Environmental Management of Marine Fish Culture in Hong Kong

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Abstract: Marine fish farming is an important commercial practice in Hong Kong. Marine fish farms located in eutrophic coastal waters often face the threat of severe dissolved oxygen depletion associated with algal blooms and red tides. On the other hand, mariculture activities also contribute to pollution. The sustainable management of mariculture requires proper siting of the fish farms and stocking density control. Both of these are related to the carrying capacity of the water body concerned, which is mainly governed by its flushing characteristics. A simple method to determine the carrying capacity of a fish farm has been developed by using 3D hydrodynamic modelling and its effective coupling with a diagenetic water quality model.

A systematic methodology using numerical tracer experiments has been developed to compute the tidal flushing in a fishfarm. The flushing time is determined from the results of a numerical tracer experiment using robust three-dimensional hydrodynamic and mass transport models. A unit tracer concentration is initially prescribed inside the region of interest and zero elsewhere; the subsequent mass transport and the mass removal process are then tracked. The fish farms are usually situated in well-sheltered shallow embayments and may not connect directly to the open water. It is found that it is necessary to define both "local" and "system-wide" flushing times to represent the effectiveness of the mass exchange with the surrounding water body and the open sea respectively. A diagenetic water quality model simulating the sediment-water-pollutant interaction is employed to address the response of the water column and the benthic layer to pollution discharges. With the flushing rate reliably computed, the carrying capacity of the fish farm can be determined in terms of key water quality parameters: chlorophyll-a, dissolved oxygen, organic nitrogen and potential lowest dissolved oxygen level on a day of negligible photosynthetic production. The predictions are well-supported by field data.

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1. INTRODUCTION

In Hong Kong, there are 26 designated fish culture zones (Fig.1). In 2000, the production is 4662 tonnes at a market value of HK$151 million. As the fish farms need to be sheltered from strong waves and currents, the great majority of fish culture zones (FCZs) are located within shallow semi-enclosed embayments. In general, the mariculture activities may introduce excessive nutrients to the surrounding water and the seabed, and contribute to local eutrophication. At the same time, organic enrichment due to other pollution sources also pose a major threat to the fish farms. Under adverse hydro-meteorological conditions (e.g. high water temperature), algal blooms can lead to severe dissolved oxygen depletion and massive fishkills (e.g. Lee *et al* 1991). Sound mariculture management based on scientific decision support tools is vital for the sustainable development of fish farming.

To effectively manage the mariculture activities, it is desirable to determine the carrying capacity of a prospective or existing site for a fish farm. This will help to determine the suitability of a given site for fish farming (whether a proposed site is able to handle the target fish stocking density), or whether an existing fish farm can cope with plans to increase or change any fish stocks. The carrying capacity is strongly related to the hydrodynamic characteristics of the water body of interest - which can often be usefully represented by the **flushing rate** (or its inverse, the flushing time). This is a measure of the self-purification capacity of a fish farm due to tidal exchange with the outer sea and turbulent dispersion. A simple and robust methodology for assessing the carrying capacity of a fish farm has been developed by coupling an accurately determined flushing rate with a water quality model. The methodology is based on long term field observation and modelling of the eutrophic coastal waters of Hong Kong over the past fifteen years.

2. DETERMINATION OF CARRYING CAPACITY

2.1 The Need for a New Methodology

The flushing rate is the single most important physical parameter for the environmental management of mariculture. This represents a lumped measure of the effectiveness of tidal flushing in removing any pollutant in the fish farm. Traditionally, the tidal flushing rate has often been calculated by simplified approaches, such as the tidal prism or salt balance method (e.g. Gowen *et al.* 1983; Dyer 1997). The tidal prism method usually overestimates the flushing rate as it is based on the assumption of complete mixing, and cannot handle stratified flow conditions. On the other hand, the salt balance method is only applicable when long term reliable detailed salinity measurements and known freshwater flow inputs are available; it is also prone to error when salinity gradients are small - as is the case in many Hong Kong bays. As far as we are aware, there has hitherto not been a systematic numerical study of the flushing of fish farms in the context of mariculture management. There is scant knowledge on the flushing rates of tidal embayments or fish farms in Hong Kong. Under the influence of the Pearl River discharge and the offshore oceanic currents, Hong Kong's coastal water is typically vertically density-stratified in the wet season. A rigorous determination of the flushing rate for the wet season using a three-dimensional hydrodynamic model has not been reported.

In this age of ever increasing computing power, it may seem attractive to use full three-dimensional time-dependent hydrodynamic and water quality models to compute the water quality and the carrying capacity of a given location. For example, all the water quality parameters at a given location can be computed by using calibrated regional 3D hydrodynamic and water quality models. This kind of real time calculation from a coupled hydraulic and water quality model will typically give the time variation of water quality (e.g. over a period of a month) in either the dry or wet season. Such a methodology, in our view, is not well-suited for mariculture management. Usually, a fish culture zone covers only a few grid points, and it is difficult to assess the long term impact or determine the carrying capacity using the voluminous output (spatial distributions and time histories) of these models. Second, tidal and water quality variations are governed by quite different time scales; the effectiveness of using complex hydrodynamic and water quality models for long-term real time simulation (with attendant numerical problems and uncertainty of rate parameters) is questionable. Third, it is often difficult to choose a particular scenario (environmental conditions) to determine the suitability of a tidal embayment for fish farming or whether more fish stocking can be permitted in an existing fish farm. This is especially so when eutrophication and algal growth kinetics need to be considered, as in the case of Hong Kong waters. For environmental management purposes, it is necessary to have a tractable water quality model which can elucidate in a simple manner the dependence of water quality on the important hydrographic, meteorological, and ecological parameters.

