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

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27 **Abstract**

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

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

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52 **Introduction**

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

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

76 In Hong Kong, Tolo Harbour (Tolo) and Victoria Harbour (Victoria) are both

77 eutrophic waters, subjected to high nutrient loading from the sewage, with up to $2.5 \times$
78 10^5 and 1.6×10^6 kg sewage discharging into Tolo and Victoria daily, respectively
79 (Broom et al. 2003). However, previous observations reveal distinctly different
80 eutrophication symptoms in both waters in response to nutrient enrichment. Tolo has
81 the most frequent red tide events among all waters of Hong Kong (Yin 2003, Wong et
82 al. 2009). Over 40% of a total 777 red tides incidents recorded in Hong Kong waters
83 during 1980-2007 occurred in Tolo Harbour (EPD 2007). The large heterotrophic
84 dinoflagellate *Noctiluca scintillans* that feeds on various plankton including diatoms
85 was the most common red tide-forming species, accounting for 15% of all red tide
86 cases and mainly occurs during the winter-spring period (Yin 2003; Liu and Wong
87 2006). In contrast, only 2% of total red tides incident occurred in Victoria Harbour
88 (EPD 2007).

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

97 The long term water quality monitoring program initiated in 1986 by the Hong
98 Kong Environmental Protection Department (HKEPD) provides a unique dataset for
99 the comparison of the response of the two ecosystems to nutrient enrichment and
100 subsequent nutrient reduction, understand factors regulating eutrophication impacts in

101 both harbors, and provide sewage management strategies. These nutrient reductions
102 provide a unique opportunity to observe an ecosystem response and they may be
103 considered to be like a long term, large scale field experiment. In this study, based on
104 a 22-year (1986-2007) water quality monitoring dataset from HKEPD, we examined
105 the role of physical processes in regulating eutrophication impacts and the ecosystem
106 recovery in response to nutrient reduction in both harbors.

107

108 **Materials and methods**

109 HKEPD has maintained a comprehensive sampling program to monitor water
110 quality at >76 monitoring stations in the territorial waters since the late 1980s
111 (website: www.epd.gov.hk). Six stations located in Victoria (VM2, VM5 and VM7)
112 and Tolo (TM4, TM6 and TM8) were selected (Fig. 1). Three stations located in Tolo
113 are representative of three areas: inner Tolo (TM4), middle Tolo (TM6) and Tolo
114 Channel (TM8). Biweekly sampling in Victoria during 1986-1991 and in Tolo during
115 1986-1998 and monthly sampling in Victoria since 1992 and in Tolo since 1999 were
116 conducted by EPD during the last 22 years (1986-2007). Based on the implementation
117 of sewage reduction, the 22-year time series was divided into two phases:
118 pre-treatment (1986-1997 in Tolo and 1986-2001 in Victoria) and post-treatment
119 (1998-2007 in Tolo and 2002-2007 in Victoria). The dry season was defined as
120 October to March and the wet season was from April to September. The year was
121 divided into four seasons: spring (March to May), summer (June to August), fall
122 (September to November) and winter (December to February).

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

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

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

131
$$SI = \frac{\Delta\sigma_t}{h} \quad (1)$$

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

136 To assess the importance of the light regime for algal growth, the mean light
137 intensity in the mixed layer, $\langle I \rangle$, was estimated using the following equation (Riley
138 1957):

139
$$\langle I \rangle = \frac{I_0(1 - e^{-kz})}{kz} \quad (2)$$

140 where I_0 ($\text{W h m}^{-2} \text{ d}^{-1}$) = mean daily solar radiation, k = coefficient of extinction (k =
141 $1.44/\text{Secchi depth}$, Holmes, 1970), z = the mixed layer depth. I_0 was obtained from
142 monthly average data from the 30 year (1971-2000) monitoring data from Hong Kong
143 Observatory (http://www.weather.gov.hk/cis/normal/1971_2000/normals_e.htm).
144 Secchi disc depth was obtained from monthly average data for 4 years (1998-2001)
145 from EPD monitoring data. The mixed layer depth is defined as the depth where $\Delta\sigma_t$
146 $\geq 0.2 \text{ kg m}^{-3} \text{ m}^{-1}$ (Therriault and Levasseur 1985). In this study, z was estimated from a
147 series of cruises conducted from 2004 to 2006. The cutoff of $465 \text{ W h m}^{-2} \text{ d}^{-1}$ 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 $< 0.2 \text{ kg m}^{-3}$ (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 $\sim 0.02 \text{ kg m}^{-4}$ (Fig. 3).

