Wet Season Tidal Circulation and flushing in Three Fathoms Cove

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Abstract

The YSA marine fish culture zone is located inside Three Fathoms Cove in Tolo Harbour. A three-dimensional flow and mass transport model have been developed to study the tidal circulation and flushing characteristics in the wet season of the semi-enclosed bay. The flow model solves the full shallow water equations with a mixing length model to represent the vertical exchanges. The mass transport model is based on the Lagrangian particle approach. Numerical tracer experiments are carried out to simulate the tidal flushing of the fish farm under different tidal conditions. In the wet season, the stronger stratification results in a stronger gravitational flow; the flushing rate for representative dry and wet season conditions is determined.

Keywords: tidal circulation, numerical model, tidal flushing, fish farm, particle method, Hong Kong

1 Introduction

Marine fish culture is an important commercial practice in Hong Kong. It involves rearing of marine fish fry to marketable size in cages suspended by floating rafts. The annual production is about 3,000 tonnes, which caters for about 10% of the local demand for live marine fish (AFD 1998). There are currently 26 designated fish culture zones occupying a total sea area of about 2.1 km^2 and most of them are located in well sheltered shallow embayments. The Yung Shu Au fish culture zone is located inside the Three Fathoms Cove, a small semi-enclosed bay inside Tolo Harbour in the northeastern part of Hong Kong. The bay is about 2.5 km long and 1 km wide with a surface area of about 3.36 km^2. The depth is about 5 m inshore and increases to over 10 m at the outer end. The fish culture zone is located in the inner part of the Cove with an area of about 0.34 km^2.

The mariculture activities both affect and are affected by the water quality of the bay. The feeding process may lead to excessive nutrients being introduced to the surrounding water and seabed, and contribute to local eutrophication. On the other hand, the fish farm can be affected by the external pollution sources. Eutrophication and pollution discharges may lead to algal blooms and severe oxygen depletion that result in fish kills. The practical ways to manage the mariculture activities include proper siting and stock density control. These are related to the tidal circulation and carrying capacity of the receiving water. The accurate determination of the flushing rate is essential in assessing the impacts of the fish farming activities and the carrying capacity of a fish farm. By carrying out numerical tracer experiments using numerical flow and mass transport model, the flushing time can be accurately determined.

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2 Numerical Flow Model

In Hong Kong, with the influence of the freshwater discharges from the Pearl River and the offshore oceanic currents, there is a distinct wet and dry season hydrodynamic regime. The water column is rather well-mixed in the dry season and significantly stratified during the wet season; it is necessary to use a three-dimensional circulation model to simulation the tidal flow. The 3D model developed is based on a formulation similar to the Princeton Ocean Model (POM) (Mellor 1988). It solves the full 3D hydrodynamics equations with the hydrostatic assumption. A topographically conformal co-ordinate system is applied in the vertical direction.

To reduce the computational effort required, the model simulation is separated into the external and internal modes. This allows the calculation of the free surface elevation without sacrificing the accuracy by solving the vertically integrated horizontal velocity transport separately from the three-dimensional computation of the velocity, salinity and thermodynamic properties. Propagation and other terms are solved explicitly. 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) five-point finite difference scheme (Choi 1986). The three-dimensional momentum and transport equations are solved by a split step scheme (Benque *et al* 1982). Backward tracking characteristic method is used to determine the advection transport. Central difference scheme is applied to model the diffusion processes.

To model the Three Fathoms Cove, a regular square grid of size 50 m and 8 uniform vertical sigma layers are used (Figure 1). A mean semi-diurnal M2 tide is prescribed at the open end with a range of 1.7 m. Constant eddy viscosity coefficients are used to represent the horizontal momentum and solute exchange, while a mixing length model is employed to model the vertical exchanges. Based on the long term water quality monitoring data between 1985-1996 obtained at a station near to the model boundary, representative vertical profiles for salinity and temperature are determined and used as the boundary condition for the model simulations. The wet season condition is calculated by averaging the measurements collected from June to September for each year.

