

Anthropogenic activities and coastal environmental quality: a regional quantitative analysis in southeast China with management implications

Kai Chen¹ · Yan Liu² · Dongren Huang³ · Hongwei Ke⁵ · Huorong Chen³ · Songbin Zhang⁶ · Shengyun Yang⁵ · Minggang Cai^{1,4,5} 

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Abstract Regional analysis of environmental issues has always been a hot topic in the field of sustainable development. Because the different levels of economic growth, urbanization, resource endowments, etc. in different regions generate apparently different ecological responses, a better description and comparison across different regions will provide more valuable implications for ecological improvement and policymaking. In this study, seven typical bays in southeast China that are a rapid developing area were selected to quantitatively analyze the relationship between socioeconomic development and coastal environmental quality. Based on the water quality data from 2007 to 2015, the multivariate

statistical method was applied to analyze the potential environmental risks and to classify the seven bays based on their environmental quality status. The possible variation trends of environmental indices were predicted based on the cross-regional panel data by Environmental Kuznets Curve. The results showed that there were significant regional differences among the seven bays, especially Quanzhou, Xiamen, and Luoyuan Bays, suffered from severer artificial disturbances than other bays, despite their different development patterns. Socioeconomic development level was significantly associated with some water quality indices (pH, DIN, PO₄-P); the association was roughly positive: the areas with higher GDP per capita have some worse water quality indices. In addition, the decreasing trend of pH values and the increasing trend of nutrient concentration in the seven bays will continue in the foreseeable future. In consideration of the variation trends, the limiting nutrient strategy should be implemented to mitigate the deterioration of the coastal environments.

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✉ Yan Liu
liuyan_ouc@126.com

✉ Minggang Cai
mgcai@xmu.edu.cn

¹ Coastal and Ocean Management Institute, Xiamen University, Xiamen 361102, China

² Department of Finance, Ocean University of China, Qingdao 266100, China

³ Fujian Marine Environment and Fishery Resources Monitoring Center, Fuzhou 350003, China

⁴ State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen 361005, China

⁵ College of Ocean and Earth Sciences, Xiamen University, Xiamen 361102, China

⁶ School of Economics and Management, Northwest University, Xi'an 710127, China

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Introduction

Regional analysis of environmental issues has always been a hot topic in the field of sustainable development. Since the different levels of economic growth, urbanization, resource endowments, etc. in different regions generate apparently different ecological responses, a better description and comparison of the relationship between socioeconomic development and environmental degradation across different regions will provide more hints for ecological improvement and policy-

making (Lee et al. 2010, Pandit and Paudel 2016, Tan et al. 2014). Most previous studies are based on political or administrative boundaries; however, the regional division based on the ecosystem will be much more appropriate for the decision-makers to set the management goals and develop mitigation strategies considering the integrity of the ecosystem (Cao and Wong 2007, Sekovski et al. 2012). Besides, there are few relevant research efforts on coastal ecosystems, although they play a key role in transport trade, commercial production, residential and infrastructure, and support for human socio-economic development due to all kinds of ecosystem service provisions (Barbier et al. 2011, Keeler et al. 2012). As a result of population growth, agribusiness, industrialization, overexploitation, and energy consumption, coastal ecosystems worldwide are severely disturbed by cumulative human impacts (Halpern et al. 2015, He et al. 2014). Accordingly, human activities often generate negative effects on coastal ecosystems, such as sea level rise, biodiversity loss, habitat degradation, and climate change (Orr et al. 2005). To summarize, it is an important issue to conduct regional studies of the relationship between human activities and coastal ecosystems.

Among all the threats to coastal ecosystems, water quality of the coastal environment, as is reflected by high levels of nutrients, oxygen deficiency in the subsurface layer, increasing acidity, and widespread persistent organic pollutants (Doney 2010, Veerasingam et al. 2011), is considered to be the most difficult to manage (Keeler et al. 2012, Wang et al. 2015a). Excess nutrient input, namely eutrophication, which induces algal blooms and the subsequent depletion of the oxygen content in water bodies as residual decomposition (Tong et al. 2015). The biological buffers that limit nutrient transfer from terrestrial to aquatic systems are significantly impaired by the input from anthropogenic sources (Carpenter 2008, Wu et al. 2014). Eutrophication has already shown major adverse ecological effects, including dead zones (hypoxia/anoxia areas with low oxygen), fish kills, acidification, phytoplankton and microbial community composition changes (Cai et al. 2011, Orr et al. 2005, Richardson 1997), and even human health problems (Johnson et al. 2010). In view of this, one motivation of coastal management has been to lower nutrient loading in order to mitigate eutrophication, due to the fact that limiting nutrient loading acts as a cost-effective strategy. Some researchers have concluded that single-factor control is not possible (Carpenter 2008, Dai et al. 2008); however, the coastal area is a sea-land integration zone, where nutrient control should be socially integrated, economic, biological, and administrative. For the mitigation and control of coastal water eutrophication, it is important to make efforts to develop and maintain sustainable and efficient monitoring methods, assessment systems, and management mechanisms by integrating interdisciplinary understanding (Chen and Hong 2012, Zhao et al. 2015).

The seminal work that reveals the quantitative relationship between economic development and environmental quality was initiated by Grossman and Krueger (1995). The paper is based on a hypothesis that environmental quality tends to get worse with early economic development until income per capita reaches a threshold, and is then improved, namely the Environmental Kuznets Curve (EKC). Empirical studies show that an inverted U-shaped pollution-income relationship generally exists in the period of industrialization of developed regions, but the relationship can be represented as N-shaped, linear, and monotonic, and even not significant in less developed or developing regions (Farzin and Grogan 2013, Tan et al. 2014). It is found that almost all studies are based on time series or cross-sectional data to test the EKC hypothesis and to explore the regional differences. A survey by Wong and Lewis (2013) concludes that the general water quality indicators for the EKC from microorganisms (e.g., fecal bacteria and coliforms) to heavy metals and toxic chemicals (e.g., cadmium, lead, and DDT), and from nutrients (e.g., nitrate and total phosphorus) to the state of the water oxygen regime (e.g., chemical oxygen demand, COD, and dissolved oxygen, DO) also yield various results. Unfortunately, compared with the EKC studies focused on air, climate and energy indicators, such as sulfur dioxide, carbon monoxide, nitrogen oxides (NO_x), and suspended particulate matter, very few efforts utilize water quality variables, especially in coastal environments (He et al. 2014, Lee et al. 2010). On the one hand, the coastal area is often a final sink for numerous anthropogenic pollutants and the flushing rate is usually limited owing to the restricted water circulation, so that coastal environmental quality changes could be similar or even greater than atmospheric ones (Doney 2010). On the other hand, coastal environments (especially bays) are relatively isolated from each other, and this leads to pollutants not being easily transported between regions, which is ideal for operating an empirical study about regional differences compared with the atmosphere.

China, as the world's biggest developing country, has experienced remarkable economic development since the late 1970s with an attendant cost in environmental deterioration (Cao et al. 2007, Liu and Diamond 2005). For example, use of excessive fertilizers, industrialized animal production, and artificial constructions (e.g., seawall), have caused one of the most turbid marine environments in the world along the coasts and estuaries of China (Cao et al. 2007, Ma et al. 2014, Tong et al. 2015). A recent survey by the China State Oceanic Administration (SOA) illustrates that China's salt marshes and mudflats have decreased by 57%, mangroves by 73%, and coral reefs by 80% since the 1950s (Liu et al. 2016). The government has paid more and more attention to coastal management during recent decades, while current understanding of the environmental situation and the practice of coastal management and conservation is rather poor in China (Liu et al. 2016, Wang et al.

