NETHERLANDS JOURNAL OF AQUATIC ECOLOGY 30(4) 297-307 (1997)

SEASONAL VARIATION OF PHYTOPLANKTON COMMUNITY IN THALE SAP SONGKHLA, A LAGOONAL LAKE IN SOUTHERN THAILAND

SAOWAPA ANGSUPANICH and SUPHAPHORN RAKKHEAW

KEYWORDS : phytoplankton, temporal variation, abundance, diversity, salinity, total nitrogen, total phosphorus, lagoonal lake, Thailand.

ABSTRACT

The phytoplankton in Thale Sap Songkhla was investigated at 2-3 month intervals from August 1991 to October 1993. The abundance of phytoplankton ranged from 1.4×10^6 to 1.3×10^9 cells m^{-3}. A total of 6 divisions with 103 genera were identified as Bacillariophyta: 49 genera, Chlorophyta: 21 genera, Pyrrhophyta: 15 genera, Cyanophyta: 12 genera, Chrysophyta: 3 genera and Euglenophyta: 3 genera. Although phytoplankton abundance was distinctly greater in the first year of study (August 1991 - June 1992) than in the second year (August 1992-October 1993), their patterns are similar : 2 peaks yearly. The peaks of phytoplankton occurred in the heavy rainy season (northeast monsoon) and the light rainy season (southwest monsoon). The main bloom was found during December-January, with a predominance of blue-green algae (*e.g. Aphanizomenon* and *Phormidium*) and green algae (*e.g. Eudorina*). Their species composition also increased, an effect of the large amount of rainfall resulting in low salinity during the northeast monsoon. The minor bloom was produced by diatoms during June-July when water salinity was moderate to seawater. Both phytoplankton numbers and species composition were high. However, unpredictably heavy rainfall during the southwest monsoon period may reduce diatom production due to rapid immediate replacement by blue-green species. Besides salinity concentration, a low total nitrogen : total phosphorus (TN : TP) ratio tended to support the growth of blue-green algae. The diversity of phytoplankton was lowest in the heavy rainy period.

INTRODUCTION

Phytoplankton is a major producer in any aquatic ecosystem. Its community structure is important to higher trophic levels because it influences the efficiency of carbon and energy transfer between trophic levels in any given system (MALLIN *et al.*, 1991). In a brackish-water lagoon, the seasonal water input controlled algal seasonality mainly through its effect on salinity and indirectly through its influence on nutrient concentration by dissolution and dilution of the excrements of the numerous cattle and other organic matter (CALJON, 1987). Studies on abundance and structure of the phytoplankton community will be crucial to an understanding of the ecosystem dynamics of lakes. Phytoplankton studies in Songkhla Lake mostly emphasized diversity, rather than the seasonal abundance of individual species (PHANITSOOK and CHONGPRASERT, 1970 cited in INSUWAN, 1981; SIRIMONTAPORN *et al.*, 1978). The objective of the present study is to ascertain seasonal patterns of phytoplankton succession from the aspects of both abundance and diversity.

Thale Sap Songkhla, a mesotrophic lake, is strongly influenced by the monsoon, which brings a heavy rain period to this area. Based on this, the year has been divided into a dry season (middle February - middle May) and a wet season (middle May - middle February) (CLIMATOLOGY DIVISION, 1989). The wet season is subdivided into a light rainy period or southwest monsoon period (middle

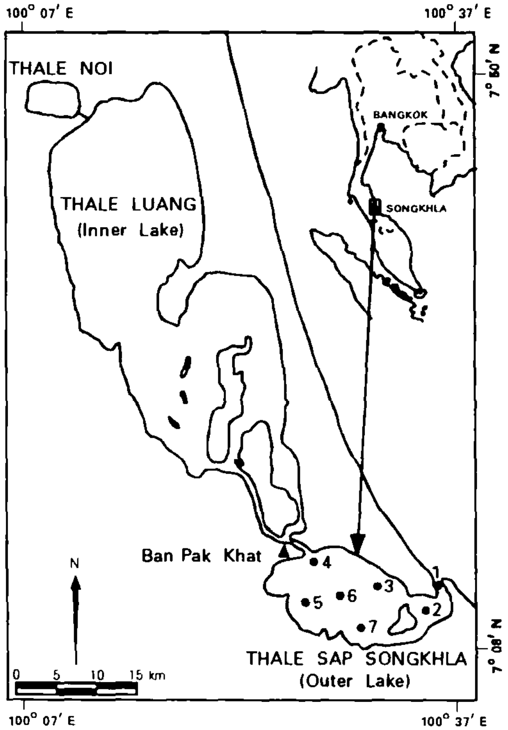

Fig. 1. Songkhla Lake and study area (Thale Sap Songkhla).

May - middle October) and a heavy rainy period or northeast monsoon period (middle October - middle February). This division of seasons may be a little different from that described by KJERFVE (1986).

SITE DESCRIPTION

Songkhla Lake is located between latitudes 7° 08' N and 7° 50' N, and between longitudes 100° 07' E and 100° 37' E (Fig. 1). It is classified as a choked coastal lagoon system (KJERFVE, 1986). It is the only lake in Thailand and covers a total area of 986.8 km^2 (98,680 ha), which is divided into Thale Noi (the uppermost part of Songkhla Lake), Thale Luang (the middle or inner lake) and Thale Sap Songkhla (the lowermost part of Songkhla Lake which is connected with the open sea) (BROHMANONDA and SUNGKASEM, 1982). The salinity of the water in Thale Sap Songkhla is brackish to seawater depending on the season. The average depth of Thale Sap Songkhla is 1.2 m. The greatest depth being 8.0 - 8.8 m is measured at Ban Pak Khat and at the mouth of Thale Sap Songkhla.

MATERIALS AND METHODS

Due to the high turbidity in the lake, phytoplankton is sampled by filtering 160 liters of subsurface water (0-50 cm) through a plankton net of 20 µm mesh size, instead of by towing. Samples were taken at all 7 stations (Fig.1), from August 1991 to October 1993, at 2-month intervals in the first year and at 3-month intervals in the second year. All samples were preserved in 4% buffered formaldehyde and later identified to genus. The number of species of phytoplankton investigated in each sample was counted but the name of each species has not been identified. Cell or colony counts were done in a 1 ml Sedgewick Rafter Counting Cell. Colony or filamentous forms were counted by average number. The collections were carried out during high tide (±2 hours) of spring tide. Water chemistry samples were collected using a 2- l Van Dorn bottle from surface and mid-depth at each station, at the same time, as the phytoplankton samples. The water salinity determination was made immediately with a salinity meter (SAL-50, Central Kagaku Co., Ltd., Japan). The water samples for total nitrogen (TN) and total phosphorus (TP) analyses were kept in an ice box during transportation to the laboratory. TN and TP determinations were made on samples filtered through 47 mm GF/C filters. TN and TP were determined after persulphate digestion (UNESCO, 1983) by the cadmium reduction method and the molybdenum blue method, respectively (STRICKLAND and PARSONS, 1972).

