CHAPTER 12

FIELD AND MODEL STUDIES OF WATER QUALITY IN HONG KONG

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1. INTRODUCTION

Hong Kong (Figure 1) is a densely populated coastal city with a population of 6.9 million in 2004. The population is predicted to increase to 9.2 million in 2030. The total land area of Hong Kong is approximately 1,103 km^2 comprising the Hong Kong Island and adjacent islands, Kowloon and New Territories. Many large-scale infrastructure developments in Hong Kong involve reclamation to provide new land for residential and commercial developments. Since 1887 there has been an increase in land area of 67.2 km^2 from reclamation. Most of the reclamations were carried out in Victoria Harbour and are gradually shifting towards the western part of Hong Kong and at Lantau Island.

The growth in population not only poses a need to create new land area but also increases the sewage flow and load discharging into the Hong Kong waters. Comprehensive sewerage studies have been conducted to plan the collection and treatment of sewage generated from the 16 catchment areas in Hong Kong. There are more than 400 major discharge points defined within the whole of Hong Kong waters in water quality modelling studies. Upgrading of the existing sewage treatment works and exporting of treated effluent to less sensitive water bodies have been implemented. The first stage of the Harbour Area Treatment Scheme (HATS), which was formerly named as Strategic Sewage Disposal Scheme (SSDS), was fully implemented in late 2001 using deep tunnels to collect about 1.4 million m^3 of sewage (~75% of the sewage) generated in the harbour area for chemically enhanced primary treatment. The treated effluent is discharged into the near shore water through a submerged outfall. The primary aim of the HATS is to improve the water quality in Victoria Harbour. The HATS Stage 2 is underway to further improve the harbour water quality by collecting all sewage from the harbour area and upgrading the treatment process to biological treatment with disinfection.

After 1997, the economic link between Hong Kong and the Pearl River delta is increasingly important. To shorten the traveling distance between Hong Kong and the major cities in the Pearl River delta. The first bridge linking Hong Kong and Shenzhen is being constructed and is scheduled to complete in 2005. The second

E. Wolanski (ed.), The Environment in Asia Pacific Harbours, 165–186.

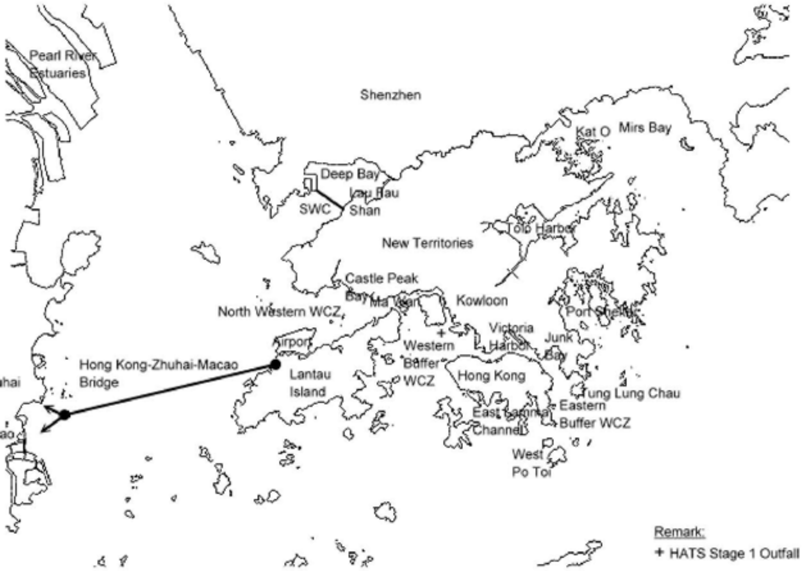


Figure 1. *A location map of Hong Kong and sites mentionned in the text.*

bridge connecting Hong Kong, Zhuhai and Macao is in the planning stage. These two bridges provide a strategic link between both sides to expedite financial cooperation, logistics and transport, tourism, trade, communications and a wide range of services. From an environmental viewpoint, the bridges built across the Hong Kong and Mainland waters may to a certain extent affect the existing coastal environments on both sides. Cross-border environmental issues and the differences in environmental regulations and standards add a challenging component to the projects.

Provision of large-scale infrastructures is required to support all these developments. During the construction and operational stages of the reclamation, bridge construction and sewage disposal projects, water quality impacts may arise from various types of construction activities associated with the projects. These include marine sediment dredging, use of fill materials, and construction of sewage outfalls, seawalls, breakwaters, bridge piers and artificial islands. The construction activities may have a short-term impact on the local water quality whilst the operation of the projects may create a long-term impact on the coastal environments. The continuous discharge of treated effluent will have a long-term impact.

The assessment of short-term and long-term effects on water quality as a result of the infrastructure developments relies on the application of mathematical models. Water quality modelling provides an effective way for checking compliance with relevant standards and determining the feasibility of the engineering works. This

Chapter presents the experience on water quality modelling of the reclamation, bridge construction and export of effluent projects in Hong Kong. The influences in relation to fish culture zones and changes in water quality conditions are addressed.

2. CHARACTERISTICS OF THE HONG KONG COASTAL ENVIRONMENTS

Both the oceanic and estuarine water masses affect the Hong Kong waters throughout the year. The months of January and February (winter) are generally the dry season whereas the months of July and August (summer) are the wet season.
The Pearl River, which is one of the largest rivers in China and is located at the western side of Hong Kong (Figure 1). The average discharge is 19,405 $m^3 s^{-1}$ in the wet season and 4,116 $m^3 s^{-1}$ in the dry season (EPD, 2003). Pearl River freshwater is heavily polluted by sewage and industrial discharges.

The oceanic currents interact with the Pearl River plume. A large amount of brackish water can be found in the western part of Hong Kong waters in the wet season, and the temperature stratification also prevails. The eastern part of Hong Kong waters is less influenced by the Pearl River discharge. The influence of the Pearl River on Hong Kong waters is smaller in the dry season when Hong Kong waters are fairly well-mixed vertically. Both the Kuroshio oceanic current and the coastal Taiwan Current influence the inshore Hong Kong waters in winter. The Kuroshio Current brings the warm water from Pacific Ocean and interacts with Taiwan Current to trigger algal blooms in the eastern part of the Hong Kong waters and spread these blooms southwestward (Wong 2003).

The Agriculture, Fisheries and Conservation Department (AFCD) of the HKSAR (Hong Kong Special Administrative Region) is a coordinating center for algal bloom or red tide outbreaks; it undertakes a programme using a computerised system together with the Geographic Information System for phytoplankton monitoring to disseminate information on red tides in real time. There are about 20 to 30 red tide incidents in a year. Most of the algal blooms occurred in Hong Kong are harmless but a few harmful algal blooms (HAB) still can be found in the Hong Kong waters.