2015a). Because of the local nature of coastal pollution and the significant differences in economic development levels, a study of specific provinces and regions would probably be more appropriate than the overall analysis of the country (Vincent 1997). This poses a challenge, since the national or provincial managers need to understand the different needs of China's many regions, and also need to develop and implement reasonable strategies to protect the local coastal environments. Fujian, a rapidly developing coastal province located in the southeast of China facing the Taiwan Strait to the east, has a rugged coastline and many islands. Fujian is suffering from a turbid and eutrophic marine environment in its coastal waters, caused by a large number of land-based waste discharges and the rapid expansion of aquaculture (Wang et al. 2011a, Wu et al. 2014). With population growth and urbanization in the coastal zone, the pollution loads flowing into the coastal waters of Fujian would not be significantly reduced in the short term, especially in terms of nitrogen and phosphorus (Wu et al. 2014). The research that concentrated on analysis and comparisons of water quality within a single bay or estuary, its results can provide important suggestions for pollutant control in detail. However, the different regional economic development characteristics and environmental protection policies lead to the patterns and trends of coastal environmental quality varying regionally, action and institutions to ameliorate pollution problems are still scarce and lag behind in the less developed areas, despite the economic scale of investments and ongoing development (Liu et al. 2016). To review and to interpret the existing data can provide the "before management" framework of reference and consider the possible management options, which is a vital step to construct scenarios and to develop strategies for coastal management (Irvine et al. 2015).

With these concerns, a regional analysis of the water quality within province-scale under similar geographic conditions and different impacts of human activities on the coastal environment is strongly needed for local governance. In this study, we used data collected from seven bays in Fujian Province, to provide a synthesis of water quality along the coastline, from 2007 to 2015. On this basis, we applied multiple statistical methods to evaluate the environmental status and classification of the seven bays. We also used the panel EKC model to predict the possible water quality trends in the future, and discussed the cost-effective management measures for coastal sustainable development. We hope such a study could not only help local managers and policymakers to make specific decisions and monitor progress towards coastal management objectives but also provide valuable lessons for many other coastal developing areas. In "Materials and methods," we briefly introduce the study area, data source and data analysis methods. "Results and discussion" gives the main results and discussions. And the last section is the "Conclusions."

Material and methods

Study area

Fujian Province is situated on the southeast coast of China, at the crossroads of the East China Sea and the South China Sea. The length of the Fujian coastline is 3752 km, characterized by meandering bedrock coasts with many bays, peninsulas, and islands. There are more than 120 bays distributed along the coastline of the Province, most being located in northern and central areas and less in southern. In our study, we paid attention to seven bays with a similar scale and physiographic features, namely Luoyuan, Fuqing, Xinghua, Meizhou, Quanzhou, Xiamen, and Dongshan Bays from north to south (Fig. 1, and Figs. S1, S2, S3, S4, S5, S6, S7 in the Supplementary Material). The sea areas of these bays range from 221.24 to 704.77 km², and most of the bays are semi-enclosed with a narrow bay mouth. Tidal flats in all bays account for 30–40% of the total area, and water areas in Luoyuan Bay, Quanzhou Bay, and Xiamen Bay are less than other bays. Owing to ease the pressure of land shortage, a large number of coastal reclamation projects have been extensively carried out along Fujian coast since the 1970s (Table 1). Fujian is subject to the influence of the Kuroshio Current and the monsoon circulation, and is a subtropical maritime monsoon climate zone, vulnerable to climate change in extreme events (e.g., typhoons and rainstorms) and seasonal oscillations (Chen 2003, Ding and Wang 2008). The average annual temperature varies from 19.2 to 22.1 °C, with the southern area being higher than the northern. The average annual precipitation is 1133.3–2038.7 mm and shows significant seasonality, with spring and summer accounting for 80% of the total annual precipitation. This means that the dominant discharge into coastal waters via surface runoff presents a significant seasonal pattern caused by changes in rainfall (Chen and Hong 2011).

Nearly three quarters of the population live in the coastal areas (including six cities: Ningde, Fuzhou, Putian, Quanzhou, Xiamen, and Zhangzhou), which contribute more than 80% of the gross domestic product (GDP) of Fujian Province (Chen 2016). Population growth, rapid socio-economic development, and changes in land-use practices in the past have led to enhanced anthropogenic pollutant discharges into the coastal waters of Fujian Province (Cai et al. 2016, Tong et al. 2015, Zhao et al. 2015). Increasing living standards result in a demand for higher food consumption, which can increase both fertilizer use and aquaculture farming (accounting for 75.87% of the sea area of Fujian) consequently resulting in a large amount of pollutants discharging into coastal waters. There are significant differences in the economic development level and population scale among the

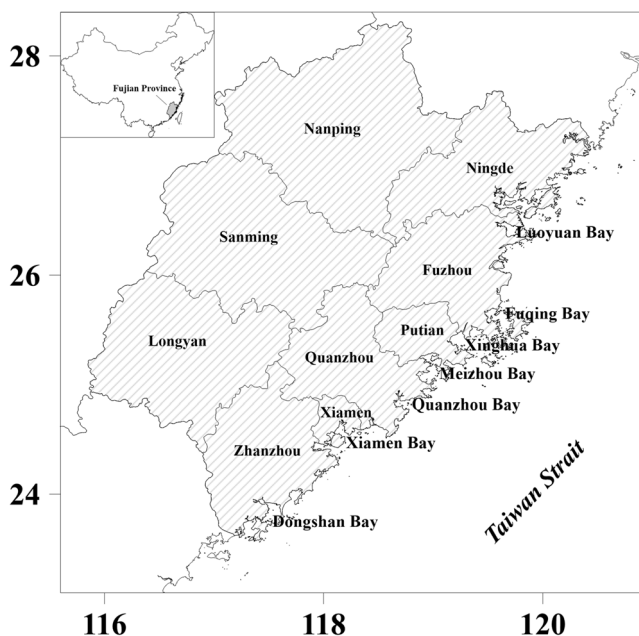


Fig. 1 The map of Fujian Province with the location of the seven bays studied

surrounding areas of the seven bays (Figs S8, S9, S10). Xiamen and Quanzhou Bays are located in the “golden triangle” economic zone of southern Fujian and play an important role in employment and tax revenue. Xiamen Bay has a diverse and highly developed economy that is famous for financial and tourist services and has the highest GDP per capita and urbanization rate. Quanzhou Bay is Fujian’s largest metropolitan region with the highest GDP and population, and its light industries including textile and apparel industry, footwear industry, and stone industry are very developed that

accounted for a large share of China’s export. The economy of the rest of the bays is mainly agriculture industry and smaller scale of harbor industry and tourist industry; hereinto, Dongshan Bay has the least GDP per capita and Luoyuan Bay has the least population and urbanization rate.

