Multivariate statistical analysis of water quality and phytoplankton characteristics in Daya Bay, China, from 1999 to 2002*

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Abstract

This study analyzed seasonal physicochemical and phytoplankton data collected at 12 marine monitoring stations in Daya Bay from 1999 to 2002. Cluster analysis

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based on water quality and phytoplankton parameters measured at the 12 stations could be grouped into three clusters: cluster I – stations S1, S2, S7 and S11 in the southern part and the north-eastern part of Daya Bay; cluster II – stations S5, S6, S9, S10 and S12 in the central and north-eastern parts of Daya Bay; cluster III – stations S3, S4 and S8 in the cage culture areas in the south-western part of Daya Bay and in the north-western part of the Bay near Aotou harbor. Bivariate correlations between phytoplankton density and the major physical and nutrient factors were calculated for all stations. Factor analysis shows that there were high positive loadings of pH, TIN and the ratio of TIN to PO_4-P in the three clusters, which indicates that all the stations in the three clusters were primarily grouped according to their respective nutrient conditions.

1. Introduction

China is a large coastal nation located along the western Pacific Ocean with 18 000 km of mainland coastline, along which there are many large and important bays. Daya Bay is one of a series of large and important gulfs along the southern coast of China, located at 113°29′42″–114°49′42″E and 23°31′12″–24°50′00″N in Guangdong Province. It covers an area of 600 km^2 with a width of about 15 km and a north–south length of about 30 km, and about 60% of the Bay's area is less than 10 m deep (Xu 1989, Wang et al. 2004). Dapeng Cove, lying between the Lingao Nuclear Power Plant (LNPP) and the Marine Biological Research Station (MBRS) in the south-western part of Daya Bay (Fig. 1), is about 4.5 km (N–S) by 5 km (E–W). Daya Bay is located in a subtropical region, and its annual mean air temperature is 22°C. The coldest months are January and February, with a monthly mean air temperature of 15°C, and the hottest months are July and August, with a monthly mean air temperature of 28°C. The sea surface temperature is lowest in winter (15°C) and highest in summer and autumn (30°C) (Xu 1989). No major rivers discharge into Daya Bay, but there are three small rivers (the Nanchong, Longqi and Pengcheng) that flow into Dapeng Cove.

The Pearl River is located in the eastern part of Daya Bay. The Bay has many kinds of subtropical habitats, including coral reefs, mangroves, rocky and sandy shores, and mudflats. The coral reefs and mangroves have a special resource value, the ecological benefits of which are very important for sustainable social and economic development in these subtropical coastal areas. Coral reefs and mangrove areas have important relationships with the regulation and optimization of subtropical marine environments and have become hotspots of international attention in the last twenty years (Mumby et al. 2004, Pearson 2005).

The Daya Bay Nuclear Power Plant (DNPP), the first nuclear power plant and the largest joint foreign investment project in China to be

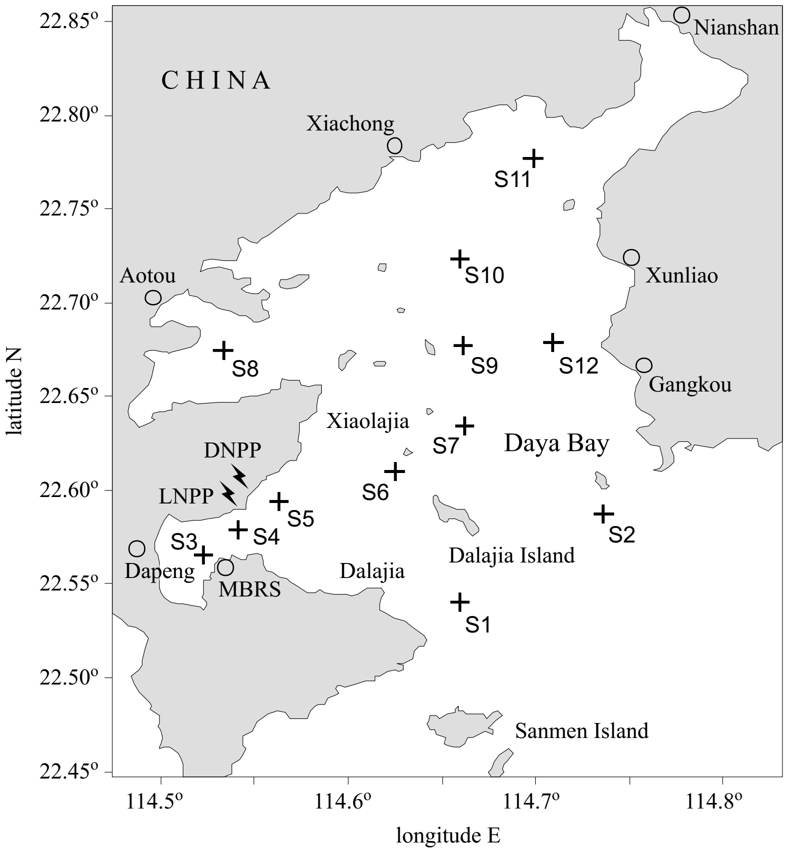

Fig. 1. Locations of the 12 monitoring stations in Daya Bay: S1 – 114.6333°E, 22.5333°N; S2 – 114.7167°E, 22.5667°N; S3 – 114.5167°E, 22.5692°N; S4 – 114.5333°E, 22.5833°N; S5 – 114.5617°E, 22.5933°N; S6 – 114.6217°E, 22.6000°N; S7 – 114.6667°E, 22.6167°N; S8 – 114.5500°E, 22.6767°N; S9 – 114.6667°E, 22.6667°N; S10 – 114.6667°E, 22.7167°N; S11 – 114.7167°E, 22.7667°N; S12 – 114.7117°E, 22.6667°N

completed since 1982, marked the first step taken by China in the development of large-capacity commercial nuclear power units (Zang 1993). Since 1993, the DNPP has been discharging warm sea water (65°C) at a rate of c. 95 m^3 s^{-1} into the southern part of Daya Bay. Another such facility – the Lingao Nuclear Power Plant (LNPP), located near the DNPP, has been in operation since 2002. These power plants may well be having an impact on the ecological environment of Daya Bay, which lies about 30 km from Hong Kong and about 60 km from the Shenzhen Special Economic Zone (Tso & Li 1992). Studies have also been conducted on the Bay's overall ecosystem, in particular by the Marine Biological Research Station

(MBRS) (founded in 1982), which is located on the south shore of Dapeng Cove. The South China Sea Institute of Oceanology of the Chinese Academy of Sciences, a branch of which is the MBRS, conducts surveys of Daya Bay four times per year (Han 1991, Pan & Cai 1996, Pan & Wang 1998).

Tang et al. (2003) applied AVHRR data to the study of the thermal plume from the DNPP: satellite remote sensing can provide information about the distribution and seasonal variation in thermal plumes from nuclear power plants that discharge cooling waters into coastal areas. The variation of phytoplankton biomass and primary production in the western part of Daya Bay during spring and summer was reported (Song et al. 2004), and elevated water temperatures and nutrient supplies from terrestrial sources were found to stimulate annual red tides. Wang et al. (2004) summarized the changes in the Daya Bay environment and the trends in the last 20 years: the characteristics of the phytoplankton can be affected by many factors, such as different seasons and water quality (Jin et al. 1999). Human activities have been the main factor affecting the ecological environment of Daya Bay (Wang et al. 2004).

