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Hypereutrophication in Ngau Mei Hoi Bay, Hong Kong

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ABSTRACT

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Investigations into eutrophication of Ngau Mei Hoi Bay, Hong Kong, were carried out in July and December 1996. The results show that Ngau Mei Hoi Bay can be classified as hypereutrophic. During summer phytoplankton blooms (average chlorophyll a = 33.96 $\mu g\ L^{-1}$), high oxygen saturation (up to 145.3%), high pH (7.8–8.4), and nutrient depletion (mean NO_3+NO_2 = 0.89 $\mu g\ L^{-1}$) at the surface in association with hypoxic (dissolved oxygen concentration was down to 0.9 mg L^{-1}), low pH (down to 4.9), and high nutrient (mean NO_3+NO_2 = 96.28 $\mu g\ L^{-1}$) conditions at the bottom layer were observed. This typical phenomenon of eutrophication resulted from nutrient enrichment by anthropogenic activities, water column stratification formed by spreading of the Pearl River plume at the surface, and outer shelf water intrusion at the bottom. The perniciousness of the hypereutrophication and future monitoring needs for environmental management are also discussed.

ADDITIONAL INDEX WORDS: *Water column stratification, water quality, hypoxia, anoxia, bottom low pH, bottom high nutrient concentration, upper layer phytoplankton bloom, Hong Kong coast, Pearl River estuary.*

INTRODUCTION

Harmful algal blooms and red tides have become an increasing problem in coastal zones and estuaries, killing invertebrates and both wild and cultured stocks of animals. A primary cause of red tides is believed to be eutrophication of estuaries and coastal zones, resulting from excessive nutrient inputs from the land and excessive growth of aquatic plants. Because the phenomenon of eutrophication has significant negative socioeconomic consequences, it has been receiving increasing attention from scientists (HARDING, DEGOBBIS, and PRECALI, 1996; NIXON, 1995), as well as coastal resource management and environmental protection agencies (SOA 2001). In the U.S.A. in 1992, an Estuarine Eutrophication Survey was initiated by Ocean Resources Conservation and Assessment, U.S.A. (ORCA), aimed at comprehensively assessing the scale and scope of nutrient enrichment and eutrophication in the National Estuarine Inventory (BRICKER *et al.*, 1999; NOAA, 1998). In China since the early 1980s, investigations on coastal and estuarine eutrophication have been carried out for the Bohai Sea (ZHOU and DONG, 1983); the Hangzhou Bay (DELFT-HYDRAULICS, 1995); the Pearl River estuary (TAN, PENG, and WANG, 1993); and Hong Kong coastal waters, especially Mirs Bay (BINNIE CONSULTANTS LIMITED, 1995), Tolo Harbor (CHUA *et al.,* 1995), Port Shelter (YUNG *et al.,* 2001), *etc.*

In Hong Kong, most coastal ecosystems receive in excess of two million tons of wastewater discharges directly from urbanized catchments and domestic, municipal, livestock, and industrial sources via streams and river water runoffs (CHUA, 1999). This huge discharge results in excessive nutrient concentration with high eutrophic potential, development of algal blooms and the risk of red tide occurrences.

Ngau Mei Hoi Bay is a semienclosed embayment in the northeastern territories of Hong Kong. It is bordered by the Sai Kung Peninsula on the north, the Clear Water Bay on the western and southwestern sides, and the Kau Sai Chau Island on the eastern and northeastern sides (Figure 1). Its average depth is about 10 m, with a maximum depth of 27 m near the bay mouth. The bay opens to the sea southeastward and is sheltered from currents and waves by Shelter Island and several other small islands, resulting in a decrease in the rate of tide variation. Along the coast of the bay are several big towns with large populations, especially Sai Kung on the northwest side and Hong Kong University of Sciences and Technology on the western side. Around the catchment of the bay, human activities such as agriculture,

