14

Understanding the Interaction of Extractive and Fed Aquaculture Using Ecosystem Modelling

Mac V. Rawson, Jr,[1] Changsheng Chen,[2] Rubao Ji,[2] Mingyuan Zhu,[3] Daoru Wang,[4] Lu Wang,[5] Charles Yarish,[6] James B. Sullivan,[2] Thierry Chopin[7] and Raquel Carmona[6]

[1]Director, Georgia Sea Grant College Program, The University of Georgia, 220 Marine Sciences Building, Athens, GA 30602–3636, USA; [2]Department of Marine Sciences, The University of Georgia, 220 Marine Sciences Building, Athens, GA 30602–3636, USA; [3]The First Institute of Oceanography, State Oceanic Administration, PO Box 98, Qingdao 266003, People's Republic of China; [4]Hainan Marine Development, Planning and Design Institute, 10th Yiyuan Building No. 69, Haifu Rd, Haikou, Hainan 570203, People's Republic of China; [5]Marine and Fishery Department of Hainan Province, Haikou, Hainan, People's Republic of China; [6]University of Connecticut, Department of Ecology and Evolutionary Biology, 1 University Place, Stamford, CT 06901–2315, USA; [7]University of New Brunswick, Centre for Coastal Studies and Aquaculture, and Centre for Environmental and Molecular Algal Research, PO Box 5050, Saint John, New Brunswick, E2L 475, Canada

---

Abstract

One of the most difficult tasks resource managers face is understanding the carrying capacity of coastal waters for aquaculture. Aquaculture, like many other human activities, can threaten coastal waters. Understanding eutrophication and the interaction of two different types of aquaculture is very important to the safe and effective management of coastal aquaculture. The first type of aquaculture, producing shrimp

©CAB *International* 2002. *Responsible Marine Aquaculture*
(eds R.R. Stickney and J.P. McVey)

and finfish, depends on supplemental feeding and can contribute to eutrophication. The second type, involving bivalve molluscs and macroalgae, extracts plankton and nutrients from surrounding waters and can have a significant positive impact on moderately eutrophic waters. These species depend on the water's basic productivity and will not grow effectively in water with low nutrient levels. Balancing extractive and fed aquaculture is of obvious importance to maximizing the safety and optimizing the carrying capacity of an embayment.

Ecosystem modelling offers a three-dimensional physical, chemical and biological simulation that can help scientists and managers understand and predict the eutrophic impact of aquaculture for a specific embayment. Such a model is being explored in China in research sponsored by the Sino-US Living Marine Resources Panel. In this study, two projects are using the model to simulate the impact of aquaculture on Jiaozhou Bay, Shangdong Province, and on Xincun Lagoon, Hainan Province. Jiaozhou Bay is in the temperate zone adjacent to the Yellow Sea. There, a major port and industrial city, Qingdao, and scallop and shrimp aquaculture interact with the physical and biological components of the bay. The other modelled environment is very different. Xincun Lagoon is a small embayment (~22 km^2) in southeastern Hainan Island adjacent to the South China Sea. Aquaculture in Xincun Bay includes 6500 fish pens (3 m × 3 m), 100 ha of shrimp ponds, pearl culture rafts and a new macroalgae culture operation that produced 3500 tonnes of *Eucheuma* in 1998–1999. The surrounding area has ~15,000 people and Xincun City is a major offshore fishing port (~500 vessels, > 10 m length) and Monkey Island Wildlife area with > 400,000 visitors annually. Extractive and fed aquaculture, along with the external activities, all have an impact on the carrying capacity of the bay for aquaculture.

These two models show much promise for simulating local eutrophic conditions and for increasing the general understanding of the complex interactions of aquaculture and other human activities. Models that simulate the impact of aquaculture and other human activities and eventually predict carrying capacity should become useful tools for resource managers.

Introduction

Effectively integrating aquaculture into coastal management is an important goal throughout the world. This chapter discusses an ecosystem approach using three-dimensional models. The first step in integrating aquaculture is to determine a body of water's capacity to sustain human activities, with an emphasis on aquaculture. This carrying capacity is the interaction of physical, chemical and biological factors. We have little or no control over the natural processes, but human activities can be altered to optimize our use of water. The key factor over which humans have control is eutrophication. Humans are the source and the solution. The input of organic matter and inorganic nutrients beyond moderate levels reduces a body of water's capacity to support water-related activities. Learning to balance inputs with nutrient extraction is a difficult goal to achieve, but it is critical if aquaculture is to be optimized.

Eutrophication affects aquacultural carrying capacity in three ways. First, eutrophication resulting from pollution and other human activities is added to natural nutrient-transport processes. In excessive amounts, nutrients become a serious threat to coastal waters. The growing number of toxic algal blooms and oxygen hypoxia events are often the result of eutrophication, but these environmental catastrophes are only symptoms of a more pernicious problem. Aquaculture's future success depends on abundant and clean water; thus, the industry is more threatened by extreme eutrophic conditions than by any other water use. In addressing eutrophication, industry needs the kind of broad-based approach that integrated coastal management provides.

Second, extractive aquaculture (bivalve molluscs and seaweeds), which removes plankton and nutrients from surrounding waters, can have a significant positive impact on moderately eutrophic waters. In fact, these species require moderate nutrient levels from natural (Blanton *et al.*, 1987) or human sources to maintain basic planktonic productivity, from which they must filter their food. Without the moderate levels and appropriate types of nutrients and plankton species, the extractive aquaculture species cannot thrive.

Third, fed aquaculture (shrimp and finfish), which depends on supplemental feeding to grow its products, contributes to eutrophication and should be balanced with extractive aquaculture species. The question is how can carrying capacity be managed to create a balance between extractive aquaculture, fed aquaculture systems, and anthropogenic nutrient inputs?

The first step is to determine the quantity of input and extraction of organic matter and nutrients into a body of water. The interactions of the complex physical, chemical and biological processes are just beginning to be understood. The techniques for simulating these interactions in ecosystem models also are improving rapidly (Chen *et al.*, 1999). Three-dimensional ecosystem modelling of coastal estuaries and embayments offers an excellent tool for integrating the natural processes and simulating both negative and positive aspects of aquaculture. The focus of this chapter is to illustrate how three-dimensional models can be used to develop a management strategy and integrate that strategy into coastal management.

Background

The negative aspects of aquaculture, particularly those systems that require supplemental feeding, have received substantial attention. Less emphasis has been placed on the positive aspects of extractive aquaculture. Seaweeds, molluscs and filter-feeding fish extract nutrients, organic particles and plankton. Used in conjunction with fed aquaculture in an integrated system, extractive aquaculture systems will utilize food supplies more efficiently, improve the water quality, reduce costs of production and increase the productivity of the ecosystem (Naylor *et al.*, 2000). How important could integrated aquaculture (polyculture) be to the environment? Naylor *et al.* (2000), in their evaluation of the ecological links between intensive aquaculture and capture fisheries, contend that worldwide, molluscs and seaweeds produced 9 and 8 million tonnes, respectively, in 1997. In the same year, fish cages and fish or shrimp ponds produced 2 and 18 million tonnes, respectively. Thus, world production was within 3 million tonnes, showing a balance between fed and extractive aquaculture; however, the two types of aquaculture are very often geographically disjunctive because of the predominant monoculture approach. Moreover, these numbers do not account for other sources of nutrients or for the difference in species composition. If integrated aquaculture can help balance extractive and fed aquaculture systems, there is hope that regionally integrated polyculture can reduce eutrophication from aquaculture.

The next step is to find a tool that will allow aquaculturists and resource managers to understand the relationships between aquaculture and physical, chemical and biological ecosystem processes. Ecosystem modelling promises to be this tool. Modelling techniques are improving rapidly and three-dimensional models provide excellent visual tools to see the potential impacts of management decisions. In this chapter, two case studies of the use of ecosystem models to evaluate the impacts of aquaculture are discussed. The first example describes conditions in Jiaozhou Bay in northern People's Republic of China, and the second describes Xincun Lagoon on Hainan Island in southern People's Republic of China.

Jiaozhou Bay Coupled Model Experiment

Jiaozhou Bay is a shallow, semi-closed bay adjacent to the Yellow Sea (YS) in the northeastern Province of Shandong, People's Republic of China. The bay's area is ~400 km^2 with an average depth of 7 m and maximum depth over 50 m in the strait to the YS. The bay has an extensive intertidal zone in its northwest quadrant. Tidal amplitude ranges from ~120 cm at the entrance to ~130 cm near the northeast shoreline. Average tidal current is > 15 cm s^{-1} with a maximum of 150 cm s^{-1} at the bay's entrance. The bay is dominated by a southerly or southeasterly wind in the spring and summer and by a northerly or northwesterly wind in the autumn and winter. Average wind velocity is ~5 m s^{-1} in summer and ~7 m s^{-1} in winter (Zhao *et al.*, 1995). Freshwater input is primarily from six major rivers, whose total maximum discharge is 135 m^3 s^{-1}. The largest river, the Dagu River, accounts for > 80% of the freshwater flow and is located on the west side of the bay (Fig. 14.1; Table 14.1; Chen *et al.*, 1999).

Qingdao (120 °22′E, 36°4′N) and surrounding districts have a population of 6.99 million people and the area is a major port and tourist destination. The ecology of Jiaozhou Bay has changed dramatically over the last three decades as a result of increased industries, aquaculture, agriculture and domestic sewage (Liu, 1992). Annual average concentrations of total inorganic nitrogen and phosphate increased from 1.2 and 0.14 μmol l^{-1} in 1962/63 to 10.4 and 0.45 μmol l^{-1}, respectively, in 1992. During the same period, the ratio of total inorganic nitrogen to phosphate shifted from ~10 to 24.2.