Water quality and phytoplankton characteristics have also been investigated in other bays of the world. San Diego-McGlone et al. (1995) studied nutrient-mediated stress in the marine communities of a coastal lagoon in Puerto Galera Bay. Yung et al. (2001) analyzed the physicochemical and phytoplankton characteristics in the Port Shelter, Hong Kong. Hidalgo-Gonzales et al. (2001) reported on remotely sensed chlorophyll profiles and the water column structure in the Gulf of California.

To the best of our knowledge, this paper is the first attempt to analyze the water quality and phytoplankton characteristics in Daya Bay by multivariate statistics based on research data obtained from Daya Bay in 1999–2002.

2. Material and methods

Field measurement sampling and laboratory analysis

A Quanta® Water Quality Monitoring System (Hydrolab Corporation, USA) was employed to collect the data for temperature, pH, salinity and depth of water at all stations. Seawater samples for the analysis of nutrients and chlorophyll *a* were taken with 5 dm^3 GO-FLO bottles at the surface and bottom, and other samples from various depths were collected according to 'The specialties for oceanography survey' (GB12763-91, China).

Two replicates of 1.5 dm^3 samples from the depths mentioned above were filtered through 47 mm GF/F filters and deep-frozen immediately at $-20°C$. At the end of the cruise, all filters were transported in liquid nitrogen to the shore laboratory. Within a week, chlorophyll a was extracted in 10 ml 90% acetone in the dark for 24 h in a refrigerator and its concentration was determined with a 10-AU Fluorometer (Turner Designs, USA). Water samples from various depths were analyzed for nitrate and silicate with a SKALAR auto-analyzer (Skalar Analytical B.V. SanPlus, Holland). Ammonium and phosphorus were analyzed with oxidation methods using hypobromite and molybdophosphoric blue with a UV1601 spectrophotometer (SHIMADZU Corporation). Dissolved oxygen (DO) was determined by Winkler titration, water transparency was assessed with a Secchi disk, and phytoplankton samples were collected with a shallow-water net-II.

All these samples were collected during one day at the beginning of the first month of each season (spring-summer-fall-winter). The samples (except phytoplankton) included those taken at the surface and the bottom, and the data for this paper are given as mean values between the surface and bottom.

Phytoplankton analysis

Phytoplankton analysis was carried out for the 12 stations by sampling water with the shallow water net-II according to 'The specialties for oceanography survey' (GB12763-91, China). The number and species were recorded with an Alphaphot-2 biological microscope (Nikon Corporation). The analyses were carried out at the Key Laboratory of the Marine Biological Research Station at Daya Bay, Chinese Academy of Sciences, Shenzhen, China.

Statistical analysis

All the statistical analysis methods were applied according to Johnson & Wichern (1998). Kendall's tau-b values were used. Bivariate correlations between phytoplankton density and major physical and nutrient factors were calculated for all stations. Flexible-Beta cluster analysis was used between groups for transforming measures with Flexible-Beta Distance. Factor analysis was used to investigate various factors, which were identified by the principal component method with varimax rotation (using PROC X16 of the SAS system). Canonical correlation analysis was carried out for selected stations – S5, S7 and S8 – for which phytoplankton data were available, and the proportion of variation was explained by the canonical variable. All statistical analysis programs are part of the Statistical Analysis System (SAS 9.0) software package (SAS Institute Inc. 2002).

3. Results and Discussion

The water quality and phytoplankton data collected from 1999 to 2002 at 12 stations in Daya Bay are summarized in Table 1, and selected physical, nutrient and biological factors at stations S3, S5, S7, S8, S10 and S12 representing different sea areas in Daya Bay are given in Figs 2–4.

The spatial distribution of the water temperature showed high values in the western part of Daya Bay near the nuclear power stations (near station 5) and low values in the western and southern parts of the Bay in each year from 1999 to 2002. The average temperature of Daya Bay ranged from 23.23°C to 25.96°C. The lowest average temperature was recorded at S2, at the mouth of Daya Bay. The average salinity varied from 31.58 to 32.70. The stratification due to temperature and salinity differences between surface and bottom waters within the Bay started to develop in June, was strongest from July to September, and disappeared in October. Temperature and salinity in the Bay were uniform with depth from November until May of the following year. Based on the 1999–2002 data, the highest surface and bottom water temperatures occurred in October and the lowest in January. The vertical and seasonal variations and distributions of water temperature in Daya Bay suggest that they are affected by the East Guangdong upwelling and the thermocline, which is in existence from June to August (Han 1991, Wang et al. 2004). During that time, the thermocline temperature gradient averaged 0.5–1°C m^{-1}. The thermocline depth varied from 6 m to 10 m, and its thickness in Daya Bay was about 2–4 m (Wang et al. 2004). The minimum water temperature at the bottom was about 23°C in June of each year. As a result of seawater mixing, the thermocline disappeared in September and was absent until the following March.

The pH averaged over all stations ranged from 8.12 to 8.24 in 1999–2002. Dissolved oxygen (DO) at all stations was higher in surface waters than in bottom waters; the average DO concentrations in Daya Bay (range: 6.64–7.10 mg dm^{-3}) were distributed more uniformly than temperature. DO concentrations were higher in spring and winter than in summer and fall, being highest in winter and lowest in summer. On the other hand, BOD_5 levels were higher at the mouth and in the fish and shellfish culturing areas than in the other parts of Daya Bay. The results indicate that the seawater of Daya Bay is within the limits of the First Class of National Seawater Quality Standards for China (DO $>$ 6.00 mg dm^{-3}, GB3097-1997) (Wang et al. 2004).

The highest turbidity level (4.04 NUT) and the lowest Secchi disk depth (2.32 m) were recorded at S3, in the southeast of Daya Bay. In contrast, the lowest turbidity level (1.62 NUT) and the highest Secchi disk depth

Table 1. Ranges and means of major physicochemical and biological factors at 12 stations in Daya Bay from 1999 to 2002

