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Nutrient and chlorophyll *a* anomaly in red-tide periods of 2003–2008 in Sishili Bay, China*

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Abstract Sishili Bay is the most important aquiculture and tourism area for the city of Yantai, China; however, red tides occurred frequently and have caused huge economic losses in this bay in recent years. To gain a better understanding of the local ecological environments in the bay, we conducted this research between 2003 and 2008 to analyze variations in nutrients and chlorophyll (chl-*a*) during high frequency red tide period (May to September). The results show that the chl-*a* concentration increased from 2.70 in 2003 to 7.26 mg/m^3 in 2008, while the concentration of total inorganic nitrogen (TIN) and silicate (SiO_3-Si) increased lineally from 5.18 and 1.45 μmol/L in 2003 to 18.57 and 9.52 μmol/L in 2008, respectively, and the annual phosphate (PO_4-P) varied between 0.15 and 0.46 μmol/L. Special attention was given to a red tide in August 2007 occurred when water temperature was high and nutrient concentrations increased sharply because of a heavy rainfall. Overall, the results show the P limitation in Sishili Bay, and reveal that red tides were caused by eutrophication from terrestrial inputs and local warm weather, particularly during rainy periods. Therefore, to control red tide, greater efforts should be made to reduce sewage discharges into Sishili Bay, particularly during rainfall seasons.

Keyword: chl-*a*; TIN; PO_4-P; red tide; frequency; Sishili Bay

1 INTRODUCTION

Coastal bays are regions of strong land-ocean interaction. The rapid progress of aquiculture and the circumlittoral economy have greatly influenced coastal environments in China, resulting in ecological imbalance, decreased biodiversity, and rapid reduction of biological resources in estuaries and coastal bays (Turner and Rabalais, 1994; Poder et al., 2003; Philippart et al., 2007). Anthropogenic nutrient loading from terrestrial systems usually causes eutrophication and increased occurrence of red tides. Indeed, red tides have become a serious ecological problem worldwide in recent years (Anderson, 1994, 1995; Zhou et al., 2001; Sarkar, 2005), including in China (Tang et al., 2004, 2006; Yu et al., 2007a, 2007b; Wang et al., 2008; Wei et al., 2008).

Sishili Bay is one of the most important areas of aquiculture in north China, and the main aquiculture and tourism area for Yantai, a rapidly developing city in China. Sishili Bay has been influenced extensively by anthropogenic activities, especially the local sewage input (Wang et al., 1995; Ye et al., 2006). Red tides have occurred frequently in this bay area in recent years, which has resulted in great damage to aquiculture and tourism in Yantai.

Most previous studies of Sishili Bay have evaluated the distribution of environmental parameters during specific times. The results of these studies have

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provided information regarding the substantial eutrophication that has occurred in the bay area (Ji, 1994; Zhao et al., 2000a, 2000b; Shan et al., 2001; Wu et al., 2001; Ye et al., 2006). Other studies have considered cultivation and oceanographic processes and the carrying capacity for scallop culture (Yang et al., 1999; Zhang et al., 2001; Zhou et al., 2002a, 2002b, 2006). However, there is no clear information regarding variations in environmental parameters in Sishili Bay, particularly during periods of high frequency red tides, and the long-term trends in nutrients and their association with red tides in this area are still not well understood.

In the present study, in-situ ecological and environmental data obtained for Sishili Bay from 2003 to 2008 are analyzed and summarized. The results presented here may provide a better understanding of ecological environmental variations and their connection with red tide events in this bay area in recent years.

2. STUDY AREA AND METHOD

2.1 Sishili Bay

Sishili Bay is a half-closed water area located in the north of the Yellow Sea, east of Yantai, China at 37.42°–37.63°N, 120.35°–120.63°E (Fig.1a). The bay covers an area of 280 km^2 and has a 20 km coastline, joining Zhifu Bay to the north-west and bordering Yangma Island in the south-east (Fig.1b) (Zhou et al., 2006; Liang et al., 2007). In Sishili Bay, the tidal range is 1.66 m and the water temperature is about 23.3–27.4°C in summer and 2.5–3.0°C during winter (Wu et al., 2001). The water depth of Sishili Bay is less than 15 m, with an average depth of 8–9 m There is no thermal stratification in the bay, and very little difference in hydrographic parameters between the surface and bottom water (less than 1°C between surface and bottom water). There is usually a high frequency of red tides in Sishili Bay from May to September (Communiqués of Marine Environmental Quality of Yantai).

