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Ecosystem-based management and models in sustainable management of coastal aquaculture

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Abstract To be successful, the complex process of ecosystem-based management requires management tools that can integrate physical, chemical and biological processes, modeling tool must function at multiple scales, be easily understood by non-scientist and above all reliably predict management alternatives. It must address specific questions about bays, lagoons or coastal oceans without the ability to predict the cumulative consequences to large marine ecosystems.

This presentation discusses the concept of ecosystem modeling and focuses on two examples representing small and medium scale semi-enclosed marine ecosystems using a modified coastal ocean circulation model (Blumberg and Mellor 1987). Xincun Lagoon in southeast Hainan Island is a 21.97km^2 (～ 6km X ～ 4km) lagoon with a maximum depth of 10.6m and a 120m-wide outlet to the South China Sea. Xincun City, a major fishing port of ～15,000 people, is on one shore of the lagoon and the other shore is a wildlife reserve. The adjacent lagoon experienced a dramatic growth up to 230ha of fish pen aquaculture in 1996 followed by a catastrophic decline. The natural circulation in the lagoon combined with increased oxygen demand that was created by the fish pens was the likely reason for the disaster. Reducing the number of fish pens (33ha) and the advent of a pearl and macroalgae culture resulted in a more sustainable aquaculture industry and environment. Data indicated that the surface water quality did not violate China's National Water Quality Standards, but the pens were responsible for an estimated 5,000 tonnes of organic pollutants. Fish pens reduced bottom water and sediment quality. Low quality bottom water also flowed in and out of fish pen area with the tide because of the slow turnover time (up to 90 days). Further analysis indicated that macroalgae culture on racks and seagrasses act nutrient scrubbers and could play an important role by reducing ecosystem risk of less desirable algal blooms (Rawson, *et al.* 2002).

The medium scale modeling experiment was conducted on Jiaozhou Bay that is a shallow bay of ～ 400km^2 with an average depth of 7m and maximum of 50m. The adjacent city is Qingdao, which is one of China's largest ports and has a population > 2 million people. During the period of this study the bay cotained three areas of scallop aquaculture pens. Simulation experiments with two-pen stocking densities (12 individual m^{-3} and 24 individuals m^{-3}) indicated that scallops dramatically decreased the concentration of phytoplankton in the culture areas. However, the impact that scallop culture had on nutrient concentrations was small (Chen, *et. al* 1999).

A new management model system has been developed with funding from the Georgia Sea

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Grant Program based on the unstructured grid, finite-volume coastal ocean model (Chen *et al.*, 2003). This system provides a powerful management tool that allows aquaculture to be integrated into the broader context of coastal and large marine ecosystem management. Fed aquaculture does create pollution, but aquaculture is rarely the only pollution source. We must address the issue of aquaculture's contribution to pollution and find practical solutions to these complex problems.

Introduction

For ecosystem-based management to be successful, there must be management tools that integrate the physical, chemical and biological processes. Until recently managers relied on broad science-based regulations and personal knowledge and experience to make judgments about the ecosystem impacts of particular human activities on natural systems. It was the only way to integrate information into an ecosystem approach to management. This, however, leaves managers vulnerable to criticism by political leaders and the broader public community who may not agree with their decisions. Managers need the credibility of a scientific tool that integrates the knowledge of ecosystem processes and the impacts of human activities to guide and to verify their decisions. The output of this scientific tool must be easily grasped by non-scientists and above all it must reliably predict the impacts. The tool also must function at multiple scales. It must address specific questions about bays, lagoons or coastal oceans without losing the ability to predict the cumulative consequences of numerous small and medium scale activities on large marine ecosystems.

New modeling technologies provide powerful management tools that allow us to integrate aquaculture into the broader context of coastal and large marine ecosystem management. Aquaculture cannot be managed outside the context of integrated coastal management. Aquaculture is only one of numerous human activities that add nutrients, organic matter and other pollutants, including some types of aquaculture (fish pens). The aquaculture industry cannot escape the fact that it creates pollution, but it is rarely the only pollution source. The issue of aquaculture's contribution to pollution should be addressed forthrightly and practical solutions developed that integrate carrying capacity into the broader concept of ecosystem management.

Polyculture is one approach to reducing impacts of aquaculture and potentially increasing the carrying capacity of a body of water. Polyculture can utilize both fed and extractive aquaculture to increase the total productivity. Extractive aquaculture, particularly macroalgae and molluscan shellfish, can help reduce nutrients and sequester other pollutants (Yarish, *et al.* 2004).

This presentation will discuss the concept of ecosystem modeling using a modified coastal ocean circulation model (Blumberg and Mellor 1987) and focus on two examples representing small and medium scale semi-enclosed marine ecosystems - Xincun Lagoon, Hainan Province and Jiaozhou Bay, Shandong Province, P. R. China.

Xincun Bay Example

a. Physical Description

Xincun Lagoon in southeast Hainan Island is a 21.97km^2 (~ 6km X ~ 4km) gourd-shaped lagoon with a maximum depth of 10.6m and 120m wide outlet to the South China Sea. Xincun City, a major fishing port of ~ 15,000 people is on one shore of lagoon and the other shore is a wildlife reserve (Figure 1). Aquaculture in the lagoon experienced a dramatic growth in the 1990s, primarily in fish pens. By 1995, fish pens covered 200ha and by 1996 there were up to 230ha of fish pens over much of the central and outlet region of the lagoon. The fish cages used in Xincun Bay are 3m×3m, and are submerged to a depth of 1 to 4m. The shrimp culture industry also thrived and reached a maximum of 100ha ponds in upper reaches of the lagoon. The shrimp ponds were not in the lagoon but their effluent was discharged into it resulting in greater eutrophication. In the 1996,