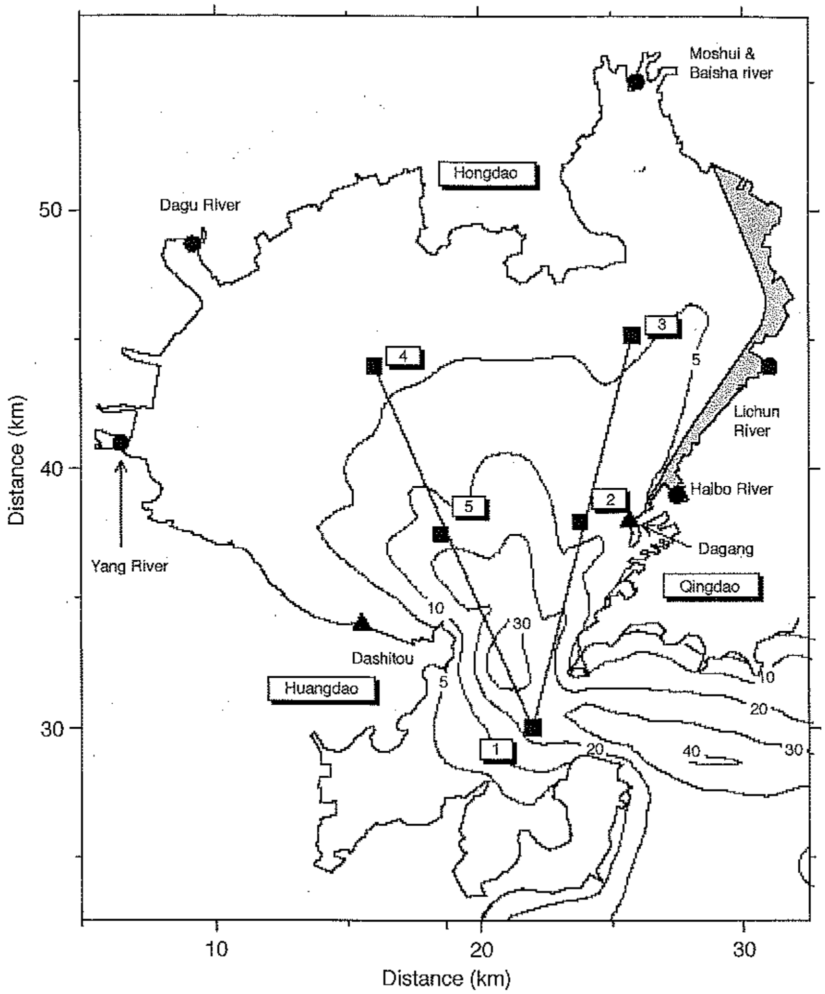

Fig. 14.1. Bathymetry (metres) of Jiazhou Bay, Qingdao, P.R. China. The solid squares are the biological measurement stations. The heavy solid lines are the sections for the model–data comparison. The solid triangles are tidal measurement stations. The light grey area indicates the intertidal zone. Locations of the six major rivers are indicated by solid circles. Dotted area indicates the initial locations of particles released at the 10th model day.

Nitrogen, which was the limiting factor in growth of phytoplankton, has given way to a phosphorus-limited ecosystem (Shen, 1995). Light intensity, water temperature, turbidity, and the continuing input of nutrients from rivers also contribute to phytoplankton productivity, which reaches a peak in summer with chlorophyll *a* readings of 0.37 to 9.5 mg m^{-3}. The highest levels are in the northwestern bay, where the Dagu River is located, and the lowest is at

Table 14.1. River discharge to Jiaozhou Bay during summer 1991 (average based on data from Liu and Wang, 1992).

River	Discharge rate (m^3 s^{-1})
Dagu	87.42
Yang	6.36
Moshui	3.66
Baisha	2.38
Lichun	0.60
Haibo	0.40

the entrance to the bay. Similarly, total primary productivity ranges from 33.60 to 2145.45 mg C m^{-2} day^{-1} with the highest values near the northern coast during summer.

Aquaculture of two scallop species (*Chlamys farreri* and *Argopecten irradians*) in suspended nets was the dominant production system along with bottom-cultured clams. The three major areas of the bay used for suspended rake culture for scallops are indicated in Fig. 14.2 (Chen *et al.*, 1999). These areas occupied 50 km^3, about one-eighth of the bay (Collaudin, 1996). The annual production of aquaculture scallops during the study period was ~40,000 tonnes (fresh total weight). The major clam species, *Ruditapes philippinarum*, cultured in the intertidal and subtidal northern part of the bay, produces ~70,000 tonnes (fresh total weight) annually (Fig. 14.2; Chen *et al.*, 1999).

The pronounced increase in nutrients in Jiaozhou Bay has caused serious environmental problems. The frequent occurrence of harmful algal blooms and the increased mortality rates and decreased rates of growth of natural and cultured organisms are evidence of the seriousness of the eutrophication problem. A three-dimensional model allows us to simulate the physical and biological processes and predict where eutrophication may become a problem or where aquaculture could have positive or negative impacts on the environment.

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: (i) tidal oscillations; (ii) wind-driven features; and (iii) 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 (87 m^3 s^{-1}; Liu and Wang, 1992). The effects of wind-induced currents and resulting mixing

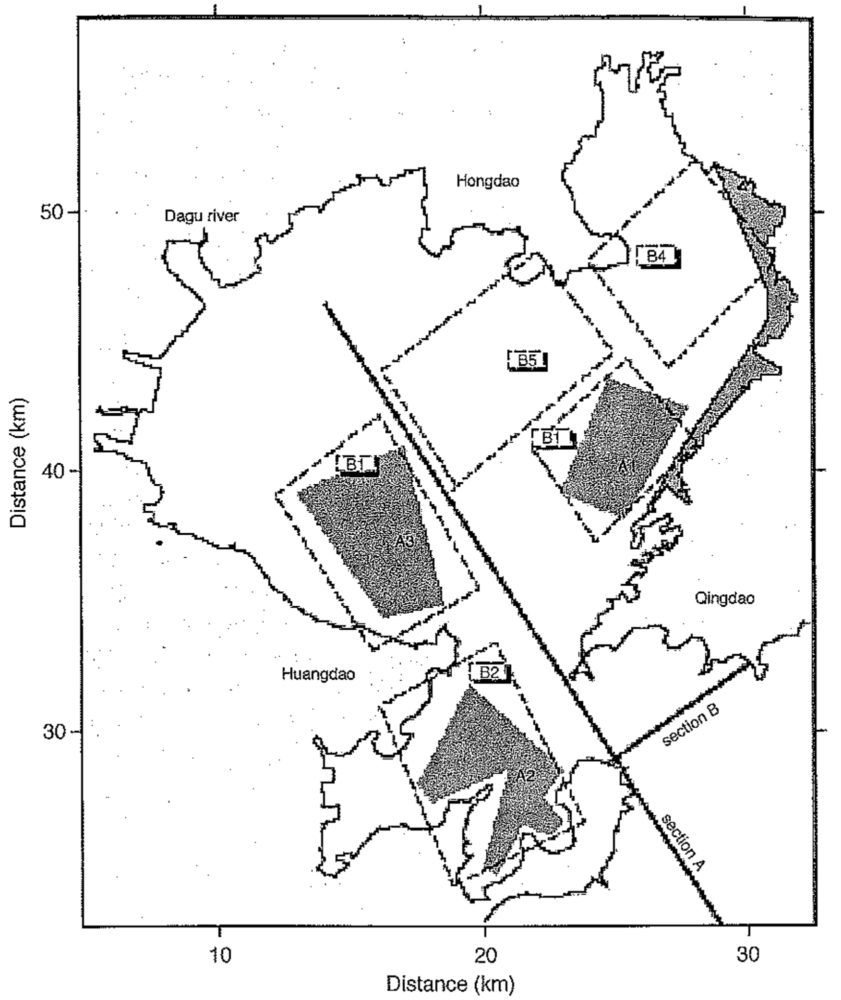

Fig. 14.2. Locations of the shellfish aquaculture sites (shaded areas) and selected regions for the flux estimation of nutrient and phytoplankton (areas enclosed by dashed line). The heavy solid lines indicate two sections used to represent our model results on a cross-bay section (Section A) and flux calculations into or out of the bay (Section B).

influences on the distribution of temperature, salinity, nutrients and phytoplankton were examined in the simulations. The dominant wind force in the summer is from strong southeast winds, but for simplification, a constant southeasterly wind of 5 m 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 (1996). 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}, which is equivalent to 0.012 individuals l^{-1}. The scallop filtration rate varies in a range of 30 to 200 l day^{-1} per individual at around 25°C. This may overestimate the filtration rates since the food availability was not taken into account (Winter, 1978). So, a filtration rate of 100 l day^{-1} per individual 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 60 C/chlorophyll *a* ratio was used to convert chlorophyll *a* to carbon.

The tidally driven physical model demonstrated that the tidal current turned clockwise as it entered the bay. The tidal amplitude of ~120 cm at the entrance to the bay reached ~130 cm on the northeast coast. It took only 6.2 min for the tidal peak to travel from the YS to the northern coast. The defining physical feature was a residual eddy that developed near the entrance to the main embayment during flood to ebb tides (Fig. 14.3; Chen *et al.*, 1999). The eddies propagated in the vicinity of the scallop rafts and influenced the biological distributions near the outer bay. The velocity was 15–20 cm s^{-1} with a vertically averaged velocity of 10–15 cm s^{-1}. In most regions of the bay where the depth was < 10 m, a weak clockwise current that was relatively stronger on the eastern side (~1.5–2.5 cm s^{-1}) than the western side (< 0.2 cm s^{-1}) was characteristic. River discharges only slightly enhanced the clockwise residual circulation.

The other major physical component was the wind, particularly the southeasterly wind that dominates during the summer months. For example, with a southeasterly wind of 5 m s^{-1}, the near-surface water in the shallow region (< 10 m) moved northwestward and caused surface convergence in the northwest region of the bay – a phenomenon that is important to the biological model.

The results of the coupled model demonstrate that the water temperature and salinity remain vertically well mixed. Summer temperatures remained near 26°C with a tongue of cooler water from the YS intruding into the mouth of the bay. The water injected into the bay has higher salinity than predicted. This was attributed to summer evaporation and the exclusion of the intertidal flats from the model. Nutrients (phosphate) and phytoplankton followed similar trends and were vertically mixed. The maximum values for phosphate and chlorophyll *a* were 1.65 μmol l^{-1} and 1.9 μg l^{-1}, respectively, near the rivers in the inner bay. They dropped to 0.42 μmol P l^{-1} and 0.8 μg chlorophyll *a* l^{-1}

