Study on the Dynamics of Algal Bloom and its Influence Factors in Tolo Harbour, Hong Kong

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ABSTRACT: In this paper, the semi-enclosed bay named Tolo Harbour and Channel in Hong Kong, which was frequently attacked by red tides, was used as a case study. Data sets related to marine water quality, river nutrients, and meteorological conditions recorded between 1988 and 1999 were chosen for statistical analysis. A multivariate analysis showed that algal growth, represented by the chlorophyll *a* concentration, had obvious spatial and temporal variations in the study area. The chlorophyll *a* concentration had a consistently decreasing trend from the inner part of the Harbour and surface waters to the outer part and bottom waters. The temporal variations had a markedly seasonal variation with high bioproductivity in spring and winter. There were long-term fluctuations in the chlorophyll *a* concentration with a high–low–high pattern in the study period. Nutrients and hydrological and meteorological conditions were important factors of algal bloom. Besides nitrogen, which was the most critical factor of algal bloom for the whole water body, total phosphorus in the surface waters and phosphate (PO_4) and silica (SiO_2) in the bottom waters also showed strongly positive or negative correlations with the chlorophyll *a* level. For the meteorological conditions, global solar radiation was the key factor of massive algal bloom in the study period, while rainfall and wind direction were the most important factors of seasonal variation. *Water Environ. Res.,* **76,** 2643 (2004).

KEYWORDS: Tolo Harbour, nutrients, algal bloom, hydrological and meteorological conditions, statistical analysis.

Introduction

Algal blooms occur in a variety of coastal waters with increasing frequency and intensity and wider geographic distribution. Hodgkiss and Ho (1997) summarized the relationship between phytoplankton blooms and the extent of pollution in coastal waters on a global scale, and concluded that the increase of phytoplankton blooms in coastal waters had an obvious relationship with the long-term increases in coastal nutrient levels, which were influenced by the hydrology and meteorology of a particular location, and even by some global environmental changes. Massive algal bloom results in the phenomenon of red tide, which is a kind of disastrous event in coastal waters because of the occurrence of a very high and localized concentration of microscopic marine planktonic algae. Red tide is the product of a general eutrophication of the marine ecosystem and is always associated with a high level of chlorophyll *a*. In Japan, the number of occurrences of red tide has been taken as one of the indices of changes in the level of environmental pollution since the 1980s. Red tides have been observed in Chinese coastal waters since the beginning of the last century, and have been a major problem since the 1970s. According to incomplete statistics, over 150 red tide incidents occurred along the coasts of China during the period of 1980 to 1990. There were 43 algal blooms recorded (excluding Hong Kong records) in the South China Sea at the same time period. Red tides in the South China Sea mostly occur in embayments (Qi et al., 1993). Since the early 1980s, red tides have occurred frequently in Hong Kong, and most of them occurred in the eastern waters including Tolo Harbour and Channel, Mirs Bay, and Port Shelter. Most of the red tides that occurred in Hong Kong's coastal waters were caused by non-toxic species and resulted from oxygen depletion in the water. Approximately 4% of red tide incidents were associated with fish kills. Since 1980, more than 60 red tide species have been identified in Hong Kong.

Red tides occur most frequently in spring. Some species have the greatest growth potential in the inner Tolo Harbour during spring to early summer, while other species are found to have a good growth potential from late autumn to early winter (Ho and Hodgkiss, 1993). Hodgkiss and Chan (1983), Chan and Hodgkiss (1987), and Lam and Ho (1989) reported that the eutrophication of Tolo Harbour had led dinoflagellates to replace diatoms as the dominant phytoplankton in the whole water column, and that the increasing dominance of dinoflagellates might be the major cause of the dramatic increase in red tide incidents in Tolo Harbour during the 1980s and early 1990s. Diatoms tended to dominate the assemblage in spring and summer months, and dinoflagellates were more prominent in the winter months (Chan et al., 1991).

Red tides have mostly occurred in enclosed and semienclosed bays when there is a combination of nutrient enrichment and favorable climatic and hydrological conditions. Tolo Harbour and Channel Water Control Zone (WCZ), as a semienclosed bay, has experienced the highest occurrence of red tides (toxic and nontoxic) in Hong Kong's coastal waters between 1988 and 1999. In this paper, a multivariate analysis of water quality and meteorological data recorded between 1988 and 1999 related to Tolo Harbour and Channel WCZ was carried out. The objective is to identify the factors influencing the occurrence of algal bloom, which is represented by the level of chlorophyll *a* in the water. The temporal and spatial variations and the relationships among nutrients and hydrological and meterological conditions were obtained.

Study Area, Data, and Methods

Tolo Harbour and Channel WCZ, declared the first water control zone in Hong Kong's coastal waters in 1982, is a semienclosed bay and covers an area of approximately 50 km^2 with a long channel leading to Mirs Bay, a major south-facing bay of the South China Sea. This zone was further subdivided into three subzones; Harbour, Buffer, and Channel subzones (Figures 1a and b). Tolo Harbour and Channel WCZ lies within the tropics but the climate is considered to a

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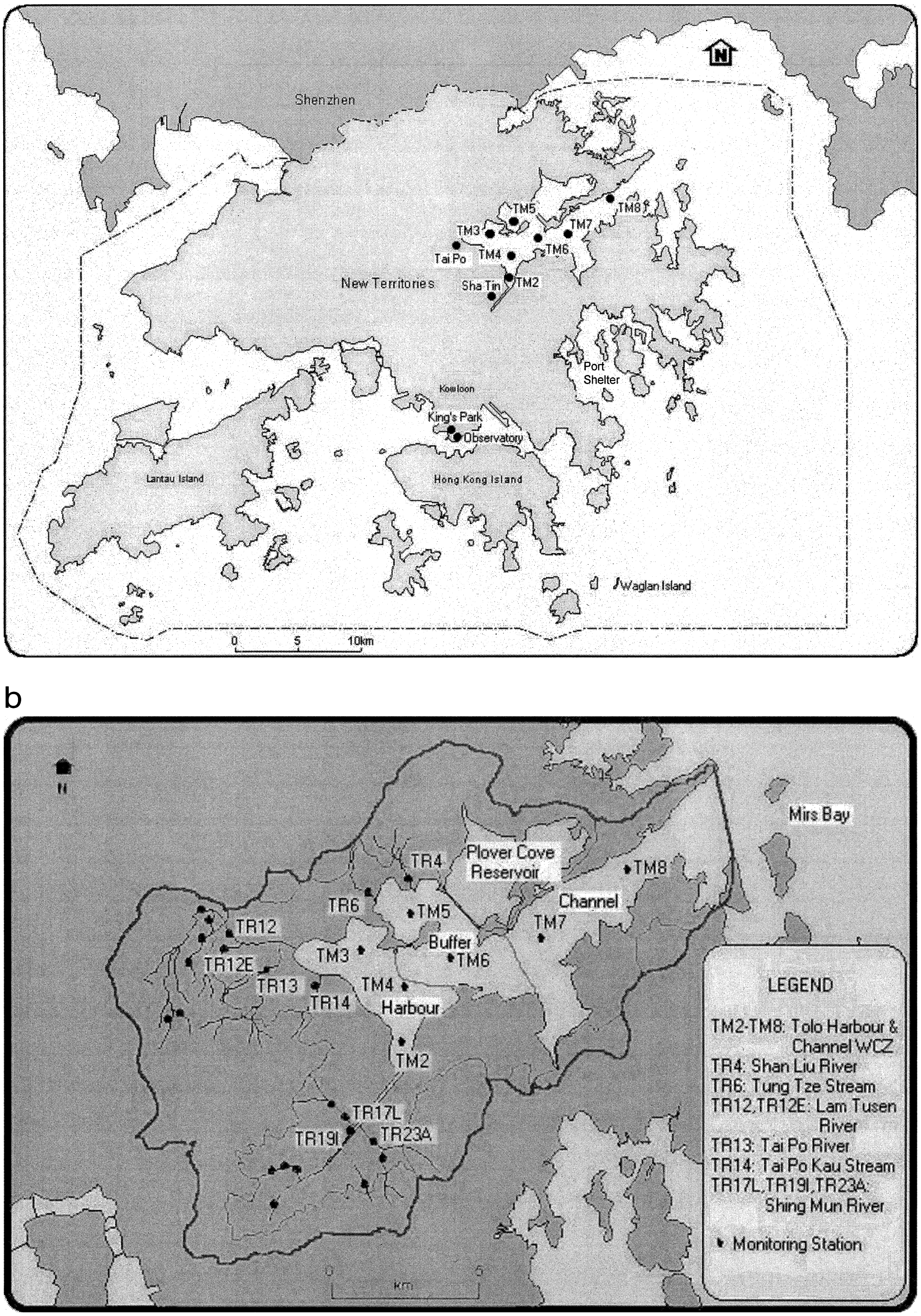