For the wet season, it is found that the flow in the surface layer is in general much stronger than those in the other 7 layers below it. The maximum surface velocity at the fish farm location can be up to over 6.0 cm/s, while those in the lower layers are well below 4.0 cm/s. The residual currents in the surface layer can exceed 1.8 cm/s, while those in lower layers are only up to about 0.6 cm/s. Figure 2a and 2b shows the residual currents in the top and fifth layer respectively. These results are consistent with those obtained in an earlier study on the same region using a *two-layer model* with different tidal conditions (Wu *et al* 1999). For the case without density stratification, the maximum surface velocity is only around 2 cm/s and residual currents are well less than 0.5 cm/s. These results indicate that density stratification has a significant effect on the flow circulation in Three Fathom Cove.

It can be observed from the computed depth averaged residual flow (Figure 3) that in the inner bay, there is a clockwise circulation flow moving in along the eastern shore and moving out to the outer bay along a path between the western shore and the middle of the bay. Also, the residual flows are mainly in the landward direction in the surface layer, and are more in the seaward direction in the lower layers. This may be related to the fact that in the present simulations, there is no fresh water discharge into the Three Fathoms Cove and the gravitational circulation is entirely driven by the vertical density profile specified at the open boundary. The surface salinity is increasing towards the inner shore as shown in Figure 4a and 4b.

3 Tidal Flushing Computation

A systematic methodology using a numerical tracer experiment has been developed for computing the tidal flushing in the marine fish farm (Choi *et al* 1999). To accurately simulate the mass transport, a Lagrangian particle model is developed. Forward particle tracking is used to compute the advection, while random walk model is employed to model the diffusion. A unit tracer concentration is assumed initially inside the fish farm at all depths and zero elsewhere. The subsequent tracer movement is then determined by the mass transport model driven by the computed flow field. Constant horizontal and vertical diffusion coefficients corresponding to well established mixing laws, 0.01 m^2/s and 10^{-6} m^2/s respectively, are used. A time step of 186 seconds is used and each tracer test lasted for 20 tidal cycles. 12,000 particles are used in each simulation to minimise the stochastic effects of the random walk method.

Figure 5a and 5b show the computed variations of tracer mass in the fish farm with time. It is found that the tidally averaged variation is best represented by a double exponential curve, as there is rapid mass removal initially (Choi *et al* 1999). By taking the flushing time as "the average lifetime of a particle in the given volume of water body", we obtain the results given below. Commencing the experiment from different tidal stage will result in a different mass removal curve. Starting from high and low water will give the two extreme cases that provide a good representation of the flushing processes. Besides the wet season condition, simulations are also carried out for the dry season condition as well as without density stratification.

	wet season		dry season		unstratified	
$\Delta\rho/\rho$	0.0065		0.0014		0.0000	
Release at	HW	LW	HW	LW	HW	LW
T_f (days)	1.47	5.38	2.73	9.04	5.00	10.59
Averaged T_f (days)	3.43		5.89		7.80	

It is noted that the flushing time T_f is significantly affected by the stratification. A stronger stratification results in a stronger gravitational flow and a better flushing. Hence, the fish farm would be better flushed in the wet season than that in the dry season. Also, the results support the fact that releasing the tracer at low water would give the worst situation, as the tracers are more likely being carried towards the inner shore by the flood tide before being flushed out when the tide turns. In assessing the impacts of fish farming activity, this condition would represent the worse scenario that needs to be considered

Figure 6a and 6b shows the predicted tracer concentrations after 1 and 2 tidal cycles with the tracer being released at the high water under wet season condition. It can be observed that the movement of the numerical tracers is mainly driven by the tidal circulation, as the horizontal mixing is rather weak. The computed concentration contours reflect well the effects of the clockwise residual circulation in the inner bay. A high concentration zone is formed around the middle part of the fish farm where the residual current is relatively weak. Also, there are two spots where signs of accumulation can be observed. One is at the southern shore where the residual flow changed direction, while the other one is at the southern side of the small island. Hence, besides computing the tidal flushing rates, the numerical tracer experiments also allow us to examine the local impact of discharges from the fish farm upon the surrounding water.

