Lake and Reservoir Management 19(1):64-78, 2003

Trophic State, Seasonal Patterns and Empirical Models in South Korean Reservoirs

John R. Jones and Matthew F. Knowlton
Department of Fisheries and Wildlife Sciences
University of Missouri, Columbia, MO 65211-7240

Kwang-Guk An
Department of Environmental Science and Engineering
Ewha Womans University
Seoul 120-750, Republic of Korea

ABSTRACT

Jones, J. R., M. F. Knowlton and K.-G. An. 2003. Trophic state, seasonal patterns and empirical models in South Korean reservoirs. Lake and Reserv. Manage. 19(1):64-78.

Data from 59 reservoirs in South Korea, sampled monthly during 1993-2000, showed that about one-third were mesotrophic, nearly one-half were eutrophic and the remainder were hypereutrophic based on conventional criteria for total phosphorus (TP), chlorophyll (Chl) and Secchi depth. Most reservoirs had >1 mg·L^{-1} total nitrogen (TN) resulting in high mass ratios of TN:TP (range 23 to 243, median 76) relative to many temperate lakes. To compensate, conventional TN criteria were provisionally adjusted upward by about 2.5-times to classify Korean reservoirs uniformly across all trophic state metrics. During the summer monsoon, TP and TN typically peaked in mesotrophic reservoirs and declined in the hypereutrophic group. The inference is that monsoon inflow produces these patterns by increasing non-point external inputs that dominate the nutrient budgets of mesotrophic reservoirs while diluting point-source inputs important in hypereutrophic impoundments. Eutrophic reservoirs showed both response patterns, so that taken in aggregate a seasonal response was not apparent. The log relation between Chl and TP was linear and showed an average yield of Chl per unit of TP on par with other temperate lakes. Seasonally, the Chl-TP relation was strongest during summer and weaker during fall-winter which is consistent with increased light-limitation during mixis in these monomictic impoundments. Seasonal development of Chl did not show strong evidence of a spring or fall bloom. About half of the time maximum Chl values were measured during the monsoon or post-monsoon (July-September). Maximum Chl was ~3 times the annual mean and during summer maximum Chl was ~ double the mean. The log relation between Chl and Secchi depth matched that found in North American lakes and the seasonal phenology for Secchi depth was the opposite of Chl and suspended solids. The analysis confirms that the monsoon is a major source of variation within and among Korean reservoirs.

Key Words: Korea, trophic state, monsoon, nutrients, chlorophyll, transparency, seasonal patterns.

Eutrophication is a major aquatic problem in South Korea. Rapid industrialization, urbanization and intensified agriculture and aquaculture have resulted in human-induced enrichment of growth-limiting nutrients to surface waters, causing troublesome algal blooms and associated problems (Heo and Kim 1997, Park et al. 1998, Kim et al. 2001). There is remarkable global unity in how nutrient enrichment is manifested in aquatic systems (Smith 2003) but several features of lake resources in Korea set them apart from many other temperate water bodies (Jones et al. 1997). There are few natural lakes in Korea and artificial reservoirs have been constructed throughout the country for water supply and hydropower, mostly since 1970. Also, the annual hydrologic cycle is dominated by a summer monsoon when approximately half of the annual precipitation occurs. The extent to which eutrophication theory and global models fit the Korean situation by accounting for reservoir dynamics and the seasonal monsoon has recently been assessed (An and Jones 2000a, 2000b, 2002, Kim et al. 2001).

In many temperate regions major breakthroughs about factors controlling lake processes have come from large-scale systematic efforts to determine the present condition of a wide range of lake resources (Jones and Bachmann 1976, Forsberg and Ryding 1980, Vollenweider and Kerekes 1980, Canfield and Bachmann 1981, Sommer et al. 1986, Marshall and

Peters 1989). In this paper we take this approach and summarize an extensive regional data base consisting of monthly limnological measurements during 1993-2000 from 59 reservoirs (Fig. 1) compiled by the Korean Ministry of the Environment. Our goal was to characterize the trophic state of Korean reservoirs, describe seasonal patterns in response to the summer monsoon and compare empirical relations for nutrients-chlorophyll and chlorophyll-transparency (Secchi) to similar models in the literature for other temperate lakes.

Physical Setting, Climate and Data Set

The Korean peninsula (36°- 38°N, 124°- 130°E) is mountainous. Peaks rarely exceed 1200 m but the terrain is rugged and slopes are steep and forested. Alluvial plains occur only near the west coast and in the southwest. Highly metamorphosed gneiss and schist groups compose most of the mountains and the metamorphic terrain consists of metamorphosed sedimentary rocks (Reedman and Um 1975). Urban areas and agriculture have developed in the alluvial plains and near rivers where slopes are gentle and water resources are available (Kim et al. 2001).

The climate of South Korea is characterized as temperate and continental with warm, humid summers and cold dry winters. About one-half of the annual rainfall occurs during the summer monsoon. During 1993-2000 precipitation data was collected by the Korea Meteorological Administration at 29 locations throughout the country (Fig. 2). Monthly averages varied by an order of magnitude between the winter minimum in December (20 mm) to the mean summer maximum in August (322 mm). The monthly maximum was 1115 mm, measured at one climate station in July 1999. Yearly total precipitation during 1993-2000 (Fig. 2) averaged 1332 mm, the minimum annual average was 894 mm in 1994 and maximum average was 1815 mm in 1998. In 1999 an annual total of 3413 mm was recorded at one site. Air temperatures are below freezing in winter and shallow reservoirs develop a

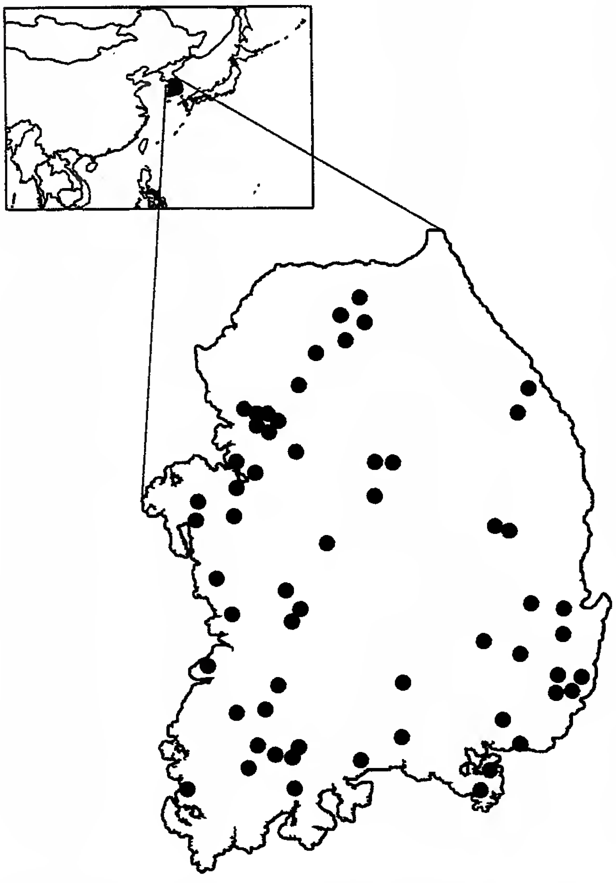

Figure 1.-Map of South Korea showing the location of reservoirs sampled in this study.

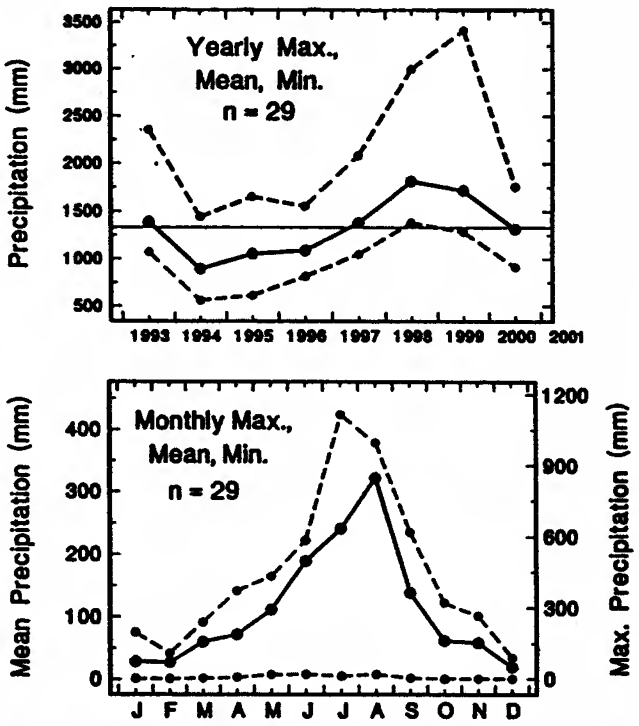

Figure 2.-Rainfall data from 29 climate stations in Korea during 1993-2000. Upper panel shows annual maximum, mean and minimum rainfall totals for the sites, and the horizontal line shows the overall average annual rainfall in this data set (1332 mm). Lower panel shows monthly maximum, mean and minimum total rainfall at the sites.

brief ice cover but larger reservoirs remain ice-free and are warm monomictic (Kim et al. 2001).

