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The status of the ecological environment and a proposed protection strategy in Sanya Bay, Hainan Island, China

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Abstract

Sanya Bay encompasses a high diversity of natural habitats, ranging from coral reefs, rocky and sandy shores and mudflats to mangroves. Seasonal physicochemical and biological investigations were conducted from 1998 to 1999 and again in April 2000. Water-related environmental quality in Sanya Bay is in good condition. The levels of dissolved oxygen, nitrogen, phosphorus and heavy metals are within the first class of National Seawater Quality Standards for China. Annual mean values of chlorophyll *a* of 0.93 mg m^{-3} and phytoplankton primary productivity of 440.8 mgC m^{-2} d^{-1}, respectively, were found in the waters, both of which show a significant correlation with inorganic nitrogen. A mean new productivity of 144.6 mgC m^{-2} d^{-1} was recorded in summer. Sanya Bay is rich in natural resources and biodiversity with 235 species of phytoplankton and 129 species of zooplankton identified in the survey. The annual mean abundance of phytoplankton and zooplankton were 1564×10 cells m^{-3} and 121 individuals m^{-3}, respectively, with an annual mean zooplankton biomass of 129 mg m^{-3}. A total of 243 species of fish were sampled in the survey including many of high economic value. Three hundred and eighty-four species of benthos in 121 families were found by mud sampling and trawling. The average biomass of benthic organisms was 11.55 g m^{-2}, with a density of 31 individuals m^{-2}. Molluscs were the dominant group, followed by crustaceans; coelenterates exhibited the lowest biomass. One hundred and twenty-six species from 48 families of intertidal organisms were collected by frame sampling, with a mean annual biomass of 644.7 g m^{-2} and average density of 816 individuals m^{-2}. The highest biomass of 1673.5 g m^{-2} was collected in a coral reef region, while the highest density of 1219 individuals m^{-2} occurred in a mangrove region. The coastline is characterized by coral reefs that accounts for 30% of the total coastline length in the bay, so coral reefs are a key ecosystem that are important for maintaining the regional marine resources and biodiversity. We need to pay much more attention to such diverse marine resources to maintain the integrity and function of these coastal ecosystems.

Keywords: Sanya Bay; Physiochemical environment; Nutrients; Marine bio-resources; Coastal protection

1. Introduction

Coastal bays are subject to factors that reflect the interaction between land and ocean. Their ecological functions are more complicated and fragile than those of the open oceans because of the effect of many human activities and the resulting land-source pollution. With the sudden increase of population and rapid economic development, littoral areas are facing many ecological problems. Eutrophication and environmental pollution have obviously occurred in many coastal sea areas, especially in estuaries and coastal bays with dense human populations on their watersheds (Cloern, 1996; Turner and Rabalais, 1994; Yin et al., 2001). This has resulted in an ecological unbalance, the decrease of biodiversity and the rapid reduction of biological resources. It has been increasingly important to make the coastal economy and the coastal environment develop in harmony (Huang et al., 2001; Menasveta, 2001). Today, when scientific research is strongly linked with national economic and social sustainable development, it is necessary and even urgent for us to engage in research on the ecological environment and biological resources of tropical bays. Observations of coastal ecosystems and the study of marine bio-resources have attracted worldwide attention (Buzzelli, 1998; Fisher, 1991;

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Huang et al., 1989, 1994, 2001; Morton and Tseng, 1982). Many international programs and projects, including OSLR, LME, GLOBEC, LOICZ and JGOFS have been launched to address the problems confronting the world's coastal ecosystems and bio-resources.

2. Study area

China is a large coastal nation located along the western Pacific Ocean, having 18,000 km of mainland coastline and many islands with a total of 14,000 km of coastline. Hainan Island is one of the largest. Sanya Bay lies in the southernmost part (109°20′–109°30′E, 18°11′–18°18′N) of Hainan Island, with a water area of 120 km^2 and an average depth of 16 m. It is a typical tropical bay in China. Dongmao Island, Ximao Island and Luhuitou, located in the bay mouth, possess mostly coastal coral reefs. The Sanya River, located in the eastern part of the bay (length 31.3 km, drainage area 337 km^2 and annual flow of 2.11×10^9 m^3), has many kinds of tropical habitats including coral reefs, mangroves, rocky and sandy shores, mudflats, etc. The coral reefs and mangroves have special resource value and ecological benefits and are, therefore very important to the sustainable social and economical development in these tropical coastal areas. Coral reefs and mangrove areas have important relationships to the regulation and optimization of the tropical marine environments and have become the foci of much international attention in the past 20 years.