Data source

The water quality data spanning May 2007 to November 2015 used in this study originated from a coastal monitoring program of Fujian Province, which was conducted by the Fujian Marine Environment and Fishery Resource Monitoring Center. These data were based on 108 monitoring sites in these bays, to investigate the water quality situation from the inner to the outer bay (Table 1). All sites had quarterly routine sampling activities (which were in January, April, August, and November) to estimate the water quality during the four seasons. Since many environmental data are sensitive and not available to the public, the water quality indices chosen were pH, DO, COD, dissolved inorganic nitrogen (DIN, which is the sum of NO₂-N, NO₃-N, and NH₄-N), active phosphate (PO₄-P), and total petroleum hydrocarbons (Oils). All sampling activities were conducted following the published protocols (China National Standardization Management Committee 2007). Briefly, pH was measured in situ using a pH meter; DO the Winkler titration method; COD the alkalinity potassium permanganate method; NO₂-N the Diazo-Azo method; NO₃-N the zinc cadmium reduction method; NH₄-N the sodium hypobromite oxidation method; PO₄-P the ascorbic acid reduction of phosphorus molybdenum blue method; and Oils fluorescence spectrophotometry with hexane extraction.

Table 1 Basic information on the seven bays studied

Bay	Location	Mouth width (km)	Coastline length (km)	Sea area (km ²)				Tidal exchange (100%/30 days)	The number of monitoring sites
				Total	Tidal flat	Reclamation	Water		
Luoyuan	26° 18' 52"–26° 30' 13" N 119° 33' 25"–119° 50' 16" E	1.9	155.8	216.44	78.18 (36.12%)	53.82 (24.87%)	84.44 (39.01%)	51.8	17
Fuqing	25° 33' 23"–25° 41' 37" N 119° 26' 14"–119° 35' 53" E	17.4	120.9	446.48	162.0 (36.28%)	67.11 (15.03%)	217.37 (48.69%)	80.0	15
Xinghua	25° 15' 50"–25° 36' 01" N 119° 06' 28"–119° 30' 57" E	16.1	221.7	704.77	223.70 (31.74%)	79.80 (11.32%)	401.27 (56.94%)	64.1	18
Meizhou	24° 57' 27"–25° 17' 51" N 118° 50' 27"–119° 09' 19" E	23.1	252.6	552.24	169.90 (30.77%)	94.52 (17.11%)	287.82 (52.12%)	61.6	18
Quanzhou	24° 46' 20"–24° 51' 21" N 118° 46' 30"–118° 46' 50" E	10.1	132.8	211.24	84.84 (40.16%)	45.70 (21.63%)	80.70 (38.20%)	74.6	15
Xiamen	24° 14' 33"–24° 42' 24" N 117° 48' 55"–118° 34' 47" E	56.6	512.3	386.50	128.60 (33.27%)	110.03 (28.47%)	147.87 (38.26%)	64.5	10
Dongshan	23° 43' 14"–23° 58' 28" N 117° 22' 21"–117° 36' 56" E	5.3	166.9	283.14	95.61 (33.77%)	20.40 (7.20%)	167.13 (59.03%)	61.1	15

Data source: Chen (2016), Liu (2008), Wang et al. (2015b) and Fujian Marine Environment and Fishery Resource Monitoring Center
The numbers in brackets represent the proportion of the total area

The socioeconomic indices including population, urbanization rate, and GDP per capita were taken from the 2008–2016 Fujian Statistical Yearbooks (<http://www.stats-fj.gov.cn/xxgk/nds/>). The detailed information for indices calculation can be seen in [Supplementary Material](#).

Data analysis

Multivariate statistical analysis

The application of multivariate statistical analysis has proved to be a very useful tool for interpreting large sets of environmental data. First, time series clustering combined with box plots is applied to analyze the pollution distribution of each seawater quality parameter. Euclidean distance is used to measure the proximity of two bays. Furthermore, we tried to cluster the seven bays depending on synthetic pollution levels. The quarterly average value of each parameter was calculated. Since the number of parameters was larger than the number of bays, we adopted principal component analysis (PCA) to convert the correlated water quality parameters into a set of linearly uncorrelated variables. Thereafter, hierarchical clustering is applied to the transformed dataset.

Panel EKC

This section introduces the EKC, including the quadratic term, in a panel framework as follows:

$$e_{it} = \alpha_i + \beta_1 y_t + \beta_2 y_t^2 + u_{it}, t = 1, \dots, T, i = 1, \dots, N (*)$$

herein e_{it} represents the pollution level in the seawater; y_t , the log real GDP per capita; α_i , the unobserved bay-specific effect; u_{it} , the residual; t , the time period; i , the bays; and β_k is the coefficient of the k explanatory variables. Since the seven bays studied in this paper are all located in Fujian Province, China, they have correspondingly similar economic development structure. Moreover, restricted by the length of the time series and to reduce the estimation errors, we considered the pooling model. By estimating equation (*), we could achieve the relationship between real GDP per capita and the environmental degradation listed below:

- $\beta_1 = \beta_2 = 0$. This means a non-existent relationship between real GDP per capita and seawater pollution. In the linear case, $\beta_1 \neq 0$, and $\beta_2 = 0$. If $\beta_1 > 0$, then there is a monotonic increasing relationship between real GDP per capita and seawater pollution, whereas a monotonic decreasing relationship exists if $\beta_1 < 0$.
- In the quadratic case, $\beta_1 \neq 0$, and $\beta_2 \neq 0$. There is an inverted U-shaped EKC relationship between real GDP per capita and seawater pollution if $\beta_2 < 0$ whereas a U-shaped relationship exists if $\beta_2 > 0$.

In the estimation procedure, we applied a general feasible generalized least square (FGLS) estimator to estimate the unknown parameters. General FGLS estimators are based on a two-step estimation process: first, an ordinary least squares model is estimated, and then, its residuals are used to estimate an error covariance matrix which is defined as

$$\hat{V} = I_n \otimes \sum_{i=1}^n \frac{\hat{u}_{it} \hat{u}_{it}^T}{n}$$

(Wooldridge 2002). This framework allows the error covariance structure inside every group of observations to be fully unrestricted and is therefore robust against any type of intragroup heteroskedasticity and serial correlation. In a pooled time series context, this estimator is able to account for arbitrary cross-sectional correlation, provided that the latter is time-invariant (Greene 2003).

Results and discussion

Overview of the coastal waters of the bays

pH is regulated by many physicochemical factors, such as CO₂, nutrients, acidic wastewater, biological reproduction, and respiration, and it changed remarkably in the different bays, where the median pH values ranged from 7.56 to 8.75 over the monitoring period (Fig. 2a). The pH values in Quanzhou Bay were 7.88 ± 0.16 and in Xiamen Bay 7.98 ± 0.09 , which were significantly lower than 8.13 ± 0.11 in Fuqing Bay, 8.11 ± 0.08 in Xinghua Bay, and 8.09 ± 0.08 in Meizhou Bay. In addition, the fluctuation range of the pH values in Quanzhou Bay was the largest. This indicated that the seawater bicarbonate-CO₂ buffer system could not control the pH value at a stable level resulting in a significant acidification trend in Quanzhou Bay, a serious artificial disturbance compared with the other bays. Based on the cluster analysis (Fig. S11a), Quanzhou Bay and Xiamen Bay were divided into the same group, which demonstrated the more intensive human activities resulting in the lower pH levels among the seven bays. Compared with the historical data, around 1990 and around 2000, the pH values of each bay decreased at different degrees over the last two and a half decades (Tables S1, S2, S3, S4, S5, S6, S7). Luoyuan Bay and Dongshan Bay had the maximum decrease of pH value (about 0.23 and 0.20 units), which means the potential acidification trend as the considerable fluctuation degrees (Duarte et al. 2013).

