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Limnological characteristics of some reservoirs in Thailand

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Introduction

This paper describes data collected from Thai reservoirs during the monsoon (October 1988) and premonsoon (February–March 1991). Little is known about limnology in Thailand (CHAIYARACH 1980) and this study emphasizes thermal structure, ionic salinity, lake trophic state and nutrient limitation of phytoplankton of some major reservoirs. In reservoirs where there were strong differences between the sampling events we speculate about seasonal patterns.

Climate and site descriptions

Most of Thailand (between 5° N and 20° N) is tropical with a prominent seasonal monsoon. The southwest monsoon causes heavy rainfall from May to November. The northeast monsoon follows, and under its influence rains subside and a cool season develops, which is dry (until February). The premonsoon ensues with increasing rain as the season progresses (March–April). Monsoon duration and intensity vary annually and regionally. Annual rainfall typically exceeds 1,200 mm, with greater amounts in the east and south. Temperature in Bangkok averages about 28 °C, with maximum and minimum values of about 38 °C and 17 °C, respectively. Monthly temperatures vary from about 30 °C during March–June, to a low in December of about 25 °C (Fig. 1). Near Bangkok rainfall is most intense during May to October, with peak values of 250–400 mm per month during September and October. Rainfall is commonly <10 mm during December and January.

We sampled reservoirs important to our cooperators, the Royal Irrigation Department, National Inland Fisheries Institute, and Electrical Generating Authority of Thailand (Table 1, Fig. 2). Field collections took place on 6–25 October 1988 and 19 February to 6 March 1991. We sampled 11 reservoirs in 1988 and again in 1991, along with two additional ones in the north, Mae Ngat and Kew Lom (Fig. 2).

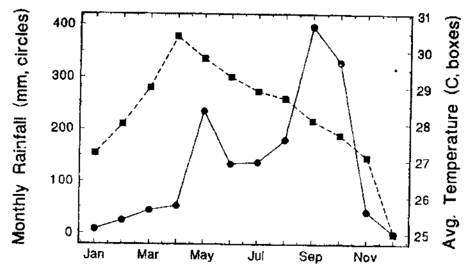

Fig. 1. Meteorological data from Bangkok supplied by the Meteorological Bureau of Thailand (monthly means averaged over 1987–90).

Table 1. Morphology data for reservoirs sampled in Thailand.

Water body	Surface area (km^2)	Volume (million m^3)
Bang Phra	16.4	110
Bumiphol	300	13 462
Bung Boraphet	212	---
Kew Lom	---	112
Khao Laem	387	8 860
Lam Pao	270	1 430
Mae Ngat	16	265
Nam Un	86	520
Nong Kor	6.4	19
Ratchaprapa	430	5 639
Srinakarin	413	17 745
Thatungna	8.0	---
Ubonratana	410	2 263

These impoundments all have flood control, water supply, irrigation and/or hydropower functions; some of the largest Thai reservoirs were included in this study. Bung Boraphet is a former swamp with an outlet structure (JUNK 1977). Each reservoir was

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Fig. 2. Map of Thailand showing the general location of reservoirs sampled in this study.

sampled in the lacustrine zone and we did not characterize longitudinal gradients. In 1991, a regional drought and water demand reduced the volume of Nong Kor to a fraction of full pool volume. We included the results in our tables, but not in the analyses because it was not a pelagic system. Nearby Bang Phra also had reduced volume in 1991 but was pelagic. Analyses were based on data from samples ≤4 m depth, unless indicated otherwise. Trophic state assessments were based on overall averages (average of both sampling events, if available).

Methods

Samples were collected from various depths of each reservoir using a sampler. Temperature and oxygen were measured, using an electronic meter (not always to maximum depth). Samples were filtered in field laboratories for determination of chlorophyll (Chl) and nanno Chl (ηChl which is Chl measured after filtration through 35 μm netting), suspended solids (NVSS, non-volatile and VSS, volatile), particulate organic carbon and nitrogen (POC and PON). Measurements were made on site for alkalinity, color, pH and conductivity. Aliquots were transferred to glass tubes for subsequent analyses of total N and P (TN and TP), and cation samples in plastic bottles were acidified. Nutrient bioassays followed the approach of JONES et al. (1990). Analyses were conducted at the University of Missouri using standard methods (APHA 1985). Organic carbon and nitrogen were measured at Iowa State University using a Carlo Erba CHN analyzer. Statistical significance was set at 0.05.

