Summary on Review of Marine Water Quality Objective on Nutrients

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1. Introduction

1.1. Nutrients are essential elements for living organisms to survive and reproduce. Nitrogen (N) and phosphorus (P), are the two major nutrients required for phytoplankton. Eutrophication (over-enrichment of nutrients), can be due to anthropogenic or natural[1] input of nutrients. When an aquatic system becomes over-enriched in nutrients due to discharges of sewage and fertilizers from agricultural uses, eutrophication could cause excessive growth of aquatic plants and algae, leading to algal blooms, and subsequent decay of algae will lead to depletion of oxygen in water (hypoxia), and hence massive death of aquatic organisms.

1.2. The Water Quality Objective (WQO) on nutrients is primarily established to minimize the impact of nutrient enrichment and the risk of eutrophication to the aquatic environment. For our marine waters, (i) a narrative nutrient WQO ("*Nutrients shall not be present in quantities sufficient to cause excessive or nuisance growth of algae or other aquatic plant*"), and (ii) a numeric nutrient WQO in terms of total inorganic nutrient (TIN) level have been adopted, except for the Tolo Harbour and Channel Water Control Zone (WCZ) where numeric nutrient WQO is based on chlorophyll-*a* level[2].

1.3. Red tide refers to the phenomenon of water discoloration due to high population of phytoplankton dominated by a single or couple of species. It could occur naturally in both polluted and unpolluted waters. There is scientific consensus that red tide is a complex phenomenon driven by a myriad of physical, chemical and biological factors, instead of attributing to a single factor. While elevated nutrient levels may provide more fuel for algal growth and increase the general risk of red tide formation, a direct causal relationship between TIN level and red tide incidence often could not be found especially in coastal waters, as illustrated in **Annex 1** and **Annex 2**. Although nutrients may be an important factor to sustain an algal bloom once it is formed, accumulating scientific evidence shows that red tides in coastal waters (including Hong Kong) are usually triggered by a combination of climatic and/or hydrodynamic conditions, such as light intensity, temperature, stratification, water current, and wind speed etc.

1.4. Despite the elevated TIN level in western waters and to a certain extent southern waters, the low incidence of red tides in these waters suggests that the environmental capacity of the water body is greatly increased due to the strong tidal flushing effect of the oceanic currents of the South China Sea which help disperse and dilute the pollution load, and reduce the aggregation of phytoplankton. For Deep Bay, notwithstanding the relatively high TIN level which exceeded the WQO by more than two folds due to poor flushing, red tide occurrence has been infrequent (2 incidents or less per year in the last decade). Nutrients have little effect in promoting red tides in Deep Bay, since other important factors, such as turbidity, zooplankton grazing and tidal mixing are limiting.

1.5. Phytoplankton growth generally follows the N/P molar ratio of 16N:1P (Redfield

[1] This generally includes natural run-off of nutrients from the soil and the weathering of rocks. For example, phosphate tends to adhere to rocks and sediments, so in nature it is mainly transported by weathering and erosion. Also, nutrients can naturally come from the ocean as conveyed by deep and nutrient-rich water currents. Natural eutrophication is usually a fairly slow and gradual process, occurring over a period of centuries or on geological time scales.

[2] Chlorophyll-*a* is the most common pigment used by aquatic plants for photosynthesis. It is a direct indicator of algal biomass which helps quantify the eutrophication status of a water body.

Ratio[3]). Environmental nutrient ratio below 16N:1P implies nitrogen may be first consumed and phytoplankton growth may potentially become N-limited. Conversely, when the ratio is greater than 16N:1P, phytoplankton growth may potentially become P-limited. In addition to the increased environmental capacity of the open waters, the low red tide occurrence in the western and southern waters of Hong Kong may also be due to the influence of the large Pearl River outflows with a high N:P ratio (roughly 50-100N:1P) in the wet season, making algal growth potentially P-limited (i.e. due to excessive N but insufficient P). Therefore, based on the limiting nutrient concept, P was introduced as an additional nutrient criterion to be considered in the Environmental and Engineering Feasibility Study and EIAs for HATS Stage 2. Owing to the increasing sewage flows collected for treatment or the upgrading of sewage treatment level, we observe that the phosphate level in our marine waters is generally on a decline as illustrated in Annex 1.

1.6. As illustrated in **Annex 1** and **Annex 2**, since nitrogen is not the sole nutrient required by phytoplankton, and it often has no direct causal relationship with the occurrence of red tides in local marine waters where other physical and biological factors can be limiting, it is therefore not scientifically sound to adopt the existing TIN WQO as the sole yardstick for assessing the risk of eutrophication.

2. *Phytoplankton*

2.1. Phytoplankton are microscopic plants that float passively in water. They are primary producers utilising nutrients in the water and solar energy to grow and reproduce. While phytoplankton is the food source for upper trophic levels, red tides due to excessive growth of phytoplankton could be an environmental nuisance, especially for those with harmful impacts such as fish kills.

2.2. Diatoms and dinoflagellates[4] are the two main taxonomic phytoplankton groups found in most coastal waters including Hong Kong. Dinoflagellates are the major red tide formers despite they have lower abundance in terms of cell density (generally below 20%). Moreover, dinoflagellates comprise the largest group of algae that may produce toxin or having other harmful effects. Diatoms, on the other hand, are considered less harmful and play an important role for marine primary production.

2.3. While nutrients and chlorophyll-a are direct measurements on the extent of nutrient enrichment and algal biomass respectively, they provide very limited information on the algal status, and direct impact and risk of eutrophication. In particular, there is generally an information gap on the relationship between these parameters and red tide incidents. Moreover, the chlorophyll-a level of different dinoflagellates species could vary significantly, as some of the dinoflagellates are not photosynthetic. For example, *Noctiluca scintillans*, the most common red tide species found in Hong Kong, is non-photosynthetic and non-chlorophyll-bearing. Therefore, supplementary biological indicators/criteria, which could indicate the direct impact of nutrient enrichment, are necessary for managing the risk of eutrophication.

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[3] Redfield (1934) found that globally the elemental composition of marine organic matter (dead and living) follows a remarkable constant stoichiometric ratio of carbon, nitrogen, phosphorus.

[4] Dinoflagellates, being a major subgroup of flagellates, are one-celled aquatic organisms bearing two dissimilar flagellae and having characteristics of both plants and animals.

2.4 There is scientific evidence showing that prolonged excessive nutrient enrichment, with a combination of physical and biological factors, can affect phytoplankton abundance and composition in a water body. Under such circumstances for example, excessive nutrients can promote the growth of dinoflagellates. The density ratio of dinoflagellates to diatoms may increase noticeably with increasing nutrient enrichment, particularly when the N:P ratio is relatively low and/or the growth of diatoms is limited by the supply of another nutrient, namely silicon (Si)[5]. The monitoring of composition shift of the phytoplankton community from diatoms to dinoflagellates could help manage the impact of eutrophication and harmful algal blooms (HABs), which is primarily caused by blooming of dinoflagellates.

