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Long-term temporal-spatial dynamics of marine coastal water quality in the Tolo Harbor, Hong Kong, China

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Abstract: The long-term temporal and spatial dynamics of marine coastal water quality in Tolo Harbor, Hong Kong were explored. The Harbor is divided into three zones represented as Harbor, Buffer, and Channel Subzones. The time range for the study covers the period from the 1970s to the 1990s. The selected indicators for the comprehensive assessment of water quality consist of physical, chemical and biological aspects, including suspended solids(SS), Secchi disk depth(SD), 5-day biochemical oxygen demand(BOD_5), total nitrogen (TN), total phosphorus(TP), faecal coliform, chlorophyll-a(Chl-a), and the number of red tide occurrences. The results indicated the presence of obvious temporal and spatial trends with regard to changes in water quality. Spatially, water quality in the Channel Subzone is the best, while that in the Harbor Subzone is the worst. On a temporal basis, the average trend from bad to good was 1980s > 1990s > 1970s as indicated by most of the selected water quality indicators. Water quality during the late 1980s reached its worst level with the lowest SD, the highest BOD_5, TN, TP, Chl-a concentrations, and the number of red tide occurrences. These long-term temporal-spatial water quality trends were also found in other studies of the Tolo Harbor. The large quantity of pollutants produced as a result of increasing population, industrial and commercial actives, and urbanization and industrialization trends in both Shatin and Tai Po seem to be primarily responsible for the changes in marine coastal water quality.

Keywords: temporal-spatial dynamics; water quality; indicators; pollution load; Tolo Harbor

Introduction

Tolo Harbor is located in the northeastern part of Hong Kong. It is a nearly land-locked water body with only one narrow exit to the open sea at Mirs Bay(Fig. 1). Its length and surface area are approximately 15 km and 52 km^2, respectively. The average depth varies from less than 10 m in the Harbor Subzone to over 20 m at the Channel Subzone near the mouth. Its present catchments area covers approximately 5000 hm^2 including agriculture land, industrial areas, two large urban areas(Sha Tin and Tai Po), numerous small rural hamlets and a few fishing villages. The hydrology of Tolo Harbor is affected by tidal influx from Mirs Bay, runoff water within the catchment, and effluents from Sha Tin (including Ma On Shan) and Tai Po. The average diurnal tide is 0.97 m, with a mean high tide of 1.75 m and a mean low tide of 0.78 m (EPD, 1994). The average annual rainfall in the catchment is about 2200 mm, with a normal runoff of 67 million m^3, 80% of which occurs between May and September(Xu, 2001). The principal runoff waters enter Tolo Harbor through rivers, including the Tai Shui Hang Steam, Shing Mun, Lam Tsuen, and Tai Po rivers whose average annual discharge rates are 4.01, 6.88, 2.49 and 5.33 million m^3, respectively (Hodgkiss, 1986). The average current velocity(recorded in the Inner Harbor) is 0.04 m/s(EPD, 1987a). This weak water circulation together with density stratification from May to September and prevailing northeasterly winds throughout the year act to prevent the rapid transport of pollutants out of Tolo Harbor. As such, Tolo Harbor has only a limited capacity to assimilate pollutants and is being progressively polluted.

Prior to the 1970s, Tolo Harbor was rich with corals, benthos, and seaweed(Binnie, 1978; Morton, 1988). However, since the early 1970s, the rapid growth of population and the intensive development of industry and agriculture(mainly the rearing of pigs and poultry) have dramatically changed the marine coastal environment. The objectives of this paper are: (1) to examine the temporal and spatial dynamics of marine coastal water quality from the 1970s to the 1990s in Tolo Harbor; (2) to analyze the main causes behind these changes; and (3) to propose some suggestions for further improvements in marine coastal water quality.