Results and discussion

Thermal characteristics and oxygen content

Surface temperatures averaged about 27 °C during both sampling periods, reflecting temperature stability at these latitudes. The coolest surface values were around 24 °C in Mae Ngat and Kew Lom; the most northerly water bodies located in the highlands. Using the classification of LEWIS (1983) the reservoirs are warm polymictic (Fig. 3). Bottom temperature varied from 22 °C to about 27 °C. Oxygen was typically between 80% and full saturation at the surface, with values usually showing a gradual decline with depth (Fig. 3). Anoxia was measured in some of the profundal samples but, given deep mixing patterns in these water bodies, anoxia was not prevalent in the measurements.

Ionic salinity and composition

Ionic salinity (Table 2) was some 40–185% of the world average for fresh waters (2.85 meq L^{-1}, WETZEL 1983) and the overall average matched the world value. Lowest values were measured in Nam Un and Lam Pao in the northeast where sandstone is the predominant geological formation and Ratchaprapa in the south where granite occurs (Fig. 2). These are regions where dissolved solids were low in river water (KOBAYASHI 1959). The largest values, in reservoirs located in west-central Thailand, reflect limestone formations and high levels of divalent cations and alkalinity in local rivers (KOBAYASHI 1959, TYLER 1984). Ionic salinity was some 20% lower during the monsoon than in the same reservoirs during the pre-monsoon. This difference was significant and may reflect a seasonal dilution during the monsoon which occurs in Thai rivers (KOBAYASHI 1959). Seasonal differences in electrolytes were not significant among conductivity measurements (Table 2), perhaps because of the influence of organic acids (KOBAYASHI 1959). Seasonal differences in

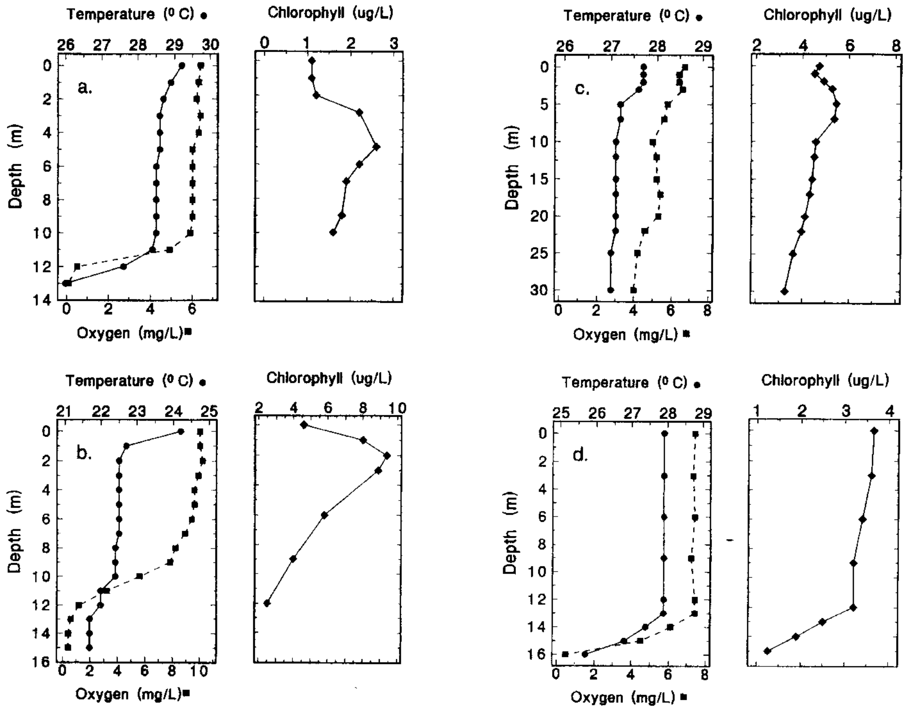

Fig. 3. Depth profiles for temperature, oxygen and chlorophyll in Ratchaprapa in 1991 (panel a), Kew Lom in 1991 (panel b), Bumiphol in 1988 (panel c) and Srinakarin in 1988 (panel d).

pH were significant, with lower values during the monsoon.