RESULTS

Stations 1and 5 (representing the high salinity and the low salinity areas, respectively) and the overall mean values (7 stations) were selected for presenting the seasonal variation of water quality and phytoplankton abundance.

Water salinity and TN : TP ratios

Seasonal changes of water salinity in Thale Sap Songkhla showed a clear trend, being low in the wet season and high in the dry season, except in April 1993 (dry season) were due to unexpected heavy rainfall in the days before sample collection. Salinity varied drastically from the mouth (station 1) to the inner part of the lake (Fig. 2). Seasonal changes of the TN :TP ratio were also obvious, being low in the wet season and high in the dry season.

Phytoplankton diversity and distribution

Phytoplankton found in Thale Sap Songkhla from August 1991 to October 1993 comprised 6 divisions and 103 genera (Table 1): Cyanophyta (12 genera), Chlorophyta (21 genera), Euglenophyta (3 genera), Chrysophyta (3 genera), Bacillariophyta (49 genera) and Pyrrhophyta (15 genera). The diversity (based on genus level) of phytoplankton was more extensive at the outlet of the lake than in the inner area. All blue-green algae reached maximum levels in the heavy rainy season, especially in December (northeast monsoon), when both the number of species and the number in each species of this group of algae were high. A similar trend was found for green algae, but its abundance was not as conspicuous. Several species of green algae were also found in the dry season: *Tetraselmis*, *Closterium*, *Cosmarium*, *Dactylococcopsis* and *Glyphodesmis*.

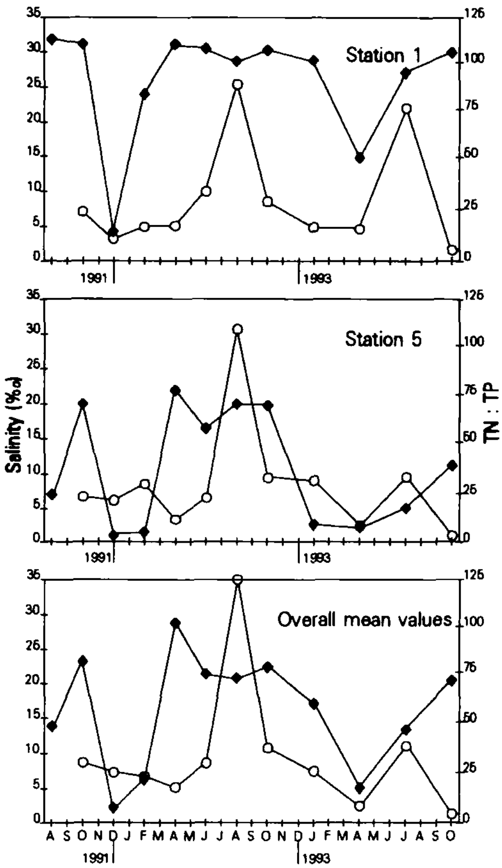

Fig. 2. The water salinity (◆—◆) and the TN:TP ratios (○—○) at stations 1 and 5, and the overall mean values (7 stations).

Even though numbers of blue-green and green algae species were considerably less than those of diatoms, each species found was widely dispersed and showed horizontal heterogeneity. They exhibited higher abundance in the inner part of the lake than at the outlet to the open sea. An inverse pattern was found for diatoms, whose diversity was higher in the dry season and southwest monsoon than in the northeast monsoon, and higher abundance was evident in the area close to the open sea (stations 1 and 2).

Chrysophyta and Euglenophyta were few both in species and number. Euglenophyta, in particular, was found only in 1993.

Seasonal pattern of abundance

There were two peaks of phytoplankton biomass yearly (Fig. 3), one in the heavy rainy period (December-January) and the other in the light rainy period (June-July). Peak productivity in the heavy rainy period of the first year of the study (December 1991, 1,346 x 10^6 cells m^{-3}) was approximately 5 times higher than that in the light rainy period (June 1992, 274 x 10^6 cells m^{-3}). A similar pattern was evident during the second year: 163 x 10^6 cells m^{-3} in January 1993 and 44 x 10^6 cells m^{-3} in July 1993.

Fig. 4 shows the seasonal variation of phytoplankton density of each division. The dominant species in the heavy rainy season peaks were

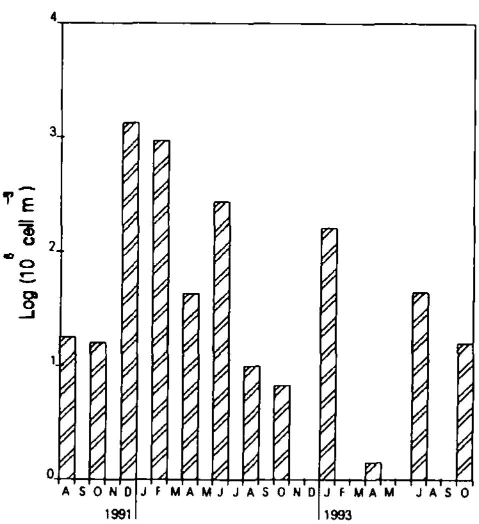

Fig. 3. Seasonal pattern of the averaged total phytoplankton density in Thale sap Songkhla since August 1991 to October 1993.

Table 1. List of phytoplankton obtained from Thale Sap Songkhla during August 1991- October 1993. Data shown relate to distribution (station), maximum density and monthly occurrence. Bold print indicates station and month of maximum density.