1 Methods

In order to examine the spatial trends in marine coastal water quality, the harbor was divided into three parts: Harbor Subzone, Buffer Subzone, and Channel Subzone. The characteristics of each are listed in Table 1. The more detailed long-term dynamics of water quality in Tolo Harbor were examined from the 1970s to the 1990s. This time span was further subdivided into three periods: 1970s, 1980s and 1990s, to analyze the average temporal trends in water quality in the three different subzones of Tolo Harbor.

In order to make a comprehensive assessment of marine coastal water quality in Tolo Harbor, the water quality indicators included physical, chemical, and biological components. The specific indicators included suspended solids(SS), Secchi disk depth(SD), 5-day biochemical oxygen demand (BOD_5), total nitrogen (TN), total phosphorus(TP), faecal coliform, chlorophyll-a(Chl-a), and a count of the number of red tide occurrences.

The data used in analyzing the temporal and spatial dynamics of Tolo Harbor's water quality were provided from the monitoring program. Beginning in 1973, the monitoring program was operated by Hong

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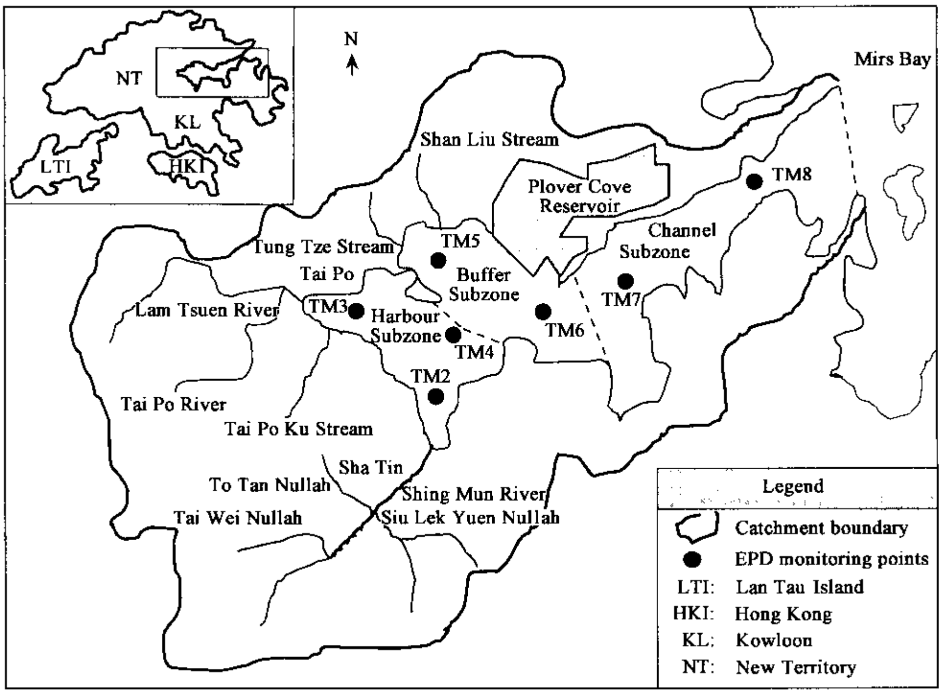

Fig.1 Sketch map of Tolo Harbor catchment showing its location, new towns, major rivers, three subzones and EPD monitoring points

Kong's Engineering Development Department (EDD). Since 1982, the task has been handled by the Environmental Protection Department (EPD). Annual average values for the selected indicators have been used to as a basis to gauge the long-term trends of water quality. In addition, individual surveys on water quality from the 1970s to the 1990s were also collected.