Ionic composition was primarily bicarbonate with a predominance of divalent cations (Table 2). Averaged across all samples, bicarbonate accounted for 87% of the anions. Sulfate was a minor constituent of most samples, a characteristic of fresh waters in Thailand (KOBAYASHI 1959). The proportion of Cl was greatest in Lam Pao and Nam Un in the northeast (Fig. 2), where Cl is high in the river water, because of salts in the local sandstone (KOBAYASHI 1959). Chloride was also important in Bang Phra, Nong Kor and Ratchaprapa, located near the sea. Among the cations, Ca accounted for 54%, Mg 23%, Na 16%, and K 7%; this composition closely matches the average for Asia (WETZEL 1983). Sodium values were typically higher in those reservoirs where Cl was important. Seasonal variation in chemical composition was slight.

Trophic state, seston and nutrient limitation

Using Chl criteria (NÜRNBERG 1996), reservoirs were almost equally divided among oligotrophic (<3.5 μg L^{-1}), mesotrophic (<9 μg L^{-1}), and eutrophic categories (Table 3). Classifications using Secchi were similar. Oligotrophic reservoirs (Khao Laem, Ratchaprapa, Srinakarin, and Thatungna) are mainly large water bodies with inflow from the uplands of western and southern Thailand. Eutrophic reservoirs are located in lowland, agricultural regions. Using N criteria, there were twice the number of oligotrophic and half as many mesotrophic reservoirs as compared to classifications using P. It seems that, several reservoirs had TN somewhat less than 350 μg L^{-1}, and TP just above 10 μg L^{-1} (Table 3), the cut-off points for these elements in oligotrophic lakes (NÜRNBERG 1996). Among reservoirs, values of TN and TP showed a strong positive correlation ($r = 0.84$). These trophic state characteristics did not show

Table 2. Ionic salinity and conductivity (KSP) data from Thai reservoirs sampled during the monsoon (1988) and pre-monsoon (1991); salinity is expressed as the sum of cations plus anions.

Water body and year	KSP ($\mu S\ cm^{-1}$)	Salinity ($meq\ L^{-1}$)	Ca	Mg	Na	K	HCO_3	SO_4-S	Cl	Color Pt	pH Units
			% of Cations				% of Anions				
1988 Data											
Bang Phra	113	1.78	28	21	38	13	80	2	19	16	7.5
Bumiphol	183	3.42	63	19	13	6	94	2	4	15	8.0
Bung Boraphet	220	2.78	69	23	3	5	87	2	11	24	8.0
Khao Laem	129	1.99	58	32	6	4	95	1	3	10	8.0
Lam Pao	133	1.36	41	28	18	13	77	2	21	22	7.5
Nam Un	74	1.12	50	28	12	11	93	1	7	10	7.1
Nong Kor	106	1.63	30	19	37	14	78	7	15	19	7.4
Ratchaprapa	90	1.41	34	38	14	13	88	0	12	13	7.5
Srinakarin	247	4.58	61	32	4	2	97	1	2	10	8.2
Ubonratana	206	3.72	57	21	19	4	94	3	3	10	7.9
1991 Data											
Bang Phra	148	2.97	48	16	28	9	81	8	12	15	8.5
Bumiphol	160	3.38	64	17	13	6	89	2	9	3	7.6
Bung Boraphet	273	5.06	38	14	45	3	88	4	8	18	7.8
Kew Lom	204	4.42	68	18	10	4	88	5	6	10	7.8
Khao Laem	117	2.59	68	23	5	3	85	3	12	9	8.7
Lam Pao	89	1.65	43	17	33	7	80	4	16	15	8.5
Mae Ngat	118	2.68	53	24	15	7	76	11	13	9	8.4
Nam Un	63	1.36	60	21	10	9	77	1	21	15	7.8
Nong Kor	123	2.27	36	16	28	20	74	16	11	-	8.5
Ratchaprapa	79	1.60	46	33	14	8	84	3	13	8	8.6
Srinakarin	234	5.28	64	30	4	2	92	2	6	15	8.3
Thatungna	256	5.30	65	28	4	2	93	2	5	15	8.5
Ubonratana	155	3.23	59	18	18	5	89	4	7	10	8.8

a seasonal pattern even though theory suggests nutrients should be greater when external processes dominate, as during the monsoon. Internal loading processes, therefore, may be important in determining nutrients in these polymictic water bodies (KILHAM & KILHAM 1990). Silica values were about twice as large during the monsoon (Table 3); this difference was significant and suggests silica input from rivers during the wet season (KOBAYASHI 1959) and a decline by biotic use during the dry period, without complete internal regeneration. Silica levels were somewhat lower in reservoirs where sandstone predominates.