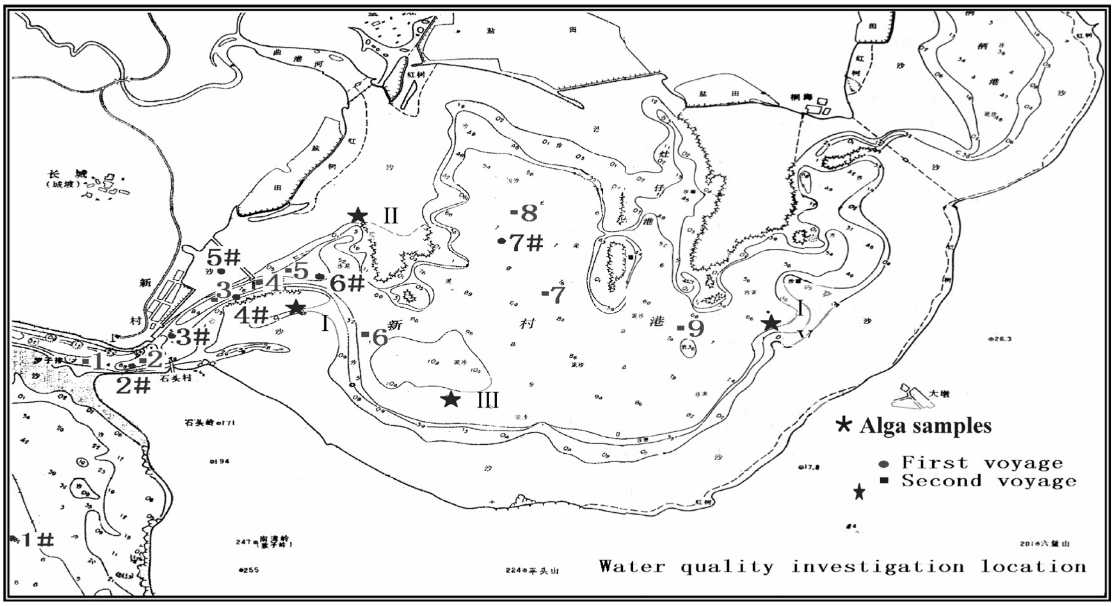


Fig. 1. Map of Xincun Bay with sampling locations

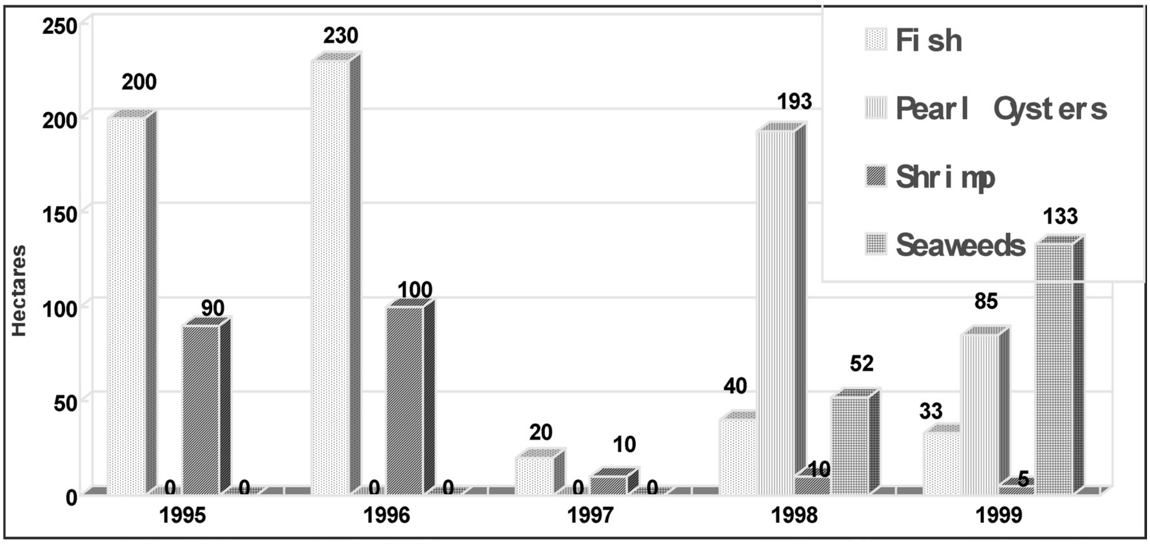


Fig. 2. Histogram of aquaculture area in 90's of Xincun Bay

catastrophic eutrophication of the lagoon occurred and the water quality declined dramatically, The resulting fish kills caused great economic loss and the aquaculture industry collapsed. During 1996, fish pen aquaculture in the lagoon was less than 10% of the coverage at its peak. An area of 20ha near the mouth of the lagoon. In 1998 the industry diversified and added pearl oysters (193ha) and seaweeds (52ha). Knowingly or not, the industry has created a lagoon-wide polyculture system. Pearl oyster culture apparently was not as successful and the coverage was reduced to 85ha. Seaweeds (macroalgae) on the other hand increased by >150% and reach 133ha in 1999 (Figure 2).

As part of the Sino-US Marine Resources Panel cooperative program, two field studies of the lagoon were conducted from July 31 to August 6, 2000. Standard parameters measured included temperature, salinity, COD, DO, DO% saturation, Ph, current speed and direction, turbidity, and tidal level. Primary productivity, nutrients and bacteria communities also were measured. The study results and existing data from earlier sampling was used to create a hydrodynamic model of the lagoon at

The University of Georgia by visiting scientists from the Hainan Marine Development, Planning and Design Research Institute. (Unless otherwise stated references for Xincun Lagoon are excerpted from Rawson *et al.* 2002.)

Analysis of water level data showed that the lagoon has an irregular diurnal tide with a relatively small average range of 69cm with a maximum of 1.55m, which resulted in a slow tidal current velocity. There was a large range in surface velocity, from 2cm s^{-1} to 155cm s^{-1}. The highest surface velocity was at Station 1 in the 120 m-wide-mouth during the spring ebb tide period. During neap tide, the maximum velocity was only 65cm s^{-1}. In the middle of the lagoon, the velocity declined to an average of 10cm s^{-1}. The estimated water flux of 6×10^7 m^3, occurred at spring tide cycle, is one-thirteenth of the lagoon's volume. This might lead one to believe that the lagoon exchanges in ~two weeks, but an earlier study indicated an exchange rate of 90-days. This slow exchange rate means that there is a low capacity to transport pollutants out of the lagoon's ecosystem. The pollutant sources, particular the fish pens, contribute high levels of organic material from the residual ground fish feed, fish respiration and fecal wastes. An estimated 5,000 tonnes per year in organic waste were contributed from the fish pens, compared to an estimated 500 tonnes from Xincun City.

b. Water Quality and Sediment Assessment

Water quality and sediment survey results are shown in Table 1 and Table 2 respectively. Data and times from 14 stations were collected during four cruises on September 10, 1998 and June 28, July 31, and August 7, 2000. The dissolved oxygen concentration was 2% lower than the Class Ⅱ water quality standard, while other water quality parameters were normal (*GB-99*, National water quality standard, P.R. China, 2000). Low dissolved

Table 1. Water Quality Data

Parameter	Max.	Min.	Ave.
Temperature (℃)	30.9	23.6	28.9
Salinity (o/oo)	32.77	28.61	31.78
DO(mg/l^{-1})	6.67	3.92	5.12
DO saturation(%)	97	61.0	87
pH	8.35	8.13	8.26
PO^-_4 ($\mu g\ l^{-1}$)	3.20	1.60	3.72
NO_2 ($\mu g\ l^{-1}$)	1.12	0.14	0.74
NO_3 ($\mu g\ l^{-1}$)	34.3	4.20	10.4
NH_4 ($\mu g l^{-1}$)	165.2	0.56	28.7
Inorganic N ($\mu g 1^{-1}$)	176.4	4.9	41.0
Silicate ($\mu g\ 1^{-1}$)	865.2	77.8	278.3
COD(mg l^{-1})	1.02	0.28	0.57
Suspended Solids(mg l^{-1})	5.5	0.2	1.84
Bacteria ($\mu g 1^{-1}$)	140	0.10	17.4
Chl–a($\mu g\ l^{-1}$)	1.92	0.49	1.24

Table 2. Sediment characteristics at four sampling stations.