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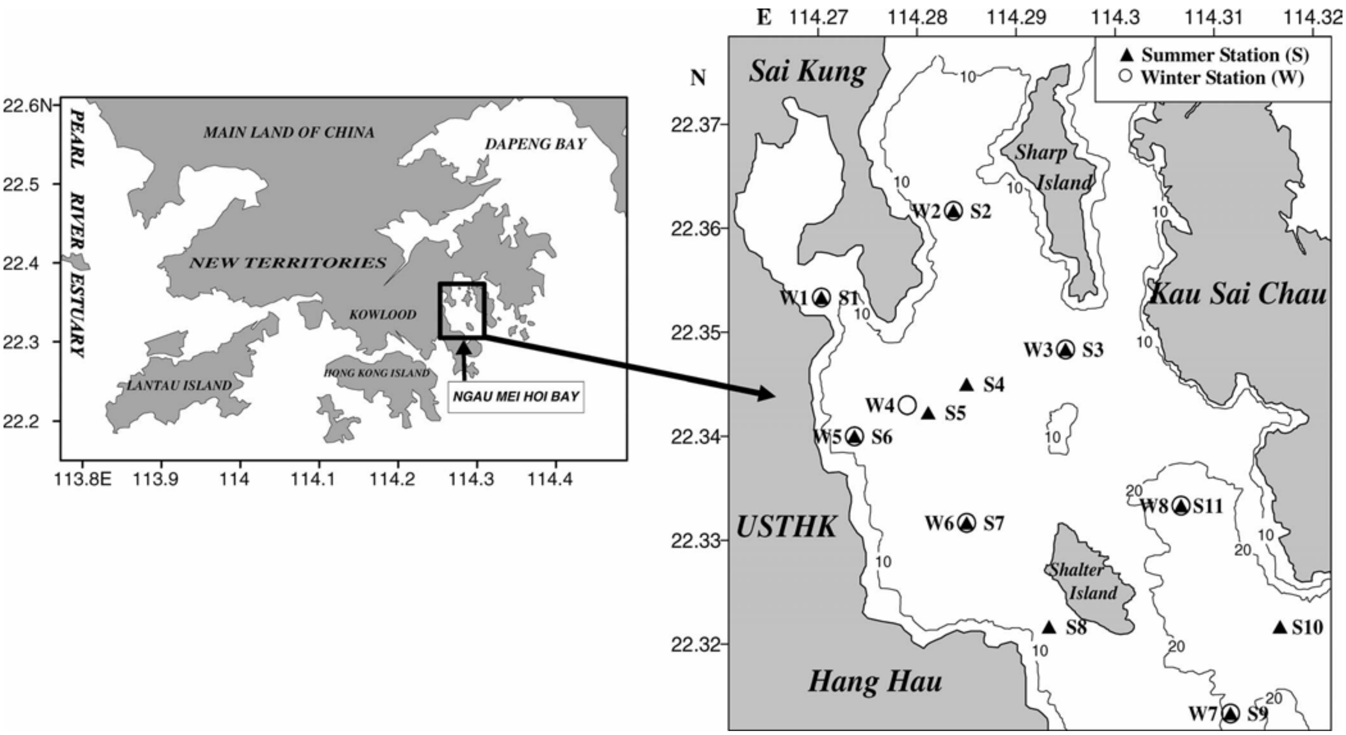

Figure 1. Topography of the Ngau Mei Hoi Bay and locations of the sampling stations during 1996.

fishing, fish farming, water sports, recreation, *etc.* are on the rise, posing serious challenges to the environmental quality of the bay.

Although the water quality of the coastal ecosystems of Hong Kong have been monitored for many years (EPDHK, 2000), studies on the eutrophication dynamics of the bays of Hong Kong are still very rare (LEE and AREGA, 1999). This study, a component of a physico-chemico-biological coupling project, conducted in 1996, was aimed at understanding the eutrophication status of Ngau Mei Hoi Bay, and the mechanisms leading to eutrophication. We use these results to recommend activities that would include additional or improved water quality monitoring in Ngau Mei Hoi Bay and, with hope, in other bays with similar situations.

MATERIAL AND METHODS

The area surveyed is located between 22°18′ and 22°22′ N and 114°16′ and 114°19′ E (Figure 1). Water depth ranges from less than 10 m at the head of the bay to more than 20 m near the Bay mouth where the sea floor deepens to the southeast.

Two cruises were conducted, one in July and one in December 1996. Eleven stations in July and eight stations in December were sampled along two transects to obtain a quasi-synoptic view of the bay area. At these stations, seawater samples were obtained in Niskin bottles from the surface and at depths of 2, 5, and 10 m and close to the bottom for the determination of chlorophyll *a* (Chl *a*), suspended solids (SS), and nutrient (NO_3+NO_2) and PO_4 concentrations. Vertical profiles of seawater temperature (*T*), conductivity, turbidity, pH, and dissolved oxygen (DO) and its saturation (O_2%) were measured with a multiparameter water quality monitor (model YSI 6000) with the precision for each variable being ±0.1°C for temperature; ±1% of the reading, or 0.1, for salinity (S); ±0.02 m for depth; ±5% of the reading for turbidity; ±0.2 for pH; and ±0.2 mg L^{-1} for DO. In addition, the transparency of seawater was measured with a Secchi disk.

Suspended solids were measured gravimetrically (STRICKLAND and PARSONS, 1972). Euphotic depth was estimated from Secchi disk readings (PLOOLE and ATKINS, 1929). Nitrate plus nitrite (NO_3+NO_2) and phosphate (PO_4) were analyzed by standard spectrophotometric methods (STRICKLAND and PARSONS, 1972) with an automatic analyzer (Lachat Instruments). Phytoplankton pigments (Chl *a* and phaeopigments) were measured by the acetone (90%) extraction fluorescence method according to HOLM-HANSEN *et al.* (1965) with a Turner Designs fluorometer, model AU 10.

RESULTS

Because the distribution patterns of nearly all the parameters for the two transects, western and eastern, were similar, we have chosen to provide the profiles from only the western transect.