4 Concluding Remarks

A three-dimensional flow and mass transport model has been developed to study the tidal circulation and tidal flushing in the shallow bays in Hong Kong. It has been applied to the Three Fathoms Cove inside Tolo Harbour. It is found that both the computed current velocity and residual flow are much stronger in the wet season than those in the dry season. The tidal flushing of the inner bay is studied using a numerical tracer experiment. It is found that the averaged tidal flushing time for the wet season is about 3.4 days, which is well less than that for the dry season and the unstratified conditions. In addition to determine the flushing rates, the model can also be used to assess the environmental impacts of pollution from the fish farm.

5 References

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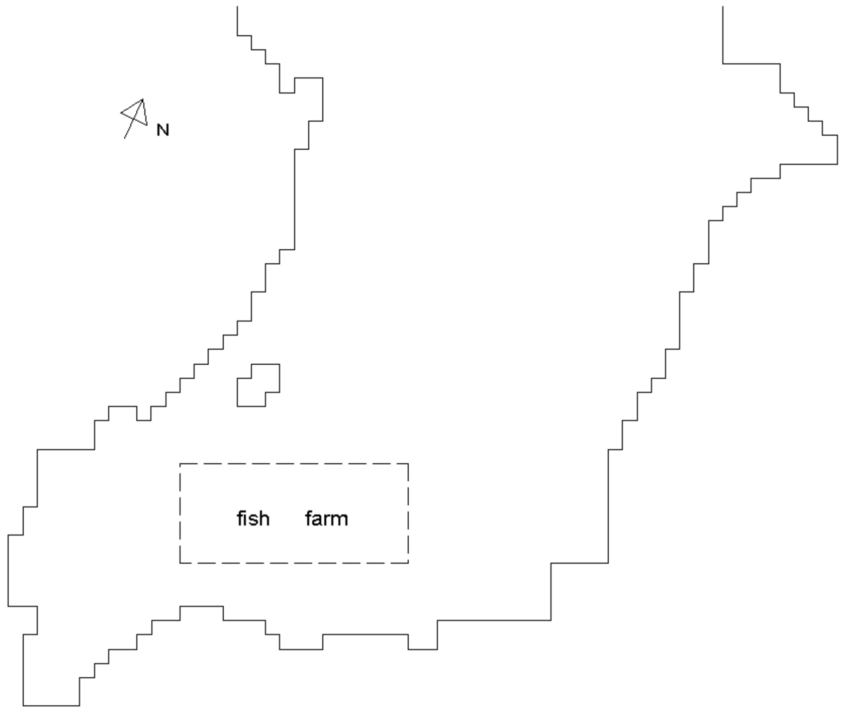

Fig. 1. Model grid for Three Fathoms Cove, Tolo Harbour, Hong Kong.

