A Comparison of Eutrophication Impacts in Two Eutrophic Harbors in Hong Kong with Different Hydrodynamics

J. Xu[1*], K. Yin[2,4], H. Liu[1], J.H.W. Lee[3], D.M. Anderson[5], A.Y.T. Ho[1], P.J. Harrison[1]

[1]Atmospheric, Marine and Coastal Environment Program (AMCE), The Hong Kong University of Science and Technology, Hong Kong

[2]Australian Rivers Institute, Griffith University, Brisbane, QLD4111, Australia

[3]Department of Civil Engineering, The University of Hong Kong, Hong Kong

[4]LED, South China Sea Institute of Oceanology, CAS, Guangzhou, China

[5]Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

*Corresponding author

E-mail: xujie@ust.hk

Fax: +852-2719 9102

Tel: +852-2358 8415

Abstract

Eutrophication impacts may vary spatially and temporally due to different physical processes. Using a 22-year time series data set (1986-2007), a comparison of eutrophication impacts between two eutrophic harbors, Victoria and Tolo Harbours, in Hong Kong with very different hydrodynamic conditions was conducted. In the highly-flushed Victoria Harbour (Victoria), the highest Chl *a* (13 $\mu g\ L^{-1}$) occurred due to stratification in summer as a result of the input of the eutrophic Pearl River discharge, but the high flushing rate restricted nutrient utilization and the further accumulation of algal biomass. In other seasons, vertical mixing induced light limitation and horizontal dilution led to low Chl *a* (< 2 $\mu g\ L^{-1}$) and no spring bloom. Few hypoxic events (DO < 2 $mg\ L^{-1}$) occurred due to strong tidal mixing. Therefore, Victoria is resilient to nutrient enrichment. In contrast, in the weakly-flushed Tolo Harbour (Tolo), year long stratification, the long residence times and weak tidal currents favored algal growth, resulting in a spring diatom bloom and high Chl *a* (up to 30 $\mu g\ L^{-1}$) all year and frequent hypoxic events in summer. Hence, Tolo is susceptible to nutrient enrichment and it responded to nutrient reduction since sewage treatment resulted in a 32-38% decrease in algal biomass in Tolo, but not in Victoria. A significant (11-22%) reduction in bottom DO in the both harbors after sewage treatment was due to a decrease in the organic loading from sewage treatment or the diversion.

Keywords: Eutrophication, nutrients, phytoplankton biomass, dissolved oxygen, sewage, stratification, hydrodynamics, light limitation

Introduction

Nutrient enrichment is an increasing problem in coastal areas (Nixon 1995; Cloern 1999; 2001; Rabalais and Turner 2001). Typical symptoms of eutrophication are enhanced primary productivity and algal blooms, as well as the formation of hypoxia or anoxia in the bottom water due to the sedimentation and decomposition of unused organic matter in the stratified waters (Cooper and Brush 1991; Turner and Rabalais 1994). However, the response to eutrophication varies widely in coastal areas (Balls et al. 1995; Justic et al. 1996). The correlation between algal biomass and nutrient concentration differs between tidally energetic and tidally weak systems (Monbet 1992). For example, algal biomass in Chesapeake Bay increased dramatically due to the increased nutrient loading from the 1950s to the 1970s (Harding 1994). In contrast, Brest Bay in France has been resistant to increased nutrient loading during the past two decades (Le Pape et al. 1996). In Delaware Bay, there was a seasonal shift in the factors regulating algal biomass from light to nutrients (Pennock and Sharp 1994).

Recent studies have shown that coastal ecosystems with different hydrodynamic conditions respond differently to climatic changes with respect to eutrophication susceptibility (Justic et al. 2003, 2005). In turn, distinctly different responses to nutrient removal or reduction occur in different hydrodynamic waters. The variability in the response of phytoplankton biomass to nutrient enrichment on a seasonal time scale is complex (Le Pape et al. 1996). Hence, we need to consider all the physical processes that control the phytoplankton response to nutrient enrichment when management strategies are developed to protect coastal ecosystems from acute responses to eutrophication (Cloern 1999).

In Hong Kong, Tolo Harbour (Tolo) and Victoria Harbour (Victoria) are both eutrophic waters, subjected to high nutrient loading from the sewage, with up to 2.5×10^5 and 1.6×10^6 kg sewage discharging into Tolo and Victoria daily, respectively (Broom et al. 2003). However, previous observations reveal distinctly different eutrophication symptoms in both waters in response to nutrient enrichment. Tolo has the most frequent red tide events among all waters of Hong Kong (Yin 2003, Wong et al. 2009). Over 40% of a total 777 red tides incidents recorded in Hong Kong waters during 1980-2007 occurred in Tolo Harbour (EPD 2007). The large heterotrophic dinoflagellate *Noctiluca scintillans* that feeds on various plankton including diatoms was the most common red tide-forming species, accounting for 15% of all red tide cases and mainly occurs during the winter-spring period (Yin 2003; Liu and Wong 2006). In contrast, only 2% of total red tides incident occurred in Victoria Harbour (EPD 2007).

The sewage abatement started in Tolo and Victoria in 1997 and 2001, respectively. Since 1998, 90% of the sewage input into Tolo was fully diverted to Victoria, while 70% of the sewage previously discharged into Victoria is treated and discharged into waters 2 km west near Stonecutters Island after the Hong Kong government implemented the Harbor Area Treatment Scheme (HATS) in 2001. Little is known about the underlying mechanism controlling eutrophication impacts before sewage treatment and the ecosystem recovery after nutrient reduction in the both harbors.

The long term water quality monitoring program initiated in 1986 by the Hong Kong Environmental Protection Department (HKEPD) provides a unique dataset for the comparison of the response of the two ecosystems to nutrient enrichment and subsequent nutrient reduction, understand factors regulating eutrophication impacts in both harbors, and provide sewage management strategies. These nutrient reductions provide a unique opportunity to observe an ecosystem response and they may be considered to be like a long term, large scale field experiment. In this study, based on a 22-year (1986-2007) water quality monitoring dataset from HKEPD, we examined the role of physical processes in regulating eutrophication impacts and the ecosystem recovery in response to nutrient reduction in both harbors.

Materials and methods

HKEPD has maintained a comprehensive sampling program to monitor water quality at >76 monitoring stations in the territorial waters since the late 1980s (website: www.epd.gov.hk). Six stations located in Victoria (VM2, VM5 and VM7) and Tolo (TM4, TM6 and TM8) were selected (Fig. 1). Three stations located in Tolo are representative of three areas: inner Tolo (TM4), middle Tolo (TM6) and Tolo Channel (TM8). Biweekly sampling in Victoria during 1986-1991 and in Tolo during 1986-1998 and monthly sampling in Victoria since 1992 and in Tolo since 1999 were conducted by EPD during the last 22 years (1986-2007). Based on the implementation of sewage reduction, the 22-year time series was divided into two phases: pre-treatment (1986-1997 in Tolo and 1986-2001 in Victoria) and post-treatment (1998-2007 in Tolo and 2002-2007 in Victoria). The dry season was defined as October to March and the wet season was from April to September. The year was divided into four seasons: spring (March to May), summer (June to August), fall (September to November) and winter (December to February).

A SEACAT 19 CTD was used to take vertical profiles of salinity and temperature. Water samples were taken at three depths: surface (1 m below the surface), middle (data not shown) and bottom (1 m above the bottom) in Victoria and

Tolo. Methods for sampling and routine water quality measurements are reported by HKEPD (EPD 1999, http://www.epd.gov.hk/epd/english/environmentinhk/water) and the methods employed were standard techniques for nutrients, dissolved oxygen (DO) and chlorophyll.

In this study, the stratification index (SI) was calculated as follows:

$$SI = \frac{\Delta\sigma_t}{h} \qquad (1)$$

where $\Delta\sigma_t$ (kg m^{-3}) is the difference in the seawater density (σ_t) between surface and bottom densities; h is the depth (m) of the water column. Seawater density (σ_t) is calculated based on Fofonoff and Millard (1983) using the monthly average salinity and temperature.

To assess the importance of the light regime for algal growth, the mean light intensity in the mixed layer, <I>, was estimated using the following equation (Riley 1957):

$$\langle I \rangle = \frac{I_0(1-e^{-kz})}{kz} \qquad (2)$$

where I_0 (W h m^{-2} d^{-1}) = mean daily solar radiation, k = coefficient of extinction (k = 1.44/Secchi depth, Holmes, 1970), z = the mixed layer depth. I_0 was obtained from monthly average data from the 30 year (1971-2000) monitoring data from Hong Kong Observatory (http://www.weather.gov.hk/cis/normal/1971_2000/normals_e.htm). Secchi disc depth was obtained from monthly average data for 4 years (1998-2001) from EPD monitoring data. The mixed layer depth is defined as the depth where $\Delta\sigma_t$ ≥0.2 kg m^{-3} m^{-1} (Therriault and Levasseur 1985). In this study, z was estimated from a series of cruises conducted from 2004 to 2006. The cutoff of 465 W h m^{-2} d^{-1} was set empirically by Riley (1957), which has to be attained for an effective increase in phytoplankton biomass to occur in the mixed layer.