The sampled reservoirs had low suspended solids (Table 3); NVSS was correlated with TP ($r = 0.85$, $n = 23$) and VSS was correlated with Chl and TN ($r \geq 0.88$, $n = 23$). Secchi depth showed a negative correlation with TN, TP, VSS and Chl ($r \geq -0.76$ to -0.89, $n = 22$), and a weaker relation with NVSS ($r = 0.67$, $n = 22$). Measured transparency and values, predicted with an empirical equation using Chl, agreed quite well (JONES & BACHMANN 1978). Collectively, these findings suggest water clarity in the lacustrine zone of these reservoirs was determined by phytoplankton rather than suspended

Table 3. Limnological data from Thai reservoirs sampling during the monsoon (1988) and pre-monsoon (1991). Values represent means of samples collected from ≤4 m depth. NVSS, nonvolatile solids; VSS, volatile solids; Chl, chlorophyll.

Water body and year	TN	TP	Chl	<η Chl	SiO_2	NVSS	VSS	Secchi
		(μg L^{-1})		(%)		(mg L^{-1})		(m)
1988 Data								
Bang Phra	590	30	15.8	63	16.4	1.6	2.3	2.4
Bumiphol	280	10	4.6	87	13.9	0.7	1.0	3.4
Bung Boraphet	510	18	8.1	82	13.7	0.2	1.3	2.7
Khao Laem	200	9	3.8	58	8.5	0.4	0.6	5.2
Lam Pao	530	29	9.1	71	9.5	4.6	1.3	1.1
Nam Un	475	12	6.6	77	8.8	0.6	0.8	1.9
Nong Kor	560	34	28.1	98	14.2	4.2	3.5	1.0
Ratchaprapa	295	10	4.7	57	8.1	0.6	0.9	4.1
Srinakarin	215	11	4.3	91	11.9	0.6	0.7	5.3
Thatungna	325	20	3.3	89	-	2.5	0.8	1.4
Ubonratana	460	20	19.0	91	12.1	1.7	1.6	2.0
1991 Data								
Bang Phra	775	43	30.0	100	6.6	4.3	3.9	1.0
Bumiphol	295	15	4.9	85	7.2	0.3	1.4	3.6
Bung Boraphet	860	23	18.5	93	11.6	0.8	4.2	1.2
Kew Lom	295	13	5.2	80	8.2	0.9	1.5	3.0
Khao Laem	150	7	1.8	82	5.0	0.2	0.4	5.1
Lam Pao	345	11	2.4	51	2.8	0.7	0.6	3.4
Mae Ngat	345	11	5.2	59	7.4	0.5	0.9	3.3
Nam Un	370	9	2.7	83	3.5	0.3	1.0	3.8
Nong Kor	780	89	10.1	-	3.9	51.7	5.8	-
Ratchaprapa	190	6	1.4	100	4.9	0.3	0.4	5.8
Srinakarin	210	9	2.0	100	6.8	0.1	0.9	5.3
Thatungna	310	14	2.2	100	6.5	0.4	0.5	-
Ubonratana	545	19	14.1	71	4.4	0.3	3.0	1.9

solids from external sources. When expressed as Trophic State Index values (TSI, CARLSON 1977), TSI deviations show algae dominate light attenuation ($TSI_{Chl} - TSI_{Secchi} > 0$, Fig. 4). In two-thirds of our samples 80–100% of the Chl was not retained by 35 μm netting, indicating that small algae dominated the phytoplankton (Table 3). In the remaining samples, field observations suggested large cyanobacteria were abundant at the time of our collection. In several reservoirs we found subsurface algal maxima (Fig. 3). They varied among reservoirs, but often were found within the water column at temperatures about 0.5–1.5 °C cooler than the surface. These layers may represent in situ growth and may be amplified by UV light suppression of Chl in surface waters (VINCENT & ROY 1993); the occurrence and magnitude of subsurface maxima are likely dynamic because of polymictic mixing patterns. In well-mixed reservoirs, Chl values were uniform or declined somewhat with depth (Fig. 3).