2.2. Modelling Methodology

The coupling of hydrodynamic and water quality models to assess the carrying capacity of a fish farm is illustrated in Fig.2. First, the flushing characteristics of the fish farm and the related adjacent water body is accurately determined using a three-dimensional hydrodynamic circulation model which resolves the vertical structure of the water column. To determine the flushing time, a numerical tracer experiment is performed. A mass of hypothetical conservative tracer is instantaneously introduced into a region of interest, such as the fish farm or an entire bay. It is assumed that a unit tracer concentration is initially found inside that region and zero concentration elsewhere. The subsequent change in tracer concentration distribution as a result of tidal advection and dispersion is computed. Due to tidal exchange with the ‘clean’ water outside of the region, the tracer mass within the region of concern decreases with time. The flushing time can be determined from the rate of decrease of tracer mass within the region.

Second, the computed flushing rate is used in a quasi-steady water quality model that includes both the eutrophication kinetics in the water column and the sediment-water interactions (Lee and Wong 1997). This model predicts the long-term average water quality condition in the fish culture zone. From the model results, the carrying capacity of the fish culture zone can be determined in terms of a Potential Lowest Dissolved Oxygen (PLDO) level. The model can be used as a tool to assess the impact of an existing fish farm, or answer “what-if” question for evaluating various management options (e.g. the degree of reduction of pollution loading or fish stock). The method has been successfully applied to six representative fish culture zones in Hong Kong (Fig.1) with different hydrographic and fishfarm loading characteristics. These consist of four FCZs in Tolo Harbour: Yung Shue Au (YSA), Yim Tin Tsai (YTT), Yim Tin Tsai East (YTTE), Lo Fu Wat (LFW); Sok Ku Wan

(SKW) on Lamma Island, and Ma Wan (MW). In the following, only results from the four zones in Tolo Harbour are discussed for the purpose of illustration.

2.3 Three-dimensional Hydrodynamic Model

The water movement or tidal circulation in a coastal embayment is driven by ocean tides, wind, and density currents. In Hong Kong, tides are mixed and predominantly semi-diurnal (with a period of approximately 12.4 hours). In a tidal inlet in which a fish farm is located, there is significant spatial variation of water velocity (the velocity typically being greater at the outer end and decreasing towards the shoreline). At any location, along with the rise and fall of water level, the velocity also changes with time (typically weak around tidal slack and reaching peak values around mid-tide). Due to freshwater inflow and solar radiation, there is also a vertical variation of salinity and temperature, leading to density stratification. The latter has a great effect on vertical mixing and hence exchange of pollutant mass. The complex water movement is determined by solving the governing equations of motion subject to a prescribed tidal variation at the ocean open boundary. For the wet season, the salinity at the open boundary (based on field measurements) is also specified. The water level and flow field in the bay can then be computed by solving the continuity and momentum equations. The solution gives the water elevation and velocity field at any time within the tidal cycle. Based on this the advective transport of any tracer or pollutant mass and turbulent diffusion in the flow can be computed. The distribution of salt (salinity) can also be computed in similar manner.

The three-dimensional (3D) flow model employs the hydrostatic pressure approximation (shallow water equations) and is essentially the same as those adopted for the Princeton Ocean Model (Blumberg and Mellor 1978; Mellor 1998) except for the turbulence closure scheme. A uniform rectangular grid is applied in the horizontal directions and sigma-coordinate is employed in the vertical direction; this means the vertical water column is represented by an equal number of layers regardless of water depth (locally the dimensionless depth co-ordinate, the sigma-coordinate, scales from zero to negative unity). Instead of using a second order turbulence closure model with the turbulent mixing coefficient described by the turbulent kinetic energy and associated turbulence length scale, a mixing length model is employed instead. This simpler approach is believed to be adequate in describing the reduction of mixing due to vertical density stratification for the purpose of the present study.

The coastal circulation is governed by fast moving external gravity waves and slow moving internal gravity waves. To reduce the computational effort required, the model simulation can be separated into the external and internal modes (Mellor 1998). This modal splitting technique allows the calculation of the free surface elevation without loss of accuracy by solving the vertically integrated horizontal velocity transport separately from the three-dimensional computation of the velocity, salinity and thermodynamic properties. The horizontal velocity transport (external mode) equations are obtained by integrating the full equations over the depth and eliminating the vertical structure. They are solved by an alternating direction implicit (ADI) finite difference scheme (Choi 1986). For the internal mode, the three-dimensional momentum and transport equations are solved by a split step scheme. The horizontal propagation, advection and diffusion in all three directions are solved in separate steps. This approach allows the more appropriate numerical schemes to be used to model the different processes and maintain numerical stability. Explicit backward tracking characteristic method is employed for the advection steps and central differencing is used for the diffusion terms. Additional details can be found in Choi and Lee (2000) and Choi (2002).

2.4 Computation of Flushing Rate

The application of the salt balance approach to Hong Kong's waters is often met with difficulties as the freshwater inflow into the bay is often negligible (routed to reservoirs) or cannot be estimated reliably, and salinity gradients along the tidal inlet often very small. The use of a numerical flow and mass transport model is hence a necessary alternative to determine the flushing rate. The "*local*" flushing rate is determined by instantaneously releasing a conservative tracer mass into the fish farm; the initial concentration is unity within the fish farm and zero elsewhere. Hence, the surrounding water in the vicinity of the fish farm is assumed to be 'clean'. Essentially, the "local" flushing time is useful for estimating the local impact of any foreign substance or short term effluent discharge from the fish farm. It can be used, for example, to compare the merits of different locations of the fish farm within the selected tidal inlet. However, for some water quality parameters such as nutrient level, the outer bay has a non-zero concentration due to the return of pollutants with the flood and ebb of tides. For estimating long term average water quality, some other indicator of flushing is needed.