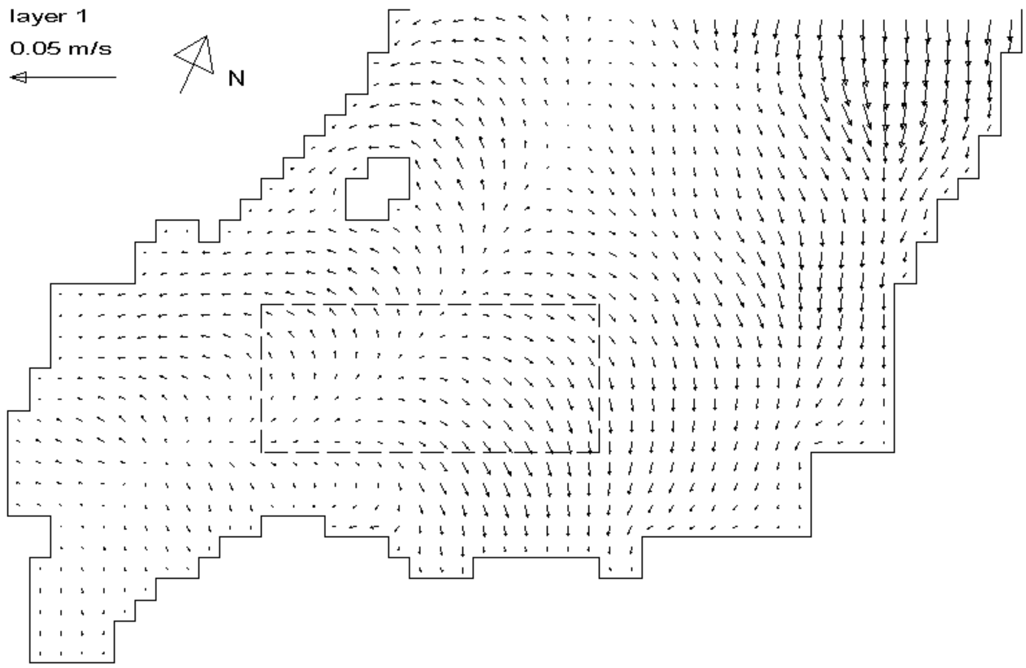

Fig. 2a. Computed residual currents in the inner bay in layer 1

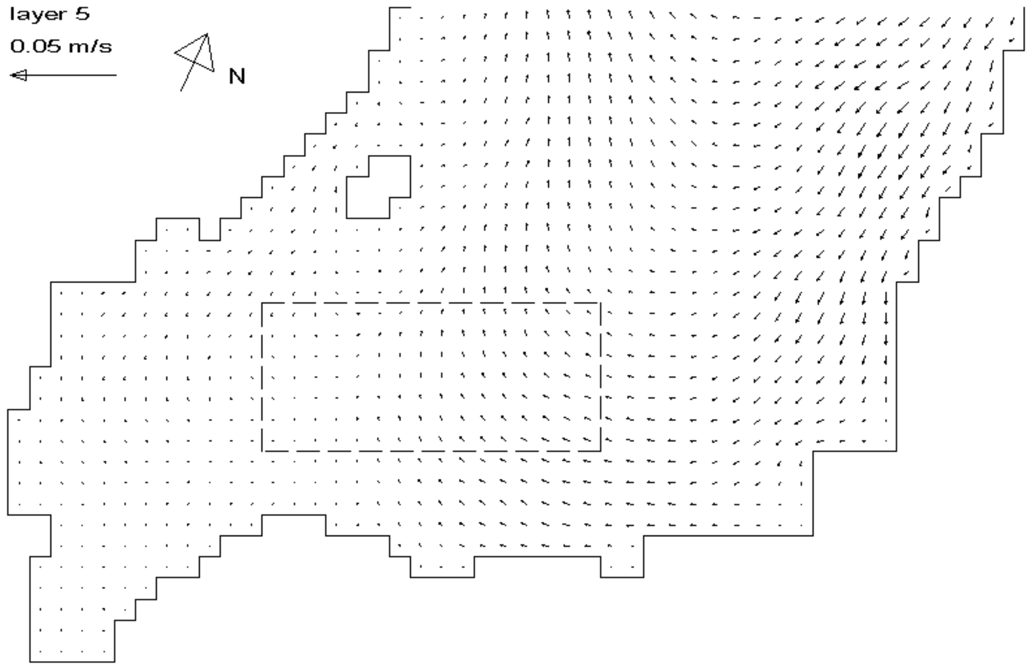