Factor	Range mean	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
temperature [°C]	min–max	18.00–28.00	17.50–27.20	16.60–331.40	18.00–32.10	16.90–32.20	16.70–30.20	16.50–29.85	14.90–31.30	16.10–30.10	16.20–30.40	14.80–30.80	15.90–30.10
	mean	23.58	23.23	23.64	24.14	25.96	24.18	24.26	24.98	24.53	24.79	24.67	10 24.37
salinity [ppt]	min–max	27.70–33.65	28.31–33.83	27.07–33.80	27.08–33.46	28.44–33.62	27.41–33.62	20.99–33.44	24.04–33.23	27.38–33.43	27.05–33.23	27.15–33.09	27.63–33.26
	mean	31.67	31.92	31.78	32.21	32.61	32.70	32.23	31.73	32.28	32.05	31.58	32.28
DO [mg dm^{-3}]	min–max	4.11–7.78	5.60–8.10	6.06–8.04	3.61–8.03	5.22–7.92	4.70–7.94	4.28–8.46	6.02–8.15	5.33-8.54	5.53–8.37	5.40–7.94	3.95–8.58
	mean	6.75	6.64	7.00	6.72	6.96	6.84	7.01	7.28	7.04	7.10	6.98	6.92
pH	min–max	7.85–8.30	7.94–8.26	7.84–8.37	8.00–8.37	7.96–8.37	7.82–8.37	7.99–8.44	7.98–8.46	8.00–8.64	7.96–8.39	7.90–8.44	7.96–8.65
	mean	8.12	8.13	8.19	8.19	8.18	8.19	8.20	8.24	8.22	8.21	8.16	8.20
Secchi [m]	min–max	2.20–5.00	1.50–3.00	1.80–5.00	1.70–4.50	2.00–5.00	1.50–5.20	1.50–6.50	1.204.00	1.50–5.50	1.50–4.50	1.20–4.00	1.50–5.70
	mean	3.03	2.32	2.47	2.82	2.91	3.32	3.20	2.53	3.26	2.86	2.60	2.91
turbidity [NTU]	min–max	0.27–9.08	0.77–8.13	0.57–6.76	0.17-7.77	0.27–4.72	0.12–8.84	0.17–8.37	0.07–12.15	0.17–6.24	0.17–6.00	0.17–9.31	0.12–5.30
	mean	4.01	4.04	2.11	1.77	2.07	1.92	2.27	2.47	1.62	2.14	2.18	1.89
NH_4-N [μmol dm^{-3}]	min–max	0.049–4.762	0.016–4.25	0.091–6.63	0.035–5.80	0.019–6.55	0.009–16.50	0.017–3.29	0.007–8.00	0.029–7.79	0.006–8.20	0.028–9.63	0.006–3.74
	mean	1.337	2.660	2.660	1.816	1.887	1.816	1.145	2.122	1.705	2.123	1.656	1.391
NO_2–N [μmol dm^{-3}]	min–max	0.015–1.400	0.009–1.41	0–2.39	0.002–1.78	0.013–2.22	0.01–4.16	0.003–3.04	0.001–1.68	0.001–1.45	0–1.14	0–1.48	0–1.78
	mean	0.258	0.523	0.382	0.274	0.408	0.495	0.447	0.324	0.255	0.257	0.337	0.341
NO_3-N [μmol dm^{-3}]	min–max	0.06–6.05	0–5.45	0.002–4.46	0.034–26.07	0.031–5.19	0.045–5.50	0–5.45	0–27.62	0–0.57	0.004–3.38	0–2.76	0–3.43
	mean	1.43	1.29	1.52	2.82	1.92	1.81	1.61	2.45	1.05	1.33	1.18	1.31
TIN [μmol dm^{-3}]	min–max	0.125–7.85	0.054–8.76	0.071–12.10	0.071–28.22	0.069–7.90	0.067–19.19	0.033-10.49 3.203	0.021–30.05	0.040–8.60	0.012–9.10	0.038–11.27	0.008–7.04
	mean	3.528	3.056	4.565	4.907	4.211	4.065	3.203	4.894	3.012	3.720	3.171	3.038
PO_4-P [μmol dm^{-3}]	min–max	0.018–0.68	0.005–0.86	0.003–0.71	0–0.58	0.011–0.65	0.007–0.64	0.06–0.37	0.009–0.53	0.001–0.38	0-0.42	0.003–0.45	0.002–0.37
	mean	0.152	0.195	0.184	0.157	0.184	0.216	0.160	0.149	0.161	0.171	0.191	0.140
SiO_3-Si [μmol dm^{-3}]	min–max	12.83–30.00	8.81–39.38	4.60–40.40	6.06–35.71	5.18–32.00	7.17–33.75	7.72–331.71	0.33–40.00	5.38–31.30	6.01–41.65	0.83–47.50	0.93–34.38
	mean	21.70	27.35	21.58	19.52	20.29	21.70	31.25	18.57	19.45	19.78	24.58	19.14
DIN/PO_4-P	min–max	4.26–162.41	8.23-30.11	8.40–338.82	5.56–303.67	4.95–193.75	4.68–58.83	5.46–64.33	2.43–433.00	2.45–120.80	5.50–92.40	2.28–119.84	7.14–162.67
	mean	23.21	15.67	24.81	31.25	22.88	18.82	20.02	32.84	18.71	21.75	16.60	21.70
SiO_3-Si/PO_4–P	min–max	37.05–1350.47	39.76–5256.17	27.75-5337.24	37.70–2442.40	33.06–2230.41	30.30–3686.64	8.12–9390.68	6.60–1377.67	23.39–50322.58	27.04–980.75	4.58–10824.37	10.33–9202.00
	mean	142.76	140.26	117.28	124.33	110.27	100.46	195.31	124.63	120.81	115.67	128.69	136.71
BOD_5[μmol dm^{-3}]*	min–max	0.42–6.61	0.42–5.39	0.79–3.32	0.63–3.39	0.53–2.64	0.43–7.17	0.33–6.58	0.96–4.35	0.40–4.29	0.85–1.53	0.65–2.92	0.41–5.58
	mean	2.09	1.63	1.63	1.81	1.28	1.71	1.94	1.69	1.51	1.13	1.40	1.50
chlorophyll *a* [mg m^{-3}]	min–max	0.29–2.91	0.19–4.42	0.24–8.75	0.14–9.68	0.34–7.90	0.27–9.17	0.12–7.93	0.58–8.85	0.10–9.96	0.32–10.72	0.46–11.14	0.34–7.64
	mean	1.34	1.63	3.78	2.69	2.45	2.53	2.76	4.14	2.52	2.58	2.98	2.44
phytoplankton [cells m^{-3}]	min–max	$5.94 \times 10^4 - 6.47 \times 10^5$	$1.08 \times 10^5 - 1.13 \times 10^6$	$3.64 \times 10^4 - 8.24 \times 10^7$	$7.33 \times 10^4 - 8.40 \times 10^7$	$6.17 \times 10^4 - 4.45 \times 10^7$	$7.44 \times 10^4 - 6.11 \times 10^7$	$4.46 \times 10^4 - 4.21 \times 10^6$	$6.69 \times 10^4 - 2.84 \times 10^8$	$3.44 \times 10^4 - 2.49 \times 10^7$	$3.41 \times 10^4 - 2.07 \times 10^7$	$1.36 \times 10^5 - 2.31 \times 10^7$	$7.18 \times 10^4 - 6.57 \times 10^6$
	mean	3.59×105	4.77×10^5	$3.64 \times 10^4 - 8.24 \times 10^7 6.85 \times 10^6$	6.51×10^6	$6.17 \times 10^4 - 4.45 \times 10^7 3.76 \times 10^6$	4.70×10^6	$4.46 \times 10^4 - 4.21 \times 10^6 1.12 \times 10^6$	2.03×10^7	$3.44 \times 10^4 - 2.49 \times 10^7 3.96 \times 10^6$	2.24×10^6	$1.36 \times 10^5 - 2.31 \times 10^7 2.89 \times 10^6$	1.49×106
bacillariophyta [cells m^{-3}]	min–max	$3.61 \times 10^4 - 6.28 \times 10^5$	$8.06 \times 10^4 - 1.11 \times 10^6$	$3.18 \times 10^4 - 8.20 \times 10^7$	$6.67 \times 10^4 - 8.39 \times 10^7$	$5.17 \times 10^4 - 4.42 \times 10^7$	$5.04 \times 10^4 - 6.10 \times 10^7$	$4.14 \times 10^4 - 4.08 \times 10^6$	$5.38 \times 10^4 - 2.84 \times 10^8$	$5.95 \times 10^4 - 2.47 \times 10^7$	$2.76 \times 10^4 - 1.73 \times 10^7$	$4.13 \times 10^5 - 2.29 \times 10^7$	$7.00 \times 10^4 - 6.47 \times 10^6$
	mean	3.18×10^5	4.53×10^5	6.72×10^6	6.43×10^6	3.65×10^6	4.67×10^6	1.05×10^6	1.97×10^7	3.89×10^6	2.18×10^6	2.76×10^6	1.41×10^6
pyrophyta [cells m^{-3}]	min–max	$1.11 \times 104 - 1.12 \times 10^5$	$8.13 \times 10^3 - 3.66 \times 10^4$	$1.67 \times 10^3 - 4.92 \times 10^5$	$2.22 \times 10^3 - 6.95 \times 10^5$	$5.42 \times 10^3 - 6.94 \times 10^5$	$4.64 \times 10^3 - 1.17 \times 10^5$	$3.21 \times 10^3 - 1.26 \times 10^5$	$3.21 \times 10^3 - 6.25 \times 10^5$	$2.38 \times 10^3 - 1.79 \times 10^5$	$3.68 \times 10^3 - 2.33 \times 10^5$	$1.54 \times 10^3 - 3.00 \times 10^5$	$1.82 \times 10^3 - 2.25 \times 10^5$
	mean	3.42×10^4	2.07×10^4	1.27×10^5	8.05×10^4	1.04×10^5	4.05×10^4	6.20×10^4	1.44×10^5	6.80×10^4	5.41×10^4	8.26×10^4	7.07×10^4
cyanophyta [cells m^{-3}]	min–max	$0.00 - 2.03 \times 10^4$	$0.00 - 8.13 \times 10^3$	$0.00 - 3.00 \times 10^4$	$0.00 - 1.78 \times 10^5$	$0.00 - 3.59 \times 10^4$	$0.00 - 1.58 \times 10^4$	$0.00 - 1.85 \times 10^4$	$0.00 - 4.08 \times 10^4$	$0.00 - 3.00 \times 10^4$	$0.00 - 1.78 \times 10^4$	$0.00 - 1.21 \times 10^4$	$0.00 - 2.76 \times 10^4$
	mean	5.99×10^3	3.39×10^3	1.80×10^3	1.30×10^3	7.75×10^3	3.95×10^3	5.13×10^3	9.60×10^3	5.42×10^3	6.51×10^3	4.94×10^4	6.20×10^3
others [cells m^{-3}]	min–max	$0.00 - 6.11 \times 10^3$	$0.00 - 9.38 \times 102$	$0.00 - 7.27 \times 10^3$	$0.00 - 1.19 \times 10^4$	$0.00 - 1.25 \times 10^4$	$0.00 - 1.79 \times 10^4$	$0.00 - 3.57 \times 10^3$	$0.00 - 1.92 \times 10^4$	$0.00 - 8.18 \times 10^3$	$0.00 - 1.88 \times 10^3$	$0.00 - 1.67 \times 10^3$	$0.00 - 6.19 \times 10^3$
	mean	1.23×10^3	1.17×10^2	1.02×10^3	7.80×10^2	1.68×10^3	1.66×10^3	8.10×10^2	1.67×10^3	7.40×10^2	9.95×10^3	2.80×10^2	8.30×10^2