3. *Overseas approaches and practices*

3.1. In recognition of the difficulty to establish realistic and scientifically sound numerical criteria for N, P or chlorophyll-*a*, and the significant resource implications in meeting such criteria if introduced, no coastal state of the USA promulgates any numeric marine water quality criteria based on these parameters[6]. The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)*, which contains guidelines on traditional nutrient parameters (N, P and chlorophyll-*a*), is still under review.

3.2. The EU recently formulated a management framework, and the target in respect of eutrophication is: "*human-induced eutrophication is minimised, especially adverse effects thereof, such as harmful algal blooms, oxygen deficiency,… etc.*" Relevant environmental status would be established for different parts or uses of marine waters, taking into account the impact of human activities, complemented by suitable treatment requirements[7] for major sewage treatment works (STWs) to reduce nutrient loadings.

3.3. The UK follows the EU approach and formulated in 2014 a proposal to develop biological standards and assessment methods using phytoplankton data to measure the impact of nutrient enrichment and assess the risk of eutrophication. The UK proposed to adopt biological indicators (e.g., cell densities of diatoms and flagellates, species shift in phytoplankton composition[8], etc.) to indicate direct environmental effects.

4. *Refinement of the proposed TIN and PO_4-P WQO values with site-specific considerations*

4.1. Based on the reference site approach, scientific analyses and rationales described in the Report on the Review of the nutrient WQOs, the initially proposed TIN and

[5] Si is a nutrient essential for the growth of diatoms but not for dinoflagellates.

[6] Florida State conducted studies to develop numerical chlorophyll-*a* criteria for estuaries and coastal waters mainly based on satellite remote sensing techniques and data. For these criteria, reference to the risk of eutrophication impact and environmental capacity of the water body concerned is not observed.

[7] *EC Directive (91/271/EEC) "Concerning Urban Waste Water Treatment".*

[8] In situations where conditions are favourable and nutrients are not limiting, the rapid growth of opportunistic fast growing species changes the population balance with diatoms being replaced by dinoflagellates, and this may eventually lead to high overall biomass throughout the growing season.

PO_4-P WQO values are refined using all the relevant updated data (water column, surface layers, etc.) collected in the period of Year 2010 to Year 2014. Seasonal criteria for TIN are suggested for the four WCZs in the western and southern sides of Hong Kong marine waters which show remarkable seasonal variations in the oceanographic and estuarine processes and the subsequent variations of TIN levels. The refined TIN and PO_4-P WQGs are listed in **Annex 3**. The approach of developing seasonal criteria for nutrients or other physical parameters is generally in line with the international practices. Although the study has further refined the initial draft nutrient criteria based on the latest data and local conditions, it should be reiterated the limitations of the sole use of the numeric nutrient parameters (e.g. TIN) for assessing eutrophication impact on local marine environment.

5. Further scientific studies

5.1. EPD has been collecting data on phytoplankton biomass (chlorophyll-*a*), cell densities and composition of diatom and flagellates over the years. The preliminary analyses of the data currently available (as presented in **Annex 4**) seems to suggest the density ratio of dinoflagellates to diatoms and/or the density ratio of dinoflagellates to total phytoplankton may serve as one of the supplementary indicators/components to measure the risk and impact of eutrophication. However, further studies would be necessary to fully develop and test the applicability of these new indicators. Moreover, the possibility of other potential indicator/criteria, such as phytoplankton composition ratio based on cell volume / size, etc., could also been examined.

5.2. In line with the latest overseas practices, the potential biological indicators or integrated nutrient criteria to be developed could be used to gauge the long-term water quality changes resulting from nutrient enrichment. The indicators/criteria should focus on specific phytoplankton group(s) (e.g. dinoflagellates) directly relevant to nutrient enrichment. Due to the high level of natural and seasonal variability in phytoplankton communities, the assessment of the impact of nutrient enrichment should be conducted based on the retrospective analyses of the historical data and the long-term trends in variations of these parameters/ indicators.

Annex 1

Analysis of nutrients and chlorophyll-*a* levels, and red tide occurrence in Hong Kong

In general, we cannot find a good correlation between nutrient levels (total inorganic nitrogen and orthophosphate phosphorus) and the occurrence of red tides in our marine waters. For chlorophyll-*a* level, there is some statistically significant correlation with red tide incidence in Tolo Harbour and Channel Water Control Zone (WCZ), which is the only WCZ adopting a nutrient WQO based on chlorophyll-*a* level.

Total Inorganic Nitrogen (TIN)

Water control zones in the central Hong Kong, including Western Buffer, Victoria Harbour, Eastern Buffer and Junk Bay generally had annual depth-averaged TIN below the TIN WQO of 0.4mg/L (except for Junk Bay WCZ which has WQO set at 0.3 mg/L) during 1986-2015. Red tide occurrence at these four WCZs was very low (<5 incidents per year, and zero incident in Eastern Buffer and Junk Bay WCZs).

Water control zones including Southern, Port Shelter, Mirs Bay, and Tolo Harbour and Channel also had TIN levels generally below 0.4 mg/L (the TIN WQO for Southern and Port Shelter WCZs is 0.1 mg/L, 0.3mg/L for Mirs Bay WCZ and no TIN WQO for Tolo Harbour and Channel WCZ). In Southern, Port Shelter and Mirs Bay WCZs, red tide occurrence was about 5 incidents per year, despite the low TIN level in these WCZs (particularly Port Shelter and Mirs Bay). Noticeably, higher red tide incident is observed in Tolo Harbour due to the semi-enclosed nature and the relatively stable water environment. Noting that the nutrients input to the harbour has been substantially reduced after the implementation of the Tolo Harbour Action Plan and the Effluent Export Scheme in late 80s to 90s, there is a corresponding reduction in the number of red tides.

The annual average TIN level in the North Western and Deep Bay WCZs was relatively high at around 0.5mg/L and above 1.5 mg/L respectively, exceeding the respective TIN WQO (0.5 mg/L for the North Western WCZ and outer Deep Bay; and 0.7 mg/L for the inner Deep Bay). The red tide occurrence in these two WCZs was, however, low (usually only 1-2 incidents per year, or mostly zero incident for Deep Bay). The low incident could be attributed to prevailing of other limiting factors such as strong flushing of tidal current and higher turbidity in these water bodies.

In conclusion, we cannot find any correlation between the TIN level and red tide occurrence in our marine waters.

Orthophosphate Phosphorus (PO_4-P)

PO_4-P levels in our marine waters follow a similar spatial pattern to TIN levels. The annual depth-averaged PO_4-P level in Deep Bay was relatively high (well above 0.1 mg/L). The PO_4-P level in the other nine WCZs was around or below 0.05 mg/L. Red tides occurred more frequently in Southern, Port Shelter, Mirs Bay and Tolo Harbour WCZs, while it occurred much less frequently at other WCZs. Again, correlation between the PO_4-P level and red tide occurrence in the 10 WCZs cannot be found. Due to the progressive provision and upgrading of sewage collection and treatment, we have also observed a long-term decreasing trend in PO_4-P levels in our marine waters.