The "*system-wide*" flushing rate is determined by looking at mass removal from a much larger water body which is connected to an adjoining 'clean' ocean. This definition takes into account the interactions between different parts of the water body which are not assumed to be 'clean' and represents the long-term flushing efficiency of the region of interest. In the tracer experiment, mass is released from everywhere inside the water system of interest (e.g. the entire bay containing the tidal inlet in which the fish farm is located). This approach is similar to determining the flushing rate using salinity (or freshwater concentration) as the tracer concentration, but it is applicable even for the cases without freshwater runoff. Extensive computations and comparison with field data have indicated this "system-wide" flushing rate should be used for determining the long term water quality and, hence, the carrying capacity of the fish culture zone.

2.4.1 Mass transport model

To determine the "*local*" flushing time, a mass transport model based on Lagrangian particle tracking is developed. Forward particle tracking is used to compute the advective movement, while random walk method is used for modelling the diffusive movement. This approach has the advantage of minimal numerical diffusion and allows an accurate simulation for the initial sharp concentration gradient that will occur at the edge of the tracer plume. In order to obtain the model results with required accuracy, it is necessary to use sufficient number of particles; typically 20,000 particles were required to give stable results. For "*system-wide*" flushing time calculations, as there is no sharp concentration gradient and a lot of particles will be needed to cover the entire model area, a three-dimensional finite difference model is employed for computational efficiency. The finite difference model employs a conservative flux-corrected scheme for computing the advective transport and central difference method is used for modelling the diffusion process; additional details can be found in Choi (2002).

2.4.2 Example Case Study – Tolo Harbour

The methodology to compute tidal flushing is illustrated for the four fish culture zones inside Tolo Harbour: *Yung Shue Au* in Three Fathoms Cove, *Yim Tin Tsai* and *Yim Tin Tsai East* in the inner Tolo, and *Lo Fu Wat* near the Tolo Channel (Fig.1). The hydrodynamic model (8 layers with 500m grid) covers the entire harbour, and computations are performed under average dry and wet season conditions. For example, Fig.3a) shows the computed peak ebb flow in Tolo in the wet season (average of the top 3 m). Based on the computed real time tidal circulation, the mass transport corresponding to the numerical tracer experiments for all four FCZs is studied at the same time. The computed three-dimensional circulation has been validated against field velocity measurements; Fig.3b) shows the comparison of computed and observed salinity at a number of water quality monitoring stations from inshore to Tolo Channel (TM2 to TM8) as shown in Fig.1.

To assist the assessment of the *system-wide* flushing characteristics, the model grid cells are grouped into 14 segments. The computed mass variations in these segments are tracked in the tracer experiments; Fig.3c) shows the tracer mass variation for the four FCZs in Tolo in the wet season. It is found that the computed mass variation can be well-fitted with double exponential curves, from which the flushing time can be accurately determined. The double exponential curve is in the following form:

$$\frac{M(t)}{M_o} = (1+\alpha)e^{-k_1 t} - \alpha e^{-k_2 t} \qquad (1)$$

where M_o is the initial mass inside the specific segment and $M(t)$ is the mass inside the same segment at time instant t. Eqn. (1) can be derived from an analytical two-segment model. α, k_1 and k_2 are related to the size of the fish culture zone, the exchange flow between the fish farm and its surrounding water, and that between the water system and the external "clean ocean". The flushing time can be determined from α, k_1 and k_2 which are obtained by fitting Eqn. (1) to the numerically computed $M(t)$ (Choi 2002). Fig.3c) also shows that the mass removal for YTT, YTTE, and YSA are very similar, while LFW has a much faster flushing rate. The flushing times obtained for all six selected fish culture zones are listed in Table 1. For Tolo Harbour, while the dry season *system-wide* flushing time is about 2~3 times that for the wet season, the averaged peak velocity in segments where the fish culture zones are located are similar in both seasons. For YTTE and YSA, it is around 2 cm/s in both wet and dry season, while at YTT it is about 4 cm/s in wet season and 3 cm/s in dry season. Local current velocity magnitude does not appear to be a key factor in determining the *system-wide* flushing, even though it will govern the *local* flushing. From the computed tracer distribution, it is found that the strength of the flow in the Tolo Channel is an important factor for the mass removal to the open sea. In wet season, the average peak velocity near LFW is over 14 cm/s, while it is only about 7 cm/s in dry season. Fig.3d) shows the tracer concentration distribution after 5 days for wet season. It is seen that the tracer mass in the inner shore near Tai Po and Shatin is not much reduced.

To study the *local* flushing for each fish culture zone in Tolo, individual detailed local models have been developed. For all cases, it is found that the flushing times in the wet season are strongly dependent on the gravitational circulation in the density-stratified flow. The tidal flushing of these fish farms is typically much stronger in the wet season; the corresponding flushing times are much smaller than in the dry season. From Table 1 it can be seen that the flushing of Yim Tin Tsai East, Yim Tin Tsai, and Yung Shue Au are significantly worse than Lo Fu Wat (located off Tolo Channel). Hence, the flushing rate of an individual tidal embayment is mainly governed by the key removal mechanism determined by the system-wide flow characteristics, and may not correlate directly with the local physical shape of the embayment.