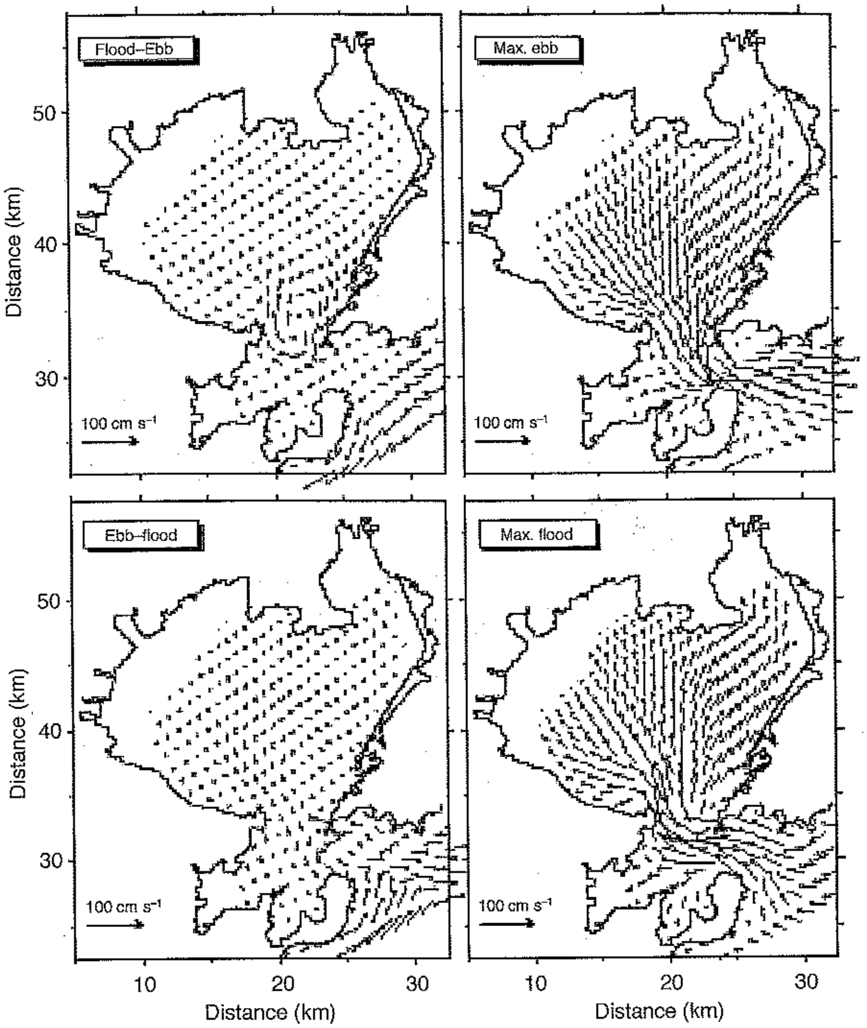

Fig. 14.3. Synoptic distributions of the surface tidal current vectors of the M_2 tide at the times of flood and ebb, with maximum ebb, ebb to flood and maximum flood.

near the southern entrance where the cool-water tongue from the YS was found (Fig. 14.4; Chen *et al.*, 1999).

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 dramatically decreased the concentrations of phytoplankton in the culture areas labelled A1–A3 in Fig. 14.2 (Chen *et al.*, 1999). The experiments suggested that the scallops would sharply reduce the concentration of phytoplankton to 0.99 μg chlorophyll *a* l^{-1} in A1, 0.52 μg chlorophyll *a* l^{-1} in A2, and 1.0 μg chlorophyll *a* l^{-1} in A3, about

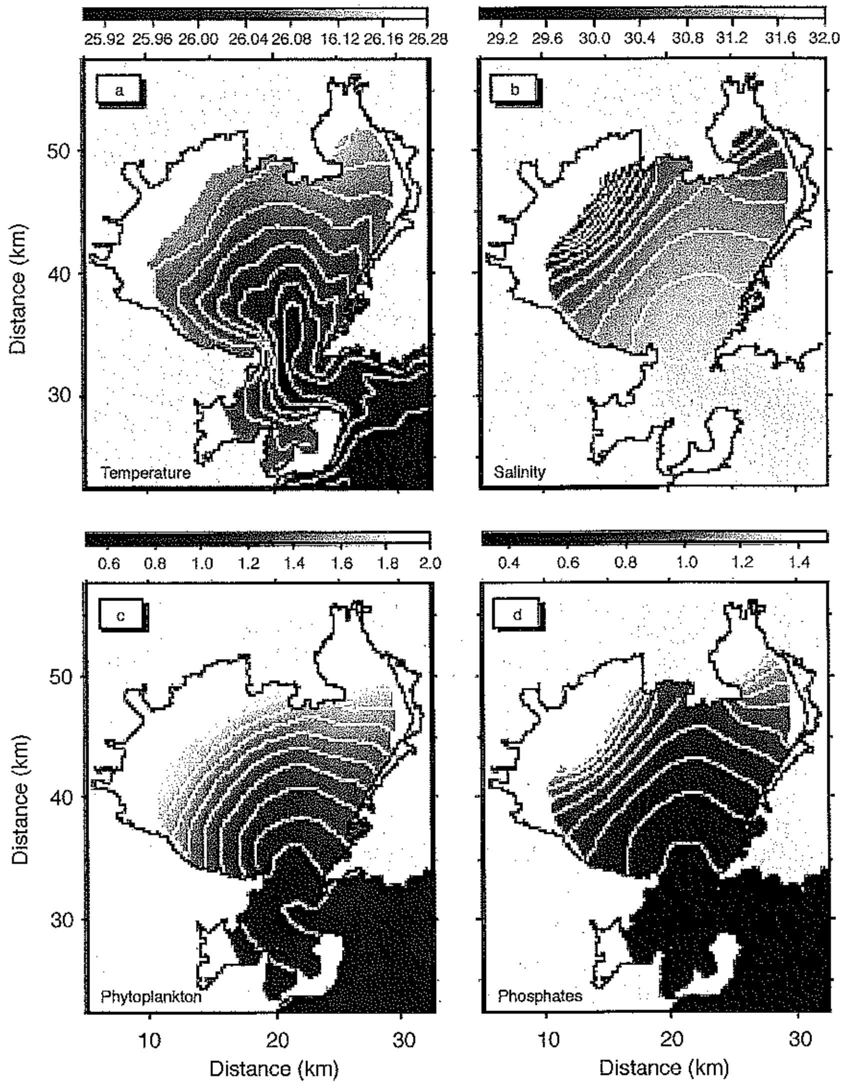

Fig. 14.4. Tidal averaged surface distributions of (a) temperature in °C, (b) salinity in parts per thousand, (c) phytoplankton in μg chlorophyll *a* l^{-1}, and (d) phosphate in μmol l^{-1} at the end of 20 model days for the case with tide and freshwater discharges.

31.8%, 33.3%, and 37.3%, respectively, lower than those in the case without shellfish (Fig. 14.5; 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 chlorophyll *a* l^{-1} in A1, 0.38 µg chlorophyll *a* l^{-1} in A2, and 0.67 µg chlorophyll *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 (Fig, 14.5b; Chen *et al.*, 1999).

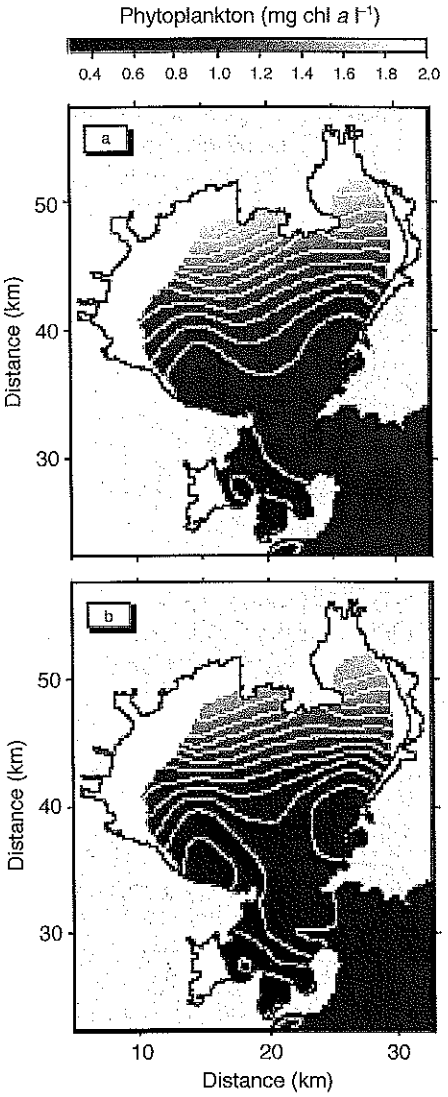

Fig. 14.5. Tidal cycle averaged surface distribution of phytoplankton after 20 model days for the case with shellfish culture densities of (a) 12 and (b) 24 individuals m^{-3}. Physical forcing factors are tide, freshwater discharge, and a southeasterly wind at 5 m s^{-1}.

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 indicating 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 faeces and pseudofaeces 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 of phosphates, or the nutrient regeneration rate may be orders of magnitude smaller than the nutrient loading rate from other sources.

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 l^{-1} day^{-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 were 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 ten 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 coast 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, which provided favourable 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 for 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 YS, 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 (Kasper *et al.*, 1985; Kautsky and Evans, 1987). The benthic processes, in turn, may alter nutrient cycling in the bay (Jorgensen, 1990; Barg, 1992; Dame, 1993). 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 can potentially be advected back to the bay during ebb tide.

Xincun Bay Modelling Experiment

Xincun Lagoon is located on the southeast coast in Lingshui County, Hainan Island (110°E, 18°25′N). The county population is more than 300,000, of which 158,000 are of the Li ethnic minority. The coastline is about 110 km long and about half the people live in the coastal townships (Marine and Fishery Department of Hainan, 1998). Xincun Bay has a gourd-shaped basin 6 km long and 4 km wide, covering an area of 21.97 km^2. Maximum depth is 10.6 m, and the bay is connected to the open sea by a single tidal inlet about 120 m wide (Fig. 14.6). People began to cultivate pearl oysters in the bay in

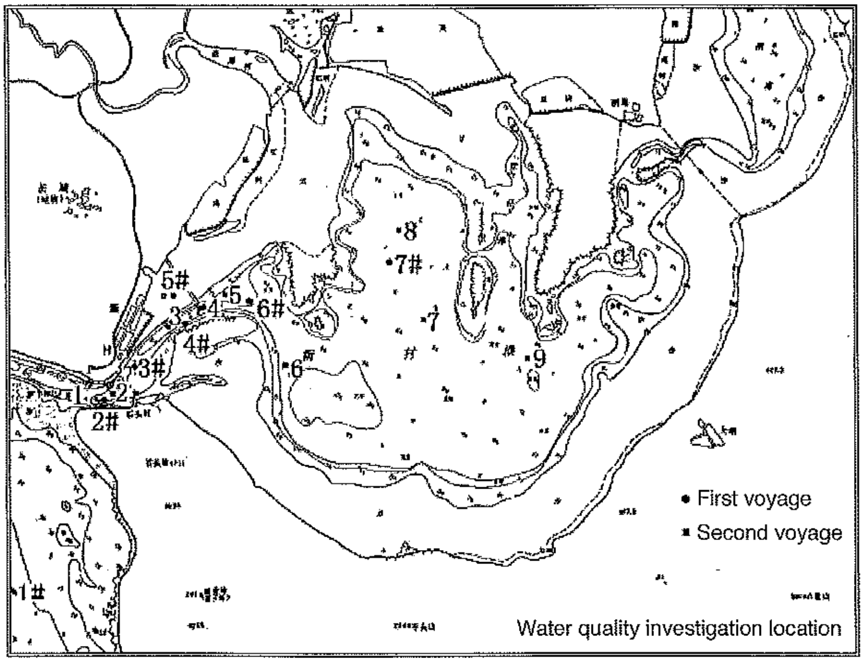

Fig. 14.6. Map of Xincun Bay with sampling locations.

the 1970s, and aquaculture has continued to grow in importance to the local economy. At present fish, shrimp, molluscan shellfish and the macroalga *Kappaphycus* sp. are cultured over an area of 160 ha in the bay. In 1997, the total income of aquaculture was about US$7 million. Lingshui County also has become an important mariculture base.