Fig. 2b. Computed residual currents in inner bay in layer 5

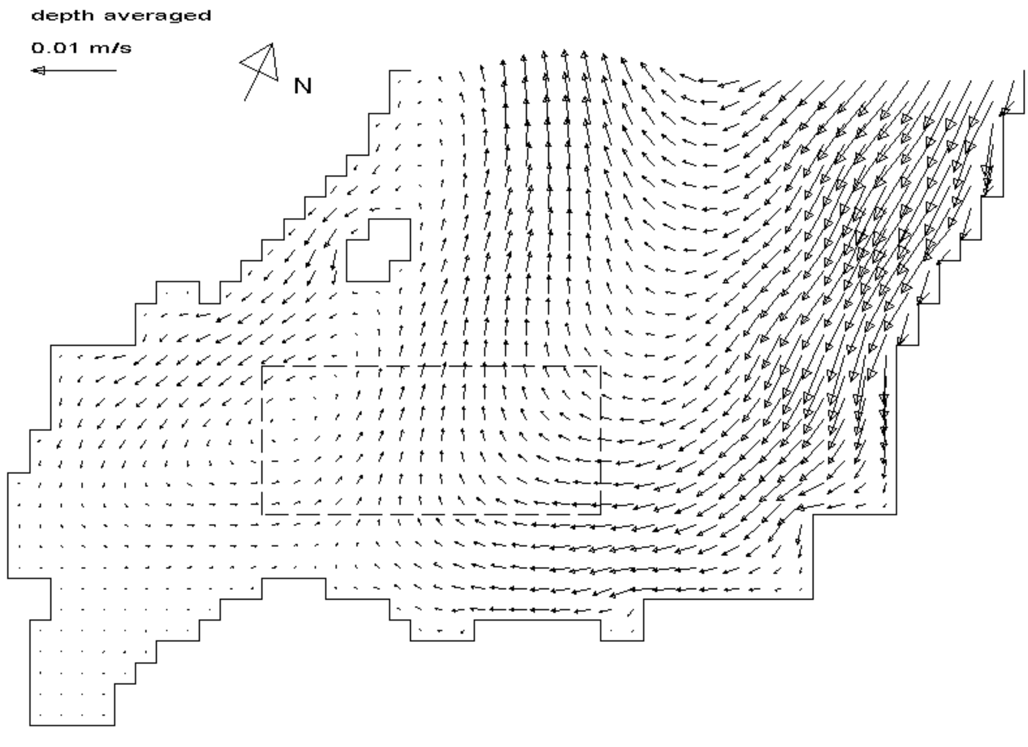

Fig. 3. Computed depth-averaged residual currents in the inner bay