The red tides are linked to the eutrophication of coastal waters. The increases in red tides in Tolo Harbour, a semi-enclosed and poorly flushed water body, between 1976 and 1986 coincided with the rapid growth in population around that area. Between 1980 and 1992, about 50% of the red tide incidents (189 incidents over 13 years) occurred in Tolo Harbour. A serious red tide outbreak occurred at Kat O and widely spread in the northern waters in 1988 causing major fish kills. The bloom was later found in Long Harbour, Tolo Harbour, Port Shelter and the southern waters with a total of 88 incidents reported. The fish culture zones in Tolo Harbour were seriously affected, with very large economic losses.

There are 26 designated fish culture zones occupying a total of 209 hectares of sea area. The fish culture zones at Ma Wan and Tung Lung Chau are located near a number of reclamation sites in the harbour area. These fish culture zones may also be affected by cooling water discharges in the harbour. Within Victoria Harbour, there is no fish culture zone.

AFCD has promoted the use of pellet feeds to replace the traditional trash fish for fish feeding. In 2003, about 47% of mariculture farms had adopted the use of pellet feed for fish feeding. Regular water quality monitoring at fish culture zones has been undertaken to ensure that the water quality is in a good condition and is suitable for fish culture. In collaboration with the City University of Hong Kong, a study of using biofilters to lower the organic waste concentrations in the sediments within the fish culture zones is ongoing.

In the past, oyster cultivation was one of the major industries in Hong Kong. Lau Fau Shan supported most of the oyster cultivation activities in Deep Bay. Oyster farming has been practiced in Deep Bay for about 200 years. Due to the shallow water depth and the Pearl River discharge, siltation created a large area of inter-tidal mudflat in Deep Bay making this bay suitable for oyster cultivation. Raft culture is now the most common method for growing oysters.

Nowadays, water pollution in the inner bay seriously affects the oyster industry in Deep Bay. The sediments contain high concentrations of heavy metals and the water also contains high concentrations of suspended solids, *E. coli* and organic matters. The oyster production has declined from about 1,200 tonnes y^{-1} in the late 1950's to about 76 tonnes y^{-1} in 2000 and 210 tonnes y^{-1} in 2004.

3. WATER QUALITY STANDARDS

The Water Pollution Control Ordinance (WPCO) (Cap.358) was enacted in 1980 to provide the statutory framework for the protection and control of water quality in Hong Kong. Under the Ordinance, water control zones (WCZs) and water quality objectives (WQOs) were declared and established.

3.1. Water Control Zones

In accordance with the WPCO and its subsidiary legislation, the whole of Hong Kong waters is divided into ten water control zones and four supplementary water control zones. In 1987, the Tolo Harbour and Channel Water Control Zone was firstly appointed. The other water control zones were subsequently declared.

3.2. Water Quality Objectives

Maximum levels of pollutants and minimum levels of essential constituents are defined under the WPCO in the water quality objectives for each of the water control zones. These maximum and minimum levels are slightly different in applying to different water control zones depending on the nature of the water body to be protected. The parameters specified in the water quality objectives include odour, colour, floating matters, *E. coli.*, dissolved oxygen, pH, salinity, temperature, suspended solids, turbidity, unionised ammoniacal nitrogen, inorganic nitrogen, 5-day biochemical oxygen demand, chemical oxygen demand and toxic substances.

The water quality objectives for general marine waters specify the depth-averaged dissolved oxygen in the water column not less than 4 mg l^{-1} for 90% of the year and within 2 m from the seabed not less than 2 mg l^{-1} for 90% of the year. In fish culture zones, dissolved oxygen level shall be higher than 5 mg l^{-1} for 90% of occasions. The pH value of the water shall be in the range between 6.5 and 8.5. Any change from natural pH range due to human activity shall not exceed 0.2. The temperature and salinity changes from natural daily temperature range and ambient salinity level shall not exceed 2 ^{o}C and 10% respectively. The increase in suspended solids level due to human activity shall not exceed 30% of the natural ambient suspended solids level. The annual arithmetic mean of unionised ammonia shall not exceed 0.021 mg l^{-1} and the annual arithmetic mean of the depth-averaged inorganic nitrogen level in the water column shall not exceed 0.7 mg l^{-1} for inner Deep Bay, 0.5 mg l^{-1} for North-western Waters and outer Deep Bay waters, 0.4 mg l^{-1} for Western and Easter Buffer Zones and Victoria Harbour, and 0.3 mg l^{-1} for Castle Peak Bay Sub-zone within the North-western Waters. There is no specific requirement on *E. coli* for general marine waters. For bathing waters, the geometric mean of *E. coli* level shall be less than 180 per 100 mL between March and October. In secondary contact recreation zones and fish culture zones, the annual geometric mean of *E. coli* level shall be less than 610 per 100mL.

The water quality objective for temperature change due to human activity in the Victoria Harbour Water Control Zone specified that the variation in temperature should not exceed 2 ºC. This is a limiting value used for assessing the increase in ambient water temperature due to the cooling water discharges. There are no statutory requirements for residual chlorine and biocides in seawater in Hong Kong. The residual chlorine concentration of 0.02 mg l^{-1} is harmful to the aquatic life. A lower value of 0.01 mg l^{-1} is used as the USEPA standard for residual chlorine and this value is generally adopted as the assessment criterion in Hong Kong. The limiting value of 0.1 mg l^{-1} (Ma et al., 1998) is used as the criterion for assessing the concentration of C-Treat-6 in the seawater.

All discharges are controlled by a licensing system within each water control zone. A Technical Memorandum sets limits for discharge of effluent into the water control zones. Specific limits apply for different areas and are different between surface water and sewers. The limits vary with the rate of effluent flow.

For the cross-border projects, both the standards of the HKSAR and mainland China shall be adopted. Under the National Standard of the People's Republic of China UCD 551463, the Sea Water Quality Standard GB3097-1997 has been implemented since 1st July 1998. It specifies water quality objectives for different beneficial uses of marine water in mainland waters.

4. WATER QUALITY MODELS

A number of water quality modelling exercises have been conducted in Hong Kong to assess the water quality impacts associated with infrastructure developments and sewage disposal studies. Assessment of impacts on fish culture zones and redistribution of nutrient load leading to reduction in eutrophication problems forms part of the objectives in some major studies.