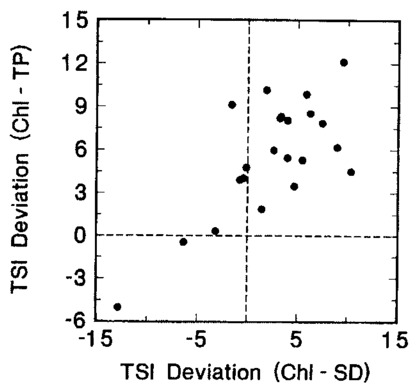

Fig. 4. Deviations among trophic state index (TSI) values after CARLSON (1991) indicating nutrient limitation and composition of the seston. Nutrient limitation is shown by positive values on the Y-axis. Light attenuation by algae are likely when $TSI_{Chl} - TSI_{Secchi} > 0$. Among Thai reservoirs, the cluster of data points in the upper right quadrangle of this TSI deviation plot suggests P limitation and algal domination of light, with large algal particles in some reservoirs.

Among reservoirs, TP_{log} explained 76% of the variation in Chl_{log} and TN_{log} explained 73% (Fig. 5). The Chl–TP relation matches that of JONES & BACHMANN (1976), and similarly the Chl–TN relation closely matches that of CANFIELD (1983). In a two variable model TN and TP are significant ($P < 0.05$) and together explain 80% of the variation in Chl_{log} ($Chl_{log} = -2.29 + 0.79\ (TN_{log}) + 0.88\ (TP_{log})$).

Ratios of POC/Chl (µmol µg^{-1}) were all ≥10, indicating a general nutrient deficiency for phytoplankton growth (HECKY et al. 1993). Ratios of TN/TP averaged 26 and varied from 16 to 40, and were similar during both sampling events. These values suggest P regulation of algal biomass (FORSBERG & RYDING 1980); N limitation was indicated in about half the samples by Walker's formula for limiting nutrients in reservoirs (TN–150/TP) that adjusts for available N (WALKER 1985). Ratios of POC/PON (5.5–9.4 µmol µmol^{-1}, HECKY et al. 1993) were not indicative of moderate N deficiency. Expressing these data as TSI values shows P limitation ($TSI_{Chl} - TSI_{TP}$ was typically >0, Fig. 4), and TSI based on both P and N (CARLSON 1991) also showed general nutrient deficiency. Deviations of TSI_N from TSI_{Chl} indicated N limitation was not prevalent. Bioassay experiments (Fig. 6) generally showed no response to P, indicating that N was not abundant. In some bioassays there was a modest response to N, but the ammonium amendment may have stimulated Chl formation (KNOWLTON & JONES

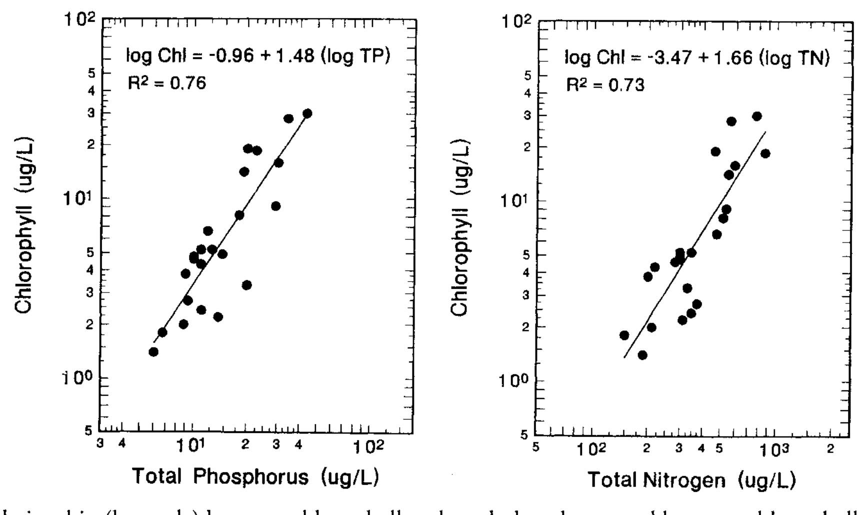

Fig. 5. Relationship (log scale) between chlorophyll and total phosphorus and between chlorophyll and total nitrogen in Thai reservoirs (Table 3).