We have carried out systemic research on the production and dynamics of the variety of environmental factors in the Sanya Bay, including the ecological function of marine biological resources and the community organization and function of coral reefs and mangroves. Our results emphasize the importance of systemic research work on ecological processes and productivity in the tropical ocean and its influential coastal areas, including the sustainable use of the biological resources of Sanya Bay.

3. Data sources and methods

In 1998–1999 and in April 2000 the ecological environment and bio-resources in Sanya Bay were surveyed at 12 stations (Fig. 1) plus two monitoring locations. Temperature, salinity and depth of water were measured in the field using a CTD probe. The iodometric method was used for measuring dissolved oxygen (DO). pH was measured using a standard hydrogen electrode and reference electrode. Sea-water samples for analysis of nutrients, chlorophyll and phytoplankton were taken using 5-L GO FLO bottles at surface, middle and bottom layers, and other organism samples were collected according to the methods and sampling tools of "Specification for Oceanography Survey" (GB12763-91, China). Sample analyses were carried out in situ at the National Experiment Station of Tropical Marine Biology, Sanya, Hainan Island, China and at the South China Sea Institute of Oceanology, Chinese Academy of Sciences. Analytical methods for the various physico-chemical and biological parameters are given in Table 1.

4. Physical–chemical environment in the bay

4.1. Physical environment

Spatial distribution of water temperature showed high values in the western and low values in the eastern portions of Sanya Bay. Water temperatures were lower in the region east of Dongmao Island all year. Stratification

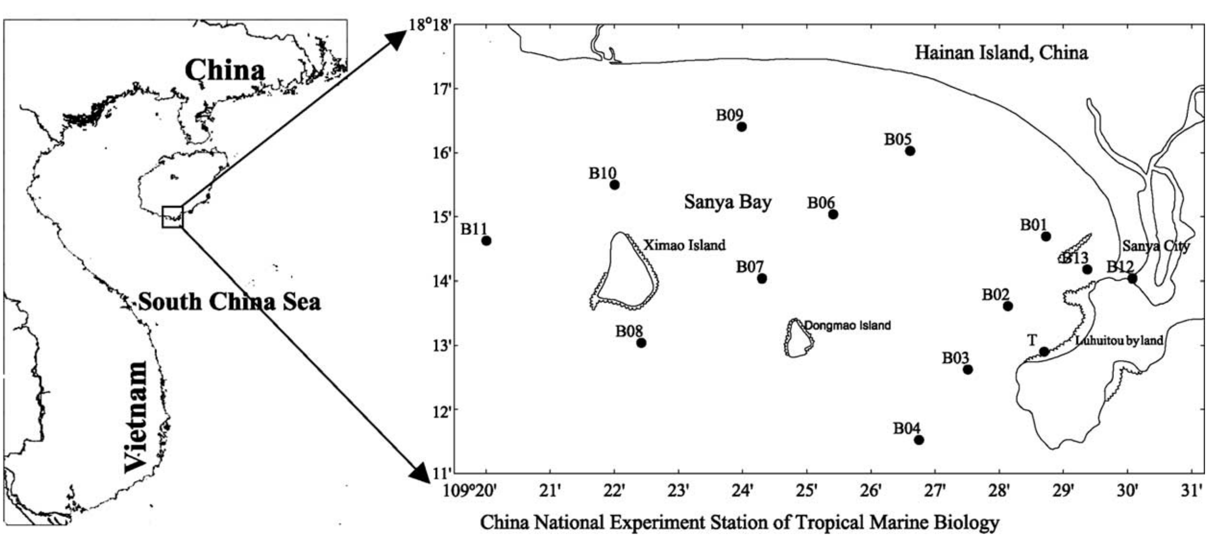

Fig. 1. Locations of sampling and environmental monitoring stations in Sanya Bay.