In 1982, the first set of comprehensive mathematical models for simulation of hydrodynamics, water quality, waves, and sediment movement in the Hong Kong waters was developed under the Study of Water Quality and Hydraulic Modelling in Victoria Harbour (WAHMO) and were later upgraded in 1987. In 1990, the Danish Hydraulic Institute's MIKE 21 and later the MIKE 3 models for two- and three-dimensional flows were introduced to Hong Kong and were applied in bridge pier protection, drainage master plan, and the Strategic Sewage Disposal Scheme studies in Hong Kong. Since 1998, the Delft3D models have been widely used in reclamation, sewage disposal, bridge construction, cooling water discharge, and the Harbour Area Treatment Scheme projects. The models are used to model 2-D and 3-D flows, water quality, ecology, wave propagation, and morphology. The hydrodynamic model is based on the finite difference method. The water quality model computes the transport of substances numerically by the advection-diffusion equation. The modelling described in this Chapter is mainly based on the framework of Delft3D models.

4.1. Model Set-up and Validation

The selection of model for the prediction of water quality impacts depends on the nature of the project. A refined grid model is generally required to provide a higher level of detail for water quality impact assessment. The model is calibrated against field data obtained from a water sampling program. Monthly water quality data measured by the Environmental Protection Department (EPD) are also used for checking the accuracy of the model. In several environmental impact assessment studies, the refined grid model was verified by comparison with the model prediction from a well-calibrated larger model, the Update model that covers the whole of Pearl River estuaries and the Hong Kong waters. The Update model is commonly used to provide boundary conditions to the refined grid model. Through the link between the larger model and the refined grid model, the influences on hydrodynamic and water quality conditions from the areas outside of the Hong Kong waters are transferred into the refined grid model at its open boundaries.

A general approach for hydrodynamic and water quality modelling is shown in Figure 2.

4.1.1. Coastline Configuration

The very first step in setting up a water quality model is to define a specific time period. Water quality data from field measurement should be available within this period to verify the model. The model coastline configuration is then fitted to the actual land boundary for that period. The only modification to the model set-up is to update the coastline to match with the time horizon for a particular scenario. This approach gives a direct comparison of the changes in water quality conditions between the baseline scenario and the future scenarios avoiding the differences in tidal stages for different simulation periods.

4.1.2. Grid Schematisation

Curvilinear grids are applied to fit the natural coastline within the study area improving the smoothness and orthogonality of the grid cells, hence minimising errors associated with the finite difference method. The total area covered by the refined grid model is much smaller than that of the larger model. A high grid resolution of less than 75 m × 75 m is applied in the vicinity of the project site and

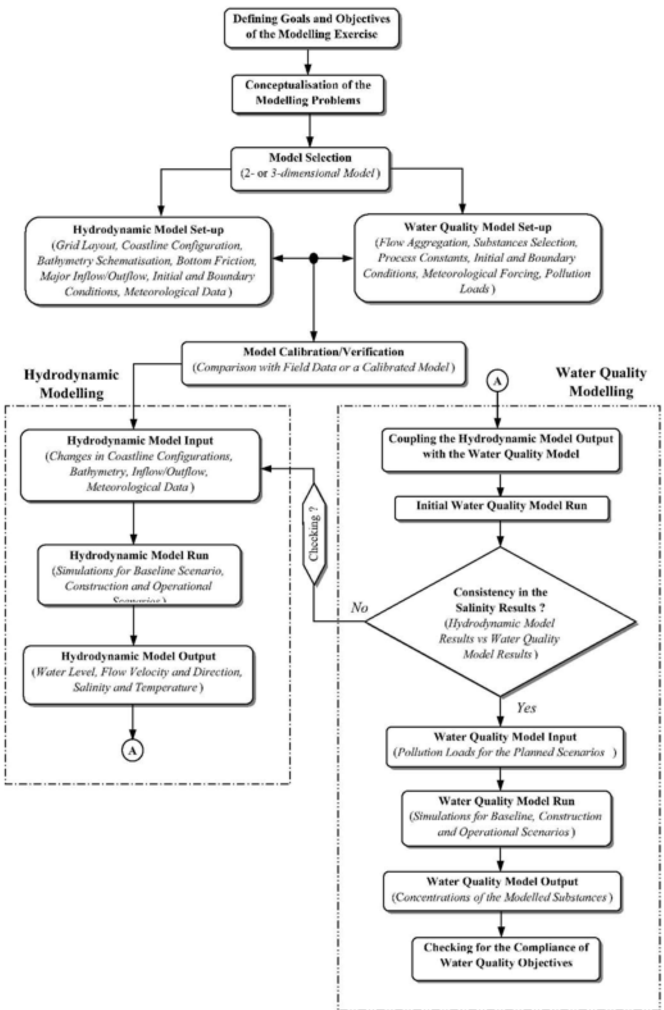


Figure 2. *A general approach for hydrodynamic and water quality modelling.*

the locations where the water sensitive receivers are situated. The grid sizes increase gradually towards the open boundaries.

For a 3-D hydrodynamic model set-up, the vertical column of water body is evenly divided into 10 layers. Depending on the coverage of the modelling area and the stratification condition of the water body, the thickness of each layer can be adjusted to give a better representation of the level of stratified layer.

4.1.3. Bathymetry

The Hydrographic Office, Marine Department of HKSAR, measures and collates bathymetry data in the Hong Kong waters and produces nautical charts. These data provide the basic information for defining the water depths in the model. The depth data are defined at nodal points of the grids. The reference level of the model is Hong Kong Principal Datum.

4.1.4. Simulation Period

Representative spring-neap tidal cycles for dry and wet seasons are used for hydrodynamic computations. The model runs for each season cover a 7-day period for model spin up and 15 days to represent a spring-neap cycle. For the annual water quality simulation, transitional seasons between the wet and dry seasons are defined by interpolating the dry and wet season conditions. The hydrodynamic data of the representative spring-neap cycle are repeatedly used in the water quality model to cover a full annual simulation. Model inputs such as the meteorological forcing and pollution loads from river discharges, storm drains and sewage outfalls vary from month to month over the year.

4.1.5. Flow Aggregation and Coupling

The vertical hydrodynamic structure of the model is aggregated from 10 layers to 5 layers generating a vertical distribution of 10%, 20%, 20%, 30% and 20% of the hydrodynamic layers from surface to bottom in the water quality model. A 2×2 flow aggregation is also applied in the spatial level. The main purpose of flow aggregation is to optimize the computational time and data storage without a significant influence on the quality of the modelling results.

4.1.6. Flow and Pollution Loads

A pollution load inventory is required to provide flow and load data for all existing discharge points including major rivers, storm drains, nullahs, sewage outfalls, landfills, typhoon shelters, and fish cultural zones. New discharge points from the proposed development are added in the model with flow and load data derived from the relevant project information. Different sets of flow and load data are compiled to represent the years for baseline, construction and operational scenarios.

