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A comparison of eutrophication impacts in two harbours in Hong Kong with different hydrodynamics

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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 was made of eutrophication impacts between the two harbours with very different hydrodynamic conditions. Victoria Harbour (Victoria) receives sewage effluent and therefore nutrients are abundant. In the highly-flushed Victoria, the highest monthly average Chl *a* (13 $\mu g\ L^{-1}$) occurred during the period of strongest stratification in summer as a result of rainfall, runoff and the input of the nutrient-rich Pearl River estuarine waters, but the high flushing rate restricted nutrient utilization and 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 re-aeration and limited accumulation at depth due to flushing and vertical mixing. Therefore, Victoria is resilient to nutrient enrichment. In contrast, in the weakly-flushed Tolo Harbour (Tolo), year long stratification, long residence times and weak tidal currents favored algal growth, resulting in a spring diatom bloom and high Chl *a* (10–30 $\mu g\ L^{-1}$) all year and frequent hypoxic events in summer. Hence, Tolo is susceptible to nutrient enrichment and responded to nutrient reduction after sewage diversion in 1997. Sewage diversion from Tolo resulted in a 32–38% decrease in algal biomass in Tolo, but not in Victoria. There has been a significant increase (11–22%) in bottom DO in both harbours. Our findings demonstrate that an understanding of the role of physical processes is critical in order to predict the effectiveness of sewage management strategies in reducing eutrophication impacts.

1. 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 bottom water due to the sedimentation and decomposition of organic matter in stratified systems (Cooper and Brush, 1991; Turner and Rabalais, 1994). However, the response to nutrient enrichment varies widely in coastal areas (Balls et al., 1995; Justić et al., 1996) with the correlation between algal biomass and nutrient concentration differing 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 has been 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 (Justić et al., 2003, 2005). In turn, distinctly different responses to nutrient removal or reduction occur in systems with different hydrodynamics. 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 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 sewage, with up to 2.5×10^5 and 1.6×10^6 kg sewage discharging daily into Tolo and Victoria, respectively (Broom et al., 2003). However, previous observations reveal distinctly different eutrophication symptoms in both systems in response to nutrient enrichment. Tolo

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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 tide incidents recorded in Hong Kong waters during 1980–2007 occurred in Tolo Harbour (EPD, Environmental Protection Department, 2007). The large heterotrophic dinoflagellate *Noctiluca scintillans* that feeds on various plankton including diatoms is 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 tide incidents occurred in Victoria Harbour (EPD, Environmental Protection Department, 2007).

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 discharged into Victoria prior to sewage abatement 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.

The long term water quality monitoring program initiated in 1986 by the Hong Kong Environmental Protection Department (HKEPD) provides a unique dataset for comparing responses of the two ecosystems to nutrient enrichment and subsequent nutrient reduction, for understanding processes regulating eutrophication impacts in both harbours, and for formulating sewage management strategies. These nutrient reductions provide a unique opportunity to observe an ecosystem response and may be considered as a long term, large scale field experiment. Using the 22-year (1986–2007) water quality monitoring dataset, we examined the role of physical processes in regulating eutrophication impacts such as algal blooms (Chl $a > 10\ \mu g\ L^{-1}$) and low bottom DO and ecosystem recovery after sewage treatment and nutrient reduction in both harbours.

2. Materials and methods

HKEPD has maintained a comprehensive sampling program to monitor water quality at >76 monitoring stations in 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) Harbour were selected (Fig. 1) for analysis. The three stations located in Tolo are representative of three areas: inner (TM4) and middle Tolo (TM6) and Tolo Channel (TM8). Biweekly and monthly sampling was conducted by EPD in Victoria during 1986–1991 and 1992 to present, respectively, while in Tolo, sampling was biweekly during 1986–1998 and monthly since 1999. Based on the implementation of sewage reduction, the time series was divided into two phases: pre- (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 from October to March and the wet season from April to September.

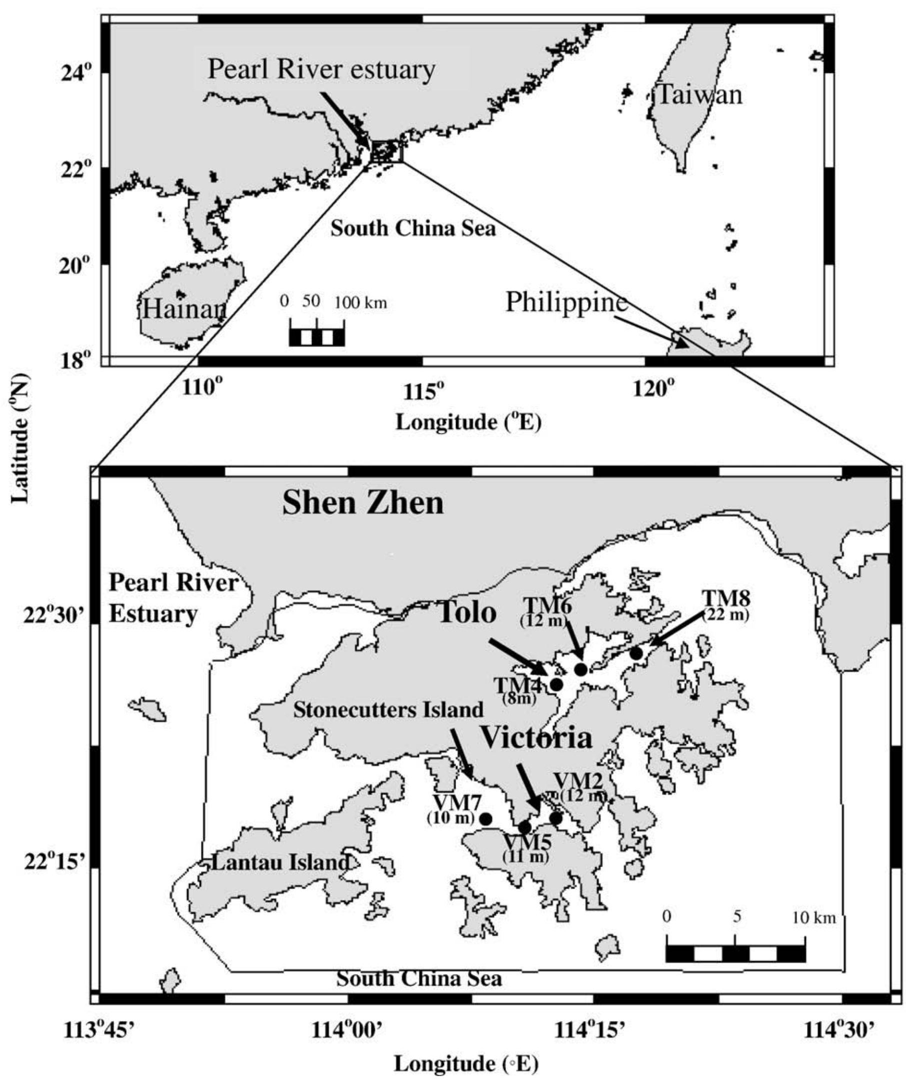

Fig. 1. Location of the six sampling stations in Hong Kong waters. The average depths of the stations are shown in brackets. These 6 stations are the same as the Environment Protection Department (EPD) stations.