Aquaculture industry characteristics

The area used for coastal aquaculture in Hainan Province has increased at an annual rate of 9% for the past 10 years. It increased from 3500 ha in 1989 to more than 8200 ha in 1997. Total aquaculture production also increased at a rate of more than 25%. The increase in aquaculture area was at the expense of some coastal forests, wetlands and estuaries, and the intensification of aquaculture resulted in increased coastal pollution (Marine and Fishery Department of Hainan, 1998).

The aquaculture industry in Xincun Bay is dominated by the fish cage culture systems that are located near the bay's entrance and adjacent to the navigation channel. There are approximately 450 floating cage units consisting of 3 m × 3 m net cages, generally configured in a square with three cages per side. Each unit also includes a house with a family (four or five people) and one or two labourers. Several species are grown in the cages from fingerlings. Included are cobia, *Rachycentron canadum* (L.), local grouper and pompano. The fish are fed 2–5% of their body weight daily with ground whole fish from the trawl fishery and nearshore light-net fisheries.

Culture of *Kappaphycus* sp. is relatively new in Xincun Bay. *Kappaphycus* sp. is cultured on suspended lines (rakes) seasonally from October to April. These rakes occupy a significant portion of the middle area of the bay and are often mixed with pearl oyster culture rafts. *Kappaphycus* sp. segments are tied on to long ropes suspended horizontally within a metre of the surface. This culture system is used extensively in the Lian Lagoon, which is adjacent but not connected to Xincun Bay. In Xincun Bay, production of *Kappaphycus* sp. is increasing and in the 1998/99 and 1999/2000 seasons production was 1500 and 2000 tonnes, respectively.

Shrimp are cultured in 85 ha of ponds and production was about 4500 kg in 1999. Some of the aquaculture ponds were constructed at the expense of the coastal forest. To date, the major species produced was the Chinese shrimp, *Fenneropenaeus chinenis*, but initial success with the Pacific white shrimp *Litopenaeus vannamei* has prompted a shift to the latter species. Food conversions of 1.5 kg of feed to 1 kg of shrimp, as compared to a 1.8 : 1 conversion ratio for the former species, and disease outbreaks led to the species change.

Pearl oysters are cultured, but the primary bivalve molluscan production is clams. They are harvested from the intertidal zone out to 3 m depth in the middle portion of the bay. The other major biological components are the beds of seagrass, *Enhalus acoroides*, located in the middle and upper portions of the bay, and mangroves in the uppermost region (Marine and Fishery Department of Hainan, personal communication, 2000).

The history of aquaculture in Xincun Bay is one of boom and bust. Rapid expansion of the fish cage aquaculture industry in the 1990s exceeded the assimilative capacity to maintain the water quality in the bay. In 1997, water quality problems became very serious. As a result the cultured species began to grow slowly and the mortality rate increased dramatically. Fish cage culture declined from 200 and 230 ha in 1995 and 1996, respectively to 20 ha after the 1997 disaster. It increased to 33 ha in 1999. The number of hectares and fish cages was reduced and they are concentrated near the mouth, where tidal exchange is greatest. Shrimp production also collapsed from 100 ha in 1996 to 10 ha in 1997 and remained low (5 ha) through 1999 (Fig. 14.7). The shrimp ponds are in the extreme interior of the bay. Although environmental factors played a role in the mortalities in the shrimp ponds, diseases that ravaged shrimp production throughout China also may have been a major factor in the disastrous decline in production. After the two major aquaculture industries (fish and shrimp) collapsed, production of other aquaculture species increased and emerged as important economic and environmental factors. Pearl oyster culture expanded dramatically in 1998 then declined to 85 ha in 1999. Seaweed culture grew from 52 ha in 1998 to 133 ha in 1999 and increased to 160 ha in 2000.

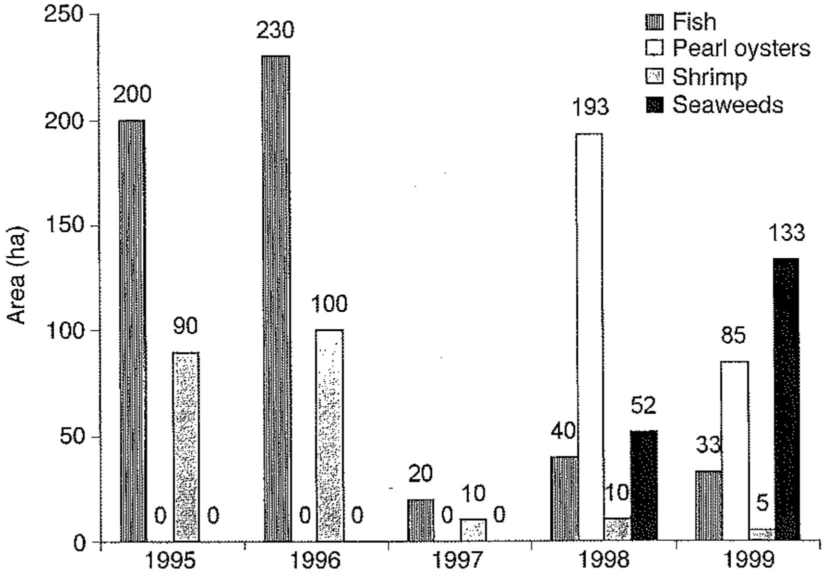

Fig. 14.7. Histogram of area utilized in the 1990s for aquaculture in Xincun Bay.

Ecosystem study and model of Xincun Bay

Observations

Environmental problems severely limit the sustainable development of Xincun Bay mariculture. To determine the severity of the existing environmental problems, two field surveys of Xincun Bay were conducted. From 31 July to 6 August 2000, two continuous stations and nine area stations were sampled (Fig. 14.6). For the continuous stations, the physical parameters monitored included temperature, salinity, DO, DO%, pH, current speed and direction, turbidity, and tidal level. Primary productivity, basic water quality and nutrients, chlorophyll *a*, ATP, chlorophyll *a*/ATP ratio, MPN (most probable number) total coliform organisms, MPN *E. coli* organisms, chemical oxygen demand (COD), suspended solids (SS), pH, turbidity, *ortho*-phosphate, nitrogen, NO_2^-, NO_3^-, NH_4^+, DO, temperature, salinity and bacterial communities were measured at the area stations. During the survey, pollutant sources were evaluated to understand the sewage discharge and its impact on water quality.

Macroalgal and seagrass samples were taken from up to four different stations in the bay. In order to evaluate their role as nutrient sinks in the ecosystem, the tissue carbon, nitrogen and phosphorus contents were analysed with a Perkin-Elmer CHN elemental analyser and by the method of Murphy and Riley (1962). Initial samples were taken in May and August for the macroalgae and seagrasses, respectively, along with the water sampling described above. Another sampling was carried out in November 2000 for both the macroalgae and seagrasses. The locations are shown on Fig. 14.6. Stations I, II and III were relatively close to the area of the bay where the fish cages are located, while station IV was in the upper part of the bay, distant from the cages.

Tidal characteristics and current

Twenty days of water level data analysis showed that the bay's tidal characteristics included an irregular diurnal tide with a small average tide range of 69 cm. The maximum tide range was only 1.55 m, which contributed to the slow tidal current velocity. In addition, the bay connects to the open sea via a 120-m-wide navigation channel, and water exchange takes place within a relatively small area adjacent to the channel.

The measurement results from two continuous current meters showed that tidal current velocity varied within a large range of 2 cm s^{-1} to 155 cm s^{-1} at the surface. At the mouth of the bay (station 1), the maximum surface velocity reached 155 cm s^{-1} during the spring ebb tide period on 31 July. During the neap tide period on 6 August, however, maximum velocity only reached 65 cm s^{-1}. At the upper end of the navigation channel (station 2, 7 m depth), the maximum velocity was relatively stable at 43 cm s^{-1} and 40 cm s^{-1} in the corresponding periods. In the middle of the bay, the velocity dropped off quickly to an average value of 10 cm s^{-1}. Station 2 data also showed that the ebb velocity values were larger than the flood velocities. An estimated water flux of 6×10^7 m^3 flowed in and out of the bay during one spring tidal cycle, which is one-thirteenth of the bay's total volume (8×10^7 m^3). It would seem that the bay's water could exchange completely within half a month, but an earlier study indicated the bay has a 90-day water exchange rate. This slow dynamic exchange leads us to conclude that Xincun Bay has a low capacity for transporting pollutants to the open sea. The present water quality environment is consistent with this fact. The pollutant sources, especially the cage culture, add to the oxygen demand by introducing residual feed and fish waste, but these are not the only sources of organic pollution. Domestic sewage and the fishing fleet also contribute to the eutrophication of the bay.

Dissolved oxygen

The dissolved oxygen concentration (DO) is an important indicator of water quality for marine life. Although it is difficult to determine the DO production and consumption mechanisms precisely, the basic trend can be understood by monitoring the degree to which the water is being polluted. The vertical distribution of DO is particularly important in order to determine 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 are shown in Fig. 14.8. DO was lower than 6 mg l^{-1} at stations 2–6 in all layers. At area stations 2, 4, 5 and 6, the DO was less than 5 mg l^{-1}, and the average value was only 4.8 mg l^{-1}. Vertically, DO declined sharply and reached a minimum at 2–3 m in the fish cage culture region. On the other hand, vertical DO distribution was different at station 1 outside the bay, where it increased with depth. DO at the surface was 5.04 mg l^{-1}, very similar to that in stations 2–6. At station 1 DO was 6 mg l^{-1} at 2 m. We speculate that this phenomenon is the result of the surface water outflow from the bay. At station 7, where there are no fish cages, water quality was better. DO was 6 mg l^{-1} at the surface, but at depths > 3 m, the DO value was below 5 mg l^{-1}. The distribution of DO at all stations was not desirable for fish cage culture. The cages used in Xincun Bay are 3 m × 3 m, and are submerged to a depth of 1–4 m. Where fish are cultured at high density, respiratory difficulties for fish may result when DO is low.

A clear distribution of DO can be seen along the survey profile (Fig. 14.8). DO concentrations were high outside the bay and in the inner bay regions. In the navigational channel region, DO concentrations were low at greater depths. This is the region where fish cage culture is concentrated. From the above analysis, we can draw the basic conclusion that DO concentration was relatively low in fish cage regions.

