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Spatial and Temporal Variability of Water Quality in Korean Dam Reservoirs

Lim, Go-Woon, Sang-Jae Lee and Kwang-Guk An*

(*Department of Biology, College of Biological Sciences and Biotechnology, Chungnam National University, Daejeon 305-764, Korea*)

The objectives of this study were to evaluate spatial and temporal variability of water quality in 10 reservoirs and identify the key nutrients (N, P) influencing chlorophyll-*a* (CHL) along with analysis of empirical models and zonal patterns of total phosphorus (TP) and CHL. We analyzed total nitrogen (TN), TP, CHL, water clarity (Secchi depth, SD), and evaluated potential limiting nutrient using ambient N : P ratios and previous criteria of ambient nutrients. Water clarity and CHL varied largely depending on the seasonal monsoon and type of reservoir, but trophic state was diagnosed as eutrophy, base on mean CHL in most reservoirs. The peak of TP did not match the contents of CHL due to rapid flushing during the high run-off period. In the reservoir of DR, regression coefficient in the P_r was 0.510 but was 0.159 in the M_o, while the TP-CHL relation in the YR increased during the monsoon compared to the premonsoon. The regression coefficient in the P_r was not statistically significant but the value of M_o was 0.250. TP showed similar longitudinal zonal gradients among the reservoirs of DR, YR and JR. Empirical models of TP-CHL, based on overall data, showed that CHL was determined by phosphorus (R^2=0.244, *p*=0.0019). Regression analysis of CHL-SD showed a stronger linear fit (R^2=0.638, p$<$0.001) than the TP-CHL model.

Key words : water clarity, TP, dam reservoir, chlorophyll, seasonality, longitudinal gradient

INTRODUCTION

Previous lake and reservoir studies (An and Kim, 2003) pointed out that water quality reflects regional hydrology and precipitation pattern. For this reason, limnology of Asian regions is directly influenced by the seasonal Asian monsoon, and the numerous studies demonstrated the importance of the duration and the intensity of the monsoon on the lake water quality and primary productivity. Such evidence is shown in studies of lentic ecosystems and lotic ecosystems (Ohtake *et al*., 1982; Zafar, 1986), and the largest variation in the trophic state occurred in the intense summer monsoon period. In contrast, studies in North America and European lakes and reservoirs, demonstrated that major rainfall occur in spring and fall seasons and the nutrient peaks occur in the season. For this reason, the algal response to the nutrient dynamics in the region is bimodal peaks, compared to the monomodal peak in the late monsoon in the Asian region, and the response change the whole ecosystem functional processes such as hydrology-nutrient availability, phytoplankton bloom, and zooplankton grazing (Dettmers and Stein, 1996).

Numerous limnological studies of dam reservoirs in Korea have been conducted in relation to nutrient dynamics, eutrophication processes, phyto-

* Corresponding author: Tel: +82-42-821-6408, Fax: +82-42-822-9690, E-mail: kgan@cnu.ac.kr

plankton bloom, zooplankton, empirical model, mechanical model and fish health assessment in terms of water quality (Lee *et al*., 2007; An *et al*., 2008). These studies has provided some current state of the reservoirs, clues of the eutrophic degradations and reservoir management strategies in each or whole regional bases. Among the researches, most long-term intensive monitorings were conducted in Soyang Reservoir, one of the Han-River watershed (Kim and Kim, 2004). These researches contributed to the functional processes of the regional lentic ecosystem and made a conner stone in Korean reservoir study. In addition, studies of other regional reservoirs such as Keum-River watershed (Daecheong Reservoir, Han and An, 2008), and Nakdong Watershed (Andong Reservoir, An *et al*., 2006) etc. Main functional processes in such reservoirs should be studied for efficient reservoir managements.

Especially, we need to understand further how the seasonality determine nutrient input patterns in the reservoirs and the variability of reservoir production, even if overall such studies of the reservoirs indicate that water quality change largely at the point of monsoon onset, and again at the cessation of intense monsoon rains. Still, it is required some information on how the timing and intensity of the seasonal precipitation determine the nutrient input, and seasonal and year-to-year variations in each individual reservoir and overall reservoirs for reservoir protections from the pollution. In this study, we identified key nutrients (TN, TP) influencing the variations of algal biomass, expressed as CHL values, and determined empirical relations using Log-transformed models of TN-CHL, TP-CHL and CHL-SD in the reservoirs. In addition, we analyzed zonal gradients of TP and CHL in the riverine, transition, and lacustrine zones.