Statistical analyses

Linear regressions were used to analyze the time series using Sigmaplot 9.0 (n= number of sampling years for the monthly average data). A t-test was conducted to determine any significant difference between variables ($p < 0.05$).

Results

Salinity, temperature and density gradients

Salinity at the surface exhibited the same seasonal variation in both harbors, with a maximum (~ 32 in Victoria and ~ 31 in Tolo) in winter and a minimum (~ 26 in Victoria and ~ 28 in Tolo) in summer (Fig. 2). In Victoria, the water column was generally homogeneously mixed at all stations during November to March, as indicated by $\Delta\sigma_t$ of < 0.2 kg m^{-3} (Fig. 2). Subsequently, the stratification index increased and was strongest (up to 0.6 kg m^{-4}) during summer and weakened again in the fall (Fig. 3). In Tolo, stratification varied spatially and temporally, with the strongest stratification occurring in summer and the weakest in winter at all stations and there was a decrease from the inner Tolo to Tolo Channel. Stratification was extremely weak in Tolo Channel (TM8) during winter with a low SI of ~ 0.02 kg m^{-4} (Fig. 3).

Nutrients and nutrient ratios

In Victoria, the maximal NO_3 concentrations (>10 μM) occurred in summer, while NO_3 concentrations were relatively low (< 7 μM) in Tolo (Fig. 4). In Victoria, NH_4, DIN (=NH_4+NO_2+NO_3) and total nitrogen (TN) concentrations exhibited the same temporal variability with the highest (> 20 μM NH_4, close to or > 30 μM DIN and > 60 μM TN) in winter and the lowest (< 10 μM NH_4, 15-20 μM DIN and < 50 μM TN) in summer, especially in July (Fig. 4). In winter, surface NH_4 concentrations were usually higher than that at the bottom due to sewage input from the upper harbor. In Tolo, a much weaker seasonal pattern was observed for these three nutrients with no pronounced summer minima. NH_4 and DIN concentrations in Tolo were < 14 and 20 μM for NH_4 and DIN respectively. TN concentrations fluctuated between 40 and 80 μM) in inner and middle Tolo (TM4 and TM6) and were < 40 μM in Tolo Channel (Fig. 4).

In Victoria, PO_4 and total phosphorus (TP) at the surface demonstrated clear seasonal variations with the highest (> 1.6 μM PO_4 and > 3.5 μM TP) in winter and the lowest (< 1.0 μM PO_4 and < 2.0 μM TP) in summer (Fig. 4). A weaker seasonal pattern was observed for these two nutrients in Tolo. PO_4 and TP concentrations at the surface decreased markedly from 2 and > 5 μM in inner Tolo (TM4) and from < 1 to 3 μM in Tolo Channel (TM8) (Fig. 4).

In Victoria, the maximal SiO_4 concentrations (17-25 μM) occurred in summer. In contrast, in Tolo, SiO_4 concentrations at the surface were 5-15 μM, which were significantly lower than those (15-25 μM) at the bottom (Fig. 5).

In Victoria, DIN:PO_4 ratios indicated clear seasonal variations with low ratios (close to the Redfield ratio of 16N:1P) in the dry season and high ratios (up to 48:1) in summer (Fig. 5). DIN:SiO_4 ratios fluctuated between 1:1 to 4:1 (Fig. 5). SiO_4:PO_4 ratios exhibited clear seasonal variations with high ratios (> 16:1) in summer and low ratios (< 16:1) in other seasons (Fig. 5). These results indicated a seasonal shift in the potential limiting nutrient from P in summer to Si during other seasons in Victoria. In contrast, in Tolo, the DIN:PO_4 ratios were ~16:1 or lower all year (Fig. 5). DIN:SiO_4

ratios at the surface decreased from >1:1 in inner Tolo (TM4) to near or < 1:1 in Tolo Channel (TM8) (Fig. 5). By comparison, the SiO_4:PO_4 ratios increased from inner Tolo (TM4) with near or < 16:1 during October-May and > 16:1 during June-September to Tolo Channel (TM8) with > 32:1 most of the year (Fig. 5). These results revealed that the primary potential limiting nutrient varied spatially from Si in inner Tolo to N+P co-limitation in Tolo Channel.

Surface Chl *a* and bottom DO

In Victoria, the surface Chl *a* concentration exhibited clear seasonal variations with the highest (~13 μg L^{-1}) in summer and the lowest (< 2 μg L^{-1}) in winter (Fig. 6). In contrast, in Tolo, the surface Chl *a* concentrations were higher than Victoria, with a maximum (30 μg L^{-1}) occurring in spring. Spatial variations in the surface Chl *a* concentrations were observed, with high Chl (10-30 μg L^{-1}) in inner Tolo (TM4), intermediate (10-20 μg L^{-1}) in the middle Tolo (TM6) and low Chl (mostly < 10 μg L^{-1}) in Tolo Channel (TM8) (Fig. 6).

The bottom DO concentrations indicated the same seasonal variability in both harbors with the highest in winter and the lowest in summer. The minimal bottom DO concentration occurred in Aug in both harbors and approached hypoxic levels (~ 2 mg L^{-1}) in Tolo, and somewhat higher (~ 3 mg L^{-1}) in Victoria (Fig. 7).

Eutrophication recovery

In Victoria, NH_4, DIN, TN, PO_4 and TP decreased by 13-48%, 14-32%, 38-43%, 24-41% and 38-53%, respectively, after sewage treatment began in 2001 (Fig. 8). A significant (17-20%) decrease in SiO_4 concentrations was observed at VM2 and VM5. In contrast, there was a significant increase (26-55%) in NO_3 concentrations at VM5 and VM7. DIN:PO_4 ratios increased significantly (40-65%) due to the increase in NO_3 and decrease in PO_4. Chl *a* concentrations increased by 15-33%, but not significantly.

The bottom DO decreased significantly (11-20%) (Fig. 8).

In Tolo, NH_4, NO_3, DIN, TN, PO_4 and TP decreased by 32-40%, 34-61%, 37-43%, 38-43%, 50-76% and 64-67%, respectively, after sewage treatment began in 1997. DIN:PO_4 and DIN:SiO_4 ratios increased significantly by 60-128% and 119-294% at TM4 and TM6, respectively due to the large decrease in nitrogen. There were a significant (32-38%) reduction in Chl *a* and an increase (11-20%) in bottom DO concentrations (Fig. 8).

Discussion

Tolo Harbour (pre-treatment:1986-1997)

Physical processes

Tolo is a nearly land-locked long inlet with a relatively long flushing time. The tidal current velocities increase from 0.01-0.02 m s^{-1} in inner Tolo to 0.2-0.3 m s^{-1} in Tolo Channel due to its narrow opening to a coastal bay (Lee and Arega 1999). The residence time of water in Tolo is on average 28 days. It varies seasonally from a very long residence time of 38 days in the dry season due to downwelling induced by the NE monsoon winds, to 14.4 days in the wet season since the input of freshwater (e.g. rainfall and runoff) and the surface outflow induced by the southwest monsoon winds produces a shorter residence time in summer (Lee et al. 2006). Stratification occurred during all months in Tolo, except for the outer channel in winter and was strongest in summer due to reduced surface salinity from the high rainfall and high bottom salinity due to upwelling induced inflow at the bottom from Mirs Bay (Figs. 2 and 3).

Nutrients

In Tolo, local sewage discharge was a major nitrogen source and NH_4 was the main contributor to DIN, accounting for > 50% of DIN. NO_3 also resulted from sewage, not runoff, since NO_3 concentration was the lowest in summer during the period of maximum runoff. On average, DIN only accounted for ~25% of TN since phytoplankton biomass was high. The continual supply of nutrients from sewage contributed sufficient NH_4 and PO_4 for algal growth.

Higher SiO_4 concentrations at the bottom implied that remineralized Si from the sediments was a major Si source for diatom growth in the dry season when weak stratification favored the replenishment of SiO_4 from the bottom. In comparison, in summer, runoff contributed Si to Tolo as the surface SiO_4 concentrations rose from a minimum in spring, and the SiO_4:PO_4 ratio was higher than other seasons, despite the decreased replenishment of SiO_4 from the bottom waters due to strong stratification. Si was rarely limiting since there was sufficient input from remineralized Si at the bottom and runoff in the summer. Grazing by *N. scintillans* might promote Si recycling to sustain diatom growth since diatoms are the most common prey (Liu and Wong 2006).