Nutrients and nutrient ratios

In Victoria, the maximal NO_3 concentrations ($>10 \text{ }\mu\text{M}$) occurred in summer, while NO_3 concentrations were relatively low ($< 7 \text{ }\mu\text{M}$) in Tolo (Fig. 4). In Victoria, NH_4 , DIN ($=\text{NH}_4+\text{NO}_2+\text{NO}_3$) and total nitrogen (TN) concentrations exhibited the

173 same temporal variability with the highest ($> 20 \mu\text{M NH}_4$, close to or $> 30 \mu\text{M DIN}$
174 and $> 60 \mu\text{M TN}$) in winter and the lowest ($< 10 \mu\text{M NH}_4$, $15\text{-}20 \mu\text{M DIN}$ and < 50
175 $\mu\text{M TN}$) in summer, especially in July (Fig. 4). In winter, surface NH_4 concentrations
176 were usually higher than that at the bottom due to sewage input from the upper harbor.
177 In Tolo, a much weaker seasonal pattern was observed for these three nutrients with
178 no pronounced summer minima. NH_4 and DIN concentrations in Tolo were < 14 and
179 $20 \mu\text{M}$ for NH_4 and DIN respectively. TN concentrations fluctuated between 40 and
180 $80 \mu\text{M}$ in inner and middle Tolo (TM4 and TM6) and were $< 40 \mu\text{M}$ in Tolo Channel
181 (Fig. 4).

182 In Victoria, PO_4 and total phosphorus (TP) at the surface demonstrated clear
183 seasonal variations with the highest ($> 1.6 \mu\text{M PO}_4$ and $> 3.5 \mu\text{M TP}$) in winter and
184 the lowest ($< 1.0 \mu\text{M PO}_4$ and $< 2.0 \mu\text{M TP}$) in summer (Fig. 4). A weaker seasonal
185 pattern was observed for these two nutrients in Tolo. PO_4 and TP concentrations at the
186 surface decreased markedly from 2 and $> 5 \mu\text{M}$ in inner Tolo (TM4) and from < 1 to 3
187 μM in Tolo Channel (TM8) (Fig. 4).

188 In Victoria, the maximal SiO_4 concentrations ($17\text{-}25 \mu\text{M}$) occurred in summer. In
189 contrast, in Tolo, SiO_4 concentrations at the surface were $5\text{-}15 \mu\text{M}$, which were
190 significantly lower than those ($15\text{-}25 \mu\text{M}$) at the bottom (Fig. 5).

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

198 ratios at the surface decreased from $>1:1$ in inner Tolo (TM4) to near or $< 1:1$ in Tolo
199 Channel (TM8) (Fig. 5). By comparison, the $\text{SiO}_4:\text{PO}_4$ ratios increased from inner
200 Tolo (TM4) with near or $< 16:1$ during October-May and $> 16:1$ during
201 June-September to Tolo Channel (TM8) with $> 32:1$ most of the year (Fig. 5). These
202 results revealed that the primary potential limiting nutrient varied spatially from Si in
203 inner Tolo to N+P co-limitation in Tolo Channel.

204 **Surface Chl *a* and bottom DO**

205 In Victoria, the surface Chl *a* concentration exhibited clear seasonal variations
206 with the highest ($\sim 13 \mu\text{g L}^{-1}$) in summer and the lowest ($< 2 \mu\text{g L}^{-1}$) in winter (Fig. 6).
207 In contrast, in Tolo, the surface Chl *a* concentrations were higher than Victoria, with a
208 maximum ($30 \mu\text{g L}^{-1}$) occurring in spring. Spatial variations in the surface Chl *a*
209 concentrations were observed, with high Chl ($10\text{-}30 \mu\text{g L}^{-1}$) in inner Tolo (TM4),
210 intermediate ($10\text{-}20 \mu\text{g L}^{-1}$) in the middle Tolo (TM6) and low Chl (mostly $< 10 \mu\text{g}$
211 L^{-1}) in Tolo Channel (TM8) (Fig. 6).