Table 1 Three subzones and their characteristics in Tolo Harbor

	Harbor subzone	Buffer subzone	Channel subzone
Surface area, km^2	13	13	25.8
Depth, m	2—10	10—20	> 20
Current velocity, m/s	0.04	0.04—0.08	0.08
Mean water temperature, ℃	23.57	23.47	23.16
Mean salinity, ‰	29.91	30.30	30.94
Mean dissolved oxygen, mg/L	8.48	8.30	7.76
Mean pH	8.43	8.40	8.35
Main inflow rivers	Lam Tsuen River, Tai Po River, Tai Po Kau Stream, Ching Mun River	Shan Liu Stream, Tung Tze Stream	No

2 Results

Trends in the average values of the water quality indicators for the three subzones of Tolo Harbor are shown in Table 2. The detailed long-term dynamics of the water quality indicators (SS, SD, BOD_5, TN, TP, faecal coliform, Chl-a, and the number of red tide occurrences), are illustrated in Figs. 2—8, respectively. As seen in Table 2, there appear to be some obvious temporal and spatial trends to the changes in water quality. Spatially, the concentrations for SS, BOD_5, TN, TP, faecal coliform, and Chl-a, are highest in the Harbor Subzone, followed by Buffer Subzone and then the Channel Subzone. For SD, the concentrations are smallest in Harbor Subzone, followed by Buffer Subzone and then the Channel Subzone. This would seem to indicate that water quality in Channel Subzone is the best, while water quality in Harbor Subzone is the worst. Temporally, the order from the highest to the lowest is more diverse. For SS is the order was 1970s > 1980s > 1990s, that for SD was 1970s > 1990s > 1980s; that for BOD_5, Chl-a, and the number of red tide occurrences was 1980s > 1990s > 1970s; and that for TN, TP, and faecal coliform was 1990s > 1980s > 1970s. In general, marine water quality in the 1970s was the best, characterized with the highest SD values and lowest values for BOD_5, faecal coliform, TN, TP, and number of red tide occurrences. Water quality during the 1980s was the worst with the lowest SD values and the highest values for BOD_5 Chl-a, and number of red tide occurrences.

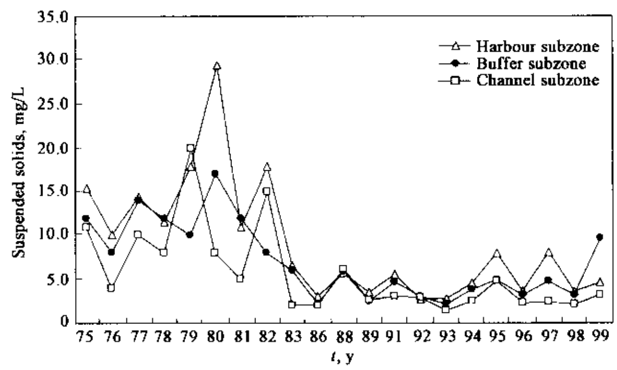

Fig.2 Long-term temporal and spatial changes of suspended solids in Tolo Harbor (1975—1981 data from EDD, 1985; 1982—1999 data from EPD, 1987a—1999)

The summarized results of the dynamics in the long-term water quality indicators are the shown in Figs. 2—8 and Table 3. As seen in Table 3 there are obvious temporal and spatial trends to the changes in the water quality indicators. Spatially, the concentrations for all of the selected indicators are the highest in the Harbor Subzone, followed by the Buffer Subzone, and the lowest in the Channel Subzone. This seems to indicate that water quality in the Channel Subzone is the best, while water quality in the Harbor Subzone is the worst. Generally, the temporal trends in SS increased during the 1970s then decreased from the early 1980s to the late 1990s. The general temporal trends for SD decreased from the early 1970s to the late 1980s, then increased during the 1990s. The general trends for BOD_5, TN, TP, Chl-a, and the number of red tide occurrences increased during the 1970s and 1980s to the early 1990s, then decreased thereafter. For faecal coliform, the general trend has increased from the 1970s to the 1990s. These changes suggest that water quality reached its worst situation during the later part of the 1980s, as evidenced by the lowest SD levels, and the highest levels in BOD_5, TN, TP, Chl-a, and the number of red tide occurrence. During the 1990s, water quality showed signs of steady improvement.