1996). In all cases the response was significantly greater when both nutrients were included (Fig. 6), suggesting that neither nutrient was present in great excess.

The limiting factors model of KAISER et al. (1994) was fit to these data; the limiting effect of a nutrient (TP or TN) is expressed in this model as a straight line through the origin, called the 'limit function'. The model fit using TN data was improved through the addition of an offset parameter in the limit function (KAISER et al. 1994). Observed Chl was modeled as the value of the limit function multiplied by a random variable assuming values in the interval (0,1). Both TP and TN/7.2 were used as potential limiting factors and Fig. 7 shows their estimated limit functions (slope = 1.033 for TP, and 1.091 for TN/7.2). We modified TN by the Redfield ratio (by weight) to account for the elemental composition of N/P in algae. Although this model has not been widely applied using TN as the limiting factor, the estimated slope of 1.033 for TP closely agrees with applications to several global data sets (KAISER et al. 1994) and the view that ratios of Chl/TP near unity indicate P control of algae. Lower panels in Fig. 7 show estimated distributions for the proportion of the maximum possi-

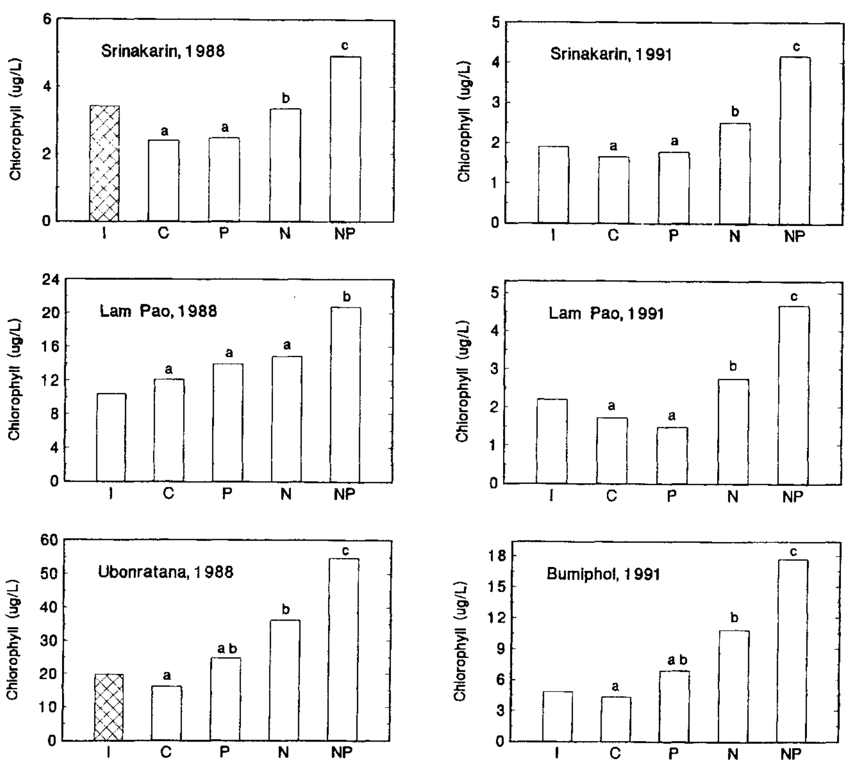

Fig. 6. Nutrient enrichment bioassays conducted in four Thai reservoirs. Unfiltered surface water was divided among 4-L translucent containers while protected from sunlight. Triplicate treatments received nutrients (as K_2HPO_4 or NH_4NO_3) in the amount of 15 µg L^{-1} P and 225 µg L^{-1} N, or both elements (NP), as nominal additions above background. Nutrient additions in Srinakarin were at half these levels. Three containers received no nutrient additions and served as controls (C). Containers were incubated at about half the Secchi depth for 2–4 days, and algal growth was measured as Chl. Statistical differences among treatments were analyzed by a one-way analysis of variance followed by a least significant difference test (alpha = 0.05). Initial values (I) are shown for reference, and a t-test (alpha = 0.05) was used to evaluate statistical differences between I and C (hatched I bars indicate significance).