*The BOD_5 data was from 2001 to 2002.

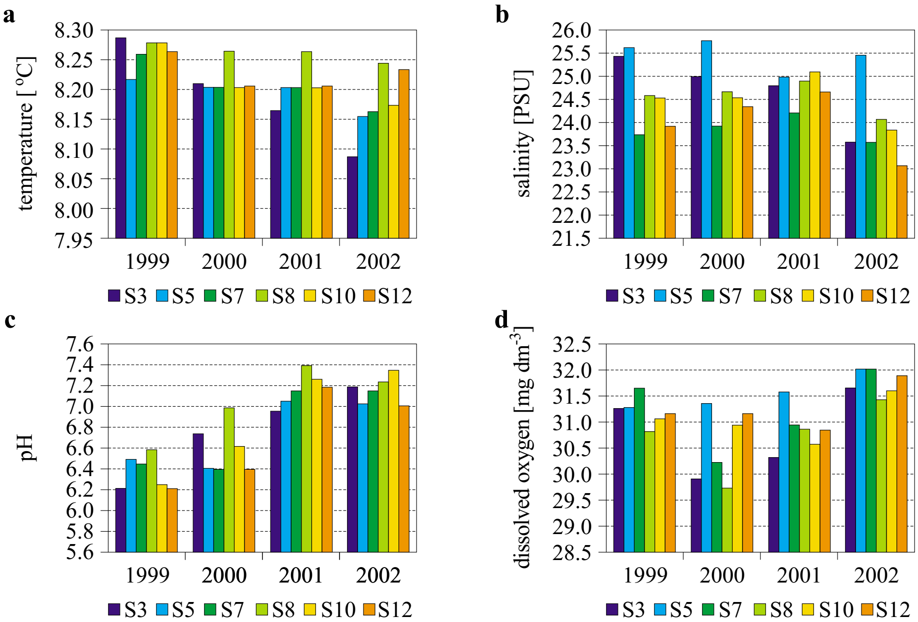

Fig. 2. Changes in annual average pH (a), temperature [°C] (b), dissolved oxygen [mg dm^{-3}] (c) and salinity [PSU] (d) at five selected sampling stations in Daya Bay from 1999 to 2002

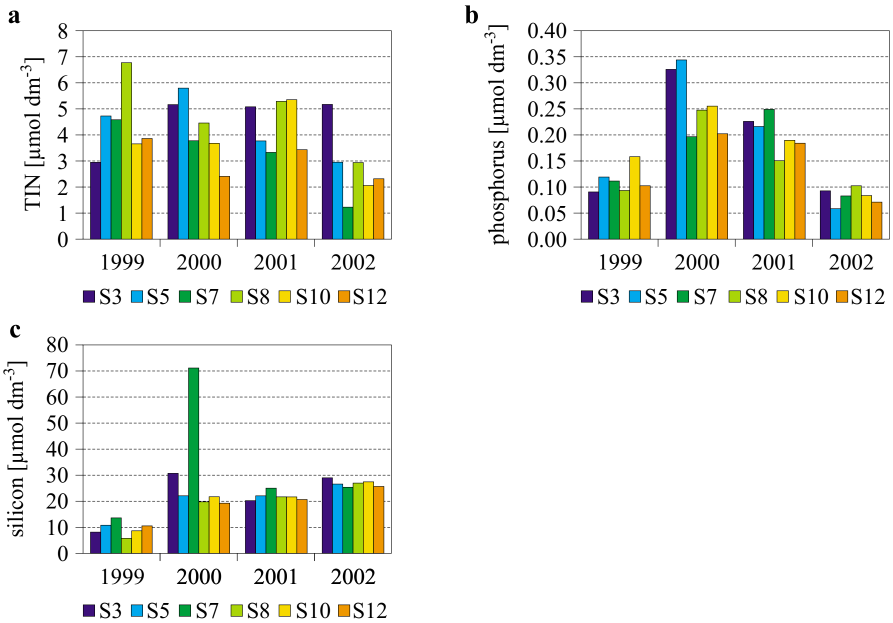

Fig. 3. Changes in annual average TIN (a) phosphorus (P) (b) and silicon (Si) (c) at five sampling stations in Daya Bay from 1999 to 2002 [μmol dm^{-3}]