In coastal waters, DO concentrations play an important role in determining the severity of adverse effects on marine organisms. In our study, the median DO concentrations differed little in the bays, with the median values distributed between 7.04 mg/L in Xiamen Bay and 7.62 mg/L in Fuqing Bay

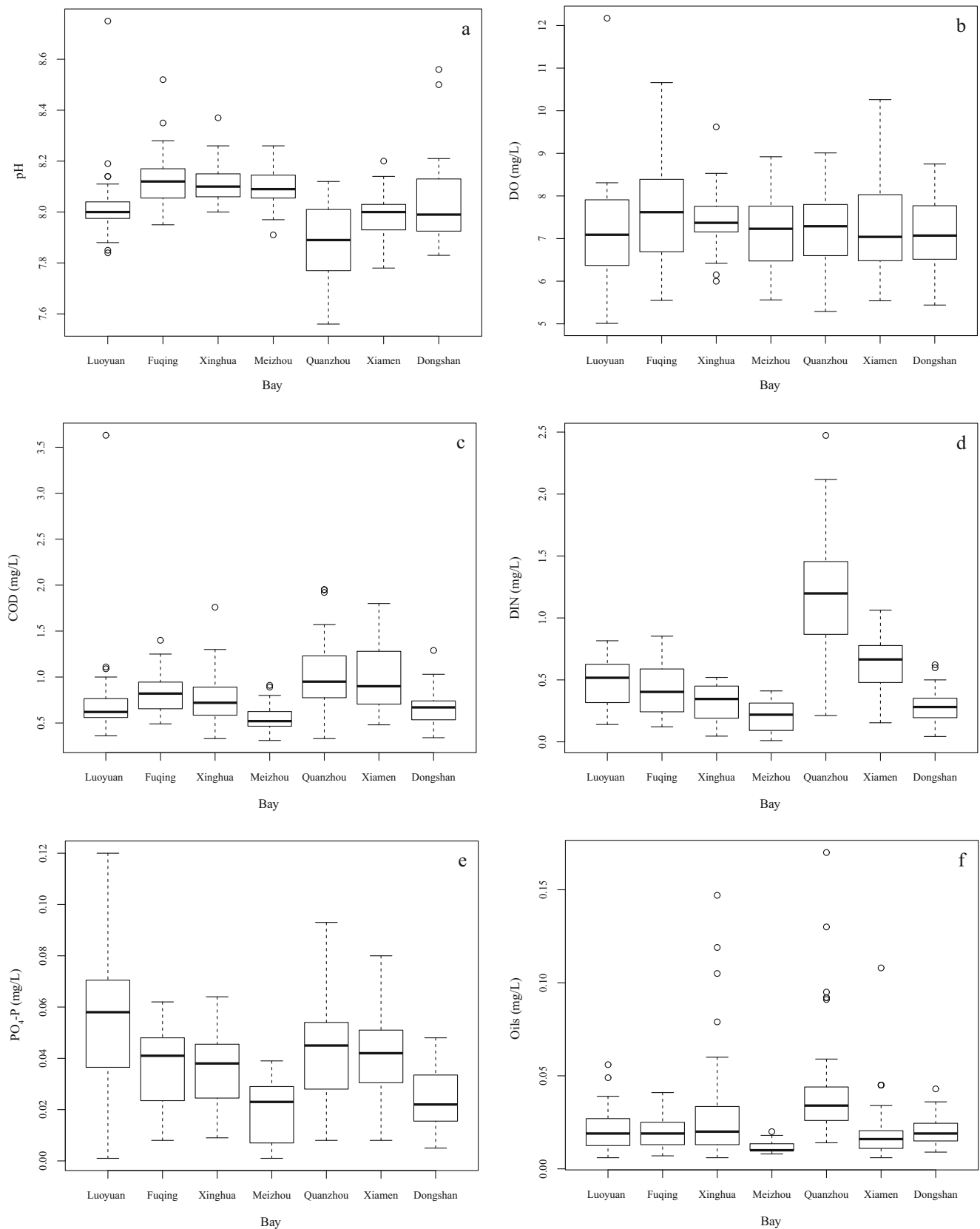


Fig. 2 Summary of water quality indices for the seven bays of Fujian Province during 2007–2015. The *horizontal lines* across the box represent the median. The *bottom* and the *top* of boxes represent the first quartile (Q₁) and the third quartile (Q₃). The *whiskers* represent the

data range defined by the following limits: lower limit: $Q_1 - 1.5(Q_3 - Q_1)$; upper limit: $Q_3 + 1.5(Q_3 - Q_1)$. Outliers are points outside the lower and upper limits and are plotted with *circles*

(Fig. 2b), which indicated that the geography and socioeconomic differences had little impact on DO in this area (Fig. S11b). Although DO concentrations showed considerable seasonal variation in a single bay, such as the range from 5.01 to 12.16 mg/L in Luoyuan Bay, none fell below 5.0 mg/L, the threshold for a water body under severe biological stress. The DO concentrations in each bay remained fairly stable for a long time compared with the historical data, except for a slight increase in Xinghua Bay (Table S3).

The COD concentrations, though, displayed significant regional differences with the median values ranging from 0.52 to 0.95 mg/L, and high values occurring in the relatively developed and dense population areas that were affected by the land-based discharge, such as Quanzhou Bay and Xiamen Bay (Wang et al. 2011a). Quanzhou Bay and Xiamen Bay had the highest concentrations of COD, 1.03 ± 0.38 and 1.03 ± 0.39 mg/L, compared with the other bays but the highest monitored values were all lower than 2.0 mg/L. Aquaculture activities is also a COD source with obvious seasonal differences that cannot be ignored in the study areas. For example, the mean COD of 0.59 mg/L in winter and 1.09 mg/L in summer of Luoyuan Bay and 83% from aquacultural pollution (Wang et al. 2011a). A decreasing trend of COD concentrations was found in Meizhou Bay, Xiamen Bay, and Dongshan Bay since 1990, but with little change in the other bays (Tables S3, S6, and S7).

The DIN concentration distribution is shown in Fig. 2d. The concentration of DIN in Quanzhou Bay (1.198 ± 0.539 mg/L) was much higher than those in the other bays, and its median concentration (1.187 mg/L) was almost twice that of Xiamen Bay (0.634 mg/L). Except for Quanzhou Bay and Xiamen Bay, the average DIN concentrations of the other bays ranged from 0.2 to 0.5 mg/L, and the lowest concentration occurred in Meizhou Bay at 0.207 ± 0.128 mg/L. We found that the average DIN concentrations of Fuqing Bay and Luoyuan Bay were higher than Xinghua Bay, Meizhou Bay and Dongshan Bay, despite their population and urbanization rate were lower. That indicated the pollutions from agricultural and aquacultural production could contribute to considerable nutrient loadings, especially in Luoyuan Bay that with weaker water circulation capacity (Wang et al. 2011a). From our analysis, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were the main forms of DIN in each bay, and $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, and $\text{NH}_4\text{-N}$ accounted for 43.1–93.5, 2.0–29.4, and 8.1–35.7% of DIN, respectively, their distribution being consistent with DIN values along the Fujian coast (Fig. S12). Moreover, the proportion of the three forms in different seasons were comparatively stable in the bays with low DIN concentration (i.e., Xinghua Bay, Meizhou Bay, and Dongshan Bay), but fluctuated with high DIN concentration in Quanzhou Bay and Xiamen Bay. As shown in

Fig. S12, the higher levels of $\text{NH}_4\text{-N}$ in Quanzhou Bay and Xiamen Bay with the higher population and urbanization rates, which means $\text{NH}_4\text{-N}$ mainly from domestic wastewater effluent in study areas (Umezawa et al. 2008). It is worth mentioning that the DIN concentrations of the selected bays have more than doubled in recent years, compared with the level in the early 1990s, and among them, the concentrations of $\text{NH}_4\text{-N}$ in Quanzhou Bay and Xiamen Bay increased dramatically, showing a strong disturbance by human activities.