Table 1
Analytical methods for the various parameters reported in this study

Item	Method	Instrument used	Method detecting limit
Temperature	Measure in situ	CTD instrument	0.002 °C
Salinity	Measure in situ	CTD instrument	0.001
pH	Measure in situ	pH meter	±0.01
Dissolved oxygen	Measure in situ	DO meter	0.01 $mg\,dm^{-3}$
NO_3^{2-}-N	Diazotizing with sulfanilamide	Spectrophotometer, model 724	0.001 $mg\,dm^{-3}$
NO_2^{2-}-N	Coloured *N*-(1-naphthyl)-ethylendi-amine-dithydrochloride	Spectrophotometer, model 724	0.0005 $mg\,dm^{-3}$
NH_4^+-N	Oxidized by hypobromite	Spectrophotometer, model 724	0.002 $mg\,dm^{-3}$
PO_4^{3-}-P	Coloured molybdophosphoric blue	Spectrophotometer, model 724	0.001 $mg\,dm^{-3}$
SiO_3^{2-}-Si	Yellow molybdosilicic acid	Spectrophotometer, model 724	0.015 $mg\,dm^{-3}$
Chlorophyll *a*	Fluorescence method	Turner fluorometry	0.05%
Primary production	^{14}C method	Scintillation Counter Packard Model 2000 CA/LL	
New production	^{15}N method	Ion Mass Spectro-graph Model ST-IMS-88	
Phytoplankton	Sampling water	Microscopy	
Zooplankton	Trawling net	Shallow I Net	
Fishes	Trawling net	Hang and Beam trawl	
Benthos	Trawl and dredge	Dredge trap and Beam trawl	

due to temperature and salinity differences between surface and bottom waters inside the bay started to develop in spring, became strongest in summer, and dissipated in autumn; temperature and salinity were uniformly distributed with depth in winter. Diel changes of temperature and salinity in the bay differed according to season. Based on data measured in situ from 1998 to 1999, the highest surface and bottom water temperatures occurred in October and the lowest in January.

Cold-water upwelling, which affects the distribution of a variety of nitrogen compounds, fluctuates in Sanya Bay. The vertical and seasonal variations and distribution of water temperature suggests that the bay is affected by an exotic cold-water upwelling and thermocline occurring during June–August. During that time, the thermocline temperature gradient averaged 0.138–0.283 $°C\,m^{-1}$, with the maximum gradient averaging 0.419–0.440 $°C\,m^{-1}$. The minimum water temperature in the bottom was about 22 °C. The thermocline disappeared from September to the following March due to the mixing of the seawater.

Sea currents inside Sanya Bay are weaker than the dominating tidal currents. The velocity of the residual current is also low. The residual current at the surface and bottom flowed in opposite directions in spring and summer and in the same direction in autumn and winter. The tidal current is governed by an irregular diurnal tide.

4.2. Chemical environment

Spatial distribution of dissolved oxygen in Sanya Bay is more uniform than for temperature and salinity, but we still observed regional and seasonal variations. Distribution of dissolved oxygen in spring and summer was higher in the southeastern than in the northwestern portions. The distribution in autumn and winter decreased from east to west and in the bay mouth. The highest dissolved oxygen content occurred in winter and the lowest in autumn (Table 2).

Seasonal changes of pH values are consistent with that of phytoplankton abundance. The phytoplankton amount was highest in autumn, as was the pH value. Opposite conditions appeared in spring and winter. COD values were much lower than that of other bays and estuaries (Huang et al., 1994, 2001). Highest values

Table 2
Dissolved oxygen content of water samples ($mg\,dm^{-3}$)

Season	Layer	Range	Average	Mean
Spring	Surface	6.01–6.35	6.20	6.17
	Bottom	5.99–6.23	6.14	
Summer	Surface	5.83–6.27	6.10	5.92
	Bottom	5.28–6.16	5.73	
Autumn	Surface	5.70–6.24	5.93	5.82
	Bottom	5.35–6.02	5.71	
Winter	Surface	6.53–7.12	6.87	6.87
	Bottom	6.48–7.12	6.87	

Table 3
Seasonal concentrations of different forms of N in Sanya Bay

Season	Average ($mg\,dm^{-3}$)					N accounting for % of TIN			TIN accounting for % of TN
	NH_4^+	NO_2^-	NO_3^-	TIN	TN	NH_4^+	NO_2^-	NO_3^-	
Autumn	0.012	0.0013	0.010	0.023	0.424	52.17	5.65	43.47	5.42
Winter	0.005	0.0004	0.006	0.011	0.226	45.45	3.63	54.54	4.86
Spring	0.013	0.0012	0.008	0.022	0.356	59.09	5.45	36.36	6.17
Summer	0.024	0.0013	0.009	0.033	0.473	72.72	3.93	27.27	6.97
Mean	0.014	0.001	0.008	0.022	0.370	63.63	4.54	36.36	5.94

occurred in summer and the lowest in spring, while the level in autumn is close that in winter. Spatial distribution of COD values in summer decreased from east to west. The average COD across all seasons was 0.25–0.63 $mg\,dm^{-3}$.