The inventory is compiled based on the field measured flow and load data, planning and development statistics including population, industrial, commercial and agricultural data, and projection for discharges from outfalls, rivers and nullahs. The basic relationship between the pollution loading and flow is expressed as:

$$\text{Loading } (g\, s^{-1}) = \text{Concentration } (mg\, l^{-1}) \times \text{Flow Rate } (l\, s^{-1}) \times \frac{1g}{1000mg} \quad (1)$$

The flow and load data for the existing discharge points include the sources from sewage, sewage flow interception, stormwater runoff and livestock. The sewage flows and loads are mainly derived based on the territory population and employment data for planning study. The data are distributed into the sewerage catchments and are multiplied by the global unit flow and load factors specified in the Sewerage Manual (DSD, 1995) to estimate sewage flows and loads for the catchments. The derived pollutants include suspended solids, biochemical oxygen demand, chemical oxygen demand, total Kjeldahl nitrogen, ammonia nitrogen and *E. coli*. Assumptions are made based on the relevant monitoring data, design standards and relevant studies for the pollutant factors not included in the Sewerage Manual such as total phosphorus, ortho-phosphate, silica, copper, organic nitrogen and total oxidized nitrogen. Pollution load reduction factors are applied to the sewage treatment works. The pollutant removal in sewage treatment works is calculated by:

$$\text{Pollutiant Removal (\%)} = \left[1 - \frac{\text{Pollution Load in Treated Effluent}}{\text{Pollution Load in Raw Sewage}}\right] \times 100\% \quad (2)$$

The flows and loads from stormwater runoff are calculated based on the catchment areas, monthly rainfall data and the load factors from the EPD river monitoring data and the relevant urban stormwater pollution studies. The pollution load measured in watercourses is higher in the wet season when compared with the measured data in the dry season. The compiled flows and loads from stormwater runoff therefore consist of two sets of data to cover the dry season and wet season cases.

A number of major storm outfalls receive livestock discharges. Estimation of livestock loading makes use of data on population of pigs and chicken, and actual biochemical oxygen demand (BOD) load discharged into streams.

The total load from each catchment area is distributed into a number of point sources represented by the sewage outfalls and storm drains. These point sources are distributed along the coastline of each catchment area.

Storm outfall discharges are made in shallow water near the water surface. Therefore, the flow and load data for storm outfall discharges are specified only in the surface layer of the model. Sewage outfall discharges are mostly at the sea bottom due to the use of submerged outfall pipes. Buoyancy effects lift up the pollutants. The sewage outfall discharges are therefore allocated in the middle layer of the vertical water column to take into account this effect.

4.1.7. Boundary and Initial Conditions

The open boundary conditions of the refined grid model can be defined either using field data or the modelling results from the larger model. It is a time consuming and expensive process to obtain field data to define the open boundary conditions. Some specially developed refined grid models covering different modelling areas may have different open boundaries. In view of this, it is a common practice to use the larger model to generate open boundary conditions for the refined grid model. The boundaries are forced by water level and velocity data generated by the larger model. Salinity and temperature data are also transferred to the refined grid model at the boundaries.

An initial model run is performed to generate a restart file at the last time step of the simulation period. The restart file gives the initial conditions to rerun the model at the first time step. By repeating the runs, the model can start the simulation at a realistic condition eliminating the influence of the arbitrary defined initial conditions at the first run.

4.1.8. Meteorological Forcing

The water quality processes link closely to the ambient environmental conditions. Meteorological data including wind, solar surface radiation and water temperature are obtained from the weather monitoring stations of the Hong Kong Observatory and the EPD's marine water monitoring data. Monthly averaged values are used in the model. It is assumed that the data are constant over the whole modelling area. An average wind speed of 5 ms^{-1} is usually applied in both the dry and wet seasons. The wind directions are from the north-east during the dry season and from the south-west during the wet season.

4.1.9. Modelled Substances

The key water quality parameters covered in the water quality model include salinity, water temperature, dissolved oxygen, suspended solids, biochemical oxygen demand, *E. coli*, phytoplankton, organic and inorganic nitrogen, phosphorus, silicate, air-water exchange and benthic processes.

Phosphorus and nitrogen are good indicators of potential algal bloom problems. Sunlight, salinity, water temperature, current condition and trace elements are important factors contributing to the algal growth. For dredging and filling activities, the increase in suspended solids in the water body affecting the fish culture zones and other water sensitive receivers is a key factor to be examined by the model.

4.1.10. Verification of Model

The Study Brief issued by the government authorities for a development project specifies the criteria for hydrodynamic model calibration/verification. The validation criteria specifying the differences between simulated results and the actual field measured data are root-mean-square values of tidal elevation < 8 %, maximum

phase error at high water and low water < 20 minutes, maximum phase error at the peak speed < 20 minutes, maximum current speed deviation < 30%, maximum direction error at peak speed < 15 degree, and maximum salinity deviation < 2.5.
Verification of the water quality model is made by comparing the prediction with the field data. Figure 3 gives an example of the comparison between the predicted annual mean depth-averaged unionised ammonia nitrogen (UIA) results and the EPD field data in 1998. The model predicts high UIA levels (> 0.021 mg l^{-1}) in Deep Bay and Victoria Harbour, and decreasing concentrations seaward. The predicted results are in good agreement with observations. Another example of the prediction of *E. coli* in Victoria Harbour is shown in Animation 1.

After a successfully model verification, the refined grid model is then applied to predict water quality impacts associated with the development project.

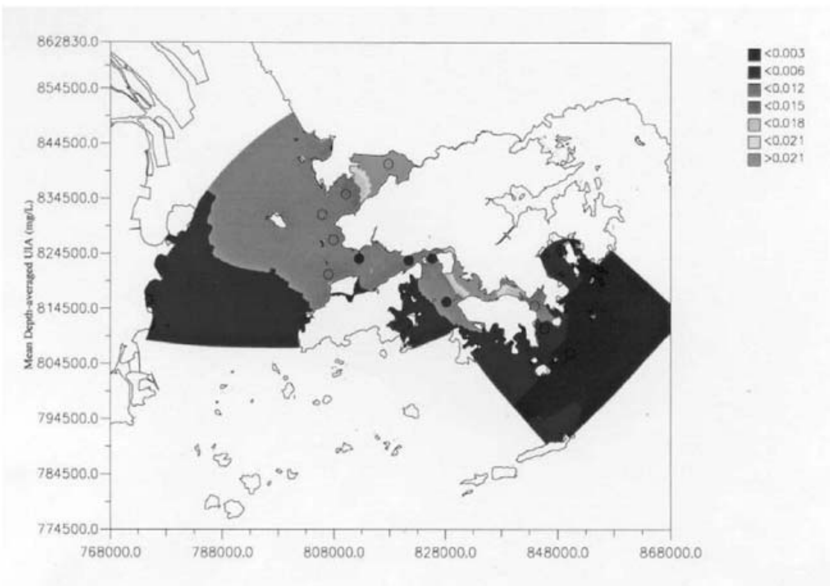
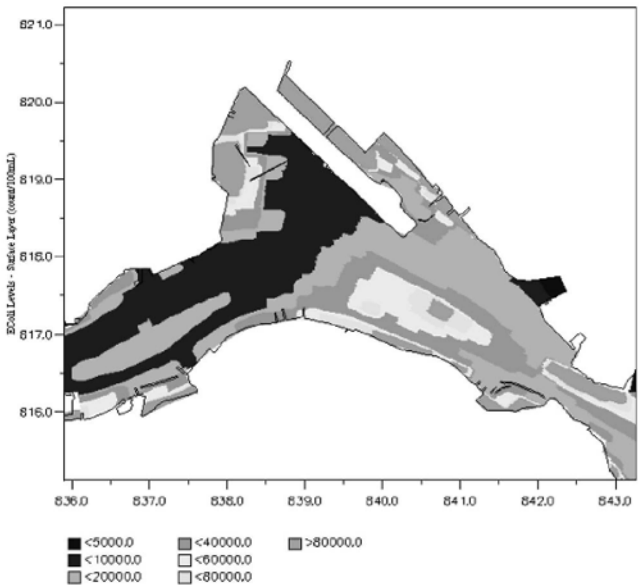