When the relationship between salinity and DO saturation was analysed, we found that DO saturation has a concave relationship with salinity, reflecting the continuum from the sea to the location of the fish cages (Fig. 14.9). When salinity was less than 31 ppt, DO approached saturation. Planktonic algal populations were larger within a salinity range of 28–31 ppt, but the data

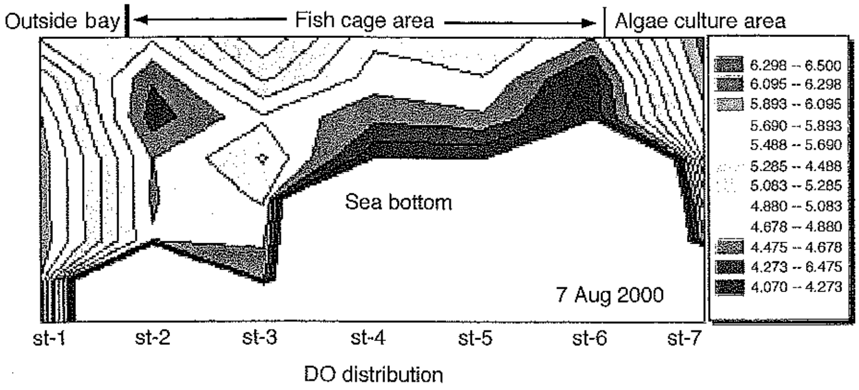

Fig. 14.8. Dissolved oxygen saturation and salinity in Xincun Bay.

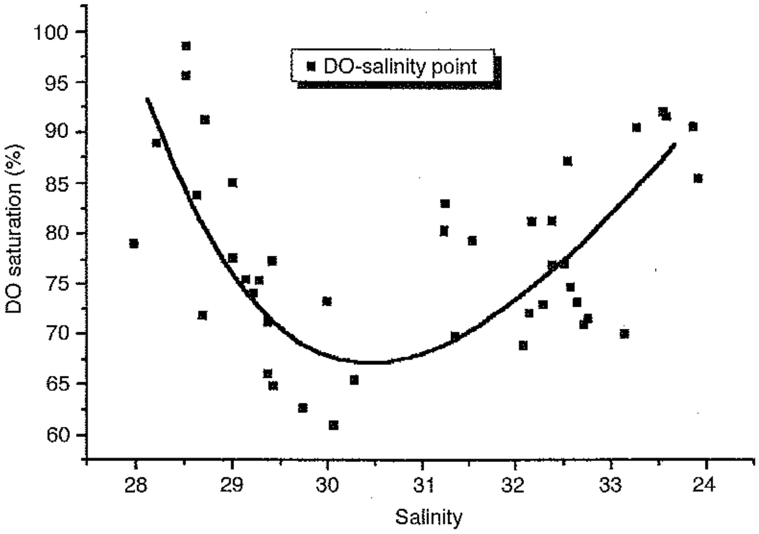

Fig. 14.9. Relationship between oxygen saturation and salinity in Xincun Bay

at station 7 indicate high DO saturation at the surface. It is assumed that larger algal populations in the middle region of the bay produced O_2 in the surface layer and/or the BOD or COD was greater in the cage culture area.

Nutrients

The distribution of nitrates (Fig. 14.10) was characterized by their spatial distribution in the outside bay, tidal channel and inner bay. The nitrate concentrations exhibited a peak of about 5.97 $\mu g\ l^{-1}$ within the channel region near the fish cages, where high levels of organic matter fall to the bottom. In both the outside bay and inner bay regions the nitrate concentration was fairly low with a value of 0.83–0.70 $\mu g\ l^{-1}$.

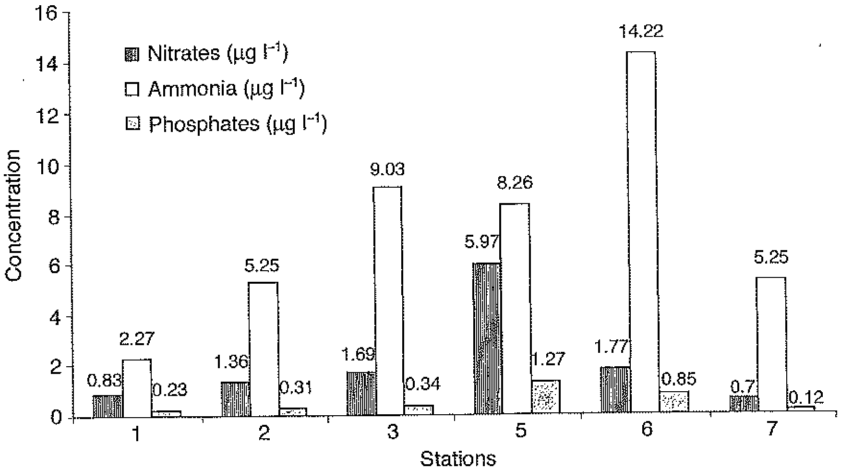

Fig. 14.10. Nutrient distributions in Xincun Bay.

Ammonium concentration had a similar distribution to nitrates in Xincun Bay. It decreased rapidly from the cage fish culture region to the outside bay. Ammonium concentrations exhibited a peak of about 14.22 μg l^{-1} in station 6 in the cage culture region, and declined sharply to 0.09 μg l^{-1} in the inner bay where seagrass beds were dominant.

The phosphorus concentrations were commonly lower than the nitrate and ammonium concentrations in the water column. Phosphorus concentrations were below 0.5 μg l^{-1} at five of the seven stations. The maximum phosphorus concentration reached 1.27 μg l^{-1} at station 5 in the fish cage region.

The spatial and temporal distributions of nutrients are reflected in the DO distribution in the water column. These biochemical characteristics are associated with the aquaculture activities in Xincun Bay. Within the fish cage area, substantial quantities of organic matter accumulate in the sediment owing to uneaten food and fish excrement. Sediment oxygen consumption increases as a result of chemical oxidation, activity of benthic organisms and bacterial decomposition of organic matter. The oxygen in the water column above the sediments can become depleted, leading to anoxic conditions. When oxygen above the sediments is depleted, nitrogen and phosphorus may be released into 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).

Phytoplankton requirements for nutrients such as inorganic nitrogen (IN) and inorganic phosphate (IP) play important roles in controlling the growth of phytoplankton and primary productivity. The ratio of IN/IP acts as an important indicator of eutrophication. In cultivation areas, the IN/IP changed

Table 14.2. Inorganic nitrogen (IN) in µg l^{-1}, inorganic phosphorus (IP) in µg l^{-1}, IN/IP ratio, and the comprehensive assessment parameter (*E*) on three dates in 2000.

		Station								
Date	Parameter	1	2	3	4	5	6	7	8	9
June 28	IN	1.68	2.52	2.72	3.78	3.02	3.64	–	–	–
	IP	0.1	0.09	0.14	0.21	0.19	0.19	–	–	–
	IN/IP	16.7	28.1	19.5	18.0	15.9	19.2	–	–	–
	$E = 10^{-3}$	–	–	–	–	–	–	–	–	–
July 31	IN	0.29	1.07	1.8	2.84	2.38	4.53	0.8	0.58	4.27
	IP	0.03	0.13	0.15	0.06	0.04	0.05	0.06	0.06	0.05
	IN/IP	9.7	8.2	12.0	47.3	59.5	90.6	13.3	9.7	85.5
	$E = 10^{-5}$	0.092	1.3	2.5	1.8	1.8	6.2	1.4	0.9	6.3
August 7	IN	3.2	6.81		10.99	15.21	16.3	0.89	–	–
	IP	0.23	0.31		0.34	1.27	0.85	0.12	–	–
	IN/IP	13.9	22.0		32.2	12.0	19.2	7.4	–	–
	$E = 10^{-3}$	0.18	1.1	–	2.2	6.2	4.8	0.06	–	–

due to the effects of cultured species. In scallop culture regions, the ratio of IN/IP was usually high, but the ratio was small in the brown alga, *Laminaria*, culture region (Song Yunli, 1996, personal communication).

Table 14.2 shows that the value of IN/IP always remained high inside the bay (stations 1–6 on 28 June; stations 3–7 and 9 on 31 July; stations 2–6 on 7 August). However, on 31 July 2000, it remained normal in the channel region (stations 1–2), due to the influence of the flood tide. This characteristic distribution of the IN/IP ratio presumably was related to the large area of fish cage culture in the channel region.

The nutrient state of the bay can be assessed by a comprehensive assessment parameter *E*:

$$\left[E = \frac{\mathrm{COD}(\mathrm{mg}^{-1}) \times \mathrm{IN}(\mu\mathrm{g\ l}^{-1})\,\mathrm{IP}(\mu\mathrm{g\ l}^{-1})}{1500} \right]$$

when $E \geq 1$ the water has an over-abundance of nutrients. The results show that the values of *E* are generally small (Table 14.2), indicating that nutrients do not exceed the critical level of eutrophication in the fish cage region. This is the reason for low chlorophyll *a* (< 0.5 µg l^{-1}) and low primary productivity at all stations sampled in Xincun Bay.

Water quality and sediment assessment

Water quality and sediment survey results are shown in Tables 14.3 and 14.4. Data from 14 stations were collected during four cruises on 10 September, 28 June, 31 July and 7 August 2000. The DO concentration was 21% lower than the Class II water quality standard, while other water quality parameters

Table 14.3. Water quality data.

Parameter	Maximum	Minimum	Average
Temperature (°C)	30.9	23.6	28.9
Salinity (‰)	32.8	28.6	31.8
DO (mg l^{-1})	6.67	3.92	5.12
DO saturation (%)	97	61	87
pH	8.35	8.13	8.26
PO_4^- (μg l^{-1})	3.20	1.60	3.72
NO_2^- (μg l^{-1})	1.12	0.14	0.74
NO_3^- (μg l^{-1})	34.3	4.2	10.4
NH_4^+ (μg l^{-1})	165.2	0.56	28.7
Inorganic N (μg l^{-1})	176.4	4.9	41.0
Silicate (μg l^{-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
E. coli MPN (individuals l^{-1})	1700	< 20	156
Bacteria (μg l^{-1})	140	0.10	17.4
Chlorophyll *a* (μg l^{-1})	1.92	0.49	1.24

Table 14.4. Sediment characteristics at four sampling stations.

Station	Sediment type	Sediment colour	Sulphate (mg kg^{-1})	Organic carbon (%)	Organic matter (%)
1	Silt/sand	Black	348.04	4.5	7.8
2	Sand	Grey	330.02	0.3	0.5
3	Silty	Grey black	454.53	1.6	2.8
4	Silty	Grey black	326.99	0.7	1.2

were normal (*GB-99*, National water quality standard, P.R. China 2000). Low DO concentration can be the result of sediment oxygen demand and biological activity in the water column. The sulphate and the organic matter are largely in the sediments. Large organic particles settling in sediment cause a serious water quality problem. The decay of sediment will 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. It is estimated that sediment oxygen demand and the biological decomposition in the water column are the major reasons for low DO concentrations in the Xincun Bay aquatic system.

Macroalgal and seagrass nutrient content

Table 14.5 shows the results for the nutrient content in *Kappaphycus alvarezii* for the May and November sampling periods. The macroalgal samples containing the higher tissue nitrogen and carbon contents were those collected in the

Table 14.5. Tissue nitrogen, carbon and phosphorus content (dry weight percentage) in *Kappaphycus alvarezii* in Xincun Bay during May and November.