Taxa	Distribution (station)	Max.density (cells m^{-3})	Occurrence 1991	1992	1993
BACILLARIOPHYTA					
Actinoptychus sp.	4	3.0×10^{3}		**Oct**	
Amphiprora sp.	1,2,3,4,**5**,6,7	3.1×10^{6}	All trips	All trips (**Feb**)	All trips
Amphora spp.	1,2,3,4,5,**6**,7	6.2×10^{5}	Aug,Oct,Dec	Feb,Apr,Jun,Aug,Oct	Apr,**Jul**,Oct
Asteromphalus sp.	**3**	5.0×10^{3}		**Oct**	
Asterionella sp.	**1**,2	4.0×10^{5}		**Feb**,Apr,Oct	
Aulacodiscus sp.	**7**	6.0×10^{3}		**Apr**	
Bacillaria sp.	**1**,2,3,4,5,7	3.6×10^{6}	Aug,Oct	**Feb**, Apr,Jun,Aug,Oct	Apr,Jul,Oct
Bacteriastrum spp.	**1**,2,3,4,5,6,7	2.4×10^{7}	Aug,Oct	**Feb**,Apr,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Bellerochea sp.	**1**,2,3,4	4.8×10^{5}		**Oct**	Jan,Apr,Jul,Oct
Biddulphia spp.	1,**2**,3,4	1.5×10^{6}	Aug,Oct	Feb,Apr,Jun,Aug,**Oct**	Jan,Apr,Jul,Oct
Caloneis sp.	**4**,6	3.0×10^{3}			**Jan**,Oct
Campylodiscus sp.	**1**,2,3,4,5,6,7	6.8×10^{4}	Aug,Oct	**Feb**,Oct	Jan,Apr,Jul,Oct
Campylosira sp.	**1**	2.1×10^{4}			**Oct**
Cerataulina sp.	**1**,2	6.6×10^{4}		Apr,Jun,Aug,**Oct**	Jul,Oct
Chaetoceros spp.	**1**,2,3,4,5,6,7	6.7×10^{7}	**Aug**,Oct	Feb,Apr,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Climacodium spp.	**1**,2,3,7	4.6×10^{5}	Aug,Oct	Feb,**Apr**,Jun	Jul
Cocconeis sp.	**3**	2.0×10^{3}		**Apr**	
Corethron sp.	**1**,2,4	1.8×10^{5}	Aug,Oct	**Feb**	Jan,Oct
Coscinodiscus spp.	1,2,**3**,4,5,6,7	6.6×10^{6}	All trips	All trips (**Feb**)	All trips
Cyclotella sp.	1,**2**,3,4,5,6,7	2.9×10^{6}	**Dec**	Feb,Apr,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Cymbella sp.	**1**,3,5,7	1.4×10^{5}	Aug,Oct	**Feb**	
Dactyliosolen sp.	1,**2**	3.0×10^{5}		**Jun**,Aug,Oct	Jul
Diploneis sp.	1,2,3,4,**5**,6	2.4×10^{5}	Oct	**Feb**,Oct	
Ditylum sp.	**1**,2	3.4×10^{4}		**Feb**,Apr,	Jan,Apr
Epithemia sp.	**1**	5.2×10^{4}	Oct	**Feb**	
Eucampia spp.	1,**2**,3,5,7	3.2×10^{5}	Aug	Feb,**Apr**,Jun,Aug,Oct	Apr,Jul
Guinardia sp.	**1**,2	8.4×10^{5}	**Aug**	Apr,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Hemiaulus spp.	1,**2**,3,4,5,6,7	9.5×10^{8}	Aug,Oct	Feb,Apr,**Jun**,Aug,Oct	Jan,Apr,Jul,Oct
Hemidiscus spp.	1,**2**,3,4,5	6.5×10^{5}	Aug	**Aug**,Oct	Jan,Apr,Oct
Hyalodiscus sp.	**1**	1.3×10^{4}		**Apr**	
Lauderia sp.	**1**,2	4.2×10^{4}		**Oct**	Jul
Leptocylindrus sp.	1,**2**,3,4,6	9.9×10^{6}	Oct	Feb,**Apr**,Jun,Aug	Jul,Oct
Lithodesmium sp.	**1**,2	4.6×10^{4}	Oct	**Feb**	
Mastogloia sp.	1,2,**3**,4,5,6	4.4×10^{5}	Aug,Oct	**Feb**	
Melosira spp.	**1**,2,3,4,6,7	2.1×10^{6}	Aug,Oct,Dec	Feb,Apr,Jun,Aug,**Oct**	Jan,Apr,Jul,Oct
Navicula spp.	1,2,3,4,5,**6**,7	1.4×10^{6}	All trips	All trips	All trips (**Jul**)
Neidium sp.	2,3,4,5,6,**7**	2.0×10^{5}		Feb,**Apr**,Jun	Jul,Oct
Nitzschia spp.	1,2,3,4,5,6,**7**	4.7×10^{7}	All trips	All trips	All trips (**Jan**)
Pleurosigma spp.	**1**,2,3,4,5,6,7	5.4×10^{6}	All trips (**Dec**)	All trips	All trips
Gyrosigma spp. (cell count was included in *Pleurosigma* spp. which was more abundant)					
Rhizosolenia spp.	**1**,2,3,4,5,6,7	1.7×10^{7}	Aug,Oct	Feb,**Apr**,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Skeletonema sp.	**1**,2,3,4,5,6,7	2.0×10^{7}	Dec	Apr	Apr,**Oct**
Stephanopyxis sp.	1,**2**	1.4×10^{5}		Apr,**Jun**	
Surirella spp.	1,**2**,3,4,5,6,7	8.3×10^{5}	Aug,Oct	Feb,Apr,Jun,Aug,**Oct**	Jan,Apr,Jul,Oct
Tabellaria sp.	1,2,3,4,5,6,**7**	1.8×10^{6}	Aug	**Feb**,Apr,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Thalassionema spp.	**1**,2,3,4,5,6,7	4.3×10^{6}	Aug,Oct	Feb,Apr,Jun,Aug,**Oct**	Jan,Apr,Jul,Oct
Thalassiosira spp.	1,**2**,3,4,5,6,7	4.4×10^{5}		**Apr**,Jun,Aug	
Thalassiotrix spp.	1,**2**,3,4,5,6,7	3.4×10^{6}	Aug,Oct	Feb,Apr,Jun,**Aug**,Oct	Jan,Apr,Jul,Oct
Triceratium sp.	1,2,**3**,5,6	3.1×10^{5}	Aug,Oct	**Feb**,Apr,Oct	Jan,Jul,Oct
CHLOROPHYTA					
Actinastrum sp.	**1**,3,5,7	1.6×10^{6}	**Oct**	Feb	Jul,Oct
Ankistrodesmus spp.	1,2,3,4,**5**,6,7	2.4×10^{6}	Dec	**Feb**	Jan,Apr,Oct
Chodatella sp.	1,2,3,4,**5**,6,7	1.5×10^{5}			**Oct**
Closteriopsis sp.	**1**,2	6.8×10^{4}		**Feb**	
Closterium sp.	**5**	1.0×10^{3}			**Jul**
Cosmarium sp.	**4**,6,7	6.0×10^{3}	**Aug**		