Hydrological Features

During summer, the water column was stratified in the whole bay. The thermocline was located between 6 and 10 m,

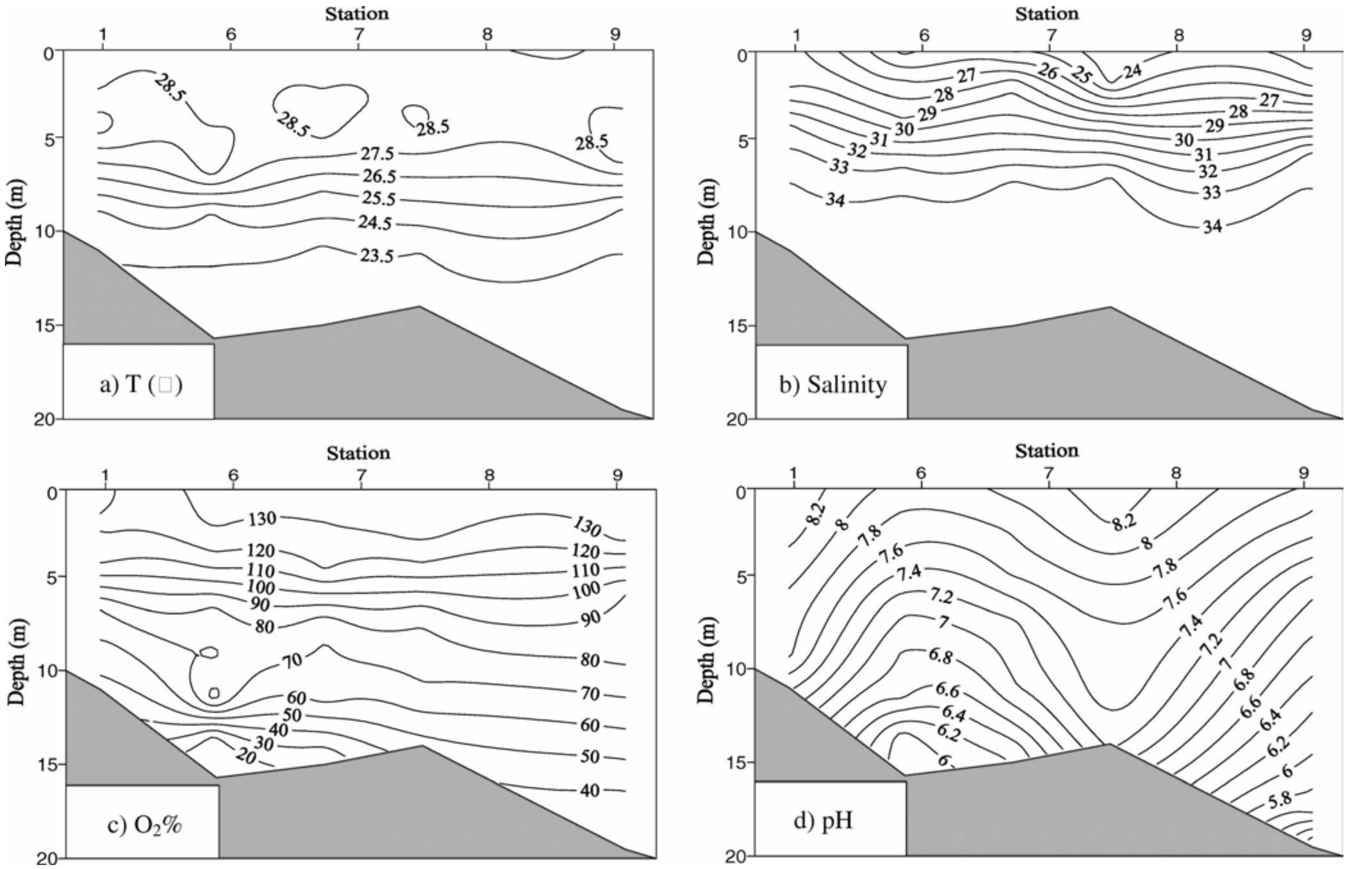

Figure 2. The transects of temperature (a), salinity (b), oxygen saturation (O_2%) (c), and pH (d) in the Ngau Mei Hoi Bay, Hong Kong, during July 1996, showing strong stratification of water column parameters during summer.

with a temperature range from 24°C to 28°C; the halocline was above 7 m, with a salinity range from 34 to 24. The less saline (average 24.65) and warm (average 28.13°C) water was present at the surface layer toward the southeast, whereas at the bottom layer, cold (average 23.02°C) and saline (average 34.39) water intruded from the southeast (Figures 2a, 2b). The horizontal gradients of temperature and salinity were small at both surface and bottom layers. During winter, no thermal and saline stratification occurred because of relatively low solar heating and the presence of strong vertical mixing (Figure 4a, 4b).

Suspended Solids and Transparency

The average SS concentration at the surface was higher in summer (9.1 mg L^{-1}) than in winter (2.6 mg L^{-1}) and higher at the bottom than at the surface in both seasons (Table 1). The maximum concentrations were encountered at station 11 (12.4 mg L^{-1}) in summer and at station 2 (5.2 mg L^{-1}) in winter. As a result of higher SS concentrations in summer, average transparency was lower in summer (Secchi depth = 2.7 m) than in winter (Secchi depth = 3.2 m, Table 1).