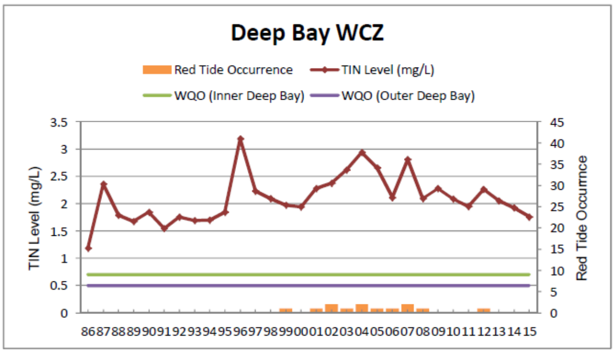
Chlorophyll-*a* (Chl-*a*)

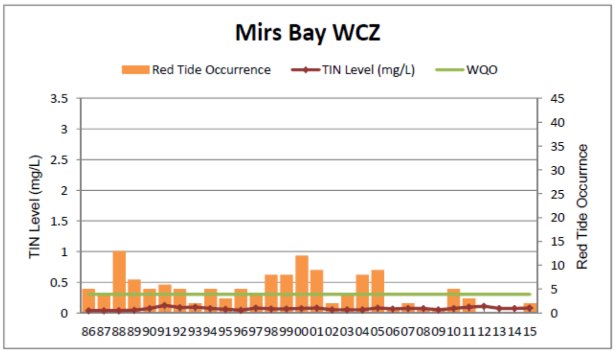
The Chl-*a* level in Tolo Harbour was also relatively higher (ranged between 4-10 ug/L and reduced to around 5 ug/L in recent years). Red tide incidents in Tolo Harbour were also more frequent in the past. Statistically significant correlation between Chl-*a* level and red tides occurrence in Tolo Harbour was found.

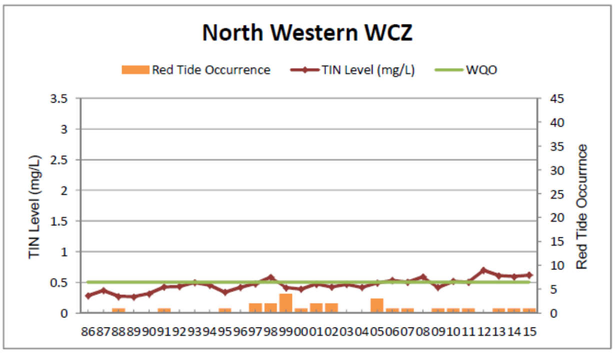
Deep Bay had noticeably higher Chl-*a* level with annual averages in the range of 5-19 ug/L. However, red tide occurrence was very low and close to zero. No correlation could be found between Chl-*a* level and red tide occurrence in Deep Bay.

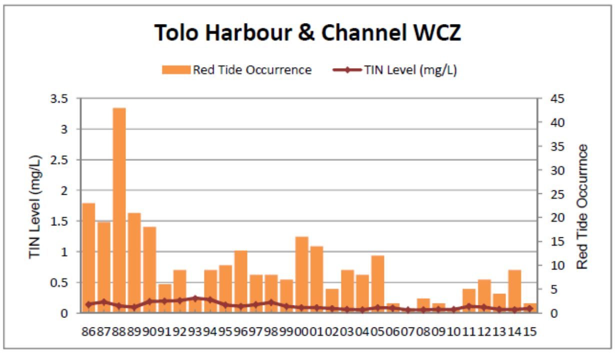
While all the other eight WCZs generally had Chl-a level around or below 5 ug/L, there was no linkage between the variation of Chl-a level and red tide occurrence in these WCZs. In summary, except for the Tolo Harbour, correlation between the Chl-a level and red tide occurrence in other WCZs cannot be established.

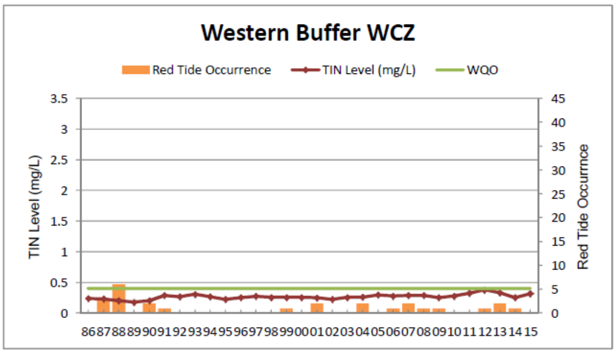
Total Inorganic Nitrogen (TIN) level and red tide occurrence in 10 Water Control Zones