2.5 Diagenetic water quality model

The flushing time represents the average ‘residence time’ of any pollutant in the system, and is one measure of the self-cleansing capacity. However, the water quality or carrying capacity depends on other factors as well: the water depth, size of fish culture zone, and organic loading. The water quality model is a box model that simulates the sediment-water-pollutant interactions to predict long-term (seasonal) average water quality in a fish culture zone. Besides the water column, a single anaerobic sediment layer is included in the model. The settled particulate organic matter from mariculture activities and external loads undergoes bacterial break down (diagenesis) inside the sediment. The decomposition of sediment organic material releases inorganic nutrients to the sediment interstitial waters that can be transferred to the water column to sustain further algal growth, and also results in the exertion of an oxygen demand at the sediment-water interface. As a result, the aerial fluxes from the sediment can furnish nutrient sources or oxygen sinks to the overlying water column.

Based on previous studies, nitrogen is assumed as the limiting nutrient. Fig.4 shows the schematic diagram of the interactions included in the water quality model. Dissolved inorganic nitrogen (DIN), mainly in ammonia form, produced by hydrolysis of non-algal organic nitrogen and decomposition of detritus algal nitrogen in the sediment is exchanged with the overlying water through diffusion. During bacterial breakdown dissolved oxygen from the water column is taken up by the sediment resulting in sediment oxygen demand (SOD). The hydrodynamics of the fish farm is represented by the flushing rate that is determined from the numerical models as described above. The general model framework is based on that adopted in the WASP program (Ambrose *et al.* 1993; Di Toro and Connolly 1980).

Organic loads generated by mariculture activities include wasted food, nutrients leached during feeding, fecal materials and excreta produced by fish, wastes generated by fish farmers' household (humans and animals living on the raft). The model is applied to analyse the steady state, long-term mean conditions for the selected fish farms with different mariculture stress and hydrographic conditions - for both the dry and wet seasons. The rate coefficients and model parameters used are based on previous field and mathematical modelling studies (e.g., Lee and Wong 1997; Lee and Feleke 1999).

From the model, the average concentrations of Chlorophyll-a, Dissolved Inorganic Nitrogen (DIN), organic nitrogen, dissolved oxygen (DO), Sediment Oxygen Demand, and Sediment DIN flux can be determined for the dry and wet season. The **potential dissolved oxygen drop** (PDOD) can then be determined. The PDOD is the DO consumption rate on a day of negligible phytoplankton or DO production (e.g., critical days of overcast skies and heavy rainfall); this is an indicator of possible DO depletion. From these two, it is possible to estimate the **potential lowest dissolved oxygen** (PLDO) level on a day of severe DO depletion. Fig.5a shows the nitrogen loads, flushing times and some of the predicted water quality indicators for the six fish culture zones in Hong Kong. It can be seen that Yim Tin Tsai East (YTTE) and Yung Shue Au (YSA) show the lowest dissolved oxygen level. This can be mainly attributed to the combination of low flushing rate (long flushing time) and the higher total organic load. The carrying capacity is dependent on both the flushing rate, the pollution loading, and the water depth and volume of the fish farm. The faster flushing rate for Sok Kwu Wan (SKW) with moderate organic loading did not create a DO depletion stress. YTTE with the lowest flushing rate and relatively high organic loads shows the most eutrophic condition; higher chlorophyll-a, low mean DO, high PDOD, high sediment nutrient flux and SOD (not shown). In the summer high algal biomass, PDOD, and sediment fluxes are predicted in all the fishfarms due to elevated temperatures. Fig.5b shows the predicted potential lowest dissolved oxygen (PLDO) under different loading (fish stocking density) conditions. It is seen that if a target DO level of 4 mg/L is set, the organic loading at Yung Shue Au, Yim Tin Tsai, and Yim Tin Tsai East need to be reduced, while there is possibility of expansion of operation at Lo Fu Wat, Sok Ku Wan, and Ma Wan (only in winter).

3. CONCLUSIONS

A systematic methodology via the use of numerical tracer experiments has been developed to determine the flushing rate of marine fish farms located in semi-enclosed shallow embayments. Robust 3D hydrodynamic and mass transport models have been developed to provide the flow field and computation of the tracer mass concentration. The computed flushing time for the dry/wet season is coupled with a quasi-steady diagenetic water quality model that includes the algal growth and nutrient kinetics in the water and the sediment-water-pollutant interactions. The long term average water quality in the fish farm can be determined for the dry/wet season. The carrying capacity of the fish farm can be assessed by reference to key water quality indices: chlorophyll-a, dissolved oxygen, organic nitrogen, and potential lowest dissolved oxygen level on a day of negligible photosynthetic production. The predicted water quality as well as the relative carrying capacity are well-supported by field observations. The quantification of tidal flushing characteristics of fish farms is of interest to a wide range of environmental studies (e.g. typhoon shelters). The general methodology can possibly be applied to the environmental management of mariculture in other sub-tropical eutrophic coastal waters.