Different from COD and DIN, the median $\text{PO}_4\text{-P}$ concentrations of Luoyuan Bay (0.058 mg/L) was higher than those in the other bays in this study (Fig. 2e), and twice more than that of Meizhou Bay (0.023 mg/L) and Dongshan Bay (0.022 mg/L). Luoyuan Bay also had the most dramatic $\text{PO}_4\text{-P}$ fluctuation among the seven bays, followed by Quanzhou Bay (0.043 ± 0.020 mg/L) and Xiamen Bay (0.042 ± 0.016 mg/L). However, as the study by Wang et al. (2011a), the loading of $\text{PO}_4\text{-P}$ discharged into Luoyuan Bay (622.00 t/a) was far less than that into Quanzhou Bay (1791.78 t/a) and Xiamen Bay (3249.00 t/a). It is indicated that the weaker water circulation capacity limits $\text{PO}_4\text{-P}$ access to ocean and stores it in the ecosystem, resulting in higher $\text{PO}_4\text{-P}$ concentrations in coastal waters of Luoyuan Bay (Cai et al. 2016, Hong et al. 1999). From the perspective of temporal variation, the $\text{PO}_4\text{-P}$ concentrations of each bay almost doubled compared with the baseline in the early 1990s, such as 0.028 mg/L in 1991 and 0.053 mg/L in 2005 for Luoyuan Bay and 0.012 mg/L in 1991 and 0.025 mg/L in 2015 for Xinghua Bay. These variations implied biological responses to human activities, especially the process of mineral phosphate precipitation in acid soils of the study area, which is often recognized to limit P input from land to coast (Chen et al. 2007). Moreover, the average levels of both DIN and $\text{PO}_4\text{-P}$ in 2007–2011 were higher than those in 2012–2015 among all the bays, which showed that the nutrient sources had declined (Tables S1, S2, S3, S4, S5, S6, S7).

For Oils, the highest concentrations occurred in Quanzhou Bay with 0.045 ± 0.020 mg/L, and the lowest was 0.012 ± 0.003 mg/L in Meizhou Bay. The average concentrations of the other bays showed little differences and ranged from 0.016 to 0.020 mg/L (Fig. 2f). Contrast to the results of cluster analysis, Oils levels in Quanzhou Bay and Xinghua Bay are higher than that in other bays, which are caused by increasingly intensive harbor operations for import and export trade (Liu and Diamond 2005). Unlike the variation trends of nutrient levels in all bays, the Oils concentrations showed the first rise before 2010 and then a decline (Table S1, S2, S3, S4, S5, S6, S7). As Veerasingam et al. (2011) reported that, the concentrations of Oils in seawater samples from non-oil production areas range mainly from 0.2 to 74 $\mu\text{g/L}$. This indicated that seawater oil pollution in our study area was partly controlled and at an acceptable level.

Classification of the seven bays

Principal component analysis

In this study, we proceeded with PCA to reduce the dimension of the water quality indices for further statistical analysis. The amount of variance spanned by each principal component (PC) depended on the relative value of its eigenvalue to the total sum of eigenvalues. The first two PCs explained 85.24% of the total variance in the original data (Table 2), which was enough to account for the variability in the raw data.

In fact, loadings are the projection of the original variables on the subspace of the PCs, which show the mutual relationships among the variables. As expected, COD was positively correlated with inorganic nitrogen and $\text{PO}_4\text{-P}$ in PC1, but was negatively correlated with pH (Table 3). This was easy to understand, since COD is often used to indicate the degree of organic pollution attributed to rural runoff, urban and industrial wastewater drainage. Organic matter in the aquatic environment can be decomposed by microbial activities, so that DIN and $\text{PO}_4\text{-P}$ are released into the water to promote phytoplankton growth. In the process of photosynthesis, CO_2 is consumed in the water, resulting in pH increase and a new acid-base balance (Gao et al. 2012). DO had high loading in PC2 and was positively correlated with almost all parameters that can be explained by the intense mixing in the water masses. In southeast China, the vertical mixing of coastal waters is stronger in autumn and winter than in spring and summer, so that DO is supplied by intensive air-sea exchange (Dai et al. 2008). Meanwhile, nutrient concentrations increased owing to the remineralization of organic matter, except that $\text{NH}_4\text{-N}$ is oxidized and reduced (Tong et al. 2015).

Cluster analysis

Based on the results of the PCA, CA was used to further classify the seven bays into different groups and to identify their pollution and hydrology status. CA rendered a dendrogram where the selected bays studied were divided into three clusters at $D_{\text{link}}/D_{\text{max}} < 50\%$ (Fig. 3). Only Quanzhou Bay was classified into cluster 1, Luoyuan Bay and Xiamen Bay were classified into cluster 2, and the other four were classified into cluster 3. Cluster 1 had the worst environmental quality, followed by cluster 2 and cluster 3. Combined with the preceding analysis, cluster 1 was characterized by high COD, nutrient (especially $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) and Oils concentration and the lowest pH value, while cluster 2 was characterized also by high COD and nutrient concentration but a moderate pH value and low Oils concentration (Fig. 2). Cluster 3 could be further divided into two parts, and coincided with the differences of nutrient concentrations and hydrology status between the sub-cluster of Fuqing

Bay and Xinghua Bay and the sub-cluster of Meizhou Bay and Dongshan Bay (Table 1).

The total areas of Quanzhou Bay, Luoyuan Bay and Xiamen Bay are smaller than the bays belonged to cluster 3, which means the same scale of anthropogenic activity would more significantly affect their geomorphologic features (Ma et al. 2014). For example, the reclamation areas of Luoyuan Bay and Quanzhou Bay are less than other bays, however, the proportions are higher than other bays except for Xiamen Bay (Table 1). And Quanzhou Bay, Luoyuan Bay, and Xiamen Bay have the least proportion of water area; it means that the poor hydrodynamic condition will reduce tidal influx and hinder the diffusion of pollution, such as COD and nutrients (Veerasingam et al. 2011, Wang et al. 2011a). Moreover, Xiamen Bay is strongly affected by the runoff of Jiulong River, which is the second largest river in Fujian Province. Jiulong River Basin has experienced population growth, rapid agriculture development, and urbanization since the 1990s; such intensive human activities led to massive nutrients (especially nitrogen and phosphorus) discharging into the river and finally deteriorated the water quality of Xiamen Bay by runoff transport (Chen and Hong 2012, Huang et al. 2013). The results of the CA were similar to the rank of GDP per capita, which Quanzhou Bay, Xiamen Bay, and Luoyuan Bay are also higher than others (Fig. S10). It manifests that the level of economic development is one of the important factors to worsen the coastal water quality in Fujian (Lee et al. 2010, Ma et al. 2014).

Comparison of nutrient variations with other coastal systems

Historical data are important for identifying whether an ecosystem is facing degradation or recovery (Irvine et al. 2015), and the coastal area of China is considered historically as one of the highest human impacted regions within the last decade (Halpern et al. 2008, Ma et al. 2014). In this study, we select Meizhou Bay (a less developed area) and Xiamen Bay (a developing area) as representations of Fujian coast, to compare the temporal variations of nutrients with other coastal areas (Fig. 4).