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

216 **Eutrophication recovery**

217 In Victoria, NH_4 , DIN, TN, PO_4 and TP decreased by 13-48%, 14-32%, 38-43%,
218 24-41% and 38-53%, respectively, after sewage treatment began in 2001 (Fig. 8). A
219 significant (17-20%) decrease in SiO_4 concentrations was observed at VM2 and VM5.
220 In contrast, there was a significant increase (26-55%) in NO_3 concentrations at VM5
221 and VM7. DIN: PO_4 ratios increased significantly (40-65%) due to the increase in NO_3
222 and decrease in PO_4 . Chl *a* concentrations increased by 15-33%, but not significantly.

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

224 In Tolo, NH_4 , NO_3 , DIN, TN, PO_4 and TP decreased by 32-40%, 34-61%,
225 37-43%, 38-43%, 50-76% and 64-67%, respectively, after sewage treatment began in
226 1997. DIN: PO_4 and DIN: SiO_4 ratios increased significantly by 60-128% and
227 119-294% at TM4 and TM6, respectively due to the large decrease in nitrogen. There
228 were a significant (32-38%) reduction in Chl *a* and an increase (11-20%) in bottom
229 DO concentrations (Fig. 8).

230

231 **Discussion**

232 **Tolo Harbour (pre-treatment:1986-1997)**

233 **Physical processes**

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

245 **Nutrients**

246 In Tolo, local sewage discharge was a major nitrogen source and NH_4 was the
247 main contributor to DIN, accounting for > 50% of DIN. NO_3 also resulted from

248 sewage, not runoff, since NO_3 concentration was the lowest in summer during the
249 period of maximum runoff. On average, DIN only accounted for ~25% of TN since
250 phytoplankton biomass was high. The continual supply of nutrients from sewage
251 contributed sufficient NH_4 and PO_4 for algal growth.

252 Higher SiO_4 concentrations at the bottom implied that remineralized Si from the
253 sediments was a major Si source for diatom growth in the dry season when weak
254 stratification favored the replenishment of SiO_4 from the bottom. In comparison, in
255 summer, runoff contributed Si to Tolo as the surface SiO_4 concentrations rose from a
256 minimum in spring, and the $\text{SiO}_4:\text{PO}_4$ ratio was higher than other seasons, despite the
257 decreased replenishment of SiO_4 from the bottom waters due to strong stratification.
258 Si was rarely limiting since there was sufficient input from remineralized Si at the
259 bottom and runoff in the summer. Grazing by *N. scintillans* might promote Si
260 recycling to sustain diatom growth since diatoms are the most common prey (Liu and
261 Wong 2006).

262 **Eutrophication impacts: algal blooms**

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

271 The high Chl *a*, but no obvious drawdown in Si in January and February
272 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 SiO₄ 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, SiO₄ 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 °C) (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 SiO₄ 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 $\mu\text{g L}^{-1}$ all year, except in April when the extremely high monthly average Chl *a* concentration (~35 $\mu\text{g L}^{-1}$) was caused by four episodic algal blooms in April (e.g. 87 and 140 $\mu\text{g Chl } a \text{ L}^{-1}$ in 1988, 67 $\mu\text{g Chl } a \text{ L}^{-1}$ in 1990 and 360 $\mu\text{g Chl } a \text{ L}^{-1}$ 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 ($\text{DO} < 0.2 \text{ mg L}^{-1}$) 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

323 to an increase in the input of the freshwater discharge volume was found to stimulate
324 the development of algal blooms by increasing the residence time of phytoplankton in
325 the euphotic zone (Howarth et al. 2000) and hypoxia in bottom waters by reducing
326 vertical oxygen transport in the northern Gulf of Mexico (Justic et al. 1996, 2005).
327 The shallow water column helped to reduce the severity of the hypoxic events in inner
328 Tolo. An inverse relationship between the volume of hypoxic bottom waters and the
329 mean depth was observed in regions of the Chesapeake Bay (Fisher et al. 2006). In
330 Tolo Channel, the episodic low O₂ events in summer were related to upwelling and
331 the possible invasion of low O₂ bottom water from offshore.