St. Num	Sediment Type	Color	Smell	Silicate (mg/kg)	O-Carbon (%)	Organic matter (%)
1	Silt Sand	Black	Rotten	348.04	4.5	7.8
2	Sand	Gray	Non	330.02	0.3	0.5
3	Silt	Gray black	Non	454.53	1.6	2.8
4	Silt	Gray black	Rotten	326.99	0.7	1.2

Note : Cl_{II} The Marine fishery water quality Standard of P. R.China.

oxygen concentration can be the result of the sediment oxygen demand and biological activity in the water column. The sulfate and the organic matter are largely in the sediment. Large organic particles settling in sediment cause a serious water quality problem. Decay processes in the sediment cause a high demand for oxygen from the overlying water column. This demand may excessively stress the oxygen resources of overlying water and deplete the dissolved oxygen concentration. Sediment oxygen demand and the biological decomposition in the water column likely are the major reasons for low dissolved oxygen concentrations in the Xincun Lagoon ecosystem.

Dissolved oxygen concentrations were normal outside the lagoon and in the inner lagoon regions. In the navigational channel region, dissolved oxygen concentrations were low at greater depths. This is the region where fish cage culture is concentrated. The vertical distribution of DO is particularly important in determining the extent to which an area is polluted. The vertical characteristics of DO at different stations located from the outside bay (station 1) to the middle bay (station 7) during the neap tide period as shown in Figure 3. DO is lower than 6mg/L at stations 2 to 6 in all layers. At area stations 2, 4, 5, and 6, the DO is less than 5mg/L, and the average value is only 4.8mg/L. Vertically, DO declines sharply and reaches a minimum 2 to 3 m under the surface in the fish cage culture region. On the other hand, vertical DO distribution is different at station 1 outside the bay; it becomes larger from surface to depth. DO at the surface is 5.04mg/L, very similar to that in stations 2 to 6. At station 1 DO is 6mg/L at depths of 2m. We speculate that this phenomena is the result of the surface water out-flow from the bay. At station 7, where there are no fish cages, water quality is better. DO is 6mg/L at surface, but at depths >3m; the DO value is below 5mg/L (Figure 4).

Nitrate concentrations exhibit a peak of about 5.97 μg/L within the channel region near the cage fish culture, where organic matter falls to the bottom. In both outside lagoon and inner lagoon regions, the nitrate concentration is fairly low with a value of 0.83 to 0.70μg/L (Figure 4). The nitrate concentration in the inner lagoon is the result of nitrate uptake by the seagrass and it remains generally low.

Ammonium concentrations have a similar distribution to nitrates in the water column. It decreases linearly from the cage fish culture region to an area outside the lagoon. Ammonium concentrations exhibit a peak of about 14.22μg/L in station 6# in the cage fish culture region, and reduce sharply to 0.09μg/L in the inner bay where seagrass. beds are dominant (Figure 4).

The phosphorus concentration is commonly lower than nitrate and ammonium concentration in the water column. Phosphorus concentrations are below 0.5μg/L in six of the seven stations. The maximal phosphorus concentration reaches 1.27μg/L at station 5# in the fish cage region (Figure 4).

The spatial and temporal distributions of nutrients reflected the dissolved oxygen distribution in the

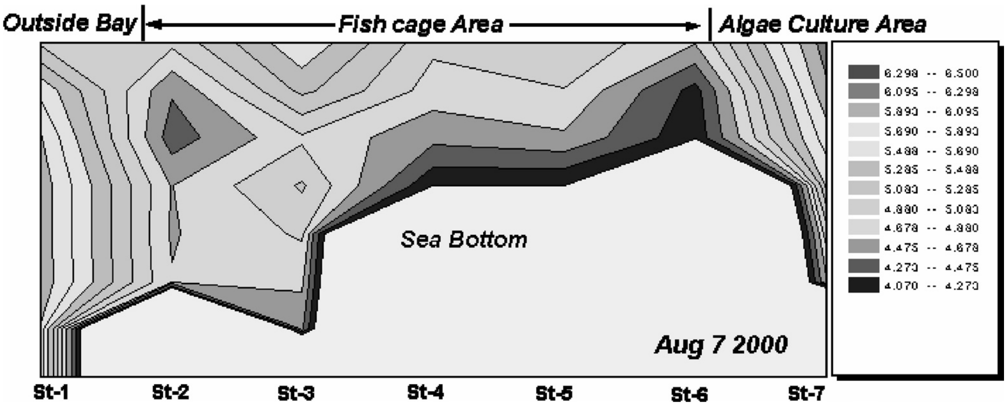


Fig. 3. Dissolved oxygen saturation and salinity in Xincun Bay

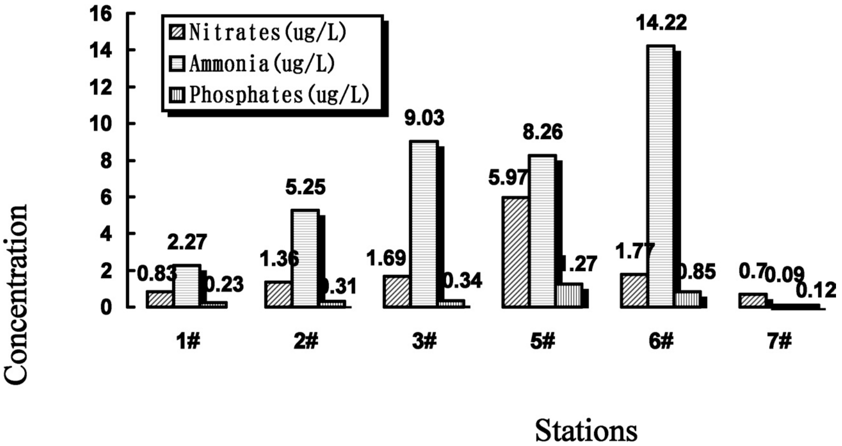


Fig. 4. Nutrient distributions in Xincun Bay.