Data were collected as part of a nationwide survey of reservoirs being complied by the Korean Ministry of the Environment. Samples were collected from the surface layer at 1 to 6 sites per reservoir (Table 1) during 1993-2000 and were analyzed by standard methods (American Public Health Association 1992). Total phosphorus (TP) was determined using the ascorbic acid method after persulfate oxidation. Total nitrogen (TN) was measured by the UV spectrophotometric method after potassium persulfate digestion. Total suspended solids were determined after drying at 105 °C for one hour. Chlorophyll (Chl) was measured using a spectrophotometer after extraction in acetone. Transparency was measured using a 30 cm Secchi disk at the time of sample collection and conductivity (µS at 25 °C) was measured in the laboratory.

Most analyses were conducted on the lake mean (average of all measurements over time and sampling

Table 1.–Limnological parameters measured in Korean reservoirs during 1993-2000. Values are lake means for the period of record and are presented by ascending total phosphorus concentration.

Lake[a]	Sites	Conductivity µS	Total P µg · L^{-1}	Total N mg · L^{-1}	Chlorophyll µg · L^{-1}	Total Suspended Solids mg · L^{-1}	Secchi m
Buan Res.	3	71	11	1.24	2.9	2.2	2.8
Unmun Res.	2	76	15	1.06	5.7	5.1	2.0
Dongbok Res.	2	75	15	0.85	13.3	3.2	2.0
Suoh Res.	2	73	15	1.26	4.0	1.6	3.4
Soyanggang Res.	4	62	17	1.71	5.5	3.8	3.1
Boryeong Res.	3	134	18	1.74	3.2	3.4	1.9
Andong Res.	3	163	19	1.73	4.2	2.3	3.1
Gucheon Res.	1	56	19	0.28	3.7	4.6	3.2
Chungju Res.	3	191	19	2.28	4.3	2.9	3.2
Juam Res.	3	92	21	0.90	4.6	2.9	3.1
Juam Aux. Res.	3	93	22	0.98	4.4	2.6	3.5
Hapcheon Res.	3	94	22	1.37	6.9	1.9	2.3
Namgang Res.	3	104	24	1.52	9.7	5.4	1.9
Seomjingang Res.	3	99	24	1.71	7.9	3.4	2.5
Gwangdong Res.	1	139	26	1.42	3.6	1.7	2.2
ImHa Res.	3	168	28	1.48	7.5	4.0	1.6
Daecheong Res.	6	123	28	1.63	7.1	3.6	2.3
Dalbang Res.	1	91	29	0.84	5.1	1.7	2.4
Yeoncho Res.	2	96	29	0.52	12.4	9.7	1.5
Yeongcheon Res.	2	104	30	1.52	9.2	3.5	1.7
Gachang Res.	2	63	31	1.34	6.4	4.4	1.9
Sayeon Res.	2	126	32	1.37	13.4	6.7	1.8
Chungju Aux. Res.	2	182	35	2.42	5.7	8.3	1.9
Chuncheon Res.	3	80	36	1.36	5.7	2.8	2.7
Cheongpyeong Res.	3	75	36	1.56	9.6	4.0	2.4
Damyang Res.	2	64	37	1.31	9.1	5.3	1.7
Hwacheon Res.	3	91	38	1.19	4.6	1.9	3.5
Daea Res.	3	39	38	1.23	5.3	3.1	2.7
Aangye Dam	1	142	42	1.88	12.8	3.7	1.6
Gwanggyo Res.	2	133	43	3.13	23.3	5.4	1.6
Goesan Res.	3	113	43	2.29	10.8	4.7	3.1
Gyeongcheon Res.	2	68	44	1.53	11.6	5.0	2.0
Paldang Res.	5	158	47	2.40	17.2	5.9	1.3
Gwangju Res.	2	86	51	1.21	9.5	5.7	1.5

Table 1 (continued).–Limnological parameters measured in Korean reservoirs during 1993-2000. Values are lake means for the period of record and are presented by ascending total phosphorus concentration.

Lake[a]	Sites	Conductivity µS	Total P µg·L-1	Total N mg·L-1	Chlorophyll µg·L-1	Total Suspended Solids mg·L-1	Secchi m
Tapjeong Res.	2	118	52	1.58	10.4	4.8	1.5
Naju Res.	2	92	54	1.59	13.6	6.2	1.3
Eedong Res.	2	333	55	5.05	17.9	10.6	0.9
Uiam Res.	3	77	59	1.60	10.4	4.9	2.2
Bomoon Res.	2	143	60	1.89	18.7	9.1	1.8
Jangseong Res.	2	92	60	1.53	12.9	5.0	1.5
Bunam Res.	3	3416	64	1.62	41.6	17.5	0.6
Daeam Res.	2	275	65	2.72	45.3	8.9	1.1
Seonam Res.	1	288	69	2.92	35.2	8.9	1.1
Nakdong Estuary Res.	3	492	69	3.49	40.7	13.7	0.9
Boseonggang Res.	2	122	71	1.82	11.3	15.6	0.8
Yedang Res.	3	160	72	1.94	19.3	8.4	0.9
Hoeya Res.	2	305	90	2.76	19.9	7.9	1.9
Woncheon Res.	3	287	102	3.75	33.0	9.5	0.7
Geumgang Estuary Res.	3	468	104	3.27	28.9	17.5	0.6
Gosam Res.	3	145	105	2.91	23.5	37.1	0.7
Ganwol Res.	3	1770	111	2.50	52.4	21.7	0.6
Junam Res.	1	266	113	2.50	24.7	16.8	–
Namyang Res.	3	924	121	4.49	35.3	17.4	0.6
Yeongsangang Estuary Res.	3	704	128	3.71	15.4	13.1	1.1
Sihwa Res.	3	33242	165	4.23	57.4	14.2	0.9
Sapgyo Res.	3	499	169	4.46	34.5	19.8	0.7
Asan Res.	3	578	260	8.57	40.6	24.9	1.0
Singal Res.	3	417	336	6.59	61.1	16.8	0.7
Seoho Res.	3	375	597	9.16	180.8	29.1	0.5
mean		832	70	2.32	19.6	8.4	1.8
minimum		39	11	0.28	2.9	1.6	0.5
25%		91	26	1.36	5.7	3.4	0.9
50%		126	43	1.71	11.3	5.3	1.7
75%		275	69	2.72	23.3	9.7	2.3
maximum		33242	597	9.16	180.8	37.1	3.5

[a] Mean values from monthly collections across 8 years except in Unmun Res. n = 7, Sihwa Res. and Junam Res. n = 6, and in Ganwol Res., Bunam Res., Buan Res. and Boryeong Res. n = 4.

sites, Table 1) and we used the growing season mean (summer averages over time and across sites) to evaluate trophic state categories. The annual mean Chl and summer mean Chl (average of all measurements in a given year or summer) were used to evaluate Chl maximums. Mean values were log transformed when appropriate for correlation and regression analyses and significance was set at <0.01. To permit among-system comparisons of seasonal patterns, individual observations from each reservoir were normalized to a zero mean after the general approach of Marshall and Peters (1989), by using the following equation from Steel and Torrie (1980):

$$Z_N = (OV - LM)/STD \qquad (1)$$

where Z_N represents a value in the standardized data set which has a zero mean, observed values (OV) are variables in Table 1 measured in each reservoir on a given date, the lake mean (LM) is the overall mean for a given variable for a particular reservoir, and STD is the standard deviation of the lake mean.

Results

Trophic State

Trophic state metrics were heterogenous among the 59 South Korean reservoirs in the data set (Table 1). Lake mean values of total phosphorus (TP) ranged from 11 to 597 $\mu g \cdot L^{-1}$ with a median of 43 $\mu g \cdot L^{-1}$. Total nitrogen values (TN) ranged from 0.28 to 9.16 $mg \cdot L^{-1}$ with a median of 1.71 $mg \cdot L^{-1}$. Chlorophyll (Chl) ranged from 2.9 to 181 $\mu g \cdot L^{-1}$ with a median of 11.3 $\mu g \cdot L^{-1}$. Secchi transparency ranged from 0.5 to 3.5 m, with a median of 1.7 m (Table 1).

Among the lake means, TSS was strongly correlated with the trophic state metrics TP, TN and Chl ($r = 0.67$-0.85, log transformed, $n = 59$). Conductivity was also correlated with the trophic state metrics ($r = 0.61$-0.68, log transformed, $n = 59$).

Using trophic state criteria proposed by Nürnberg (1996) for TP, Chl and Secchi depth, about one-third of the sampled reservoirs were mesotrophic, nearly one-half were eutrophic and the others (20%) were hypereutrophic when ranked using their lake means (Table 2). None of the reservoirs were classified as oligotrophic using Nürnberg's criteria. Lake mean Chl values in two reservoirs and the mean TN value of one reservoir were within the oligotrophic range but other mean values suggest these water bodies were mesotrophic. Trophic state criteria proposed for TN in Table 2 are about 2.5-times the limits of conventional criteria (Forsberg and Ryding 1980, Nürnberg 1996). The adjustment was necessary because in most Korean reservoirs TN is abundant relative to TP (An and Jones 2002, Kim et al. 2001), and TN criteria of Nürnberg (1996) would place 88% of the reservoirs in the hypereutrophic category. Using proposed criteria for TN (Table 2), the proportion of reservoirs in each trophic state category shows close agreement across all trophic state metrics.