Figure 3. *Comparison of the predicted UIA with field data.*

5. APPLICATIONS OF WATER QUALITY MODELS

5.1. General

A large-scale development project may have a construction period lasting several years. Reclamation of new land to support the development can be divided into several phases involving a range of dredging and filling activities. Modelling scenarios generally cover the baseline, construction, and operational phases. A direct comparison of the model results between the construction phase scenario and the



Animation 1. *Predicted E. coli Concentrations in Victoria Harbour.*

baseline scenario can check for compliance with the water quality objectives and relevant requirements, identifying the key issues that need to be avoided or mitigated. A similar comparison can be made between the operational scenario and the baseline scenario to examine the long-term water quality impacts associated with the development.

5.2. Reclamation Projects

The high population density and limited developable land area in Hong Kong causes a strong demand on new land from reclamation. The natural coastline and seabed conditions have been significantly changed. Since most of the reclamation sites are located within Victoria Harbour, the cross-sectional area of the Victoria Harbour channel is continuously reduced creating short-term and long-term impacts on the flushing capacity and water quality of the harbour water. During the construction stage, massive dredging and filling activities are carried out in the reclamation sites. Generation of sediment plumes and disturbance to the seabed pose a potential risk to the nearby water sensitive receivers.

Examples of some of the major reclamation projects and studies with reclamation sites in Victoria Harbour include Central Reclamation Phase I/II/III (58 hectares), Wanchai Reclamation Phase I/II (35 hectares), West Kowloon

Reclamation (340 hectares) and South East Kowloon Development (previously planned new land of 133 hectares).

For Lantau, major reclamation projects include reclaiming 112 ha of land after completion of the new airport at Chek Lap Kok, and the Tung Chung New Town. Penny's Bay Reclamation and Yam O Reclamation involve reclamation of about 290 hectares of land.

Public fill, and marine sand fill are the major fill materials for reclamation in Hong Kong. Crushed rock from land sources is also an alternative fill but is less commonly used when compared to public fill and marine fill. Since 1990 more than 270 million m^3 of sand have been extracted from the seabed within the Hong Kong waters for use in reclamation projects. Marine borrow areas such as West Po Toi and East Lamma Channel are the specified areas to provide sand fill. Public fill is generated from construction and demolition (C&D) materials, which are inert rock and soil. In some public filling areas, the C&D materials are used for reclamation reducing the reliance on sand fill.

The major concerns on water quality from reclamation are the dispersion of sediment and release of heavy metals and organic micro-pollutants from the disturbed seabed during the construction stage and the long-term changes in hydrodynamics and water quality after the completion of the project. The impact on aquatic life depends on the location of the reclamation sites. There are 26 designated fish culture zones in Hong Kong. Local fish farmers have reported fish-kills that they blame the sediment plumes generated from dredging and filling activities on reclamation sites. The other water sensitive receivers located within the harbour and in the adjacent regions including seawater intakes for cooling and flushing purposes, enclosed water bodies and gazetted beaches are also subject to the influence from dredging and filling activities.

The development projects in Victoria Harbour may also involve relocation or provision of cooling water discharges from water-cooled air conditioning systems. A District Cooling Scheme has been proposed by the Government to explore more economical and environmental attractive air conditioning systems for Hong Kong. The temperature of the extracted seawater for cooling can be heated up to 3 to 7 ^{o}C. In addition to the temperature rise, the discharges may also contain anti-fouling and anti-corrosion chemicals like residual chlorine and biocides causing harmful effects to the aquatic life.

For a large-scale reclamation, dredging and filling are required to carry out in phases. Therefore, a number of construction scenarios can be determined based on the planned construction programme to identify the worst-case scenarios where the sediment load releasing into the water body is expected to be critical. There are different construction methods for the dredging and filling activities on reclamation sites. One of the methods is to carry out the filling behind seawall. Construction of external seawall or barrier is conducted to enclose the inner area where massive filling will be subsequently carried out. In this case, there will be almost no release of sediment during filling. Sediment plume dispersion modelling may not be required. The impact on the nearby sensitive receivers including the fish cultural zones in this case is minimal. An alternative method is to install silt curtain surrounding the dredging and filling sites to confine the sediment plumes within the works areas. The effectiveness of using silt curtain depends on the management and operational control of the dredging and filling works, and the tidal current conditions. The workable tidal current speeds are in the range between 0.3 and 0.5 $m\,s^{-1}$.

Under a fully controlled operating condition, a reduction factor of 80% (silt curtain efficiency) can be applied in calculating the sediment loss rate, which is inputted into the model for simulation of sediment plume dispersion. The third method is not to execute any mitigation measures such as provision of external seawall or silt curtain. In simulation this situation, it is considered to be the worst-case scenario. Figure 4 shows a time series plot for suspended solids at Ma Wan Fish Culture Zone, with and without reclamation activities. In this case the increase in suspended solids appears to be within acceptable levels (< 30% increase of the background level).