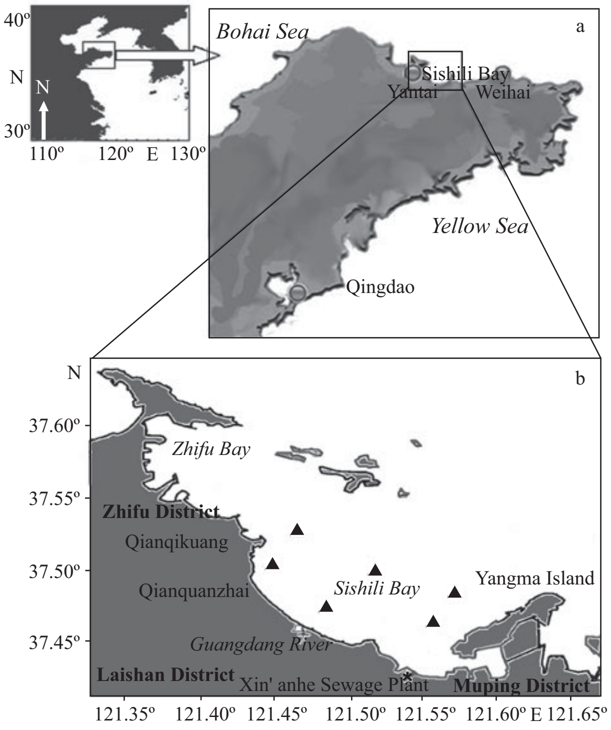

Fig.1 Location of Sishili Bay and the study area

a. The location of Sishili Bay (small box); b. Sishili Bay map with the six survey stations (black triangles)

There are three important districts along the coast of Sishili Bay: Zhifu, Laishan and Muping Districts in Yantai. In addition, there is an estuary of Guangdang River and an outlet of the Xin'anhe Sewage Plant along the coast (Fig.1b). Since 2003, most residential and industrial sewage from the Laishan District has been treated by the Xin'anhe Sewage Plant, which discharges 5–6 tons of sewage into Sishili Bay every day. Additionally, the seriously polluted water in Guangdang River has also been treated by the Xin'anhe Sewage Plant since March, 2005.

From 2002 to 2007, the total population of the three aforementioned districts has increased, while the city's total output values and per capita Gross Domestic Products have also increased (Table 1) With that gain, Yantai's discharge of municipal sewage increased from 2002 to 2007 (Table 1). The suspension aquaculture activity in the bay has also increased in the last two decades (Zhou et al., 2006), and the total mariculture of the three districts was about 1.03×10^5 tons in 2007 (Table 1). These changes can also have an impact on the ecological environment of Sishili Bay.

2.2 Method of environmental observation

Environmental and biological parameters were measured in the surface layer of the sea water at six survey stations (Fig.1b) every May, June, July, August and September from 2003 to 2008. There were two cruises during each month and the monthly mean values of all parameters evaluated during the cruises were calculated.

The physical parameters of sea water were measured in-situ, while the chemical parameters

Table 1 Economic status of main areas along Sishili Bay coast during 2002–2007

Year	Yantai City			Zhifu, Laishan and Muping Districts			
	Municipal Sewage (10K** tons)	Total output values (10K Yuan)	Per capita GDP* (10K Yuan)	Population (10K population)	Cultured animals (10K tons)	Cultured plants (10K tons)	Industrial wastewater (10K tons)
2002	11 367	11 150 000	1.71	130.50	10.00	0.47	2 045
2003	11 955	13 160 000	–	132.39	–	–	–
2004	12 269	16 310 200	2.51	–	10.93	0.43	1068.57
2005	12 470	20 124 609	3.09	136.06	10.72	0.52	819.19
2006	12 649	24 057 483	3.46	137.66	10.62	0.41	912.64
2007	14 445	28 799 576	4.13	137.82	9.75	0.51	1 012.29
Mean annual increase	5.01%	20.92%	19.43%	1.03%	-1.61%	5.06%	-6.22%

* Per capita GDP indicates per capita Gross Domestic Product

** "K" means "one thousand"

were measured in the lab according to the standard methods (SOC, 1998). Briefly, samples for chemical analysis were filtered through cellulose filters (pore diameter 0.45 μm), after which the nitrate nitrogen (NO_3-N) was determined by the zinc cadmium reduction method, the nitrite nitrogen (NO_2-N) was determined by the naphthyl ethylenediamine spectrophotometric method, the ammonia nitrogen (NH_4-N) was determined by the hypobromite oxidation method, the total dissolved inorganic nitrogen (TIN) was calculated as TIN=NO_3-N+NO_2-N+NH_4-N, the dissolved phosphate (PO_4-P) was determined by the phosphorus molybdenum blue spectrophotometric method, and the dissolved silicate (SiO_3-Si) was determined by the sodium molybdenum blue spectrophotometric method. Samples for chl-*a* determination were filtered using Whatman GF/F filters, after which the chl-*a* collected on the GF/F filters was extracted with 90% acetone and then measured using a TU-1810 ultraviolet visible spectrophotometer. Phytoplankton samples were collected using a type III plankton net for shallow water (the pore diameter was 0.077 mm). The samples were then kept in 5% formaldehyde liquor, after which they were analyzed according to the method described by Utermöhl (1958). Observations were made under an Olympus light microscope at magnifications of 100–400, and the phytoplankton abundance was expressed as cells/m^3.

The precipitation data for May to September during 2003 to 2008 were obtained from the Weather Bureau of Yantai. Economic data for the coast of Sishili Bay (Table 1) were obtained from the Communiqué of Marine Environmental Quality of Yantai and Statistical Yearbook of Yantai (http://www.soshoo.com/).