water column. Within the fish cage area, substantial quantities of organic matter accumulate in the sediment. Sediment oxygen consumption increases as a result of chemical oxidation, activity of benthic organisms, and bacterial decomposition of organic matter. Oxygen in the water column above the sediments can then become depleted, leading to anoxic conditions. When oxygen above the sediments is depleted, nitrogen and phosphorus are released to the water column more readily. Phosphorus is released under anoxic, reducing conditions, whereas it normally complexes with oxidized iron and becomes immobilized. Previous research has examined these relationships between nutrients, dissolved oxygen and sediment oxygen consumption in aquatic systems (Stumm 1973, Frevert. 1980, Nixon 1982).

c. Model Results

A three dimensional conventional water quality analysis simulation model that was originally developed by Ambrose *et al.* in 1993 (known as WASP5) was modified and used to study the dissolved oxygen in Xincun lagoon. The equations solved by WASP5 are based upon the key principle of conservation of mass. They include three major components, the advection and dispersion of transport, kinetic interaction and transformation, and external loading. WASP5 eutrophication water quality model considered eight water quality state variables- DO, PHYT, CBOD, NH_3, NO_3, ON, OPO_4 and OP and used the kinetic framework developed by DiToro *et al.* (1971). In our water quality model, we only consider DO, NH_3, NO_3 and their major kinetic interaction. This is based on evidence that low DO is the major problem of eutrophication, and the nitrate and ammonium concentration are relatively large within the fish cages region in Xincun lagoon.

The two major components of the hypolimnetic oxygen depletion are water column oxygen demand (WOD) and sediment oxygen demand (SOD). WOD embraces the biological and chemical oxygen demand primarily due to algal, bacterial and fish respiration. SOD reflects utilization of dissolved oxygen from overlying and interstitial water of the sediment by biological and chemical oxygen demands. As discussed above, DO which acts as an eutrophication indicator is predominantly low within the fish cage culture region, where much of the organic matter deposits to the sediment. Low chlorophyll *a*, low primarily productivity, even low nutrients in water column, but large quantities of organic matter in sediment, SOD is the major reason for depletion of DO rather than WOD. For this reason, we mainly consider SOD as a important sink of dissolved oxygen in our water quality model. Macroalgal and seagrass photosynthesis and respiration are also considered in this model due to the fact that they remove the nutrients from the water column. Thus, the DO kinetic interaction and transformation includes processes of reaeration, macroalgal (*Kappaphycus alvarezii*) and seagrass (*Enhalus acoroides*) photosynthesis and respiration, cage fish respiration, nitrification and SOD.

Factors that affect SOD are rather complex. These factors include temperature, oxygen concentration, makeup of the biological community, organic and physical characteristics of sediment, current velocity, and chemistry of the interface. Velocity effects on SOD were not due to physical resuspension of bottom material to the overlying water. It was hypothesized that the increase in turbulence generated by increased velocity was responsible for increased transport of soluble organic material across the sediment interface, resulting in high SOD. Measurements of SOD showed that it changes in spatial and temporal variation due to different situations (Hickey 1984, Whittemore 1984).

Within aquatic systems sediment nutrient fluxes play an important role on the nutrient concentration in the water column. Studies indicate that nitrogen and phosphorus may be released to the water column more readily when oxygen above the sediments is depleted (Smith and Fisher 1986). Within the large SOD region, sediments were the dominant sources of ammonium and phosphorus (Boynton and Kemp 1985; Fisher *et al.* 1982). The processes of nutrient fluxes of sediment are complex and it is necessary to calibrate by the in-situ measurement. In our model, we simply consider nutrient fluxes of sediment as the linear relationship with SOD and bottom velocity. The ammonium fluxes and nitrate fluxes ranged between 60 and 600umol/m^2/hour and 3 and 39umol/m^2/hour in the Xincun water quality model.

The water quality model is coupled with the physical model developed by Blumberg and Mellor (1987). The physical model runs prognostic problems with tidal and wind driven oscillations and rainfall water discharge. When the physical model reaches equilibrium state, the water quality parameters are added and run with the cases of (1) a 450 fish cage platforms at the channel region, without the effect of macroalgal culture; (2) double the fish cages, without the effect of macroalgal culture; and (3) double the fish cages and factor in the macroalgal culture.

The model was initialized using the temperature and salinity field on 28 July. The model demonstrates that the temperature and the salinity remain stratified in Xincun lagoon. Tidal cycle average surface temperature and salinity inside the lagoon is uniform with a magnitude of 30.8℃ and 31.8 ppt. Temperature is lower and salinity is high in the deepest part of the lagoon. Outside of the entrance of the lagoon, a strong gradient of temperature and salinity is demonstrated by the effect of flood and ebb tidal current.

A uniform DO, NH_4, NO_3 field is initialized after the temperature and salinity field is adjusted. Figure 5 shows the spatial and temporal distribution of DO concentration in cases (1) and (2). The distribution of DO is closely related to the tide, during flood tide (upper Figure 5), the minimum DO concentration center occurs not in the channel cage fish culture region but in the inner Bay. During ebb tide, the minimum DO occurs in the outside lagoon near the entrance. The lowest DO concentration occurs in the cage fish culture region only during the middle flood-ebb tide. In cases (1) and (2), the lowest DO concentration is 5.0mg/L and 4.5mg/L, respectively. The experiments demonstrate that the tidal average DO concentration reduces 10% when the fish cages are doubled. It seems that the effect of cage fish in the model is not sensitive to the DO concentration. The response of this process indicates that strong tidal currents in the channel region enhance mixing with outside bay water and increases DO concentration.

The DO concentration distribution in selected area 1 had a stratified structure with the lowest DO over the sediments in the channel region. Large SOD in the fish cage region consumes dissolved oxygen and leads to the DO concentration depletion.