Eutrophication impacts: algal blooms

Tolo appears to be vulnerable to eutrophication due to the stable physical processes (e.g. slow water velocity, long flushing time and stratification). The high input of nutrients and poor circulation favored the development of algal blooms and the utilization of nutrients in inner Tolo where Chl *a* was >10 μg L^{-1} all year, and the main nitrogen component was organic forms (i.e. TN-DIN = organic N) (Fig. 4). Algal blooms were mainly caused by dinoflagellates (e.g. *Prorocentrum minimum* and *Prorocentrum triestinum*) during the winter-early spring and diatoms (e.g. *Skeletonema costatum*) during late spring and summer (Yin et al. 2003).

The high Chl *a*, but no obvious drawdown in Si in January and February suggested that these blooms were mostly dinoflagellates or other flagellates. This suggestion was supported by the observations that dinoflagellate blooms (e.g. *P. minimum*) peaked during the winter-early spring period (Yin 2003, EPD 2007). During this period, grazing on diatoms by *N. scintillans* might favor the development of dinoflagellate blooms. In the late spring (May), the minimum SiO_4 concentrations occurred as well as the peak in chlorophyll, indicating a spring bloom of diatoms (Figs. 5 and 6), which was coincident with the previous reports that *Skeletonema costatum* peaked in May (Yin 2003). During this late spring period, SiO_4 concentrations episodically decreased below the growth limiting threshold of 2 μM. This was likely related to the decreased grazing on diatoms due to rapid decline in abundance of *N. scintillans* at high temperatures (> 25 ^oC) (Liu and Wong 2006).

Over the winter-spring period, the downwelling induced by the northeast monsoon winds promoted the concentration of phytoplankton biomass in the inner harbor (Yin 2003). As a result, the maximal Chl *a* concentrations occurred during this period. In contrast, in summer, the relatively more rapid surface outflow of freshwater due to high rainfall and runoff restricts the accumulation of the phytoplankton biomass despite the stronger stratification, high temperature and growth rate during this period. Furthermore, the prevailing southwest monsoon wind helps to move the surface water out of the harbor and through Tolo Channel in summer. Therefore, phytoplankton biomass and nutrients other than SiO_4 were diluted by freshwater in summer, and this suggestion was supported by the lowest TN concentrations in summer (Fig. 4), since, in general, nutrient loading from the sewage should remain relatively constant all year. In summer, high rainfall and runoff had a significant effect on semi-enclosed Tolo with a small surface area as indicated by a sharp (4 unit) reduction in surface salinity compared to the dry season.

In Tolo, light may rarely limit phytoplankton growth near the surface since the year round stratification and long residence times provided a long growing period for the phytoplankton in Tolo where Secchi disc depth was 1.8 m in the inner Tolo and up to 5.0 m in Tolo Channel (Yung et al. 1997).

The tidal currents speed increases ~15 times from the inner Tolo to Tolo Channel (Lee and Arega 1999), and over this transect there was a decline in nutrient concentrations and phytoplankton biomass due to dilution by coastal/oceanic water, as well as a shift in the potential limiting nutrient. For example, the dilution caused a 30% reduction in TN in Tolo Channel. Chl *a* concentrations were < 8 μg L^{-1} all year, except in April when the extremely high monthly average Chl *a* concentration (~35 μg L^{-1}) was caused by four episodic algal blooms in April (e.g. 87 and 140 μg Chl *a* L^{-1} in 1988, 67 μg Chl *a* L^{-1} in 1990 and 360 μg Chl *a* L^{-1} in 1995). Hence high nutrient loading in the inner Tolo had limited effects on eutrophication impacts in Tolo Channel due to relatively active hydrodynamic conditions induced by narrow topography and invasion of the oceanic water and less nutrient input.

Eutrophication impacts: hypoxia

Hypoxia is another important eutrophication impact in estuarine and coastal waters (Boynton et al. 1995, Kemp et al. 1999, Hagy et al. 2004). A summer bottom DO minimum approached the hypoxic level (~ 2 mg L^{-1}) in terms of the monthly average DO concentrations. However, more frequent sampling data revealed that frequent hypoxic events and even a few anoxic (DO < 0.2 mg L^{-1}) events occurred during summer, as indicated by a minimal DO concentration of ~ 0.1 mg L^{-1} (Fig. 10). Probably the decomposition of organic matter from the sewage and algal blooms consumed substantial amounts of oxygen at the bottom. Furthermore, stratification diminished vertical oxygen transport and promoted the development of hypoxia in bottom waters, especially in summer. In previous studies, increased stratification due to an increase in the input of the freshwater discharge volume was found to stimulate the development of algal blooms by increasing the residence time of phytoplankton in the euphotic zone (Howarth et al. 2000) and hypoxia in bottom waters by reducing vertical oxygen transport in the northern Gulf of Mexico (Justic et al. 1996, 2005). The shallow water column helped to reduce the severity of the hypoxic events in inner Tolo. An inverse relationship between the volume of hypoxic bottom waters and the mean depth was observed in regions of the Chesapeake Bay (Fisher et al. 2006). In Tolo Channel, the episodic low O_2 events in summer were related to upwelling and the possible invasion of low O_2 bottom water from offshore.

Victoria Harbour (pre-treatment: 1986-2001)

Physical processes

Victoria is a highly-flushed narrow shallow channel, characterized by strong vertical mixing most of the year and with a high tidal current velocity up to 1.2 m s^{-1} and 25 times higher than Tolo (Lee et al. 2006). Strong vertical mixing occurred during the dry season due to the influence of the tidal current and coastal/oceanic water induced by the strong northeast monsoon wind, while strong stratification occurred in summer due to the invasion of the Pearl River discharge. However, high Pearl River discharge increased the horizontal water velocities. As a result, the water residence times (1.5-2.5 days) in the wet season were 3 times shorter than the dry season (5-7 days) (Kuang and Lee 2004, Lee et al. 2006).

Nutrients

In Victoria, nutrient concentrations were influenced by year round local sewage inputs, the Pearl River discharge in summer and coastal/oceanic water in winter (Yin and Harrison 2007, Ho et al. 2008, Xu et al. 2008). High NH_4 and PO_4 concentrations were attributed mainly to the local sewage effluent input (Yin and Harrison 2007). In the dry season, NH_4 concentrations was around 4-fold higher than NO_3, indicating the high NH_4 contribution from local sewage discharge. DIN and TN followed the NH_4 pattern and therefore confirmed that NH_4 was much more abundant than NO_3. In summer, the Pearl River discharge delivered high NO_3 and SiO_4 concentrations (Xu et al. 2008), while the concentrations of nutrients other than NO_3 and SiO_4 were diluted, as reflected by the lowest TN (< 50 μM) in summer. Lower TN concentration (~ 42 μM) at VM7 in summer than (~ 50 μM) other two stations, indicated that stations nearest to the Pearl River estuary were subjected to more dilution since TN loading was comparable in three stations without the influence of the Pearl River discharge in the dry season. Further evidence for the influence of the Pearl River nutrient input was the higher SiO_4:PO_4 ratios at VM7 than the other two Victoria stations farther away since the Pearl River discharge is characterized by high SiO_4:PO_4 ratio (~100:1) (Xu et al. 2008).

Victoria received sewage loading that was almost 10-fold higher than Tolo (Broom et al. 2003). However, TN, PO_4 and TP concentrations were similar in Victoria and the inner Tolo (Fig. 4), probably attributed to high dilution in Victoria. In Victoria, DIN was at least 50% higher than Tolo and accounted for roughly 50% of TN because of high input of sewage discharge and the Pearl River discharge in summer and less biological uptake, while DIN was < 30% of TN in Tolo due to high biological uptake.

Eutrophication impacts: algal blooms

Victoria was more resistant to eutrophication due to the active physical processes (e.g. strong vertical mixing and flushing). In contrast to Tolo, phytoplankton biomass in Victoria was much lower (Fig. 6) and the maximal Chl *a* concentrations (~ 13 μg L^{-1}) in Victoria occurred in summer when the water column was stratified. In Victoria, the phytoplankton standing stock appeared to be more dependent on the water column stability rather than nutrients, as indicated by the highly significant correlation between surface Chl *a* concentrations and the stratification index (Fig. 9). The establishment of strong stratification not only maintained phytoplankton cells in the euphotic zone, but reduced the mixed layer depth and increased the light availability in the mixed layer (Table 1), which favored phytoplankton growth and nutrient utilization. As a result, the lowest NH_4 and PO_4 concentrations occurred in this period. This Chl *a* was mainly composed of diatoms (e.g. *Skeletonema costatum*) because of the continual high input of Si from the Pearl River discharge (Xu et al. 2009). On the other hand, the high volume Pearl River discharge also prevented further accumulation of phytoplankton biomass by reducing residence times (Xu et al. 2009). Furthermore, it is difficult for the surface water to remain in the surface for a long period due to strong tidal currents. The tidal-induced vertical mixing transported phytoplankton biomass below the photic zone, as indicated by fairly high Chl *a* concentrations (~ 5 $\mu g\ L^{-1}$) at the bottom in summer.