Water Chemistry

Along with the stratification of the water column in summer, the distribution of all the chemical indices, such as DO, O_2% (Figure 2c), pH (Figure 2d), nutrients (*e.g.,* NO_3+NO_2; Figure 3a), and PO_4 (Figure 3b), were vertically stratified. Dissolved oxygen concentrations ranged from 7.7 to 9.9 mg L^{-1} (average 9.04 mg L^{-1}) at the surface and from 0.9 to 3.7 mg L^{-1} (average 2.23 mg L^{-1}) at the bottom (Table 1), with increasing gradients from the bay head to the bay mouth at both surface and bottom layers; O_2% ranged from 116.2% to 145.3% (average 132.8%) at the surface and from 12.5% to 54.3% (average 33.3%) at the bottom (Table 1), with the same horizontal distribution patterns as those of DO concentration. Averaged values for both oxygen measurements at the bottom were about 25% of the values at the surface. The lowest values (DO < 1.3 mg L^{-1} and $O_2\% < 25\%$) were encountered at the bottom of stations 2, 5, and 6. The pH values ranged from 7.8 to 8.4 (average 8.1) at the surface and 4.9 to 7.8 (average 6.7) at the bottom (Table 1). The lowest values of pH at the bottom were encountered at stations 6 (5.92) and 9 (4.94). NO_3+NO_2 concentration ranged from 0 to 8.0 μg L^{-1} (average 0.89 μg L^{-1}) and mostly could not be detected at the

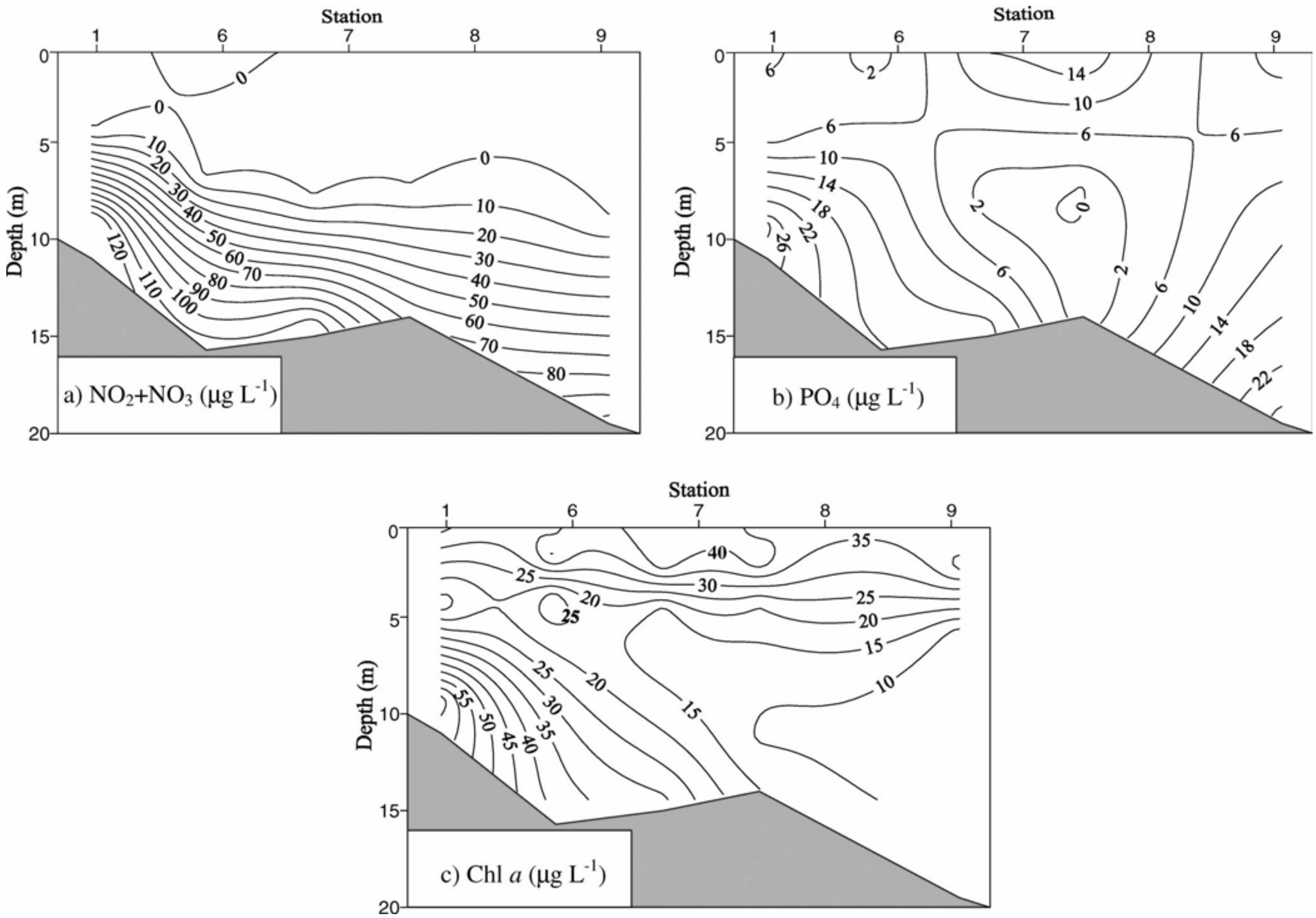

Figure 3. The transects of NO_2+NO_3 (a), PO_4 (b), and Chl *a* concentrations (c) in the Ngau Mei Hoi Bay, Hong Kong, during July 1996, showing strong stratifications of the water column parameters during summer.

surface; it ranged from 64.50 to 139.50 μg L^{-1} (average 96.28 μg L^{-1}) at the bottom (Table 1), with the average value being about 108 times higher at the bottom than at the surface (Figure 3a). Phosphate concentrations ranged from 0 to 28.0 μg L^{-1} (average 8.11 μg L^{-1}) at the surface and 0 to 32.0 μg L^{-1} (average 19.83 μg L^{-1}) at the bottom (Figure 3b). The average value was about 2.5 times higher at the bottom than at the surface.