Table 1. (Continued)

Taxa	Distribution (station)	Max.density (cells m^{-3})	Occurrence 1991	1992	1993
Crucigenia sp.	**5**,7	$4.0x10^4$			**Oct**
Dactylococcopsis sp.	**2**,4,6,7	$3.7x10^4$	Dec	Feb,**Apr**	
Dictyosphaerium sp.	**5**	$1.1x10^6$			**Oct**
Eudorina spp.	1,**2**,3,4,5,6,7	$1.4x10^7$	**Dec**		Jan,Apr,Jul,Oct
Glyphodesmis sp.	**1**	$3.3x10^4$		**Jun**	
Golenkinia sp.	**1**,2	$3.7x10^4$		**Feb**	
Micrasterias sp.	**5**	$1.0x10^3$			**Oct**
Pediastrum spp.	1,**3**,4,5,6,7	$6.8x10^6$	Aug,Dec	**Feb**	Jan,Jul,Oct
Scenedesmus spp.	1,2,3,4,5,6,**7**	$7.3x10^6$	**Dec**	Feb,Apr	Jan,Apr,Jul,Oct
Selenastrum sp.	5,**6**,7	$1.2x10^4$			**Oct**
Spirogyra sp.	**4**	$1.7x10^6$	Dec	**Feb**	Jan
Staurastrum sp.	1,2,3,**4**,5,6,7	$1.8x10^5$	Oct	**Feb**,Apr,Jun	Oct
Tetraedron sp.	3,4,5,**6**	$5.0x10^3$			**Oct**
Tetraselmis sp.	**2**	$2.4x10^4$			**Jul**
Westella sp.	**5**,6	$3.0x10^5$			**Oct**
CHRYSOPHYTA					
Dictyocha sp.	**1**,2,3,4,5,6,7	$2.2x10^5$	Aug,Oct	Feb,Aug,**Oct**	Jan,Apr,Oct
Dinobryon sp.	4,**5**	$4.1x10^5$			**Oct**
Distephanus sp.	**1**	$2.0x10^3$			**Jan**
CYANOPHYTA					
Anabaena spp.	1,2,3,4,5,6,**7**	$1.9x10^8$	**Dec**	Feb,Apr,Jun	Jan,Apr,Jul,Oct
Aphanizomenon sp.	1,2,3,**4**,5,6,7	$5.2x10^8$	**Dec**	Feb	Jan,Jul,Oct
Aphanocapsa spp.	1,**2**,3,4,5,6,7	$2.1x10^6$	**Dec**		
Chroococcus spp.	1,**2**,3,4,5,6,7	$2.9x10^7$	Oct,**Dec**	Feb,Apr	Jan,Apr,Jul,Oct
Lyngbya spp.	1,2,3,4,**5**,6	$1.1x10^9$		**Feb**	
Merismopedia spp.	1,**2**,3,4,5,6,7	$1.3x10^9$	**Dec**	Feb	Jan,Apr,Jul,Oct
Microcoleus spp.	2,**3**,4,5	$4.1x10^8$		**Feb**	
Microcystis spp.	1,**2**,3,4,5,6,7	$3.0x10^7$	**Dec**	Feb	Jan,Jul
Oscillatoria spp.	1,2,**3**,4,5,6,7	$3.2x10^8$	All trips	All trips (**Feb**)	All trips
Phormidium spp.	1,**2**,3,4,5,6,7	$1.3x10^9$	All trips (**Dec**)	All trips	All trips
Spirulina spp.	1,2,3,4,5,6,**7**	$6.5x10^7$	**Dec**	Feb,Oct	Jan,Apr,Jul,Oct
Unidentified (blue-green rod)	**7**	$5.8x10^7$	**Dec**		
EUGLENOPHYTA					
Euglena spp.	**7**	$4.8x10^4$			**Oct**
Phacus spp.	3,**7**	$9.1x10^4$			**Oct**
Trachelomonas sp.	4,**7**	$1.3x10^5$			Jan,**Oct**
PYRRHOPHYTA					
Alexandrium sp.	**2**	$4.0x10^3$		**Feb**	
Ceratium spp.	**1**,2,4,5,6,7	$2.3x10^5$	Aug,Oct	Feb,**Apr**,Jun,Aug,Oct	Apr,Jul,Oct
Dinophysis spp.	1,2,3,4,5,**6**,7	$5.4x10^4$	Aug,Oct	**Oct**	
Diplopsalis sp.	1,**2**,3,4,5,6,7	$2.5x10^6$	All trips (**Dec**)	All trips	All trips
Exuviella sp.	1,2,3,4,5,6,**7**	$9.7x10^5$	**Oct**	Feb	
Gonyaulax sp.	1,2,3,4,5,6,**7**	$1.3x10^6$	Aug,**Oct**	Apr,Jun,Aug,Oct	Jul
Gymnodinium spp.	1,**2**,3,4,5,6,7	$3.1x10^5$	Aug,**Oct**	Feb,Apr,Oct	Jul
Noctiluca sp.	1,4,5,**6**	$1.0x10^5$	Aug	**Feb**	
Peridinium spp.	1,2,3,4,5,**6**,7	$1.8x10^6$	All trips	All trips	All trips (**Jul**)
Phalacroma sp.	**5**,6	$1.5x10^5$	**Oct**		
Prorocentrum sp.	1,**2**,3,4,5,6,7	$8.4x10^4$	**Aug**,Oct	Feb,Apr,Jun,Oct	Apr,Jul
Protoperidinium spp.	1,2,3,4,5,6,**7**	$1.4x10^6$	Aug,**Oct**,Dec	Apr,Jun,Aug,Oct	Jan,Apr,Jul,Oct
Pyrocystis sp.	**1**,2,3,4,5,6	$7.0x10^5$	**Oct**	Feb,Oct	Apr,Jul
Pyrophacus sp.	1,**2**,3,5,6,7	$2.2x10^4$	Oct	**Apr**,Jun,Oct	Jan,Apr
Triposolenia sp.	1,**2**	$1.3x10^4$		**Oct**	