Trophic state assessments were virtually unchanged from the proportions shown in Table 2 when Korean reservoirs were classified using summer mean values (May-September), which is the original basis for Nürnberg's criteria. Ratios of the May-September mean values to annual lake means averaged near unity for both plant nutrients, 1.2 for Chl and 0.9 for Secchi depth.

Among mesotrophic reservoirs (<30 $\mu g \cdot L^{-1}$ TP), the relation between TN_{log} and TP_{log} was highly variable and not significant (Fig. 3). Whereas among eutrophic and hypereutrophic reservoirs the relation was significant ($r = 0.84$, $n = 39$) and the slope of a LOWESS fit through these data was ~0.7, meaning that among the most fertile reservoirs the cross-system increase in P is accelerated relative to increases in N (Fig. 3). Mass

Table 2.–Trophic state criteria based on total P and chlorophyll from Nürnberg (1996) and the percentage of reservoirs in this data set that fall within these categories. Total N criteria are proposed for Korean reservoirs and cut points were chosen to have correspondence with proportion of reservoirs in various categories as judged by total P and chlorophyll.

	Total P ($\mu g \cdot L^{-1}$)		Total N ($mg \cdot L^{-1}$)	
Trophic State	**Criterion**	**% of Reservoirs**	**Criterion**	**% of Reservoirs**
Mesotrophic	10 - 30	34	<1.5	32
Eutrophic	>30 - 100	46	>1.5 - 3	48
Hypereutrophic	>100	20	>3	20
	Chlorophyll ($\mu g \cdot L^{-1}$)		**Secchi m**	
Mesotrophic	<9	36	>2<4	31
Eutrophic	>9 - 25	42	>1<2	43
Hypereutrophic	>25	22	≤1	26

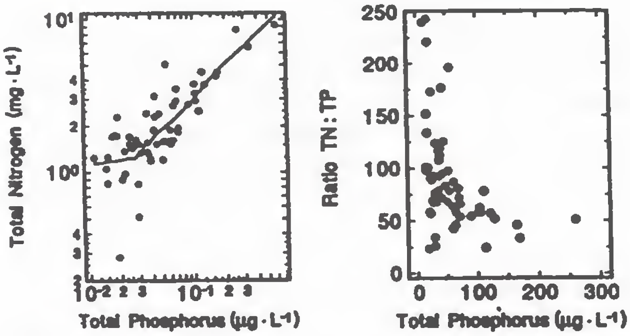

Figure 3.–Left panel shows the relationship between mean TN (mg·L^{-1}) and TP (µg·L^{-1}) in Korean Reservoirs. The average trend in the data (solid line) was estimated by locally weighed sequential smoothing (LOWESS). Right panel shows the relationship between TN:TP mass ratios and mean TP values in Korean reservoirs.

ratios of TN:TP declined with trophic state (Fig. 3). Among mesotrophic reservoirs the median TN:TP ratio was 92 and values ranged from 23 to 243, which is the entire range within the data set. Among eutrophic reservoirs the median was 81 (range 42 to 195) and among hypereutrophic reservoirs the median was 51 (range 24 to 78). The overall median was 76. These values suggest potential P-limitation is prevalent among Korean reservoirs (Forsberg and Ryding 1980, Smith 1982).

Seasonal Patterns

Phenological patterns of nutrients and Chl in the Korean reservoirs differed by trophic state (Fig. 4). Among mesotrophic reservoirs normalized values (equation 1) of TP_N and TN_N were lowest in winter and reached an annual peak during the monsoon. This pattern suggests delivery of external inputs in monsoon runoff is a major influence on the annual nutrient budget of mesotrophic reservoirs. In contrast, among hypereutrophic reservoirs there was a sharp decline in TN_N during the monsoon with minimal values occurring in September. This pattern suggests external inputs dilute in-reservoir concentrations and that peak runoff is not the principal source of N for these reservoirs. Instead, processes such as point source inputs, internal loading and/or runoff during moderate to low flow, are likely responsible for maximum N levels in hyper-

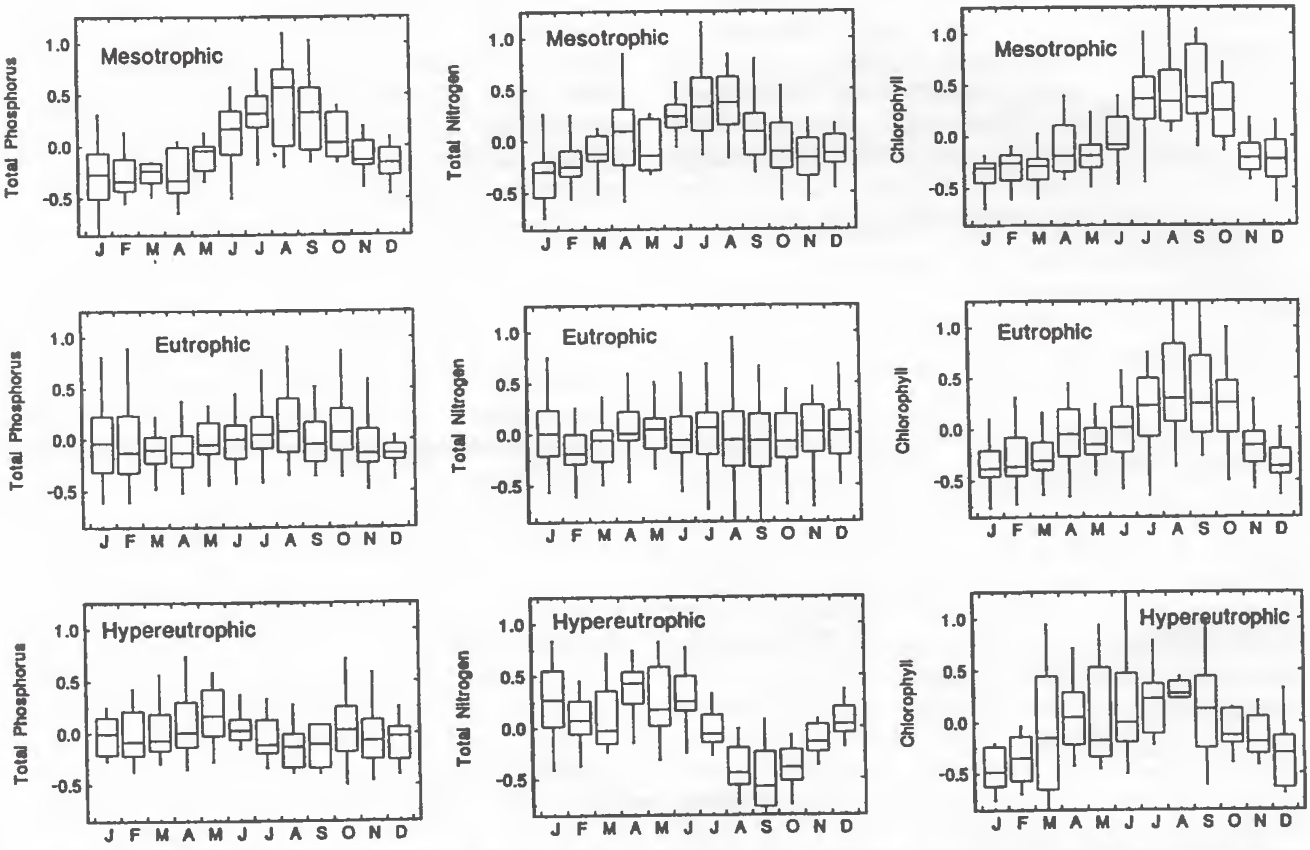

Figure 4.–Box plots of monthly mean normalized values of TP (µg·L^{-1}), TN (mg·L^{-1}), and Chl (µg·L^{-1}) for 59 Korean reservoirs presented by trophic state categories described in Table 2. In the box plots the horizontal line represents the median value, the box represents the interquartile range, and the solid lines represent a distance 1.5 times the interquartile range. Outlying data points are not shown in these panels.

eutrophic reservoirs. The TP_N seasonal pattern in hypereutrophic reservoirs was less pronounced. TP_N showed a modest seasonal peak during spring (April-May) concurrent with increased rainfall and runoff (Fig. 2), followed by a small monsoon decline and a second modest peak concurrent with fall overturn, which is consistent with internal loading (Fig. 4). In contrast, the among-system seasonal pattern in eutrophic reservoirs was not strong for either TP_N or TN_N and the frequency of positive and negative values of TP_N and TN_N in this group were approximately equal over time. Both nutrients, however, showed increased among-system variation in winter and again during the monsoon. Increased variation during periods of minimal and peak inflow would occur if in-reservoir concentrations were concurrently increasing in some impoundments in response to inflow and decreasing in others, as depicted in Fig. 5 for TN_N in two eutrophic reservoirs.