The four seasons in this study are defined as spring (March to May), summer (June to August), fall (September to November) and winter (December to February).

A SEACAT 19 CTD was used for vertical profiles of salinity and temperature. Water samples were taken at three depths: surface (1 m below the surface), middle (mid-depth of the water column) and bottom (1 m above the bottom) in Victoria and Tolo. In this study, data from the middle depth were omitted since we primarily focused on nutrients and Chl *a* at the surface and dissolved oxygen (DO) at the bottom. Methods for sampling and routine water quality measurements are reported by HKEPD (EPD, Environmental Protection Department, 1999, http://www.epd.gov.hk/epd/english/environmentinhk/water) and were standard techniques for nutrients and chlorophyll. NO_3 and NH_4 were measured by the Cu–Cd column reduction method (APHA, American Public Health Association, 1995, cf EPD, Environmental Protection Department, 1999) and indophenol blue color formation, respectively (ASTM, American Society for Testing and Materials, 1991, cf EPD, Environmental Protection Department, 1999). PO_4 was analyzed by the ascorbic acid method (ASTM, American Society for Testing and Materials, 1991, cf EPD, Environmental Protection Department, 1999) and SiO_4 was determined using molybdate, oxalic acid and a reducing reagent (ASTM, American Society for Testing and Materials, 1991, cf ASTM, American Society for Testing and Materials, Environmental Protection Department, 1991, Environmental Protection Department). Chlorophyll was extracted with 90% acetone and measured using a spectrophotometer (APHA, American Public Health Association, 1995, cf EPD, Environmental Protection Department, 1999). DO was measured by a SBE23Y dissolved oxygen sensor linked to a SEACAT 19 CTD.

In this study, the stratification index (SI) was calculated as follows (Chen, 2005):

$$SI = \Delta\sigma_t / h \tag{1}$$

where $\Delta\sigma_t$ (kg m^{-3}) is the difference in seawater densities (σ_t) between surface and bottom densities and h (m) is the difference in water depth between surface and bottom water samples (= the depth of the water column minus 2 m). Seawater density (σ_t) is calculated based on Fofonoff and Millard, (1983) using monthly average salinities and temperatures.

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):

$$\langle I \rangle = I_o(1-\exp(-kz)) / kz \tag{2}$$

where I_o (W h m^{-2}) = mean daily solar radiation at the surface water, k = extinction coefficient (k = 1.44/Secchi depth, Holmes, 1970), and z = the mixed layer depth. I_o at the surface water was obtained by multiplying the mean daily solar radiation in the surface air by 70% using the monthly average data from the 30-year (1971–2000) Hong Kong Observatory monitoring data (http://www.weather.gov.hk/cis/normal/1971_2000). The albedo factor of 70% converting the

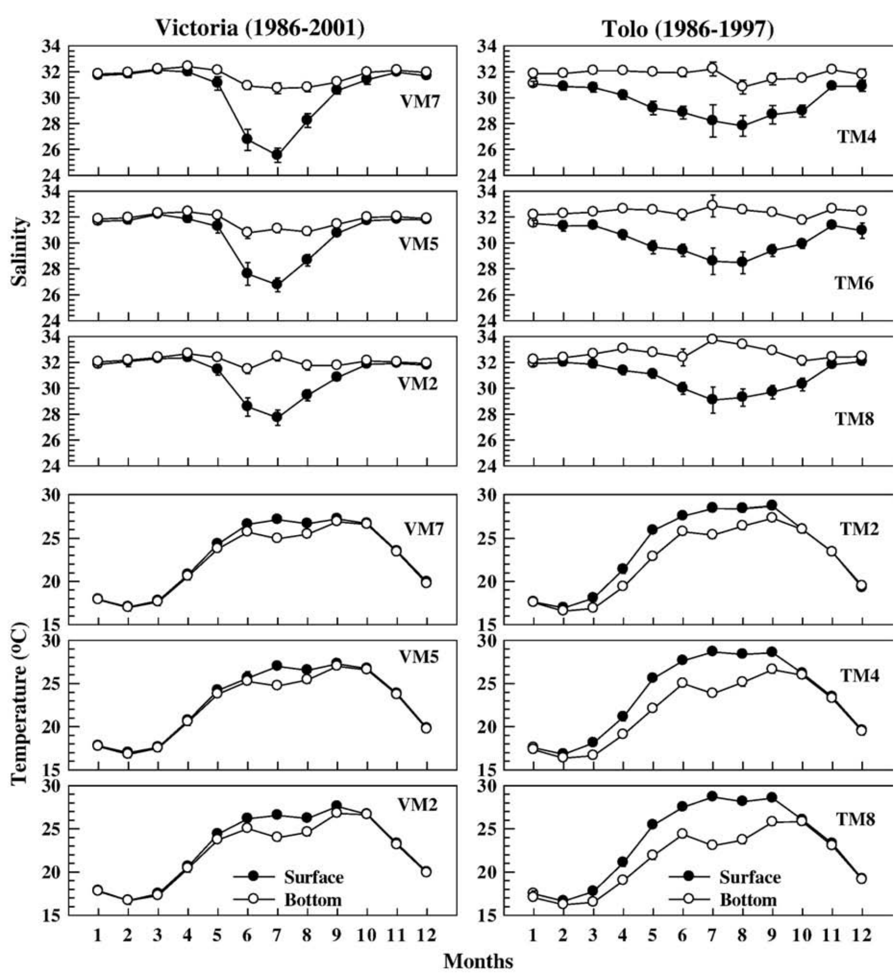

Fig. 2. Monthly average salinity and temperature at the surface and bottom at three stations (VM7, VM5 and VM2) in Victoria from 1986 to 2001, and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 1997, before sewage abatement. Bars = ± 1 SE, n = 22.
Data from EPD, Hong Kong.