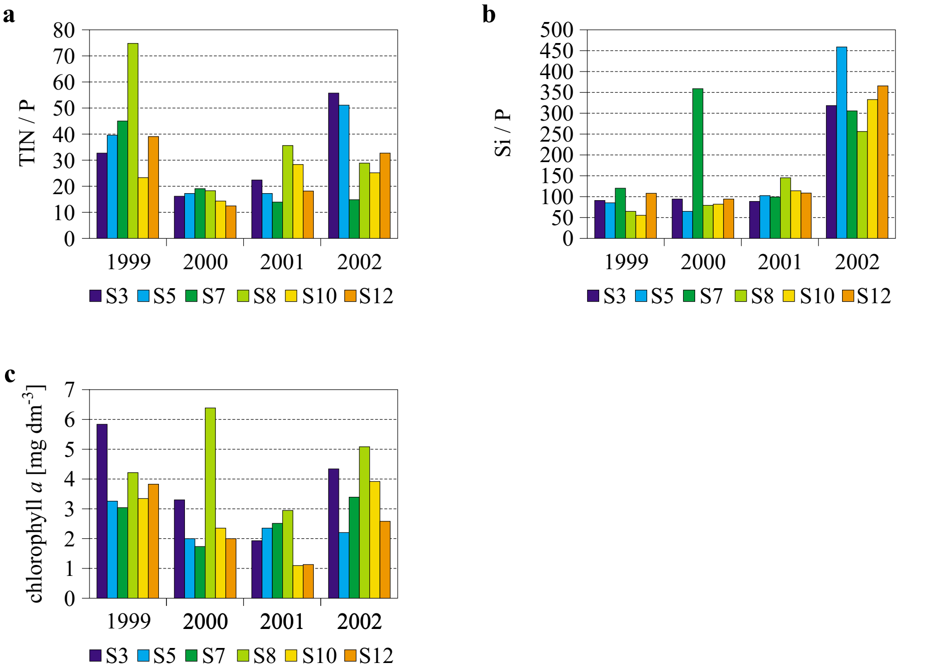

Fig. 4. Changes in annual average (a) TIN to P ratios (b) Si to P ratios and (c) chlorophyll *a* [mg dm^{-3}] at five sampling stations in Daya Bay from 1999 to 2002

(3.26 m) were recorded at S9 at the central part of Daya Bay. In general, Secchi disk depths were the highest in the center of Daya Bay, whereas turbidities were the highest at the Bay's mouth.

Average concentration ranges of total dissolved inorganic nitrogen (TIN), phosphorus (PO_4-P) and silicon (SiO_3-Si) in Daya Bay were 3.038–4.907 μmol dm^{-3}, 0.140–0.195 μmol dm^{-3} and 18.57–31.25 μmol dm^{-3} (Table 1), respectively. The respective ranges of the ratios TIN/PO_4-P and PO_4-P/SiO_3-Si ratios were 15.67–32.84 and 100.46–195.31. Inorganic nitrogen and phosphorus levels were within the limits of the National First Class Water Quality Standards for China from 1999 to 2002 (Wang et al. 2004). NH_4-N (c. 49%) and NO_3-N (c. 43%) were the dominant total dissolved inorganic nitrogen (TIN) forms, accounting for about 90% of the TIN in these years; NO_2-N was only about 8%. The NO_3-N content was lower relative to NH_4-N, revealing a thermodynamic imbalance between NH_4-N, NO_2-N and NO_3-N. Biological activity could be the main factor influencing the balance (Huang 2003), but there were different degrees of NH_4-N transformation in the different parts of the Bay. The NH_4-N and TIN concentrations at S3, S3 and S8 in these parts – the cage culture areas for fish and shellfish in Daya Bay – were higher than at the other monitoring stations. The water quality of Daya Bay was better than in the Port Shelter of Hong Kong (Yung et al. 2001) and in the Pearl River (Xu et al. 2005), but worse than in Sanya Bay (Huang et al. 2003).

Mean chlorophyll *a* levels in Daya Bay ranged form 1.34 to 4.14 mg m^{-3} (Table 1), the higher values always being recorded in summer and fall. The average annual abundances of phytoplankton tended to decrease slightly from 1999 to 2002 (Wang et al. 2004). The highest chlorophyll *a* levels (mean 4.41) were recorded at station S8, the next highest at S3. Both located in the cage culture areas for fish and shellfish, stations S8 and S3 were also situated near Aotou harbor and the Pengcheng River in Dapeng Cove, respectively (Wang et al. 2004, Song et al. 2004). Nutrient levels were higher at stations S8 and S3 than elsewhere. These results are consistent with phytoplankton data (Sommer et al. 2002). Compared with the East China Sea (Furuya et al. 2003), the chlorophyll *a* levels in Daya Bay were very high. Nutrients were the main factors determining the concentrations of chlorophyll *a* and phytoplankton in Daya Bay (San Diego-McGlone et al. 1995, Hidalgo-Gonzales et al. 2001), but it should be noted that between 1985 and 1999 the limiting nutrient in Daya Bay changed from N to P (Wang et al. 2004).

164 species of phytoplankton have been identified in Daya Bay since 1983 (Xu 1989, Wang et al. 2004). The phytoplankton species belonged to the cyanophyta, bacillariophyta, pyrophyta, chrysophyta and xanthophyta. Most of the phytoplankton species were diatoms (about 70%) and flagellates (about 20%). The main phytoplankton divisions in Daya Bay included the bacillariophyta (127 species) and xanthophyta (30 species), and the principal genera of the bacillariophyta were *Rhizosolenia* (21 species) and *Chaetoceros* (38 species) (Xu 1989). The bacillariophyta, pyrophyta, cyanophyta and chrysophyta at the different stations are shown in Fig. 5. The dominant of diatom genera in Daya Bay were *Chaetoceros*, *Nitzschia*, *Rhizosolenia*, *Leptocylindrus* and *Skeletonema*, with species such as *Chaetoceros affinis*, *Ch. compressus*, *Ch. lorenzianus*, *Ch. curvisetus*, *Ch. pseudocurvisetus*, *Rhizosolenia alata* f. *grecillisma*, *Nitzschia delicatissima*, *Leptocylindrus danicua*, *Skeletonema costatum* and *Thalassionema nitzschioide*, and the dominant species of flagellate was *Ceratium* sp. The mean abundance of phytoplankton in Daya Bay ranged from 3.59×10^5 to 2.03×10^7 cells m^{-3}. Phytoplankton abundance peaked in summer with 2.84×10^8 cells m^{-3} at station S8 and was lowest in spring with 3.41×10^4 cells m^{-3} (1/9044) at station S10.