Data source: Harima-Nada, Japan, from Nishikawa et al. (2014); Skagerrak, Norway, from Frigstad et al. (2013); Patos Lagoon, Brazil, from Haraguchi et al. (2015); Helgoland Roads, Germany, from Raabe and Wiltshire (2009); Suisan Bay, the USA, from Glibert et al. (2011); Chesapeake Bay, the USA, from Harding et al. (2016); Deep Bay, Hong Kong (China), from Xu et al. (2010); Jiaozhou Bay, China, from Liang et al. (2015); Meizhou Bay and Xiamen Bay, China, from Cai (2007), and this study.

Figure 4 presents the concentration variations of nutrients in most of the selected coastal areas since the 1960s.

Table 2 Importance of the various principal components in the analysis for water quality indices of the seven bays during 2007–2015

Component	Standard deviation	Proportion of variance (%)	Cumulative variance (%)
1	2.5148	70.27	70.27
2	1.1608	14.97	85.24
3	0.8703	8.42	93.66
4	0.6259	4.35	98.01
5	0.3675	1.50	99.51
6	0.2096	0.49	100

Generally, the areas with high urbanization and dense population are prone to have higher nutrient levels, such as Deep Bay, Helgoland Roads, and Suisan Bay (Glibert et al. 2011, Raabe and Wiltshire 2009, Xu et al. 2010), while the areas with sparse population or less developed places have lower levels of nutrients, such as Skagerrak and Patos Lagoon (Frigstad et al. 2013, Haraguchi et al. 2015). The concentrations of nutrients in Xiamen Bay were low before the 1990s, but they significantly increased during the past decades. Population growth and industrial activities have led to greater waste discharge into Xiamen Bay, but insufficient treatment capacity and environmental awareness have significantly increased nutrient fluxes into its coastal waters (Cai et al. 2016). The similar scene can also be seen in Meizhou Bay, where the nutrient concentrations increased slowly with relatively low levels at present. It is noted that, compared with developing areas (e.g., Jiaozhou Bay and Xiamen Bay), where the nutrient concentrations increased significantly, the nutrient levels changed little or even decreased in the developed areas over the last decades. The temporal variation trends of nutrients in developed areas generally reach peak values and then fall after appropriate management, such as Harima-Nada and the Chesapeake Bay. The effective organic pollutant reduction and implementation of a ban on PO₄-P in detergents lead to the decline of the nutrient concentrations after the mid-1980s (Harding et al. 2016, Nishikawa et al. 2014). The different variation trends indicate that the developing areas have a higher priority on socioeconomic development rather than

coastal environmental conservation, compared with the developed areas. This matches the implications of the EKC where environmental quality deteriorates first and then improves with increases in average income level.

It is proposed that the average DIN/PO₄-P ratios are more than 30 in most of the selected bays, even more than 100 in the Chesapeake Bay. The nutrient structure suggests that a large number of potential losses of nitrogen to coastal ecosystems from human activities and nitrogen utilization efficiency should be improved in urban and agriculture use (Zhang et al. 2015). Furthermore, it may be useful to identify which nutrient is more limiting and design strategies that minimize the cost of eutrophication mitigation in some cases (Chen and Hong 2012, Doney 2010). For example, wastewater treatment plants can be engineered to adjust the ratio of DIN/PO₄-P discharges to coastal ecosystems without causing algal bloom (Carpenter 2008).

The results of panel EKC estimation

It should be noted that the reliability of the EKC is affected by sample size, data accuracy, and model selection, so that the case study of specific countries and regions is superior to the overall analysis of the international regions (Dinda 2004). Based on the above discussion, the control and alleviation of the high level of nutrient concentrations in the coastal waters of Fujian should be given more attention. Therefore, we used a panel data set containing observations from these bays during

Table 3 Results of principal component analysis for water quality indices of the seven bays during 2007–2015

Component Parameter	Loading						
	1	2	3	4	5	6	7
pH	0.3572	0.3720	-0.0529	0.0619	-0.0565	0.2451	-0.5770
DO	0.0687	0.8789	-0.2504	-0.1821	-0.2109	0.0023	0.2521
COD	-0.3509	0.2484	0.0596	-0.4225	0.6631	-0.3716	-0.1548
NO ₂ -N	-0.3687	0.0127	0.2771	-0.3685	0.0050	0.8050	0.1555
NO ₃ -N	-0.3912	0.0643	-0.0251	-0.0042	-0.4238	-0.1892	0.0609
NH ₄ -N	-0.3775	-0.1022	-0.3176	-0.0291	-0.2420	-0.0756	-0.6988
DIN	-0.3923	-0.0022	-0.1181	-0.0355	-0.3327	-0.1042	0.2313
PO ₄ -P	-0.2434	0.3216	0.7058	0.5247	-0.0365	-0.1182	-0.1307
Oils	-0.3160	0.1053	-0.4905	0.6093	0.4031	0.2958	0.1291

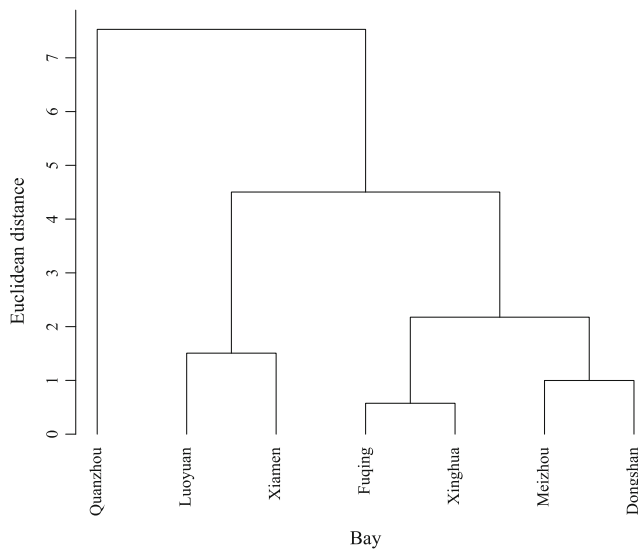


Fig. 3 Dendrogram of the time series cluster of the seven bays of Fujian Province during 2007–2015