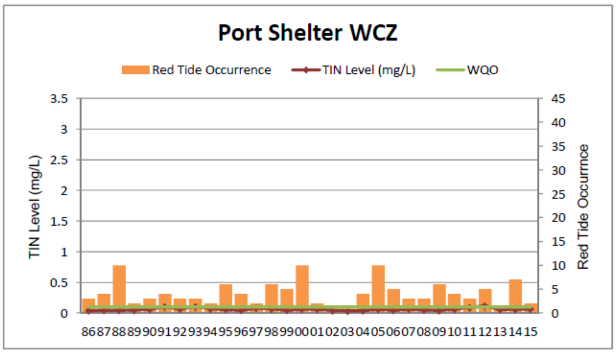


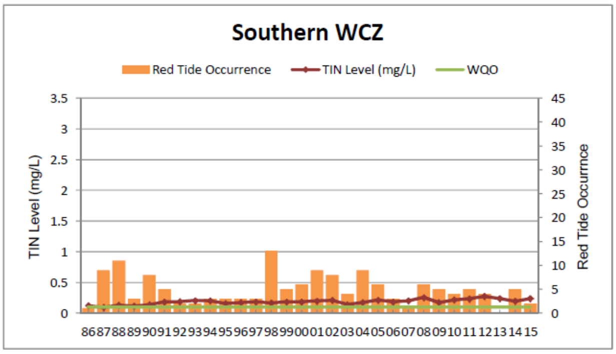


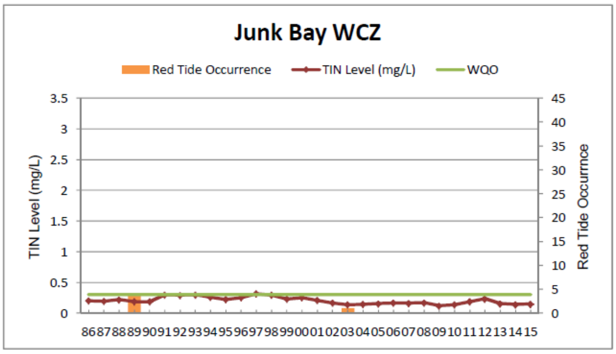


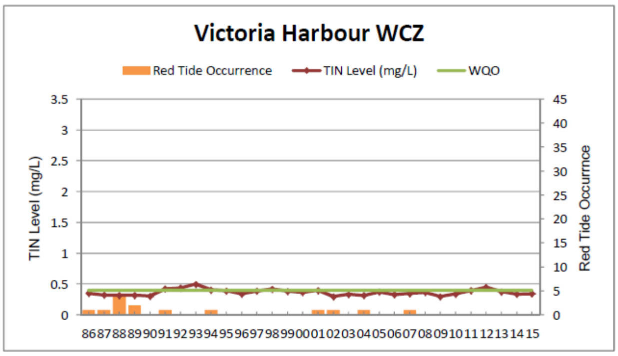


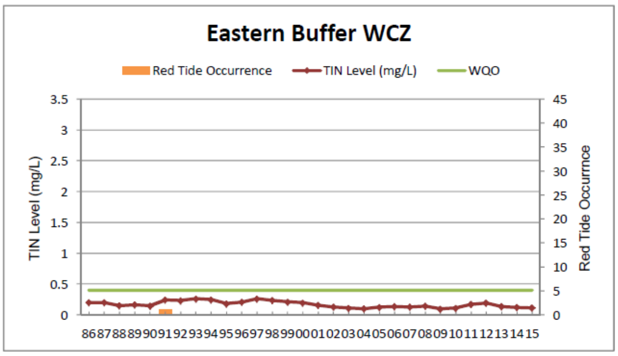




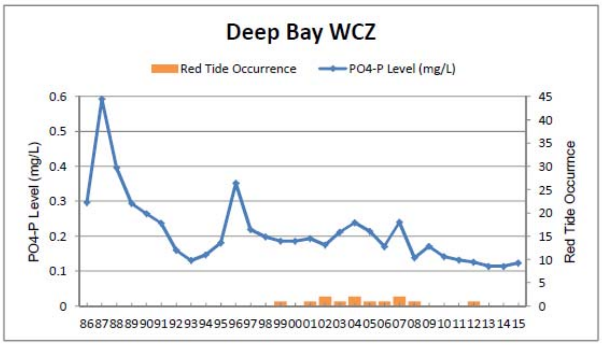


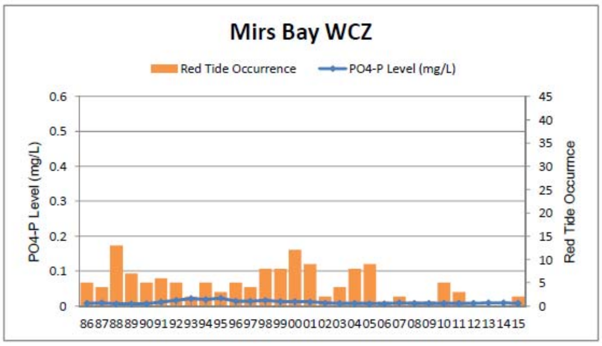


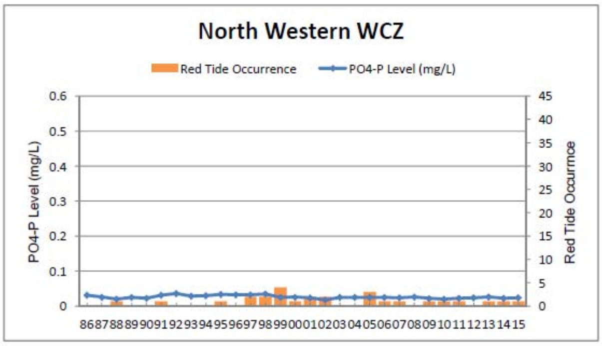


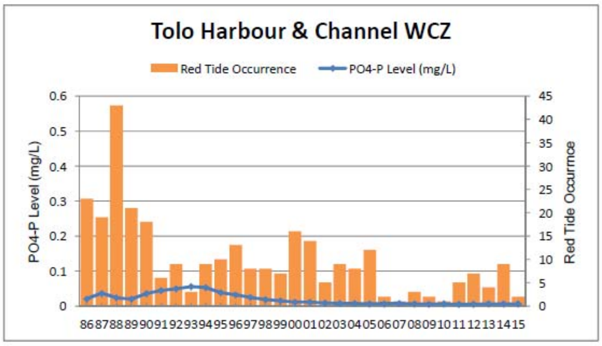


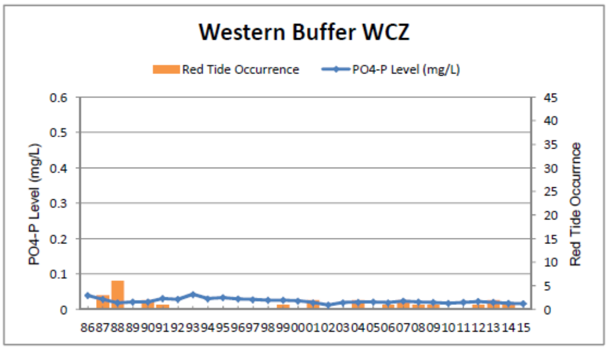
Orthophosphate Phosphorus (PO_4-P) level and red tide occurrence in 10 Water Control Zones