3. RESULT

3.1 Environmental characteristics during high frequency red tide periods

In Sishili Bay during May to September (the period of high frequency red tides), water temperature ranged from 12.28°C (May 8, 2006) to 27.07°C (Aug. 23, 2007), while the annual averages ranged from 21.07°C (2003) to 22.36°C (2007) (Fig.2a). The highest water temperatures (25.22–27.07°C) were observed in August (Fig.2a). The monthly pH of Sishili Bay did not change greatly, ranging from 7.88 to 8.36 during 2003 to 2008 (Fig.2b). The salinity decreased linearly from 32.22 (2003) to 30.80 (2008), with the highest values being observed in May and the lowest being observed in August or September (Fig.2c). The annual mean precipitation in Yantai increased linearly from 98.36 mm (2003) to 168.58 mm (2008), with the highest values being observed in July and August (Fig.2d).

The temporal changes in dissolved oxygen (DO) and chemical oxygen demand (COD) in Sishili Bay were as uniform as the precipitation in Yantai from 2003 to 2008 (Fig.2e, f). The annual mean values of DO increased linearly from 7.72 mg/L (2003) to 9.33 mg/L (2008), while the annual mean values of COD increased from 0.95 mg/L (2003) to 1.39 mg/L (2008), with the highest value (1.59 mg/L) being observed in 2007. Based on the COD values, the sea water in Sishili Bay was within the First Class of National Seawater Quality Standards for China (≤2.00 mg/L, GB3097-1997).

The concentrations of TIN, PO_4-P and SiO_3-Si changed every month and every year (Table 2, Fig.3). NO_3-N, NO_2-N, and NH_4-N accounted on an average for 77.63%, 5.41%, and 16.96% of the TIN,

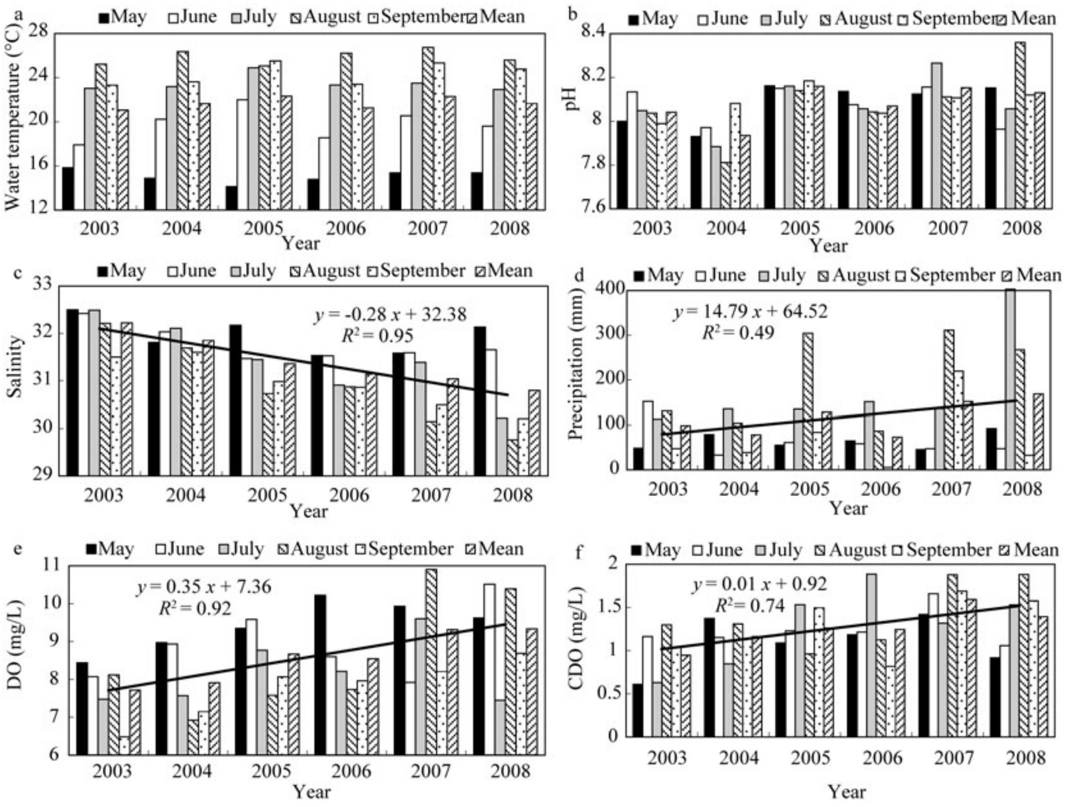

Fig.2 Variations in monthly mean and annual mean of environmental parameters in Sishili Bay

Regression lines showing the changing trend of corresponding parameters. a. water temperature; b. pH; c. salinity; d. precipitation in Yantai City; e. concentrations of DO; f. concentrations of COD

respectively. The annual mean TIN, SiO_3-Si, molar N/P and Si/P increased linearly from 2003 to 2008 (Fig.3a, c, d, & e); however, no changes in the annual mean PO_4-P were observed (Fig.3b). The atomic N/P ratios were usually higher than the Redfield Ratio of 16 (Table 2). The PO_4-P value showed that the nutrient level was within the First Class of National Seawater Quality Standards for China, and that the TIN was also within the First Class of National Seawater Quality Standards for China, except for 2008, when it was within the Second Class (Table 2).