In winter, vertical distributions of all the chemical parameters were relatively uniform (Figures 4a–c and 5a–c), which resulted from the absence of stratification of the water column. Dissolved oxygen concentration ranged from 5.3 to 7.6 mg L^{-1} (average 6.3 mg L^{-1}) at the surface and 5.7 to 7.3 mg L^{-1} (average 6.4 mg L^{-1}) at the bottom (Table 1). Oxygen saturation ranged from 70.0% to 101.7% (average 83.9%) at the surface and 76.2% to 98.1% (average 86.2%) at the bottom. With a distribution pattern reverse that in summer, decreasing gradients of both DO and O_2% from the bay head to the bay mouth were present. Nitrate plus nitrite concentration ranged from 34 to 228 μg L^{-1} (averaged 127.15 μg L^{-1}) at the surface and 17 to 261 μg L^{-1} (averaged 103.25 μg L^{-1}) at the bottom. In contrast to oxygen, the gradient of NO_3+NO_2 concentration increased from the bay head to the bay mouth. Phosphate concentrations ranged from 15 to 31 μg L^{-1} (average 18.25 μg L^{-1}) at the surface and 15 to 26 μg L^{-1} (average 19.0 μg L^{-1}) at the bottom, a similar horizontal distribution pattern as was found for NO_3+NO_2.

Chlorophyll *a*

In summer, Chl *a* concentration varied from 29.19 to 38.27 μg L^{-1} at the surface (average 33.96 μg L^{-1}) and from 5.22 to 56.10 μg L^{-1} at the bottom (average 22.58 μg L^{-1}; Table 1). In general, surface Chl *a* concentrations were higher in the middle area of the bay. In the deeper layers, Chl *a* concentrations were higher in the western and northwestern areas, but decreased toward the bay mouth. In general, the high values were above 5 m with Chl *a* concentrations in excess of 20 μg L^{-1}, except at the bay head (station 1), where Chl *a* concentration was still high at the bottom layer (Figure 3c).