The required model inputs for modelling the cooling water discharges in the harbour include:

- Maximum discharge flow rate
- Number of discharge points, locations and submerged/surface discharge
- Maximum temperature excess of the cooling water discharges: 6 – 7 ^{o}C
- Residual chlorine concentration at discharge: 0.3 – 0.5 mg l^{-1} with no decay for a conservative approach or with a decay factor of T_{90} = 0.021 day
- Biocide (C-Treat-6) concentration at discharge: < 2 mg l^{-1} with a decay rate of 64% (decayed amount) in 8 days

The required dilution rates to comply with the WQO for temperature are about 3 – 3.5. This is rather easy to achieve in the open waters with fast flowing tidal currents. To meet the recommended standards for residual chlorine and biocide, the

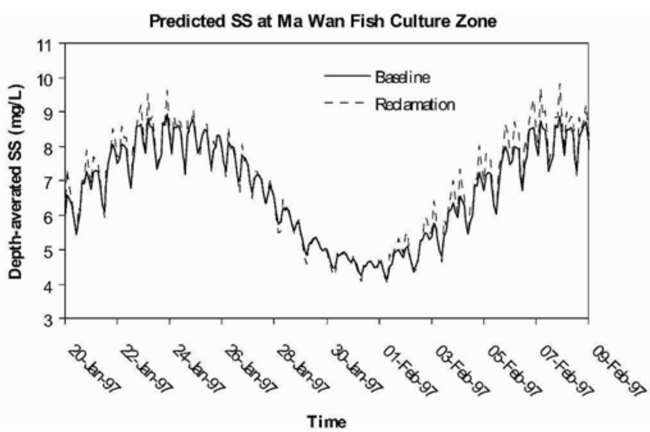


Figure 4. *Time series plot for suspended solids with and without reclamation activities.*

required dilution rates are 50 and 20, respectively. This implies that the area influenced by the high residual chlorine and biocide concentrations is larger than that under the thermal impact. Based on the water quality modelling results from various reclamation studies, no significant impacts in terms of sediment plume and thermal plume dispersion have been identified.

A rigorous environmental process is undertaken to safeguard the water quality that is sensitive to pollution. In the environmental impact assessment stage, water quality modelling is required to assess the impacts from sediment plume dispersion and changes in water quality conditions. All the assessment results shall comply with the relevant water quality objectives before the actual implementation of the project. Mitigation measures to avoid and minimize water quality impacts shall be proposed and implemented in accordance with an implementation schedule.

During the construction and operational stages of the project, water quality monitoring is required to ensure that any unforeseen situations affecting the water quality in the receiving water body and the water sensitive receivers can be detected and rectified. This provides a second level of protective measure to safeguard the coastal environments. An example of the monitoring results for suspended solids of a reclamation project is shown in Figure 5. If the suspended solids (SS) levels exceed the action or limit level, an Event and Action Plan will be implemented. For depth-averaged suspended solids, the action level defines 95%-ile of baseline data or 120% of the SS levels measured at the upstream control station at the same tide of the same day and the limit level defines 99%-ile of baseline or 130% of the SS levels measured at the upstream control station at the same tide of the same day.

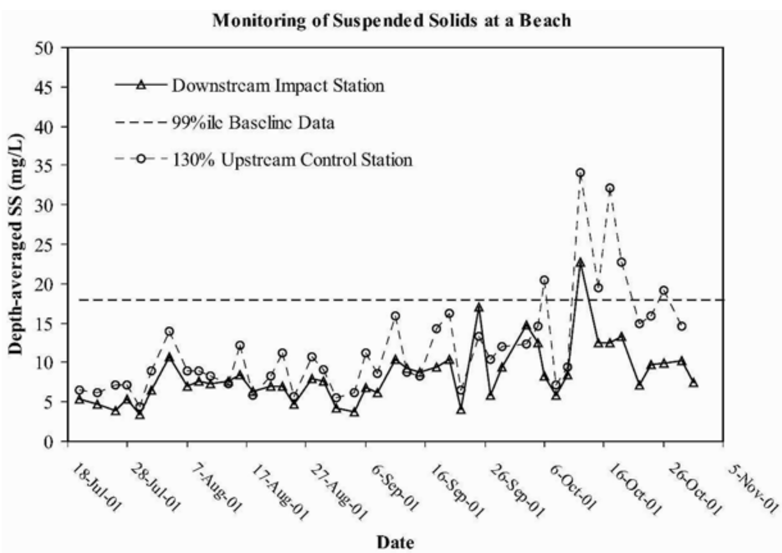


Figure 5. *Monitoring of suspended solids concentrations at a beach.*

5.3. Bridge Projects

In 1997 to 1999, the construction of three major bridges to support high-capacity transport links in the western part of Hong Kong were completed serving the new airport at Che Lap Kok and the new industrial and residential developments at Lantau. These three bridges are the Tsing Ma bridge (1,377 m), the Ting Kau bridge (448 m) and the Kap Shui Mun bridge (430 m). In addition, two bridges linking Hong Kong and the mainland China will be constructed. These are the Shenzhen Western Corridor (SWC) and the Hong Kong-Zhuhai-Macao Bridge (HZMB).

These two bridge projects share some common features with the needs for bridge pier and pile cap construction, dredging of marine sediment and sand filling, construction of major structures in the navigation channels (cable-stayed bridge/submerged tunnel) and reclamation. All these activities during the construction stage may cause impacts on the exiting aquatic environment. The presence of the bridges may also have long-term water quality impacts. One of the major water quality issues of these projects is the reduction in flushing capacity leading to degradation of water quality. The major water sensitive receivers are the Chinese White Dolphin feeding ground, finless porpoise area, a marine park, horseshoe crab areas, and Special Site of Scientific Interest (SSSI). These projects may also impact Deep Bay, which is a semi-enclosed water body supporting many special areas with high ecological value, e.g. Ramsar Site, Mai Po Nature Reserve Area, oyster farms, seagrass beds, SSSI and horseshoe crab areas, possibly leading to the disappearance of mud flats and the loss of feeding grounds for birds and many animals.

The water depth in Deep Bay is shallow. In the near shore region, the water depth is mostly below 2.5 m. During ebb tides, a large area of mud flats is exposed and provides a feeding ground for many species of birds. Deep Bay has been known as a highly polluted water body with nutrient levels often exceeding the corresponding water quality objectives. Water quality in the outer sub-zone of Deep Bay is in general better than that in the inner sub-zone. Exceedances of the WQOs for dissolved oxygen, total inorganic nitrogen and unionised ammonia are commonly recorded in the inner sub-zone. Ortho-phosphate and total phosphorus levels are also high in inner sub-zone.

The environmental impact assessment of the SWC project was completed in 2002 (Highways Department 2002). The model grid matches with the varying seabed conditions in Deep Bay. The small channels in the shallow water region and the areas near the Inner Deep Bay contain finer grid sizes. The grid sizes vary from 25 m in the small channels to 800 m near the open boundaries. There were 2,700 computational grid cells. The horizontal eddy viscosity and diffusivity were 1 $m^2\ s^{-1}$. The k-ε model was used to compute the vertical eddy viscosity and diffusivity. Minimum values for the vertical eddy diffusivity and vertical eddy viscosity were set at $10^{-7}\ m^2\ s^{-1}$ and $5 \times 10^{-5}\ m^2\ s^{-1}$ respectively.