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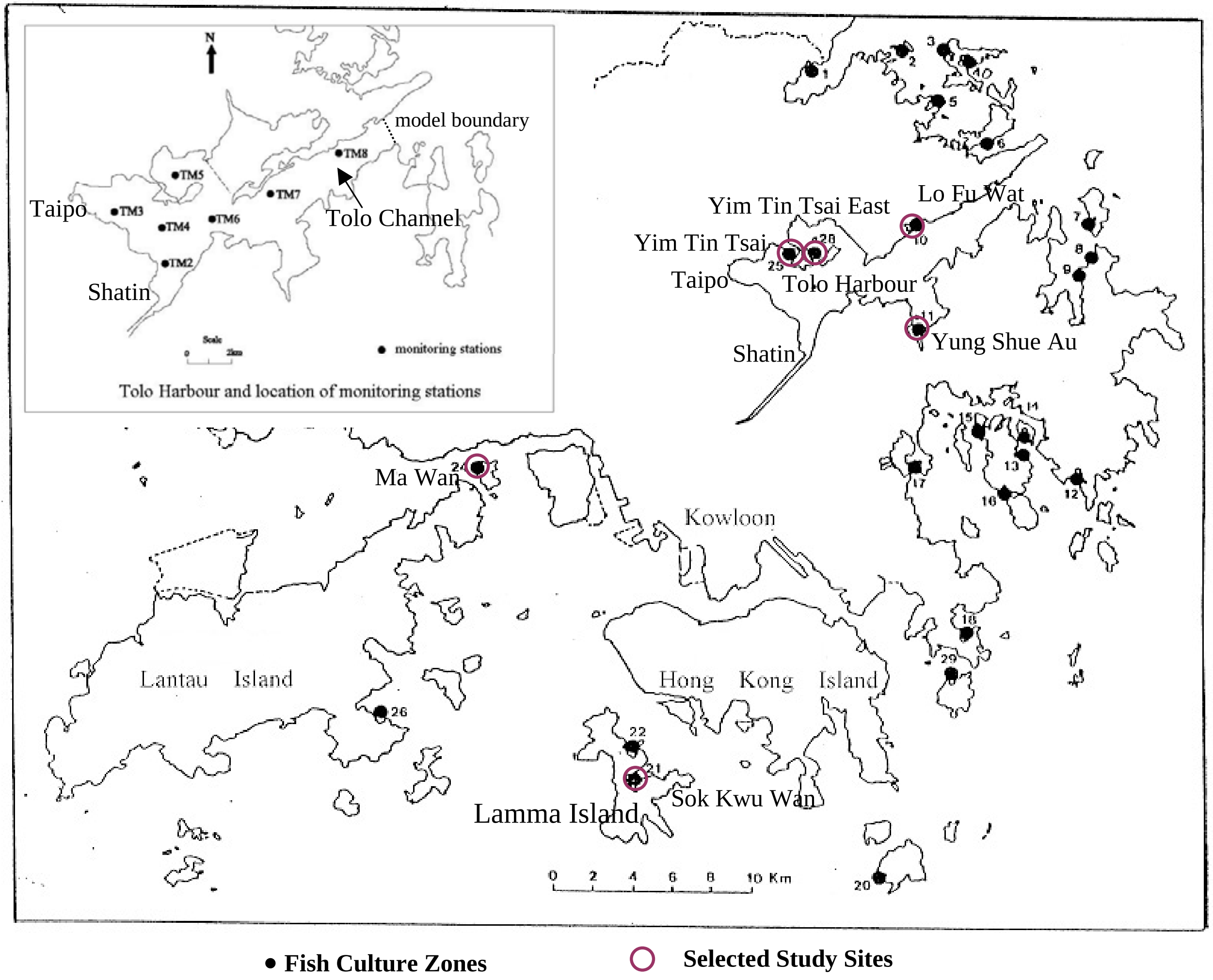