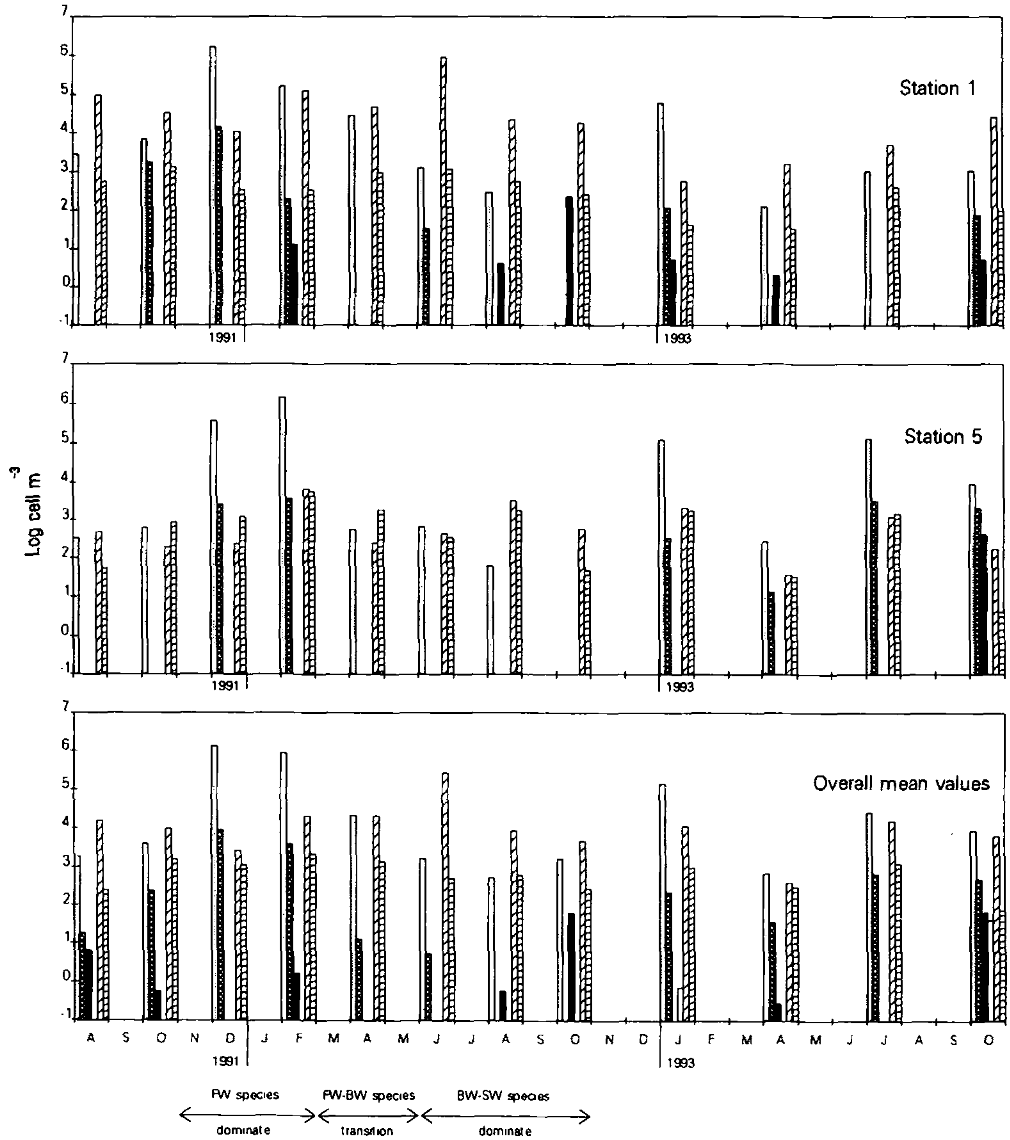

Fig. 4. Seasonal pattern of phytoplankton density at stations 1 and 5, and the overall mean values since August 1991 to October 1993: Cyanophyta ( ), Chlorophyta ( ) Chrysophyta ( ), Euglenophyta ( ), Bacillariophyta ( ) and Pyrrophyta( ). FW = freshwater, BW = brackish water, SW = seawater.

blue-green and green algae, most of which were of filamentous and colonial types. Diatoms were the dominant phytoplankton species in the smaller peaks during the light rainy period, except in July 1993, when blue-green algae were more dominant. Dinoflagellates were less abundant than diatoms and blue-green algae. Their density did not differ much in the wet and dry seasons. But the number of species was lowest in the heavy rainy period. Only *Diplopsalis* was abundant in that period. Chrysophyta were also sparse and were not found in December when the lake salinity was lowest.

Comparing the periods August 1991 - June 1992 and August 1992 - October 1993, phytoplankton density in the second period was

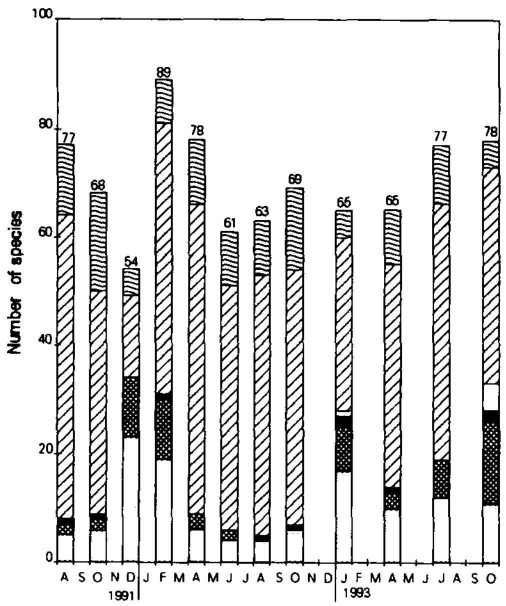

Fig 5. Seasonal pattern of phytoplankton diversity in Thale Sap Songkhla from August 1991 to October 1993: Cyanophyta (▤), Chlorophyta (▩), Chrysophyta (■), Euglenophyta (□), Bacillariophyta (▨) and Pyrrophyta (▤).

3.6 times lower than that in the first period, with a lower density in every division. The differences in the magnitude of the corresponding peaks for each year may be due to non-synchronous sampling times. Other possible contributing explanations are suggested in the Discussion of this paper.

Seasonal pattern of diversity

The phytoplankton diversity found over the 2-year study period ranged from 54-89 species (Fig.5). Blue-green algae and diatoms played a major role in the seasonal patterns of phytoplankton diversity. Green algae and dinoflagellates contributed also significantly, while Chrysophyta had a minor contribution. The highest number obtained of phytoplankton species found in all samples was 120. This number consisted of 22 species of blue-green algae, 15 species of green algae, 3 species of chrysophytes, 5 species of euglenoids, 57 species of diatoms and 18 species of dinoflagellates. On a yearly basis (August 1991-August 1992), the structure of the phytoplankton community in Thale Sap Songkhla can be divided into 3 periods.