Table 2 Temporal-spatial changes of some indicators in harbor, buffer and channel subzones from the 1970s to the 1990s(calculated from EDD, 1985; EPD, 1987a-1999)

Indicators	1970s			1980s			1990s		
	HS	BS	CS	HS	BS	CS	HS	BS	CS
SS, g/L	13.9	11.2	10.6	11.0	7.6	5.8	4.9	4.4	2.8
SD, m	2.35	3.5	4.6	1.45	1.95	2.75	1.8	2.22	2.99
BOD_5, mg/L	1.78	1.38	1.00	3.05	2.18	1.39	2.39	1.84	1.17
TN, mg/L	0.236	0.221	0.145	0.578	0.395	0.324	0.775	0.620	0.545
TP, mg/L	0.032	0.027	0.025	0.068	0.046	0.037	0.12	0.091	0.076
Chl-a, mg/m^3	6.45	2.93	1.43	16.68	11.13	5.16	9.94	6.08	3.90
Number of red tide occurrence		4			156			89	
Faecal coliform	45.5	3.0	1.3	286.3	31.8	9.4	792.8	107.5	8.1

Notes: 1. HS: harbor subzone; BS: buffer subzone; CS: channel subzone; 2. SS: suspended solids; SD: Secchi disc depth; BOD_5: 5-day biochemical oxygen demand; TN: total nitrogen; TP: total phosphorus; Chl-a: chlorophyll-a; 3. EDD: Engineering Development Department; EPD: Environmental Protection Department

Table 3 Summarized results of long-term water quality dynamics in Tolo Harbor from Figs. 2—8

Figure	Indicator	Spatial changes(from high to lower)			Temporal changes	
		Trend	Exception	Uniformity	Trends for HS	Abnormity
Fig. 2	SS	HS > BS > CS	79, 81, 82, 99	Fair	75—80: ↑; 80—99: ↓	
Fig. 3	SD	HS > BS > CS	No	Good	73—89: ↓; 89—99: ↑	97, 98, 99
Fig. 4	BOD_5	HS > BS > CS	No	Good	75—89: ↑; 89—99: ↓	80, 96
Fig. 5	TN	HS > BS > CS	76, 77, 79	Good	73—90: ↑; 90—99: ↓	97, 98
Fig. 6	TP	HS > BS > CS	No	Good	73—91: ↑; 91—99: ↓	96
Fig. 7	F. coli.	HS > BS > CS	79,80	Fair	73—99: ↑	75, 99
Fig. 8	Chl-a	HS > BS > CS	No	Good	77—89: ↑; 89—99: ↓	81, 95, 96
Fig. 8	Red tides				77—89: ↑; 89—99: ↓	96

Notes: 1. HS: harbor subzone; BS: buffer subzone; CS: channel subzone; 2. SS: Suspended solids; SD: Secchi disc depth; BOD_5: 5-day biochemical oxygen demand; TN: total nitrogen; TP: total phosphorus; F. coli.: faecal coliform; Chl-a: chlorophyll-a; 3. ↑: increase; ↓: decrease

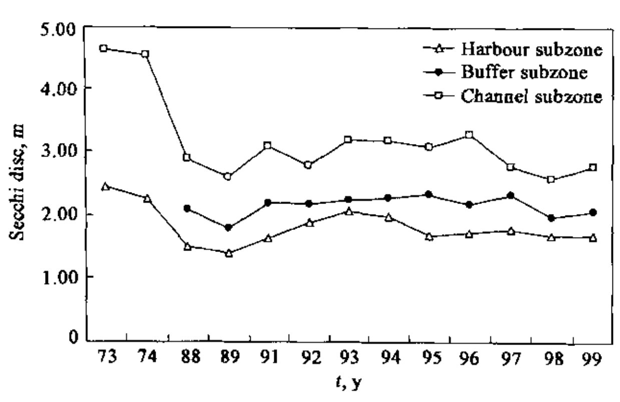

Fig.3 Long-term temporal and spatial changes of Secchi disc depth in Tolo Harbor(1973—1974 data from Kueh, 1975; 1988—1999 data from EPD, 1988—1999)