Fig. 1 Location of marine fish culture zones in Hong Kong

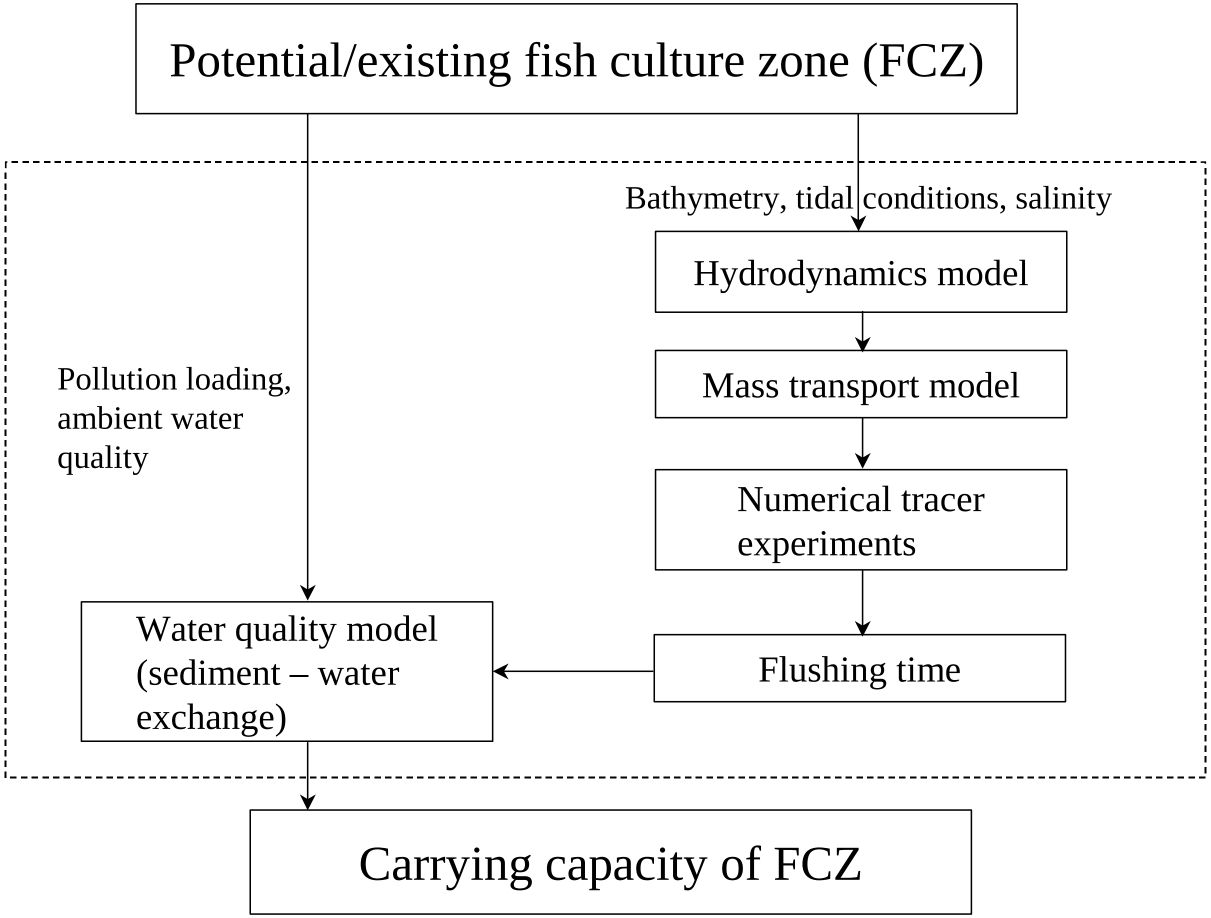
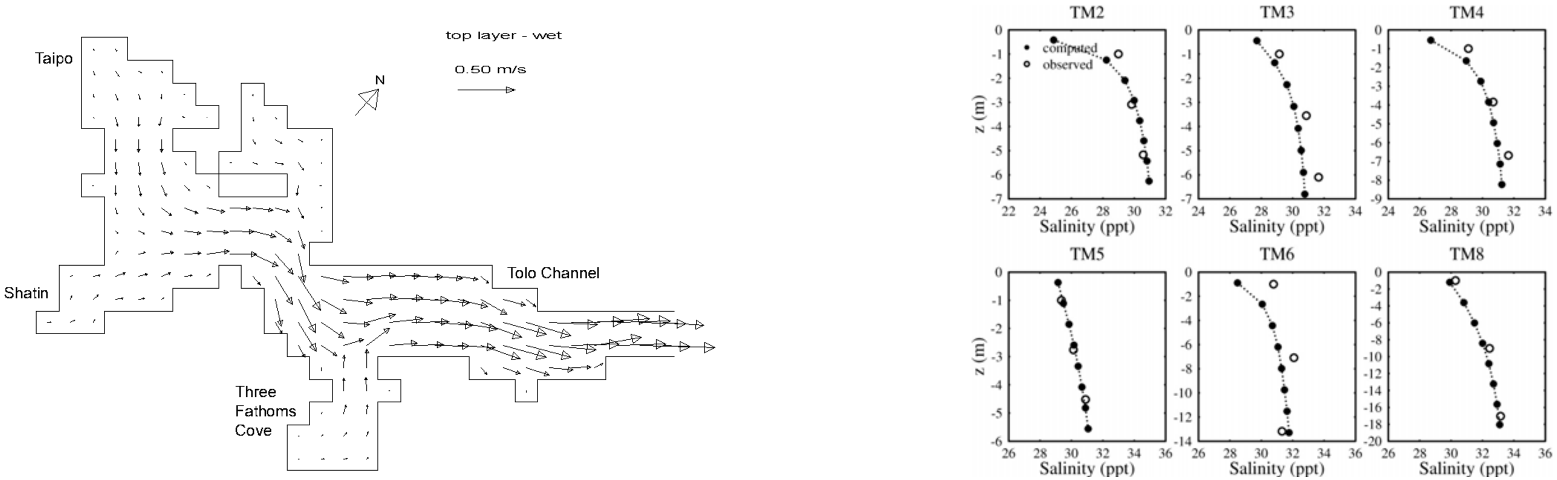
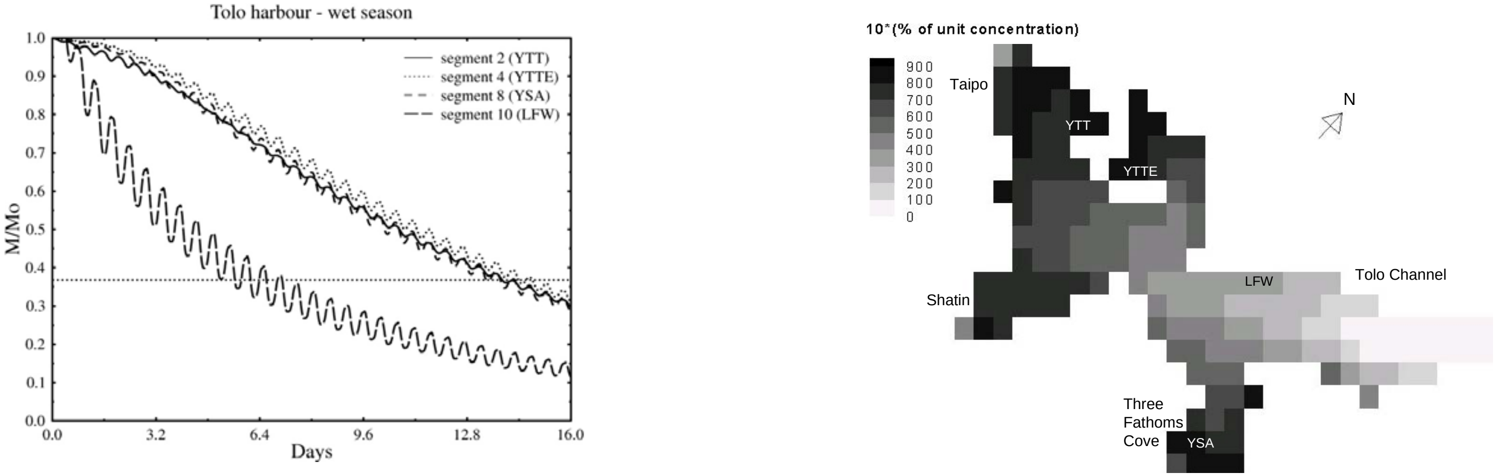