During winter, Chl *a* concentration ranged from 1.29 to

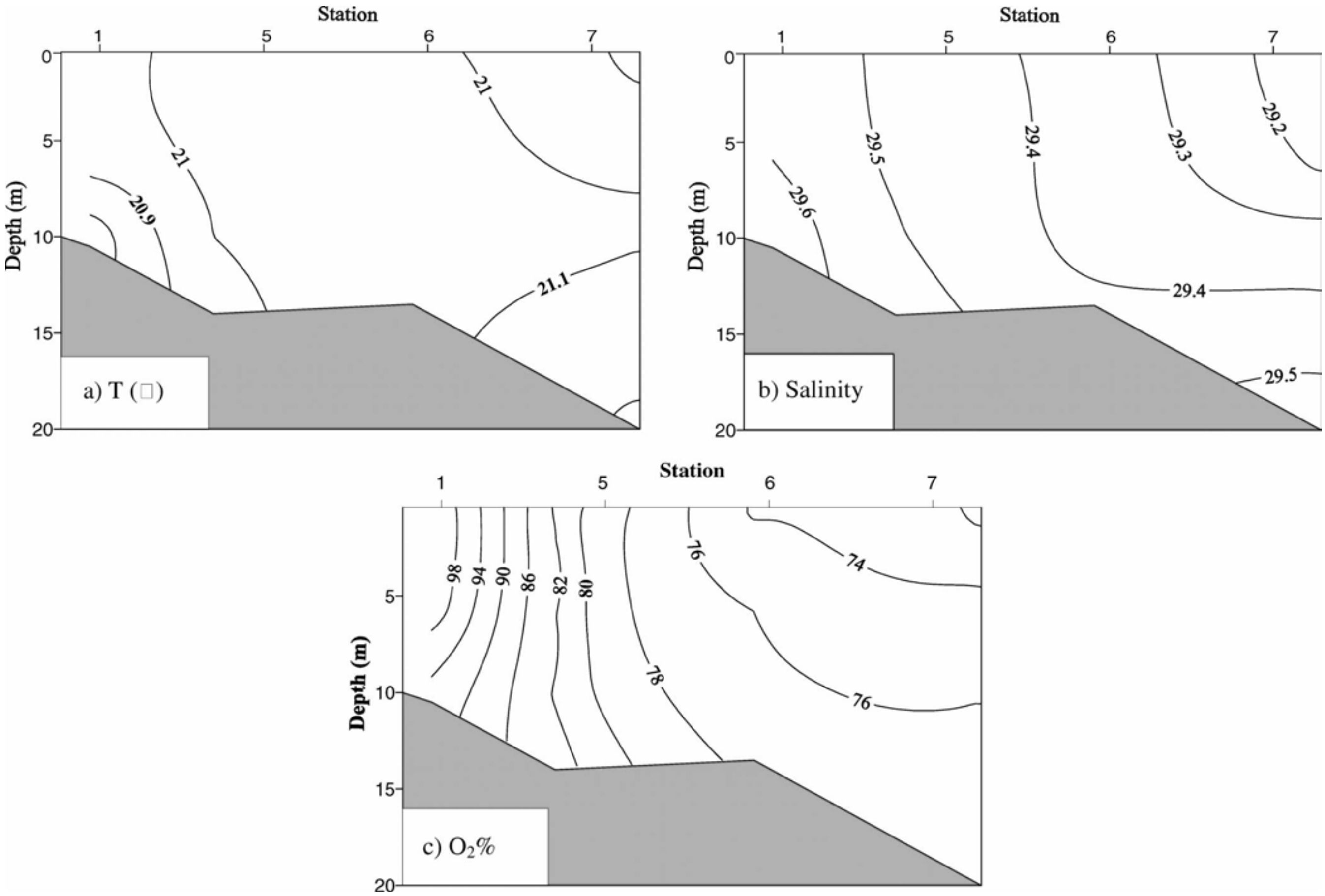

Figure 4. The transects of temperature (a), salinity (b), and oxygen saturation (O_2%) (c) in the Ngau Mei Hoi Bay, Hong Kong, during December 1996, showing vertical homogeneity of the water column parameters during winter.

Table 1. *Water quality data of Ngau Mei Hoi Bay, Hong Kong, in 1996.*

Parameter*	Oligotrophic Water†	Eutrophic Water†	Hypereutrophic Water†	July 1996		December 1996	
				Surface	Bottom	Surface	Bottom
T (°C)				28.14 ± 0.23	23.02 ± 0.29	21.01 ± 0.06	21.05 ± 0.17
S				24.65 ± 1.46	34.39 ± 0.08	29.56 ± 0.16	29.58 ± 0.13
SD (m)				2.7 ± 0.2		3.2 ± 0.5	
ED (m)				8.6 ± 0.6		10.2 ± 1.6	
SS (mg L^{-1})				9.1 ± 2.3	11.7 ± 0.1	2.6 ± 0.6	3.1 ± 1.3
pH	7.5~8.4	7.3~8.8	6.5~9.0	7.8~8.4	4.9~7.8		
DO (mg L^{-1})	<5	<4	<3	7.7~9.9	0.9~3.7	5.3~7.6	5.7~7.3
				9.04 ± 0.58	2.46 ± 0.98	6.29 ± 0.82	6.45 ± 0.63
O_2 (%)	80~100	30~80	100~200 (surface) 0~30 (bottom)	116.2~145.3	12.5~54.3	70.0~101.7	76.2~98.1
				132.8 ± 8.3	33.3 ± 15.2	83.9 ± 11.8	86.2 ± 8.9
TIN (μg L^{-1})				0.89 ± 2.67‡ (NO_3 + NO_2)	96.28 ± 23.09‡ (NO_3 + NO_2)	127.15 ± 67.69 (NO_3 + NO_2)	103.25 ± 93.58 (NO_3 + NO_2)
PO_4 (μg L^{-1})				8.11 ± 9.81‡	19.83 ± 9.85‡	18.25 ± 5.41	19.0 ± 5.58‡
Chl *a* (μg L^{-1})	<1	1~10	10~200	33.96 ± 2.49	22.58 ± 18.46	5.43 ± 2.26	4.61 ± 1.07

* SD = Secchi disk; ED = euphotic depth; SS = suspended solids; TIN = total inorganic nitrogen.
† The three trophic levels of water quality standard (Zhang *et al.,* 1994).
‡ Data obtained in the cruise of July 1998.