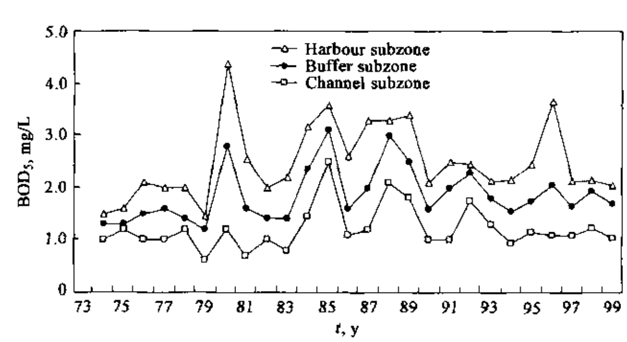

Fig.4 Long-term temporal and spatial changes of BOD_5 Tolo Harbor (1973—1981 data from EDD, 1985; 1982—1999 data from EPD, 1987a—1999)

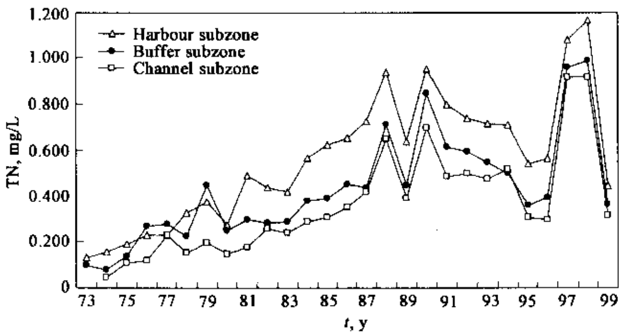

Fig.5 Long-term temporal and spatial changes of TN in Tolo Harbor (1973—1981 data from EDD, 1985; 1982—1999 data from EPD, 1987a—1999)

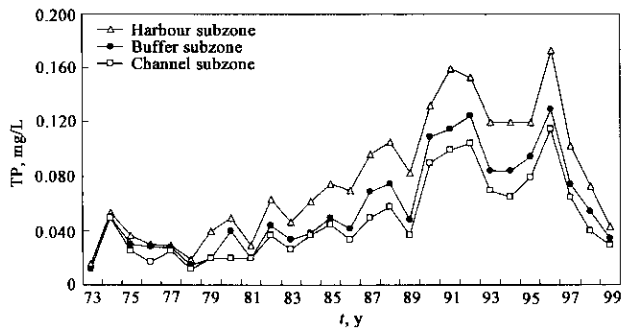

Fig.6 Long-term temporal and spatial changes of TP in Tolo Harbor(1973—1981 data from EDD, 1985; 1982—1999 data from EPD, 1987a—1999)

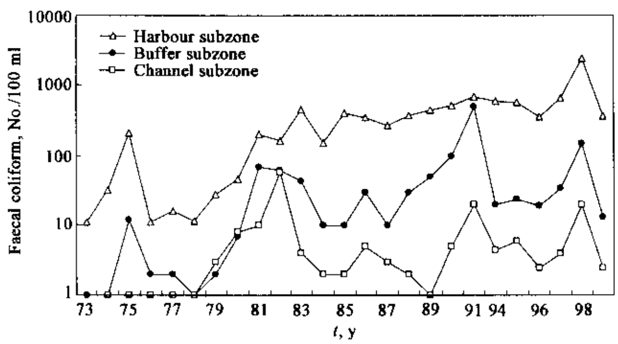

Fig.7 Long-term temporal and spatial changes of faecal coliform Tolo Harbor (1973—1981 data from EDD, 1985; 1982—1999 data from EPD, 1987a—1999)