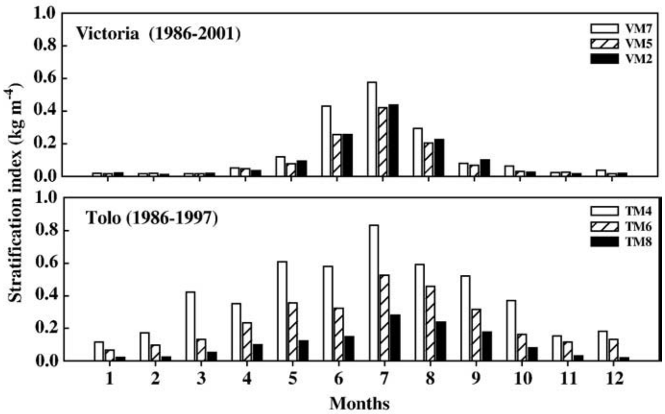

Fig. 3. Monthly average stratification index between the surface and bottom at three stations (VM7, VM5 and VM2) in Victoria from 1986 to 2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 1997 before sewage abatement. Bars = ±1 SE, $n = 22$. Data from EPD, Hong Kong.

light intensity in air to that immediately sub-surface was estimated from our in situ light measurements (Yin et al., unpubl. data). Secchi disc depth was obtained from monthly average data for 4 years (1998–2001) from EPD monitoring. The mixed layer depth is defined as the depth where the vertical density gradient exceeds a threshold $\Delta\sigma_t \geq 0.2$ kg m^{-4} (Therriault and Levasseur, 1985). In this study, mixed layer depth z was estimated from a series of cruises conducted from 2004 to 2006. A cutoff of 465 W h m^{-2} was set empirically by Riley (1957) and used as a threshold for an increase in phytoplankton biomass by photosynthesis in the mixed layer.

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 ($p < 0.05$).

3. Results

3.1. Salinity, temperature and density gradients

Salinity at 1 m exhibited the same seasonal variation in both harbours, 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 homogeneous at all stations from November to March, as indicated by $\Delta\sigma_t$ of <0.2 kg m^{-4} (Fig. 3). Subsequently, stratification increased and was strongest (up to 0.6 kg m^{-4}) during summer and weakened again in the fall. In Tolo, stratification varied spatially and temporally, with the strongest stratification occurring in summer and the weakest in winter at all stations, decreasing from the inner Tolo (TM4) to Tolo Channel (TM8). Stratification was extremely weak in Tolo Channel (TM8) during winter with a low SI of ~0.02 kg m^{-4} (Fig. 3).

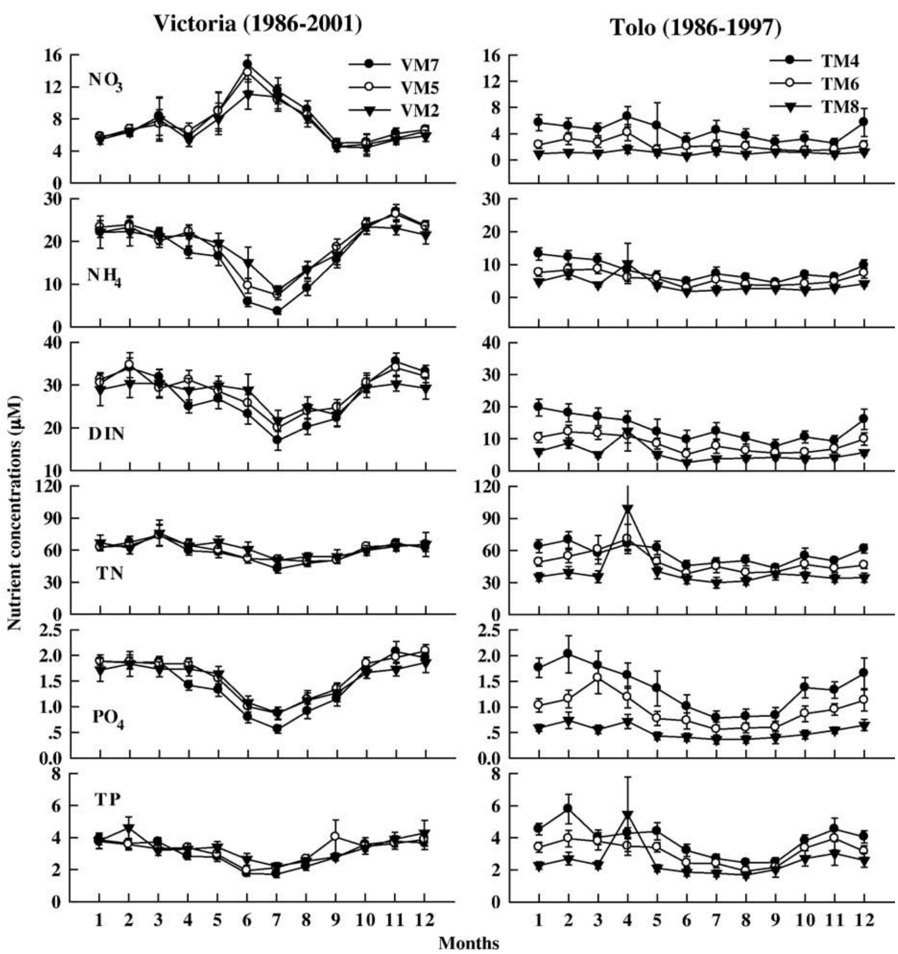

Fig. 4. Monthly average nutrient (NO_3, NH_4, DIN, TN, PO_4, and TP) at the surface at three stations (VM7, VM5 and VM2) in Victoria from 1986 to 2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 1997 before sewage abatement. Bars = ±1 SE, $n = 22$.
Data from EPD, Hong Kong.

3.2. Nutrients and nutrient ratios during pre-treatment

In Victoria, 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 highest (>20 μM NH_4, close to or >30 μM DIN and >60 μM TN) levels in winter and lowest (<10 μM NH_4, 15–20 μM DIN and <50 μM TN) levels in summer, especially in July. In winter, surface NH_4 concentrations were usually higher than that at the bottom (data not shown) due to sewage input from the inner harbour. 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, respectively. TN concentrations fluctuated between 40 and 80 μM in inner (TM4) and middle Tolo (TM6) and were generally <40 μM in Tolo Channel (TM8) except in March when TN was up to 90 μM.

In Victoria, PO_4 and total phosphorus (TP) at the surface demonstrated clear seasonal variations with highest concentrations (>1.6 μM PO_4 and >3.5 μM TP) in winter and lowest levels (<1.0 μM PO_4 and <2.0 μM TP) in summer. A weaker seasonal pattern was observed for these two nutrients in Tolo. PO_4 concentrations at the surface decreased markedly from 0.8–2.0 μM in inner Tolo (TM4) to 0.3–0.8 μM in Tolo Channel (TM8). Similarly, TP declined from 2.4–5.9 μM at TM4 to generally <3.0 μM at TM8.