The mean TIN, PO_4-P and COD of the 2003–2008 values were high along the coast, especially near the estuary of Guangdang River and the outlet of the Xin'anhe Sewage Plant (Fig.4).

3.2 Biological parameters during high frequency red tide periods

Diatoms were the dominant phytoplankton in Sishili Bay, and the community structure of the species was relatively invariant from 2003 to 2008 (Table 3) during periods of high frequency red tides. The phytoplankton cell density was usually high in August (Fig.5a), and a high chl-*a* usually appeared in September. A sharp peak in chl-*a* was observed in August 2007 (Fig.5b) when a red tide occurred.

The annual mean phytoplankton cell density increased slightly during 2003–2008 (Table 2, Fig.5a), while the annual mean concentration of chl-*a* linearly increased with a regression coefficient of $R^2=0.57$ (Table 2, Fig.5b). The mean concentration of chl-*a* during the period of high frequency red tides from 2003 to 2008 was highest along the coast near the outlet of the Xin'anhe Sewage Plant (Fig.5).

3.3 Red tides during 2004 to 2009

Red tides occur along the shore in Sishili Bay almost every year, and they have occurred with increasing frequency in recent years. Indeed, nine red tides have been observed from 2004 to 2009 (Table 4).

From August 26 to September 7 in 2007, a red tide caused by *Akashiwo sanguinea* and *Prorocentrum mican*s occurred along the shore from the Guangdang River bayou to Yangma Island. During the temporal process of this red tide, the respective values of TIN, PO_4-P, SiO_3-Si and COD in the surface layer of water increased from 3.54 μmol/L, 0.10 μmol/L,