When macroalgal culture is considered in sites Area 2 and site Area 3 that are further in the lagoon, macroalgae seem to not enhance the DO concentration in fish cage region and, obviously, in the macroalgal culture regions. The change of DO concentration in selected points of the bay, fish cage region and inner bay. Co-incides with the tidal elevation (tidal current). In the fish cage region, lowest DO concentration occurs before lowest tidal with a magnitude of 4.2mg/L at the bottom; highest DO concentration occurs at the beginning of flood with a magnitude of 5.5mg/L. But in the open part of the lagoon where macroalgae are cultured, the

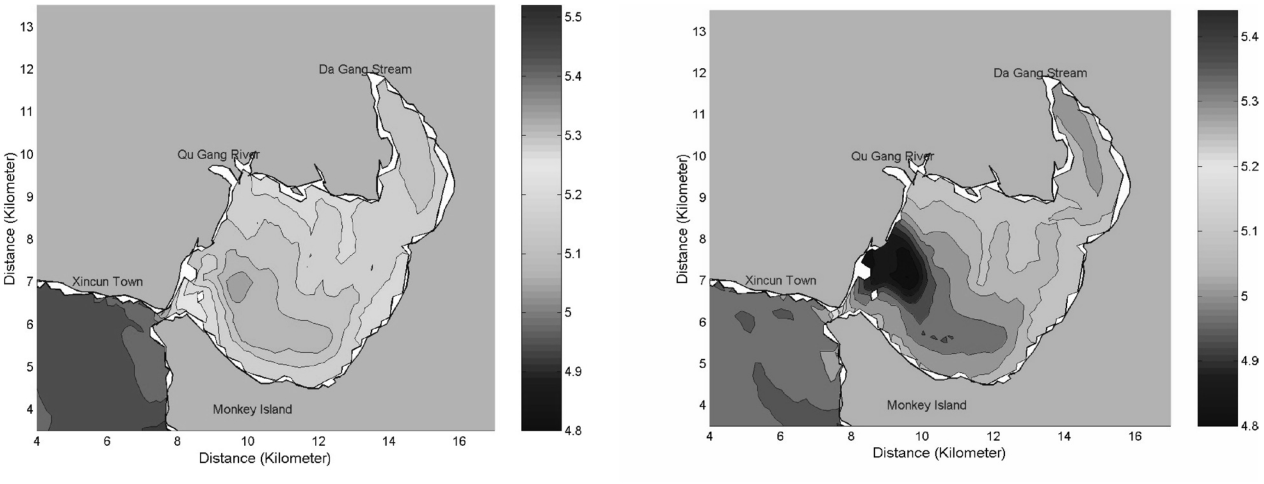
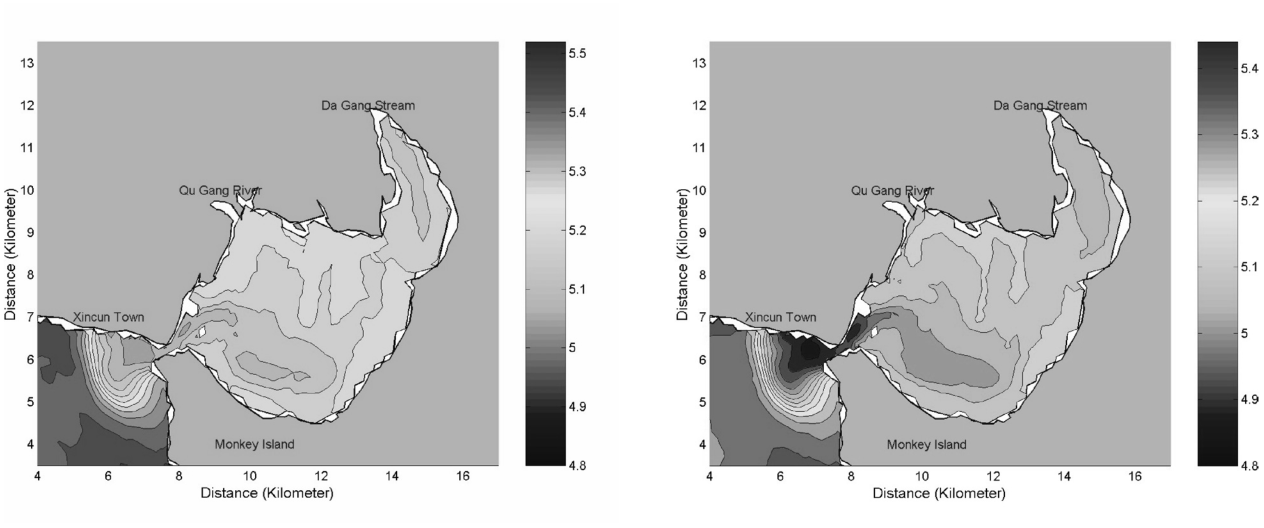


Figure 5



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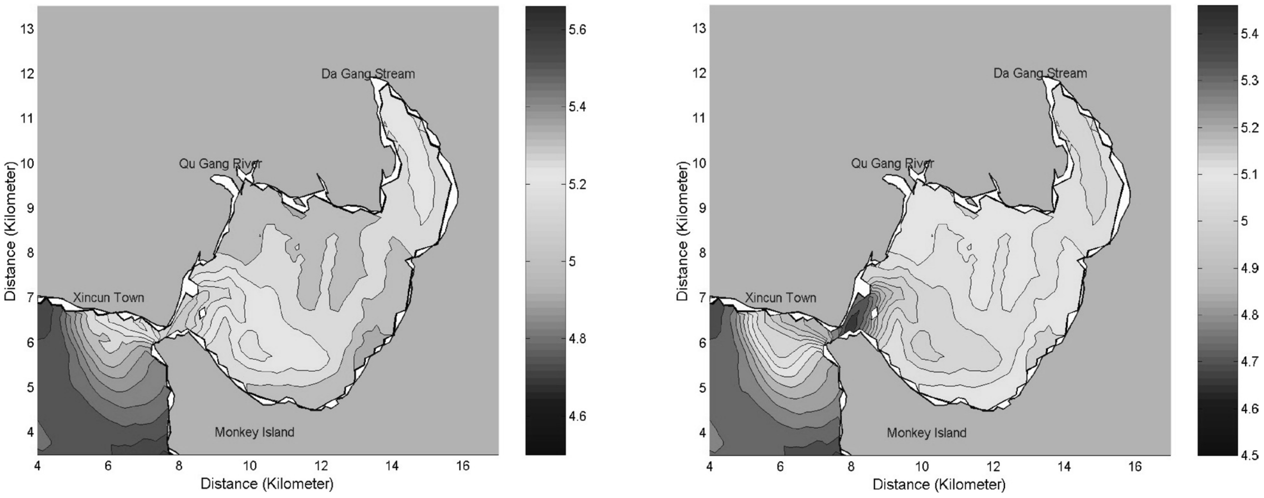

Fig. 5. DO concentration distribution during the flood tide (upper pair), ebb tide (middle pair), flood-ebb tide (lower pair) under existing conditions (left) and with a 50% increase of fish cages (right) in Xincun Bay.