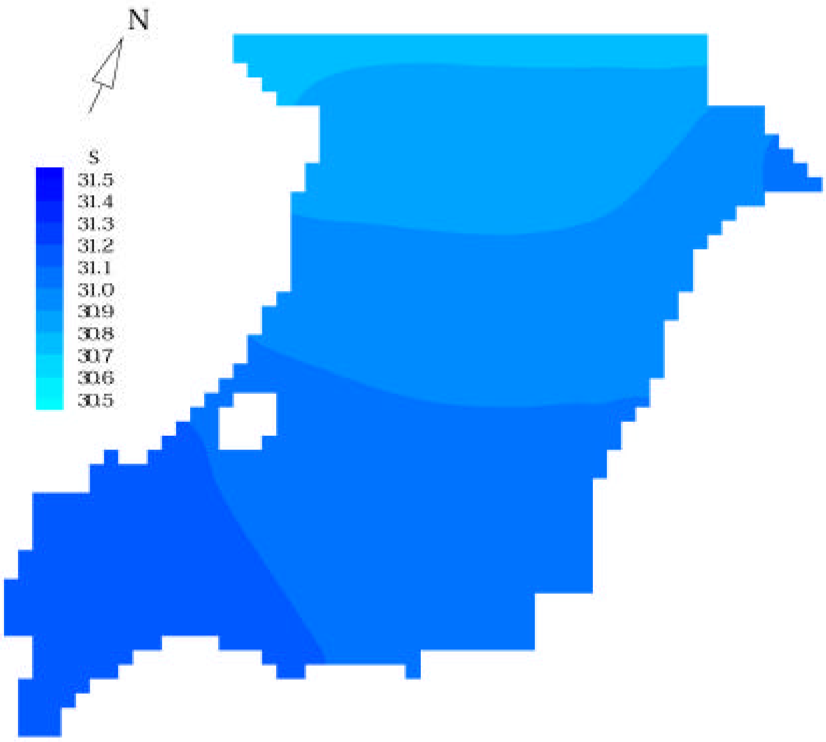

Fig. 4a. Tidally averaged salinity (ppt) in the surface layer

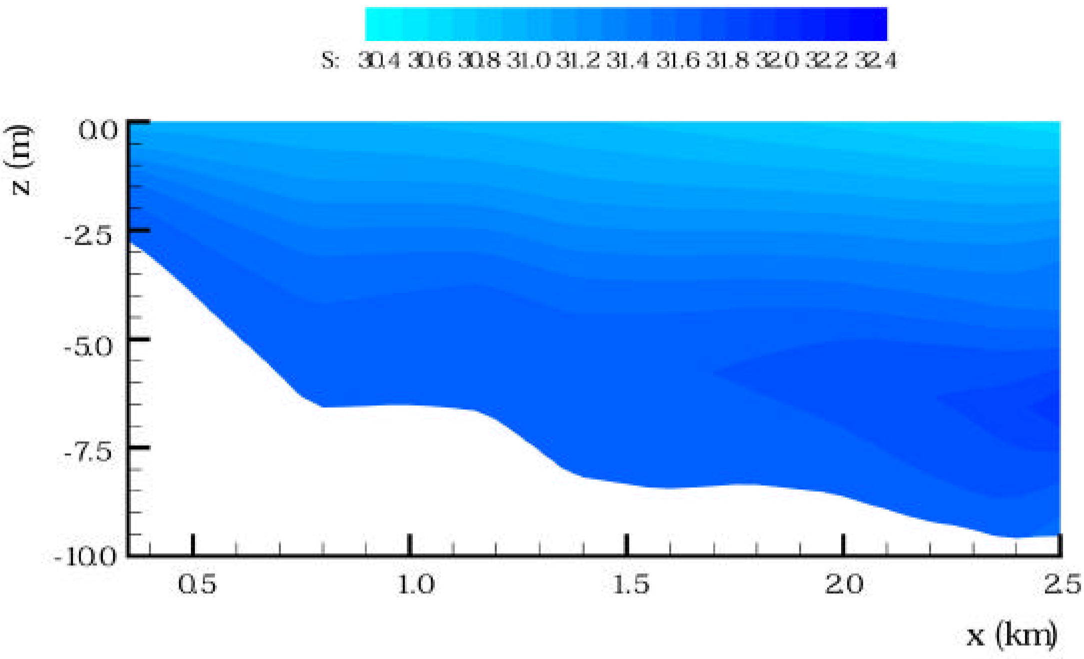