The bridge piers create friction to the tidal flows reducing the flushing capacity in the bay. An additional quadratic friction term is added to the momentum equations to simulate the frictional effect along the bridge alignment (Hyder, CES and Delft Hydraulics 1998, and Netherlands Marine Technological Research 1980). Loss coefficient in the x- and y-directions (C_{Lx} and C_{Ly}) are expressed as:

$$C_{Lx} = \frac{nD}{2} \cdot C_d \cdot \left[\frac{A^2}{A_b^2} \right] \frac{1}{\Delta y} \tag{3}$$

$$C_{Lx} = \frac{nD}{2} \cdot C_d \cdot \left[\frac{A^2}{A_b^2} \right] \frac{1}{\Delta x} \tag{4}$$

where,
n is the number of bridge piers in the control grid cell;
C_d is the drag coefficient;
D is the diameter of the bridge pier (m);
A is the total cross-sectional area of the pier (m^2);
A_b is the effective area and is the difference between the total cross-sectional area and the area blocked by the pier (m^2); and
Δx and Δy are the grid distances in the x- and y-directions (m).

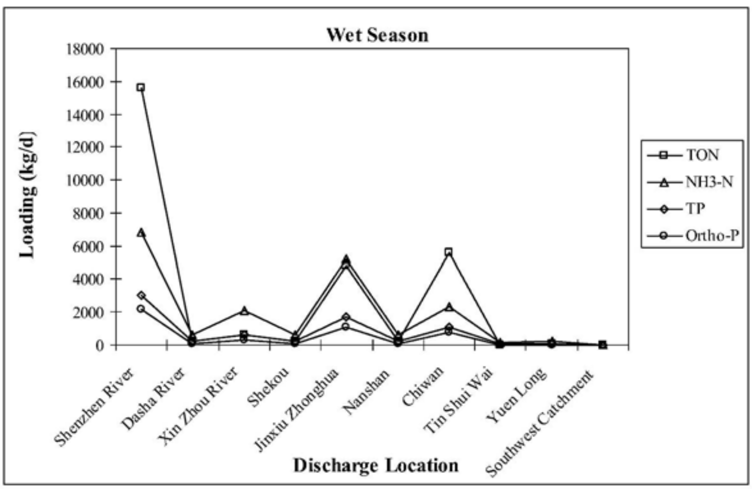


Figure 6. *Nutrient loadings in Deep Bay – wet season.*

There are ten major locations discharging pollutants into Deep Bay. Figure 6 shows the total loadings of total oxidized nitrogen (TON) (27,455 kg d^{-1}), ammonia nitrogen (NH_3-N) (18,779 kg d^{-1}), total phosphorus (TP) (7,216 kg d^{-1}) and ortho-phosphate (Ortho-P) (4,738 kg d^{-1}) at the major discharge locations in the wet season. Shenzhen River, catchment of Jinxiu Zhonghua and Chiwan appear to be the major nutrient sources. The total *E. coli* (1.12×10^{17} no. d^{-1}) and biochemcial oxygen demand (248,860 kg d^{-1}) loads are also high. The pollution loads for the wet season are higher than those pollution loads for the dry season. The differences in nutrient loads for organic nitrogen, ammonia nitrogen, total phosphorus and ortho-phosphate are approximately 13.5%, 1.5%, 5.2% and 1.6% respectively. The highest differences are in biochemical oxygen demand (16.8%) and suspended solids (33.2%).

Using the same model set-up to perform a water quality simulation, the predicted total inorganic nitrogen (TIN) results for dry and wet seasons were compared with the field data (Figure 7) . The predicted TIN levels are higher in the wet season and are within the natural fluctuations of the field data.

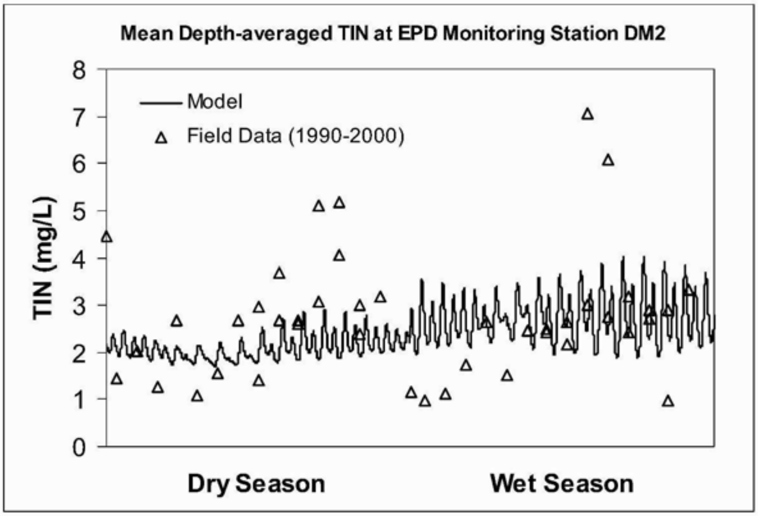


Figure 7. Water quality model prediction and field data showing natural fluctuation of total inorganic nitrogen in Deep Bay.

In the water quality impact assessment of the SWC project (Highways Department 2002), the predicted reduction in flushing capacity to be caused by bridge piers alone was 0.76% and by the reclamation at the landing point togather with the bridge piers was 3.3%. The overall change in water quality conditions in Deep Bay due to the project was approximately 2.5%. No significant deviation of water quality conditions from the baseline conditions was found. The predicted cumulative impacts for different scenarios due to sediment dredging along the bridge alignment and filling at the reclamation sites on the mainland side increased the suspended solids levels at the oyster beds near Lau Fau Shan to about 4.1 – 5.95% (1.24 – 1.8 mg l^{-1}) in the dry season and 5.06– 5.12% (1.5 – 1.52 mg l^{-1}) in the wet season. All the predicted increases were below the WQO for SS (< 30 mg l^{-1} increase of the background value).

5.4. Export of Effluent Projects

To cope with the growing population and increasing sewage flows, the Hong Kong Government initiated a sewage disposal strategy in 1989. In the northern district and Tolo areas of Hong Kong, expansion and upgrading of sewage treatment works (STW), and export of treated effluent to the less sensitive water bodies have been studied by the government authorities. The Tolo Harbour Effluent Export Scheme (THEES) has been implemented in phases since 1995-96 to reduce nitrogen loadings on Tolo Harbour. Treated effluent is discharged into Victoria Harbour.

The North District effluent is discharged into the Deep Bay waters. The water quality monitoring data (Figure 8) shows that total nitrogen and total inorganic nitrogen levels in the inner bay of Tolo Harbour were high before 1998 and gradually reduced after the full implementation of the THESS. The nutrient levels in the bay were still relatively high. The frequency of red tide incidents also remained high although the nutrient levels in the harbour dropped.