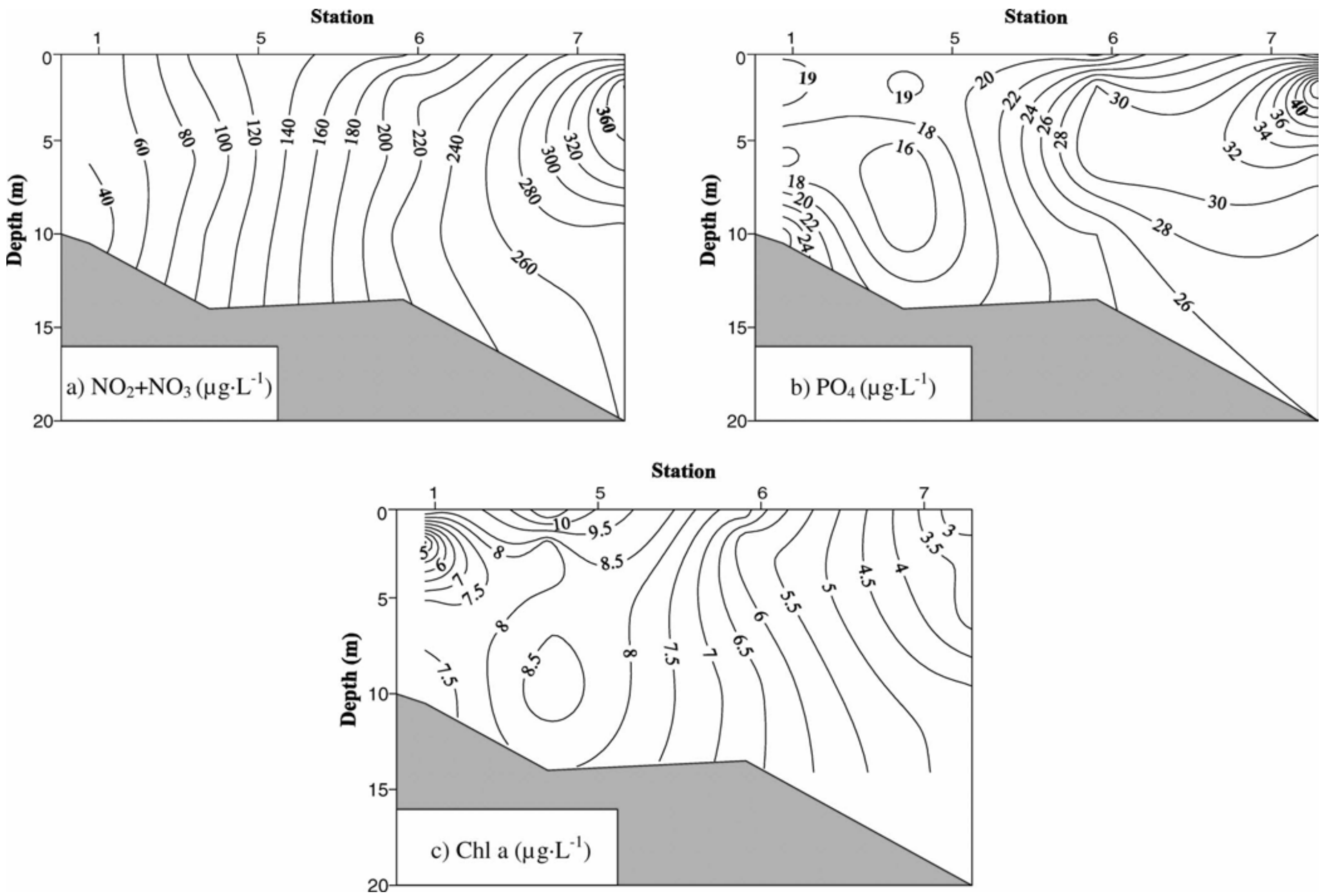

Figure 5. The transects of NO_2+NO_3 (a), PO_4 (b), and Chl *a* concentrations (c) during December 1996 in the Ngau Mei Hoi Bay, Hong Kong, showing vertical homogeneity of the water column parameters during winter.

9.16 μg L^{-1} (average 5.43 μg L^{-1}) at the surface and 3.01 to 6.08 μg L^{-1} (average 4.61 μg L^{-1}) at the bottom (Table 1). The Chl *a* concentration gradient decreased (from >6.0 to <2.0 μg L^{-1}) from the bay head to the bay mouth (Figure 5c), whereas nutrients displayed the opposite trend.

DISCUSSION

Only some pronounced and typical phenomena, such as the hypereutrophication of this bay, hypoxia, and low pH in the bottom layer during summer, are discussed, and future research and monitoring needs are also described below.

Hypereutrophication of the Studied Sea Area

Secchi disk values (SD), pH, and DO at the bottom layer; O_2% at both surface and bottom; NO_3+NO_2 concentrations at the bottom, and Chl *a* concentrations at both the surface and bottom (Table 1) in summer, compared with water quality standards prescribed in ZHANG *et al.* (1994), fell clearly into the range of hypereutrophication. The most hypereutrophic area was the western part of the bay (stations 1, 2, 5, and 6) at the bottom layer with the lowest DO concentration (0.9 mg L^{-1}), lowest O_2% (12.5%), lowest pH (<5), highest NO_3+NO_2 (139.50 μg L^{-1}) and PO_4 (32 μg L^{-1}) concentrations, and highest Chl *a* concentration (56.10 μg L^{-1}). These results are in general comparable to those in Tolo Harbor (LEE and AREGA, 1999). The NO_3+NO_2 and PO_4 in the bay studied here are slightly lower than in Tolo Harbor. The maximum Chl *a* concentration in this bay (56.10 μg L^{-1}) is comparable to that in Tolo Bay (>60 μg L^{-1} in 1989; EPDHK, 1990). In general, mean Chl *a* level above 10 μg L^{-1} can be considered unacceptably high, and such levels indicate the onset of eutrophication. Ngau Mei Hoi Bay waters, therefore, can be regarded hypereutrophic.

This hypereutrophication in all likelihood is associated with anthropogenic activities, such as dredging and dredged material disposal, around this region. Municipal and livestock waste discharges have also been a major environmental concern over the past two decades (LEE and AREGA, 1999). Although public sewers have been built surrounding bay areas since 1990, rapid urbanization, commercial-industrial activities, and a lack of legislative control around the present bay catchments produce large quantities of untreated or partially treated municipal sewage and agricultural wastes. The situation is exacerbated by increasing areas of aquaculture, village houses with poor flushing capacity, and weak water circulation within the bay.

In summer, a serious NO_3+NO_2 depletion at the surface of almost the whole bay was observed as a result of the large amounts of nutrients consumed by the phytoplankton bloom. Although high concentrations of NO_3+NO_2 were present in the deeper layers, the presence of a strong thermocline and halocline effectively prevented these nutrients from being mixed into the upper layer (Figure 2a, 2b). This surface depletion of NO_3+NO_2 suggested that our observations were at the end of a phytoplankton growth phase, when N was becoming a limiting factor to further development of the phytoplankton bloom. These observations differ from those obtained by YIN *et al.* (2000), who reported that during July 1998, a high concentration of N remained at the surface in the waters south of Hong Kong Island and in the eastern territorial waters. Their observations followed a period of prolonged rainfall, which resulted in large nitrogen inputs from the land and led to P limitation and silicon exhaustion. Our observations were undertaken during a year that can be classified as normal, when N depletion at the surface in summer would last until the onset of the typhoon season in mid-August.