Month	Station	Nitrogen	Carbon	Phosphorus
May	III	2.69	28.64	0.11
November	I	1.69	30.64	0.15
	II	1.50	28.61	0.14
	III	1.60	31.69	0.19
	IV	1.21	27.28	0.22

areas close to the fish cages. These areas had an average nitrogen content of 1.6% dry weight (DW) and 30% DW for carbon, compared to the lower values of those two nutrients in specimens from station IV at the head of the bay. On the other hand, internal phosphorus content followed the inverse pattern, since plants at station IV were enriched in that nutrient (0.22% DW). These results reveal that seaweeds are active nutrient scrubbers, which also has an impact on their biomass. Considering the average seaweed production between 1999 and 2000 of 2000 tonnes, the calculated potential nutrient removal by these primary producers would be 28.8 tonnes for nitrogen and 3.66 tonnes for phosphorus for the November sampling period. However, if we based our estimations on the May collections, then the amount of nutrient removal for nitrogen would be 53.8 tonnes and 2.24 tonnes for phosphorus. Obviously, the nutrient removal capacity of *Kappaphycus* is substantial, but does appear to vary seasonally. Other reports have documented how other red seaweed species can act as biofilters; removing nutrients efficiently from fish farm effluents: Kautsky *et al.* (1996) integrated the culture of *Gracilaria* and salmon aquaculture in Chile, reducing the ecological footprint for nitrogen and phosphorus assimilation by 56% and 94%, respectively. Similarly, Chopin *et al.* (1999) reported high values of phosphorus and nitrogen in *Porphyra* grown close to salmon cages in Cobscook Bay, Maine, USA.

Nutrient contents in seagrass tissue (leaves, roots and rhizome) were also determined when material was available, and are reported in Table 14.6. The pattern of tissue nitrogen content indicated different strategies of nitrogen storage and subsequent use, which has been demonstrated in other seagrasses (Kraemer and Mazzella, 1999). Leaf samples collected in August showed higher nitrogen content than those collected in November, but lower carbon and phosphorus levels, coinciding with the peak of fish production in the Bay. It is noteworthy that *Enhalus acoroides* presented high values of nitrogen in leaves and rhizome tissues, even higher than those found in *K. alvarezii* in the same area, as well as higher phosphorus contents in leaves and rhizomes, and higher carbon contents in all three parts. Previous studies showed that the nitrogen uptake and assimilation by leaves can be more important than acquisition by roots (Hemminga *et al.*, 1991; Kraemer and Mazzella, 1996). Therefore, leaves and rhizomes appear to have a nutrient (mainly nitrogen) storage function

Table 14.6. Tissue nutrient content in leaves, roots and rhizomes (dry weight percentage) of *Enhalus acoroides* in Xincun Bay.

		Tissue		
Date	Station	Leaves	Roots	Rhizomes
Nitrogen				
August	III	3.97	0.82	–
November	I	2.13	0.77	2.13
	II	2.42	0.88	1.47
Carbon				
August	II	28.72	39.04	–
November	I	32.43	35.78	32.03
	II	38.22	34.43	34.40
Phosphorus				
August	II	0.17	–	–
November	I	0.48	–	0.91
	II	0.48	–	0.85

and may have a significant role in the ecosystem as a sink/source of nutrients, which must be recognized in any modelling effort.

Dissolved oxygen modelling

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

The dissolved oxygen cycle

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 DO from overlying and interstitial water of the sediments by biological and chemical oxygen demands. As discussed above, DO, which acts as a eutrophication indicator, is predominantly low within the fish culture region, where much of the organic matter deposits to the sediment. With low chlorophyll *a*, low primary productivity, even low nutrients in the water column, but large organic matter in sediments, SOD is the major reason for depletion of DO, rather than WOD. For this reason, we considered SOD to be an important sink of DO in our water quality model. Macroalgal and seagrass photosynthesis and respiration were also considered in the model, owing to the fact that they remove 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.

The ammonium and nitrate cycle

The nitrogen cycle (only ammonia and nitrate are considered) is simple in our model. The kinetic processes include the macroalgal and seagrass uptake, nitrification, denitrification and the benthic fluxes.

Determination of the major sinks/sources in the model

Sediment oxygen demand

Factors that affect SOD are rather complex. They include temperature, oxygen concentration, make-up of the biological community, organic and physical characteristics of the sediments, current velocity and chemistry of the sediment–water interface. Velocity effects on SOD were not due to physical resuspension of bottom material to the overlying water. The measurement of SOD showed that it changes in spatial and temporal variation owing to different situations (Hickey, 1984; Whittemore, 1984). In some estuaries, SOD is responsible for 40–50% of the total oxygen uptake (James, 1974).

In water quality models, some studies estimate the SOD as an empirical function of site characteristics such as the sediment depth, sediment chemical or physical properties, biological parameters, or overlying water quality. WASP simulates SOD as a function of the net settling velocity of particulates including algae, first-order reaction rates of particulates and dissolved nutrients and organic material including algal decomposition, and the diffusive exchange rate between dissolved concentration in the sediment interstitial water and the overlying water column (Di Toro *et al.*, 1971). Walker and Snodgrass (1986) defined SOD as the temperature-adjusted rate with DO in linear formula, the temperature-adjusted rate written in Van't Hoff form. In our water quality model, SOD is expressed as:

$$[\mathrm{SOD} = K_{Tr}\theta^{(T - Tr)}]$$

where K_T is the rate at a reference temperature, and θ is the temperature-adjusted rate. K_T, determined according to the *in situ* study domain, ranges between 0.05 and 3.4 g O_2 m^{-2} day^{-1} in Xincun lagoon.

Nutrient fluxes

Within aquatic systems sediment nutrient fluxes play an important role in nutrient concentrations 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 (Fisher *et al.*, 1982; Boynton and Kemp, 1985). The processes of nutrient fluxes in sediments are complex. 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 600 μmol m^{-2} h^{-1} and 3 and 39 μmol m^{-2} h^{-1}, respectively, 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 oscillations, along with wind-driven and rainfall water discharge. When the physical model reaches the equilibrium state, the water quality parameters are added and run with the cases of: (i) 450 fish cages in the channel region (Area 1 in Fig. 14.11) and without the effect of macroalgal culture; (ii) double the fish cages and without the effect of macroalgal culture; and (iii) double the fish cages and consider the macroalgal culture (Area 2 and Area 3 in Fig. 14.11).

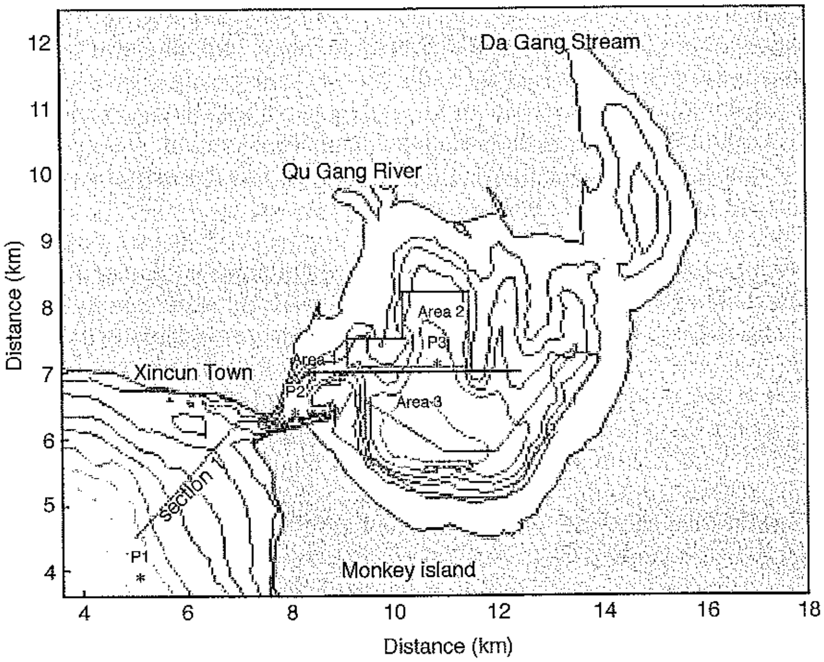

Fig. 14.11. Location of fish cages and macroalgal culture regions at selected points (P1, P2 and P3) in Section 1 in Xincun Bay.

Model results

The model was initialized by the investigation temperature and salinity field on 28 July. The model demonstrated that the temperature and the salinity remain stratified in Xincun lagoon. Tidal cycle average surface temperature and salinity inside the bay is uniform with a magnitude of 30.8°C and 31.8 ppt, but at the bottom, temperature is low and salinity high in the deepest part of the bay. Outside the bay entrance, 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 was initialized after the temperature and salinity field was adjusted. Figure 14.12 shows the spatial and temporal distribution of DO concentration in cases i and ii (described in the preceding subsection). The distribution of DO is closely related to the tide. During flood tide (upper portion of Fig. 14.12), the minimum DO concentration centre occurs

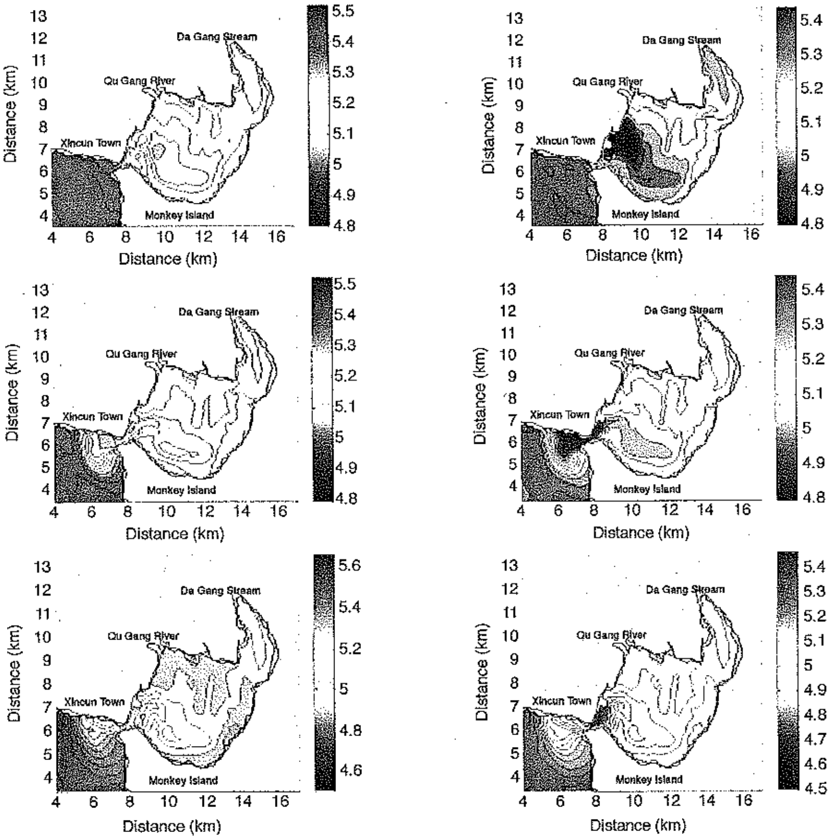

Fig. 14.12. DO concentration distribution during the flood tide (upper pair), ebb tide (middle pair), and flood–ebb tide (lower pair) under existing conditions (left) and with a 50% increase in the number of fish cages (right) in Xincun Bay.

not in the channel fish culture region, but in the inner bay. During ebb tide, the minimum DO occurs outside of the region, near the entrance of the bay only during the middle flood–ebb tide. The lowest DO concentrations occur in the cage culture region. In cases 1 and 2, the lowest DO concentrations are 5.0 mg l^{-1} and 4.5 mg l^{-1}, respectively. The experiments demonstrate that the average DO concentration is reduced by 10% when the fish cages are doubled. It seems that the effect of caged fish 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 increase DO concentration.