Figure 1a—Location of Hong Kong's coastal waters.
Figure 1b—Location of Tolo Harbour and Channel Water Control Zone and its catchment.

be subtropical as a result of the cool, dry winds of the northeasterly monsoon in the winter and the warm, rain-bearing southwesterly monsoon in the summer. There are six main rivers and streams (Shing Mun River, Lam Tsuen River, Tai Po River, Tai Po Kau Stream, Shan Liu Stream, and Tung Tze Stream) in the catchment of Tolo Harbour and Channel WCZ (Figure 1b). Among them, Lam Tsuen, Shing Mun, and Tai Po Rivers have been of special concern because of serious pollution and have been identified as part of 12 priority rivers in Hong Kong for remediation (Environmental Protection Department, Hong Kong, 1993, 1995, 1997, 1999, 2000). The Shing Mun River flowing through Sha Tin, which has the largest catchment area, has the highest annual discharge rate. The river was worst affected because of large scale reclamation along the shoreline and the construction of a wastewater treatment

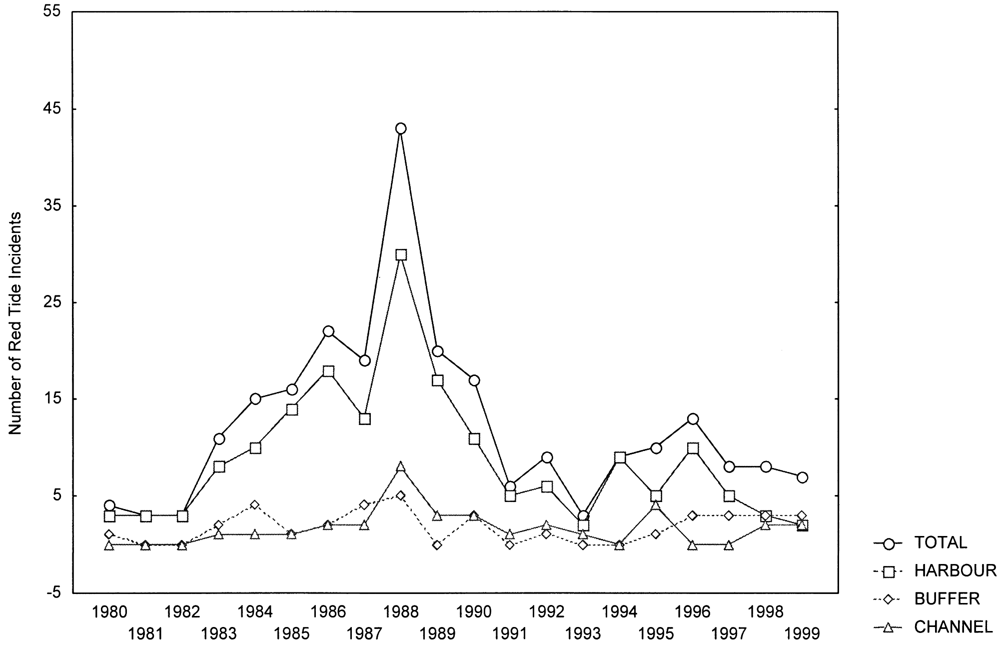

Figure 2—Spatial and temporal distributions of red tide incidents in Tolo Harbour and Channel Water Control Zone during 1980 and 1999.

plant at the downstream end of the river. The effluent from the Sha Tin treatment plant was later diverted to other parts of Hong Kong for disposal to reduce pollution. Furthermore, a Water Pollution Control Ordinance was enforced in 1987 to control the industrial effluents (Holmes, 1988).

The water area, length of the coastline, catchment area, and freshwater runoff in the WCZ have all been significantly reduced because of human activities since the 1960s. The depth of the euphotic zone is generally estimated as three times the Secchi disk depth (Round, 1981). In Tolo Harbour and Channel WCZ, the average depth of the water column is approximately 12 m, with a range of approximately 2 to 3 m in the inner part to approximately 20 m in the outer part, and the euphotic zone typically extends to the bottom. Thus, incident light should be sufficient to sustain phytoplankton growth throughout the water column and the year. Tolo Channel is a bottleneck to both ebbing and flooding tides. The

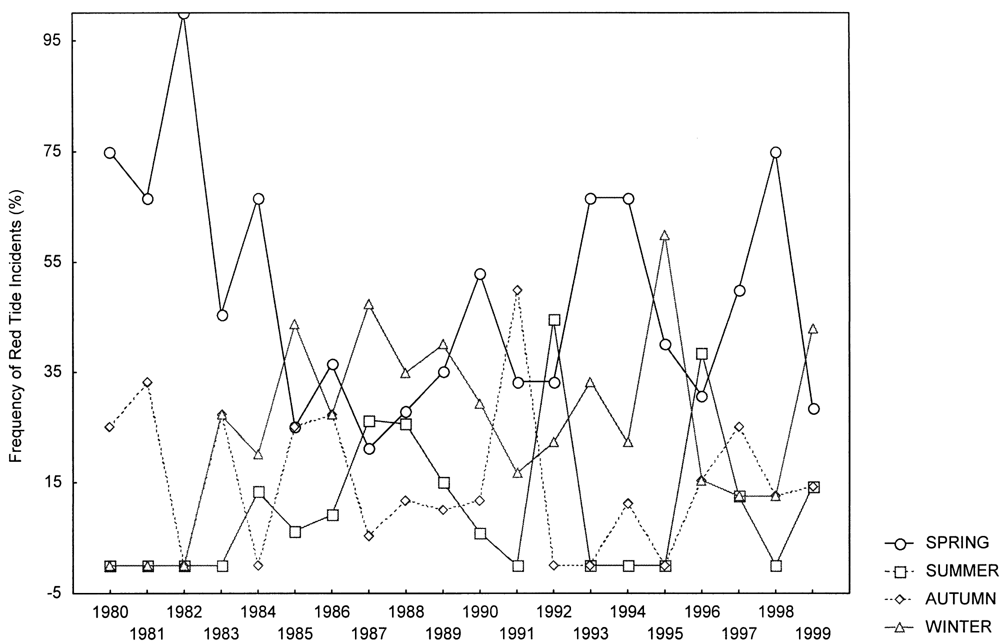

Figure 3—Seasonal variation of red tide incidents in Tolo Harbour and Channel Water Control Zone during 1980 and 1999.