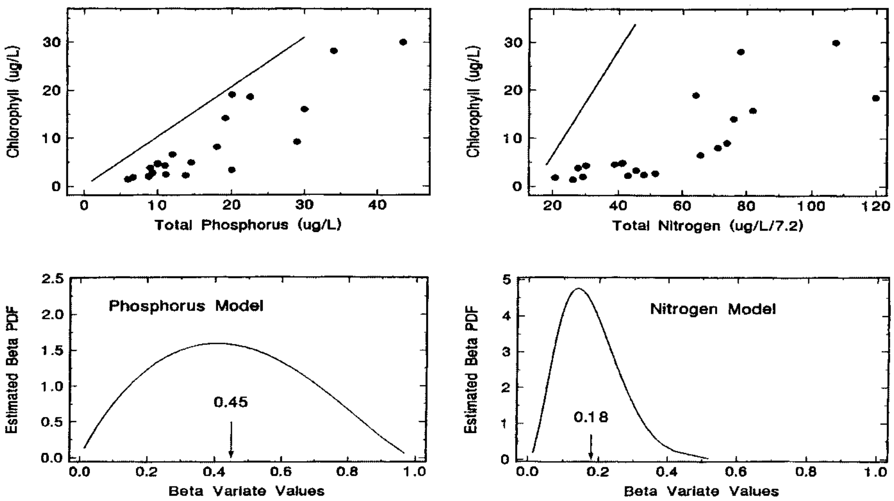

Fig. 7. Fitted limiting factor models with TP and TN. Upper panels show scatter plots of data with estimated limit functions. Lower panels show estimated distributions for proportions of maximum attainable Chl (i.e., limit functions). Proportions are read off to abscissa and probability densities for those values are read off of the ordinate. Estimated expected values are shown as arrows. Data from Nong Kor, Mae Ngat and Kew Lom in 1991 were not included in this analysis.

ble Chl values attained (mean 0.45 for TP and mean 0.18 for TN/7.2). These, too, are similar to distributions estimated for global data sets. Reservoirs in our study are apparently more diverse in terms of the probabilities of reaching various proportions of the maximum Chl value possible under existing TP conditions than under existing TN conditions (shown by greater spread of the estimated distribution in the TP model, Fig. 7). In total, the fits of these models indicate that Chl values typically reach less than one half of the potential maximum for the observed levels of TP and TN. This outcome suggests neither P nor N is consistently the sole limiting factor for algal growth.

Conclusions

The South-east Asian region is poorly studied by limnologists (FERNANDO 1984). In Thailand, most work has addressed the distribution of freshwater organisms (MIZUNO & MORI 1970, JUNK 1977, GEISLER et al. 1979, LAI & FERNANDO 1981) with modest information on water quality. Our study expands the data base on water chemistry and fertility of Thai reservoirs and major findings show the sampled reservoirs are warm polymictic with an oxygenated water column in the mixed layer; salinity, dominated by bicarbonate and divalent cations, approximates the world average and reflects regional geology. Low suspended solids, and algal domination of light attenuation characterized the lacustrine zone of reservoirs in our study; there were near equal numbers among oligo-, meso- and eutrophic categories. There was a general fit of the Chl data to published Chl–TP and Chl–TN relations, suggesting these tropical reservoirs have algal-nutrient relations similar to lakes elsewhere; nutrient ratios, physiological indicators, TSI deviation plots, regression analysis, bioassays and a model of limiting factors (Fig. 7) show, to various degrees, both N and P are associated with phytoplankton biomass. It may be that both nutrients are in short supply in these reservoirs, which differs from the suggestion that Asian lakes are predominately limited by N (DUSSART 1974). The nominal seasonal comparison suggests that salinity and pH were reduced while silica was greater during the monsoon than the pre-monsoon. Our findings are tentative because the data base is modest and samples were not collected within the same annual cycle. In terms of lake function, the question of how polymixis influences internal nutrient cycling may be important in explaining nutrient levels and factors controlling algal growth in Thai reservoirs. How nutrients and nutrient limitation are altered by external inputs during the monsoon also deserves additional consideration.

Acknowledgments

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