Fig. 4b. Tidally averaged salinity (ppt) structure along a longitudinal transect

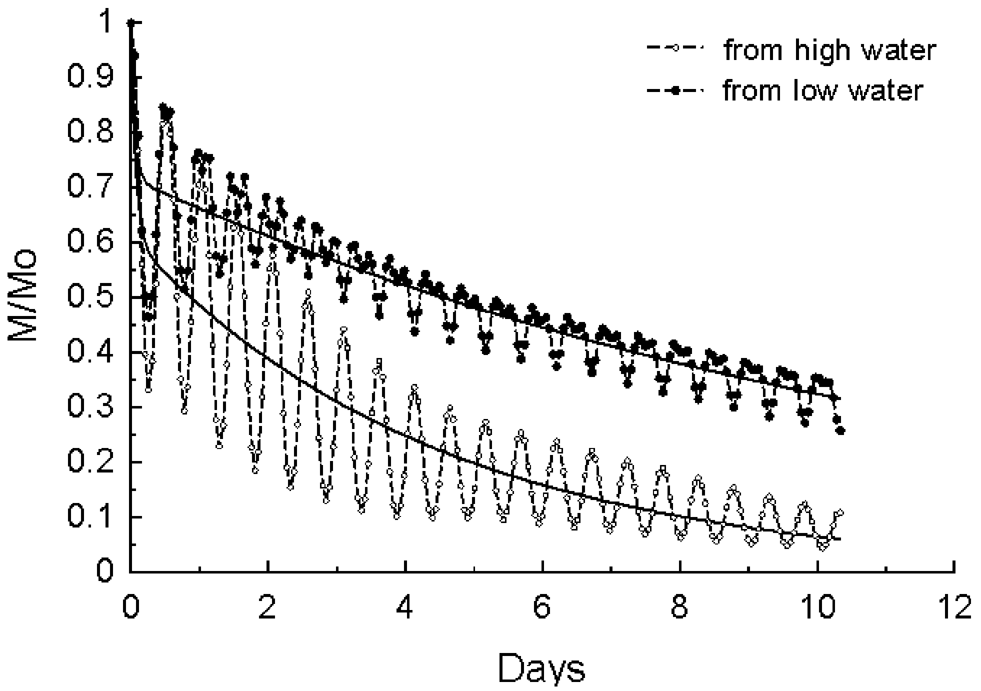

Fig. 5a. Variation of tracer mass in fish farm for wet season.