– *The freshwater phytoplankton domination period.* This period covers the middle of the heavy rainy period (November-January). In December 1992, the salinity in the lake dropped to 1-4‰ (Fig. 2) and the number of phytoplankton species concomitantly decreased to 54 species, the lowest number during the year. Blue-green algae increased both in number of species (22 species) and density (1,333 x 10^6 cells m^{-3}). Green algae also increased (12 species), but not as conspicuously. The dominant genera of blue-green algae were *Phormidium, Merismopedia* and *Aphanizomenon*, while those of green algae were *Scenedesmus* and *Eudorina*. Both density and species number of diatoms (15 species) decreased during this period. The diversity of dinoflagellates also decreased (5 species) but their density did not change due to the high number of *Diplopsalis* sp. (8.3 x 10^5 cells m^{-3}) in this season.

– *The high diversity period.* This period, during February, when the salinity of the water increased to 2-20 ppt, covered the transition period between wet and dry seasons. During this period the density of freshwater phytoplankton began to decrease while the species number did not change. Diatoms and dinoflagellates, which did not survive during the heavy rainy season, began to increase both in number of species (50 for diatoms and 8 for dinoflagellates) and in density. This period was the most diverse during the year, with 62 genera (89 species) of phytoplankton.

– *The diatom domination period.* This period covered the dry season and the light rainy period which lasts for 7-8 months. Apart from diatoms (41-57 species), dinoflagellates tended to have a higher diversity (10-18 species) than in the heavy rainy season. Salinity at this time was changing from freshwater-brackish to brackish-seawater. The number of species found during this period was 61-78, while *Chaetoceros* was the most dominant genus. (It should be noted that this genus was not found in December). Blue-green algae and green algae dropped to 4-6 species and 0-3 species, respectively.

Although similar, the seasonal patterns of succession in the phytoplankton community were found in both years, that of the second year was less prominent.

DISCUSSION

Tidal influence in choked coastal lagoons is usually confined to the entrance channel (KJERFVE, 1986). Thus, the salinity of Thale Sap Songkhla water varies seasonally because of both rainfall and land drainage found in the estuaries (TORO, 1985; DEVASSY and GOES, 1988) and its connection to the open sea. During the northeast monsoon period, a large amount of freshwater enters Thale Sap Songkhla, resulting in low salinity. This seasonal change creates a complex phytoplankton community. A seasonal succession of phytoplankton species was evident during the transition period from the rainy to the dry seasons, indicating that seasonal variations of phytoplankton composition are controlled by the amount of rain and intrusion of seawater. A decrease in salinity caused by the onset of the monsoon resulted in high salinity-tolerant forms being immediately replaced by low salinity-tolerant species (DEVASSY and GOES, 1988).

During the peak of the monsoon season in Cochin backwater, freshwater phytoplankton was dominant (GOPINATHAN, 1974 cited in DEVASSY and GOES, 1988). In the heavy rainy period (December-January) in Thale Sap Songkhla freshwater blue-green and green algae also increased in abundance and were dispersed throughout the area. On the other hand, diatoms were distributed normally, and were found in high densities only around the mouth of the lagoon connected to the open sea (stations 1and 2), while at inner stations, their density was substantially reduced to the same pattern as reported by FARFAN and ALVAREZ-BORREGO (1983). Moreover, maximum abundance of phytoplankton has been found in estuaries during heavy rainfall in the monsoon period with the lowest salinity (QASIM *et al.*, 1972 ; MALLIN *et al.*, 1991). This result suggests that during the heavy rainy period, freshwater from the inner lake and canals has more influence than tidal the force. Primary production in the heavy rainy period therefore is high throughout the lake but lasts only 1-3 months.

A high abundance of freshwater phytoplankton was found in the heavy rainy period, when salinity was 1-4‰. This finding agrees with the results of JACKSON (cited in JACKSON *et al.*, 1987) who reported high growth of freshwater phytoplankton in the optimum salinity range of 0-8‰. In this coastal lagoon ecosystem, while nutrient levels showed less seasonal variation (RAKKHEAW, unpubl. data), the salinity variation was probably the most important factor contributing to the phytoplankton growth and succession of the major species. In Tamar Estuary, abundance of freshwater phytoplankton tended to be affected by hydrodynamic processes (JACKSON *et al.*, 1987). Both factors seem to play a certain role in Thale Sap Songkhla.

When salinity in the lake decreases due to rainfall, freshwater phytoplankton density increases rapidly. Hydrodynamics is responsible for the distribution of phytoplankton throughout the lake. Apparently, the freshwater input from the inner lake during the heavy rainy period exceeds that brought in by the tidal current. In addition, it has been suggested that the low TN : TP ratio is an important factor controlling the bloom of blue-green algae in the lake (SMITH, 1983; STOCKNER and SHORTREED, 1988). In this study of Thale Sap Songkhla low TN : TP ratios (<29) were found during December-April and ratios higher than 29 during the other months.

Total phosphorus during December-April (average>5 µM P l^{-1}) was higher than that in June-July (average<1 µM P l^{-1}). Blue green algae tended to be rare when the TN : TP ratio exceeded 29 (SMITH, 1983). Blue-green algae in Thale Sap Songkhla were certainly dominant in December 1991 and January 1993 (northeast monsoon), while the bloom of diatoms occurred in the southwest monsoon period when phosphorus levels were lower. TILMAN *et al.* (1982) suggested that blue-green algae (both those fixing and not fixing nitrogen) are generally inferior to diatoms as phosphorus competitors, while nitrogen-fixing cyanophytes should be superior nutrient competitors under conditions of nitrogen limitation (SMITH, 1983). The heterocysts of *Aphanizomenon* were highly negatively related to the nitrate concentration and positively related to the phosphate concentration (HORNE *et al.*, 1979). However, the non-heterocystous species *Microcystis aeruginosa* may be as abundant as nitrogen-fixing forms during times of nitrogen deficiency (FOGG *et al.*, 1973). Both heterocyst and nonheterocyst blue-green algae certainly bloomed during the heavy rainy season in Thale Sap Songkhla.

Although the TN : TP ratio in April was low, blue-green algae were not dominant. This phenomenon may be due to the increase of salinity being more influential (SELLNER *et al.*, 1988). The increased nutrient input into the system in unfavourable conditions – in this case high salinity – caused the low utilization of nutrients (DEVASSY and GOES, 1988).

Based on the results of our study, Thale Sap Songkhla seems to show lake-like (in the heavy rainy period) and estuary-like (in other periods) characteristics. HOWARTH *et al.* (1988) have suggested that significant nitrogen fixation by plankton in eutrophic lakes generally occurs when the N : P ratio is near or below the Redfield ratio of 16. In estuaries this ratio is generally lower. Yet the total N_2 fixed may become important in the nitrogen budget of the choked coastal lagoon Thale Sap Songkhla, as is the case in the tropical Lake George (HORNE and VINER, 1971).