Table 1—Distribution of chlorophyll *a* concentration at seven monitoring stations in the water column in Tolo Harbour and Channel Water Control Zone during 1988 and 1999 (%).

Chlorophyll *a* level (μg/L)	TM2S	TM3S	TM4S	TM5S	TM6S	TM7S	TM8S
(0, 2)	11.4	13.4	10.6	18.7	13.4	20.7	36.6
(2, 10)	34.1	30.5	35.8	56.9	47.6	58.9	50.8
(10, 20)	24.4	28.5	28.5	18.3	21.1	14.2	7.3
(20, 40)	20.7	22.0	17.1	4.1	15.9	5.7	3.7
>40	9.3	5.7	8.1	2.0	2.0	0.4	1.6
	TM2M	TM3M	TM4M	TM5M	TM6M	TM7M	TM8M
(0, 2)		24.4	21.5		32.5	40.2	60.6
(2, 10)		39.8	44.7		52.0	52.0	35.8
(10, 20)		24.4	23.6		9.3	6.1	2.8
(20, 40)		10.2	9.3		6.1	1.2	0.8
>40		1.2	0.8		0.0	0.4	0.0
	TM2B	TM3B	TM4B	TM5B	TM6B	TM7B	TM8B
(0, 2)	23.6	41.5	44.7	23.9	57.1	60.9	79.8
(2, 10)	41.2	44.3	41.8	57.7	38.4	36.7	19.4
(10, 20)	21	9.8	11.5	13.7	3.3	2	0.8
(20, 40)	12	4.1	2	4.7	0.4	0.4	0
>40	2.2	0.4	0	0	0.8	0	0

residence time is long, ranging from one-half to one month. Because most of the exogenous organic materials might be decomposed and recycled within the WCZ, the limited capacity for assimilating organic waste materials could easily be exceeded (Hodgkiss and Chan, 1983; Morton, 1986). As early as the 1980s, Tolo Harbour was reported to have reached a stage where pollution loading exceeds receptive capacity (Hodgkiss and Chan, 1986).

The data used in this study were recorded by monitoring stations from 1988 to 1999. Marine water samples were taken biweekly or monthly at seven monitoring stations (TM2 to TM8) from surface (TM2S to TM8S), middle (TM3M, TM4M, and TM6M to TM8M), and bottom (TM2B to TM8B) layers from the inner part of the Harbour to the outer area. The data were divided into three groups and were used to represent the water quality in the Harbour (TM2S/B, TM3S/M/B, and TM4S/M/B), Buffer (TM5S/B and TM6S/M/B), and Channel (TM7S/M/B and TM8S/M/B) subzones, respectively (Figures 1a and b). The sampling depth was 1 m for the surface water samples of all stations and middle layer samples were taken at the mid-depth of water columns, while for the bottom samples, the measurement depth was at 1 m above the seabed. Eighteen parameters were selected to represent the algal growth: chlorophyll *a* (Chl-*a*), marine nutrients (ammonium [NH_4], nitrite [NO_2], nitrate [NO_3], total kjeldahl nitrogen [TKN], phosphate [PO_4], total phosphorus [TP], silica [SiO_2], total inorganic nitrogen [TIN] and total nitrogen [TN]), hydrological conditions (temperature [TEMP], pH, salinity [SAL], dissolved oxygen [DO], turbidity [TURB], suspended solid [SS], and total volatile solid [TVS]), and organic pollution (five-day biochemical oxygen demand [BOD_5]). For the riverine waters, nine control stations (TR4, TR6, TR12, TR12E, TR13, TR14, TR17L, TR19I, and TR23A) were selected to show the quality of the discharge of the six main watercourses in the catchment. The meteorological data were obtained from the Hong Kong Observatory. Four main weather stations were selected in this study. The locations are in the south of Kowloon (site of the Hong Kong Observatory), King's Park in Kowloon, Waglan Island in the southeast of Hong Kong Island, which is exposed to the action of wind and waves from the open sea, and Sha Tin located in the catchment of Tolo Harbour & Channel WCZ (Figure 1a). The records at the Observatory, King's Park, and Waglan Island were from January 1980 to December 1999, and at Sha Tin were from October 1988 to December 1999. The data recorded at the Observatory and King's Park were of high quality and no data were missing. However, there were 0.94 and 4.33% of records missing at Waglan Island and Sha Tin, respectively. For the first three stations, daily records were used including total rainfall, mean air temperature, mean relative humidity, mean pressure at sea level, and mean cloud amount. In addition, prevailing wind direction and mean wind speed at the Observatory and Waglan Island and total bright sunshine and global solar radiation at King's Park were selected for analysis. Sha Tin station is an automatic weather station and there were some missing data because of equipment failure or telecommunication problems.

A statistical software package, STATISTICA v.5.5, was used to analyze temporal and spatial variations and relationships among algal growth, nutrients, organic pollution, and hydrological and meteorological conditions. Multivariate analysis and spline interpolation were used to identify the factors affecting algal blooms. A significant level of 0.05 was used for statistical tests.

Results and Discussion

Massive Algal Bloom and Chlorophyll *a* Concentration. Red tides have been occurring more frequently in Hong Kong's coastal waters and the affected areas have become more widespread since the early 1980s. According to data collected from 1980 to 1999, most red tides occurred in the eastern waters of Hong Kong, including Tolo Harbour and Channel, Mirs Bay, and Port Shelter, and 45% of those were recorded in the Tolo Harbour and Channel WCZ.

Red tides that occurred in Tolo Harbour and Channel WCZ had obvious spatial and seasonal variations (Figures 2 and 3). During the period 1980 to 1999 (except for 1998 and 1999), more than 50% of red tide incidents occurred in the Harbour subzone, which directly accepted the discharge from most of the rivers and streams in the catchment. The water in the area of the monitoring station TM3 was significantly influenced by Lam Tsuen River, Tai Po River, and Tai Po Kau Stream and had the most frequent occurrence of red tides. The average frequency of occurrence of red tides in the Harbour subzone was 4.85 times that in the Buffer subzone and 5.58 times that in the Channel subzone. This fact suggests that the pollutants from the rivers were responsible for the red tide occurrence in the Tolo Harbour and Channel WCZ. Although red tides might occur in all seasons, Figure 3 clearly showed that spring was the most favorable season for red tides. From 1980 to 1999, the proportion of red tide incidents in spring ranged from 21.1 to 100%, with an average value of approximately 50%. The next favorable season for the red tide occurrence was winter, with an average proportion of approximately 25%, followed by autumn with an average proportion of 15%. Summer had the least likelihood for red tide occurrence, with an average proportion of only 10%.

