processes was 31, 20, and 16%, respectively. Wastewater discharge quality complies with the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB/T 18918-2002) and Discharge Limits of Water Pollution (DB 44/26-2001).

6. Conclusions

Few studies have systematically and comprehensively analysed the specific factors affecting the PRE of South China. This paper study considered the unique geographical location, and analysed the water quality, water quality risk assessment and wastewater treatment practices in the main sections of the PRE. The following conclusions were reached:

(1) The total water resources in the PRD region have de-

creased in recent years. Additionally, the PRD region has been severely impacted by seasonal marine disasters that occur each year. The construction of an adaptable monitoring and early-warning system would minimise the direct economic loss and loss of life and provide a scientific basis for establishing management strategies to secure and conserve water resources in coastal areas.

(2) Water quality monitoring revealed that the concentrations of heavy metals and organic pollutants varied seasonally but haved gradually decreased in recent years. Efforts are needed to meet the Class I and Class II. Chinese water quality standards in the nearshore environment; in particular, the levels of nitrogen, BOD, and organic pollutants need to be reduced. Strengthening pollution control measures in the region would improve the estuarine water quality.

(3) Multiple water quality risk assessments indicated that the water quality in the estuary nearest the sea, Yamen, presented the highest risk. Pollution control measures in rivers entering the sea should be strengthened to prevent marine water pollution. Considering the spatial distributions and variations of the water monitoring indices, pollution control strategies and approaches for estuarine water quality management are required.

(4) The wastewater treatment efficiency in China rapidly increased from 1991 to 2020. The average wastewater treatment efficiency in the PRD region was above 95%. The most widely used technologies for wastewater treatment in the PRD region were the A_2/O and improved A_2/O processes. New treatment technologies should be exploited in the future.

(5) To minimise economic losses and casualties, governmental action is required to establish reasonable and comprehensive estuary water discharge standards; construct marine disaster early-warning and emergency management systems; manage the variations in pollutant concentrations.

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