In contrast, in the dry season, strong vertical mixing by tidal currents transported the phytoplankton cells below the euphotic zone and distributed phytoplankton evenly in the entire water column. The mean light intensity in the mixed layer was close to or below the cutoff of 465 $W\ h\ m^{-2}\ d^{-1}$ (Table 1), implying that phytoplankton growth was light-limited. Light limitation might extend to spring since strong vertical mixing still occurred in April (Xu et al. 2009). Hence, strong vertical mixing was likely responsible of the low Chl *a* concentrations (< 2 $\mu g\ L^{-1}$) and the lack of a typical spring bloom, although grazing might also be important.

Eutrophication impacts: hypoxia

In Victoria, few hypoxic events (DO < 2 $mg\ L^{-1}$) occurred despite the much higher inputs of sewage relative to Tolo. In Victoria, destratification due to strong tidal currents in summer and strong vertical mixing in other seasons favored vertical oxygen transport to the bottom waters. High flushing in Victoria diluted the organic matter, which reduced the demand for oxygen (Ho et al. 2008). As a result, hypoxic events rarely occurred. Therefore, Victoria is much more resilient to nutrient enrichment due to its active hydrodynamic conditions.

Nutrient reduction and eutrophication recovery

Tolo Harbour (post-treatment: 1998-2007)

A 90% reduction in sewage loading resulted in a significant reduction in the concentrations of nutrients other than SiO_4 at all stations. A significant decrease in NO_3 confirmed that NO_3 mainly resulted from sewage, not freshwater. The percentage reduction in phosphorus was more than nitrogen and this was accompanied by a significant increase in DIN:PO_4 and SiO_4:PO_4 ratios (Fig. 8). DIN:PO_4 and SiO_4:PO_4 ratios were on average > 16:1 after sewage treatment, suggesting that P was the potential limiting nutrient. In inner and outer Tolo, a small (5-13%) increase in SiO_4 after treatment was likely linked to the decrease in Chl *a* as diatoms were usually the dominant group in Tolo most of the year (Yung et al. 1997; Wong and Wong 2004) and Si input should remain relatively constant. The percentage increase in SiO_4 was much less than the reduction in Chl *a*. Hence, we speculate that most of reduced phytoplankton biomass was from non-silicious species and the contribution of diatoms to the phytoplankton community might have increased after sewage treatment since the potential limiting nutrient shifted from Si to P in response to sewage treatment.

Eutrophication impacts have been reduced significantly in response to nutrient reduction. The magnitude and frequency of algal blooms (> 10 μg Chl L^{-1}) have fallen dramatically. High Chl *a* concentrations (> 40 μg Chl L^{-1}) were frequently observed and the peak value was up to 150 μg L^{-1} at TM4 before sewage treatment. In contrast, Chl *a* concentrations declined to mostly < 20 μg L^{-1} after sewage treatment. The frequency of algal blooms events decreased from 13-56% of sampling cases before sewage treatment to 6-41% after sewage treatment. The frequency of red tides occurrences decreased from on average 15 per year before sewage treatment to 8 per year after treatment (EPD 2007), likely due to the reduction in diatom biomass. These results confirmed that Tolo was mainly a nutrient-controlled ecosystem. The bottom DO levels have improved and few hypoxic events were detected after the sewage treatment since the biological oxygen demand decreased by 83% after sewage treatment (Broom et al. 2003).

The response in eutrophication impacts to nutrient reduction was more obvious in the inner Tolo, as indicated by the higher percentage reduction in Chl *a* and the increase in bottom DO. The surface Chl *a* declined significantly by 32 and 38% respectively and the bottom DO level increased significantly by 20 and 11% respectively in the inner and outer Tolo (Fig. 8). This response decreased towards Tolo Channel. In Tolo Channel, although nutrient loading has fallen significantly, recovery for eutrophication was not significant (Fig. 8). This is probably related to the spatial increase in hydrodynamic conditions from inner Tolo to Tolo Channel. There was little change in the bottom DO between pre- and post-treatment since the bottom DO was more related to summer upwelling and the input of low O_2 bottom water from offshore, rather than nutrient enrichment.

Victoria Harbour (post-treatment: 2002-2007)

After sewage treatment in 2001, there was a significant reduction in nutrient concentrations. The reduction in nutrients from sewage demonstrated a clear gradient along the west (VM7) to east (VM2) transect. The highest percentage decrease in nutrients (NH_4, PO_4, TN, and TP) from the sewage often occurred at VM2 far from the Pearl River estuary (Fig. 8). The higher average post-treatment NO_3 concentrations compared to pre-treatment were associated with an increase in NO_3 concentrations in the Pearl River discharge in recent years (Xu et al. 2008). A rise in NO_3 was more obvious (55%) at VM7 and due to the increase in NO_3 concentrations in the Pearl River discharge over the last several decades (Xu et al. 2008). The increased NO_3 compensated for the loss of NH_4, resulting in a slight (8%) increase in DIN (Fig. 8). On the other hand, the high Pearl River discharge in summer pushed some of the sewage from the Stonecutters Inland to Victoria Harbour, reducing the eutrophication recovery. Similar to Tolo, a greater reduction in phosphorus relative to nitrogen led to a significant (40-65%) increase in DIN:PO_4 ratios. In summer, P became the potential limiting nutrient as a result of the high input of NO_3 and SiO_4 from the Pearl River discharge (Xu et al. 2009). In contrast to Tolo, a significant (16-20%) decrease in SiO_4 was observed in Victoria (VM5 and VM2), which was most likely attributed to the 26-33% increase in Chl *a* after treatment, since an increase in SiO_4 was not significant at VM7 despite a 15% increase in Chl *a* after sewage treatment, suggesting that Si input did not change significantly.

In Victoria, algal biomass and bottom DO differed in response to nutrient reduction. After sewage treatment, the magnitude of algal blooms has not been reduced and the observed peak in Chl *a* concentration (~53 $\mu g\ L^{-1}$) at VM5 and VM2 was higher than during pre-treatment. Overall, nutrient reduction did not result in a decrease in algal biomass. In fact, the average post-treatment surface Chl *a* concentration was 15-33% higher than during pre-treatment (Fig. 8). The frequency of algal blooms increased from 9-10% of sampling cases before sewage treatment to 10-14% after sewage treatment (Fig. 7). In contrast, no hypoxic events were detected after sewage treatment and a significant (11-22%) increase in the bottom DO levels was likely attributed to a 50% decrease in the organic pollution loading due to sewage treatment in Victoria (Broom et al. 2003).

Summary

The susceptibility of coastal and estuarine ecosystems to eutrophication was strongly influenced by the physical processes in the two contrasting harbors in Hong Kong. The weakly-flushed Tolo was vulnerable to nutrient enrichment, especially in inner and outer Tolo where long water residence times, weak currents and year round stratification favored nutrient utilization and the development of phytoplankton blooms. During the winter-early spring period, the favorable physical processes (e.g. downwelling) helped concentrate the algal biomass, resulting in some dinoflagellate blooms. In the late spring, a spring diatom bloom occurred possibly due to a decrease in grazing pressure on diatoms. In summer, the inputs of rainfall and runoff shortened water residence times and diluted the algal biomass and consequently, algal biomass was lower relative to other seasons. Frequent hypoxic events occurred in summer in this region due to stratification. A significant decline in algal biomass was observed in response to nutrient reduction after sewage treatment. However, in Tolo Channel, eutrophication impacts were not significantly reduced after nutrient reduction due to the slow flushing time caused by its narrow opening to the coast and the large reservoir of nutrients in the sediments from the pre-treatment period.

In contrast, in the highly-flushed Victoria, the ecosystem appeared to be less susceptible to nutrient enrichment. In summer, an increase in stratification due to the invasion of the Pearl River discharge stimulated phytoplankton growth by increasing the residence time of phytoplankton in the euphotic zone. On the other hand, the high volume Pearl River discharge increased the flushing rate and shortened the water residence times, which restricted the further accumulation of the phytoplankton biomass in the water column and in the sediments. Furthermore, it is difficult to maintain stratification due to strong tidal mixing. During fall, winter and spring, strong vertical mixing resulted in light limitation and dilution of the algal biomass. Since vertical mixing favored the vertical transport of oxygen, hence, few hypoxic events occurred in Victoria. In Victoria, nutrient reduction after sewage treatment had no contribution to a reduction in the phytoplankton biomass since phytoplankton growth was mainly regulated by the physical processes (e.g. strong vertical mixing and high flushing rate). In fact, Chl *a* increased by up to 33% after sewage treatment. In both harbors, the bottom DO has increased due to a reduction in the loading of organic pollutants after sewage treatment.

In summer, the phytoplankton biomass responded differently to the freshwater inputs in Tolo and Victoria because of their distinctly different inputs and physical properties. In the weakly-flushed Tolo, the freshwater inputs reduced the residence time and diluted phytoplankton biomass. This response was similar to the Hudson River estuary (Howarth et al. 2000). In contrast, in the highly-flushed Victoria, the freshwater inputs weakened the vertical mixing, which promoted the growth and accumulation of phytoplankton in the euphotic zone. Similar results were reported in the northern Gulf of Mexico (Justic et al. 1996, 2005).