Fig. 2 Schematic framework of modelling of carrying capacity of a fish farm



a) Computed peak ebb flow for wet season (top 3 m)

b) Vertical salinity profiles for wet season – tidally averaged



c) Variation of mass in segments with FCZ inside Tolo Harbour

d) Computed concentration 5 days after release of tracer mass

Fig. 3 Tolo Harbour - typical 3D model results: salinity, current, tracer concentration and flushing time

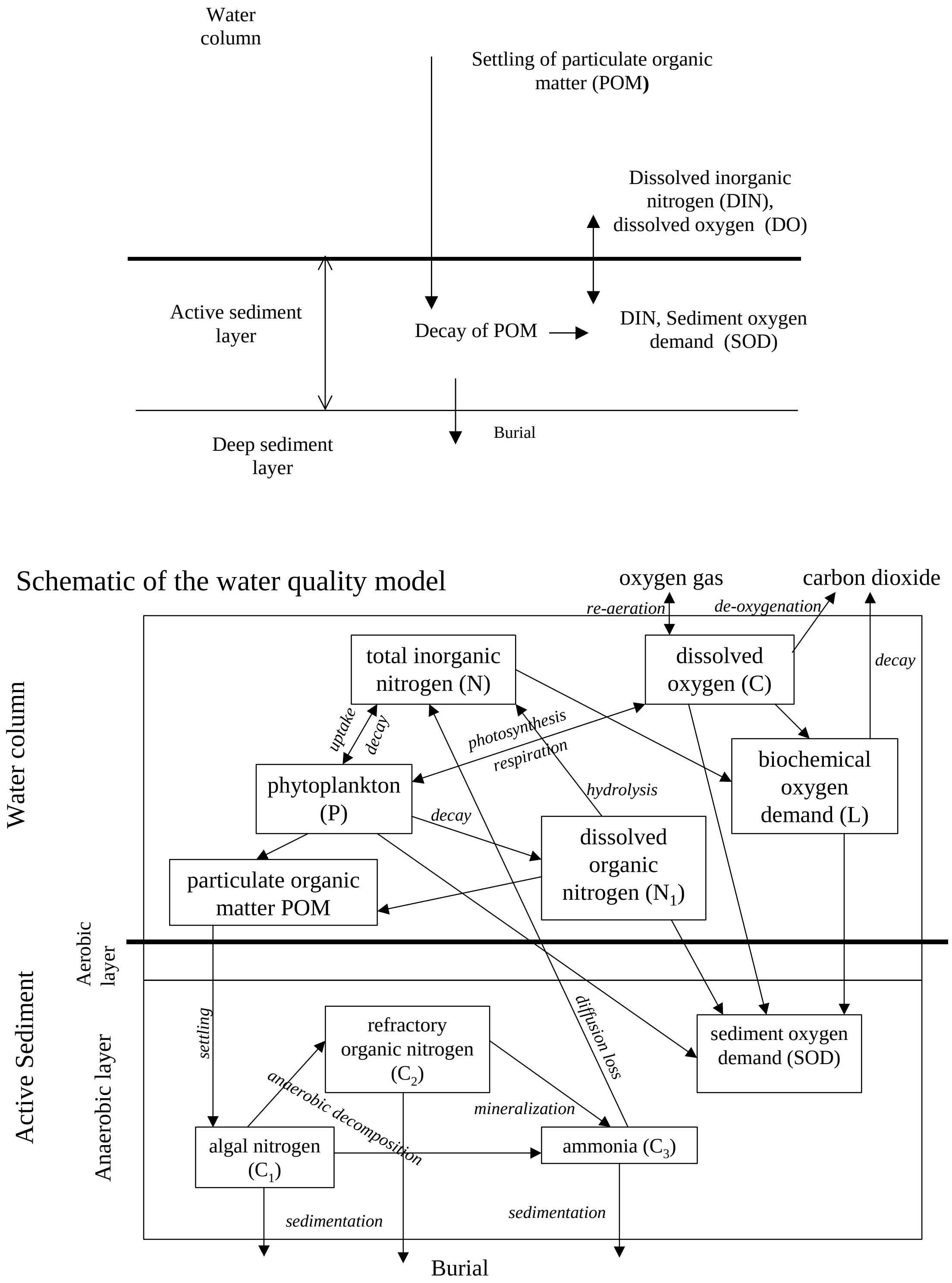
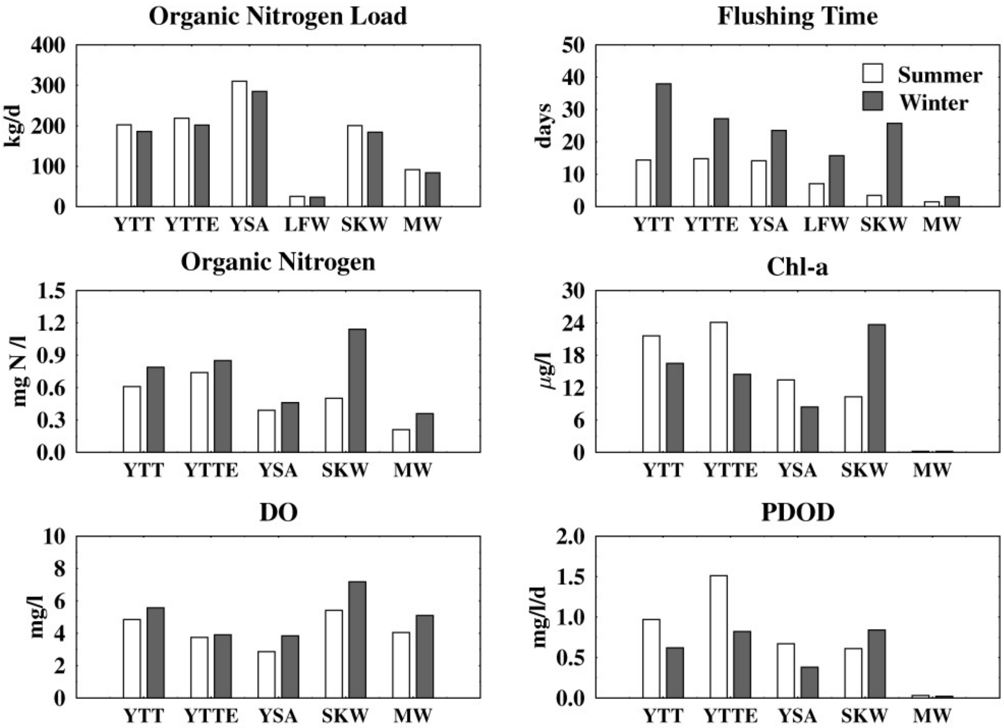