Chlorophyll *a* level is often used to represent the algal biomass. It is used for the determination of productivity because it is the most abundant and important pigment in living materials. Krey (1973) used a chlorophyll *a* concentration of 0.5 μg/L to indicate eutrophic conditions in natural water from the point of view of primary productivity. For offshore oceanic waters, the chlorophyll *a* levels

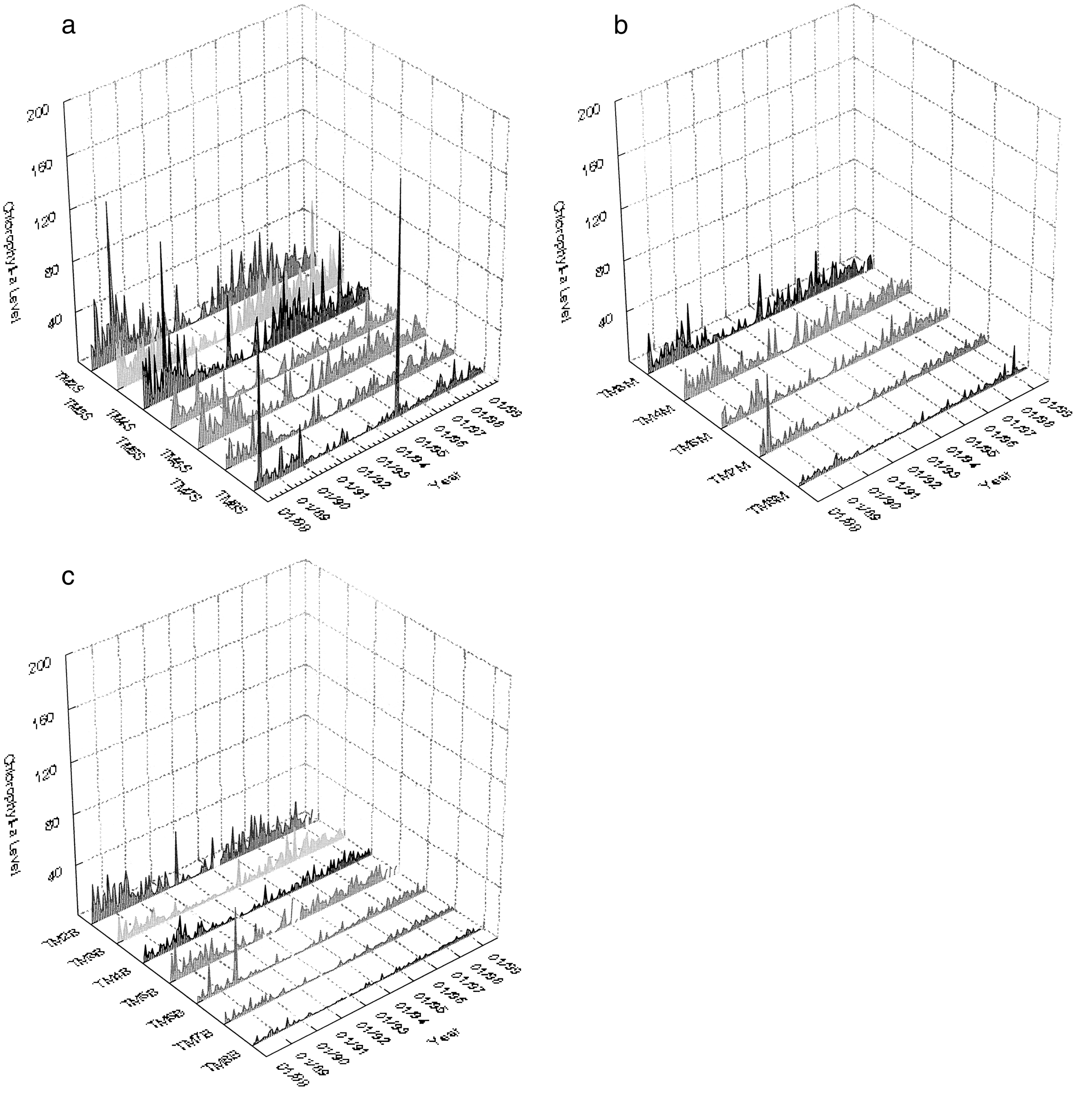

Figure 4—Spatial and temporal variations of chlorophyll-a concentration in Tolo Harbour and Channel Water Control Zone during 1988 and 1999: (a) surface layer of water column; (b) middle layer of water column; (c) bottom layer of water column.

are typically below 2 μg/L. Mean chlorophyll *a* levels above 10 μg/L have been regarded as unacceptably high and such levels indicate eutrophication, while a level of 20 μg/L indicates vigorous algal blooms (Chan and Hodgkiss, 1987; Chiu et al., 1994). Taking these values as general guidelines, Tolo Harbour and Channel WCZ could be regarded as highly eutrophic, exhibiting high algal growth. It could be seen from Table 1 that a chlorophyll *a* level of over 10 μg/L occurred for approximately 60, 40, and 25% of the time in the surface, middle, and bottom layers, respectively, in the Harbour Subzone. The corresponding values are 35, 20, and 15% in the Buffer subzone, and 20, 9, and 3% in the Channel subzone. The chlorophyll *a* level was more than 20 μg/L in the Harbour subzone for approximately 25 to 30% of the time. While in the Buffer and Channel subzones, all the stations except TM6 had a corresponding frequency of less than 10%. A chlorophyll *a* concentration of less than 10 μg/L occurred in the whole water column for 80 to 99% of the time at the outer part of Tolo Harbour near Mirs Bay. The results indicate severe eutrophication in the inner part of the Harbour.

According to the data collected from 1988 to 1999, the chlorophyll *a* level had obvious temporal and spatial variations in

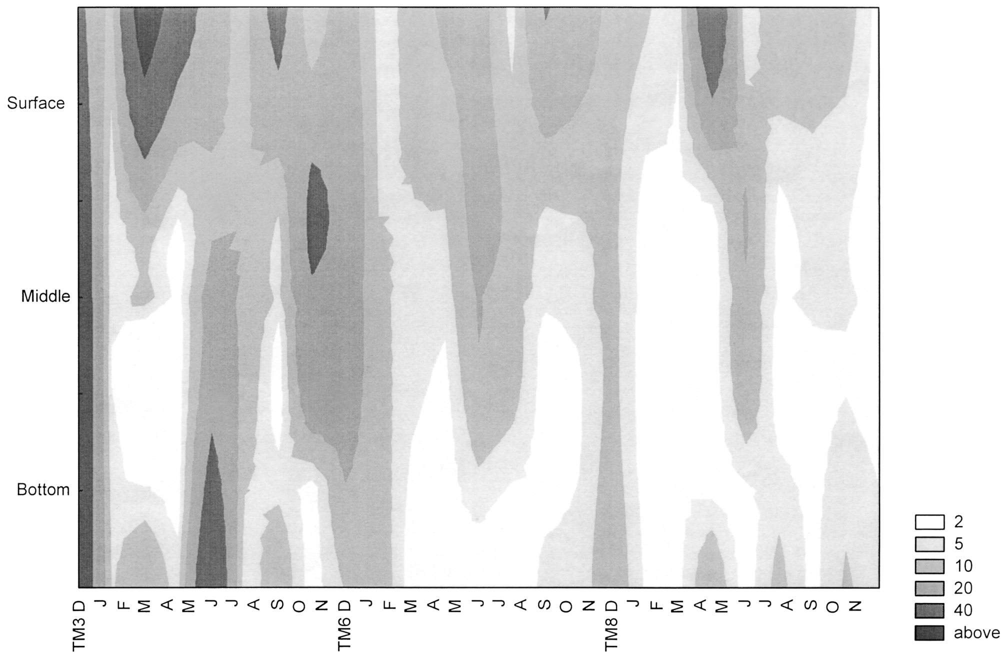

Figure 5—Vertical distribution of seasonal variation of chlorophyll-a concentration for the water column in different subzones of Tolo Harbour and Channel Water Control Zone during 1988 and 1999.