To show response to the monsoon across the continuum of nutrient conditions in the data set, the mean normalized TP_N and TN_N during July-August from each reservoir were plotted against respective lake mean values in Fig. 6. For TP_N the monsoon peak was most pronounced among reservoirs with the lowest mean TP levels and the response declined with trophic state such that most reservoirs with >75 $\mu g \cdot L^{-1}$ TP were near their overall mean TP_N during this period (Fig. 6). About half the reservoirs showed elevated TN_N during the monsoon and the magnitude of this response declined with trophic state (Fig 6). Among eutrophic reservoirs about 40% showed below average TN_N during the monsoon and the rest were above average (e.g., Fig. 5). Among reservoirs with >3 mg $\cdot L^{-1}$ TN only one water body did not show below average TN_N during the monsoon.

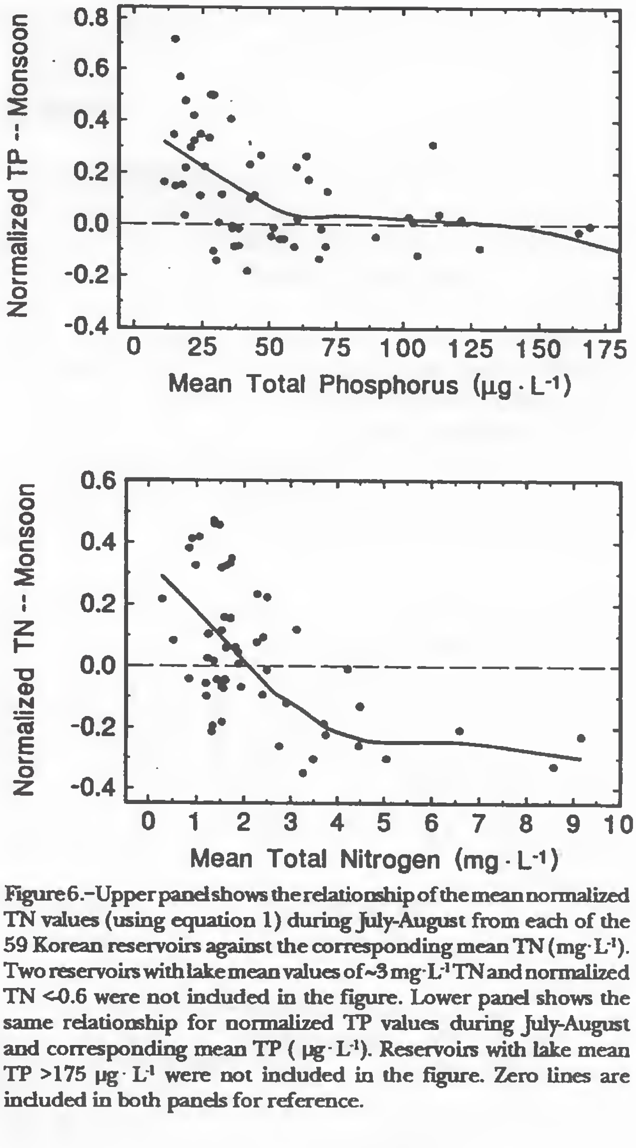

Figure 6.–Upper panel shows the relationship of the mean normalized TN values (using equation 1) during July-August from each of the 59 Korean reservoirs against the corresponding mean TN (mg $\cdot L^{-1}$). Two reservoirs with lake mean values of ~3 mg $\cdot L^{-1}$ TN and normalized TN <0.6 were not included in the figure. Lower panel shows the same relationship for normalized TP values during July-August and corresponding mean TP ($\mu g \cdot L^{-1}$). Reservoirs with lake mean TP >175 $\mu g \cdot L^{-1}$ were not included in the figure. Zero lines are included in both panels for reference.

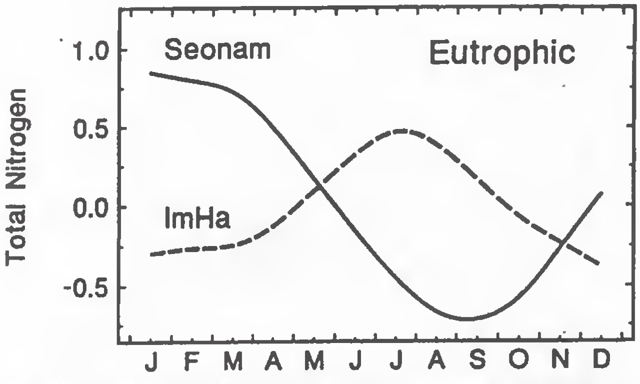

Figure 5.–Seasonal pattern of mean monthly normalized TN values (using equation 1, data points not shown) in two eutrophic Korean reservoirs (Seonam and ImHa) showing opposite responses during the monsoon. Trend lines were estimated by locally weighed sequential smoothing (LOWESS).

Seasonal increases in normalized values of Chl_N during the summer monsoon were similar in mesotrophic and eutrophic reservoirs (Fig 4); in both trophic state categories Chl_N increased during April, declined slightly in May, and peaked again during July-August, with considerable among-system variation in the pattern. In most mesotrophic and eutrophic reservoirs, Chl_N declined to less than the normalized mean between November and March (Fig. 4). Hypereutrophic reservoirs also showed low Chl_N in fall and winter, but Chl_N and among- system variation increased sharply in March, a month earlier than in the other trophic state groups. Chl_N remained at about the same level through the monsoon period with reduced variation among hypereutrophic reservoirs in August (Fig. 4).

Mean ratios of Chl:TP ranged from 0.16 to 1.6 with a median of 0.47 (as $\mu g \cdot L^{-1}$:$\mu g \cdot L^{-1}$), and ratios of

Chl:TN ranged from 2 to 33 with a median of 8 (as $\mu g \cdot L^{-1}$: mg $\cdot L^{-1}$) and this ratio increased along the trophic gradient (Fig. 7). Generally, both ratios peaked during the monsoon (Fig. 7) but there was also evidence of an increase during spring, concurrent with the spring increase in Chl (Fig 4).

Deviations in Carlson's Trophic State Index (TSI) values based on Chl, TP and Secchi (Carlson 1992), expressed as TSI(Chl)–TSI(TP) and TSI(Chl)-TSI(Secchi), were simultaneously plotted in Fig. 8. During winter mixis, points scattered below the origin suggesting there was less Chl than predicted by TP which is consistent with deep mixing and physically induced light-limitation in these monomictic reservoirs (Kim et al. 2001). Beginning in spring, and during the monsoon, values centered around the origin with about one-half of the points above the origin suggesting normal to higher than average yields of Chl per unit TP at this time. Points to the left of center suggest Secchi depth over-predicts Chl which occurs when light limitation by mineral turbidity is a factor and points to the right of center suggest there is more Chl than expected from Secchi measurement which occurs when algal cells are large. Across seasons, the Korean data suggest large algal cells were prevalent in July-October. The scatter in May is consistent with zooplankton grazing (lower right quadrant) and mineral turbidity at the onset of the seasonal rains (Fig 2) but these survey data do not permit a direct test of the controlling mechanism.

In mesotrophic and eutrophic reservoirs conductivity (KSP_N) increased beginning in fall through the winter presumably as a result of increased groundwater flow and evaporation during the dry season, and values