Figure 14.13 shows the DO concentration distribution in Area 1 (Fig. 14.11). It clearly demonstrates the effect on DO concentration by SOD, with a stratified structure in the channel region. Large SOD in the fish cage region consumes dissolved oxygen and leads to DO depletion.

Figure 14.14 shows the spatial and temporal distribution of surface DO concentration when macroalgal culture is considered in Areas 2 and 3. Although macroalgae seem not to enhance DO concentration in the fish cage region, within the macroalgal culture regions the DO concentration is improved by macroalgal photosynthesis and nutrient uptake. Figure 14.15 shows the change of DO concentration at selected points outside the bay (P1), in the fish cage region (P2) and in the inner bay (P3) during three tidal

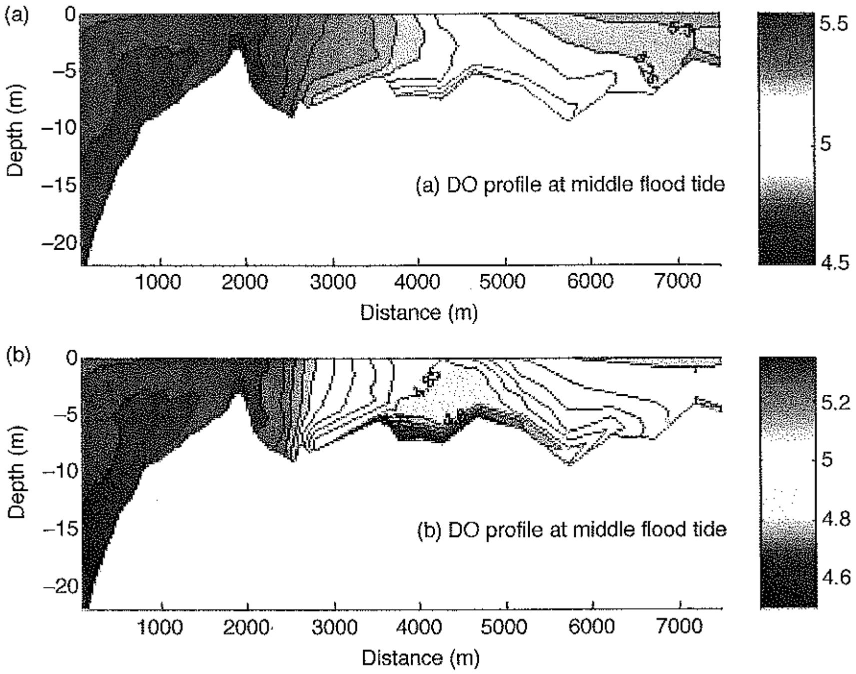

Fig. 14.13. DO profile in a selected section at present (a) and with a doubling of the number of fish cages (b) during mid-ebb tide in Xincun Bay.

cycles. We can see that the change in DO concentration in these three regions coincides with tidal elevation (tidal current). In P2, lowest DO concentration occurs before low tide with a magnitude of 4.2 mg l^{-1} at the bottom; highest DO concentration occurs at the beginning of the flood with a magnitude of 5.5 mg l^{-1}, as at P1. But at P3, the surface DO concentration seems unchanged, while the bottom DO concentration declines to 4.8 mg l^{-1}.

Discussion on the Xincun Bay case

The results showed that the water column in the Xincun Bay aquaculture region was heavily polluted by organic material and, according to sediment sample analyses, was also high in silicate. Except for DO, 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 the standards, the environmental health of the caged fish area and navigation channel region has declined considerably as evidenced by the mortality of cultured fish and low DO.

Two kinds of pollutants affect water and sediment quality in Xincun Bay. One source is the pollutants produced by four factories, four restaurants, seven gasoline stations and an estimated 481 tonnes of COD from sewage discharge. The other source is a by-product of fish cage operations, which results in

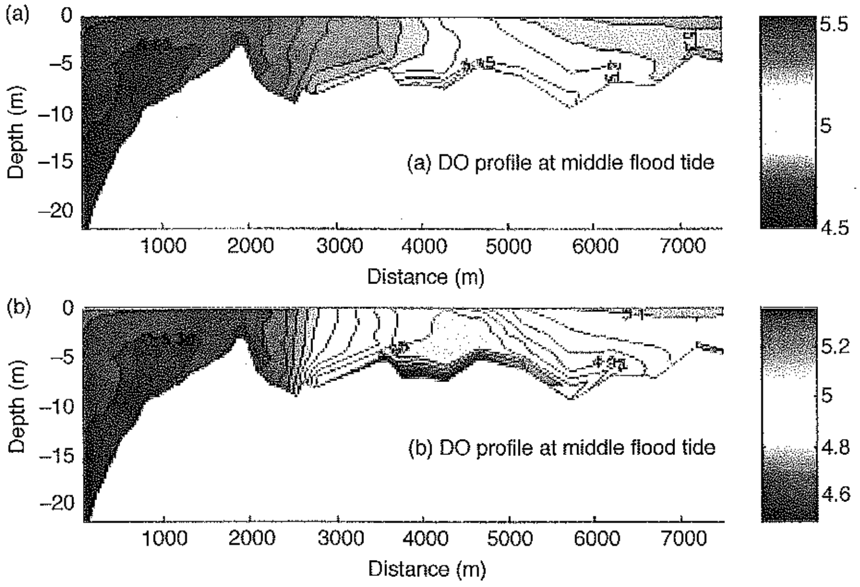

Fig. 14.14. The DO distribution in case iii with the DO at flood tide (left) and at ebb tide (right) in Xincun Bay.

an estimated 5000 tonnes of organic pollutants annually. Water quality sampling indicated that DO is always lower than the value of national water quality standards in fish culture areas. The results show that the main source of pollution is the fish cages. Large amounts of uneaten food and faeces descend to the bottom under the cages. The sediments release NH_3, H_2S and other pollutants by degradation of the organic matter by bacteria. These chemical reactions require large quantities of oxygen and reduce the DO substantially in both the sediments and the water column. The results of DO concentration modelling support that conclusion. 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 has less contribution to the DO concentration in the cage fish region.

The assessment of nutrient status showed that inorganic phosphorus is low relative to other nutrients in Xincun Bay, which are also generally present at low levels. This is frequently the case for most aquaculture of *Kappaphycus* sp. cultured in oligotrophic, tropical or subtropical regions. Moreover, nutrient requirements vary greatly between species. The point is that with integrated aquaculture, potential nutrient limitation is alleviated by moving seaweeds closer to the source of nutrients. Also, the internal nitrogen and phosphorus tissue contents in seaweeds and seagrasses in the bay suggest that these producers can act as nutrient scrubbers from water column and sediments,

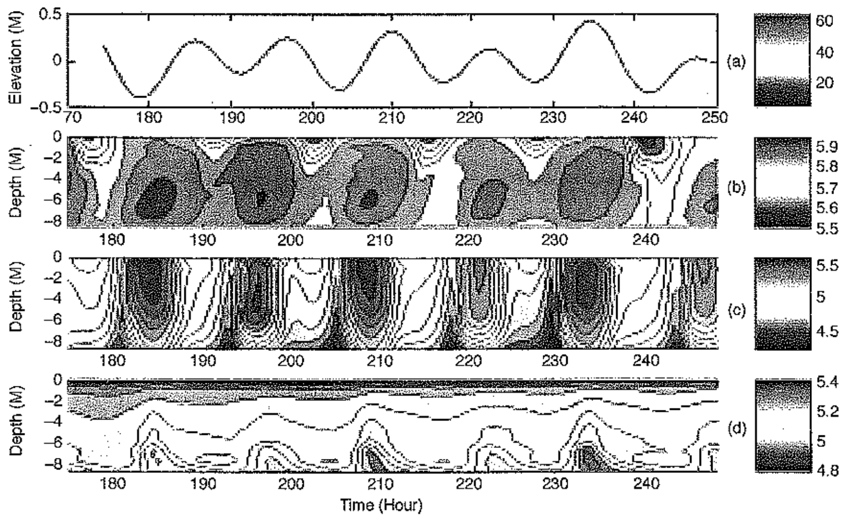

Fig. 14.15. The DO distribution within three tidal cycles at the selected points: (a) is the elevation at the channel; (b) selected point (P1) outside the bay; (c) selected point (P2) in the channel region; (d) selected point (P3) in the inner portion of Xincun Bay.

thus playing an important role in the ecosystem by reducing the risk of other less desirable algal blooms.

Summary

The management of aquaculture in embayments is influenced by numerous physical, chemical and biological factors, many of which cannot be controlled by the aquaculturist alone. It is the responsibility of the resource managers to maintain and improve the environmental situation in the bay for multiple uses, including aquaculture. Balancing the uses of the bay is not a simple task. It calls for advanced technological tools, such as three-dimensional modelling, to inform and integrate the process of coastal management. This chapter presented two examples of how integrated ecosystem models can enhance the understanding of the processes affecting water quality.

Jiaozhou Bay is a relatively large bay (~400 km^2) adjacent to a major city, Qingdao, and has numerous sources of nutrient inputs. In Jiaozhou Bay, tides and southeast winds dominated the summer distribution of nutrients, phytoplankton and zooplankton, but the basic productivity in this phosphorus-limited ecosystem could be altered in the scallop aquaculture areas. Simulation experiments made at scallop stocking densities of 12 and 24 individuals m^{-3} illustrated the potential impact of stocking rate on phytoplankton. In both cases, scallops grazing in suspended rake culture dramatically decreased the concentrations of phytoplankton in the culture areas. However, the potential impact of scallop culture on the concentrations of nutrients was very small, which contrasts with previous studies (Dame, 1993). One explanation is that the model did not consider the impact of biodeposition from the shellfish. Biodeposition could result in shellfish taking up small particulate organic matter and producing faeces and pseudofaeces that decompose into organic nutrients. This model did include shellfish excretion that was converted directly to phosphates. Another 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. The implication for the coastal manager is that the scallop rakes in Jiaozhou Bay had little impact on the water quality of this large bay, other than to reduce phytoplankton in the aquaculture areas. Importantly, the model did point to the danger of the nutrients accumulating in the shallow northwest quadrant of the bay, where they could contribute to local blooms and red tides.