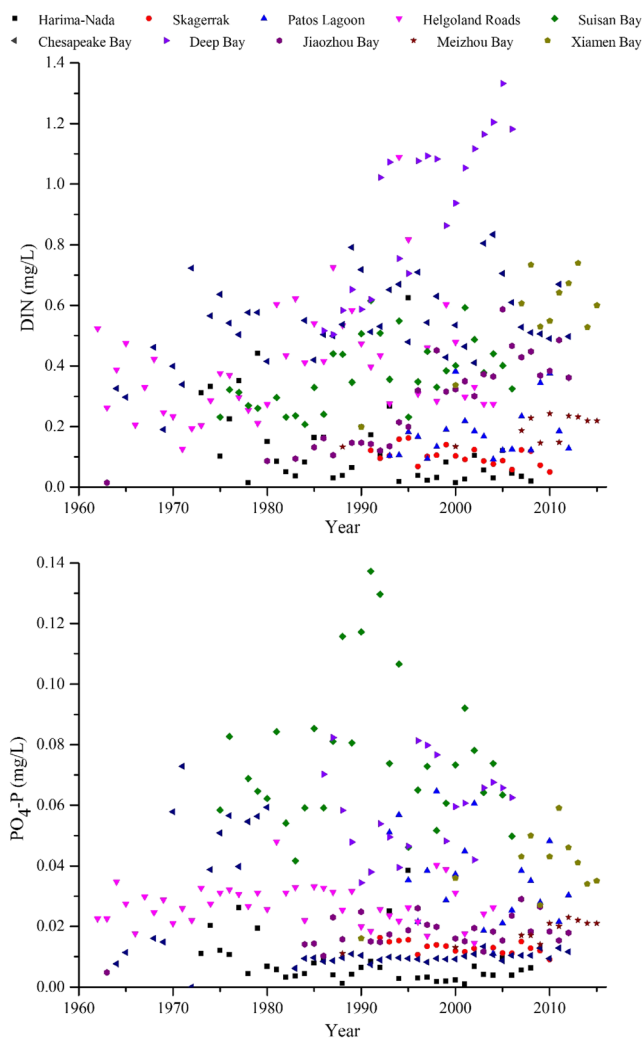


Fig. 4 The temporal variations of DIN and $\text{PO}_4\text{-P}$ in some coastal areas

the monitoring period, to estimate pollution-GDP per capita relationships specific to the Fujian coast for five water quality indices that related to seawater eutrophication: pH, COD, DIN, $\text{PO}_4\text{-P}$, and Oils (Table 4 and Fig. S14).

According to Table 4, for COD, DIN, and $\text{PO}_4\text{-P}$, the estimated coefficients of intercept, \ln GDP per capita and $\ln(\text{GDP per capita})^2$ were all not significant (significance level >0.05). It can thus be speculated that an inverted U-shaped EKC relationship between economic development and these indicators does not exist in Fujian coastal waters. The organic matter in the seawater can be decomposed to release DIN and $\text{PO}_4\text{-P}$ by microbial activities in a short time, so that COD concentrations showed no insensitivity to external organic matter input and economic development. The concern is that the estimated results of DIN and $\text{PO}_4\text{-P}$ mean that the upward trends of the two nutrients will not change in the current situation and the potential threat of eutrophication is increasing. However, patterns of nutrient loading are neither automatic nor inevitable since socioeconomic circumstances and policies influence the turning points of the EKC.

One of the reasons for the relationship is that in developing areas, economic development often comes along with the increase of pollutant discharge and population growth; land-use change and higher living standards intensify this trend (Chen et al. 2011, Huang et al. 2013). For instance, industrial livestock production and mariculture have expanded rapidly to meet the requirements of population growth and maintain a modernized urban lifestyle. However, on average, 70% of nitrogen and 82% of phosphorus is lost from the human food supply and insufficient wastewater treatment systems have worsened the aquatic environment in China (Gu et al. 2013, Wang et al. 2011b). A previous study based on the data from 17 countries shows that, the turning point for $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ are up to US\$19,608 and US\$9013 (Cole 2004), and higher than GDP per capita of this study area (lowest: US\$6304.4 in Dongshan Bay, highest: US\$12,440.8 in Xiamen Bay). Hence, in this study, the relatively developed areas (e.g., Quanzhou Bay and Xiamen Bay) generally have the higher nutrient concentrations in coastal waters, compared with the less developed areas (e.g., Meizhou Bay and Dongshan Bay). It is noteworthy that the inverted U-shaped relationship for $\text{PO}_4\text{-P}$ could appear in the individual bay, since its turning point is lower than DIN's. For example, Cai et al. (2016) found that $\text{PO}_4\text{-P}$ concentration of Xiamen Bay starts to fall according to the effective source control based on the time series analysis of 1980–2012. Another important reason is the biogeochemical behavior of the nutrients in most of China's coastal seas, where phosphorus is the limiting nutrient for net primary production and that control of eutrophication (Chen and Hong 2012). This means that most $\text{PO}_4\text{-P}$ was taken in by phytoplankton and finally removed from the water into the sediment by the biological pump mechanism, which results in the relatively dull response of phosphorus to economic development. Zhang et al. (2015) and Cai et al. (2016) also

Table 4 EKC estimation results for the coastal waters of Fujian during 2007–2015

Indicators	pH	COD	DIN	PO ₄ -P	Oils
Intercept	-2.842	1.269	21.947	0.731	-0.420**
ln GDP per capita	2.182**	-0.110	-4.529	-0.148	0.087**
ln (GDP per capita) ²	-0.109**	0.006	0.236	0.008 ^Δ	0.004**
Total sum of squares:	0.755	4.363	7.063	0.011	0.020
Residual sum of squares:	0.734	4.349	5.580	0.009	0.020
Multiple R-squared:	0.028	0.003	0.210	0.133	0.003
Pattern	Inverted U-shaped	No relation- ship	No relation- ship	No relation- ship	Inverted U-shaped
Turning point (Chinese yuan, CNY)	22,821.6	-	-	-	27,395.9

**<0.01, *<0.05, and ^Δ<0.1.

suggest that many coastal areas show a pattern similar to an EKC, in which nitrogen or phosphorus pollution in aquatic environments first increases and then decreases with economic growth. Although rising public awareness and new technologies application contribute to reduce nutrient loadings, time for the recovery of aquatic environmental quality is also needed, which would lag even economic development reaching the turning point (Borja et al. 2010, Dinda 2004).

For pH and Oils, the empirical results showed significant evidence of an inverted U-shaped EKC relationship between GDP per capita and water quality indices. The estimated turning points were, respectively, CNY 22,821.6 and 27,395.9 (constant prices in 2007, which approximately equal US\$ 3042.9 and 3652.8) which fell within the conclusions (US\$ 2703–11,632) proposed by Grossman and Krueger (1995). The same EKC relationships of pH and Oils highlighted different implications, which were optimistic for Oils and is pessimistic for pH. The fact that the coefficient of Oils was significant and negative implied that there are persistent concentrations of Oils reduction from 1 year to the next, due to effective oil spill sources control, in oil spills and shipping activities. For example, polycyclic aromatic hydrocarbon (mainly from refined oil products) levels are reported to be decreasing considerably compared with the previous studies in Xiamen Bay (Ya et al. 2014). However, the values of pH kept decreasing, meaning that the coastal waters continued to be acidized along with the economic development of the Fujian coastal region, a similar result to that reported in Malaysia (Vincent 1997). Lee et al. (2010) indicate that the threshold of income per capita for pH increasing is US\$ 7686, which is much higher than that of study areas. In addition, Chen et al. (2011) find that acid deposition exhibits a significant increase since the mid-1990s, with increased NO_x into the sea and N-induced acidification caused by escalating vehicle exhausts. The pH of the coastal waters will decrease if acidic gas emissions and nutrients load cannot be effectively reduced and this is likely to have a large impact on coastal ecosystems in Fujian.

In comparison, the levels of DIN and PO₄-P in China coastal areas were monotonously increasing recently (Fig. 4). China’s environmental protection laws/regulations are often poorly enforced and compromised by conflicts with economic development (Cao and Wong 2007, He 2014). However, good public awareness, economic power, and advanced technology to reverse the upward trend of nutrient in developed countries are needed (Nishikawa et al., 2014). For coast areas in Fujian, the turning points of water quality improvement still have a significant space to reach as mentioned above, despite the remarkable economic development. In a management perspective, however, there is no any silver-bullet policy or measurement that can reduce all kinds of pollutant loading (Wong and Lewis 2013). Fortunately, developing areas can learn the experience of pollution management and control from developed areas and restructure growth pattern to avoid repeating the same pollution stages and inevitable environmental costs (Dinda 2004). Due to regional differences, however, the response of the coastal environment to economic development is usually non-linear and full of uncertainty. Thus, we proposed that the precautionary principle should be adopted to bring scientific uncertainty into the decision-making process by explicitly formalizing precaution in developing areas.