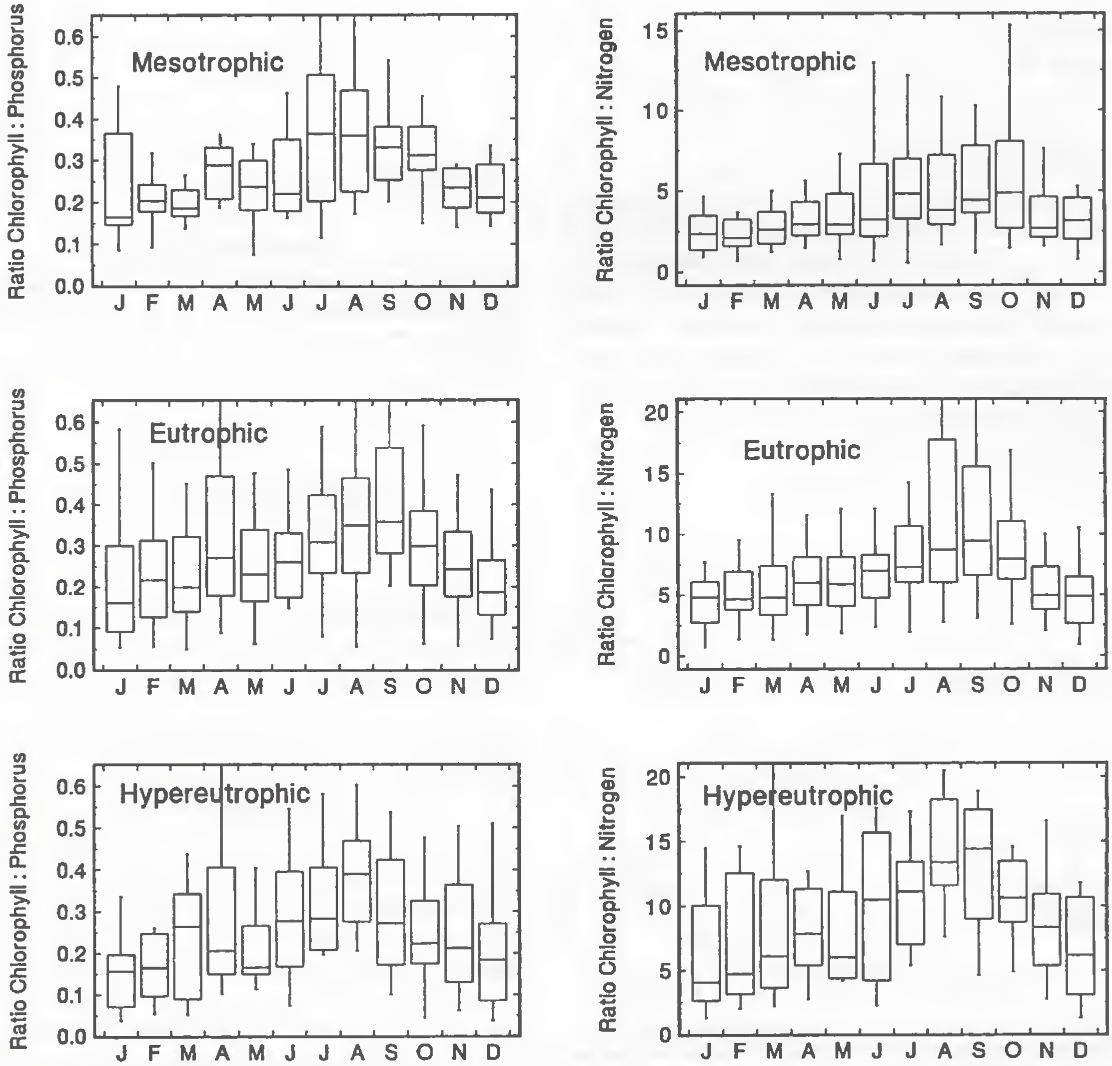

Figure 7.–Box plots of monthly mean ratios of Chl:TP ($\mu g \cdot L^{-1}$:$\mu g \cdot L^{-1}$) and ratios of Chl:TN ($\mu g \cdot L^{-1}$:mg $\cdot L^{-1}$) for 59 Korean reservoirs presented by trophic state categories described in Table 2. Box plots are described in Fig. 4.

declined during the monsoon presumably as a result of surface runoff (Fig. 9). This pattern has been documented across seasons in Daechung Reservoir (An and Jones 2000a). In hypereutrophic reservoirs among-system variation was large, but the median pattern showed a sharp decline in KSP_N during the monsoon followed by a rapid increase in fall and the median was invariable during winter and spring. As would be expected, normalized values of total suspended solids (TSS_N) increased in mesotrophic and hypereutrophic reservoirs over the spring to summer period concurrent with increases in Chl and external inputs during the monsoon. The seasonal pattern among eutrophic reservoirs was less apparent (Fig. 9) but showed increased variation during the monsoon. In each trophic state category the seasonal pattern for Secchi depth (Fig. 9) was the opposite of the phenology for Chl_N and TSS_N with minimal values during monsoon and maximum values during winter.

Empirical Relations

In a linear relation (Fig. 10) annual lake mean values of TP_{log} explained 77% of the variance in Chl_{log} among the Korean reservoirs. Adding TN_{log} to the regression was not statistically significant and eliminating the most enriched lake (TP = 597 µg·L^{-1}) did not appreciably change the fit ($R^2 = 0.73$) or the coefficients (intercept = -0.48 and slope = 0.94, n = 58). Nor did coefficients appreciably change when the regression was based on summer mean values (May-September), as is the typical basis for such analyses. Several empirical Chl-TP models in the literature have coefficients similar

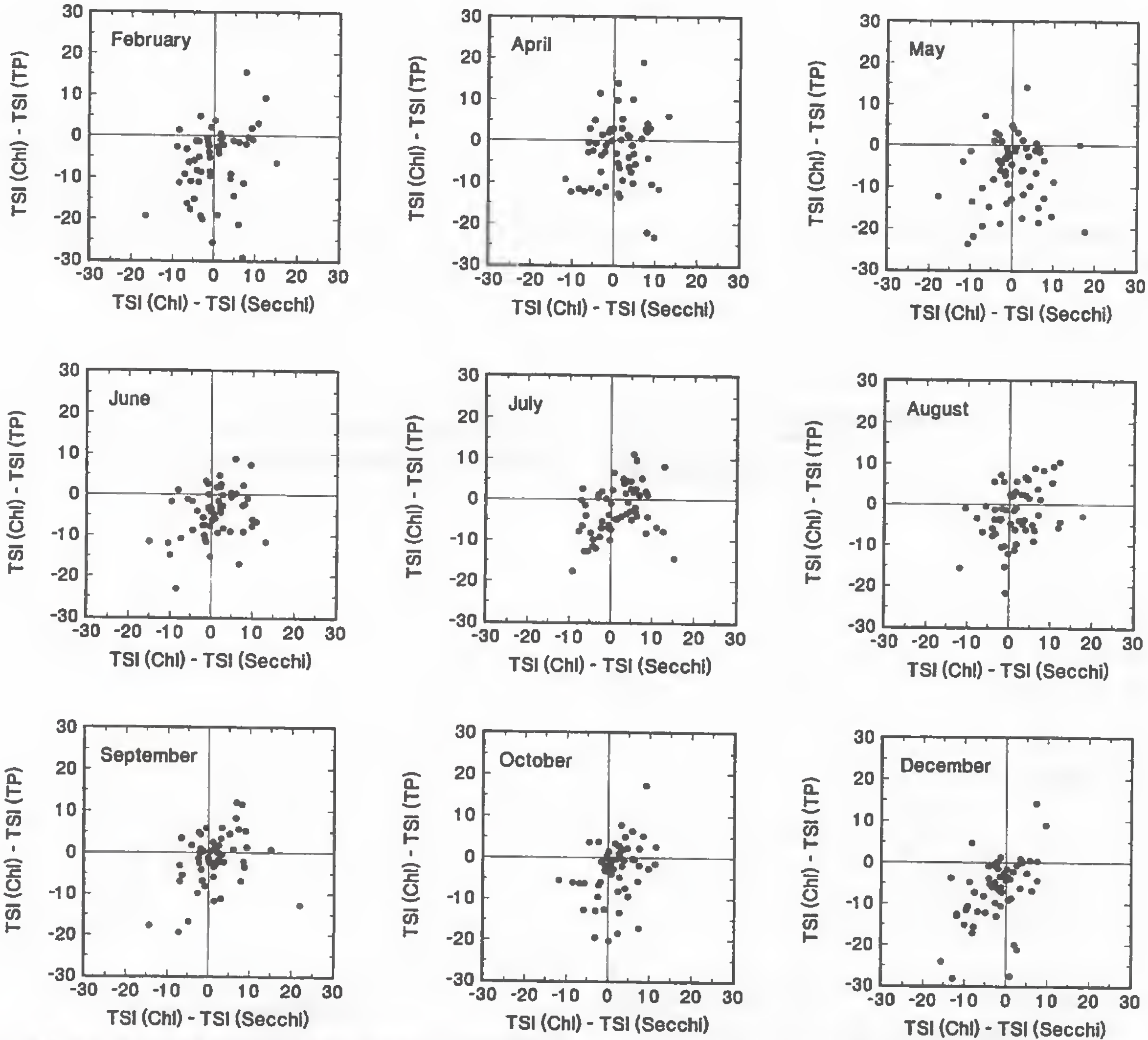

Figure 8.–Deviations in Carlson's Trophic State Index (TSI) values based on monthly mean values of Chl, TP and Secchi (Carlson 1992), expressed as TSI(Chl)–TSI(TP) and TSI(Chl)–TSI(Secchi), are simultaneously plotted for selected months.