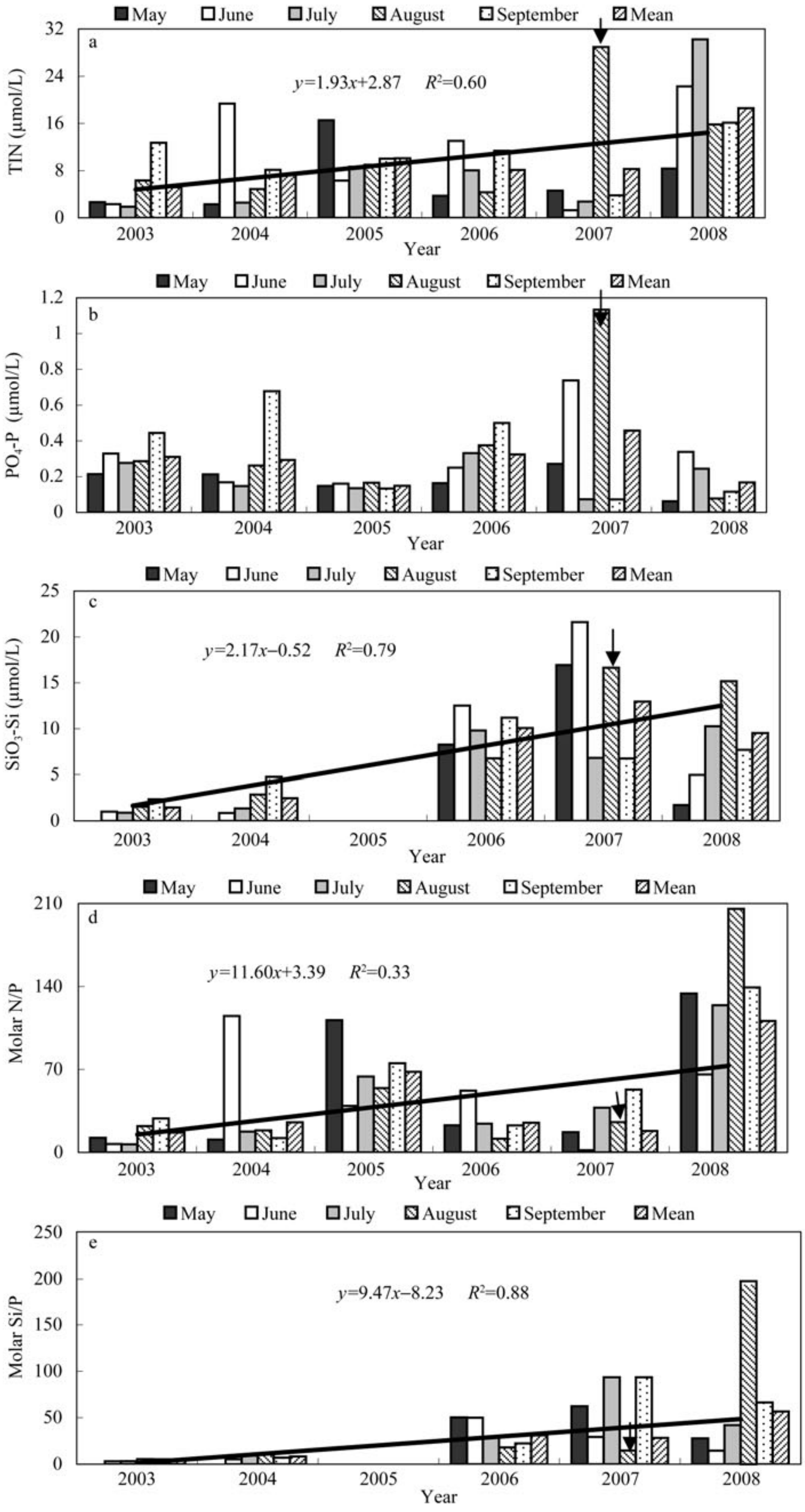

Fig.3 Variation in monthly and annual mean values of nutrients

Regression lines show the changing trend of corresponding parameters, the arrows indicate the especially high or low value in August 2007 when there was a red ride. a. TIN; b. PO_4-P; c. SiO_3-Si (no data available for May 2003, May 2004, or 2005); d. Molar N/P ratio; e. Molar Si/P ratio (no data available for May 2003, May 2004, or 2005)

Table 2 Annual averages of nutrients, chl-*a* and phytoplankton in surface water of Sishili Bay from 2003 to 2008

Year	NH_4-N (μmol/L)	NO_2-N (μmol/L)	NO_3-N (μmol/L)	TIN* (μmol/L)	PO_4-P* (μmol/L)	SiO_3-Si** (μmol/L)	N/P	Si/P	chl-*a* (mg/m³)	Phytoplankton (cells/m³)
2003	2.87	0.31	2	5.18	0.31	1.45	16.71	4.68	2.70	7.20×10^6
2004	1.47	0.48	5.5	7.44	0.29	2.46	25.66	8.48	2.73	2.00×10^7
2005	1.71	0.16	8.24	10.11	0.15	–	67.4	–	4.64	7.21×10^7
2006	1.2	0.92	5.99	8.1	0.32	10.06	25.31	31.44	3.84	1.69×10^7
2007	0.8	0.59	6.89	8.28	0.46	12.95	18	28.15	11.50	2.42×10^8
2008	1.72	0.69	16.15	18.57	0.17	9.52	109.23	56	7.26	2.61×10^7
Mean	1.63	0.52	7.46	9.61	0.28	7.29	34.32	26.04	5.44	6.40×10^7

* Quality standards of seawater from GB3097-1997: TIN. China first class (μmol/L) ≤14.28, second class (μmol/L) ≤21.43; PO_4-P. China first class (μmol/L)≤0.483 9, second class (μmol/L) ≤0.967 7

** The data shown are the mean SiO_3-Si values of June, July, August, and September

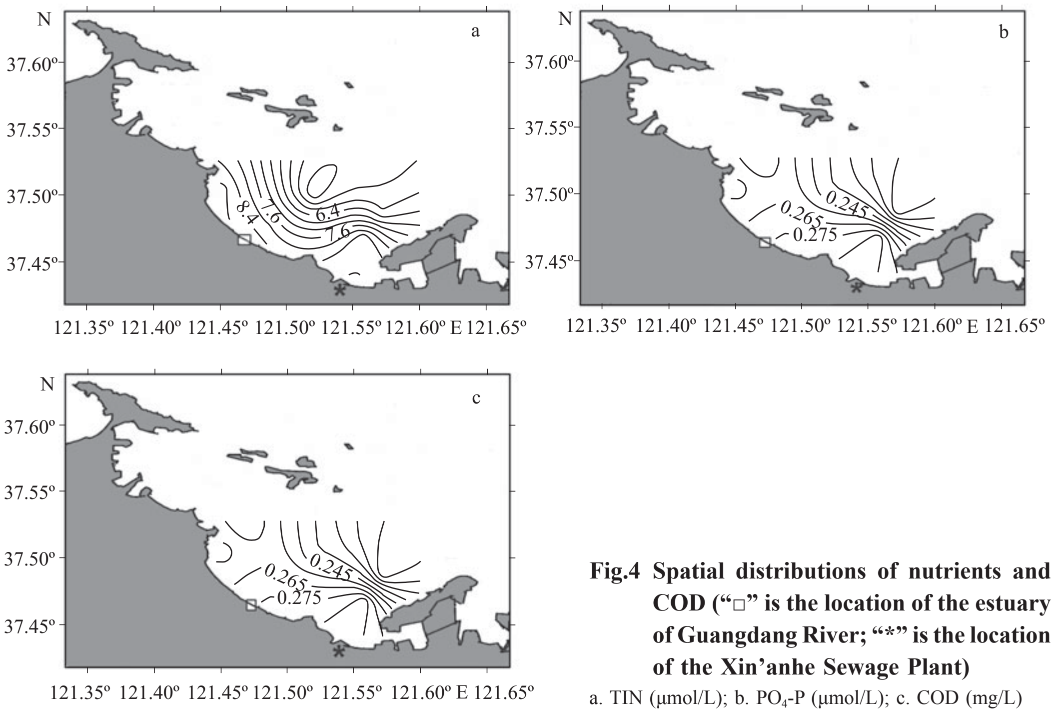

Fig.4 Spatial distributions of nutrients and COD ("□" is the location of the estuary of Guangdang River; "*" is the location of the Xin'anhe Sewage Plant)

a. TIN (μmol/L); b. PO_4-P (μmol/L); c. COD (mg/L)