Organic N constitutes more than 90% of the total N in Sanya Bay waters. Inorganic N levels are low according to the National First Class Water Quality Standards for China. NH_4-N is the dominant DIN form, accounting for more than 50% of the TIN in spring, summer and autumn. We found that the NO_3-N content is lower relative to NH_4-N, revealing a thermodynamic imbalance between NH_4-N, NO_2^--N and NO_3^--N. Biological activity may be the main factor influencing the balance, but there were different degrees of transformation of NH_4^+-N for the different bay regions. Inorganic and organic N concentrations ranked summer > autumn > spring > winter, averaging 0.022 and 0.370 $mg\,dm^{-3}$, respectively (Table 3). Their spatial distribution decreased from inshore to offshore waters.

Spatial distribution of the dissolved inorganic nitrogen (DIN) suggested that NO_3^--N and NO_2^--N were significantly affected by upwelling; NO_3^--N and NO_2^--N increased 10.2% and 37.2% (surface), 83.81% and 64.04% (middle), and 82.96% and 119.41%, respectively. In contrast, the distribution of NH_4^+-N appears not to be affected by the upwelling.

The composition of nutrients clearly undergoes seasonal variations in Sanya Bay. Assessment standards of nutrient limitations are given by Justice et al. (1995), that is, (a) if Si:P > 22 and DIN:P > 22 then DIP is the limiting factor; (b) if DIN:P < 10 and Si:DIN > 1 then DIN is the limiting factor; and (c) if Si:P < 10 and Si > DIN > 1 then dissolved inorganic silicon is the limiting factor. The observed data suggest that N limitation in summer and autumn changes to P limitation in winter in Sanya Bay, while there is little probability of Si limitation. The results of nutrient enrichment experiments in the laboratory agreed with the conclusions of the field investigation.

The concentration of both P and Si were low. Spatially both the nutrients decrease from east to west and from inshore to offshore waters, probably as a result of the effects of land sources and the Sanya River. We linked the enrichment experiments with the in situ investigation to explore the relationship between the chemical form and the effects of environmental changes on the release P from sediments in the bay. The results suggest that the total phosphorus (TP) in the sea-water in Sanya Bay consists mainly of the total dissolved phosphorus (TDP), which accounts for more than 60% of TP. TP in the sediment consists mainly of inorganic phosphorus (IP, accounting for 70% of TP). TP, organic phosphorus (OP) and IP have a greater effect on the release of P from the sediment than the other forms, and changes of temperature, salinity and pH have also definite effects on P release. Correlation analysis suggests that the same factors affect the release of TDP. All of the PO_4^{3-}, TP and SiO_3^{2-} have exhibited seasonal changes (Table 4), with concentrations in the wet season higher than in the dry season.

Table 4
Concentrations of PO_4^{3-}-P, TP, SiO_3^{2-}-Si content ($mg\,dm^{-3}$) in different seasons

Season	Layer[a]	PO_4^{3-}-P	TP	SiO_3^{2-}-Si
Spring	S	0.001	0.008	0.162
	B	0.002	0.007	0.165
Summer	S	0.003	0.012	0.686
	B	0.003	0.015	0.692
Autumn	S	0.001	0.014	0.187
	B	0.002	0.012	0.160
Winter	S	0.002	0.010	0.141
	B	0.001	0.011	0.119

Quality Standards of Seawater from GB3097-1997, China first class ($mg\,dm^{-3}$) $\leqslant 0.015$; second class ($mg\,dm^{-3}$) $\leqslant 0.030$.
[a] S: surface layer water, B: bottom layer water.

5. Status of ecology and bio-resources

5.1. Chlorophyll a and primary production

The chlorophyll *a* (chl *a*) content in Sanya Bay ranged 0.45–1.55 $mg\,m^{-3}$ and averaged 0.93 $mg\,m^{-3}$ lower than that of Daya Bay and Zhujiang Estuary (Huang et al., 1989, 1997). The means of chl *a* in spring, summer, autumn and winter were 0.41, 1.08, 0.86 and 1.36 $mg\,m^{-3}$, respectively (Table 5). Diurnal changes of chlorophyll showed a single peak in surface water and a