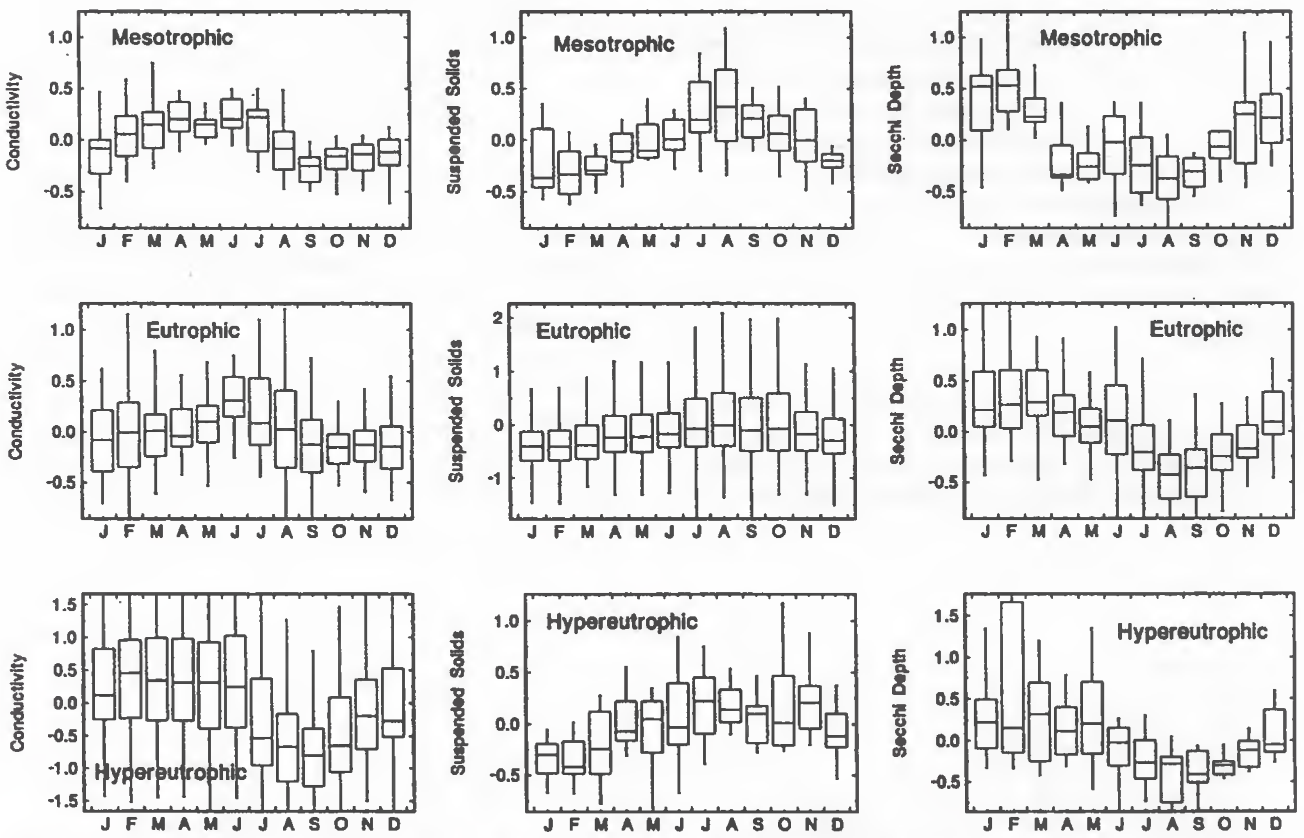

Figure 9.–Box plots of monthly mean normalized values of conductivity (µS), total suspended solids (mg·L^{-1}) and Secchi depth (m) for 59 Korean reservoirs presented by trophic state categories described in Table 2. Box plots are described in Fig. 4.

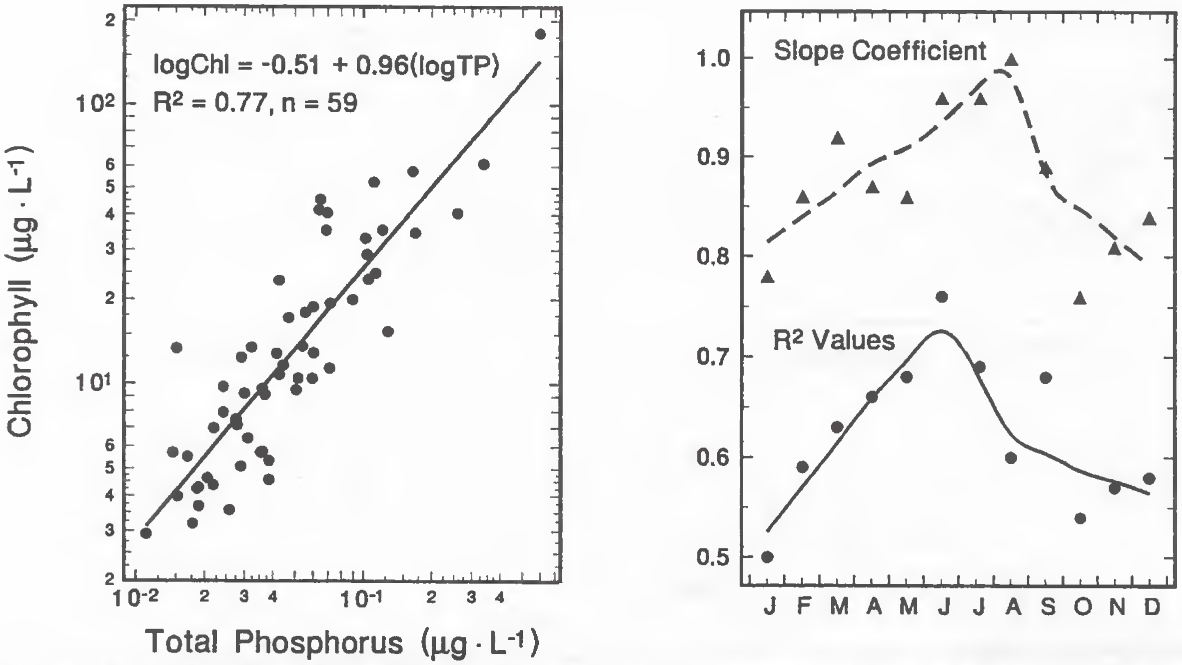

Figure 10.–Left panel shows the relationship between lake mean values of Chl_{log} and TP_{log} for 59 Korean reservoirs. Right panel shows the slope coefficient and R^2 values for regressions calculated using monthly mean values of Chl_{log} and TP_{log} for 59 Korean reservoirs.

to the Korean relation and predict lake mean Chl quite well (Table 3). This comparison suggests the relation between annual algal biomass and the limiting nutrient is typical of that found in many other temperate lakes.

Averaged by month of the year, the strength of the Chl_{log} - TP_{log} relation peaked in early summer ($R^2 = 0.76$ in June) concurrent with the slope coefficient approaching unity (Fig. 10). The cross-system relation was weakest during winter ($R^2 < 0.6$) when the slope coefficient was ~0.8 (Fig. 10). All of the monthly regression relations were linear and the square of TP_{log} was not significant as an additional independent variable.

Annual maximum Chl showed a linear arithmetic relation with annual lake mean Chl_{mean} in the reservoirs:

$$Chl_{max} = -10.8 + 4.0(Chl_{mean}),\ n = 451,\ R^2 = 0.86 \tag{2}$$

On average, annual Chl_{max} values were ~3.2 times the annual Chl_{mean} (median = 2.8, range 1.2 to 15.0) and in half of the lake-year comparisons Chl_{max} occurred during July-September (~16-17% each month). This period includes the peak of the monsoon and immediately thereafter when Chl was elevated (Fig. 4). Summer Chl_{max} values were about double summer Chl_{mean} (~1.9 times the average during July-September, and 2.3 times the average during May-September).

Values of Chl_{log} explained 76% of the among-reservoir variance in $Secchi_{log}$ (Fig. 11) and the regression coefficients for the Korean data set were virtually identical to those in a North-American lake Secchi-Chl relation (Jones and Bachmann 1978). Total suspended solids (TSS_{log}) was strongly correlated with Chl_{log} ($r = 0.85$, $n = 58$). As an independent variable TSS_{log} explained 79% (negative coefficient) of the variance in $Secchi_{log}$ and in a two variable model with Chl_{log} 84% of the variance was explained. It is known that Chl imposes a maximum on water clarity and that deviations below this can result from mineral turbidity and dissolved color. The negative influence of suspended solids on water clarity has been documented in other turbid reservoirs (Canfield and Bachmann 1981, Jones and Knowlton 1993). These measurements, however, do not allow us to separate the role of the non-volatile fraction on water clarity, which would largely be from allochthonous sources, from the volatile fraction which would be generated largely by autochtohonous processes (An and Jones 2002).

Discussion

Korean reservoirs in this data set are fertile with most classified as mesotrophic or eutrophic and ~20% hypereutrophic (Table 2). This classification is consistent with the summary of 13 Korean reservoirs by Kim et al. (2001) but additional data are needed to determine whether these assessments adequately represent conditions in the estimated 18,000 reservoirs located throughout the nation. A noteworthy feature of Korean reservoirs is that most have TN concentrations >1 $mg \cdot L^{-1}$ (Table 1, Kim et al. 2001) and previous studies have shown a high proportion of inorganic nitrogen (Heo and Kim 1997, An and Jones 2000a). These nitrogen-rich conditions result in high ratios of TN:TP in Korean reservoirs as compared to many other temperate lakes (Forsberg and Ryding 1980, Smith 1982, Jones and Knowlton 1993, Nürnberg 1996). To compensate for this difference, trophic state criteria for TN were adjusted upward to classify Korean

Table 3.–Chlorophyll (Chl) - total phosphorus (TP) models from the literature and for data from Korea (n = 58, the reservoirs with 597 $\mu g \cdot L^{-1}$ TP was eliminated from this analysis) and comparisons of predicted and observed Chl values using each of these models. Mean square error was calculated as the sum of the mean difference squared and the variance.