the water column in Tolo Harbour and Channel WCZ. Figures 4a, b, and c showed the temporal and spatial distributions of chlorophyll *a* concentration in surface, middle, and bottom waters, respectively. It could be seen that the trend was similar in the whole water column in both the temporal and spatial domains with the chlorophyll *a* concentration generally reducing from surface to bottom throughout the time at all seven stations. Chlorophyll *a* concentrations attained the highest values on average from 1988 to 1990, and there was a second peak in the years 1995 and 1996. The values in the period between 1991 and 1994 were much lower, and the lowest values occurred in 1993. There was a general decrease in concentration from the inner part to the outer part of Tolo Harbour and Channel WCZ. The average values of chlorophyll *a* concentrations from 1988 to 1999 at the surface, middle, and bottom layers of monitoring stations TM2 to TM4 in the Harbour subzone were 17.2, 9.5, and 6.9 μg/L, respectively. The

Table 2—Significant correlations of chlorophyll *a* concentration with other water quality parameters for the water column in Tolo Harbour and Channel Water Control Zone during 1988 and 1999 (+/−: positive/negative significant correlation at level of 0.05). Significant correlations when chlorophyll *a* concentration is over 10 μg/L are put in parentheses.

	Chlorophyll *a* in surface waters							Chlorophyll *a*	
Parameter	**TM2**	**TM3**	**TM4**	**TM5**	**TM6**	**TM7**	**TM8**	**TM3**	**TM4**
TEMP	(−)		(−)						
pH	+ (+)	+ (+)	+ (+)	+	+ (+)	+	+	+ (+)	+ (+)
SAL	−			−	−	−			
DO	+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	+	+ (+)	+	+
TURB		+ (+)	+ (+)	+	+ (+)	+ (+)	+	+	+
SS	(+)	+ (+)	+ (+)		+ (+)	+	+ (+)	+	
TVS	+	+	+ (+)	+ (+)	+	+	+ (+)	+	+
BOD_5	+	+ (+)	+ (+)	+	+ (+)	+	+ (+)	+ (+)	+ (+)
NH_4	− (+)	(+)	(+)	− (+)	− (+)	−	+ (+)	−	−
NO_2	− (+)	− (+)	(+)	(+)	(+)	(+)	+ (+)	−	−
NO_3		−	−	−	−		(+)	−	−
TKN	+	+	+	+	+	+	+ (+)	+ (+)	
PO_4		−		−	−	−		−	−
TP	+ (+)	+ (+)	+ (+)	(+)	+ (+)	(+)	+ (+)		
SiO_2	−		(+)				+	−	− (−)
TIN	−	−	−	−	−	−	+ (+)	−	−
TN	+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	

corresponding average values were 9.7, 5.9, and 5.1 μg/L at TM5 and TM6 in the Buffer subzone; and 7.4, 3.8, and 2.1 μg/L at TM7 and TM8 in the Channel subzone. However, all the stations had an average level of higher than 2 μg/L. For the whole water column, it is clear that the average chlorophyll *a* level decreased and the vertical differences increased from the inner to the outer part. Each station had a pattern of high–low–high values in the time series, with the low values appearing in the early 1990s.

To examine in detail the temporal and spatial variations of the chlorophyll *a* concentrations, three stations (TM3, TM6, and TM8) were selected for comparison, which represent the conditions at Harbour, Buffer, and Channel subzones, respectively, as shown in Figure 5. The TM3 station primarily had a high chlorophyll *a* level of more than 10 μg/L throughout the time series in the whole water column, while the higher levels mainly concentrated in the surface and middle layers at TM6. At station TM8, a low chlorophyll *a* level (less than 10 μg/L) occurred most of the time in the whole water column and the value was less than 2 μg/L in the bottom nearly 80% of the time. For stations TM3 and TM6, a high concentration of chlorophyll *a* appeared mostly in spring and winter. As for TM8 in the Channel subzone, high levels generally appeared in the surface in summer.

Relationship Between Algal Growth and its Influence Factors. The results of correlation analysis between chlorophyll *a* and other parameters in the marine waters showed that chlorophyll *a* concentration had a significant correlation with most parameters of nutrients, organic pollution, and hydrology as summarized in Table 2. It could be seen from Table 2 that chlorophyll *a* showed positive significant correlations with pH, DO, TVS, BOD_5, and TKN in the whole water column, with TURB, SS, and TN in the surface and middle layers and with TP in the surface waters. Chlorophyll *a* had negative significant correlations with NH_4, NO_3, PO_4, and TIN in the whole water column and with NO_2 mainly in the water column of the Harbour subzone. Silica mainly showed negative significant correlation with chlorophyll *a* in the bottom waters. Among all the parameters, BOD_5 showed the most significant correlation with chlorophyll *a* in the whole water column. The TEMP had negative significant correlation only when chlorophyll *a* was over 10 μg/L and seemed to have less significant influence on algal growth in the study area. The SAL showed negative significant correlation with chlorophyll *a* only in the surface waters, while pH and DO had positive significant correlations with chlorophyll *a* in both the surface and bottom waters. Parameters related to transparency and light penetration, namely TURB, SS, and TVS, were correlated to the algal growth in the surface and middle waters. The TIN consists of NH_4, NO_2, and NO_3. The TIN had a negative significant correlation with chlorophyll *a* in the whole water column, and its three components also showed negative significant correlations with chlorophyll *a* in the whole water column. The TN consists of TKN, NO_2, and NO_3. However, NO_2 and NO_3 only accounted for 1 to 7% and 3 to 13% of TN, respectively, and TKN was the most abundant form of nitrogen that accounted for 85 to 96% of TN during the study time period. From Table 2, it could be seen that TN had a positive significant correlation with chlorophyll *a* in both surface and middle layers, while among its three components, only TKN showed a positive significant correlation, especially in surface waters. Chlorophyll *a* showed a strongly negative correlation with PO_4, SiO_2, NH_4, and NO_3 in the whole water column.