Since nitrate concentrations (<5 µM N l^{-1}) in Thale Sap Songkhla are low thoughout the year, ammonium concentrations (>2-42 µM N l^{-1}) are higher (RAKKHEAW, unpubl. data). Ammonium may play a more important role in the growth of non-nitrogen-fixing phytoplankton, because nitrate is only preferred when ammonium is $\leq$2 µM N l^{-1} (CARPENTER and DUNHAM, 1985; BERMAN *et al.*, 1984). Urea nitrogen appeared to be used after ammonium, and when the sum of available ammonium and urea nitrogen is insufficient to meet the phytoplankton nitrogen demand, nitrate was used (MCCARTHY *et al.*, 1977).

The high phosphorus levels in the heavy rainy season may originate from the inner lakes (Thale Noi and Thale Luang) which are habitats for macrophyte communities, and from the degradation of seagrasses in Thale Sap Songkhla during the heavy rainy period (ANGSUPANICH, 1996). *Ceratophyllum demersum* and *Hydrilla verticillata* are the predominant species in Thale Noi (PURINTAVARAGUL and LHEKNIM, 1983). Rapid growth of macrophytes and high biomass of plants may cause limitation of nitrogen but not of phosphorus (VAN DONK *et al.*, 1989; OZIMEK *et al.*, 1990). In addition, a very low TN : TP ratio (1.14) was recorded during the decomposition of *Ceratophyllum demersum* at 18°C over 4 days in the laboratory (BEST *et al.*, 1990). The total phosphorus released was about 11 mg l^{-1}. Since organic phosphorus can indeed be the major source of phosphorus for algae (CURRIE and KALFF, 1984), phytoplankton biomass may show significant increases in response to senescing macrophytes (LANDERS, 1982).

Even though the total phytoplankton abundance in the heavy rainy season is higher than in the dry season, the species richness shows a reverse trend. High diversity but low density of phytoplankton is found during the transition period between the two seasons. Some freshwater algae apear even able to survive in seawater, although the cells become distorted and are unable to divide (JACKSON *et al.*, 1987). At the same time, numbers of diatoms and dinoflagellates increase as salinity increases due to lower freshwater input and higher amounts of seawater intrusion. Seawater phytoplankton species also increase as they are carried in by the incoming seawater.

Although phytoplankton abundance was higher in the first year of the study, their patterns of variation were similar during both study years. The amount of rain determines phytoplankton biomass, diversity and structure of the phytoplankton community in each season. The first peak in the heavy rainy period comprised freshwater phytoplankton as a major component, while the second peak comprised diatoms as the dominant species, except in July 1993, when freshwater phytoplankton also increased. This devation, however, might have been due to the relatively low salinity levels (3-5‰) at stations 4 and 5. The appearance of these freshwater phytoplankton may have been caused by freshwater discharges from several canals around the lake. Unpredictably heavy rainfall occurred about one week before the sampling of the phytoplankton (personal observation). Unpredictably rainfall events may cause seasonal production pulses through nitrogen loading and may consequently influence phytoplankton species composition (MALLIN *et al.*, 1991). However, not only nitrogen loading but also phosphorus loading is possible since if the run-off is influenced by untreated urban sewage (GRANELI, 1987). Moreover, the abundance of phytoplankton in the last sampling at the end of October 1993 was similar to that found in October 1991 but in October 1993 there were more freshwater species. In the latter period the amount of rainfall was also greater (CLIMATOLOGY DIVISION, unpubl. data). At the same time, TN : TP ratios in October 1993 were very low in relation to the level that is able to stimulate blue-green algae (SMITH, 1983).

The number of phytoplankton species found in this study (103 genera) was lower than that reported by SIRIMONTAPORN *et al.*, (1978) who found 117 genera. Phytoplankton density in the present study seems to be higher than that reported in 1978. The species composition of phytoplankton reported by SIRIMONTAPORN *et al.* (1978) must be higher because his study covered Thale Luang and Thale Sap Songkhla. Although the number of genera in each division in both studies differs, diatoms still maintain the highest diversity. Moreover, the highest abundance of phytoplankton were shown to occur in the heavy rainy period. The phytoplankton abundance reported in this study is lower than expected because dominant phytoplankton species are mostly filamentous blue-green and colonial green algae. These structures make cell counts quite difficult. Generally, average cell numbers per colony or filament were used to estimate cell density. The chlorophyll *a* concentrations in Thale Sap Songkhla (YAMAGUCHI *et al.*, 1994) correspond with those in mesotrophic or moderately eutrophic water (ARUGA and MONSI, 1963; SAKAMOTO, 1966). The observed specific characteristics of the seasonal phytoplankton pattern will be very useful for the management of the development of Songkhla Lake.

ACKNOWLEDGEMENTS

This research received financial support from the National Research Council of Thailand and the Japan Society for the Promotion of Science. We would like to thank Prof. Yusho Aruga, Prof. Gilbert W. Bane, Dr. Sommai Chiayvareesajja, Ms. Kusuma Supattrakul and Mr. Suteera Tongkao for assistance and encouragement.

REFERENCES

ANGSUPANICH, S., 1996. Seagrasses and epiphytes in Thale Sap Songkhla, Southern Thailand. La mer 34: 67-73.

ARUGA, Y. and M. MONSI, 1963. Chlorophyll amount as an indicator of matter productivity in bio-communities. Plant Cell Physiol. 4: 29-39.

BERMAN, T., B.F. SHERR, E. SHERR, D. WYNNE and J.J. MCCARTHY, 1984. The characteristics of ammonium and nitrate uptake by phytoplankton in Lake Kinneret. Limnol. Oceanogr. 29: 287-297.

BEST, E.P.H., J.H.A. DASSEN, J.J. BOON and G. WIEGERS, 1990. Studies on decomposition of *Ceratophyllum demersum* litter under laboratory and field conditions: Losses of dry mass and nutrients, qualitative changes in organic compounds and consequences for ambient water and sediments. Hydrobiologia 194: 91-114.

BROHMANONDA, P. and P. SUNGKASEM, 1982. Lake Songkhla in Thailand. In: Report of training course on seabass spawning and larval rearing. Held in June 1-20, 1982. Songkhla, Thailand. UNDP/FAO. Manila, p. 59-61.