Model	Equation for Chl_{log}		Mean difference between predicted and observed Chl (bias)	Mean square error
	Intercept	Slope TP_{log}		
White et al. (1985)	-.052	0.85	-7.26	177,472
Jones and Knowlton (1993)	-0.23	0.88	4.39	64,849
Quirós (1990)	-0.57	0.96	-3.05	31,326
Vollenweider and Kerekes (1980)	-0.57	0.99	-1.10	4,146
Korean Data (this study)	-0.51	0.96	-1.01	3,523
Vyknalek et al. (1994)	-0.51	0.98	0.45	778

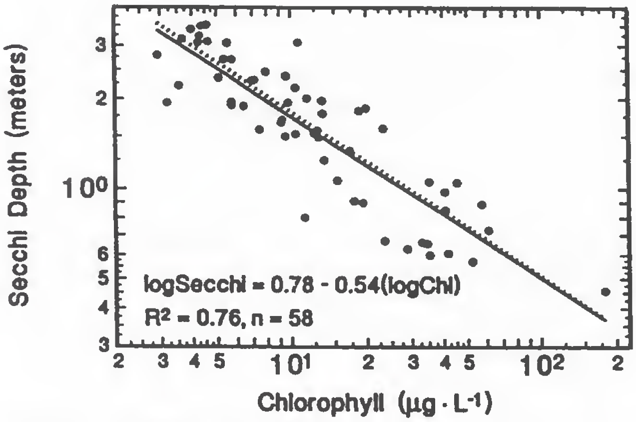

Figure 11.–Double logarithmic plot of lake mean Secchi depth (m) on Chl ($\mu g \cdot L^{-1}$) for 58 Korean reservoirs. The solid line represents the regression line fitted to these data, and the dashed line represents the regression line from the North American lake analysis by Jones and Bachmann (1978).

reservoirs uniformly across all trophic state metrics (Table 2). The limits proposed for separating Korean reservoirs on the basis of TN are about 2.5-times larger than conventional boundaries (Forsberg and Ryding 1980, Nürnberg 1996). This approach is considered provisional and should be evaluated in future studies.

Ratios of TN:TP declined with increasing trophic state (Fig. 3), as is a common among-system pattern in lakes (Downing and McCauley 1992). All reservoirs in this suite, however, had mean TN:TP values >23, which suggests P limitation was prevalent (Forsberg and Ryding 1980, Smith 1982). Among all individual samples (n = 12,971), only ~5 % had TN:TP ratios <10 and ~15 % of the total were <20, providing additional evidence that TN was abundant relative to TP in these reservoirs. In Korea the three major sources of nutrients are agricultural fertilizer, animal manure and municipal sewage, with caged fish culture being locally important in some reservoirs (An 1997, Heo and Kim 1997). Nutrient loads from forests are typically much reduced relative to either agriculture or urban runoff (Field et al. 1996). The two reservoirs in our suite with the lowest TN levels (< 0.6 mg$\cdot$L^{-1} in Gucheon and Yeoncho reservoirs, Table 1) are located in mountainous, forested catchments with little agriculture and no point-source inputs. In a study of Daechung Reservoir and its inflows, An (1997) found forested streams had about one-fifth the TN content of the next most nitrogen-poor stream (0.32 vs. 1.56 mg$\cdot$L^{-1}) which was influenced by agriculture, and about one-twentieth the content of the most nitrogen-enriched stream (7.32 mg$\cdot$L^{-1}). Collectively, this evidence suggests that anthropogenic inputs account for elevated N above background levels in Korean waters.

Paddy fields in Korea are heavily fertilized. Kim et al. (2001) estimated that the N budget for agriculture (fertilizer plus imported feed) is ~4-times greater than human discharge and that the P budget for agriculture exceeds human discharge by ~7-times. Ratios of TN:TP in water bodies reflect their source of nutrients. Research conducted elsewhere shows that undisturbed watersheds such as forests and unfertilized fields have larger TN:TP values than in agricultural runoff, and ratios are lowest in urban runoff (Downing and McCauley 1992, Field et al 1996). In Korea, large urban areas are located in the middle and lower reaches of rivers and agriculture has developed adjacent to rivers where slopes are gentle and on lowland alluvial plains. Kim et al. (2001) found reservoir nutrient levels are higher and TN:TP are reduced in downstream reservoirs, and attributed this to anthropogenic loading.

A remaining task in this nationwide assessment is to relate land use in the catchment of each reservoir to lake mean nutrient levels (Field et al. 1996, Meeuwig and Peters 1996) with the expectation that in-reservoir nutrient levels will increase proportionally with agricultural and urban areas and concurrently decrease with forest cover. In-reservoir processes also contribute to the observed TN:TP ratios. An and Jones (2002) found that ratios of TN:TP increased longitudinally from the upreservoir, riverine reach of Taechung Reservoir to the lacustrine region near the dam as a result of sedimentation of TP and suspended load during advective flow that dominates reservoir processes (Thornton et al. 1990).

Seasonal patterns (Fig. 4) suggest meotrophic reservoirs have dissimilar nutrient sources from more fertile Korean reservoirs. The pattern among mesotrophic reservoirs suggests non-point external inputs during the monsoon, with reduced conductivity and increased suspended solids (Fig. 9), were the major determinant of annual peaks in TP and TN in these systems. A contrasting pattern was found among hypereutrophic reservoirs in which nutrient levels decreased with monsoon runoff; the decline, however, was more marked for TN than TP (Fig. 4). This pattern was noted by Kim et al. (2001) and it suggests point source additions, directly to the reservoirs or their tributaries, are the critical factor determining annual peaks in TP and TN during the non-monsoon period and that monsoon surface runoff dilutes in-reservoir concentrations. Additional information is needed to assess whether the nutrient content of monsoon inflow differs between these two trophic state categories; direct measurements and land use information would be helpful in this regard. Factors such as internal loading and/or the nutrient subsidy (Meyer et al. 1988) that occurs in streams during moderate to low flow, are also likely important in determining seasonal maximum nutrient levels in some reservoirs. Eutrophic reservoirs were influenced by a combination of both patterns so that taken in aggregate a seasonal pattern was not apparent (Fig. 4). Across the range of nutrient conditions in the data set, individual water bodies responded differently to monsoon inflow (Figs. 5 and 6) with the inference being that point sources become increasingly important to the nutrient budget of fertile reservoirs in Korea and monsoon inflow dilutes in-reservoir conditions. Municipal and industrial discharge information is needed for each reservoir to better quantify the importance of point-source inputs and monsoon inflow to the nutrient budget of Korean reservoirs across the continuum of trophic state conditions.

The empirical Chl-TP model (Fig. 10) suggests the average yield of Chl per unit of the limiting nutrient is on par with many other temperate lakes (Table 3). These data, aggregated across time, show a linear increase in Chl with increasing TP with a slope coefficient near unity and the inference is a strong cross-system response to the limiting nutrient. Seasonally, the relation was strongest during the summer when slope coefficients were ≥0.9 and declined slightly during fall turnover and winter mixis (Fig. 10). The cross-system response to the limiting nutrient was significant during fall-winter but TSI-deviation analyses suggest less Chl than predicted by TP. This seasonal decline is consistent with nutrients in excess of requirements for algal growth and physically induced light-limitation during these months (Kim et al. 2001).

General patterns in the seasonal distribution of Chl showed a spring increase in concentrations (Fig. 4) and in Chl:TP ratios (Fig. 7) which occurred during March in hypereutrophic reservoirs with similar seasonal increases occurring in April in mesotrophic and eutrophic reservoirs. This temporal pattern is consistent with the onset of the spring bloom (Marshall and Peters 1989) which is tied to increased solar radiation and the beginning of thermal stratification. Earlier onset of the spring bloom in hypereutrophic reservoirs may be a function of their overall shallower depth (Kim et al. 2001). In the month following the spring increase, both Chl values (Fig. 4) and in Chl:TP ratios (Fig. 7) showed an among-system decline which was particularly apparent in both mesotrophic and eutrohic reservoirs. This seasonal change is also apparent in the TSI-deviation plots; in April values centered around the origin and in May most points were below the origin, suggesting there was less Chl than predicted by TP (Fig. 8). The timing of a decrease in Chl is consistent with the clear-water phase associated with zooplankton grazing and/or stratification which is typically found in mesotrophic lakes and is less-strong among fertile water bodies (Kalff 2002).

The increase in transparency often associated with the clear-water phase was not evident in our among-system comparison of Secchi depth (Fig. 9). It may have been concealed by inputs of suspended solids carried by inflows which mix directly with reservoir water during mixis, and during the early stages of thermal stratification (Knowlton and Jones 1995, Jones et al. 1997). Therefore, light-limitation and advective flow may have contributed to the seasonal drop in Chl and Chl:TP, as is the case in turbid reservoirs elsewhere (Jones and Knowlton 1993). Subsequently, Chl and Chl:TP increased during summer in all trophic state categories (Figs. 4 and 7) when cool inflows associated with monsoon storms largely pass through reservoirs as interflows at the depth of the metalimnion (Kim et al. 2001, An and Jones 2002). Interflows serve to isolate the mixed surface layer from turbid external loads, particularly in down-reservoir locations (An and Jones 2002), thereby promoting surface algal growth. The mechanisms controlling the seasonal development of Chl can not be quantified with this data set but should be a feature of the long-term evaluation of processes in Korean reservoirs.