Acknowledgements

Financial support for this research was provided by the University Grants Council of Hong Kong AoE project (AoE/P-04/0401). We thank the Hong Kong Government EPD for permitting us to use their water quality monitoring data for this publication.

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Table 1 Mean daily solar radiation (I_o), Secchi disc depth, mixed layer depth (z) and mean light intensity in the mixed layer (<I>). I_o was obtained from monthly average data from the 30-year (1971-2000) monitoring data from Hong Kong Observatory. Secchi disc depth was obtained from monthly average data for 4 years (1998-2001) from EPD monitoring data. Z was obtained from cruises conducted from 2004-2006. NA denotes not available.

Month	**I_o**	**VM7**			**VM5**			**VM2**		
		Secchi	**z**	**<I>**	**Secchi**	**z**	**<I>**	**Secchi**	**z**	**<I>**
Jan	2931	2.50	10	507	2.63	11	484	2.38	12	403
Feb	2669	2.25	10	416	2.28	11	383	2.70	12	416
Mar	2828	1.95	10	383	2.00	11	357	2.25	12	368
Apr	3286	1.83	10	416	2.08	11	430	1.95	12	371
May	3986	2.00	NA	NA	1.93	NA	NA	2.35	NA	NA
Jun	4253	2.00	2	2254	1.93	2	2206	1.95	2	2222
Jul	4867	2.75	3	2454	2.43	1	3670	3.00	2	3128
Aug	4447	2.13	3	1901	2.38	3	2048	2.38	3	2048
Sep	4206	2.00	10	584	1.75	11	465	2.38	12	578
Oct	4017	1.80	NA	NA	1.63	NA	NA	2.15	NA	NA
Nov	3511	2.25	10	548	2.25	11	498	2.25	12	457
Dec	3092	2.55	10	546	2.45	11	477	2.63	12	469

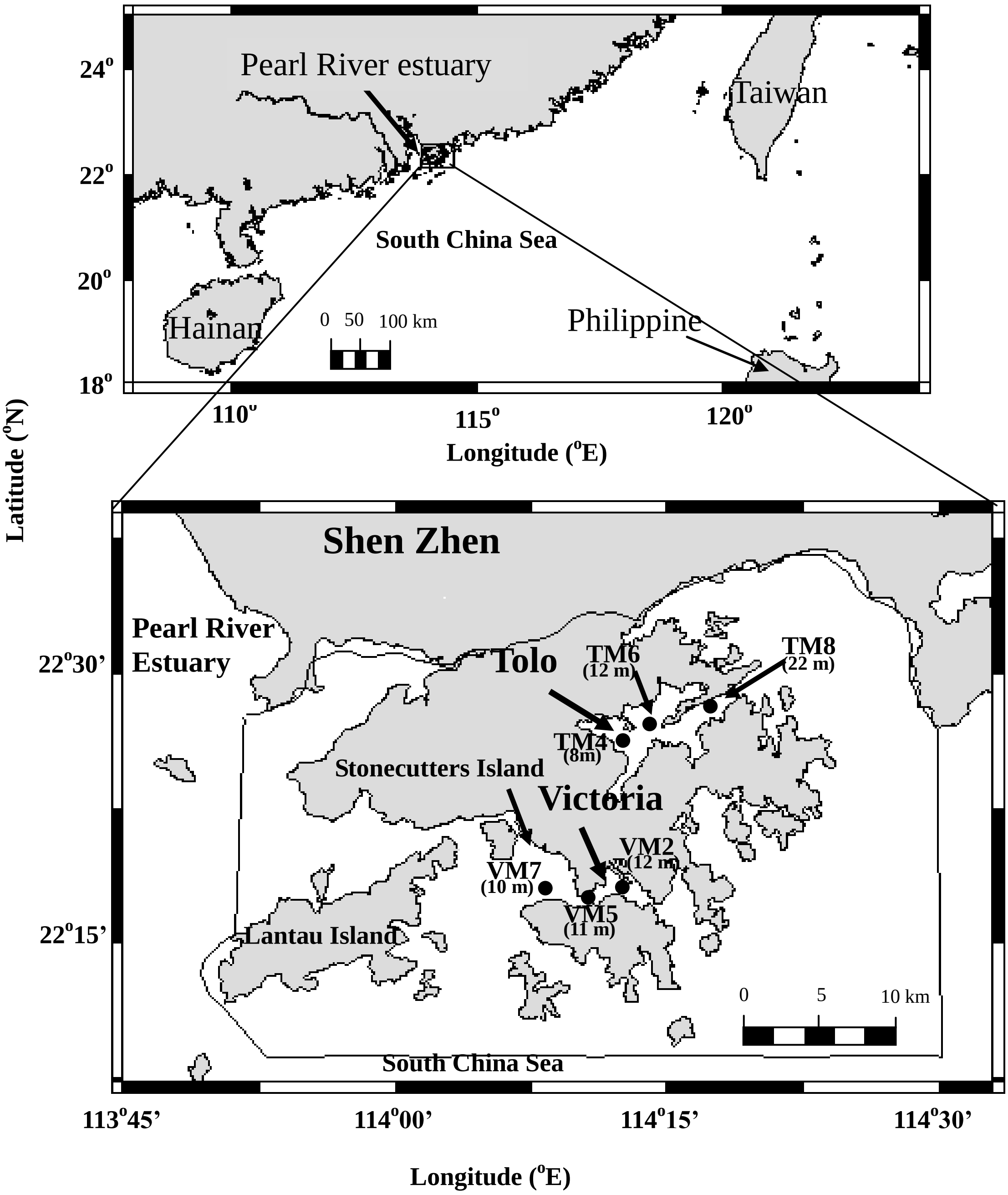

Fig. 1 Location of the six sampling stations in Hong Kong waters. The depths of the stations are shown in brackets. These 6 stations are the same as the EPD stations.

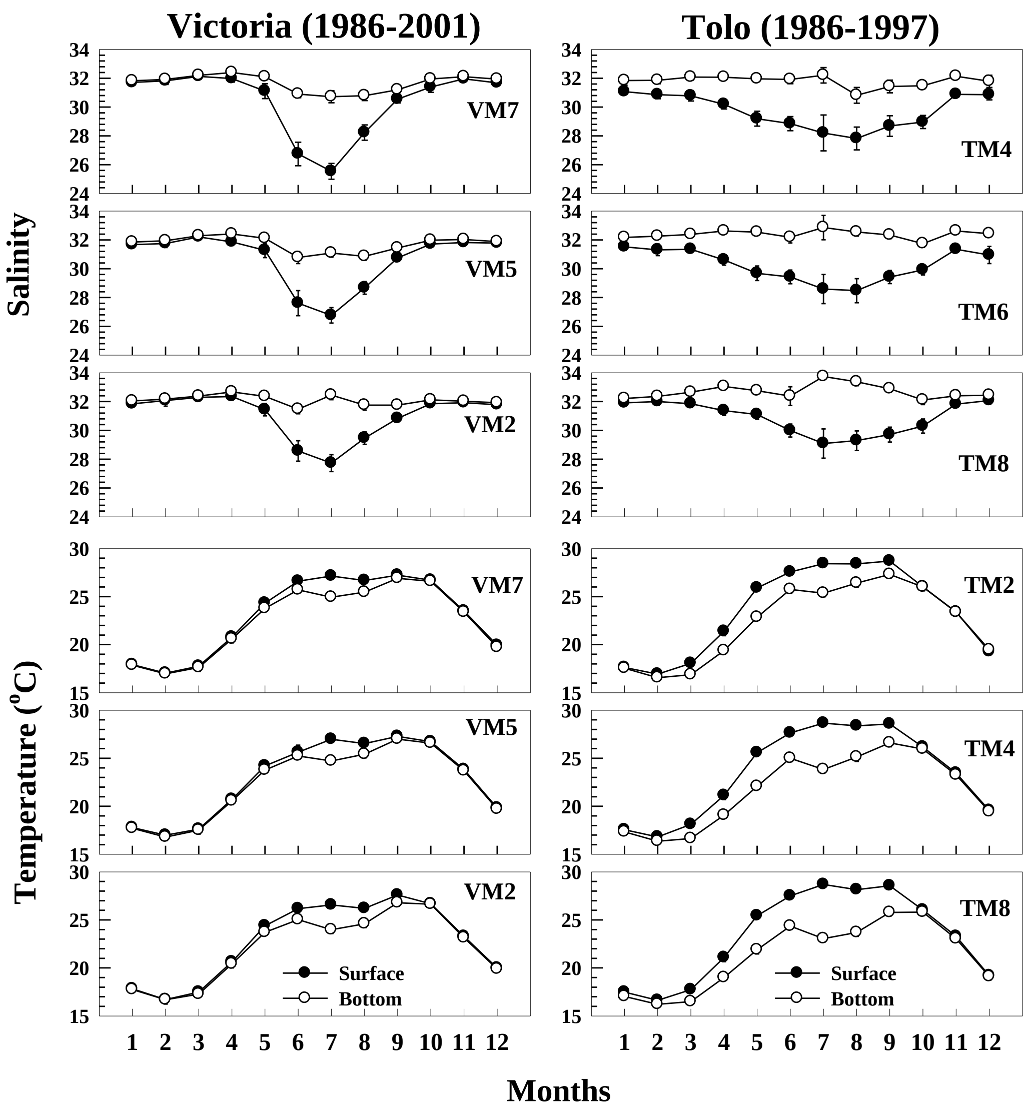

Fig. 2 Monthly average salinity and temperature at the surface and bottom at three stations (VM7, VM5 and VM2) in Victoria from 1986-2001, and at three stations (TM4, TM6 and TM8) in Tolo from 1986-1997, before sewage abatement. Bars = ±1 SE, n=22 (data from EPD, Hong Kong).