CALJON, A.G., 1987. A recently landlocked brackish-water lagoon of Lake Tanganyika: Physical and chemical characteristics, and spatio-temporal distribution of phytoplankton. Hydrobiologia 153: 55-70.

CARPENTER, E.J. and S. DUNHAM, 1985. Nitrogenous nutrient uptake, primary production, and species composition of phytoplankton in the Carmans River estuary, Long Island, New York. Limnol. Oceanogr. 30: 513-526.

CLIMATOLOGY DIVISION, 1989. The climatology. Meteorological Department, Ministry of Transport and Communication. Bangkok (in Thai).

CURRIE , D.J. and J. KALFF, 1984. The relative importance of bacterioplankton and phytoplankton in phosphorus uptake in freshwater. Limnol. Oceanogr. 29: 311-321.

DEVASSY, V.P. and J.I. GOES, 1988. Phytoplankton community structure and succession in a tropical estuarine complex (central west coast of India). Estuar. Coast. and Shelf Sci. 27: 671-685.

FARFAN, B.C. and S. ALVAREZ-BORREGO, 1983. Variability and fluxes of nitrogen and organic carbon at the mouth of a coastal lagoon. Est. Coast. Shelf Sci. 17: 599-612.

FOGG, G.E., W.D.P. STEWART, P. FAY and A.E. WALSBY, 1973. The blue-green algae. Academic Press, London.

GRANÉLI, E., 1987. Nutrient limitation of phytoplankton biomass in a brackish water bay highly influenced by river discharge. Estuar. Coast. Shelf Sci. 25: 555-565.

HORNE, A.J. and A.B. VINER, 1971. Nitrogen fixation and its significance in tropical Lake George, Uganda. Nature 232: 417-418.

HORNE, A.J., J.C. SANDUSKY and C.J.W. CARMIGGELT, 1979. Nitrogen fixation in Clear Lake, California. 3. Reproductive synoptic sampling of the spring *Aphanizomenon* bloom. Limnol. Oceanogr. 24: 316-328.

HOWARTH, R.W., R. MARINO and J.J. COLE, 1988. Nitrogen fixation in freshwater, estuarine, and marine ecosystems. 2. Biogeochemical controls. Limnol. Oceanogr. 33: 688-701.

INSUWAN, S., 1981. Research report on algae in Songkhla Lake (outer). Department of Biology, Faculty of Science. Srinakharinwirot University, Songkhla campus. Songkhla (in Thai).

JACKSON, R.H., P.J. le B. WILLIAMS and I. R. JOINT, 1987. Freshwater phytoplankton in the low salinity region of the River Tamar estuary. Estuar. Coast. Shelf Sci., 25: 299-311

KJERFVE, B., 1986. Comparative oceanography of coastal lagoons. In : D.A. Wolf, Ed., Estuarine variability. Academic Press, Inc. Florida, p. 63-81.

LANDERS, D.H., 1982. Effects of naturally senescing aquatic macrophytes on nutrient chemistry and chlorophyll *a* of surrounding waters. Limnol. Oceanogr. 27: 428-439.

MALLIN, M.A., H.W. PAERL and J. RUDEK, 1991. Seasonal phytoplankton composition, productivity and biomass in the Neuse River Estuary, North Carolina. Est. Coast. and Shelf Sci. 32: 609-623.

MCCARTHY, J.J., W.R. TAYLOR and J.L. TAFT, 1977. Nitrogenous nutrition of the plankton in the Chesapeake Bay. 1. Nutrient availability and phytoplankton preference. Limnol. Oceanogr. 22: 996-1011.

OZIMEK, T., R.D. GULATI and E. VAN DONK, 1990. Can macrophytes be useful in biomanipulation of lakes? The Lake Zwemlust example. Hydrobiologia 200/201: 399-407.

PURINTAVARAGUL, C. and V. LHEKNIM, 1983. Seasonal appearance of macrophytes in Thale Noi. In: N. Nachiangmai and N. Sumalee, Eds., Proceedings of Songkhla Lake basin development program. Prince of Songkla University/Fourth Army Area/National Economic and Social Development Board, Songkhla, p. 117-121. (in Thai).

QASIM, S.Z., P.M.A. BHATTATHIRI and V.P. DEVASSY, 1972. The influence of salinity on the rate of photosynthesis and abundance of some tropical phytoplankton. Mar. Biol. 12: 200-206.

SAKAMOTO, M., 1966. Primary production by plankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiol. 62: 1-28.

SELLNER, K. G., R. V. LACOUTURE and C. R. PARRISH, 1988. Effects of increasing salinity on a cyanobacteria bloom in the Potomac River estuary. J. Plankton Res. 10: 49-61.

SIRIMONTAPORN, P., C. RATANACHAI, S. KRABUANRATANA, T. PECHMANEE and S. VICHIANSAN, 1978. Study on the phytoplankton in Songkhla Lake. In: Annual report 1978. Songkhla Fisheries Station. Department of Fisheries, p. 341-361. (in Thai).

SMITH, V.H., 1983. Low nitrogen to phosphorus ratios favour dominance by blue-green algae in lake phytoplankton. Science 221: 669-671.

STOCKNER, J.G. and K.S. SHORTREED, 1988. Response of *Anabaena* and *Synechococcus* to manipulation of nitrogen: phosphorus ratios in a lake fertilization experiment. Limnol. and Oceanogr. 33: 1348-1361.

STRICKLAND, J.D.H. and T.R. PARSONS, 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Canada 167.

TILMAN, D., S.S. KILHAM and P. KILHAM, 1982. Phytoplankton community ecology: The role of limiting nutrients. Ann. Rev. Ecol. Syst. 13: 349-372.

TORO, J.E., 1985. Annual cycle and composition of the phytoplankton in the Quempillen River Estuary, southern Chile. Estuar. Coast. Shelf Sci. 21: 461-469.

UNESCO, 1983. Chemical methods for use in marine environmental monitoring. Manuals and guides. Intergovernmental Oceanographic Commission.

VAN DONK, E., R.D. GULATI and M.P. GRIMM, 1989. Food-web manipulation in Lake Zwemlust: Positive and negative effects during the first two years. Hydrobiol. Bull. 23: 19-34.

YAMAGUCHI, Y., S. RAKKHEAW, S. ANGSUPANICH and Y. ARUGA, 1994. Seasonal changes of phytoplankton chlorophyll *a* and their relation to the suspended solid in Thale Sap Songkhla, Thailand. La mer 32: 31-39.

Address of the authors:

Department of Aquatic Science, Faculty of Natural Resources, Prince of Songkhla University, Hat Yai, Songkhla 90110, Thailand