332 **Victoria Harbour (pre-treatment: 1986-2001)**

333 **Physical processes**

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

343 **Nutrients**

344 In Victoria, nutrient concentrations were influenced by year round local sewage
345 inputs, the Pearl River discharge in summer and coastal/oceanic water in winter (Yin
346 and Harrison 2007, Ho et al. 2008, Xu et al. 2008). High NH₄ and PO₄ concentrations
347 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 ($< 50 \mu\text{M}$) in summer. Lower TN concentration ($\sim 42 \mu\text{M}$) at VM7 in summer than ($\sim 50 \mu\text{M}$) 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 $\text{SiO}_4:\text{PO}_4$ ratios at VM7 than the other two Victoria stations farther away since the Pearl River discharge is characterized by high $\text{SiO}_4:\text{PO}_4$ ratio ($\sim 100:1$) (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 ($\sim 13 \mu\text{g L}^{-1}$) 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 NH₄ and PO₄ 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 ($\sim 5 \mu\text{g L}^{-1}$) 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 $465 \text{ W h m}^{-2} \text{ d}^{-1}$ (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 ($< 2 \mu\text{g L}^{-1}$) and the lack of a typical spring bloom, although grazing might also be important.

Eutrophication impacts: hypoxia

In Victoria, few hypoxic events ($\text{DO} < 2 \text{ mg L}^{-1}$) occurred despite the much

398 higher inputs of sewage relative to Tolo. In Victoria, destratification due to strong tidal
399 currents in summer and strong vertical mixing in other seasons favored vertical
400 oxygen transport to the bottom waters. High flushing in Victoria diluted the organic
401 matter, which reduced the demand for oxygen (Ho et al. 2008). As a result, hypoxic
402 events rarely occurred. Therefore, Victoria is much more resilient to nutrient
403 enrichment due to its active hydrodynamic conditions.

404

405 **Nutrient reduction and eutrophication recovery**

406 **Tolo Harbour (post-treatment: 1998-2007)**

407 A 90% reduction in sewage loading resulted in a significant reduction in the
408 concentrations of nutrients other than SiO_4 at all stations. A significant decrease in
409 NO_3 confirmed that NO_3 mainly resulted from sewage, not freshwater. The percentage
410 reduction in phosphorus was more than nitrogen and this was accompanied by a
411 significant increase in $\text{DIN}:\text{PO}_4$ and $\text{SiO}_4:\text{PO}_4$ ratios (Fig. 8). $\text{DIN}:\text{PO}_4$ and $\text{SiO}_4:\text{PO}_4$
412 ratios were on average $> 16:1$ after sewage treatment, suggesting that P was the
413 potential limiting nutrient. In inner and outer Tolo, a small (5-13%) increase in SiO_4
414 after treatment was likely linked to the decrease in Chl *a* as diatoms were usually the
415 dominant group in Tolo most of the year (Yung et al. 1997; Wong and Wong 2004)
416 and Si input should remain relatively constant. The percentage increase in SiO_4 was
417 much less than the reduction in Chl *a*. Hence, we speculate that most of reduced
418 phytoplankton biomass was from non-silicious species and the contribution of
419 diatoms to the phytoplankton community might have increased after sewage treatment
420 since the potential limiting nutrient shifted from Si to P in response to sewage
421 treatment.

422 Eutrophication impacts have been reduced significantly in response to nutrient

reduction. The magnitude and frequency of algal blooms ($> 10 \mu\text{g Chl L}^{-1}$) have fallen dramatically. High Chl *a* concentrations ($> 40 \mu\text{g Chl L}^{-1}$) were frequently observed and the peak value was up to $150 \mu\text{g L}^{-1}$ at TM4 before sewage treatment. In contrast, Chl *a* concentrations declined to mostly $< 20 \mu\text{g L}^{-1}$ 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