Table 1 and Figs 1–5 give the temporal trends of the major water quality and phytoplankton parameters at the selected monitoring stations in Daya Bay during the study period from 1999 to 2002.

A statistically significant decreasing trend in pH was observed at all stations (Fig. 2a); this result was similar to the research results from the Port Shelter of Hong Kong (Yung et al. 2001). With the exception of S5 near the nuclear power plants, the water temperature at all stations increased from 1999 to 2001(Fig. 2b); this could have been affected by Global Change. Climate change scenarios for the year 2100 indicate a significant increase in air temperature (by 2.3–4.5°C), which would constitute the greatest threat to the Bay's environment (Kont et al. 2003). The temperatures in 2002 were almost the lowest at all stations – this may have been due to the El Niño phenomenon (Chao et al. 1996, Chen et al. 2005).

All nutrient parameters remained relatively unstable during the study period. The ratios of TIN to phosphorus (P) and silicon (Si) decreased at the beginning and then increased, except at S8 and S10 (Fig. 4a), and the ratios of silicon (Si) to phosphorus (P) increased, except at S7 (Fig. 4b). This showed that although the concentrations of TIN and P did change, there were significant decreasing trends at all stations (Fig. 2a,b). The silicon levels increased somewhat at five stations from 1999 to 2002. The levels of chlorophyll a decreased at first, then increased, except at S8 (Fig. 4c), where the value was higher than at the other stations in Daya Bay from 1999 to 2002. The bacillariophyta were the dominant phytoplankton species in Daya Bay (Wang et al. 2004). Phytoplankton levels tended to decrease from 1999 to 2002 (Fig. 5). The mean density of phytoplankton at station S5 was almost the lowest from 1999 to 2002 (Fig. 5g). The warm waste-water was one of the factors that could directly influence the density of phytoplankton in Daya Bay (Zheng et al. 2001). Assuming the temperature of the waste water from the nuclear power plant to be 1°C warmer than the surrounding seawater, then the area of Daya Bay affected by this warmer water was about 5.51 km^2 (Han 1991). The highest phytoplankton density was at station S8 near Aotou harbor and the cage culture areas in the north-western part of Daya Bay. This result is connected with the higher nutrient levels near station S8; similar results were obtained at stations S3 and S4. Nutrients and temperature could play an important role in determining the density of phytoplankton in Daya Bay (San Diego-McGlone et al. 1995, Edwards et al. 2003). Shtereva et al. (1999) drew attention to the high level of nutrients and the capacity of the ecosystem required to produce and maintain a high phytoplankton biomass.

Bivariate correlations between phytoplankton density and major physical and nutrient factors were calculated for all stations. The density of phytoplankton at all stations were positively correlated with temperature, salinity, DO, pH, and the ratios of TIN to PO_4-P, NH_4-N, NO_3-N, TIN and PO_4-P; it was negatively correlated with Secchi disk transparency, turbidity, and the ratios of SiO_3-Si to PO_4-P, SiO_3-Si and NO_2-N. According to the results of correlation analysis, not only pH, TIN and the ratio of TIN to PO_4-P, but also temperature, DO and pH could play an important role in determining the density of phytoplankton in Daya Bay (Håkanson & Boulion 2003). These results were similar to the ones obtained in the Port Shelter, Hong Kong (Yung et al. 2001) and to the succession of dominant phytoplankton species at Dapeng Cove in Daya Bay in spring 2000 (Wei et al. 2003).

Cluster analysis based on the major water quality parameters measured (the first column of Table 2) revealed that the 12 monitoring stations could be grouped into three clusters. Flexible-Beta Cluster Analysis was applied, and the corresponding dendrogram using the Flexible-beta method between groups and transforming measures with Flexible-Beta Distance is shown in Fig. 6. Cluster I consisted of stations S1, S2, S7 and S11 in the southern part of Daya Bay. Cluster II consisted of stations S5, S6, S9, S10 and S12 in the central and north-eastern parts of Daya Bay. Cluster III consisted of

Table 2. Factor loadings (after varimax rotation) of the first two factors for clusters I, II and III

Parameter	Cluster I		Cluster II		Cluster III	
	FI	F2	F1	F2	F1	F2
temperature [°C]	0.01249	0.99037	0.16669	0.49016	0.87157	0.49027
salinity [ppt]	0.12846	0.02911	0.92371	−0.3071	0.26872	−0.96322
DO [mg dm^{-3}]	0.19712	0.97137	−0.85093	0.25263	0.15601	0.98775
pH	0.07382	0.78155	−0.90136	−0.35794	0.62899	0.77741
Secchi [m]	0.90952	0.33258	0.23706	−0.94526	0.50374	−0.86386
turbidity [NTU]	0.06313	−0.98470	0.29705	0.88071	0.17229	0.98505
NH_4-N [μmol dm^{-3}]	−0.81998	−0.57232	−0.01719	0.28781	−0.86639	0.49936
NO_2-N [μmol dm^{-3}]	−0.61670	−0.18310	0.98970	−0.09451	−0.80358	0.59520
NO_3-N [μmol dm^{-3}]	0.72416	0.01289	0.92253	0.26891	0.90624	−0.42277
TIN [μmol dm^{-3}]	0.87689	−0.16412	0.73706	0.31524	0.98197	−0.18905
PO_4-P [μmol dm^{-3}]	−0.99369	0.01984	0.73275	−0.22751	−0.99800	−0.06318
SiO_3-Si [μmol dm^{-3}]	−0.19294	0.29027	0.81653	−0.23589	−0.98767	−0.15652
TIN/PO_4-P	0.98732	−0.11482	0.03293	0.92628	0.99951	0.03141
SiO_3-Si/PO_4-P	0.45590	0.26096	−0.60317	0.19426	0.99274	−0.12029
BOD_5 [mg dm^{-3}]*	0.89595	−0.36263	0.44634	−0.75797	0.64454	−0.76457
chlorophyll a [mg m^{-3}]	−0.23591	0.95703	−0.33466	−0.12719	−0.12588	0.99205
cumulative % of variance explained	39.40	32.61	42.60	25.33	56.90	43.10