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

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 and 4:1. SiO_4:PO_4 ratios exhibited clear seasonal variations with high ratios (>16:1) in summer and low ratios (<16:1) in other seasons. In contrast, in Tolo, the DIN:PO_4 ratios were ~16:1 or lower all year. DIN:SiO_4 ratios at the surface decreased from >1:1 in inner Tolo (TM4) to near or <1:1 in Tolo Channel (TM8). By comparison, the SiO_4:PO_4 ratios increased to approximately 16:1 to lower ratios during October–May and were >16:1 during June–September in inner Tolo (TM4), and were >32:1 in Tolo Channel (TM8) most of the year.

3.3. Surface Chl a and bottom DO during pre-treatment

In Victoria, the surface Chl *a* concentration exhibited clear seasonal variations with the highest (~13 μg L^{-1}) and lowest (<2 μg L^{-1}) values in summer and winter, respectively (Fig. 6). In contrast, in Tolo, the surface Chl *a* concentrations were higher than in Victoria, with a maximum (30 μg L^{-1}) occurring in spring. Spatial variations in surface Chl *a* concentrations were observed, with high Chl *a* (10–30 μg L^{-1}) in inner Tolo (TM4), intermediate levels (10–20 μg L^{-1}) in the middle Tolo (TM6) and generally low concentrations (mostly <8 μg L^{-1}) in Tolo Channel (TM8). The extremely high monthly average Chl *a* concentration

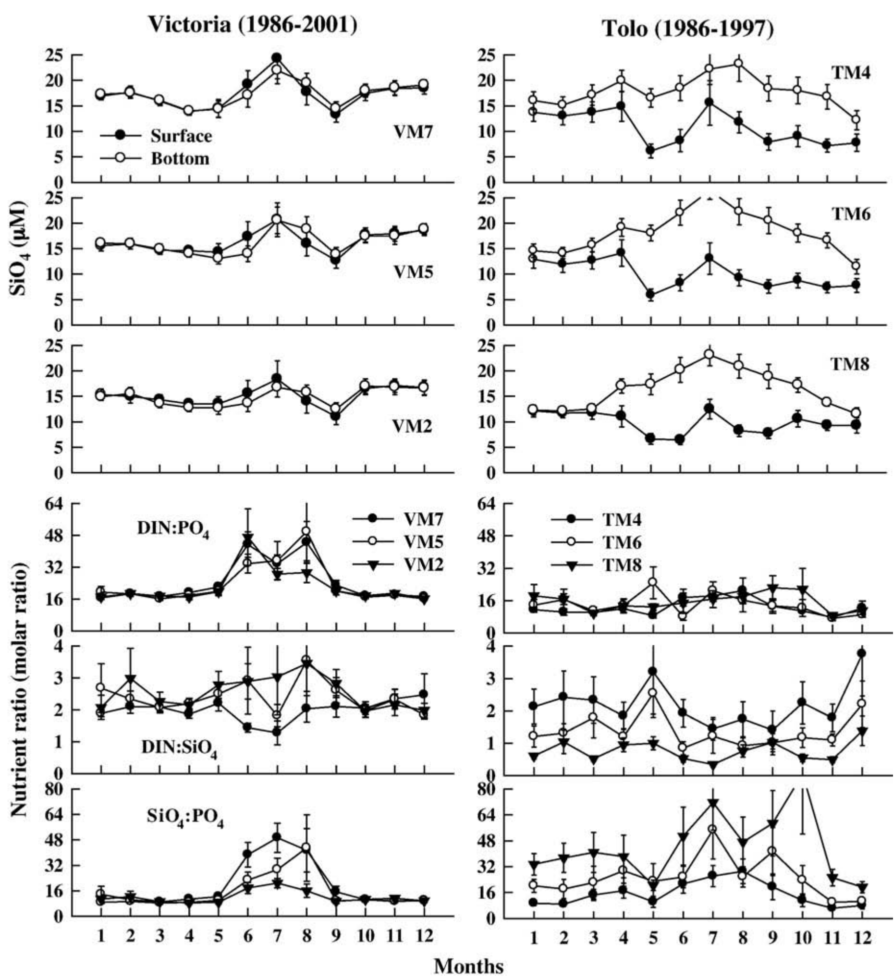

Fig. 5. Monthly average SiO_4 at the surface and bottom and nutrient ratio at the surface at three stations (VM7, VM5 and VM2) in Victoria from 1986 to 2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 1997 before sewage abatement. Bars = ±1 SE, $n=22$.
Data from EPD, Hong Kong.