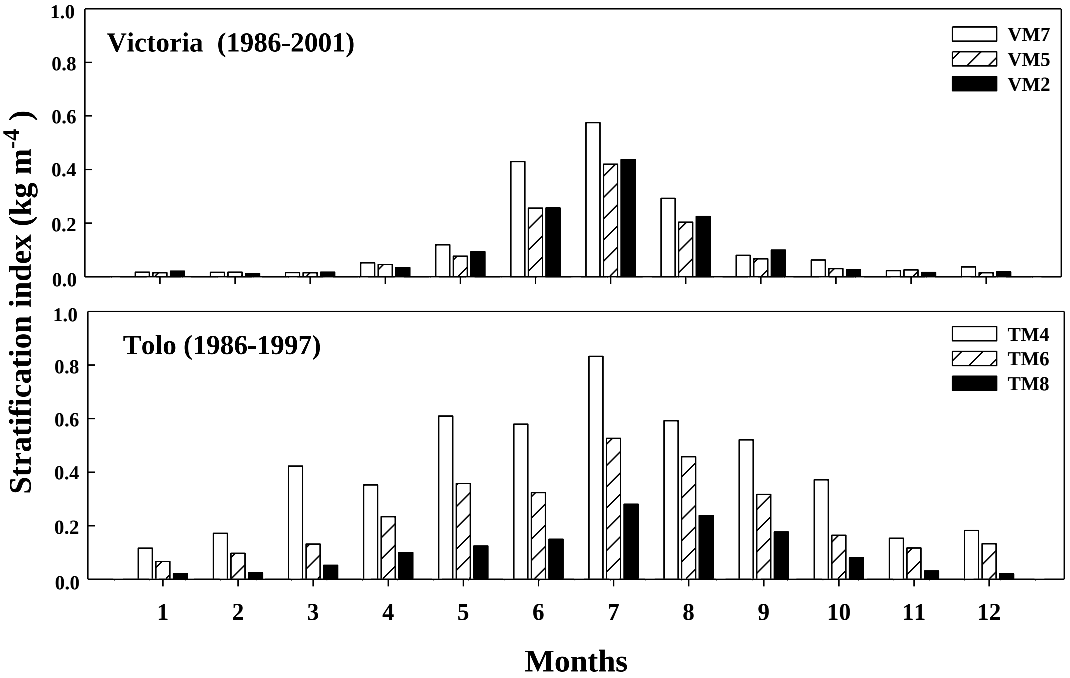

Fig. 3 Monthly average stratification index between the surface and bottom at three stations (VM7, VM5 and VM2) in Victoria from 1986-2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986-1997 before sewage abatement. Bars = ±1 SE, n=22 (data from EPD, Hong Kong).

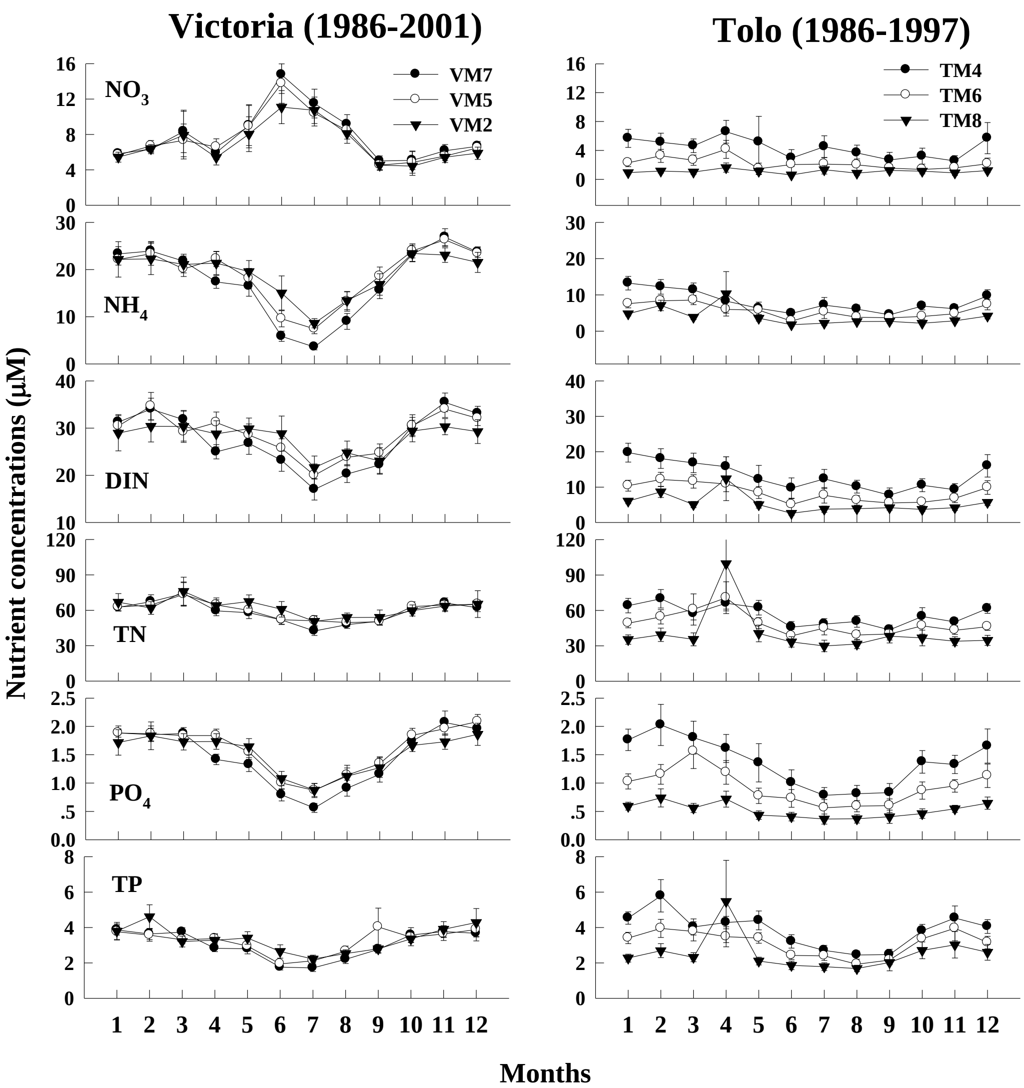

Fig. 4 Monthly average nutrient (NO_3, NH_4, DIN, TN, PO_4, TP) at the surface at three stations (VM7, VM5 and VM2) in Victoria from 1986-2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986-1997 before sewage abatement. Bars = ±1 SE, n=22 (data from EPD, Hong Kong).