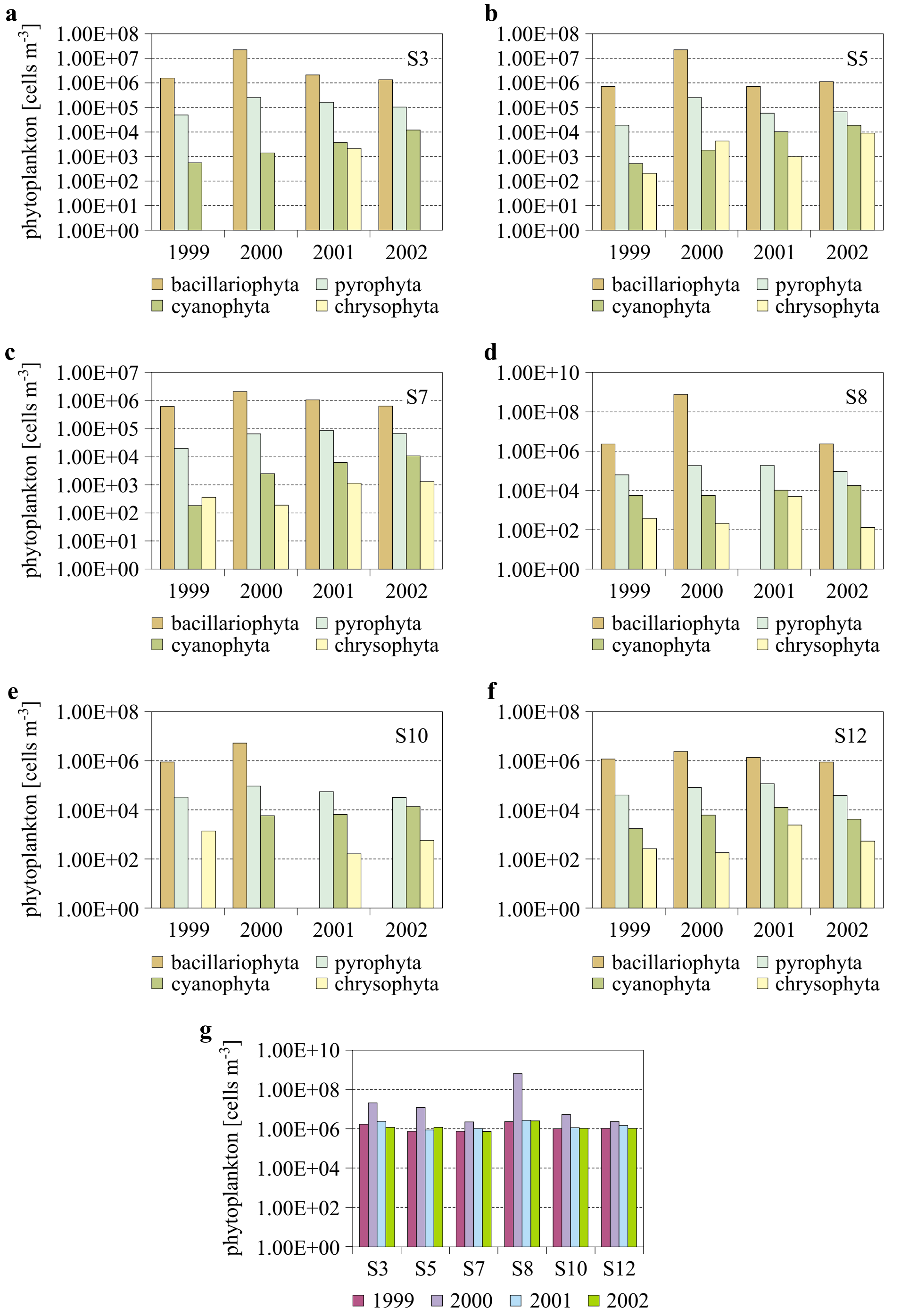

Fig. 5. Changes in the annual average phytoplankton levels at six stations in Daya Bay from 1999 to 2002 [cells m^{-3}]

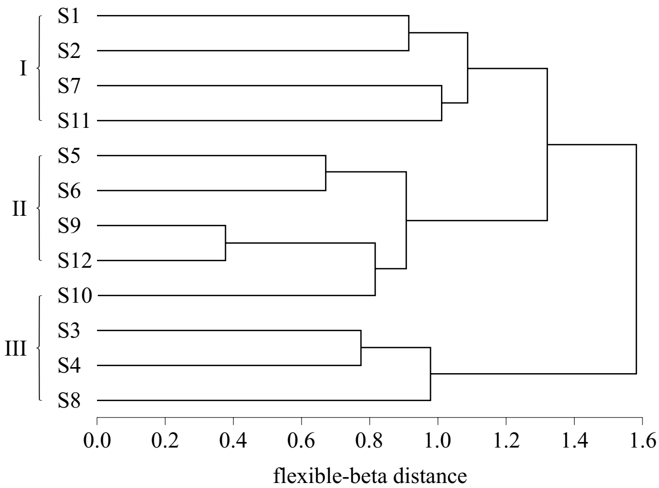

Fig. 6. Results of the Flexible-beta method for cluster analysis showing the three clusters (I, II, III) of stations

stations S3, S4 and S8 in the cage culture areas of the south-western part of Daya Bay and the north-western part near Aotou harbor. The results of the Flexible-beta method for cluster analysis also reflect the different functional areas in the seawater of Daya Bay, such as near the nuclear power plant area and the cage culture areas.

Factor analysis techniques were used to investigate the various factors that are present in each of the three clusters identified by cluster analysis. Factors were identified by the principal component method with varimax rotation (using PROC X16 of the SAS system). Eigenvalues and cumulative proportions of the correlation matrix are presented in Table 2. In each cluster, more than 60% of the data variance could be explained by the first two principle components. In general, pH, NO_3-N, TIN and TIN/PO_4-P are the most important factors in differentiating the characteristics of the three clusters, as is evident from the factor loadings. Cluster I with factor 1 (positive loadings for Secchi, NO_3-N, DIN, TIN/PO_4-P and BOD_5) and factor 2 (positive loadings for temperature, DO, pH and chlorophyll a) together accounted for 32.61% of the data variance. Cluster II with factor 1 (positive loadings for NO_2-N, NO_3-N, TIN, PO_4-P, SiO_3-Si, and chlorophyll a) and factor 2 (positive loadings for turbidity, TIN/PO_4-P and chlorophyll a) together accounted for 25.31% of the data variance. Cluster III with factor 1 (positive loadings for temperature, pH, Secchi, NO_3-N, TIN, TIN/PO_4-P, SiO_3-Si/PO_4-P and BOD_5) and factor 2 (positive loadings for DO, pH, turbidity, NO_2-N and chlorophyll a) together accounted for 43.10% of the data variance.

Table 2 shows the relevant factor loadings in three clusters. It should be noted that NO_3-N and TIN/PO_4-P were important factors among the stations in the three clusters, whereas concentrations of individual nutrient factors (i.e. NO_2-N, NO_3-N, TIN, PO_4-P and SiO_3-Si) were more important in cluster II. These results differed from those obtained at the Port Shelter, Hong Kong (Yung et al. 2001), which showed that nutrient ratios (i.e. TIN to TSi and TP to TSi) were apparently the more important factors among the stations in the different clusters.

In order to investigate the association between physicochemical and biological variables, canonical correlation analysis was carried out for S5, S7 and S8, for which phytoplankton data were available. The proportion of variation explained by the canonical variable and the correlation coefficients between individual parameters and their canonical variables for stations S5, S7 and S8 are shown in Table 4.

At S5 near the DNPP and LNPP in the south-western part of Daya Bay, three pairs of significant canonical variables were identified, which accounted for 100% of the variations. The correlations between the physicochemical/biological parameters and their corresponding factors are presented in Table 3. The first canonical variable of the physicochemical parameters involved a contrast between DO, pH, NO_2-N, TIN, PO_4-P, TIN/PO_4-P and SiO_3-Si/PO_4-P. It was strongly associated with the density of phytoplankton. The second canonical variable was chiefly associated with temperature, salinity, Secchi, turbidity, NH_4-N, NO_2-N, NO_3-N, TIN, SiO_3-Si, SiO_3-Si/PO_4-P and the density of phytoplankton except bacillariophyta. The third canonical variable involved a contrast between temperature, DO, NO_3-N and the density of phytoplankton except cyanophyta.

