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Integrated Water Quality Management in Tolo Harbour, Hong Kong - A Case Study

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Abstract

Tolo Harbour is an almost land-locked semi-enclosed sea inlet with a narrow outlet in the South China Sea. With the rapid growth in economic development and urbanization, evidence of increasing eutrophication is seen by the drastic increase in the severity and frequency of algae blooms, which are closely correlated to the excessive nutrient loading. The bottom waters in Tolo Harbour exhibit serious dissolved oxygen depletion. A co-ordinated sequence of pollution control activities are being undertaken by the Hong Kong Government. Technological advances can be utilized in effective water quality management in the coastal zone. This paper presents the application of a robust three-dimensional numerical eutrophication model, integrating hydrodynamics with water quality, for simulation of the algal growth dynamics and water quality processes. After calibration and verification, the tool is used to predict different eutrophication scenarios as well as the effectiveness of alternative management solution strategies.

Introduction

Tolo Harbour is an almost land-locked semi-enclosed sea inlet with a narrow outlet in the South China Sea. With the rapid growth in economic development and urbanization, evidence of increasing eutrophication is seen by the drastic increase in the severity and frequency of algae blooms, which are closely correlated to the excessive nutrient loading. Eutrophication leads to degradation of the environment, less desirable water quality and usage of the water body in terms of water supply, fish maintenance, aesthetics and recreation, and is associated with problems such as bottom-water anoxia, decline in fisheries, and loss of submerged aquatic vegetation. The importance of this issue as well as the financial benefits of cleaner production and preventive strategies to non-traditional stakeholders was highlighted by Huhtala et al. (2003). The water quality and hydrology in Tolo Harbour have been investigated by a number of researchers (Trott, 1973; Hodgkiss and Chan, 1983; Bowler, 1985; Chau and Sin, 1992; Sin and Chau, 1992; Jin et al., 1998).

Technological advances, such as eutrophication modelling, can be utilized in effective water quality management in a coastal zone. Whilst the initial research was focussed on seasonal steady-state conditions, time-varied modelling for a longer period in years was later explored (Lung et al., 1993). Previously, owing to the limitation of computing resources, pollutant transport modelling was undertaken with several water quality parameters in depth-integrated two-dimensions or small number of parameters in three-dimensions (Cerco and Cole, 1993; Chau and Jin, 1998). With the advances of computer technology, fluid flow and interactions of various water quality variables in natural water bodies can be described fully in real-time. In order to assess accurately the long-term recovery of an ecosystem through different possible management strategies, eutrophication modelling has been integrated with hydrodynamic models incorporating sediment layers (Chau and Jiang, 2002; Chau, 2004).

This paper presents the application of a robust three-dimensional numerical eutrophication model, integrating hydrodynamics with water quality and incorporating sediment oxygen demand and sediment nutrient releases, for simulation of temporal water quality transport in a density stratified natural water body during the eutrophication process in Tolo Harbour. After calibration and verification with real data, the tool is used to predict different eutrophication scenarios as well as the effectiveness of alternative management solution strategies.

Physical Conditions in Tolo Harbour

Tolo Harbour (Fig. 1), is a characteristically estuarine environment in an almost land-locked sea inlet with a narrow outlet in the South China Sea. It is very irregular in shape and includes some small side coves. It is located in the north-eastern side of the New Territories of Hong Kong and is one of the most valuable natural resources in Hong Kong. The influence of the Pearl River locating at the west of Hong Kong diminishes rapidly at the eastern side of Hong Kong. Thus, water conditions in Mirs Bay at the mouth of the Tolo Channel are more oceanic in characteristics.

Tolo Harbour covers an area of about 52 km^2 and is approximately 16km from the southwest at the inner harbour to the northeast at the outer channel. The water depth varies from about 2m in the inner reaches, where the new towns of Shatin and Taipo are located, to over 20m in the outer part of Tolo Channel and about 12m on average. The averaged diurnal tidal difference is about 0.97 m, mean high tide is 1.75 m and mean low tide is 0.78 m. The harbour may be classified as a vertically fully mixed estuary, with an average ratio of freshwater inflow per tidal period in the order of 0.01. For most of the year, freshwater inflow has an insignificant effect on the dynamics of the harbour circulation.

By its very nature, Tolo Harbour has a sensitive environment. The harbour circulation is mainly driven by the tidal forcing at the entrance to the harbour. Tides in the area are of the mixed type with a predominant semi-diurnal component, and are often distorted due to amplification of the shallow water constituents. Tidal flushing in the inner harbour of Tolo Harbour is very limited. Prior to the commencement of modern exploitation of Tolo Harbour, the marine water body already showed some signs of natural eutrophication, though of minor nature.