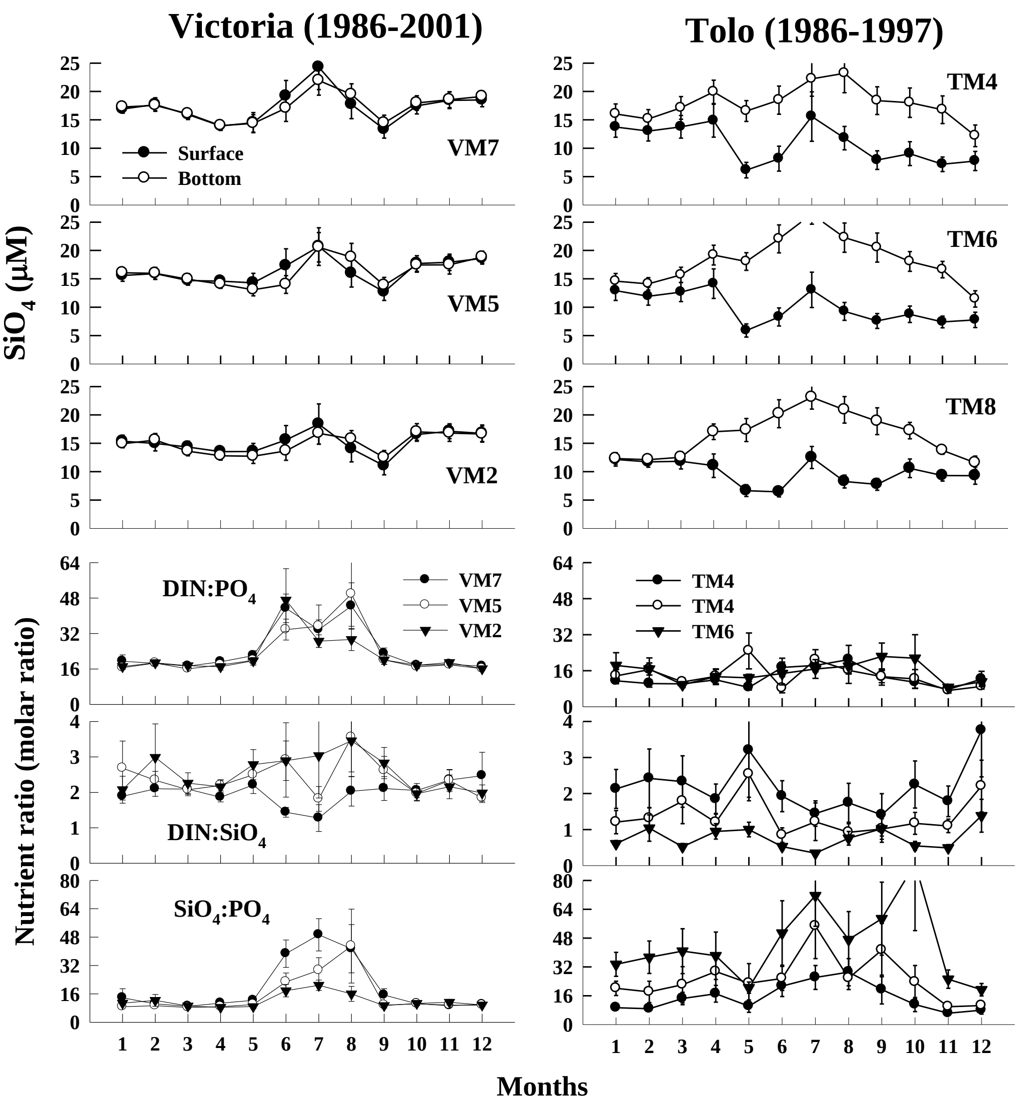

Fig. 5 Monthly average SiO_4 at the surface and bottom and nutrient ratio at the surface at three stations (VM7, VM5 and VM2) in Victoria from 1986-2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986-1997 before sewage abatement. Bars = ±1 SE, n=22 (data from EPD, Hong Kong).

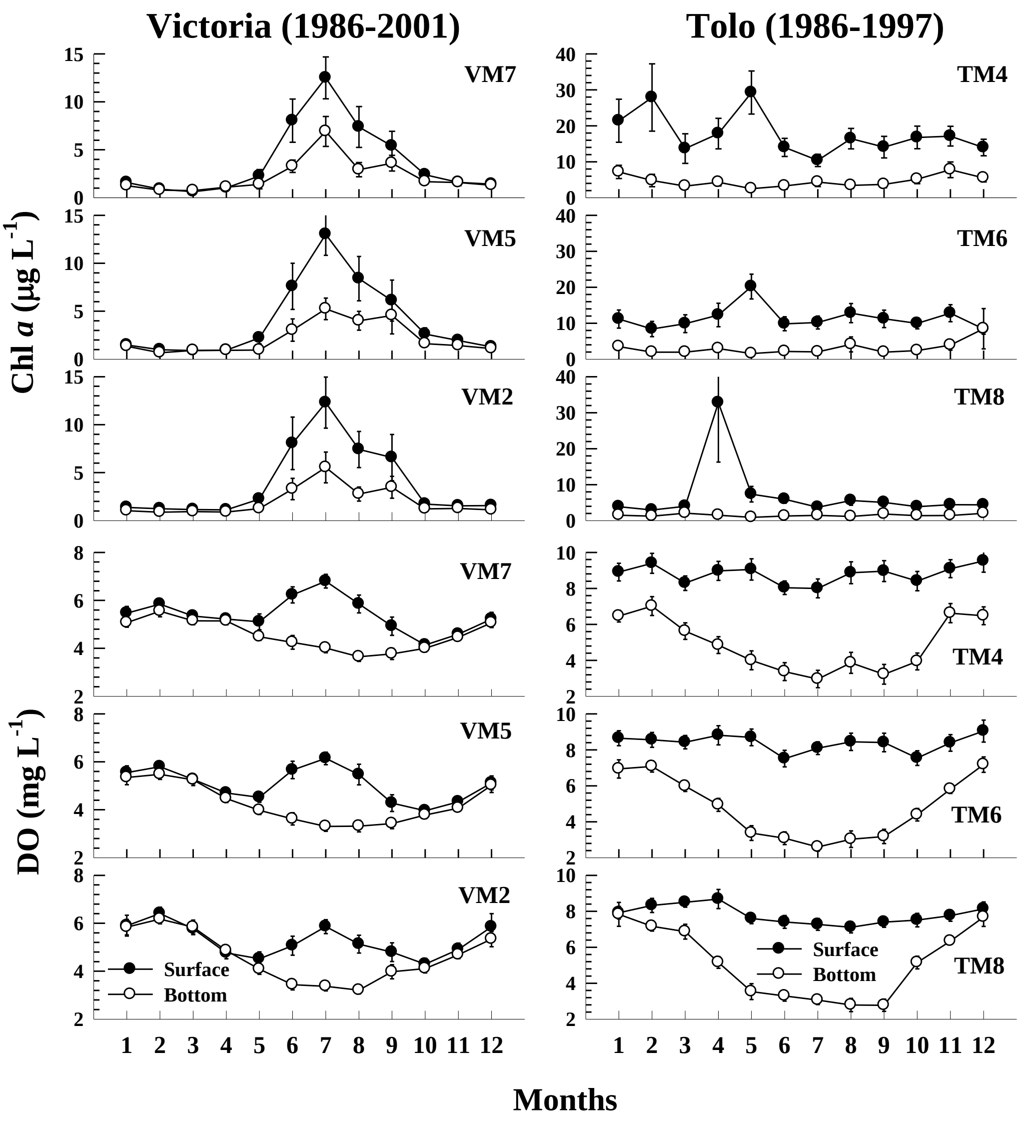

Fig. 6 Monthly average Chl *a* and DO at the surface and bottom at three stations (VM7, VM5 and VM2) in Victoria from 1986-2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986-1997 before sewage abatement. Bars = ±1 SE, n=22 (data from EPD, Hong Kong). Note the different scale for Chl between Victoria and Tolo