7.06 μmol/L and 1.89 mg/L on August 23 to 51.50 μmol/L, 2.34 μmol/L, 25.47 μmol/L and 4.12 mg/L on August 30, and then decreased to 7.57 μmol/L, 0.067 μmol/L, 6.74 μmol/L and 1.69 mg/L on September 13 when the red tide disappeared (Fig.7). The temporal change in chl-*a* concentration and cell density of phytoplankton showed the same trends as nutrients, while the salinity showed an opposite changing trend (Fig.7).

4. DISCUSSION

4.1 Ecological status during red tides periods

In Sishili Bay, the highest nutrients and COD and lowest salinities were always observed together with the highest precipitation and water temperature. In addition, high concentrations of nutrients and COD were observed along the coast. The high nutrient concentrations coincident with rainy months indicate that high levels of nutrients and COD were loaded from terrestrial sources during the rainy season.

The ecosystem of Sishili Bay is influenced by frequent human activities and land-based pollution, including domestic sewage and industrial wastewater (Table 1) As a half-closed bay, there is no major freshwater input to the Sishili Bay. Additionally, the only river draining into the bay (Guangdang River) was dammed in March, 2005, although it was not completely controlled until 2008 (http://news.qq.com/a/20080714/000587.htm (accessed on July

Table 3 Dominant species of phytoplankton in Sishili Bay during 2003–2008

Year	Dominant species
2003	*Chaetoceros* sp., *Nitzschia pungens*, *Rhizosolenia stolterfothii*, and *Leptocylindrus danicus*
2004	*Chaetoceros* sp., *Nitzschia pungens*, *Ceratium fusus*, and *Leptocylindrus danicus*
2005	*Chaetoceros* sp., *Skeletonema costatum*, *Rhizosolenia stolterfothii*, and *Melosira sulcata*
2006	*Chaetoceros* sp., *Nitzschia pungens*, *Rhizosolenia stolterfothii*, and *Melosira sulcata*
2007	*Chaetoceros* sp., *Nitzschia pungens*, *Skeletonema costatum*, and *Coscinodiscus* sp.
2008	*Chaetoceros* sp., *Nitzschia pungens*, *Leptocylindrus danicus*, and *Rhizosolenia stolterfothii*

14, 2008), http://www.ytlaishan.gov.cn/zhengwu/newsinfo.asp?info_id=1415 (accessed on July 24, 2008), http://xxgk.yantai.gov.cn/index_show.jsp?sid=0117-05-2007-111731&dept_code=CGJ&

Table 4 Major red tides and their causative species from 1994 to 2009

Time of bloom	Dominate causative species	Scale
August, 1994	*Chaetoceros* sp.	30 km^2
August, 1998	*Akashiwo sanguinea*	100 km^2
May, 2004	*Phaeocystis* sp., and *Noctiluca scintillans*	Patches
September, 2004	*Akashiwo sanguinea*	Patches
August, 2005	*Gymnodimum* sp., *Prorocentrum* sp., and *Thalassiosira* sp.	110 km^2
September, 2006	*Alexandrium tamarense*, and *Prorocentrum micans*	2.37 km^2
August, 2007	*Akashiwo sanguinea*, and *Prorocentrum micans*	8.76 km^2
August, 2008	*Heterosigma akashiwo*	1.65 km^2
September, 2008	*Nitzschia pungens*	1.00 km^2
October, 2008	*Skeletonema costatum*	9.42 km^2
August, 2009	*Akashiwo sanguinea*, and *Chattonella marina*	42.04 km^2