Phytoplankton blooms near the surface during summer also resulted in high pH and high O_2% because of uptake of dissolved CO_2 and release of DO during photosynthesis of phytoplankton communities. In contrast, O_2% and pH decreased sharply below the thermocline (Figure 2c, 2d). A simultaneous occurrence of high Chl *a* concentration in the upper layer (Figure 3c) and low O_2% (Figure 2c) in the lower layer is a typical hypereutrophication feature.

The mechanism of stratification of the waters in this bay is complex, but basically it can be explained by the huge quantity of Pearl River discharge, which reduces the salinity of the upper layers of the waters surrounding Hong Kong, including our study area, creating a highly stratified water column. On the other hand, upwelling saline, cool, and low-oxygen outer shelf waters intrude from the bottom layer along the coastal shelf of the South China Sea, as observed previously by CHEN (1993) in the Pearl River Estuary and by HAN (1995) in the Dapeng Bay, both of which are close to our study area. The coastal upwelling of the northern South China Sea is forced by the SW monsoon during summer, the topography of the shelf sea floor, and the Coriolis inertial force, resulting in a cross-shelf and offshoreward transportation of surface water, the so-called Ekman Transport, which causes coastal upwelling of deep water into the coastal region (CHAI, XUE, and SHI, 2001).

During winter, nearly all the parameters were vertically homogeneous (Table 1), which results from surface water cooling and strong wind-induced vertical mixing of the water column.

Hypoxia and Low pH in the Bottom Layer During Summer

The water quality results obtained during summer clearly demonstrated that hypoxia is related to stratification of the water column. The hypoxic layer near the bottom was distinguished from the upper layer by temperature, ranging from 22.5°C to 24°C (Figure 2a); a salinity of 34.4 (Figure 2b); a DO concentration of <2 mg L^{-1}, and an O_2% of $<30\%$ (Figure 2c). The maintenance of stratification requires the lack of mixing forces, such as wind and tidal currents. The tidal current in the study sea area is weak, and the strong winds necessary to break the stratification until typhoon season commences are lacking.

In the bottom layer, below the euphotic zone, very little DO is produced by photosynthesis of phytoplankton, and respiration of organisms becomes the major process, consuming DO. Furthermore, on account of an increase in vertical stability of the water column, the particulate organic matter that results from photosynthesis settles out, mainly as detritus, after phytoplankton blooms. The decomposition of dead algae by bacteria near the bottom layer consumes and even depletes DO and can cause the death of benthic animals, as was observed by dive surveys in Mirs Bay (BINNIE CONSULTANTS LIMITED, 1995), the Chesapeake Bay, and the Northern Adriatic (NEWELL and OTT, 1999). As more organisms die, more oxygen is consumed. Eutrophication could thus be greatly harmful to the benthic ecosystems in our study area. Furthermore, low bottom water pH because of dissolved CO_2 and sulfide from respiration releases by organisms and decomposition of organic matter by bacteria, respectively, could seriously damage coral reefs in this region, as observed in the neighboring Mirs Bay (BINNIE CONSULTANTS LIMITED, 1995).

Future Research and Monitoring Needs

This preliminary study demonstrates that the Ngau Mei Hoi Bay is highly susceptible to eutrophication. Information on ecological consequences of eutrophication, in particular the effects of hypoxia and low pH, are still inadequate. Further research that provides a quantitative assessment of (1) the extent of the effect of eutrophication on the ecosystem, especially the structure and function of benthic communities; (2) responses on the molecular level to the degree of ecosystem eutrophication (WU, 2002); and (3) the role that heterotrophic bacteria play in hypoxia and low pH formation in this bay would provide valuable information that could help in managing coastal ecosystems. Time series observations could also aid in understanding the variation of environmental and physicobiological processes in the bay.

CONCLUSIONS

A preliminary study on water quality of the Ngau Mei Hoi Bay demonstrates that this bay can be classified as a hypereutrophic system. Typical hypereutrophic conditions (*i.e.,* the simultaneous presence of phytoplankton blooms at the surface and hypoxia and low pH at the bottom layer) was observed during summer. This hypereutrophic condition resulted from stratification of the water column, induced by the discharge and spread from the Pearl River, followed by solar heating at the surface; intrusion of oceanic water near the bottom; and anthropogenic organic inputs along the coast of the bay. Red tides and harmful algae blooms could occur easily as a result of the hypereutrophication conditions in the bay. On the other hand, benthic organisms could be killed easily by hypoxia, and coral reefs would be damaged by low pH near the bottom layer. Further detailed studies dealing with the consequences of hypereutrophication on the structure and function of ecosystems and the effects of anthropogenic activities on hypereutrophication are needed, as suggested by CLOERN (2001) in phase III of a coastal eutrophication study meant to aid in the evolution of a conceptual model and guide coastal science in the early 21st century. The future field monitoring programs will provide a stronger scientific basis for environmental management and protection in this area.

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