When the chlorophyll *a* level was more than 10 μg/L, the strong correlation between the chlorophyll *a* level and other water quality parameters mainly occurred in the surface waters where both hydrological conditions and nutrients showed significant correlations with the chlorophyll *a* level. However, the hydrological conditions had more significant correlation than nutrients in the middle and bottom layers. The dramatic change appeared in nitrogen in which almost all the negative significant correlations disappeared or replaced by a positive significant correlation. On the other hand, the correlations of TKN and NO_3 turned very weak, while those of NO_2 and NH_4 became strongly positive. It is obvious that the strong correlation between nitrogen and chlorophyll *a* level was no longer

Table 2—(Extended)

in middle waters			Chlorophyll *a* in bottom waters						
TM6	TM7	TM8	TM2	TM3	TM4	TM5	TM6	TM7	TM8
+ (+)			+ (+)	+	+	+	+		+
						−		(+)	
	(−)		+	+	+			+	
+	+ (+)	+	+						
+ (+)	+ (+)	+		+ (+)		(+)			
+ (+)	+ (+)	+	+	+ (+)		+ (+)	+		+
+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	+	+	+	+ (+)	+
−	+ (+)		−	−	−	−		−	−
−		−	−	−	−			−	
−		−	−	−	−	−		−	−
+	+ (+)	+	+	+	+	+		+	+
−	(+)	−	−	−	−	−	−	−	−
	+ (+)		(+)		+				
−			−	− (−)	−	− (+)	−	−	−
−	+ (+)	−	−	−	−	−	−	−	−
+	+ (+)	+		+				+	

Table 3—Significant correlation of nutrients between marine water quality monitoring stations in Tolo Harbour and Channel Water Control Zone and the control stations of rivers in the catchment (at a statistically significant level of 0.05).

River or stream	Shan Liu Stream	Tung Tze Stream	Lam Tsuen River	
Station	**TR4**	**TR6**	**TR12**	**TR12E**
NH_4				
S[a]		TM2, TM6, TM8		
M[b]		TM4		
B[c]				
NO_2				
S				
M			TM6	
B			TM3, TM4, TM6	
NO_3				
S	TM2	TM2, TM4		TM4
M			TM6	
B		TM2, TM5, TM7		TM7
TKN				
S	TM2, TM6, TM7, TM8	TM2, TM6, TM8		TM2, TM3, TM5, TM6, TM7, TM8
M	TM4, TM6, TM7	TM6		TM4, TM6, TM7
B	TM2, TM5	TM2		TM2, TM3, TM5, TM6, TM7
PO_4				
S		TM2, TM3, TM4, TM5, TM6, TM7, TM8		
M	TM7	TM3, TM4, TM6, TM7, TM8	TM8	
B	TM7, TM8	TM2, TM4, TM5, TM7	TM7, TM8	
TP				
S	TM2, TM3, TM4, TM5, TM6, TM7, TM8	TM2, TM4, TM5, TM6, TM7		
M	TM4, TM6, TM7, TM8	TM4, TM6, TM7, TM8		
B	TM2, TM3, TM5, TM6, TM7, TM8	TM2, TM4, TM5, TM6, TM7		
SiO_2				
S	TM8		TM2, TM4, TM5	TM5, TM6
M	TM4, TM7		TM3, TM4, TM6, TM7, TM8	
B			TM2, TM4, TM5	TM2, TM4

[a] S: Surface layer of marine water column; [b]M: Middle layer of marine water column; [c]B: Bottom layer of marine water column.

because of TKN, and the limiting nutrients became NO_2 and NH_4 in the surface waters. The results given in Table 2 might suggest that when the water column reached the level of eutrophication, the massive algal bloom was mainly influenced by a number of parameters in the surface waters. The most significant influences were mainly associated with nutrients NH_4, NO_2, TN, and TP, organic pollution factor BOD_5, transparency parameters TURB, SS, and TVS, and hydrological conditions pH and DO. Any increase in values of any of the parameters would enhance the algal bloom.

Nutrients. Eutrophication, as a process (Nixon, 1995), is always associated with nutrient enrichment in the water body. To reveal the relationship between chlorophyll *a* level and nutrients in Tolo Harbour and Channel WCZ and the relationship between nutrients and land source pollution, seven parameters (NH_4, NO_2, NO_3, TKN, PO_4, TP, and SiO_2) were selected because they were measured monthly or biweekly in both stream and marine waters. Table 3 showed the significant correlations of the seven selected nutrients between river and marine waters. Significant correlations of nutrient concentrations measured in the water column in the WCZ (TM2S/M/B to TM8S/M/B) with those measured at the control stations of rivers in the catchment (TR4, TR6, TR12, TR12E, TR13, TR14, TR17L, TR19I, and TR23A) could be found. Among the seven selected nutrients, TKN, PO_4, and TP showed the most significant correlation, and NH_4, NO_3, and SiO_2 also had relatively significant correlations, while NO_2 only showed a significant correlation at TR12 in Lam Tsuen River. For all the control stations of rivers and streams in the catchment, the most significant correlations existed at TR19I in the main stream of Shing Mun River, which had significant correlations with most marine monitoring stations of the WCZ in the whole water column for all parameters except with NO_2. The control station TR13 in Tai Po River showed significant correlations with marine surface waters in the WCZ for TKN, NH_4, PO_4, and TP. The stations TR12 and TR12E in Lam Tsuen River mainly showed significant correlations with marine stations of the WCZ for TKN, SiO_2, and NO_2. Significant correlations existed for the TR14 station in Tai Po Kau Stream for TKN, PO_4, and TP, the TR4 station in Shan Liu Stream for TKN and TP, and the TR6 station in Tung Tze Stream for PO_4, TP, TKN, NH_4, and NO_3. The results showed that the Shing Mun River was the main source of nutrients in the marine waters of the

Table 3—(Extended)

Tai Po River	Tai Po Kau Stream	Shing Mun River		
TR13	**TR14**	**TR17L**	**TR19I**	**TR23A**
TM2, TM6, TM8	TM8	TM2, TM6	TM2, TM6, TM8	
TM7			TM7	
			TM2	
TM7		TM3, TM4, TM5, TM6, TM7, TM8	TM2, TM3, TM4, TM5, TM7, TM8	TM4
		TM3, TM4	TM3, TM4, TM7	
		TM2, TM5, TM8	TM2, TM5, TM7, TM8	
TM2, TM3, TM4, TM6, TM7, TM8	TM2, TM3, TM4, TM6, TM7, TM8	TM2, TM3, TM4, TM5, TM6, TM7, TM8	TM2, TM3, TM4, TM5, TM6, TM7, TM8	TM2, TM3, TM4, TM5, TM6, TM7, TM8
TM4	TM4, TM6	TM3, TM4, TM6, TM7	TM3, TM4, TM6	TM3, TM4, TM6
TM2	TM2	TM2, TM6, TM7, TM8	TM2, TM5, TM6	TM2, TM3, TM6, TM8
TM2, TM3, TM4, TM5, TM6, TM7, TM8	TM7	TM2, TM4, TM5, TM6, TM8	TM2, TM3, TM4, TM5, TM6, TM7, TM8	
TM3, TM4	TM8	TM6, TM7	TM3, TM4, TM6, TM7, TM8	
TM2, TM8	TM4, TM7, TM8	TM2, TM5	TM2, TM3, TM4, TM5	
TM6, TM8	TM2, TM6, TM8	TM2, TM6	TM2, TM3, TM4, TM5, TM6, TM7, TM8	TM2, TM6, TM8
TM7		TM7	TM4, TM6, TM7, TM8	TM6
TM2			TM2, TM3, TM4, TM8	
TM5	TM8	TM2	TM2, TM3, TM4, TM6, TM7	
TM4	TM7, TM8		TM3, TM4	
		TM3, TM6	TM2, TM3, TM6, TM8	

Tolo Harbour and Channel WCZ for all the selected nutrients except NO_2. Tai Po River, Tai Po Kau Stream, Shan Liu Stream, and Tung Tze Stream had an influence on both nitrogen and phosphorus, and Lam Tsuen River on nitrogen and silicate.