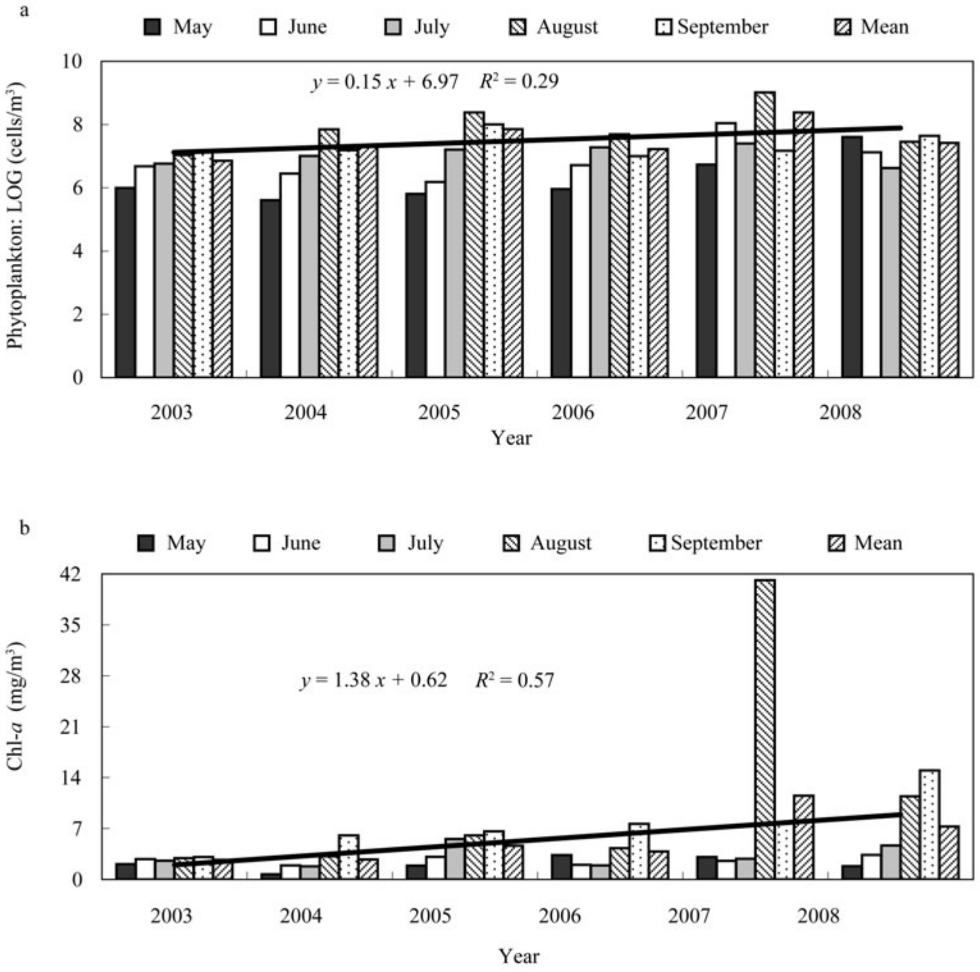

Fig.5 Monthly variations and annual mean variations of biological parameters in Sishili Bay

The regression lines indicate the changing trend of corresponding parameters. a. Phytoplankton cell density; b. Concentrations of chl-*a*

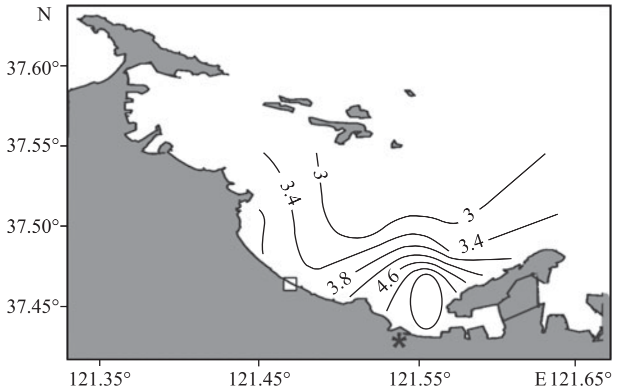

Fig.6 Spatial distributions of chl-*a* concentration (mg/m^3)

"□"is the location of the estuary of Guangdang River; "*" is the location of the Xin'anhe Sewage Plant

columncode=CGJXXGKMLNJ (accessed on July 3, 2008, in Chinese). However, large volumes of local sewage run into the coastal zone of Sishili Bay through the channel of Guangdang River during raining days. As a result, high nutrient and COD concentrations are still found near its estuary, even though the river has been dammed.

In most marine environments, nitrogen appears to be the limiting factor of primary production; accordingly, the concentration of TIN, PO_4-P and molar N/P ratio can control the pattern and function of the ecosystem of a bay, as well as alter the structure, production, and biomass of phytoplankton (Balode et al., 1998; Lenton and Watso, 2000; Leonardos and Geider, 2004; McQuatters-Gollop et al., 2007). However, more N than P entered Sishili Bay from terrestrial sources during rainfall events, as indicated by the increasing trend of TIN concentrations during precipitation. The molar N/P ratios were much higher than 16/1 in Sishili Bay, suggesting a comparative N-abundance and P-limitation status (Redfield, 1958).

Phytoplankton biomass and chl-*a* are usually controlled by nutrient loading (Lenhart et al., 1997; Cadee and Hegeman, 2002; Vermaat et al., 2008). In Sishili Bay, high chl-*a* concentration zones were distributed along the coast and the outfalls coincident with high nutrient concentrations. The changing trend of chl-*a*, nutrients and precipitation were also coincident, indicating that the chl-*a* concentration was influenced by nutrient loading from terrestrial sources during rainfall.

However, phytoplankton blooms can be influenced by other factors in addition to nutrient concentrations, such as sea surface temperature (McQuatters-Gollop et al., 2007; Loebl et al., 2008). In Sishili Bay, the changing trend of chl-*a* lagged behind that of water temperature by one month, except in 2007, showing that high water temperature tends to increase the concentration of chl-*a*. High water temperature may favor algal growth in Sishili Bay.