surface DO concentration seems unchanged, and the bottom DO concentration reaches a lowest value of 4.8mg/L.

d. Follow up sampling on Xincun Lagoon

Since the 2000 study, the aquaculture mix in and around the lagoon has changed. The number of 3m X 3m fish cages increased substantially in 2001 to 6,500 cages (87ha) then decreased to steadily to 5,200 (70ha) (Table 3). (Fish pen platforms usually have nine cages).). The macroalgae *Kappaphycus alvareezii* culture increased during the 2001 to 2004 period from 146ha to 233ha and the shrimp ponds adjacent to the lagoon are 200ha. The Hainan Marine Development, Planning and Design Research Institute continues to monitor the lagoon. The most obvious change is the continued increase in the average ammonia levels in the lagoon from 28.7μ

Table 3. Area of culture species (hectare)

Year	Fish cane Culture (Ind./hectare)	Eucheuma Macroagale	Shrimp pool
2001	6500/87	146	200
2002	6400/85	200	200
2003	6200/80	213	200
2004	5200/70	233	200

Personal communication: Wang DaoRu, Hainan Marine Development Planning Design Research Institute, Hainan, P.R. China

Table 4. Water quality monitoring results in 2003

Content	Min.	Max.	Ave.	Water quality standards (P.RChina)	
				Class I	Class II
Salinity	32.645	33.655	33.286		
Ph	8.24	8.29	8.27	7.8-8.5	
Do	5.31	6.73	6.09	>6	>5
COD	0.27	0.73	0.47	<=2	<=3
NO3(μg/l)	12.041	17.501	14.561		
NO2(μg/l)	0.420	1.680	1.092		
NH(μg/l)	11.481	47.746	29.262		
IN(μg/l)	0.026	0.066	0.045	<=0.20	<=0.30
IP(μg/l)	0.002	0.014	0.008	<=0.015	<=0.03
Chl--a (μg/ l)	0.02	0.1	0.05		

Table 5. Water quality monitoring results in 2004

Content	Min	Max	Ave.	Water quality standards (P.R China)	
				Class I	Class II
Salinity	32.645	33.655	33.286		
Ph	8.15	8.29	8.27	7.8-8.5	
Do	5.68	6.46	6.1	>6	>5
COD	0.62	0.99	0.81	<=2	<=3
NO3(μg/l)	12.041	17.501	14.561		
NO2(μg/l)	0.420	1.680	1.092		
NH(μg/l)	26.481	67.746	49.262		
Chl--a (μg/ l)	0.35	0.71	0.5		

Rawson, Mac C. Chen, R. Ji, M.Zhu, D. Wang, L. Wang, C. Yarish, J. Sullivan, T. Chopin and R. Carmon, 2002 Understanding the Interaction of Extractive and Fed Aquaculture Using Ecosystem Modelling, in: Responsible Marine Aquaculture, R. Stickney and J.P. Mcvey, eds. CABI publishing, Oxford UK.

g/l in 2000 to 49.3 μg/l in 2004 (Tables 4 & 5) The model simulations pointed out that the water column in the fish cage area was heavily polluted by organic matter. The resulting low DO was an indication that carrying capacity has been exceeded and the impact of the fish culture must be reduced. Since the study took place four years ago, the fish cages and shrimp ponds numbers have been limited and the number of cages reduced. Also, the ecological importance of the seagrass has been recognized and a new seasgrass special protected zone set up (Wang DaoRu, personal communications).

e. Discussion of Xincun Lagoon Results

The results showed that the water column in the Xincun Lagoon aquaculture region was heavily polluted by organic material and according to sediment sample analysis, was also high in silicate contents. Except for dissolved oxygen, sampled chemical parameters and nutrients did not exceed the national water quality standards Class Ⅰ. The data were also evaluated according to Criteria for Surface Water Quality Classifications, Class Ⅱ (Florida EPA). Although the water generally met standards, the environmental health of the fish cage culture and navigation channel region has declined considerably as evidenced by the mortality of cultured fish and low DO.

Two kinds of pollutants affect water quality and sediment quality in Xincun Lagoon. One source is the pollutant produced by four factories, four restaurants and seven gasoline stations, and an estimated 481tons of COD from the sewage discharging. The other pollutant is a by-product of fish cage operations that results in an estimated 5,000tons of organic pollutants annually. Water quality samples indicate that DO is always lower than the value of national water quality standards in fish culture areas. The assessment results show the main source of pollution is the fish cages. When feeding fish, large amounts of uneaten food and feces descend to the bottom. Sediment under the pens releases NH_3H_2S and other pollutants by degradation of the organic matter by bacteria. This chemical reaction requires large quantities of oxygen and reduces the dissolved oxygen substantially in the sediment and water column. Results of DO concentration-modeling support the above viewpoint. The model experiments also show that average DO concentration will decrease by about 10% when fish cages are doubled. This result shows the effect of strong tidal current mixing and transport. Macroalgal culture increases the DO concentration in the culture region, but contributes less to the DO concentration in the cage fish region

Ⅳ. Jiaozhou Bay Example

a. Physical Description

Jiaozhou Bay is a shallow bay of ~ 400 km^2 with an average depth of m and maximum of 50m. The adjacent city is Qingdao, which is one of top five ports in China and has a population >2 million people. During the period of this study the bay contain three areas of scallop aquaculture pens (Chen, *et al.* 1999).

b. The Model

The physical model used in this study was a modified version of the coastal ocean circulation model developed by Blumberg and Mellor (1987). The model's forcing functions are: (1) tidal oscillations, (2) wind driven features, and (3) time-variable inputs of rivers. The time-variable river inputs and onshore intake/outflow discharges were used to simulate the buoyancy flow caused by river discharges. By far, the largest river discharge (85%) into Jiaozhou Bay during summer was from the Dagu River ($87m^3\ s^{-1}$, Liu and Wang, 1992). The effects of wind-induced currents and resulting mixing influences on the distribution of temperature, salinity, nutrients, and phytoplankton were examined in the simulations. The dominant wind forcing in the summer is from strong southeast winds, but for simplification, a constant southeasterly wind of 5m s^{-1} was added into the model after 10 model days.