3 Discussion

The long-term temporal-spatial water quality trends indicated above have also been observed in other studies of the Tolo Harbor. Several studies undertaken during the 1970's indicated that, in the Harbor Subzone, dissolved oxygen concentrations fell appreciably during the summer(Watson, 1971; Okaley, 1972; Trott, 1972), and that the existing concentrations of nitrate and phosphate as well as levels of coliform bacteria were already high in surface waters(Watson, 1971; Trott, 1973a; 1973b; Kueh, 1974a; 1974b; 1975; Gordon, 1975; Preston, 1975) clearly indicating that the polluted state of the Harbor Subzone. At that time, the channel waters were considered generally free

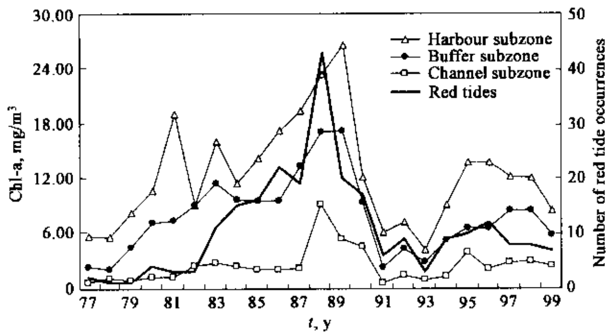

Fig.8 Long-term changes of Chl-a and the number of red tide occurrence in Tolo Harbor(1973—1981 data from EDD, 1985; 1982—1999 data from EPD, 1987a—1999)

of organic pollution(Trott, 1972; 1973; Kueh, 1974a; 1974b; 1975). Further research during the later 1970s and 1980s have demonstrated the steady and progressive decline in both harbor water quality and level of channel fauna towards the open sea (Morton, 1976; 1982; 1985; 1987; 1988; 1989; 1990; Stirling, 1977; Wong, 1977; 1980; Hodgkiss, 1981a; 1981b; 1988; 1983; 1986; Scott, 1982; 1990; Dudgeon, 1982; Thompson, 1982; Wear, 1984; Holmes, 1985; 1988; Yip, 1988; Lam, 1989). The situation became worse during the late 1980s with frequent occurrences of red tides and associated fish kills(Wu, 1979; 1982; 1988; Hodgkiss, 1988; Holmes, 1988; Morton, 1985, 1988; Yip, 1988; Lam, 1989), and coral deaths(Scott, 1982; 1990; Dudgeon, 1982). Morton(Morton, 1988) referred to Tolo Harbor as "Hong Kong's first marine disaster," indicating that Inner Tolo Harbor was effectively dead.

The large amounts of pollutants produced by human activities are responsible for the changes in Tolo Harbor's marine coastal water quality. By 1974, the harbor was already polluted by untreated sewage from about 70000 people and their livestock, but the impacts were primarily local(Wear, 1984; Morton, 1988). Since that time, however, the rapid growth in population(over 1 million in 1990) coupled with more intensive industrial and commercial actives, and increased urbanization in the new towns of Shatin and Tai Po has increased considerably the pollution loading to the harbor. By the early 1990s, for the 37 km^2 catchment area of the Shing Mun River, there were approximately 250 industrial and 460 commercial discharge facilities, 10 sewage treatment plants, 36 institutional discharge facilities, 5750 domestic discharge facilities, and 3 livestock farms(EPD, 1993b). In 1986, the BOD load produced from point sources in Shing Mun River catchment area was estimated to be 8300 kg/d, of which 45% came from commercial effluent, 43% from domestic sewage, 7% from livestock waste, and 5% from industrial wastewater. For the Lam Tsuen and Tai Po River catchment areas, the discharges amounted to approximately 6416 kg/d and 8300 respectively, with more of the contributions coming from livestock wastes and industrial wastewater, and less from commercial effluent and domestic sewage. Total TN loading into Tolo Harbor from point sources in 1986 amounted to 6000 kg/d, some 7.5 times the TN loading in 1976 (800 kg/d), with 69% of the TN load attributed to the sewered population, 12% from the unsewered population, 11% from pigs, and 8% from poultry sources (Holmes, 1988).