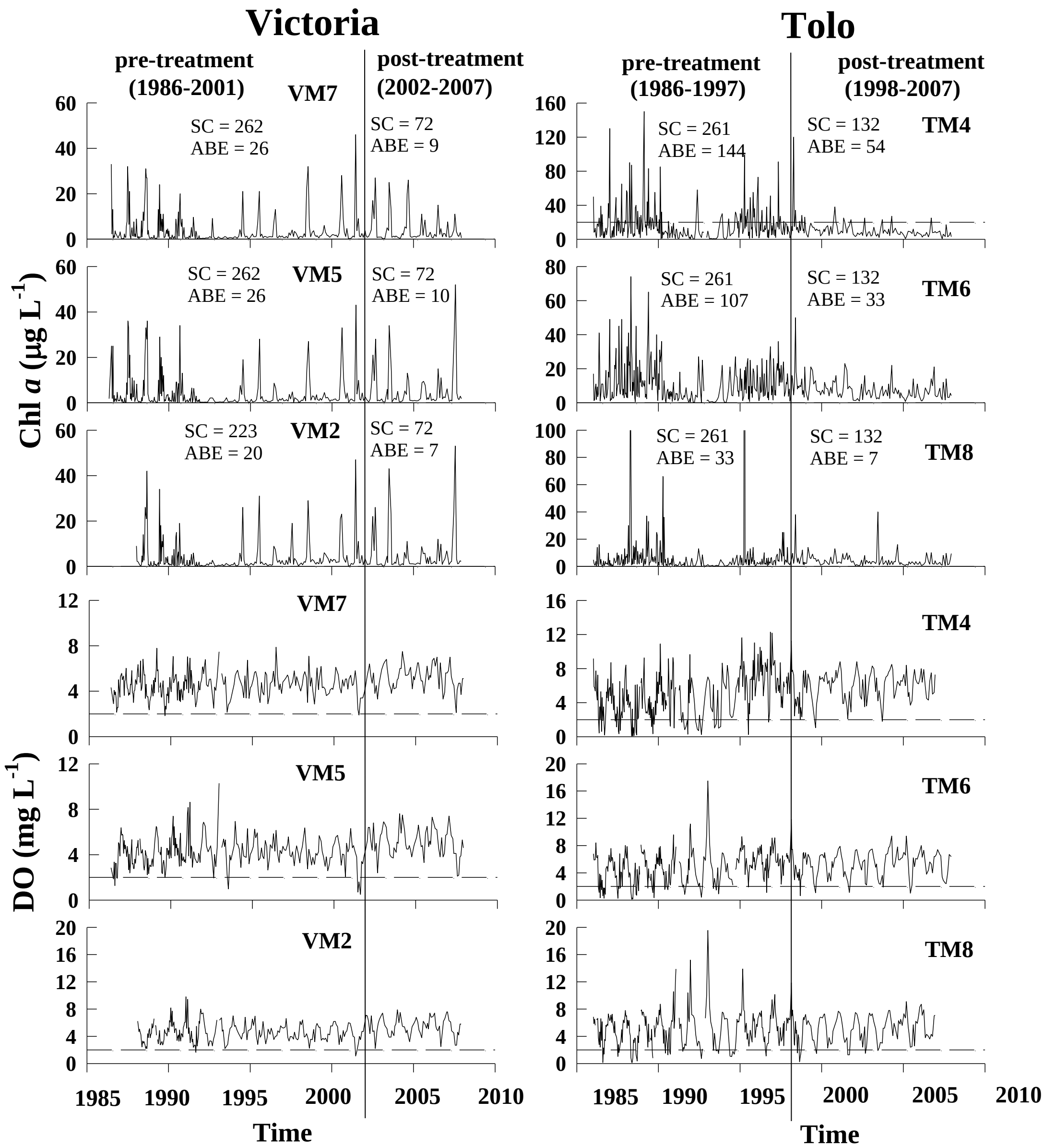

Fig. 7 Changes in the surface Chl *a* and the bottom DO at three stations (VM7, VM5 and VM2) in Victoria and at three stations (TM4, TM6 and TM8) in Tolo from 1986-2007 during pre-treatment and post treatment phases. The dashed line = 2 mg O_2 L^{-1} below which hypoxic events occur (data from EPD, Hong Kong). SC and ABE denote sampling cases and algal blooms events.

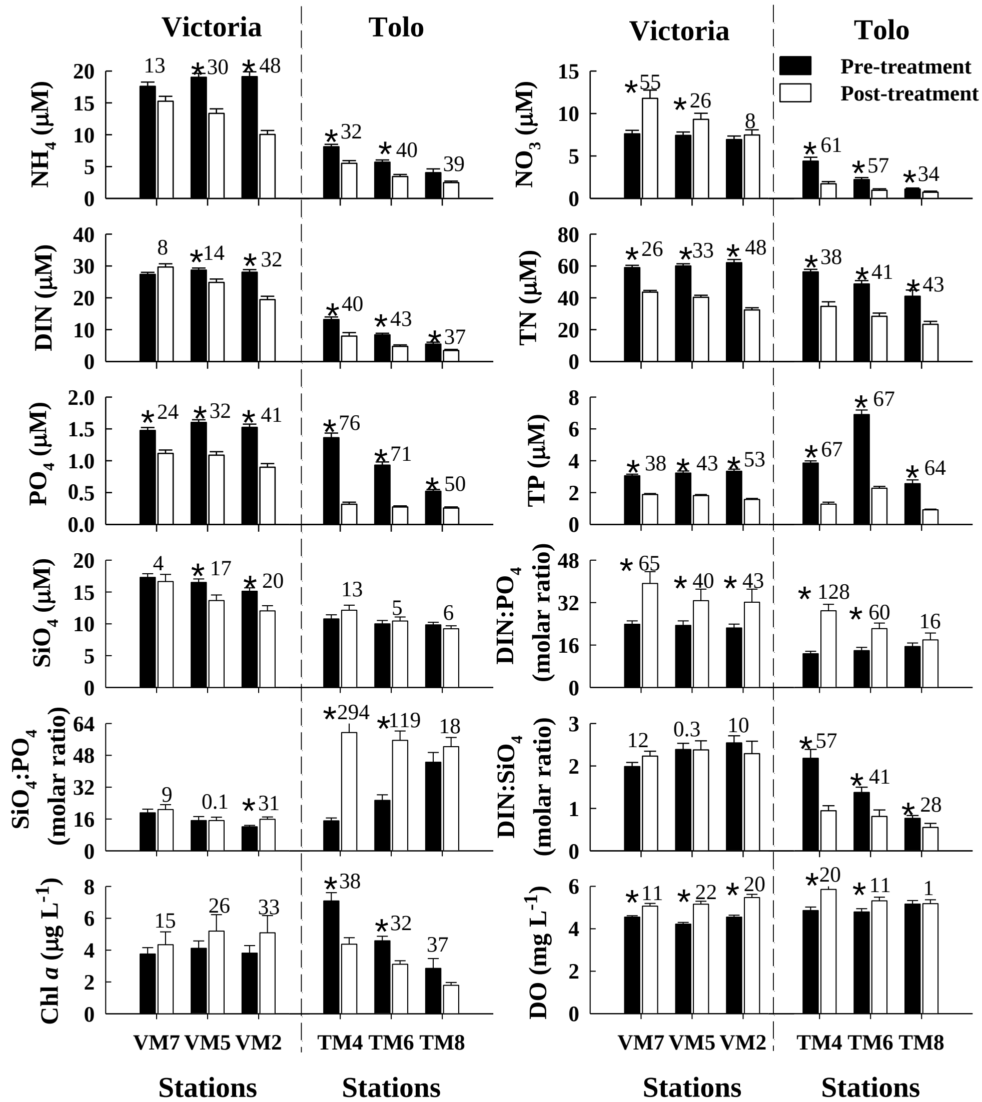

Fig. 8 Average pre-treatment and post-treatment surface nutrients and nutrient ratios (NH_4, NO_3, DIN, TN, PO_4, TP, SiO_4, DIN:PO_4, SiO_4:PO_4, DIN:SiO_4), Chl *a* and bottom DO at three stations (VM7, VM5 and VM2) in Victoria and at three stations (TM4, TM6 and TM8) in Tolo. Bars = ±1 SE. * denotes a significant difference at $p < 0.05$ level. Note that pre-treatment is from 1986 to 2001 (n = 222) in Victoria and 1986 to 1997 (n = 262) in Tolo, and post-treatment is from 2001 to 2007 (N = 72) in Victoria and 1997 to 2007 (n = 132) in Tolo. The number above bars represents the percentage of the increase or decrease in the parameter after sewage treatment relative to pre-treatment.

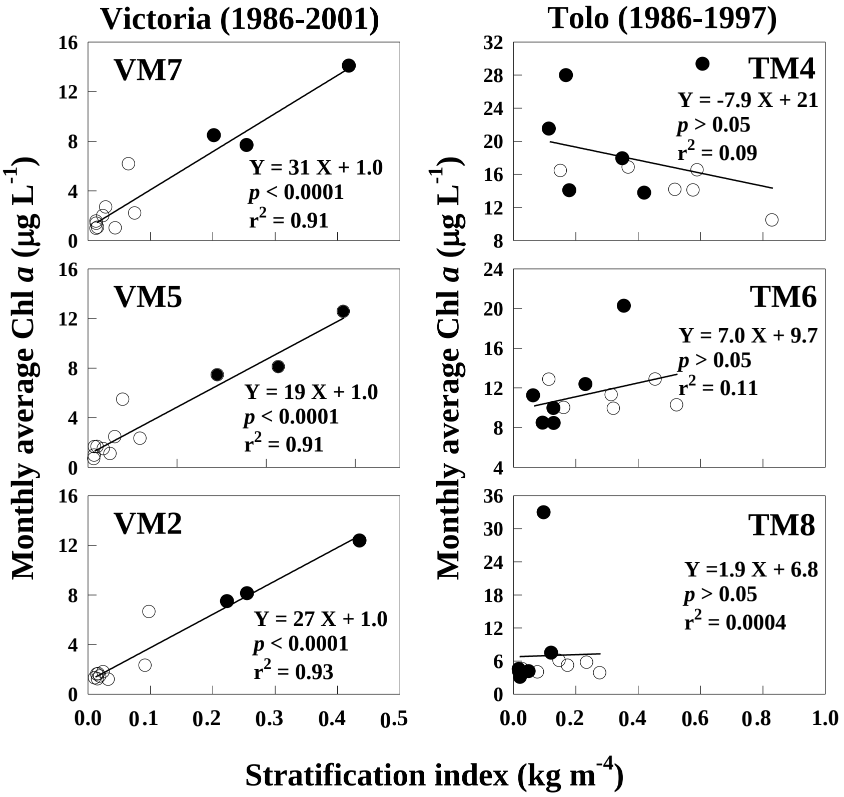

Fig. 9 Monthly average stratification index versus monthly average surface Chl *a* at three stations (VM7, VM5 and VM2) in Victoria from 1986-2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986-1997. The correlation coefficient, r, is given (data from EPD, Hong Kong). Filled circles denote summer (Jun-Aug) in Victoria and winter-spring (Dec-May) in Tolo, respectively, the period when Chl *a* is usually the highest in each harbor. Open circles represent other months.