Changes in Conditions in Tolo Harbour

The development of Tolo Harbour dates back to 1970s, when a large portion of Tolo Harbour was cut off from the sea to form the Plover Cove reservoir. The development of water resources in Tolo Harbour areas was reduced significantly by the completion of both the Plover Cove reservoir and the High Island reservoir, through the draw off of freshwater to their associated catchwaters. Around the same time, two new towns, namely, Shatin and Taipo (originally an fishing village and a market town) were established at along the shore of Tolo Harbour, involving large scale reclamation of the mangrove swamps of Tide Cove and platform cutting on the hillsides. The populations at the predevelopment level were 35,000 and 25,000 at Shatin and Taipo respectively; the corresponding planned populations will be 750,000 and 350,000, respectively. This will be achieved mainly through extensive development of high rise buildings. The problem incurred is two-fold and includes both physical impact and increase in pollution loading.

Table 1 shows the significant percentage reductions in the water area, the length of the coastline, the catchment area, and the fresh water runoff in the previous decades by anthropogenic activities. It can be observed that the dramatic loss of catchment area and corresponding freshwater runoff are mainly attributed to the establishment of catchwaters to the new reservoirs. Moreover, a large proportion of the loss in the natural mangrove coastline is in the inner Tolo Harbour which has the highest degree of urbanization.

Together with the rapid development of the area and the two new towns, unauthorized pollutant loads from domestic sewage and manufacturing industries have increased dramatically. The combined effect of the pattern of urbanization in Tolo Harbour, the substitution of mangrove with modern seawalls, the loss of freshwater flow and unpolluted seawater volume, together with the drastic increase of nutrient load, has resulted in severe environmental degradation. These changes have had a severe impact on the quality of the environment, in terms of the socio-economic well-being of the rapidly growing human population of the Tolo area. In fact, eutrophication was predicted at quite an early stage during the urbanization of Tolo Harbour.

The water quality has deteriorated drastically in recent years. In particular, during the summer, the differences in surface and bottom water temperature and salinity, engendered by solar radiation and rainfall, result in density stratification within the water column. It enlarges the vertical gradient of pollutant concentration and weakens the vertical mixing. Bottom waters in Tolo Harbour exhibit serious dissolved oxygen (DO) depletion; the DO content remains adequate at the surface (EPDHK, 2000). There is a pressing need to control and improve the water quality in the harbour. It is believed that technological advances can be utilized in order to attain effective water quality management in the coastal zone.

Application of a Three-Dimensional Eutrophication Model

Eutrophication modelling can be employed to simulate the balance of mass and energy within an ecosystem, in which a variety of physical, chemical, biochemical, and biological processes underlie the transport and interaction among the nutrients, phytoplankton, zooplankton, carbonaceous material, and DO in the aquatic environment. In fact, the entire system is highly coupled since the energy and mass balances for each constituent are linked to one another. For this case in the coastal waters of Tolo Harbour, a real-time three-dimensional finite difference numerical model for eutrophication dynamics (Chau, 2004), employing the numerically generated, boundary-fitted, orthogonal curvilinear grid system as well as a grid "block" technique, is employed. In this model, a system of nine state variables are considered: three organic parameters (carbonaceous biochemical oxygen demand, nitrogen and phosphorus), four inorganic parameters (DO, ammonia nitrogen (NH_4-N), nitrite and nitrate (NO_2 + NO_3-N), and phosphate (PO_4-P)), and two biological constituents (phytoplankton and zooplankton). This model has been developed, calibrated, and verified for Tolo Harbour, Hong Kong. Both organic nitrogen and organic phosphorus are divided into particulate and dissolved concentrations. NH_4-N, NO_2 + NO_3-N and PO_4-P are considered as the available nutrients taken up by phytoplankton. PO_4-P is also divided into particulate and dissolved concentrations, and its dissolved phase is available for phytoplankton uptake. The existing field data covering the 10 years from 1991 to 2000 in Tolo Harbour shows that silicate is plentiful and thus it is excluded as a limiting nutrient. Local field data on hourly solar radiation intensity, water temperature, and salinity are also used.

The model has been calibrated and verified with available field data sets. Figure 2 shows the comparison of computed and measured layer-averaged chlorophyll-a as well as dissolved oxygen at different locations in the Tolo Harbour, Hong Kong, from 1995 to 1997. From the results, the model is found to have the capability to reasonably represent the tidal flow and various principal water quality concentrations in Tolo Harbour, including the weak tidal flushing effect at the inner harbour. The verification of the numerical model is very useful for water quality management, since different scenarios can then be accurately and readily simulated which can assist in formulating the best strategy to enhance and control the water quality situation.