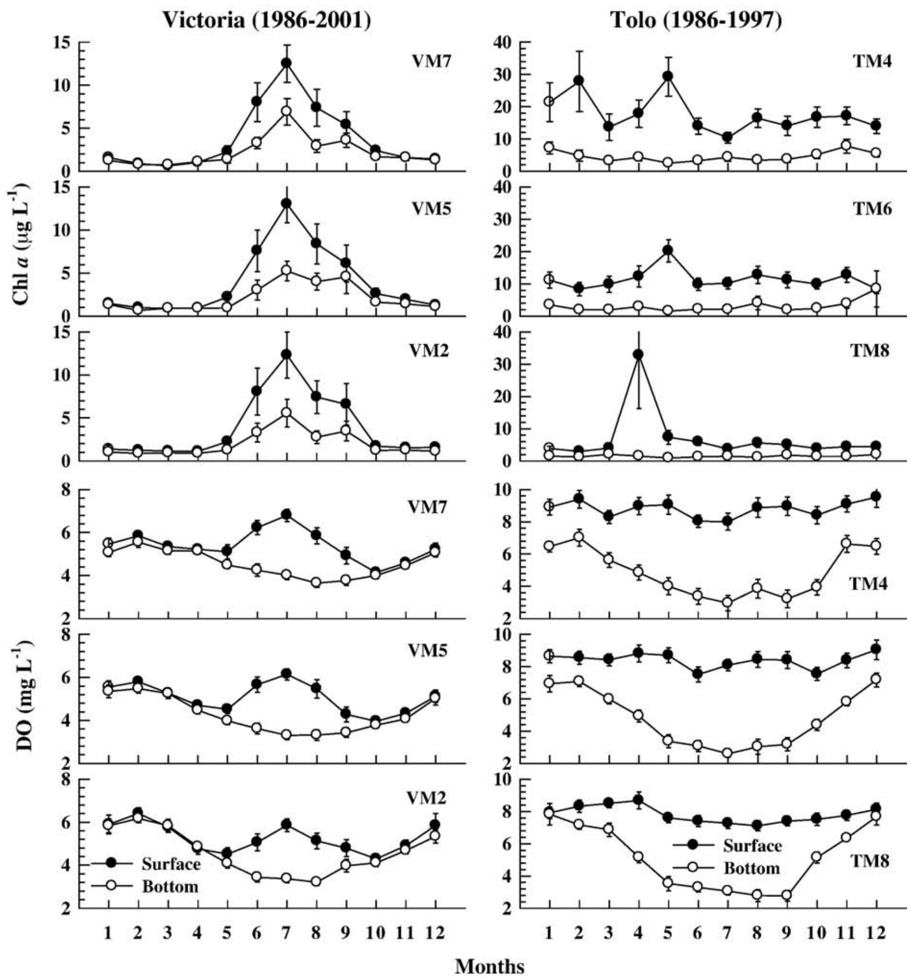

Fig. 6. Monthly average Chl *a* and DO at the surface and bottom at three stations (VM7, VM5 and VM2) in Victoria from 1986 to 2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 1997 before sewage abatement. Bars = ±1 SE, $n = 22$. Note the different scale for Chl between Victoria and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

(~35 μg L^{-1}) at TM8 in April was caused by four episodic algal blooms or high biomass red tides (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).

The bottom DO concentrations indicated the same seasonal variability in both harbours with the highest values in winter and lowest values in summer, respectively. The minimal bottom DO concentration occurred between July and September in both harbours and approached hypoxic levels (~2 mg L^{-1}) in Tolo, and higher levels (~3 mg L^{-1}) in Victoria (Figs. 6 and 7).

3.4. Recovery from pre-treatment eutrophication impacts

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 increased significantly (11–20%) in Victoria after sewage treatment. 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 SiO_4:PO_4 ratios increased significantly, by 60–128% and 119–294% at TM4 and TM6, respectively due to the large decrease in phosphorus. There was a significant (32–38%) reduction in Chl *a* at these two stations and a significant (11–20%) increase in bottom DO concentrations.

4. Discussion

4.1. Tolo Harbour

4.1.1. Physical processes

Tolo is a land-locked long inlet with tidal current velocities from 0.01–0.02 m s^{-1} in inner Tolo to 0.2–0.3 m s^{-1} in Tolo Channel due to a narrow opening to Mirs Bay (Lee and Arega, 1999). The residence time of water in Tolo is long, averaging 28 days. Residence time varies seasonally, ranging from 38 days in the dry season due to down-welling induced by northeast monsoon winds, to 14.4 days in the wet season due to the input of freshwater (e.g. rainfall and runoff) and the surface outflow induced by southwest monsoon winds in summer (Lee et al., 2006). The strongest stratification in summer was due to reduced salinity at the surface from high rainfall and high salinity at the bottom (Figs. 2 and 3) due to upwelling induced inflow at the bottom from Mirs Bay (Yin et al., in press).

4.1.2. Nutrients (pre-treatment: 1986–1997)

In Tolo, local sewage discharge was a major source of nitrogen and phosphorus, and NH_4 was the main contributor to DIN, accounting for >50% of the dissolved inorganic pool. The lowest NO_3 concentration in summer during the period of maximum runoff suggested that NO_3 resulted from sewage, not runoff. Higher SiO_4 concentrations at the

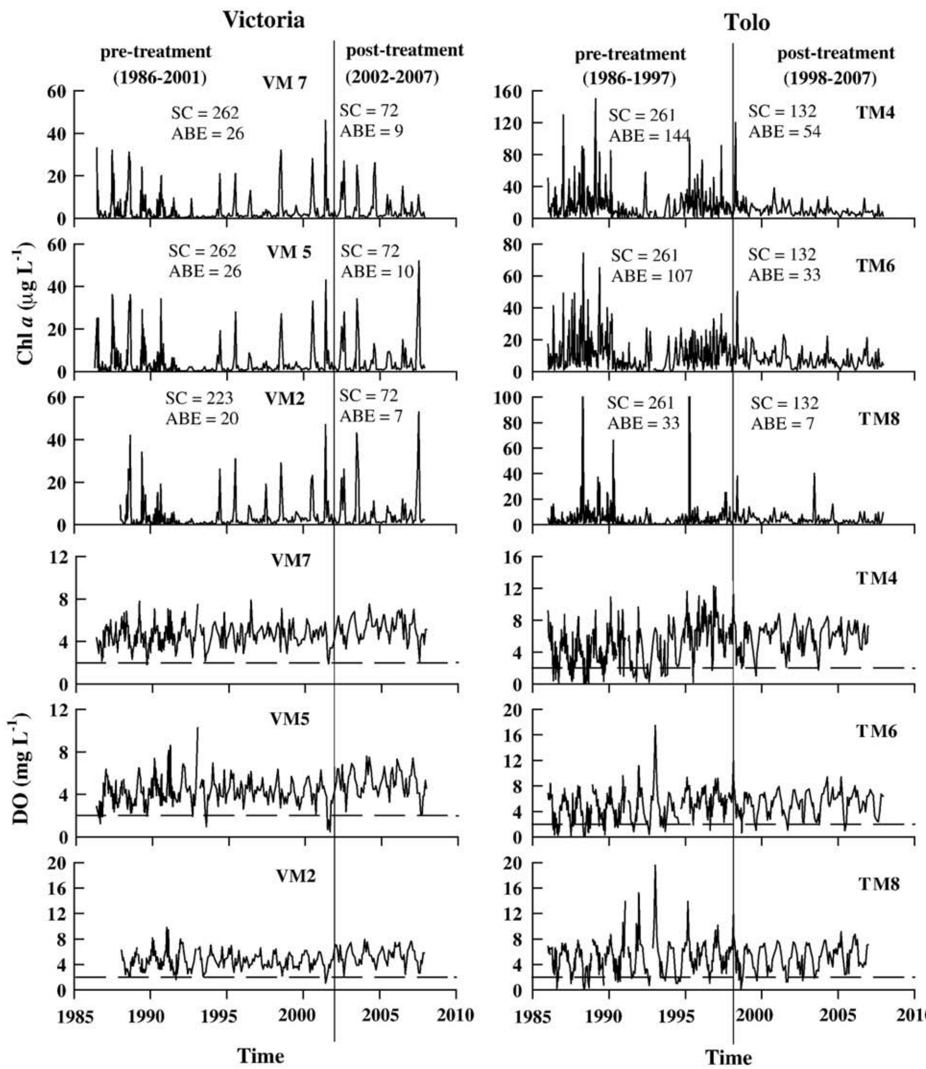

Fig. 7. Changes in the surface Chl *a* and the bottom DO (individual sampling data) at three stations (VM7, VM5 and VM2) in Victoria and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 2007 during pre-treatment and post-treatment phases. The dashed line = 2 mg O_2 L^{-1} below which hypoxic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

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 depth. In comparison, in summer, runoff contributed Si to Tolo as the surface SiO_4 concentrations rose from a minimum in spring, despite the decreased replenishment of SiO_4 from bottom waters due to strong stratification. Silicate was usually >5 μM all year, but periodically it decreased to <2 μM, below which diatom growth is likely Si-limited (Harrison et al., 1977, Nelson and Brzezinski, 1990).