Values of Chl were elevated during the monsoon and extended into the period of fall turnover across all trophic state categories represented in the Korean data set (Fig. 4). This pattern differs from the temperate lake paradigm in which Chl_{max} develops during spring and fall blooms, most commonly observed in eutrophic lakes (Marshall and Peters 1989). On average, annual Chl_{max} was ~3 times Chl_{mean} and during summer Chl_{max} was ~double Chl_{mean}. Other studies of temperate lakes have also found that Chl_{max} during the growing season is about double Chl_{mean} (Smith 2003).

This among-system comparison provides information on trophic state and general patterns in the seasonal development of Chl and nutrient variation in Korean reservoirs based on data from 59 reservoirs located throughout the country (Fig. 1, Table 1). The analysis also confirms that the monsoon is a major source of variation within and among Korean reservoirs (Jones et al. 1997). Seasonal patterns differ among trophic state categories such that monsoon inflow increases in-reservoir nutrients in mesotrophic reservoirs and dilutes concentrations in hypereutrophic water bodies. The seasonal response to the monsoon was described as categorical, within trophic state groups (Fig. 4), and as a continuous response over the continuum of nutrient concentrations in the data set (Fig. 6). We hypothesize that point-source inputs become increasingly important along the trophic gradient and are the basis for observed differences in the measured response to seasonal inflow. These seasonal patterns are based on aggregated data, and likely represent the long-term temporal pattern in Korean reservoirs. The analysis also shows that at the level of the lake mean, the empirical relation between Chl and the limiting element TP, matches that of many temperate lakes (Fig. 10, Table 3), as does the relation between Chl and water clarity (Fig. 11). At this level of aggregation, therefore, nutrient abatement should follow the temperate paradigm and result in reduced algal biomass, greater transparency and other associated improvements in reservoir water quality in Korea.

Trophic state metrics and seasonal patterns and algal-nutrient relations, however, are known to vary in response to the intensity of the monsoon (Jones et al. 1997). Studies in Daechung Reservoir show that the intensity of monsoon inflow influences thermal stratification, water residence time, nutrient levels and the suspended load to favor higher yields of Chl per unit TP during a weak monsoon relative to an above average monsoon (An 1997, An and Jones 2000a, 2000b and 2002). These studies also showed that the strong longitudinal gradients, characteristic of mainstem reservoirs (Thornton et al. 1990) change dramatically in response to the intensity of monsoon inflow (An and Jones 2002). Neither the intensity of the monsoon, nor the spatial variation within reservoirs was considered in this analysis, and these features remain as the next-step in quantifying the eutrophication process in Korean reservoirs.

ACKNOWLEDGMENTS: Limnological data for this analysis came from the nationwide reservoirs survey being compiled by the Korean Ministry of the Environment (endorsement document 67400-351). We thank Tony Thorpe for crafting the final map (Fig. 1) and Karen Decker for creating the tables. We also thank Drs. Gertrud Nürnberg and Dongil Seo and Bryn Tracy for helpful comments on an early draft of the manuscript.

References

American Public Health Association. 1992. Standard methods for the examination of water and wastewater. 18th ed. American Public Health Association, Washington DC.

An, K. -G. 1997. Influence of the Asian monsoon on the limnology of Daechung Reservoir, Korea. Ph. D. Dissertation, University of Missouri. 361 p.

An, K. -G. and J. R. Jones. 2000a. Factors regulating bluegreen dominance in a reservoir directly influenced by Asian monsoon. Hydrobiol. 432:37-48.

An, K. -G. and J. R. Jones. 2000b. Temporal and spatial patterns in salinity and suspended solids in a reservoir influenced by the Asian monsoon. Hydrobiol. 436:179-189.

An, K. -G. and J. R. Jones. 2002. Reservoir response to the Asian monsoon with an emphasis on longitudinal gradients. J. Freshwater Ecol. 17:151-160.

Canfield, D. E., Jr. and R. W. Bachmann. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depths in natural and artificial lakes. Can. J. Fish. aquat. Sci. 38:414-423.

Carlson, R. E. 1992. Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs. P. 59-71. *In:* Proceedings of a National Conference on Enhancing the States' Lake Management Programs. Monitoring and Lake Impact Assessment. Chicago, Il.

Downing, J. A. and E. McCauley. 1992. The nitrogen:phosphorus relationship in lakes. Limnol. Oceanogr. 37:936-945.

Field, C. K., P. A. Siver and A. -M. Lott. 1996. Estimating the effects of changing land use patterns on Connecticut lakes. J. Environ Qual. 25:325-333.

Forsberg, C. and S. -O. Ryding. 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. Arch. Hydrobiol. 89:189-207.

Heo, W. -M. and B. Kim. 1997. The change in N/P ratio with eutrophication and cyanobacterial blooms in Lake Soyang, Korea. Verh. Internat. Verein. Limnol. 26:491-495.

Jones, J. R. and R. W. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. J. Water Pollut. Cont. Fed. 48:2176-2182.

Jones, J. R. and R. W. Bachmann. 1978. Trophic status of Iowa lakes in relation to origin and glacial geology. Hydrobiol. 57:267-273.

Jones, J. R. and M. F. Knowlton. 1993. Limnology of Missouri reservoirs: an analysis of regional patterns. Lake and Reserv. Manage. 8:17-30.

Jones, J. R., M. F. Knowlton and K. -G. An. 1997. Developing a paradigm to study and model the eutrophication process in Korean reservoirs. Korean J. Limnol. 30:463-471.

Kalff, J. 2002. Limnology. Prentice Hall. 592 p.

Knowlton, M. F. and J. R. Jones. 1995. Temporal and spatial dynamics of suspended sediment, nutrients, and algal biomass in Mark Twain Lake, Missouri. Archiv. Hydrobiol. 135:145-178.

Kim, B., J. -H. Park, G. Hwang, M. -S. Jun and K. Choi. 2001. Eutrophication of reservoirs in South Korea. Limnology 2:223-229.

Marshall, C. T. and R. H. Peters. 1989. General patterns in the seasonal development of chlorophyll a for temperate lakes. Limnol. Oceanogr. 34:856-867.

Meeuwig, J. J. and R. H. Peters. 1996. Circumventing phosphorus in lake management: a comparison of chlorophyll a predictions from land-use and phosphorus-loading models. Can. J. Fish. Aquat. Sci. 53:1795-1806.

Meyer, J. L., W. H. McDowell, T. L. Bott, J. W. Elwood, C. Ishizaki, J. M. Melack. B. L. Peckarsky, B. J. Peterson, and P. A. Rublee. 1988. Elemental dynamics in streams. J. N. Amer. Benthol. Soc. 7:410-432.

Nürnberg, G. K. 1996. Trophic state of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. Lake and Reserv. Manage. 12:420-431.

Park, H. D., Kim B., Kim E. and T. Okino. 1998. Hepatotoxic microcystins and neurotoxic anatoxin-a in cyanobacterial blooms from Korean lakes. Environ. Toxicol. Water Qual. 13:225-234.

Quirós, R. 1990. Factors related to variance of residuals in chlorophyll – total phosphorus regressions in lakes and reservoirs of Argentina. Hydrobiol. 200/201:343-355.

Reedman, A. J. and S. H. Um. 1975. The geology of Korea. Geological and Mineral Institute of Korea, Seoul. 139 p.

Smith, V. H. 1982. The nitrogen and phosphorus dependence of algal biomass in lakes:An empirical and theoretical analysis. Limnol. Oceanogr. 27:1101-1112.

Smith, V. H. 2003. Eutrophication of freshwater and coastal marine ecosystems. A global problem. Environ. Sci. and Pollut. Res. In press.

Sommer, U., Z. M. Gliwicz, W. Lampert and A. Duncan. 1986. The PEG-model of seasonal succession of planktonic events in fresh waters. Arch. Hydrobiol. 106:433-471.

Steel, R. G. D. and J. H. Torrie. 1980. Principles and procedures of statistics. A Biometrical Approach. McGraw-Hill Pub. Co., New York. 633 p.

Thornton, K. W., B. L. Kimmel and F. E. Payne. 1990. Reservoirs limnology: ecological perspectives. John Wylie and Sons, New York. 246 p.

Vollenweider, R. A. and J. J. Kerekes. 1980. Background and summary results of the OECD Cooperation Program on Eutrophication. *In:* Restoration of Lakes and Inland Waters, U.S. EPA 400/5-81-010:25-36.

Vyhnalek, V., J. Fott, and J. Kopacek. 1994. Chlorophyll–phosphorus relationship in acidified lakes of the Hight Tatra Mountains (Slovakia). Hydrobiol. 274:171-177.

White, E., K. Law, G. Payne and S. Pickmere. 1985. Nutrient demand and availability among planktonic communities – an attempt to assess nutrient limitation to plant growth in 12 central volcanic plateau lakes. New Zealand J. Mar. Freshwat. Res. 19:49-62.