Integrated Water Quality Management

In order to restore the water quality in Tolo area back to a favourable standard, a co-ordinated sequence of pollution control activities are being undertaken by the Hong Kong Government. The load reduction, in terms of BOD and nitrogen, are covered by the Tolo Harbour action plan, in which different strategies are considered. Their impacts on receiving water quality are tested using the three-dimensional eutrophication model. Table 2 shows the relative effectiveness of various strategies on the load reduction in terms of BOD and nitrogen.

The results obtained show that in order to attain the water quality objectives, all the proposed strategies have to be undertaken together. After the implementation of the action plan, the concentrations of ammonia and nitrate dropped to a trace amount, indicating that nutrient uptake rates by the biomass are equivalent to their discharge rates to the harbour. Moreover, the mean chlorophyll is lower than 10 mg/m^3. In the summer, the DO level is in general lower than its in winter, probably due to the much reduced photosynthesis. Nevertheless, the average DO value is still well above 4 mg/l. In summary, the pollution control strategy adopted effectively but expensively addresses an anthropogenic problem.

Insight from Case Study

It is fortunate that the action plan is successful, prior to an irreversible destruction of the ecosystem. It should be noted that the current problem would not have been so severe or even have happened at all, if proper integrated planning and development of the coastal environment, with due recognition to the ecological consequences and sustainable management, has been undertaken beforehand. More thought as to the ecological consequences of the development, for example, by preserving mangroves as a nutrient sink, might have significantly reduced the scale of this problem. In fact, in planning sustainable development in a particularly sensitive system like this, considerations should have been given to the cumulative impact of all individual factors, including development, water supply, urbanization, industrialization, and so on. This might serve as a good example so that similar mistakes will never occur again during the development of other coastal areas of the world with similar characteristics.

Conclusions

This paper examines the nature of Tolo Harbour’s sensitive environment, the pollution resulting from its exploitation, the application of eutrophication modelling to predict different scenarios as well as the effectiveness of alternative management solution strategies, and the accomplishment of the water quality objectives via the action plan by the Hong Kong government. Some lessons are drawn upon for the urbanization of coastal areas in both Hong Kong and elsewhere in the world with similar characteristics. It is shown that the three-dimensional eutrophication model can mimic the physical behaviour and inter-relationships among various water quality state variables. The model can also be applied to other water bodies elsewhere.

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Table 1. Physical impacts in Tolo Harbour by anthropogenic activities

Physical impact	Percentage reduction (%)
Water area	28
Catchment area	68
Freshwater runoff	68
Length of coastline	22
Natural mangrove coastline	42

Table 2. Relative effectiveness of different strategies on load reduction in Tolo Harbour

Strategy employed to effect load reduction	Relative effectiveness (%)	
	BOD load	Nitrogen load
Export of sewage treatment effluents to Victoria Harbour	35	32
Modification of existing sewage treatment works processes	14	50
Provision of sewage disposal for villages	18	3
Complete ban on commercial livestock keeping in new towns	15	6
Provision of livestock waste disposal for villages	15	3
Treatment to alum sludge produced by water treatment works	3	6