In Xincun Bay on Hainan Island, the situation is very different. Xincun Bay is a shallow subtropical lagoon of about 22 km^2 with a 120-m-wide inlet. Macroalgae, pearl oysters, shrimp and fish are cultured in the lagoon. The fish pen culture site near the navigation channel is the most economically and environmentally important aquaculture activity in the lagoon. Fish pen culture units that occupied 230 ha of the lagoon in 1996 declined to 33 ha in 1999 after disastrous losses. Results of this study indicated that organic matter heavily polluted the water in the fish pen areas. Still, except for DO, chemical parameters and nutrients did not exceed China's national water quality standard Class I, nor would they have exceeded Florida's (USA) water quality standards. Although the water generally met the standards, the environmental health in the cage culture area and navigation channel is declining as evidenced by the fish deaths and low DO. Two types of pollutants influence water and sediment quality in the lagoon. Organic pollutants from the town of Xincun help reduce the DO, but the main source of organic pollution is from the fish cages. Uneaten food and faeces decay and fall to the bottom. As a result, the sediments have become anaerobic and release NH_3, H_2S and other pollutants. Simulation experiments using the three-dimensional model predicted that the average DO concentration would decrease by 10% if the number of cages was doubled. Macroalgal culture in the middle region of the lagoon can enhance DO concentrations in the macroalgal culture areas but has little impact on DO concentrations in the fish cage areas.

The assessment of nutrient levels shows that inorganic phosphorus is low relative to other nutrients in Xincun Bay. The latter are generally at low levels, except in the fish culture region of the bay: this is beneficial for most aquaculture. As *Kappaphycus* sp. is usually cultured in oligotrophic, tropical or subtropical regions, its productivity is limited by nutrient-depleted waters. Moreover, nutrient requirements vary greatly between species. The point is that with integrated aquaculture, moving commercially important seaweeds closer to the source of nutrients alleviates potential nutrient limitations for seaweed production. Also, from looking at the internal nitrogen and phosphorus tissue contents in seaweeds and seagrasses in the bay, our data suggest that these primary producers can act as key nutrient scrubbers from the water column and sediments. These organisms may play a key competitive role in the ecosystem by reducing the risk of other less desirable, potentially harmful micoalgal blooms.

The case studies presented here illustrate three-dimensional integrated hydrodynamic models that can be used to assess water quality issues. In these cases, we focused on aquaculture. The impacts of extractive aquaculture may be benign or positive. Fed aquaculture, as is the case in Xincun Bay, can have serious impacts on water quality if it is concentrated in small or poorly flushed areas. A solution may be to integrate extractive and fed aquaculture in each embayment. This is not a simple task, but ecosystem modelling offers promise of a management tool to evaluate the consequences of management alternatives. The same ecosystem modelling approach is a valuable tool to identify potential problem areas. For example, in Jiazhou Bay, the model reveals the tendency for nutrient accumulation in the northwest quadrant, thus identifying likely areas of blooms.

References

Ambrose, R.B. Jr, Wool, T.A. and Martin, J.L. (1993) *The Water Quality Analysis Simulation Program, WASP5, Part A: Model Documentation.* US Environmental Protection Agency, Athens, Georgia, 202pp.

Barg, U.C. (1992) *Guidelines for the Promotion of Environmental Management of Coastal Aquaculture Development.* FAO Fisheries Technical Report. No. 328. Food and Agriculture Organization of the United Nations, Rome, 328pp.

Blanton, J.O., Kinner, K.R., Castillejo, F., Atkinson, L.T., Schwing, F.B. and Lavin, A. (1987) The relationship of upwelling to mussel production in the Rias on the western coast of Spain. *Journal of Marine Research* 45, 497–511.

Blumberg, A.F. and Mellor, G.L. (1987) A description of a three-dimensional coastal ocean circulation model. In: Heaps, N.S. (ed.) *Three-Dimensional Coastal Ocean, Coastal Estuarine Science*, Vol. 4. American Geophysical Union, Washington, DC, pp. 1–16.

Boynton, W.R. and Kemp, W.M. (1985) Nutrient regeneration and oxygen consumption by sediments along an estuarine salinity gradient. *Marine Ecology Progress Series* 23, 45–55.

Chen, C., Ji, R., Zheng, L., Zhu, M. and Rawson, M. (1999) Influences of physical processes on the ecosystem in Jiaozhou Bay: a coupled physical and biological model experiment. *Journal of Geophysical Research* 104(C12), 29,925–29,949.

Chopin, T., Yarish, C., Wilkes, R., Belyea, E., Lu, S. and Mathieson, A. (1999) Developing *Porphyra*/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. *Journal of Applied Phycology* 11, 463–472.

Collaudin, B.A. (1996) *A First Approach of Aquaculture Development in Jiaozhou Bay (PR China).* Investigation Report, IFREMER, Brest, France.

Dame, R.F. (1993) The role of bivalve filter-feeder material fluxes in estuarine ecosystems. In: Dame, R.F. (ed.) *Bivalve Filter-Feeders in Estuarine and Coastal Ecosystem Processes. NATO Advanced Study Institute Series* 33, 235–270.

Di Toro, D.M., O'Connor, D.J. and Thomann, R.V. (1971) A dynamic model of phytoplankton population in the Sacramento–San Joaquin Delta. In: Hem, J.D. (ed.) *Nonequilibrium Systems in Natural Water Chemistry.* American Chemistry Association, Washington, DC, pp. 131–180.

Fisher, T.R., Carlson, P.R. and Barber, R.T. (1982) Sediment nutrient regeneration in three North Carolina estuaries. *Estuarine, Coast and Shelf Science* 14, 101–106.

Franks, P.J.S. and Chen, C. (1996) Plankton production in tidal fronts: a model of Georges Bank in summer. *Journal of Marine Research* 54, 631–651.

Frevert, T. (1980) Oxygen uptake rates in the sediment of the profundal zone of lake of Constance (Obersee) under oxic and anoxic conditions. *Journal of Hydrology* 42, 56–64.

Hemminga, M.A., Harrison, P.G. and Van Lent, F. (1991) The balance of nutrient losses and gains in seagrass meadows. *Marine Ecology Progress Series* 71, 85–96.

Hickey, C.W. (1984) Chamber studies of benthic oxygen uptake kinetics in the Waioyapu River, New Zealand. In: Hatcher, K. (ed.) *Sediment Oxygen Demand.* Institute of Natural Resources, University of Georgia, Athens, Georgia, pp. 37–62.

James, A. (1974) The measurement of benthal respiration. *Water Research* 8, 955–959.

Jorgensen, C.B. (1990) *Bivalve Filter Feeding: Hydrodynamics, Bioenergetics, Physiology, and Ecology.* Olsen and Olsen, Fredensborg, Denmark, 140pp.

Kasper, H.F., Gillespie, P.A., Boyer, I.C. and Mckenzie, L. (1985) Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepru Sounds. *New Zealand Marine Biology* 85, 127–136.

Kautsky, N. and Evans, S. (1987) Role of biodeposition by *Mytilus edulis* in circulation of matter and nutrients in Baltic coastal ecosystem. *Marine Ecology Progress Series* 38, 201–212.

Kautsky N., Troell, M. and Folke, C. (1996) Ecological engineering for increased production and environmental improvement in open sea aquaculture. In: Etnier, C. and Guterstam, B. (eds) *Ecological Engineering for Waste Water Treatment.* Lewis Publishers, Boca Raton, Florida.

Kraemer, G. and Mazzella, L. (1996) Nitrogen assimilation and growth dynamics of the Mediterranean seagrasses *Posidonia oceanica, Cymodocea nodosa,* and *Zostera noltii.* In: *Proceedings of the Rottnest Island International Seagrass Symposium,* Perth, Australia, pp 181–190.

Kraemer, G. and Mazzella, L. (1999) Nitrogen acquisition, storage, and use by the co-occurring Mediterranean seagrasses *Cymodocea nodosa* and *Zostera noltii. Marine Ecology Progress Series* 183, 95–103.

Liu, F. and Wang, K. (1992) The rivers along Jiaozhou Bay coastline and their geological effects. *Marine Science* [in Chinese] 1, 25–28.

Liu, R. (1992) The natural environmental characteristics of Jiaozhou Bay. In: Liu, R. (ed.) *Ecology and Living Resources of Jiaozhou Bay.* Science Press, Beijing, pp. 2–3.

Marine and Fishery Department of Hainan (1998) Coast and Marine Environment Plan. Asia Development Bank Report ADB-5712. Haikou, Hainan, PR China.

Murphy, J. and Riley, J.P. (1962) A modified single solution approach for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27, 31–36.

Naylor, R.L., Goldberg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. and Troell, M. (2000) Effect of aquaculture on world fish supplies. *Nature* 405, 1017–1024.

Nixon, S.W. (1982) Nutrient dynamics, primary production and fishery yields in lagoons. *Oceanology Acta* 5, 357–371.

Shen, Z. (1995) The variations of nutrients in Jiaozhou Bay. In: Dong, J. and Jiao, N. (eds) *Ecological Study of Jiaozhou Bay.* Science Press, Beijing, pp. 47–52.

Smith, L.K. and Fisher, T.R. (1986) Nutrient fluxes and sediment oxygen demand associated with the sediment–water interface of two aquatic systems. In: Hatcher, K. (ed.) *Sediment Oxygen Demand.* Institute of Natural Resources, University of Georgia, Athens, Georgia, pp. 343–366.

Stumm, W. (1973) The acceleration of biogeochemical cycles in phosphorus. *Progress in Water Technology* 2, 133–144.

Walker, R.R. and Snodgrass, W.J. (1986) Modeling for sediment oxygen demand in lakes. *Journal of Environmental Engineering* 112, 25–43.

Whittemore, R.C. (1984) Implementation of *in-situ* and laboratory SOD measurements in water quality modeling. Water Pollution Control Federation 56th Annual Conference, Atlanta, Georgia, 2–6 October 1983.

Winter, J.E. (1978) A review on the knowledge of suspension-feeding in lamellibrachiate bivalves, with special reference to artificial aquaculture systems. *Aquaculture* 13, 1–33.

Zhao, Y., Chen, Y. and Lin, Z. (1995) The climate around Jiaozhou Bay. In: Dong, J. and Jiao, N. (eds) *Ecological Study of Jiaozhou Bay.* Science Press, Beijing, pp. 8–24.