In the Tolo Harbour and Channel WCZ, all the nutrients had a similar spatial variation, with the levels generally decreasing from the inner part to the outer part. This pattern was consistent with the conclusion that the supply of nutrients was from various rivers and streams in the catchment. The temporal variations of nutrients were small and the highest concentration for each of the nutrients occurred generally in spring, with relatively high concentrations in winter and autumn. The lowest level occurred in summer for all sites. This pattern was highly consistent with the temporal variations of chlorophyll *a* levels.

Fisher et al. (1988) quoted several critical values of half-saturation constants for nutrient uptake, with NH_4, NO_2, and NO_3 at 1 to 2 µM, phosphate at 0.1 to 0.5 µM, and silicate at 1 to 5 µM, which represented the concentrations at which nutrient uptake was half of its maximum value. Taking the concentrations at the upper limit of the half-saturation constants as the reference, concentrations of ammonium, phosphate, and silicate were never less than 2, 0.5, and 5 µM, respectively, in the whole water column from 1988 to 1999. Nitrite concentrations of less than 2 µM occurred 40 to 60% of the time in the surface waters for all the monitoring stations, except at TM2, which had a lower percentage of 20% in the surface, approximately 45% in the middle layer, and approximately 30% in the bottom of the water column. Nitrate concentrations of less than 2 µM occurred 20 to 40% of the time in the surface water for all the stations, except at TM2, which had only 7.7%. The corresponding values in the middle layer and bottom were approximately 30 and 20%, respectively. The values at the surface waters were, in almost all cases, higher than those in the middle and bottom waters. This clearly showed that nitrogen was the most important limiting nutrient in the whole water column, especially in the surface layer and outer part of the Tolo Harbour and Channel WCZ. As a result, red tide incidents mostly occurred in the Harbour subzone throughout the study period.

It was once reported that the suitable nitrogen-to-phosphorus (N:P) ratio for marine phytoplankton could be from less than 3:1 to over 30:1, and the ratio varied according to the kind of algae grown and the availability of both nutrients. Ratios of less than 15:1 were common in the surface marine waters (Ryther and Dunstan, 1971),

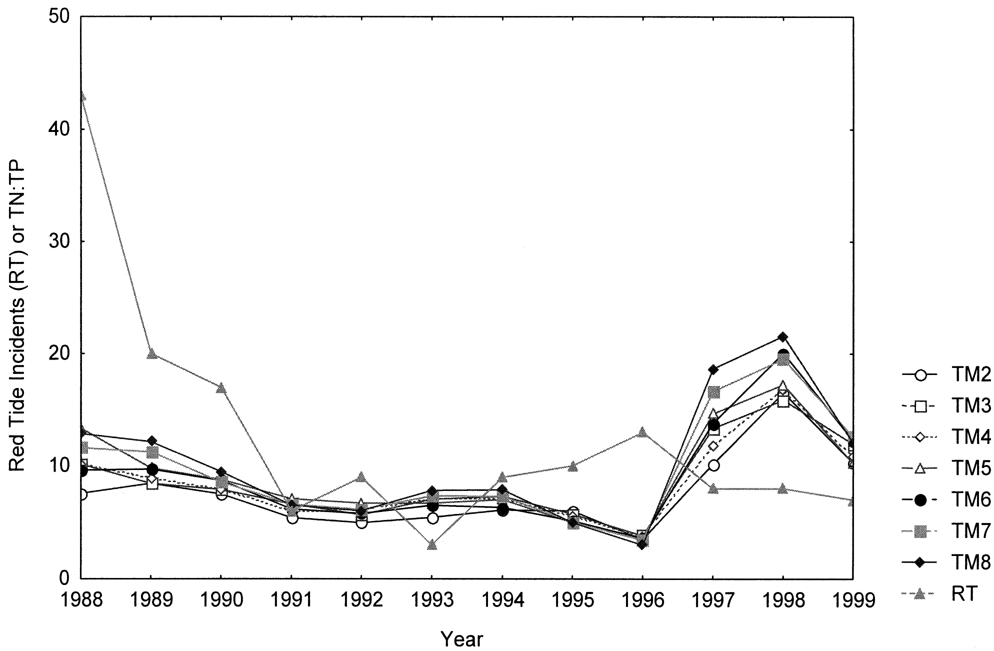

Figure 6—Number of red tide incidents and TN:TP ratios in Tolo Harbour and Channel Water Control Zone.

while the optimal N:P ratio for the dinoflagellates of oceanic environment is 16:1, as suggested by Redfield (1958). In the Tolo Harbour and Channel WCZ, the average TN:TP ratios at the seven monitoring stations ranged from 8.4 to 11.1 with a minimum value of 0.2 and maximum value of 76.6. Although the levels of both TN and TP had an obvious decrease towards the outer part of the Tolo Harbour and Channel WCZ, the TN:TP ratio had a general increase, which suggested the important influence of TN and TP concentrations to red tide occurrences.

The TN:TP ratios changed through the time series. In the early years of the study period, the chlorophyll *a* concentration increased with the increase of the TN:TP ratio. While in the later years, the chlorophyll *a* concentration decreased with the increase of TN:TP ratio in the inner part of the Tolo Harbour and Channel WCZ, where red tides occurred most frequently. This phenomenon might be associated with an alteration in species dominance in the phytoplankton population from diatoms to dinoflagellates (Hodgkiss and Ho, 1997). The TN:TP ratios showed a complicated relationship with red tide occurrences in the Tolo Harbour and Channel WCZ, as shown in Figure 6. It could be seen from Figure 6 that the time series could be divided into three parts. In the time period between 1988 and 1991, the average TN:TP ratios were approximately 8:1 to 10:1. The red tides mainly occurred in the Harbour subzone and the number of red tide incidents decreased with the decrease of TN:TP ratios, which might imply a nitrogen-limiting environment. In the following time period from 1992 to 1996, the red tides still occurred mostly in the Harbour subzone. However, the number of red tide incidents fluctuated. Red tide occurrences mainly increased when the TN:TP ratio decreased, which might imply a phosphorus-limiting environment or an alteration in species dominance in the phytoplankton population as suggested by Hodgkiss and Ho (1997). In the last time period from 1997 to 1999, the TN:TP ratio became larger and had an average range of 13:1 to 17:1. In this time period, red tides occurred infrequently, although there were significant changes in the TN:TP ratio. Red tide occurrences spread to the whole of the WCZ, unlike that in the previous years, which concentrated in the Harbour subzone. This might imply a combined influence of a phosphorus-limiting environment and a species alteration of the phytoplankton population.

Hydrological and Meteorological Conditions. Chlorophyll *a* showed significantly positive correlation with pH, DO, TVS, SS, TURB, and BOD_5 in the WCZ, and less significant correlation with SAL and TEMP (Table 2). The average pH value at TM2 was as low as 8.0 to 8.3 because it was located near the Shing Mun River where the mean pH was 7.2 to 7.8. The other stations had an average value of 8.3 to 8.5. The pH had a significant correlation with the chlorophyll *a* level at all sites. This suggested that pH might be an important hydrological parameter indicating the level of dissolved carbon dioxide in the water which might, in turn, reflect the activity of phytoplankton and the level of DO in the water. There was an obvious trend in the inner part of the WCZ, where red tides occurred more frequently, that high pH generally occurred when the chlorophyll *a* level was high in the time periods 1988 to 1990 and 1994 to 1996. Also, relatively low pH was accompanied by a low chlorophyll *a* concentration in the time period 1991 to 1993 and 1997 to 1999 when red tides occurred infrequently, which obviously agreed with the view of Hodgkiss and Chan (1986) that high productivity values were related to alkaline pH values.