4.1.3. Eutrophication impacts: algal blooms and hypoxia (pre-treatment: 1986–1997)

Tolo Harbour appears to be vulnerable to nutrient enrichment because of its year-round stratification and long residence times. The Secchi disc depth was 1.8 m in inner Tolo and up to 5.0 m in Tolo Channel (Yung et al., 1997). Hence, light may rarely limit phytoplankton growth near the surface. The high input of nutrients from sewage and year-round stratification increased the occurrence of large algal blooms in inner Tolo all year. High Chl *a*, but no obvious drawdown of silicate in January and February indicates few diatoms were present in winter. Yin (2003) suggested that downwelling promoted the concentration of phytoplankton biomass in the inner harbour over the winter–spring period, favoring dinoflagellate blooms (e.g. *Prorocentrum minimum*). We note that diatoms are the preferred prey for *N. scintillans* in Tolo (Liu and Wong, 2006), which might favor Si cycling and 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), coincident with a previous report that *Skeletonema costatum* peaked in May (Yin, 2003). This was likely related to decreased grazing on diatoms due to a rapid decline (>90%) in abundance of *N. scintillans* at high temperatures (>25 °C) (Liu and Wong, 2006). In summer, a relatively rapid surface outflow of freshwater due to high rainfall diluted the algal biomass. Furthermore, the prevailing southwest monsoon wind helped to move the surface water out of the harbour and through Tolo Channel.

A summer bottom monthly average DO minimum approached hypoxic levels (~2 mg L^{-1}) at TM6 and TM8 (Fig. 7). Episodic hypoxic events and even a few anoxic (DO<0.2 mg L^{-1}) events occurred at TM4 in inner Tolo under strong stratification, especially in summer. In the northern Gulf of Mexico, increased stratification due to an increase in freshwater discharge was found to stimulate hypoxia in bottom waters by reducing vertical oxygen transport (Justić et al., 1996, 2005). A positive relationship between volume of hypoxic bottom water and mean depth has been observed in regions of the Chesapeake Bay (Fisher

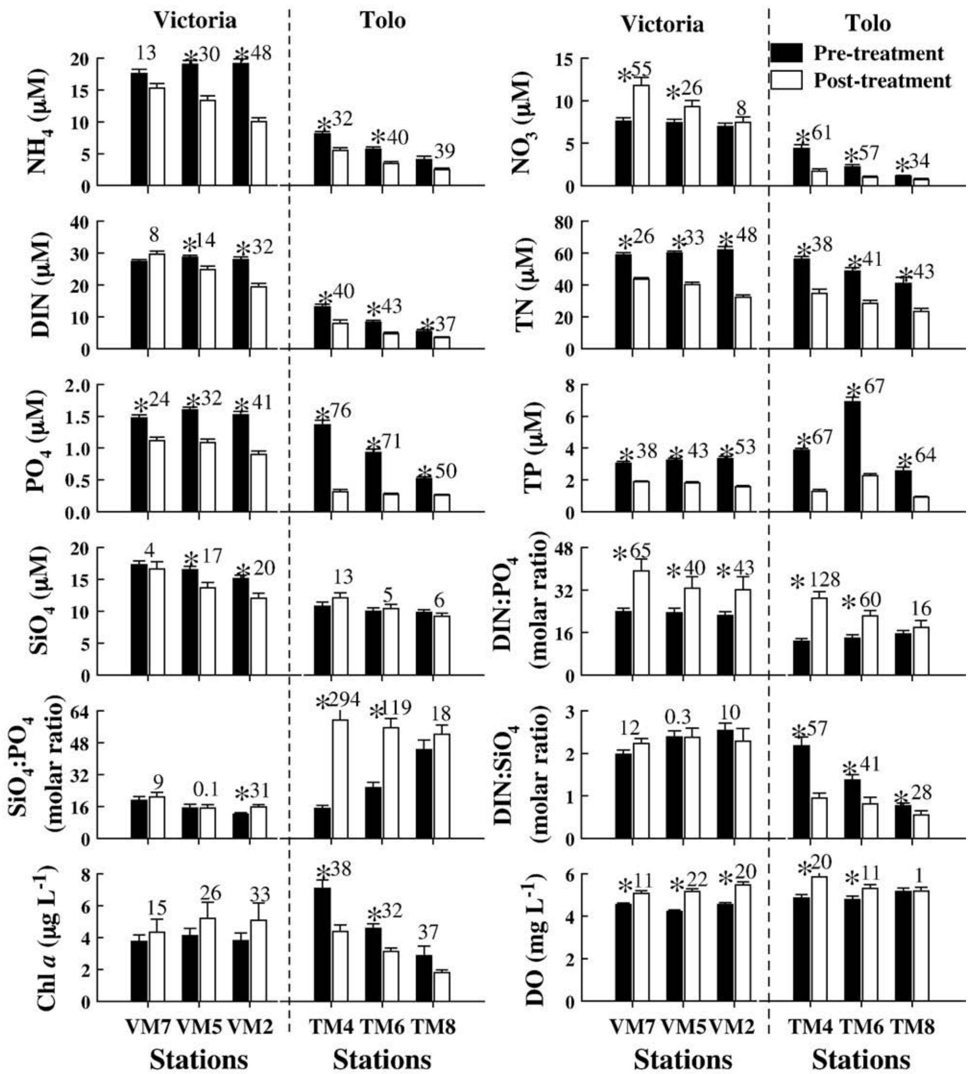

Fig. 8. Average pre-treatment and post-treatment surface nutrients and nutrient ratios (NH_4, NO_3, DIN, TN, PO_4, TP, SiO_4, DIN:PO_4, SiO_4:PO_4, and DIN:SiO_4), Chl *a* and bottom DO at three stations (VM7, VM5 and VM2) in Victoria and at three stations (TM4, TM6 and TM8) in Tolo. Bars = ± 1 SE. * 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 the bars represents the percentage of the increase or decrease in the parameter after sewage treatment relative to pre-treatment.

et al., 2006), suggesting that severe DO problems at depth in Tolo Harbour were likely alleviated by the harbour's shallow depth.