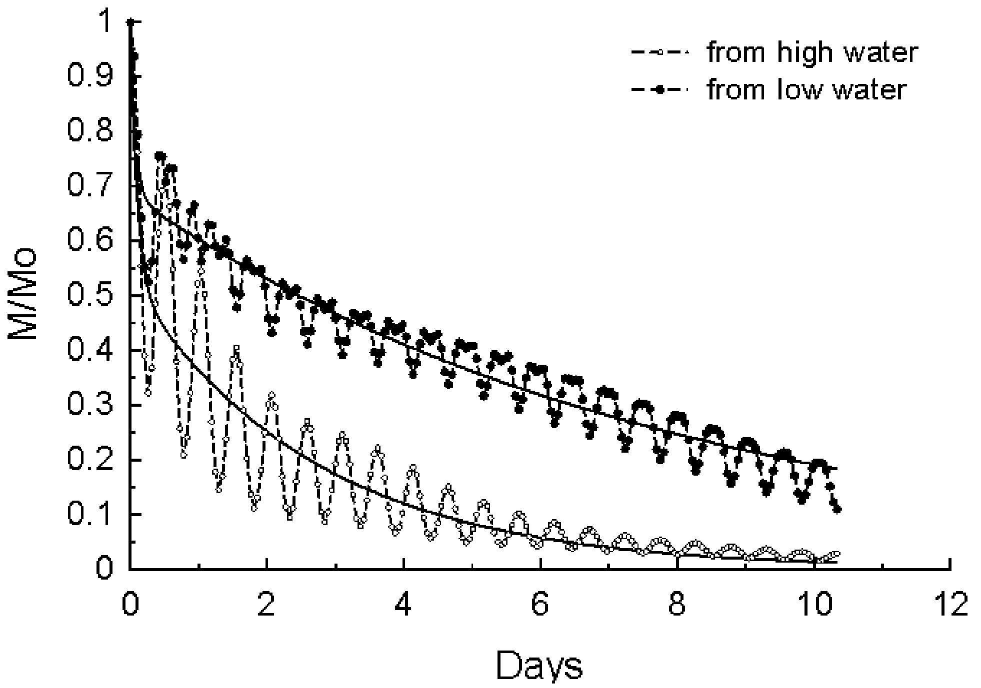

Fig. 5b. Variation of tracer mass in fish farm for dry season

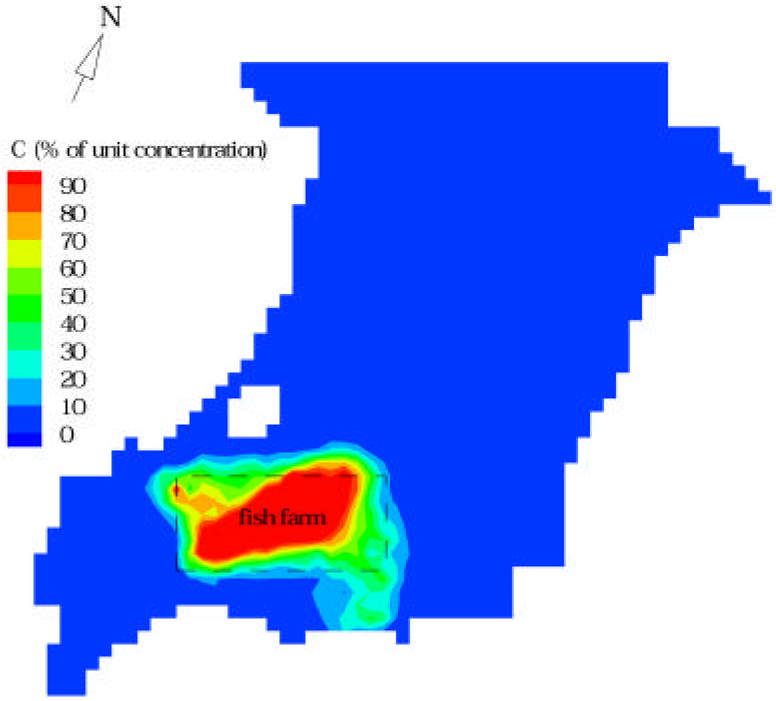

Fig. 6a. Predicted tracer concentration at t = 1 T for releasing at high water

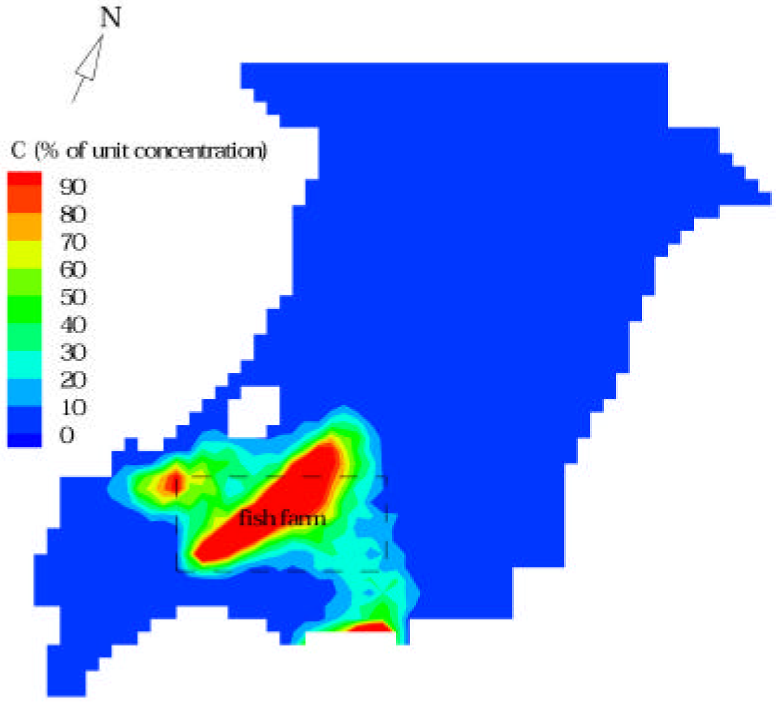

Fig. 6b. Predicted tracer concentration at t = 2 T for releasing at high water