Management implications for sustainable development

The variation trends of pH in the seven bays fluctuated by 0.2–0.5 pH unit, which was remarkably much larger than the 0.1 unit decline of pH attributable to ocean acidification via anthropogenic CO₂ (Duarte et al. 2013). The impacts of high nutrient concentration on the bicarbonate-CO₂ buffer system can exceed that of anthropogenic CO₂ by either increasing the pH while enhanced CO₂ uptake by photosynthesis prevails, or by decreasing the pH, where phytoplankton respiration is enhanced (Cai et al. 2011), a condition often associated with coastal hypoxia (Feely et al. 2010). Greening and Janicki

(2006) studied the long-term variation of pH in Tampa Bay, which strongly increases with high population growth in the watershed, and then increases owing to the removal of nitrogen from the wastewater. The implementation of the nutrient management program contributes to submerged aquatic vegetation expanding and water quality improving, which leads to enhanced CO₂ uptake and pH increase. This implies that it is necessary to reduce the nutrient load into the sea, which can effectively alleviate acidification in these coastal waters.

Cai et al. (2016) interpret their results in the light of characteristics of the economy and environmental policies of the Western Xiamen Bay and find that the results confirm the importance of policy decisions in determining coastal environmental outcomes. When the government planned to alleviate the eutrophication risk, this raised the question of which nutrient is the most limiting and the answer to this question became critical in making a cost-effective decision, which had a large financial implication. It is commonly accepted that marine phytoplankton absorbs N and P from water based on the Redfield ratio (N/P = 16:1) and that the ratio can be used to identify the limiting factors for a phytoplankton bloom (Yin et al. 2011). The median DIN/PO₄-P ratios of the seven bays ranged from 22.22 in Luoyuan Bay to 60.55 in Quanzhou Bay (Fig. S13). This showed that PO₄-P is a shortage relative to N, and any increase in PO₄-P inputs from human activities can result in stimulating phytoplankton growth and even harmful algal blooms. As Zhao et al. (2015) note that the assimilative capacity of the receiving water is small in terms of P discharge and will be rapidly filled and exceeded in Quanzhou Bay. Schindler et al. (2008) present a 37-year observation program in a small lake, which shows that P inputs directly control algal blooms. However, the authors also observe that algal blooms are made worse if N inputs are decreased without also decreasing P inputs. In addition, another finding indicates that when P is deficient and N is sufficient, the dominant species of phytoplankton communities readily changes from diatoms to dinoflagellates (Richardson 1997). Based on the ratios of DIN/PO₄-P along the Fujian coast since 2000, we speculated that this was the reason why the dominant species of algal blooms change from *Skeletonema costatum* and *Chaetoceros curvisetus* to *Noctiluca scintillans*, *Prorocentrum donghaiense*, and even toxic *Karenia mikimotoi* (Li et al. 2017). This finding is of critical importance for current programs aimed at mitigating eutrophication of coastal waters and fisheries resources conservation. For example, not only has the fishery biomass decreased, but also the fish community has changed from bottom fish to pelagic fish as the abundant species owing to overfishing and environmental degradation (Jin 2004).

Hence, a P limitation strategy would play an important role in controlling eutrophication in Fujian coastal waters, such as updating wastewater treatment plants, banning P-based

detergents, and changing agriculture practices (Taylor et al. 2010, Williams et al. 2010, Wu et al. 2014). Improving wastewater treatment capacity and water reuse may be feasible for the urbanized areas (e.g., Quanzhou Bay and Xiamen Bay), while agriculture practices should be changed in the rural areas (e.g., Luoyuan Bay). It is reported that large-scale reclamation projects and coastal engineering construction could be potential factors for increased algal blooms (Wang et al. 2015a). Because of the destroyed hydrodynamics of the environment, the environmental self-purification capacity decreased, resulting in nutrient enrichment in the coastal ecosystem, especially Quanzhou Bay, Xiamen Bay, and Luoyuan Bay (Table 1). When intensifying integrated coastal management and reasonable planning of the coastal zone, considering the cumulative effect of new reclamation projects should be restricted or no longer allowed (Wu et al. 2011). Remediation combined with periodic dredging would help to improve water quality, because algal growth may not then lead to such an accumulation of algae as to cause an algal bloom if the receiving waters are frequently diluted by horizontal advection or vertical mixing (Yin et al. 2011).

Based on the experience of the developed areas, an increase at the socioeconomic level can affect environmental quality through three aspects: scale effect, composition effect, and technique effect (Dinda 2004, Lee et al. 2010). While it will take a long time for Fujian and China to reduce DIN loading substantially, PO₄-P loading into the ocean is likely to increase in the future since urbanization is occurring rapidly on a large scale (Yin et al. 2011). As Borja et al. (2010) indicate, based on a series of marine ecosystem recovery programs after removing different human pressures, the time for recovery from eutrophication ranges from 3 to 20 years.

Conclusions

Owing to the influences of human activities, within only a few decades, numerous previously pristine, oligotrophic estuarine and coastal waters have undergone a transformation to more mesotrophic and eutrophic conditions. China plays a major role in the global transport of organic matter into the ocean, but data is mostly available only for large bays and estuaries although small- to medium-sized sources or runoff may also contribute a considerable proportion of the pollution loading (Kaiser et al. 2014). For local sustainable development and effective coastal management, therefore, it is important for researchers and managers to assess and understand the anthropogenic influences on the coast, both positive and negative.

In this study, we attempted to describe the water quality of seven bays in Fujian Province, where a rapid developing area located on the southeastern coast of China. We found that (1) all of the seven bays had high levels of nutrients and DIN/PO₄-P ratios and, except for Meizhou Bay, are considered to

suffer from nutrient pollution; (2) cluster analysis showed that Quanzhou Bay, Xiamen Bay, and Luoyuan Bay were the most affected by different human activities, despite their different development patterns; (3) pH fluctuation was mainly due to anthropogenic nutrient input, and unfavorably, the decreasing trend of pH values and increasing trend of nutrient concentration cannot reach the turning point using panel EKC analysis; and (4) the concentrations of Oils in the coastal waters showed that the oil spill source had been effectively controlled, compared with the historical records. Socioeconomic development level was not significantly associated with some water quality indices in any fashion (DO, COD), while some were (pH, DIN, PO₄-P), the association was roughly positive: the areas with the higher GDP per capita have the worse water quality. It is mainly due to increasing consumption of meat food and amount of motor vehicle with the improved living standard (Chen et al. 2011, Cai et al. 2016), so that more nutrients through domestic wastewater, runoff, and atmospheric deposition enters into the coastal environment without strict treatment efforts (He et al. 2014). The consequences of water quality deterioration would negatively affect the bay as a regional resource, important for its ecological, economic, and recreational value. The measures to mitigate eutrophication should be site-specific, because the nutrient loadings vary from urban and rural areas. To balance economic growth and the coastal environmental quality, an integrated health assessment of coupled human-coastal ecosystems for each bay would be an important next step (Halpern et al. 2015).

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