4.1.4. Nutrient reduction and eutrophication recovery (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 that for 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 greater than the Redfield ratio (16N:1P) after sewage treatment, suggesting that P was deficient relative to N and Si. In inner and middle Tolo Harbour, 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 the harbour most of the year (Yung et al., 1997; Wong and Wong, 2004) and the external input of Si input likely remained relatively constant.

Eutrophication impacts decreased significantly in response to nutrient reduction. The recovery from eutrophication was more obvious in inner Tolo, as indicated by the significant (32–38%) reduction in Chl *a* and the significant (11–22%) increase in bottom DO at TM4 and TM6 (Fig. 8). Chl *a* concentrations declined from high biomass blooms (>40 μg Chl a L^{-1}) frequently observed at TM4 before sewage treatment to mostly <20 μg L^{-1} after treatment. The frequency of algal bloom events in inner and middle Tolo decreased from 41–56% of sampling cases before treatment to 25–41% after treatment. These results confirmed that Tolo was mainly a nutrient-controlled ecosystem. Bottom DO concentrations have improved and few hypoxic events were detected after treatment, accompanied by a decline in biological oxygen demand that decreased by 83% after treatment (Broom et al., 2003).

Although there was a significant reduction in nutrient concentrations and algal biomass after sewage treatment, the absence of a significant increase in bottom DO confirmed that eutrophication impacts were related to the higher flushing rate in the Channel. We speculate that the bottom DO in the channel was more likely related to the input of low O_2 bottom water from offshore due to upwelling induced by the southwest monsoon, rather than nutrient enrichment.

4.2. Victoria Harbour

4.2.1. Physical processes

Victoria is a highly-flushed and rapidly-mixed narrow channel, and tidal current velocities are up to 1.2 m s^{-1}, 25 times higher than noted in Tolo Harbour (Lee et al., 2006). During the dry season, coastal/oceanic water invaded due to the strong northeast monsoon wind, while strong stratification occurred in summer due to the advection of Pearl River estuarine water. High Pearl River discharge increased horizontal water velocities and therefore decreased water residence times (1.5–2.5 days) in the wet season, which were 3 times shorter than during the dry season (5–7 days) (Kuang and Lee, 2004, Lee et al., 2006).

4.2.2. Nutrients (pre-treatment: 1986–2001)

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 indicative of the local sewage effluent input (Yin and Harrison, 2007). In the dry season, NH_4 concentrations were ~4-fold higher than NO_3 levels. In summer, Pearl River discharge delivered high NO_3 and SiO_4 concentrations (Xu et al., 2008), while concentrations of nutrients other than NO_3 and SiO_4 were diluted, as reflected by the lowest TN concentrations (<50 μM) in summer. Summertime TN concentrations (~42 μM) at station VM7 nearest to the Pearl River estuary were lower than other two stations further away and we attribute this to more dilution. In contrast, TN loading was comparable between the three stations when there was little influence of Pearl River discharge in the dry season. Further evidence for the influence of the Pearl River 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 ratios (~100:1) (Xu et al., 2008).

Victoria receives about 10 times more sewage effluent than Tolo Harbour (Broom et al., 2003). However, TN, PO_4 and TP concentrations were similar in Victoria and inner Tolo Harbours (Fig. 4), probably attributed to high dilution in the former. In Victoria Harbour, DIN was at least 50% higher than noted in Tolo Harbour and accounted for roughly 50% of TN because of high input of sewage discharge and invasion of the Pearl River water in summer, and less biological uptake. In Tolo Harbour, DIN was <30% of TN, also likely due to high biological uptake.

4.2.3. Eutrophication impacts: algal blooms and hypoxia (pre-treatment: 1986–2001)

Victoria is more resistant to nutrient enrichment due to the vigorous physical processes (e.g. strong vertical mixing and flushing). Phytoplankton biomass appeared to be more dependent on 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), favoring phytoplankton growth and nutrient utilization. This suggestion was supported by the significant correlation between the mean light intensity in the mixed layer and monthly average Chl *a* concentrations in Victoria Harbour (Table 2). As a result, the maximum Chl *a* concentrations (~13 μg L^{-1}) in Victoria occurred in summer and were accompanied by the lowest NH_4 and PO_4 concentrations. Chl *a* biomass was mainly composed of diatoms (e.g. *S. costatum*) because of continual high input of Si from the Pearl River discharge (Xu et al., 2009). On the other hand, the high volume of the Pearl River discharge also prevented further accumulation of phytoplankton biomass by increasing dilution (Xu et al., 2009). The tidal-induced vertical mixing was able to destratify and transport phytoplankton below the photic zone, as indicated by fairly high Chl *a* concentrations (~5 μg L^{-1}) at the bottom in summer (Yin and Harrison, 2007).

In contrast, in the dry season, strong vertical mixing was likely responsible for the low Chl *a* concentrations (<2 μg L^{-1}) and the lack

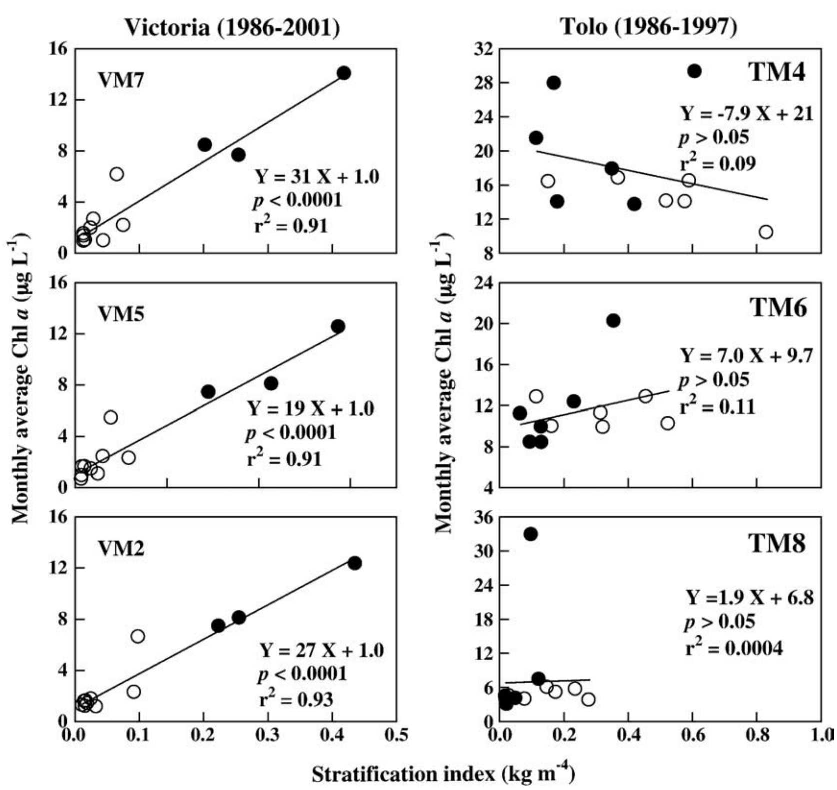

Fig. 9. Monthly average stratification index versus monthly average surface Chl *a* at three stations (VM7, VM5 and VM2) in Victoria from 1986 to 2001 and at three stations (TM4, TM6 and TM8) in Tolo from 1986 to 1997. The correlation coefficient, *r*, is given. Filled circles denote summer (Jun–Aug)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