Aquaculture and nutrients input can also influence phytoplankton (Cadee and Hegeman, 2002; Philippart et al., 2007); for example, cultured scallops can strongly reduce chl-*a* concentrations (Dame et al., 1991; Phelps, 1994; Kohata et al., 2003). As one of the most intensive culture areas in China, Sishili Bay is influenced by cultured organisms, such as scallops and kelp (Zhang et al., 2001; Cadee and Hegeman, 2002; Zhou et al., 2002b). Cultured scallops can remove up to 45% of the suspended matter from the water column every day, which would benefit the N and P flux (Zhou et al., 2002b, 2006). Therefore, the temporal change of nutrients in Sishili Bay is also influenced by cultivated organisms.

4.2 Red tides associated with nutrients

It has been suggested that scallop aquaculture in Sishili Bay with high anthropogenic nutrient loadings would be ecologically advantageous (Zhou et al., 2006), but eutrophication might be a result of urban

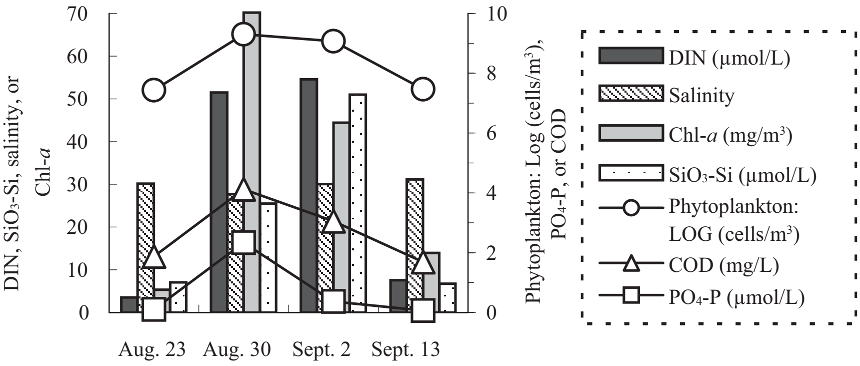

Fig.7 Temporal variations of water parameters during the red tide in 2007

effluent and agricultural runoff to Sishili Bay. Indeed, the annual N and P inputs into the bay are estimated at 1910 and 150 tons, respectively (Wu et al., 2001).

Phytoplankton blooms are usually associated with eutrophication (Riegman et al., 1992; Johnsen and Sakshaug, 2000; Graneli et al., 2008). Algal species that can compete successfully for available growth-limiting nutrient(s) have the potential to become dominant and form blooms (Graneli et al., 2008). In Sishili Bay, red tides only occur under certain circumstances, such as good weather immediately after rainfall, abundant nutrition, and a suitable N/P ratio. P-limitation has a greater effect on eutrophication than N-limitation in Sishili Bay (Ji, 1994; Wu et al., 2001; Ye et al., 2006; Liang et al., 2007). For example, in August 1998 and May 2004, the N/P ratio in Sishili Bay was 10 and 3.4 when algal blooms occurred (Ye et al., 2006). Conversely, in August 2007, there were remarkably low atomic N/P and Si/P ratios even though there was abundant precipitation and a high influx of N and Si nutrients into the bay. These low ratios were attributed to the very high concentration of PO_4-P that was observed.

In August 2007, there was heavy rainfall in Yantai of over 200 mm before the occurrence of the red tide, which resulted in formation of a mass of sewage water that exceeded the managing capability of the Xin'anhe Sewage Plant. As a result, sewage entered the bay directly with rainwater. This influx of sewage coupled with the weak water body exchange in Sishili Bay prevented the contamination from being diluted and diffused to the open sea in time, resulting in local eutrophication. In addition, the high water temperature in Sishili Bay likely stimulates the growth of phytoplankton. During the periods before and after the red tide (before Aug. 25, and after Sept. 8) in 2007, the chl-*a* concentration and phytoplankton abundance were at normal levels that were coincident with the low concentrations of TIN, PO_4-P, SiO_3-Si, and COD. The nutrient concentrations returned to normal levels when the bloom ended because the nutrients were consumed by the algae.

5. CONCLUSION

In Sishili Bay, the highest nutrient concentrations, chl-*a* concentration, and phytoplankton cell density were coincident with the highest water temperature and the maximum precipitation in August. The molar N/P ratios showed comparative P-limitation in Sishili Bay during the periods of high frequency red tides.

Both high concentrations of nutrients and chl-*a* presented along the coast of Sishili Bay, indicating that the high nutrient loadings were from terrestrial resources and entered the bay in response to rainfall runoff.

Red tides coincided with the sharp increase in nutrient concentrations, especially PO_4-P in Sishili Bay. Suitable high water temperature and precipitation appeared to be the original cause of the red tides. Therefore, greater efforts should be made to reduce sewage discharges into Sishili Bay during rainfall periods, especially during the period of high frequency red tides.

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