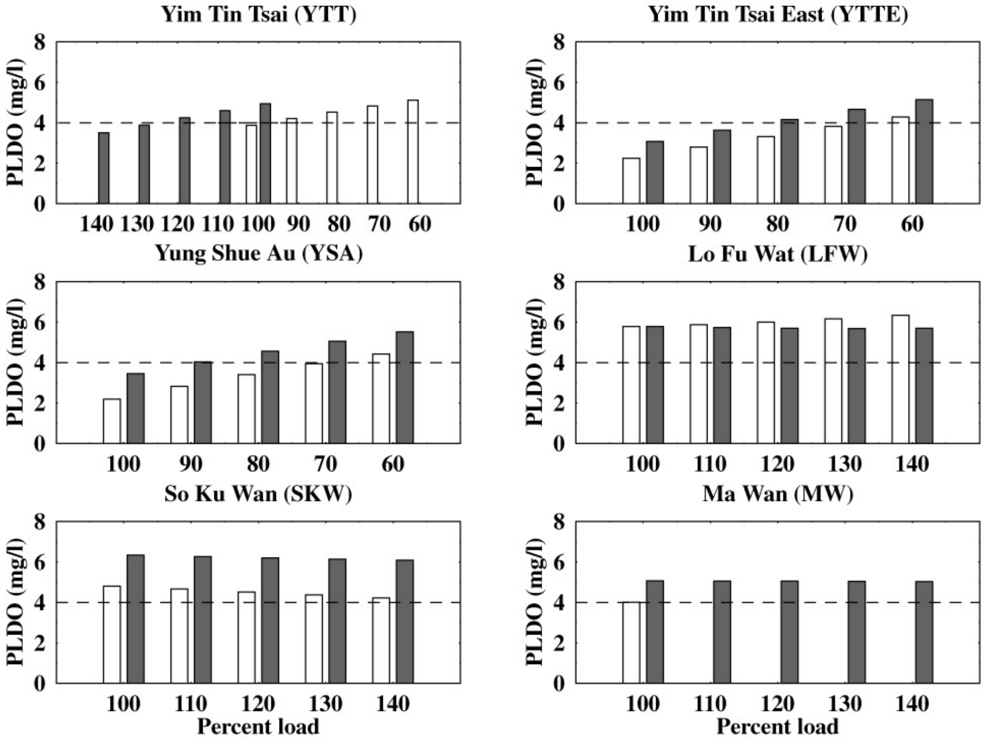
Fig. 4 Schematic diagram of diagenetic water quality model and sediment-water interactions

(a)



nitrogen loads, flushing time and water quality indicators

(b)



potential lowest dissolved oxygen (PLDO) levels with different loads

Fig. 5 Water quality model results for six representative fish culture zones in Hong Kong

Table 1 Computed flushing times for six representative fish culture zones in Hong Kong

Fish culture zones	System-wide flushing time (d)		Local flushing time (d)	
	Wet	Dry	Wet	Dry
Yim Tin Tsai	14.4	38.0	2.7	3.3
Yim Tin Tsai East	14.8	27.2	3.3	4.9
Yung Shu Au	14.2	23.6	6.4	8.6
Lo Fu Wat	7.1	15.8	0.4	0.8
Sok Kwu Wan	3.5	25.8	0.4	3.8
Ma Wan	1.5	3.1	-	-