The critical water quality situation during the late 1980s resulted in the implementation of an integrated catchment management plan, the Tolo Harbor Action Plan(THAP) by Hong Kong Government in 1988. THAP is composed of seven component actions, such as livestock waste disposal control, the process modification of Sewage Treatment Works (STW), village sewerage collection, and effluent export scheme for Shatin & Tai Po STW. Since then, 83% of the BOD and 82% of the TN load from point sources have been reduced. This decrease in pollution loads may be responsible for the improvement in water quality during the 1990s. However, the improvement is unstable, with inverse fluctuations. Additional work is still needed to further improve water quality in Tolo Harbor. Two important areas for improvement are the elimination of internal nutrient loads and establishment of new management goals.

Eutrophication caused by excessive nutrient input is currently the most serious water quality problem in Tolo Harbor. Although 83% of TN load from point sources has been removed, algal blooms still occur with some frequency. This may be because the nutrients necessary for algal bloom are derived not only from external sources, but also from internal sources(Perking, 2001). A number of investigators have indicated that large nutrient discharges into natural aquatic ecosystems can accumulate in the sediments in both organic and inorganic forms. They can then be re-released back into the water under certain environmental conditions (Evans, 2001). This reduction in external supply loading through management, however, may increase the importance of internal nutrient loading from the sediment(van de Molen, 1994). For Tolo Harbor, the results for N and P release experiments performed by Hu *et al*. (Hu, 2001) demonstrated that sediments release significant amounts of nutrients especially orthophosphates and ammonia nitrogen, with the maximum release rates on the order of 15.0 and 206.0 $mg/(m^2 \cdot d)$, respectively. Although external nutrient loading has been reduced, nutrients could gradually be re-released back into the water column from the contaminated sediments and delay improvement in water quality and ecosystem health. The elimination of internal nutrient loadings from sediments remains a key step in further improving Tolo Harbor's water quality(in addition to continued efforts to control pollutant loadings from various point sources).

In terms of the integrated management of the Tolo Harbor catchment, it is recommended that the restoration and protection of marine coastal ecosystem health becomes the new goal, replacing the current water quality objectives. The increased compliance percentages for key water quality objectives and improvements in some of the physical, chemical and biological features in Tolo Harbor can only be considered a first sign of the ecosystem's restoration, since ecosystem health covers not only physical, chemical and biological aspects of an ecosystem, but also ecosystem-service-function aspects as well (Schaeffer, 1988; Costanza, 1992; Rapport, 1995; 1998a, 1998b; Xu, 2001). Only through the restoration and maintenance of ecosystem service functions, such as the providing of see food(fish, shellfish, crustaceans), marine farming, and primary contact recreation(bathing, diving), etc., can the marine coastal ecosystem in Tolo Harbor be completely restored.

4 Conclusions

The long-term temporal-spatial dynamics of marine coastal water quality in Tolo Harbor have been presented in this paper. The results indicated the presence of obvious temporal and spatial trends in water quality. Spatially, water quality trends proceed from good to bad in movement from the Channel Subzone to the Buffer Subzone to the Harbor Subzone. Temporally, the average trends from good to bad can be depicted according to the 1970s > 1990s > 1980s as indicated by most of the selected water quality indicators. Water quality during the later 1980s was the poorest, as evidenced by the lowest SD levels, and the highest BOD_5, TN, TP, Chl-a, and number of red tide occurrence levels. The rapid increase in population coupled with intensification in industrial, commercial, and agricultural activities within the catchment area remain the primary causes of change. The control of eutrophication brought on by excessive nutrient inputs remains a key task in improving water quality in Tolo Harbor. For the integrated catchment management scheme in Tolo Harbor, the restoration and protection of marine coastal ecosystem health should be instituted as a new goal, replacing the earlier goal designed around water quality objectives.

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