448 concentrations. The reduction in nutrients from sewage demonstrated a clear gradient
449 along the west (VM7) to east (VM2) transect. The highest percentage decrease in
450 nutrients (NH_4 , PO_4 , TN, and TP) from the sewage often occurred at VM2 far from
451 the Pearl River estuary (Fig. 8). The higher average post-treatment NO_3
452 concentrations compared to pre-treatment were associated with an increase in NO_3
453 concentrations in the Pearl River discharge in recent years (Xu et al. 2008). A rise in
454 NO_3 was more obvious (55%) at VM7 and due to the increase in NO_3 concentrations
455 in the Pearl River discharge over the last several decades (Xu et al. 2008). The
456 increased NO_3 compensated for the loss of NH_4 , resulting in a slight (8%) increase in
457 DIN (Fig. 8). On the other hand, the high Pearl River discharge in summer pushed
458 some of the sewage from the Stonecutters Inland to Victoria Harbour, reducing the
459 eutrophication recovery. Similar to Tolo, a greater reduction in phosphorus relative to
460 nitrogen led to a significant (40-65%) increase in DIN: PO_4 ratios. In summer, P
461 became the potential limiting nutrient as a result of the high input of NO_3 and SiO_4
462 from the Pearl River discharge (Xu et al. 2009). In contrast to Tolo, a significant
463 (16-20%) decrease in SiO_4 was observed in Victoria (VM5 and VM2), which was
464 most likely attributed to the 26-33% increase in Chl *a* after treatment, since an
465 increase in SiO_4 was not significant at VM7 despite a 15% increase in Chl *a* after
466 sewage treatment, suggesting that Si input did not change significantly.

467 In Victoria, algal biomass and bottom DO differed in response to nutrient
468 reduction. After sewage treatment, the magnitude of algal blooms has not been
469 reduced and the observed peak in Chl *a* concentration ($\sim 53 \mu\text{g L}^{-1}$) at VM5 and VM2
470 was higher than during pre-treatment. Overall, nutrient reduction did not result in a
471 decrease in algal biomass. In fact, the average post-treatment surface Chl *a*
472 concentration was 15-33% higher than during pre-treatment (Fig. 8). The frequency of

473 algal blooms increased from 9-10% of sampling cases before sewage treatment to
474 10-14% after sewage treatment (Fig. 7). In contrast, no hypoxic events were detected
475 after sewage treatment and a significant (11-22%) increase in the bottom DO levels
476 was likely attributed to a 50% decrease in the organic pollution loading due to sewage
477 treatment in Victoria (Broom et al. 2003).

478 **Summary**

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

495 In contrast, in the highly-flushed Victoria, the ecosystem appeared to be less
496 susceptible to nutrient enrichment. In summer, an increase in stratification due to the
497 invasion of the Pearl River discharge stimulated phytoplankton growth by increasing

498 the residence time of phytoplankton in the euphotic zone. On the other hand, the high
499 volume Pearl River discharge increased the flushing rate and shortened the water
500 residence times, which restricted the further accumulation of the phytoplankton
501 biomass in the water column and in the sediments. Furthermore, it is difficult to
502 maintain stratification due to strong tidal mixing. During fall, winter and spring,
503 strong vertical mixing resulted in light limitation and dilution of the algal biomass.
504 Since vertical mixing favored the vertical transport of oxygen, hence, few hypoxic
505 events occurred in Victoria. In Victoria, nutrient reduction after sewage treatment had
506 no contribution to a reduction in the phytoplankton biomass since phytoplankton
507 growth was mainly regulated by the physical processes (e.g. strong vertical mixing
508 and high flushing rate). In fact, Chl *a* increased by up to 33% after sewage treatment.
509 In both harbors, the bottom DO has increased due to a reduction in the loading of
510 organic pollutants after sewage treatment.

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

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Table 1 Mean daily solar radiation (I_0), Secchi disc depth, mixed layer depth (z) and mean light intensity in the mixed layer ($\langle I \rangle$). I_0 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_0	VM7			VM5			VM2		
		Secchi	z	$\langle I \rangle$	Secchi	z	$\langle I \rangle$	Secchi	z	$\langle I \rangle$
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 O₂ 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 (NH₄, NO₃, DIN, TN, PO₄, TP, SiO₄, DIN:PO₄, SiO₄:PO₄, DIN:SiO₄), 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.