Table 5
Seasonal production measurements in Sanya Bay

Season	Production	Range	Average
Spring	Chl *a* ($mg\,m^{-3}$)	0.28–0.83	0.41
	Phytoplankton ($cells\,m^{-3}$)	1.06×10^5–8.26×10^6	2.11×10^6
	Zooplankton ($ind\,m^{-3}$)	4.1–55	28
	Biomass ($mg\,m^{-3}$)	7–85	28
	Div. index (H')	1.14–2.43	1.91
	Equality (J)	0.71–0.86	0.77
Summer	Chl *a* ($mg\,m^{-3}$)	0.15–1.38	0.69
	Phytoplankton ($cells\,m^{-3}$)	2.67×10^6–2.53×10^7	1.19×10^7
	Zooplankton ($ind\,m^{-3}$)	67.4–289.1	143.1
	Biomass ($mg\,m^{-3}$)	58.3–206.3	117.6
	Div. index (H')	2.24–2.77	2.45
	Equality (J)	0.66–0.83	0.74
Autumn	Chl *a* ($mg\,m^{-3}$)	0.43–2.17	0.86
	Phytoplankton ($cells\,m^{-3}$)	2.49×10^5–2.74×10^8	3.43×10^7
	Zooplankton ($ind\,m^{-3}$)	63.5–271.3	114.3
	Biomass ($mg\,m^{-3}$)	58–708	197
	Div. index (H')	1.05–2.45	1.90
	Equality (J)	0.47–0.69	0.56
Winter	Chl *a* ($mg\,m^{-3}$)	0.72–3.07	1.16
	Phytoplankton ($cells\,m^{-3}$)	8.49×10^5–3.68×10^7	1.43×10^7
	Zooplankton ($ind\,m^{-3}$)	5.6–371.6	141.4
	Biomass ($mg\,m^{-3}$)	33–335	172
	Div. index (H')	1.95–3.67	2.70
	Equality (J)	0.81–0.99	0.87

double peak in bottom water. There was an obvious correlation between chl *a* and DIN in surface waters. Chl *a* was negatively correlated with zooplankton biomass in spring and winter. Seasonal variation of potential primary production ranked summer > winter > spring > autumn; the coefficient of assimilation ranked spring > summer > winter > autumn, with an annual average of 3.77 mgC $(mgChl\text{-}a)^{-1}h^{-1}$. Primary production in winter and summer was more than twice of that in spring and autumn, respectively; the annual average 440.8 $mgC\,m^{-2}\,d^{-1}$ is higher compared with other bays (Huang et al., 1989). The f-ratio and new production show some differences from one research station to another. In summer, the f-ratios in the surface and bottom water were 0.16 and 0.21, respectively, showing that the uptake rate of NO_3^--N of the phytoplankton in the bottom was greater than that in the surface. New production in summer averaged 144.6 $mgC\,m^{-2}\,d^{-1}$ and exhibited a similar distribution with that of primary production; it decreased gradually from the southeast part of the sea area to the northwest.

5.2. Plankton

We identified 219 species of phytoplankton in Sanya Bay. Of the 183 species of diatoms, *Chaetoceros* had many more species than other genera (45 spp), followed by *Rhizosolenia* (23 spp) and *Coscinodiscus* (22 spp). The dominant species showed a clear seasonal succession, with an average annual abundance of 1.57×10^7 $cells\,m^{-3}$. Phytoplankton abundance peaked in autumn at 3.43×10^7 $cells\,m^{-3}$ (Table 5) and was lowest in spring at 2.11×10^6 $cells\,m^{-3}$ (only 1/16 of that in autumn). The coastal sea area around the city of Sanya and the adjacent waters of the Shaoqi River in the bay had higher abundance, while the mouth of the bay always showed a lower value than that in the inner bay. The vertical distribution of phytoplankton abundance in the day is uniform in spring, summer and autumn, and there were no obvious variations between the water layers. In the autumn the bottom water layer (10–15 m) had less abundance of phytoplankton at night, while in winter the distribution form was pyramid-shaped with higher abundance at the bottom.

Zooplankton sampled from the Sanya Bay studies comprised 129 species in 14 genera. They can be divided into four ecological forms: estuary and inner bay type, warm coastal type, and warm open sea type. The latter two types accounted for the most species. Variations of dominant species exhibited a seasonal succession. In these studies the abundance of zooplankton varied seasonally, with a single maximum; the peak of biomass occurred in autumn while the maximum number of individuals occurred in winter. Minimum values of both parameters occurred in spring. The differences between the biomass and individual numbers in different seasons were caused by the composition of species. The annual average biomass of zooplankton was 129 $mg\,m^{-3}$ and the annual individual number was 121.38 ind m^{-3}. Both showed a spatial distribution with lower values in the western area of the mouth of the bay. The variation of zooplankton biomass had the same trend as that of phytoplankton, but it was opposite to the seasonal variation of chl *a* concentration.