MATERIALS AND METHODS

We selected 10 reservoirs for data analysis of seasonal and temporal patterns. The reservoirs are as follows: Daecheong Reservoir (DR, 6 sites), Yongdam Reservoir (YR, 4 sites), Andong Reservoir (AR, 3 sites), Seomjin Reservoir (SR_1, 3 sites), Juam Reservoir (JR, 3 sites), Hwacheon Reservoir (HR, 3 sites), Soyang Reservoir (SR_2, 5 sites), Chuncheon Reservoir (CR_1, 3 sites), Uiam Reservoir (UR, 3 sites) and Chungju Reservoir (CR_2, 4 sites). The selections of the reservoirs were mainly based on the artificial dam reservoirs used for mainly for drinking water and this reason was to determine trophic state and eutrophic conditions. Also, we selected the dendritic-shaped reservoirs in order to understand spatial variations of riverine zone, transition zone, and lacustrine zone dendritic reservoirs. The specific sampling sites are as follows: DR (S1=Chu-dong, 36°22′N, 127°28′E; S2=Deogyu-ri, 36°29′N, 127°29′E; S3=Sangjang-ri, 36°30′N, 127°30′E; S4=Janggye-ri, 36°21′N, 127°37′E; S5=Eoseong-ri, 36°26′N, 127°33′E; S6=Daejeong-ri, 36°23′N, 127°32′E), YR (S1=Samnak-ri, 35°55′N, 127°32′E; S2=Seunggeum-ri, 35°53′N, 127°33′E; S3=Mojeong-ri, 35°53′N, 127°28′E; S4=Hangdong-ri, 35°49′N, 127°29′E), AR (S1=Seonggok-dong, 36°33′N, 128°44′E; S2=Nosan-ri, 36°34′N, 128°50′E; S3=Ma-ri, 36°34′N, 128°52′E), SR_1 (S1=Yongsu-ri, 35°31′N, 127°06′E; S2=Jangmyeon-ri, 35°34′N, 127°01′E; S3=Unjeong-ri, 35°34′N, 127°05′E), JR (S1=Daegwang-ri, 35°03′N, 127°13′E; S2=Daegok-ri, 34°59′N, 127°13′E; S3=Deokji-ri, 34°55′N, 127°10′E), HR (S1=Guman-ri, 38°05′N, 127°45′E; S2=Dongchon-ri, 38°10′N, 127°49′E; S3=Bangcheon-ri, 38°04′N, 127°51′E), SR_2 (S1=Cheonjeon-ri, 37°56′N, 127°47′E; S2=Ohang-ri, 37°59′N, 127°53′E; S3=Seokhyeon-ri, 38°02′N, 127°58′E; S4=Bupyeong-ri, 37°59′N, 128°07′E; S5=Sangsunae-ri, 37°58′N, 128°03′E), CR_1 (S1=Owol-ri, 37°59′N, 127°40′E; S2=Owol-ri, 37°57′N, 127°38′E; S3=Sinpo-ri, 38°01′N, 127°37′E), UR (S1=Uiam-ri, 37°49′N, 127°41′E; S2=Hyeonam-ri, 37°53′N, 127°40′E; S3=Jungdo-dong, 37°52′N, 127°42′E), CR_2 (S1=Jongmin-dong, 36°59′N, 127°59′E; S2=Yangpyeong-ri, 36°59′N, 128°06′E; S3=Hwanggang-ri, 36°56′N, 128°03′E; S4=Janghoe-ri, 36°55′N, 128°15′E)

The reservoirs have been mainly used for the multi-purposes of drinking water supply, agricultural irrigations, industrial water supply, and electric power generation.

Data were collected as a part of a nationwide survey of being compiled by the Korean Ministry of the Environment during 2003∼2007. In the survey, total phosphorus (TP) was determined in the unfiltered water by ascorbic acid method after persulfate oxidation. Total nitrogen (TN) was analyzed by UV spectrophotometric method after a potassium sulfate digestion. Secchi depth or water clarity was determined by the Secchi disk (diameter: 30 cm). For the measurements of chlorophyll-

Table 1. Mean±standard error and range of water quality parameter in the reservoirs. The abbreviations of reservoirs are as follows: Daecheong Reservoir (DR), Yongdam Reservoir (YR), Andong Reservoir (AR), Seomjin Reservoir (SR_1), Juam Reservoir (JR), Hwacheon Reservoir (HR), Soyang Reservoir (SR_2), Chuncheon Reservoir (CR_1), Uiam Reservoir (UR) and Chungju Reservoir (CR_2).