Table 1
Mean daily solar radiation at the surface water I_o (W h m^{-2}), Secchi disc depth (m), mixed layer depth z (m) and mean light intensity in the mixed layer <I> (W h m^{-2}). 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. Mixed layer depth z was obtained from cruises conducted from 2004 to 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	355	2.63	11	339	2.38	12	282
Feb	2669	2.25	10	291	2.28	11	268	2.70	12	291
Mar	2828	1.95	10	268	2.00	11	250	2.25	12	256
Apr	3286	1.83	10	291	2.08	11	301	1.95	12	260
May	3986	2.00	NA	NA	1.93	NA	NA	2.35	NA	NA
Jun	4253	2.00	2	1578	1.93	2	1544	1.95	2	1555
Jul	4867	2.75	3	1718	2.43	1	2569	3.00	2	2190
Aug	4447	2.13	3	1331	2.38	3	1434	2.38	3	1434
Sep	4206	2.00	10	409	1.75	11	326	2.38	12	405
Oct	4017	1.80	NA	NA	1.63	NA	NA	2.15	NA	NA
Nov	3511	2.25	10	384	2.25	11	349	2.25	12	320
Dec	3092	2.55	10	382	2.45	11	334	2.63	12	328

of a typical spring bloom. The mean light intensity in the mixed layer was below the cutoff of 465 W h m^{-2} (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).

Victoria was more resilient to nutrient enrichment and therefore few hypoxic events (DO$<$2 mg L^{-1}) occurred despite the much higher inputs of sewage than Tolo, due to strong vertical mixing. High flushing in Victoria diluted organic matter, which reduced the demand for oxygen (Ho et al., 2008).

4.2.4. Nutrient reduction and eutrophication recovery (post-treatment: 2002–2007)

After sewage treatment in 2001, there was a significant reduction in nutrient concentrations with an obvious gradient from west (VM7) to east (VM2). The highest percentage decrease in nutrients (NH_4, PO_4, TN, and TP) after sewage treatment often occurred at VM2, the station farthest from the sewage outfall and Pearl River estuary (Fig. 8). The higher average post-treatment NO_3 concentrations were associated with an increase in NO_3 concentrations in Pearl River discharge in recent years (Xu et al., 2008). The increased NO_3 from Pearl River compensated for the loss of NH_4 from the reduction in sewage effluent, resulting in a slight (8%) increase in DIN (Fig. 8). On the other hand, high Pearl River discharge in summer pushed some of the sewage from Stonecutters Inland into Victoria Harbour, overshadowing the recovery signal from eutrophication. 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 relatively deficient as a result of the high input of NO_3 and SiO_4 from the Pearl River discharge, but high flushing likely prevented nutrient limitation (Xu et al., 2009). In contrast to Tolo Harbour, a significant (16–20%) decrease in SiO_4 was observed in Victoria Harbour stations (VM5 and VM2), which was most likely attributable to the 26–33% increase in Chl *a* (mostly diatoms) after treatment, probably due to the improved water transparency.

Table 2
Correlation coefficient, r, between mean light intensity (data from Table 1) in the mixed layer and monthly Chl *a* concentrations for 3 stations (VM7, VM5 and VM2) in Victoria Harbour. The degree of freedom was $n=10$ because light intensity in the mixed layer was not available in May and October.

Stations	Pearson correlation coefficient (r)
VM7	0.94**
VM5	0.93**
VM2	0.93**

** represents a significant correlation at the 0.01 level (two-tailed).

In Victoria, algal biomass and bottom DO responded differently to nutrient reduction. After sewage treatment, the magnitude of algal blooms was not significantly reduced. In fact the observed peak in Chl *a* concentration (~53 μg L^{-1}) at VM5 and VM2 was higher than during pre-treatment. The average post-treatment surface Chl *a* concentration was 15–33% higher than during pre-treatment (Fig. 8), likely due to the improvement in water transparency as a result of primary treatment. 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 attributable to a 50% decrease in the organic loading due to sewage treatment in Victoria Harbour (Broom et al., 2003).

5. Summary

The susceptibility of coastal and estuarine ecosystems to nutrient enrichment was strongly influenced by physical processes in the two contrasting harbours in Hong Kong. The weakly-flushed Tolo was vulnerable to nutrient enrichment, especially in the inner and middle areas of the harbour 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, favorable physical processes (e.g. downwelling) helped concentrate 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 algal biomass and consequently, algal biomass was lower relative to other seasons. Frequent hypoxic events occurred in summer 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 high flushing rates caused by its narrow opening to Mirs Bay.

In contrast, in highly-flushed Victoria Harbour, the ecosystem appeared to be less susceptible to nutrient enrichment. In summer, an increase in stratification due to the introduction of Pearl River waters stimulated phytoplankton growth by retaining phytoplankton in the euphotic zone. On the other hand, the high volume of the 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, stratification tends to be lower in Victoria due to strong tidal mixing. During fall, winter and spring, strong vertical mixing resulted in light limitation and dilution of the algal biomass. Since mixing favored the vertical supply of oxygen, few hypoxic events occurred in Victoria. In Victoria, nutrient reduction after sewage treatment did not result in a reduction in phytoplankton biomass since phytoplankton growth was mainly regulated by physical processes (e.g. strong vertical mixing and high flushing rate) and not by nutrients. In both harbours, bottom DO has increased due to a reduction in organic loading after sewage treatment (Broom et al., 2003).

Our findings confirm that an understanding of the role of physical processes is critical to predict the effectiveness of sewage management strategies for mitigating eutrophication. The current sewage management strategies are effective in reducing eutrophication impacts such as high Chl *a* and low bottom DO in Tolo Harbour. At the present level of sewage treatment in Victoria Harbour, bottom DO increased. However, there was no decrease in Chl *a* since algal growth was primarily regulated by physical processes, such as strong tidal-induced mixing and dilution by the Pearl River discharge.

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