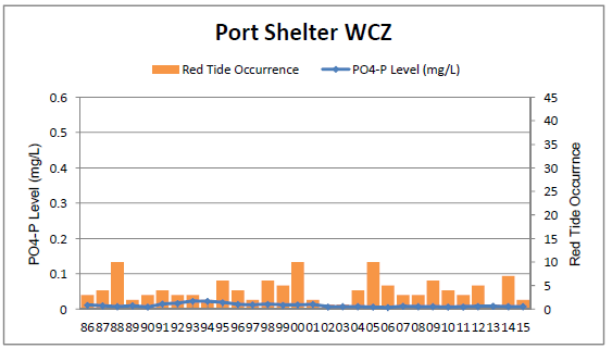


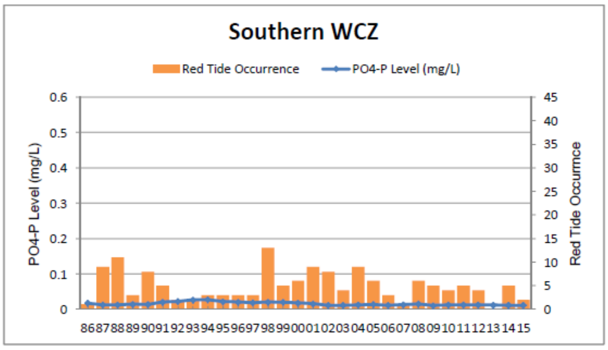


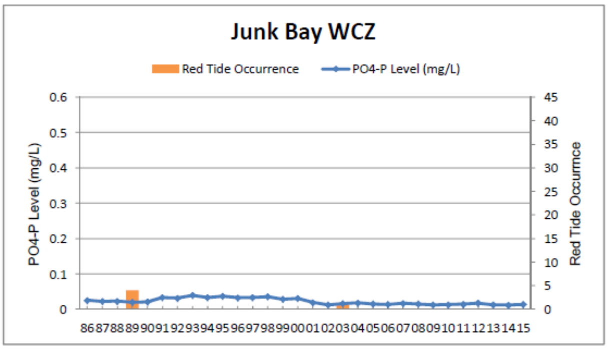


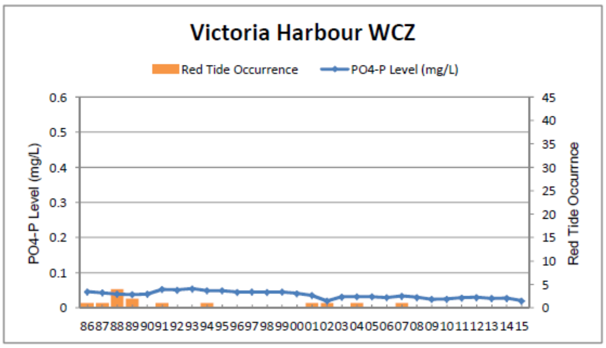


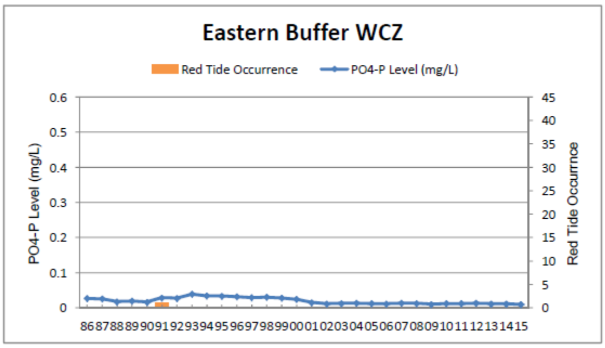




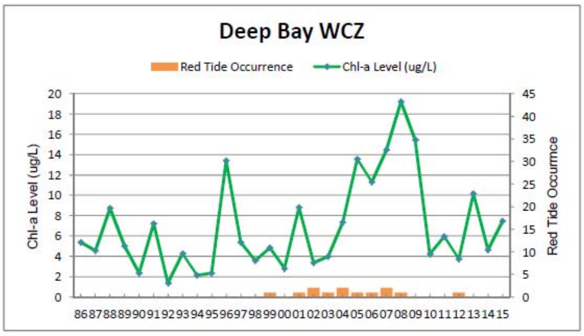


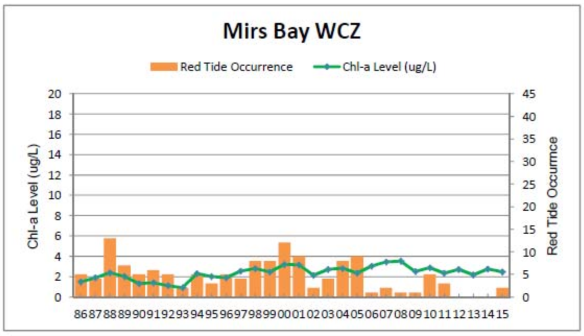


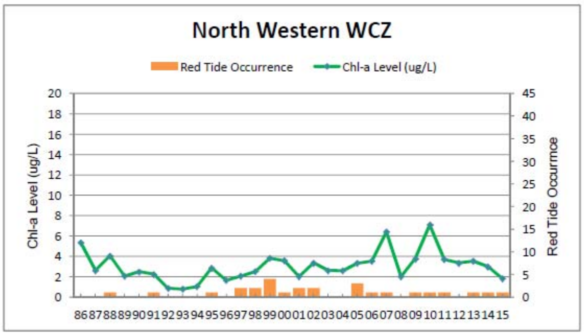


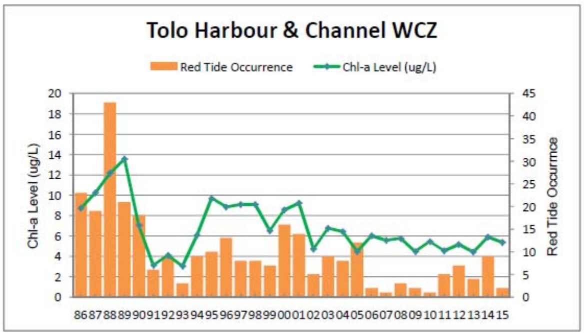


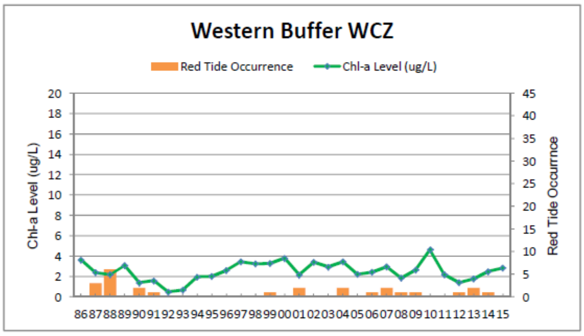
Chlorophyll-*a* (Chl-*a*) level and red tide occurrence in 10 Water Control Zones