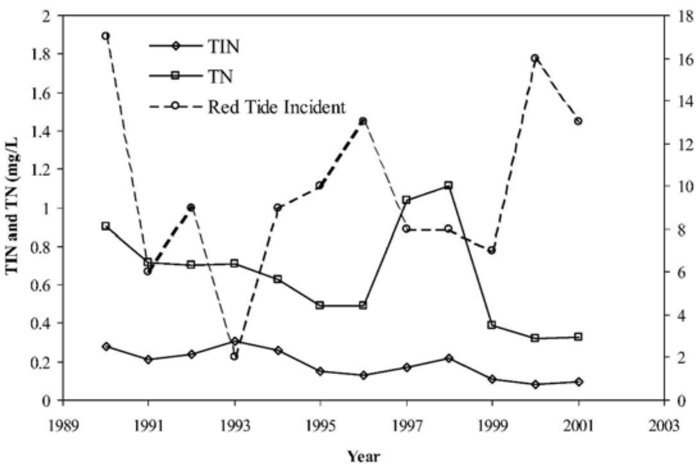


Figure 8. *Measured total inorganic nitrogen and total nitrogen in inner bay of Tolo Harbour Water Control Zone and red tide indicents.*

There is a need for the sewage from the North District to be exported out of Deep Bay. Victoria Harbour, North Western, Western Buffer and Eastern Buffer waters appear to be the more suitable receiving water bodies for the discharge of exported effluent from sewage treatment works. In fact, the Tolo effluent from Sha Tin STW and Tai Po STW has already been collected and discharged via Kai Tak Nullah to the Victoria Harbour.

Water quality modelling for the study of effluent export schemes aims to cover all the possible discharge locations of the exported effluent. Depending on the export location, the potential water quality impact zones and water sensitive receivers that may be affected by the dispersed pollutants arising from different export options include marine parks, fish culture zones, typhoon shelters, cooling and sea water intakes, beaches and secondary contact recreational zones. The long-term water quality impacts over all seasons in a year are the major concern for the case of effluent export. The requirements for modelling of effluent exported from sewage treatment works are outlined as follows:

- Define all possible scenarios including treatment levels of the sewage treatment works and effluent export routes
- Identify potential export locations and water sensitive receivers
- Calibrate a 3-dimensional hydrodynamic model to cover a real sequence of representative 15-day spring-neap tidal cycle in both dry and wet seasons
- Calibrate a 3-dimensional water quality model to run for a complete year using repeating tides of full spring-neap cycles in both dry and wet seasons with the incorporation of monthly variations in flows and loads from Pearl River estuaries and meteorological factors
- Define time horizons for different water quality modelling scenarios
- Compile a pollution load inventory to distribute accurate flows and loads in all the discharge points within the modelling area for all the time horizons under consideration
- Identify water quality objectives and relevant criteria for water quality impact assessment
- Conduct hydrodynamic and water quality modelling of the baseline and all export scenarios
- Perform sensitivity tests of the preferred option for different flows and loads from sewage treatment works
- Model emergency discharge cases as a result of the shut-down of sewage treatment works by allocating the flows and loads at the discharge point during neap tide to represent a worst-case situation
- Carry out cumulative impact modelling by incorporating the flows and loads from the concurrent projects
- Assess the compliance of water quality objectives and relevant criteria of all the cases and identify the scenario with minimal water quality impacts.

In the case where the discharge of the exported effluent is through a submerged outfall (for location of major outfalls, see Figure 1), near-field modelling is required to determine the compliance with mixing zone criteria and to assess the water quality impacts in the near-field region. The JETLAG and CORMIX models have widely been used for near-field modeling in the Hong Kong projects. JETLAG, which was developed by Lee and Cheung (1991), has been designed for modeling outfall plume behaviour from single port discharges to rosette diffusers and is capable of calculating an arbitrarily inclined buoyant jet with a three-dimensional trajectory. CORMIX, which was developed by USEPA, can simulate single diffuser discharges (CORMIX 1), multi-port diffuser discharges (CORMIX 2) and surface discharges (CORMIX 3). The model is capable of predicting the outfall discharge behaviour in the near-field region and the subsequent mixing zone. Extensive laboratory and field data have been used to verify the applicability of the model.

In order to compare the near-field model predictions with the water quality objectives for annual, depth-average values, the pollutant concentration at the edge of the initial dilution zone (C_Z) is calculated by the following equation:

$$C_Z = C_B + \frac{C_0 - C_B}{S} \tag{5}$$

Where,
C_B = background concentration of the pollutant in the ambient water;
C_0 = initial concentration of the discharged effluent;
S = dilution at the edge of the initial dilution zone.

The pollutant concentration C_Z is compared with the corresponding water quality objective to check for compliance. A selected near-field model predicts the dilution under different discharge and ambient conditions. Hourly simulation is performed using the near-field model for 12 months to give the annual results and to generate statistics of the pollutant concentration. For the depth-averaged requirement of the WQOs, the following equation calculates the depth-averaged concentration of the pollutant ($C_{depth\text{-}averaged}$):

$$C_{depth-averaged} = \frac{T}{H}\left[\frac{C_0 - C_B}{S} + C_B\right] \tag{6}$$

where,
T = plume thickness at the edge of the initial dilution zone; and
H = total water depth.

The near-field model results provide details of the vertical structure of effluent plume in the mixing zone. The predicted results of plume height and dilution can be inputted into the water quality model as the loading from the submerged outfall for prediction of water quality changes in the far-field. The allocation of pollution load in the far-field model may affect the accuracy of the model prediction. The link between near-field and far-field models needs to be accurately established in order to ensure that reliable model prediction can be provided for decision-making. At this stage, there is no standard method to couple the near-field model and the far-field model. Bleninger and Jirka (2005) recommended a coupling procedure using CORMIX and Delft3D to improve the quality of the model results in the far-field.

6. CONCLUSIONS

This chapter presented the general characteristics of the Hong Kong coastal environments and the potential impacts associated with large-scale developments. The approach for water quality model validation and application of the validated models for prediction of water quality changes in reclamation, bridge construction and export of effluent projects are briefly described.

Dredging and filling activities are of major concern in the reclamation and bridge construction projects. Examples have been given of the increase in suspended solids in fish culture zones and oyster beds in Deep Bay. Export of effluent from sewage treatment works to less sensitive water bodies on one hand reduces the eutrophication in the originally affected water body but on the other hand introduces additional loads into the receiving water body. Through the application of water quality modelling, the potential impacts and benefits of the project can be examined providing accurate data for decision making on the feasibility of the development projects.

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