The coupled biological model simulates simple nutrients (N), phytoplankton (P), and zooplankton (Z) using a modified model developed by Franks and Chen (1986). The biological parameters varied widely in time and space. The model was run with an initial set of parameters. Sensitivity analyses were then run over the parameter range. The stock density of shellfish was calculated directly from measurements taken in Jiaozhou Bay in 1996 (Collaudin, 1996). The scallop rafts consist of vertical lines of lantern nets. Based on the average number per lantern net, the standing stock parameter was set at 12 individuals m^{-3} that is the equivalent to 0.012 individuals L^{-1}. The scallop filtration rate varies in a range of 30 to 200L d^{-} $individual^{-1}$ at around 25℃. This may overestimate the filtration rates since the food availability was not taken into account (Winter, 1978). So, a filtration rate of 100L d^{-1} $individual^{-1}$ was used in the model. The excretion fraction of the filtered food was assumed to be 0.3 or 30%.

Jiaozhou Bay is a phosphorus-limited ecosystem, and in the experiments, phytoplankton and zooplankton were measured in units of carbon (C) and nutrients by units of phosphorus (P). A constant C/P ratio of 100 was used to convert carbon to phosphorus. A 60C/Chl *a* ratio was used to convert chlorophyll *a* to carbon.

c. Effects of Aquaculture

Simulation experiments were made with two scallop stocking densities of 12 individuals m^{-3} (0.012 individuals L^{-1}) in the first case and 24 individuals m^{-3} in the second case. In both cases, scallops were grazing dramatically and decreased concentrations of phytoplankton in the culture areas labeled A1 to

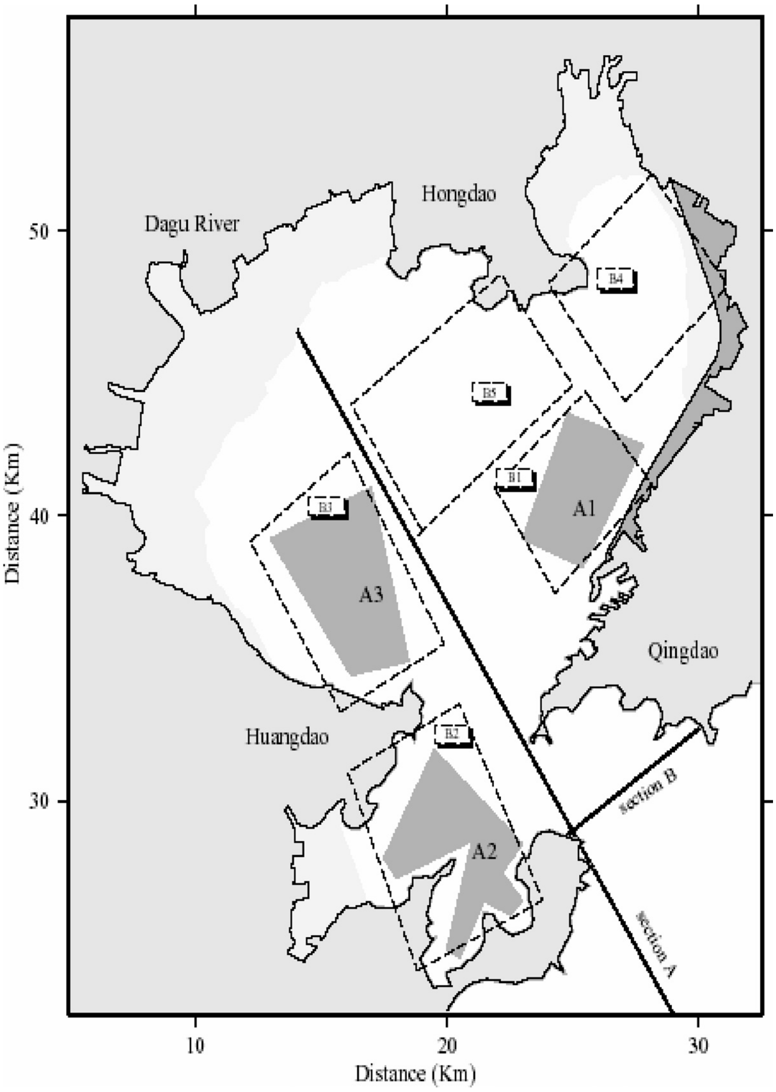

Fig. 6. Locations of the shellfish aquaculture sites (shaded area) and selected regions for the flux estimation of nutrient and phytoplankton (areas enclosed by dashed line). (The heavy solid lines indicate two sections used to represent our model results on cross-bay section (section A) and flux calculation into of out of the Bay (section B).

A3 (Figure 6, Chen *et al.*, 1999). The experiments suggested that the scallops would sharply reduce the concentration of phytoplankton to 0.99 μg Chl *a* L^{-1} in A1, 0.52 μg Chl *a* L^{-1} in A2, and 1.0 μg Chl *a* L^{-1} in A3, about 31.8%, 33.3% and 37.3% lower than those in the case without shellfish (Plate 2, Chen *et al.*, 1999). The response of phytoplankton to increased shellfish stocking densities was not linear. When the stocking density was doubled to 24 individuals m^{-3} the concentrations decreased to 0.71 μg Chl *a* L^{-1} in A1, 0.38 μg Chl *a* L^{-1} in A2, and 0.67 μg Chl *a* L^{-1} in A3. These concentrations were ~51.1%, 50.8% and 55.6% lower than the case without shellfish, but only 19%, 18% and 22% lower than the first case with shellfish (Figure 7, Chen *et al.*, 1999).

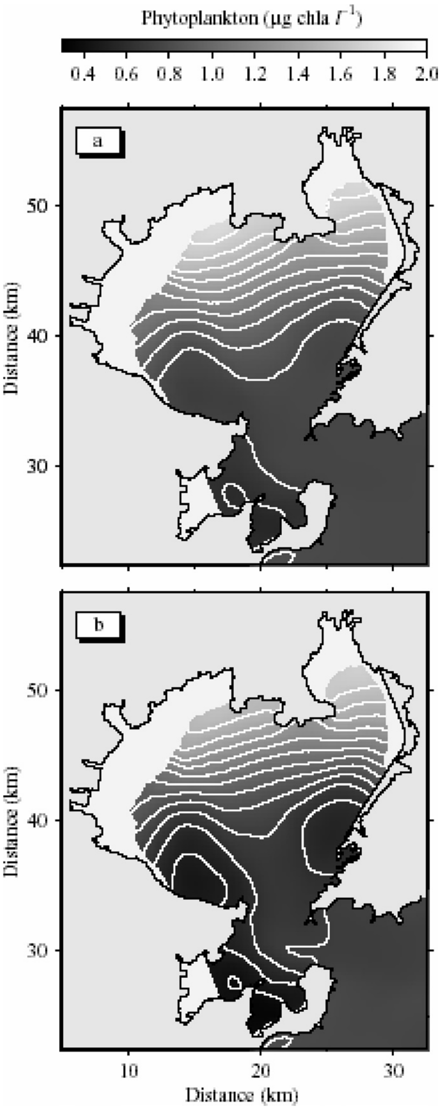

Fig. 7. Tidal-cycle averaged surface distribution of phytoplankton at the 20 model days for the case with the shellfish culture densities of (a) 12 and (b) 24 individuals m^{-3}. Physical forcings are tide, freshwater discharge and a southeasterly wind (5 ms^{-1}).