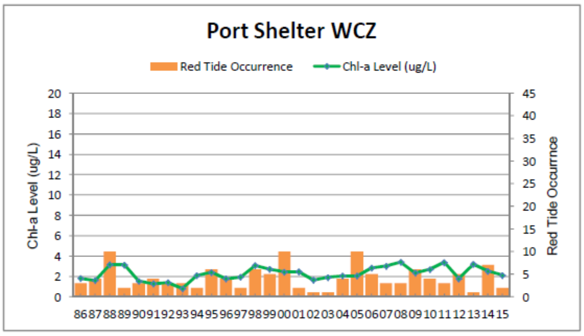


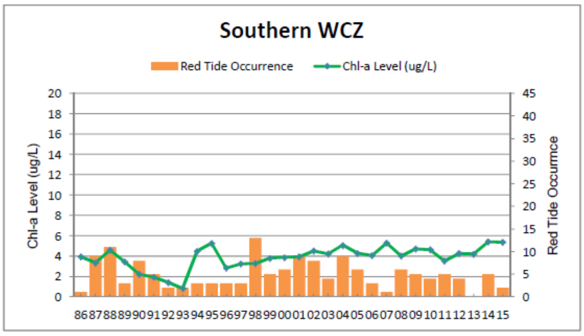


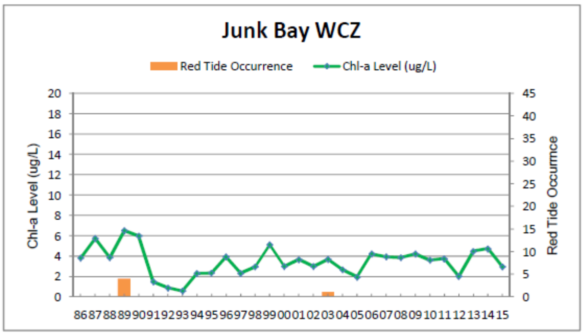


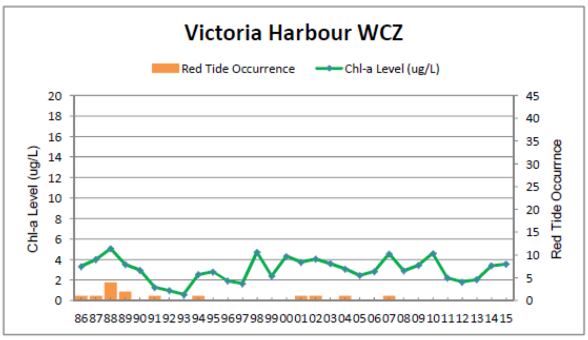


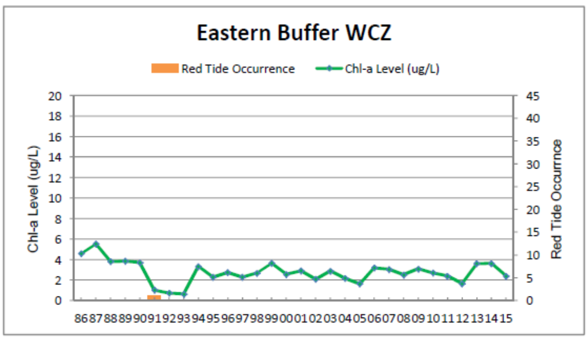








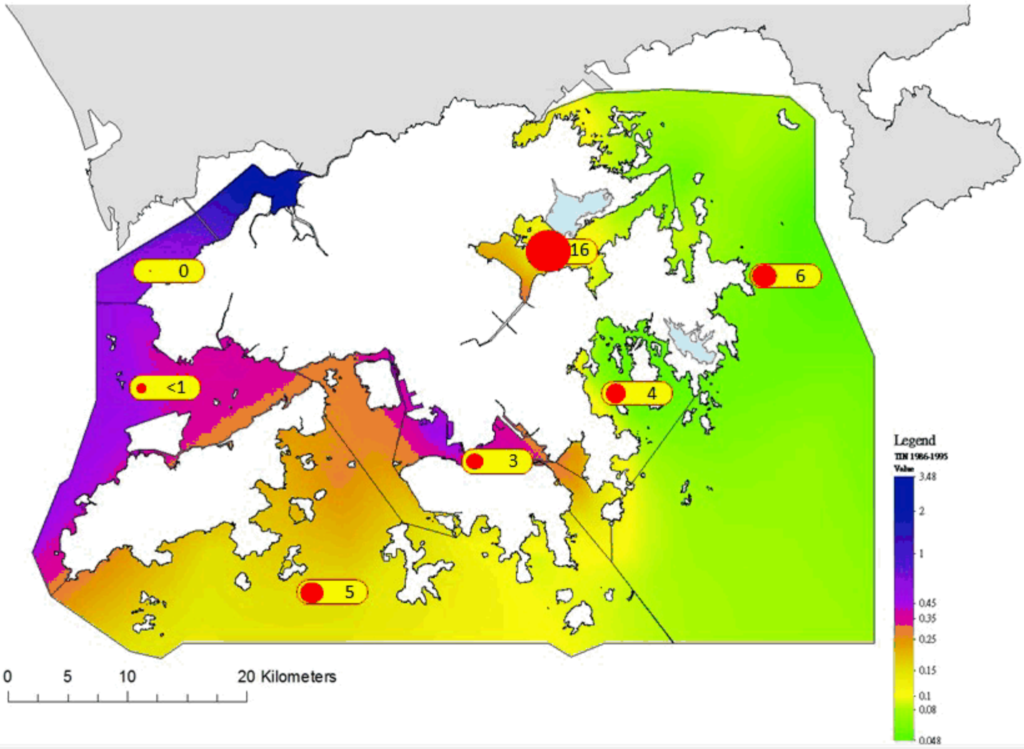




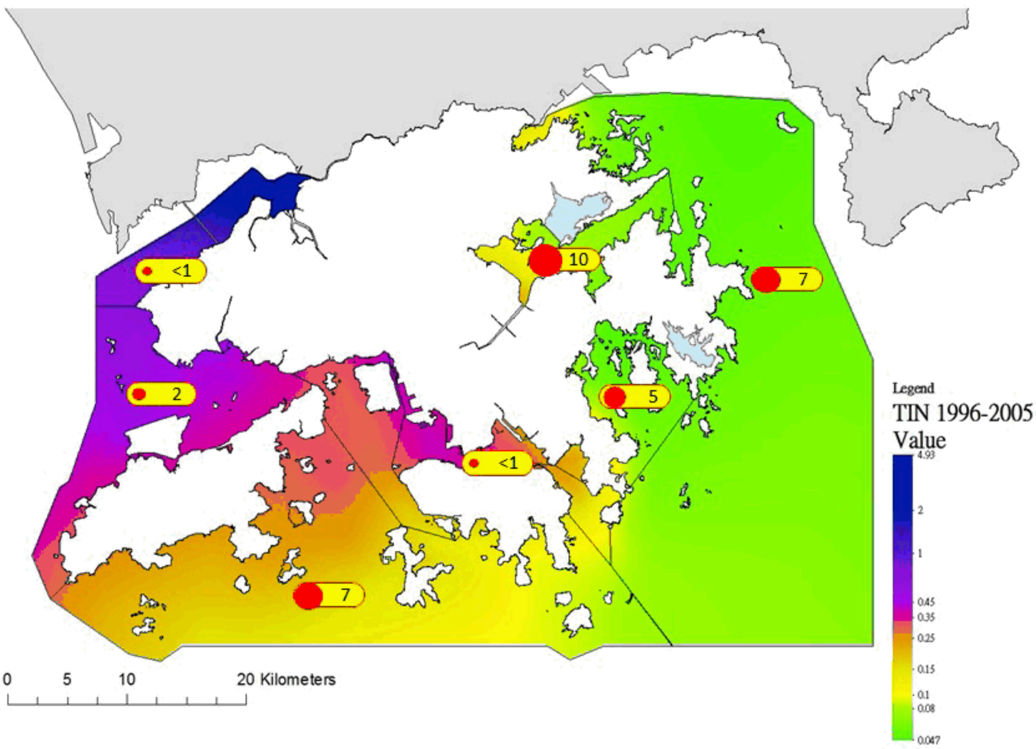
Annex 2

Changes in spatial variations in TIN levels
and the number of red tide incidents over the past 30 years (from 2006 to 2015)