The DO in Tolo Harbour was once reported to fall to zero in the effluent from a textile dyeing factory (Morton and Wu, 1975). The concentration in general increased towards the outer part of the WCZ, but there was a lower level at TM5 and the lowest level occurred at TM2, as both stations were near the coast and the water there was shallow. In general, the DO fluctuated throughout the year, with high levels occurring in spring and winter and low levels in summer. The DO levels at the surface water were higher than those at the bottom waters. Dissolved oxygen had a strongly positive correlation with chlorophyll *a* level at all monitoring stations. The DO had an inverse spatial variation but a similar

Table 4—Differences in meteorological characteristics at Observatory and King's Park weather stations between the period of red tide occurrence and the period of no red tide occurrence between 1980 and 1999 in Hong Kong.

Season	Temperature (°C)	Atmospheric pressure (hPa)	Bright sunshine (h)	Solar radiation (MJ/m^2)	Cloud amount (%)
Spring					
March	+0.17	−0.78	+0.48	+1.20	+1.10
April	−0.09	−0.45	−0.07	+0.26	−1.20
May	−0.29	+0.14	−0.18	+0.05	+2.55
Summer					
June	+0.11	+0.30	+0.42	+0.65	−3.66
July	+0.07	+1.97	+1.69	+2.58	−9.36
August	+0.16	−0.14	+1.44	+2.56	−6.34
Autumn					
September	−0.67	+1.73	+1.93	+2.80	−21.81
October	+0.40	+0.16	+1.49	+1.87	−6.21
November	+1.04	−1.63	+0.60	+0.94	−0.60
Winter					
December	+0.51	−0.47	+1.86	+1.61	−17.64
January	+0.98	−0.62	+0.59	+0.72	−7.56
February	+0.50	−0.55	+0.44	+1.29	−2.24

temporal variation as BOD_5. In general, the value of BOD_5 was higher in the inner part of the WCZ and seasons of spring and winter than in the outer part and summer.

The average meteorological characteristics in the time period with occurrence of red tides were different from those without red tide incidents (Table 4). When red tides occurred, the mean air temperature at the observatory was approximately 0.5 °C higher in both autumn and winter, but the air temperature was the same in spring and summer. The mean pressure at sea level at the observatory was always a little higher by approximately 1.0 hPa in summer and autumn and a little lower by approximately 0.5 hPa in winter and spring. The total bright sunshine at King's Park was approximately one hour longer for all the seasons, except in spring when the duration was almost the same. Global solar radiation at King's Park was higher, ranging from 0.5 to 2.0 MJ/m^2 for all seasons. The mean cloud amount at the observatory was approximately 5 to 10% lower for all seasons except spring, when the cloud was 0.82% higher on average. All the selected parameters except the cloud amount mostly had higher values when red tides occurred. It seemed that a high value of solar radiation would be favorable to red tide occurrence for all seasons. This result supported the modeling result in Tolo Harbour by Lee and Arega (1999). Pennock and Sharp (1986) also had a similar conclusion in a nutrient-rich estuarine environment.

The prevailing wind direction in Hong Kong was northeasterly, except for summer when the southwesterly wind occurred much more frequently. The frequency of occurrence of those two directions was approximately 80 to 90% in one year in the study period. There were distinct seasonal variations between the two directions of wind. In summer, the southwesterly wind had a frequency of occurrence of approximately 50%. In the other three seasons, the frequency of occurrence of northeasterly wind was as high as 70 to 80%, which matched the seasonal variations of chlorophyll *a* concentration and the nutrients in the marine waters. With the southwesterly wind in summer, which was favorable to the pollutant dispersion and water exchange, the chlorophyll *a* concentration appeared to have the lowest average value. In the other three seasons when the northeasterly wind occurred much more frequently, it was not easy for the pollutants to move out of the bay. As a result, the chlorophyll *a* concentration was maintained at a relatively high average level.

Conclusions

In this paper, an 11-year data set of various parameters associated with algal bloom was used to systematically analyze the dynamics of algal bloom. Statistical analysis showed that the dynamics of algal bloom were strongly influenced by nutrients, organic pollution, and hydrological and meteorological conditions in the Tolo Harbour and Channel WCZ. Rivers and streams in the catchment were the main sources of nutrients. Algal growth could occur in the whole water body and massive algal bloom associated with red tides mainly occurred in the inner Harbour subzone in the spring season. Algal growth was at a high level in the end of the 1980s and early 1990s, and again in the late 1990s. When a level of eutrophication was reached with a chlorophyll *a* level of more than 10 μg/L, the values of the different parameters in the surface layer seemed to have the most important influence on algal growth. The most significant correlations were mainly associated with nutrients NH_4, NO_2, TN, and TP, organic pollution factor BOD_5, transparency parameters TURB, SS, and TVS, and hydrological conditions pH and DO. Increase in values of any of the parameters would result in the enhancement of algal bloom. From the relationship between the number of red tide incidents and TN:TP ratios, it could be concluded that in the early years of the study period, nitrogen seemed to be a dominant limiting factor for the algal blooms, and the chlorophyll *a* concentration increased with the increase of the TN:TP ratio. In the later years, when the number of red tide incidents increased, the TN:TP ratios showed a decrease trend, which might suggest the combination of a phosphorus-limiting environment and species alteration of the phytoplankton population. Meteorological conditions were also important factors for algal bloom. Global solar radiation was a key factor of red tide occurrence in the study period. The seasonal variations of rainfall and wind direction were the most important factors affecting the seasonal distribution of red tides. The lowest level was in summer for all sites, which was because of the dilution by heavy rainfall and more efficient pollutant dispersion by the prevailing southwesterly wind. The high levels in other seasons might possibly result from the action of wind, when the prevailing northeasterly wind was unfavorable to the dispersion of pollutants.

Although there were numerous studies in the literature on different aspects of the dynamics of algal blooms, a quantitative set of relationships between the intensity of an algal bloom and its various influence factors is still not available at present. Such a set of relationships should not be site-specific and should ideally include all the key factors that govern the mechanism of the formation of red tides. In this study, the factors that contribute to the occurrence of red tides in the Tolo Harbour and Channel WCZ are identified. However, the relative contributions of the various factors are still unknown because of the complexity of the mechanism. The group of factors that has been identified in this study can be collated with factors found to be significant in other parts of the world, after taking into account the site-specific conditions. Such a systematic comparison is not possible without detailed analyses of the algal growth in different coastal regions. The analysis presented in this paper would help explain the dynamics of algal growth and would serve as a useful case study for a complete understanding of the complex mechanism in the future, especially the role played by the TN:TP ratio in massive algal blooms.

Acknowledgments

Credits. The project was funded by The Hong Kong Polytechnic University (No. 8755) and the National Natural Science Foundation of China (No. 40176032). The data were provided by the Environmental Protection Department of the Hong Kong Government and the Hong Kong Observatory.

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Submitted for publication June 22, 2001; revised manuscript submitted October 30, 2003; accepted for publication February 3, 2004.

The deadline to submit Discussions of this paper is March 15, 2005.

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