The impact of scallop culture on the concentration of nutrients was very small, even at the higher stocking density. This is in contrast to previous studies which indicated that shellfish have an important role in nutrient cycling and distribution (Dame, 1993). One explanation is that Chen's model did not consider the impact of the biodeposition process of shellfish. The biodeposition process could result in shellfish taking up small particulate organic matter and producing feces and pseudo-feces that decompose into inorganic nutrients. Our model did include shellfish excretion, which was directly converted to phosphates. If the above explanation is correct, there should be significant modification of nutrient concentrations when the excretion rate or stocking density is increased. However, that was not the case in simulation experiments. Another possible explanation is that most of the phosphates in Jiaozhou Bay were the result of loading from the land and rivers. The recycling of nutrients by shellfish may directly influence the concentration of nitrogen but not phosphates, or the nutrient regeneration rate may be orders of magnitude smaller than the nutrient loading rate from other sources.

d. Nutrient Uptake and Regeneration

To understand the roles of biological processes, the nutrient uptake and regeneration processes in the coupled model must be examined. Nutrient uptake in this modified NPZ model was controlled by the phytoplankton growth rate, incident radiance, the half-saturation constant, phytoplankton biomass and nutrient concentration. Nutrient regeneration was estimated by the sum of zooplankton excretion, death of phytoplankton and zooplankton, and shellfish excretion.

In the case with only tides and freshwater discharges, the model indicated that surface distributions of the uptake and regeneration rates were similar to nutrient distribution, which decreased from the inner to outer bay with the highest values on the northwestern and northern coasts. The maximum regeneration rate in the inner bay was ~2 μmol C L^{-1} d^{-1}, which was ~5 times smaller than the maximum uptake rate. This suggests that the physical process associated with river discharge was a major source of nutrients for phytoplankton in the inner bay. Adding a southerly wind did not significantly change the distributions of nutrient uptake or regeneration. The uptake rate was relatively large in the inner bay along the coast as a result of nutrient accumulation by the wind-induced northwestward advection. This phenomenon may explain why a phytoplankton bloom occurs in the innermost bay during a southeasterly wind.

When consumption of phytoplankton by shellfish was included, distribution of nutrient uptake and regeneration was modified, particularly in the aquaculture areas. Nutrient uptake rates in the aquaculture sites dramatically decreased because the phytoplankton decreased. Yet, the nutrient regeneration rate in these sites increased as a result of shellfish metabolism. As a result, the distribution of phosphates was similar in the case with and without shellfish aquaculture, suggesting that the decrease in nutrient uptake rates due to phytoplankton consumption was almost compensated for by the physical processes of advection and diffusion.

One of the main interests in this study was to identify, qualify and quantify the roles of physical and biological processes in maintaining ecosystem health. In the simple NPZ food web, the physical processes included advection and diffusion, M_2 tide, river discharge and wind. Biological processes related to phytoplankton included nutrient uptake and regeneration, phytoplankton grazing and mortality, and shellfish consumption. To examine effects of freshwater discharge and shellfish aquaculture, the net flux of nutrients and phytoplankton in five closed regions and across the outer strait were estimated. The flux was calculated based on tidally averaged values over the 10 tidal cycles. When we say "equilibrium state," that means the flux is balanced for a first-order approximation in which the biological field changes slowly but no steady state could be reached over the course of the study period. Sensitivity analysis of the phytoplankton revealed that the spatial distribution of phytoplankton remained unchanged, although the concentration varied remarkably with changes in parameters. This suggests that the model results for phytoplankton were robust.

The model results revealed that physical processes had a direct impact on temporal and spatial distributions of nutrients and phytoplankton as well as on shellfish aquaculture. Tidal mixing caused physical and biological variables to be well mixed vertically. The concentrations of nutrients and phytoplankton were high near the northwestern and northern coasts near river sources but decreased from the inner bay to the outer bay. The model results suggested that prevailing river discharges and tidal mixing, and the southeasterly wind in the summer may cause unusual nutrient accumulation and lead to phytoplankton blooms in the innermost bay. The fact that a phytoplankton bloom can occur under a condition of southeasterly wind implies that physical processes may have a direct impact on the occurrence of "red tide" along the northern coast of Jiaozhou Bay. The overloading of nutrients from inland shrimp aquaculture, industries and other urban human activities caused a high nutrient concentration in the inner bay that provided favorable conditions for eutrophication. Accumulation of nutrients due to the southeasterly wind speeds up the eutrophication process and causes the "red tide".

The estimation of nutrient and phytoplankton fluxes in the five identified sites suggested that the nutrients were maintained by physical processes, while the phytoplankton was controlled predominantly by biological processes. Shellfish aquaculture tended to alter the entire Jiaozhou Bay ecosystem. The loss of phytoplankton in shellfish aquaculture sites was compensated by nutrients that advected and diffused from surrounding waters. High levels of phytoplankton consumption also caused a net flux of phytoplankton into the bay from the Yellow Sea, even though nutrients were advected out of the bay. In addition to eutrophication caused by human activities, high densities of suspended feeding shellfish will alter the lower trophic food web by grazing phytoplankton, excretion and biodeposition. Aquaculture populations of bivalves tended to transfer large quantities of materials from the water column to the sediment, which can dramatically change the content of the organic matter in the benthic layer (Kautsky and Evans, 1987; Kasper *et al.*, 1985). The benthic processes, in turn, may alter nutrient cycling in the bay (Barg, 1992; Dame, 1993; Jorgensen, 1990). It also should be noted that this model did not include the intertidal zone. The direct impact of the intertidal process remains unclear, but a large quantity of nutrients potentially can be advected back to the bay during ebb tide.

Ⅲ. Conclusion

Management of aquaculture in semi-enclosed embayments is influenced by numerous physical, chemical and biological processes. Resource managers who are tasked with maintaining and improving environmental quality must balance the multiple uses of bays. Three-dimensional models provide tools that can help determine carrying capacity for aquaculture by integrating knowledge of physical, chemical and biological processes and accounting for multiple sources of pollutants. The models also will provide credibility to the decisions of managers and allow the development of sustainable aquaculture in locations throughout the world.

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