5.3. Fishes

A total of 243 species of fishes were captured by three kinds of nets in four cruises, including many edible species of high economic value such as *Clupanodon punctatus*, *Anchoviella* sp., *Saurida undoquamis*, *Trachinocephalus myops*, *Gerres filamentosus*, *Sparus berola*, *Epinephelus* sp., *Upeneus subvittataus*, *Trichiurus haumela* and *Inegocia guttatus*. Most fishes in the Sanya Bay are small coastal species. However, because it has a sandy bottom with coral reefs and an environment suitable for growth, the fish resources are abundant compared with other small bays that have less suitable environments.

5.4. Benthos

Sanya Bay has a high diversity of natural habitats. Three hundred and eighty-four species of benthos from 121 families were found by mud sampling and trawling. Except for a very few species, the benthic organisms in the bay are almost all warm-water species with relatively few individuals. The average biomass of benthic organisms was 11.55 g m^{-2} with a density of 31 ind m^{-2}. Molluscs were the dominant group, followed by crustaceans; coelenterates exhibited the lowest biomass. Seasonal variation of biomass and density show similar trends with a maximum in winter and minimum in autumn and a nearly equal value in spring and summer. The biomass maximum occurred at the central part of the bay, caused by the species *Laganum depressum* (Lesson) and *Laganum decagonale* (Blaiuville).

Intertidal benthos, frame-sampled from all four habitat types, revealed 126 species from 48 families with a mean annual biomass of 644.7 g m^{-2} and average density of habitat of 816 ind m^{-2}, respectively. The highest biomass of 1673.5 g m^{-2} as well as the greatest number of species were collected from the coral reef regions, while the highest density of habitat, 1219 ind m^{-2}, was in the mangrove region.

5.5. Coastal coral reefs and mangrove

Coral reefs, which account for 30% of the total coastline in Sanya Bay, are concentrated in the vicinity of Luhuitou and the islands to the east and west in the mouth of the bay. Based on data investigated in 1962–1965 (Zou et al., 1975), there were formerly at least 81 coral species along the Luhuitou coast, accounting for 70.4% of the madrepore reef for all of Hainan Island. Yu and Zou (1996) found only 58 species in 1993–1994, while only 35 species were collected during 1998–1999. Obviously, the Sanya Bay coral reefs have been seriously degraded since the 1960s. We need to make a much greater effort to protect these diverse resources to maintain their ecological function.

Mangrove only grows on the coast near the Sanya estuary. It covers 60–90% of this area (14 ha) and is mainly comprised of small shrubs. The dominant species were *Rhizophora apiculata* and *Avicennia marina*, but a total of eight species were identified. The annual production of litter in the mangrove area is 194 t.

6. Conclusion: strategy of protect and management in Sanya Bay

Sanya Bay is essentially a tropical marine ecosystem that possesses a superior environment and many economically important species. It is a good place for the reproduction and culturing of fish, shrimp, crabs and shellfish. Its diverse coastal habitats include coral reefs, mangroves, rocky and sandy shores, and an accompanying rich biodiversity. Like other coastal bays it is exposed to the constant interaction between land and ocean and its ecology is more complicated and fragile than that of the open sea. And, like other coastal bays, it is especially vulnerable to the effects of frequent human activities and land-based pollution. With tourism expansion and the rapidly growing population of Sanya city (currently at 400,000 inhabitants), the effects of human activities on the bay are increasingly significant, including more domestic sewage and industrial waste water discharge as well as nutrient enrichment and toxins derived from the cage culture of fishes. Despite the good water quality Sanya Bay at present, the concentrations of N, P, Si, DO, COD and heavy metals must not be allowed to exceed water quality standards at the risk of serious ecosystem degradation. Regional coordination in protection and management of such vulnerable coastal marine ecosystems should be strengthened (Kirkman, 2001).

The following strategic protection and management steps are recommended:

(1) Enhance information dissemination and education to improve environmental protection awareness of all people in the region.
(2) Strengthen the long-term monitoring of the marine environment and coastal ecosystems in Sanya Bay, enhance the study of regional environmental capacity, and use that capacity to establish large-scale control of pollutant discharges.
(3) Promote the protection of coral reefs, mangroves, seagrass farms and coastal ecosystem and regional

biodiversity by carrying out scientific plans for resource use based on marine system functions.
(4) Strictly enforce regulations relating to the marine environment and fisheries.

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