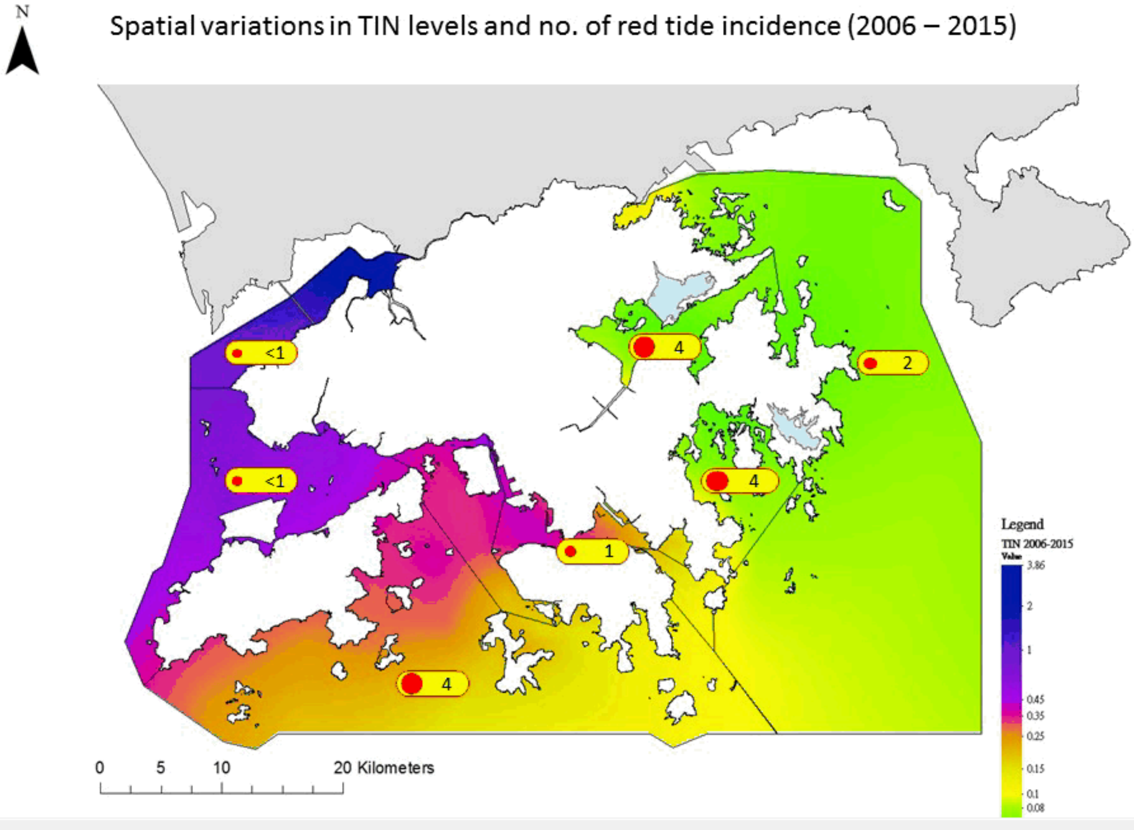
Spatial variations in TIN levels and no. of red tide incidence (1986 – 1995)



Spatial variations in TIN levels and no. of red tide incidence (1996 – 2005)



Spatial variations in TIN levels and no. of red tide incidence (2006 – 2015)



Summary of the existing TIN WQOs, the previously proposed nutrient WQGs for TIN and PO_4-P, and the refined WQGs

Water Control Zone	TIN (mg/L)		PO_4-P (mg/L)
	Existing WQOs (Annual average)	**Refined proposal (Annual or seasonal average)**	**Refined proposal (Annual average)**
Tolo Harbour and Channel	-	≤ 0.2	≤ 0.02
Port Shelter	≤ 0.1	≤ 0.2	≤ 0.02
Mirs Bay	≤ 0.3	≤ 0.2	≤ 0.02
Junk Bay	≤ 0.3	≤ 0.3	≤ 0.02
Eastern Buffer	≤ 0.4	≤ 0.3	≤ 0.02
Victoria Harbour	≤ 0.4	≤ 1.0	≤ 0.03
Southern	≤ 0.1	≤ 0.7 (wet) ≤ 0.3 (dry)	≤ 0.02
Western Buffer	≤ 0.4	≤ 1.4 (wet) ≤ 0.5 (dry)	≤ 0.03
North Western	≤ 0.5 (except Castle Peak Subzone ≤ 0.3)	≤ 1.7 (wet) ≤ 0.7 (dry)	≤ 0.04
Deep Bay (inner)	≤ 0.7	≤ 2.0 (wet) ≤ 1.1 (dry)	≤ 0.05
Deep Bay (outer)	≤ 0.5		

Preliminary review of red tides and phytoplankton monitoring data

- EPD has been collecting data on phytoplankton biomass (chlorophyll-*a*), cell densities and composition of diatom and flagellates over the years. Surface water samples are collected from 25 routine monitoring stations in local marine waters (Figure 1) on a monthly basis for phytoplankton enumeration. In addition, data on the occurrence of red tides and harmful/toxic algal blooms, and the species involved are collected by AFCD.

- From 1980 to 2015, a total of 898 red tides were recorded in Hong Kong waters. Some 39% (349 incidents) occurred in the Tolo Harbour and Channel Water Control Zone (WCZ), followed by 17% (153 incidents) in the Mirs Bay WCZ, 18% (158 incidents) in the Southern WCZ, 16% (142 incidents) in the Port Shelter WCZ and 10% (96 incidents) in other WCZs. Among all these red tides recorded, some 65% were caused by dinoflagellates, 16% due to diatoms and 19% due to other minor phytoplankton groups.

- As illustrated in Figure 2 and Figure 3, among the 10 WCZs, the ratio of dinoflagellates to diatoms and the ratio of dinoflagellates to total phytoplankton are highest in Tolo Harbour which also has the highest historical red tide occurrence. During the period of late 1980s to early 1990s (the peak period), red tides occurrence increased significantly with an increase in the dominance of dinoflagellates (the number of dinoflagellate blooms increased) when the nutrient input was also high and the annually averaged N:P ratio decreased from 20:1 to 11:1 over a seven year period with a marked increase in the human population. This clearly suggested a sign of eutrophication (Hodgkiss and Ho, 1997[9]).

- Nutrient enrichment in Tolo Harbour brought about a shift in the phytoplankton community with a noticeable increase in the ratio of dinoflagellates to diatoms (>0.3) (Figure 3) and the ratio of dinoflagellates to total phytoplankton (>0.1) in the peak period (Figure 3). After the implementation of the Tolo Harbour Action Plan which included the Tolo Harbour Effluent Export Scheme (THEES) fully commissioned in 1998, the nutrient input has been substantially reduced, accompanied by a remarkable decrease in the red tide occurrence (from 14.1 incidents per year to 6.4 incidents per year), and the ratio of dinoflagellates to diatoms (<0.3) (Figure 2), as well as the ratio of dinoflagellates to total phytoplankton (<0.1) (Figure 3).

- Despite the elevated levels of nutrients in western waters, the red tides occurrence, the ratio of dinoflagellates to diatoms and the ratio of dinoflagellates to total phytoplankton remained low and relatively stable, indicating that the impact of nutrient enrichment and the risk of eutrophication remain relatively low. This could be attributed to the greater assimilation and tidal water flushing of the open sea environment, and/or high N:P ratio of the Pearl River discharges.

- Statistical analyses also revealed that the overall ratio of dinoflagellates to diatoms (with data from all 25 monitoring stations pooled) shows significant correlation with red tide incidents and TIN level. For Tolo Harbour which is an enclosed water body sensitive to the impact of nutrient enrichment, statistically significant correlation

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[9] Hodgkiss, I., and Ho, K. C. *Are changes in N:P ratios in coastal waters the key to increased red tide blooms?* Hydrobiologia 352 (1997), 796-822.

between red tide incidents and both parameters (the ratio of dinoflagellates to diatoms, and the ratio of dinoflagellates to total phytoplankton) was observed.

- These biological parameters (changes in the density ratio of dinoflagellates to diatoms ratio and the density ratio of dinoflagellates to total phytoplankton) could provide useful information, in additional to nutrients (N and P) and chlorophyll-*a*, to reflect the eutrophication status of our marine waters in respect of the overall impact of nutrient enrichment and other relevant limiting factors such as assimilation and stability of water body, water clarity, etc. These parameters may also have an advantage over chlorophyll-*a* that they include the measurement of the relevant non-photosynthetic phytoplankton which could not be covered by the measurement of chlorophyll-*a* alone.