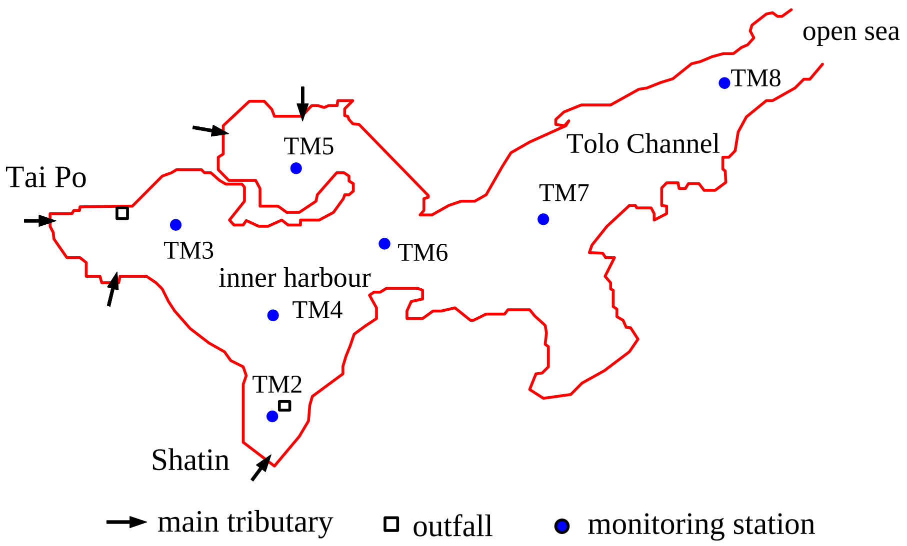

Fig.1 The Tolo Harbour, Hong Kong

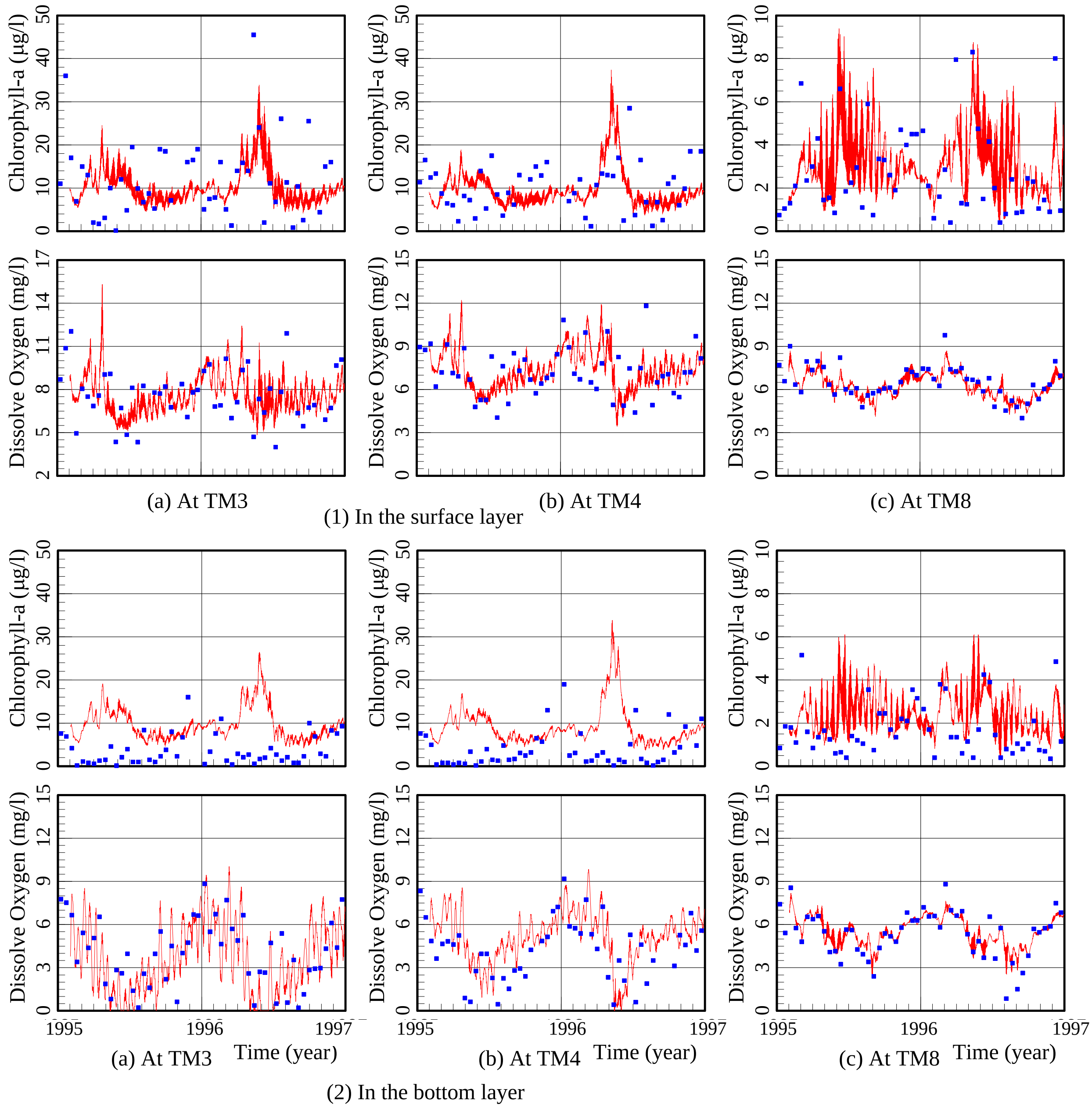

Fig.2 Comparison of computed and measured layer-averaged chlorophyll-a and dissolved oxygen at different locations in the Tolo Harbour, Hong Kong from 1995 to 1997 (— computed, ▪ measured)