Table 3. First four eigenvalues ($\lambda_1 - \lambda_4$) of the correlation matrix of the clusters using the principle component method in factor analysis

Cluster	Eigenvalues (Proportion)			
	λ_1	λ_2	λ_3	λ_4
cluster I	6.76812668 (0.4230)	5.70393888 (0.3565)	3.52793443 (0.2205)	0
cluster II	7.24152240 (0.4526)	4.76995531 (0.2981)	3.19852828 (0.1999)	0.78999401 (0.0494)
cluster III	9.80026128 (0.6125)	6.19973872 (0.3875)	0	0

At S7, in the southern part of Daya Bay, three pairs of significant canonical variables were also identified, which accounted for 100% of the variations. The correlations between the physicochemical/biological parameters and their corresponding factors are presented in Table 4. The first canonical variable of the physicochemical parameters consisted of a contrast between pH, Secchi, turbidity, NH_4-N, NO_3-N, NO_2-N, TIN, SiO_3-Si, TIN/PO_4-P, SiO_3-Si/PO_4-P and the density of cyanophyta. The second canonical variable was associated chiefly with temperature, DO, turbidity, NO_2-N, PO_4-P, TIN/PO_4-P and the density of phytoplankton except bacillariophyta. The third canonical variable involved a contrast between temperature, DO, salinity, Secchi, NH_4-N, PO_4-P, SiO_3-Si, chlorophyll a and the density of phytoplankton except pyrophyta and cyanophyta.

At S8 in the north-western part of Daya Bay near Aotou harbor, three pairs of significant canonical variables were also identified, which accounted for 100% of the variations. The correlations between the physicochemical/biological parameters and their corresponding factors are presented in Table 3. The first canonical variable of the physicochemical parameters consisted of pH, turbidity, NO_2-N, NO_3-N, TIN, SiO_3-Si, TIN/PO_4-P, SiO_3-Si/PO_4-P and the density of pyrophyta and cyanophyta. The second canonical variable was associated chiefly with temperature, DO, turbidity, NH_4-N, chlorophyll a and densities of bacillariophyta and others. The third canonical variable involved a contrast between temperature, salinity, pH, Secchi, PO_4-P, SiO_3-Si/PO_4-P and the density of phytoplankton except others, such as xanthophyta and chrysophyta.

The first canonical variable of the physicochemical parameters could be accounted for by different factors, whereas the second canonical variable was accounted for by the different factors in S5, S7 and S8. The third canonical variable was positively and negatively associated with different factors. With respect to the biological parameters, the first canonical variables all consisted of the density of cyanophyta. The second canonical variables were all positively associated with the density of the other, minor algal groups.

4. Summary

In summary, the results of the present study indicate that the mean abundances of phytoplankton at all stations were correlated positively with temperature, salinity, DO, pH, the ratio of TIN to PO_4-P, NH_4-N, NO_3-N, TIN and PO_4-P but negatively with Secchi, turbidity, SiO_3-Si to PO_4-P, and SiO_3-Si and NO_2-N by calculation with bivariate correlations. All stations could be grouped into three clusters using Flexible-Beta Cluster Analysis. Cluster I consisted of stations S1, S2, S7 and S11 in the southern and north-eastern parts of Daya Bay. Cluster II consisted of stations S5, S6, S9, S10 and S12 in the central and north-eastern parts of Daya Bay. Cluster III consisted of stations S3, S4 and S8, which were situated in the

Table 4. Results of canonical correlation analysis for stations S5, S7 and S8. Correlations between PHYCHEM, BIO and their canonical variables

Canonical variable	S5 Canonical correlation			S7 Canonical correlation			S18 Canonical correlation		
1	1.000000			1.000000			1.000000		
2	1.000000			1.000000			1.000000		
3	1.000000			1.000000			1.000000		
	Phychem 1	Phychem 2	Phychem 3	Phychem 1	Phychem 2	Phychem 3	Phychem 1	Phychem 2	Phychem 3
temperature	0.4567	0.7191	0.5237	−0.4886	0.6100	−0.6238	0.0017	0.5732	0.8194
salinity	−0.4893	0.8558	0.1680	0.0116	−0.0714	0.9974	−0.0028	0.4084	−0.9128
DO	−0.6483	0.4294	−0.6288	0.1748	0.8477	0.5009	−0.0012	−0.9227	−0.3854
pH	−0.9447	0.2556	0.2056	−0.7863	0.1871	−0.5889	−0.5281	0.4374	0.7279
Secchi	−0.4782	0.8720	0.1046	0.6111	0.3375	0.7160	0.4964	−0.1956	−0.8458
turbidity	−0.1593	−0.9870	−0.0193	−0.5107	−0.8597	−0.0117	−0.5941	−0.8034	−0.0394
NH_4-N	0.4620	−0.7438	−0.4831	−0.7004	0.0662	−0.7107	0.2693	0.9410	0.2048
NO_2-N	0.5740	−0.7853	0.2322	−0.5131	−0.7708	−0.3777	−0.9259	−0.0714	0.3711
NO_3-N	−0.2664	0.7885	0.5544	−0.9344	0.2848	−0.2139	0.8261	0.4816	−0.2928
TIN	0.6219	−0.7569	0.2006	−0.7509	−0.4433	−0.4896	−0.7405	0.4913	0.4585
PO_4-P	0.9937	−0.0712	−0.0869	−0.3308	0.5611	−0.7587	0.4385	−0.4102	0.7997
SiO_3-Si	0.1187	0.9578	0.2618	0.5231	−0.1205	−0.8437	0.9401	−0.1607	−0.3007
TIN/PO_4-P	−0.9406	0.0029	0.3395	−0.5692	−0.7969	0.2024	−0.8987	0.4054	−0.1674
SiO_3-Si/PO_4-P	−0.6849	0.6255	0.3737	0.9223	−0.2500	−0.2948	0.5747	−0.0586	−0.8162
	BIO1	BIO2	BIO3	BIO1	BIO2	BIO3	BIO1	BIO2	BIO3
chlorophyll a	0.0000	−1.0000	0.0000	0.0000	0.0000	1.0000	0.0448	−0.9852	0.1656
bacillariophyta	0.7503	−0.0925	0.6546	0.2623	−0.0798	−0.9617	0.2086	−0.6768	0.7059
pyrophyta	−0.5339	0.6271	0.5672	0.3824	0.8572	−0.3449	0.6894	0.2871	0.6651
cyanophyta	−0.6489	0.6875	0.3260	0.5701	0.6878	0.4494	0.5225	−0.1500	−0.8394
others	−0.5182	0.6352	0.5727	0.2439	0.7524	0.6119	0.4208	0.8766	0.2335

PHYCHEM, BIO = physicochemical and biological.

cage culture areas in the south-western part of Daya Bay and in its north-western part near Aotou harbor. The results also suggest that nutrients and phytoplankton are good environmental indicators, which can rapidly reflect the changing water quality in Daya Bay. This has been the first attempt to analyze the water quality and phytoplankton characteristics in Daya Bay by multivariate statistics on the basis of research data obtained in the Bay. The results of multivariate statistical analysis show that temperature, dissolved oxygen, NH_4-N and NO_3-N may also be playing an important role in determining the density of phytoplankton in Daya Bay.

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