Figure 1 EPD's phytoplankton monitoring stations in Hong Kong marine waters

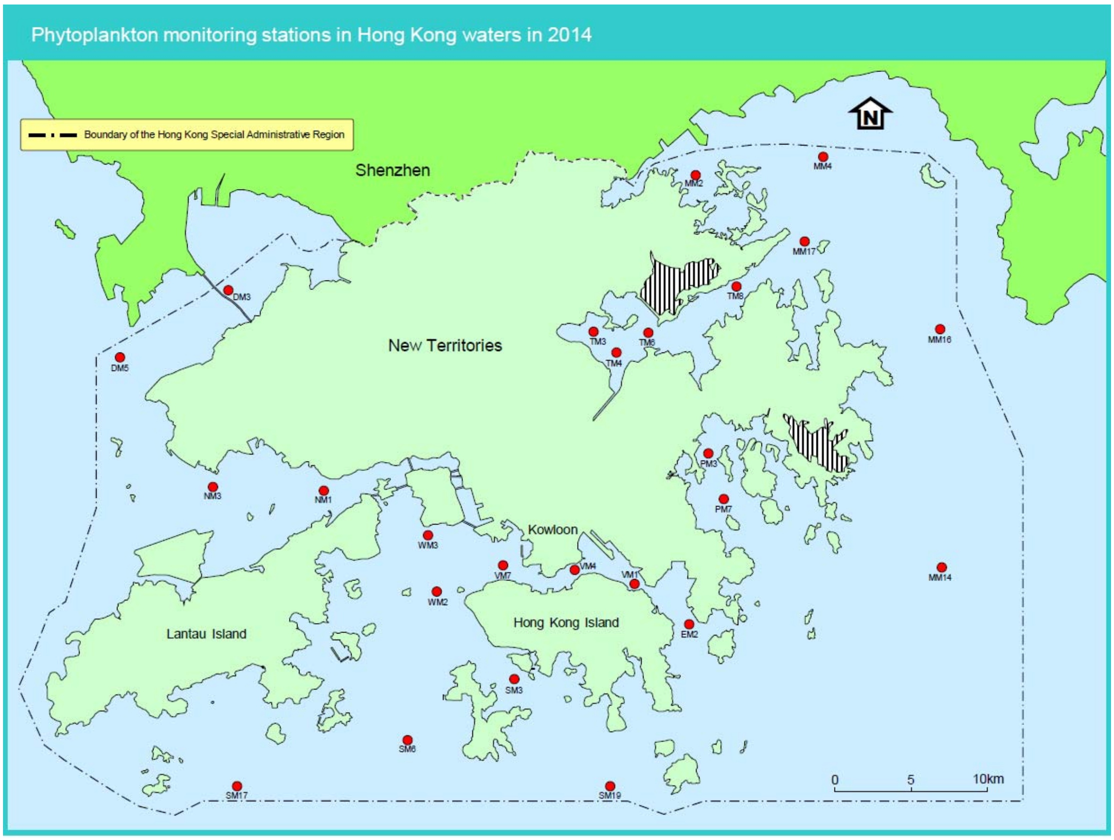

Figure 2 TIN levels and density ratio of dinoflagellates to diatoms in Hong Kong marine waters

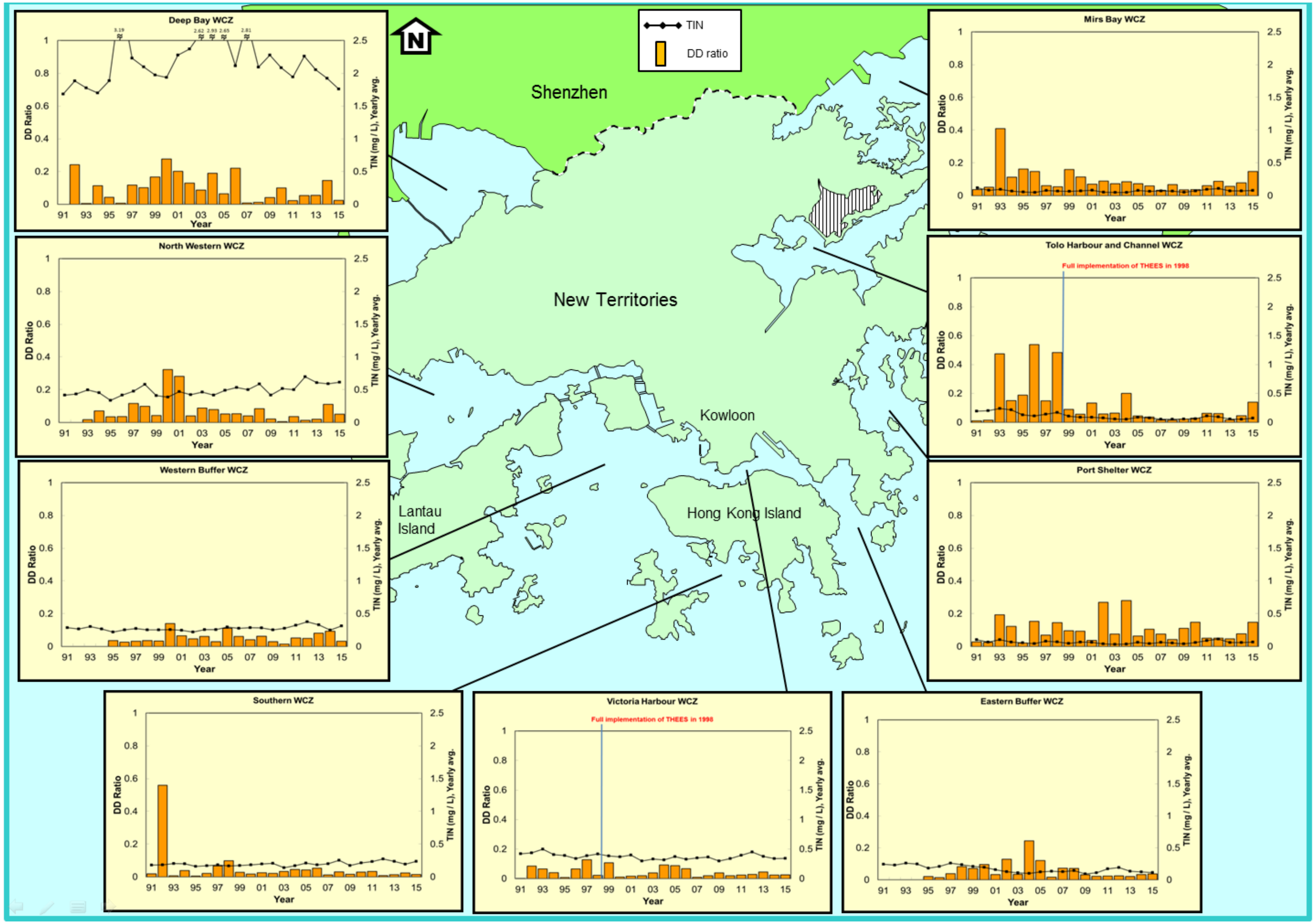

Figure 3 TIN levels and density ratio of dinoflagellates to total phytoplankton in Hong Kong marine waters