No.	Site	Parameter							
		TN (mg L^{-1})	TP (μg L^{-1})	SD (m)	CHL (μg L^{-1})	TN : TP	Potential limitation	TSI [TP]	TSI [CHL]
1	DR	1.572±0.243 (1.11~2.31)	24.2±6.1 (16~40)	2.6±0.7 (1.4~4.7)	9.1±3.2 (4.1~17.4)	67.0	P	23.9 (Me)	39.7 (Eu)
2	YR	1.534±0.119 (1.35~1.76)	20.0±6.3 (11~36)	3.1±0.5 (1.9~4.0)	4.5±1.4 (2.3~7.3)	82.3	P	22.6 (Me)	36.8 (Eu)
3	AR	1.432±0.198 (1.17~1.70)	16.4±3.2 (10~20)	3.2±0.6 (2.2~3.8)	4.1±1.6 (1.7~8.0)	89.8	P	21.5 (Me)	36.3 (Eu)
4	SR_1	1.862±0.083 (1.67~1.98)	19.8±5.9 (12~31)	2.5±0.2 (2.2~3.0)	7.4±2.2 (4.7~11.0)	100.9	P	22.6 (Me)	38.9 (Eu)
5	JR	0.945±0.171 (0.68~1.35)	19.9±7.5 (7~31)	2.5±0.6 (1.8~3.9)	9.7±8.0 (1.7~24.9)	53.1	P	22.4 (Me)	38.8 (Eu)
6	HR	1.052±0.065 (0.94~1.13)	16.8±6.1 (9~28)	6.0±0.9 (4.7~7.2)	2.3±0.3 (1.9~2.9)	70.7	P	21.4 (Me)	34.2 (Eu)
7	SR_2	1.517±0.148 (1.34~1.91)	24.2±11.1 (14~50)	3.0±0.9 (1.7~4.9)	3.7±1.7 (1.2~7.6)	71.0	P	23.6 (Me)	35.7 (Eu)
8	CR_1	1.311±0.085 (1.16~1.45)	20.5±6.9 (8~30)	2.5±0.2 (2.0~2.9)	4.4±4.1 (1.5~18.2)	73.7	P	22.6 (Me)	35.9 (Eu)
9	UR	1.690±0.168 (1.48~2.07)	39.7±10.7 (24~58)	2.3±0.3 (1.8~2.8)	7.3±3.1 (2.9~14.7)	44.9	P	26.9 (Eu)	38.7 (Eu)
10	CR_2	2.386±0.155 (2.11~2.80)	20.0±5.2 (15~36)	3.2±0.9 (1.5~5.0)	3.3±1.6 (1.5~8.4)	124.9	P	22.7 (Me)	35.3 (Eu)

Table 2. Empirical model of CHL vs. TP, CHL vs. TN and SD vs. CHL in the annual mean. The abbreviations of reservoir name are in Table 1.

No.	Site	Parameter	Linear model (equation)	R^2	P value	n
1	DR	CHL vs. TP SD vs. CHL	Log (CHL)=0.568 Log (TP)+0.157 Log (SD)=−0.520 Log (CHL)+0.901	0.159 0.433	0.0290* <0.0001**	30
2	YR	CHL vs. TP SD vs. CHL	Log (CHL)=0.789 Log (TP)−0.375 Log (SD)=−0.425 Log (CHL)+0.781	0.523 0.648	0.0003** <0.0001**	20
3	AR	CHL vs. TN SD vs. CHL	Log (TN)=1.836 (CHL)+0.307 Log (SD)=−0.405 Log (CHL)+0.737	0.430 0.575	0.0079** 0.0010**	15
4	SR_1	CHL vs. TP SD vs. CHL	Log (CHL)=0.611Log (TP)+0.117 Log (SD)=−0.079 Log (CHL)+0.468	0.119 0.175	0.2264 0.1356	14
5	JR	CHL vs. TP SD vs. CHL	Log (CHL)=1.372 Log (TP)−0.844 Log (SD)=−0.185 Log (CHL)+0.566	0.521 0.722	0.0035** 0.0001**	14
6	HR	CHL vs. TP SD vs. CHL	Log (CHL)=0.097 Log (TP)+0.251 Log (SD)=−0.635 Log (CHL)+1.008	0.074 0.247	0.4180 0.1190	11
7	SR_2	CHL vs. TN SD vs. CHL	Log (CHL)=4.243 Log (TN)−0.231 Log (SD)=−0.400 Log (CHL)+0.670	0.641 0.421	<0.0001** 0.0011**	22
8	CR_1	CHL vs. TP SD vs. CHL	Log (CHL)=0.305 Log (TP)+0.051 Log (SD)=−0.131 Log (CHL)+0.449	0.143 0.259	0.2253 0.1976	12 8
9	UR	CHL vs. TP	Log (CHL)=0.302 Log (TP)+0.353	0.039	0.6215	11
10	CR_2	CHL vs. TN SD vs. CHL	Log (CHL)=5.302 Log (TN)−1.511 Log (SD)=−0.395 Log (CHL)+0.687	0.599 0.267	<0.0001** 0.0196*	20

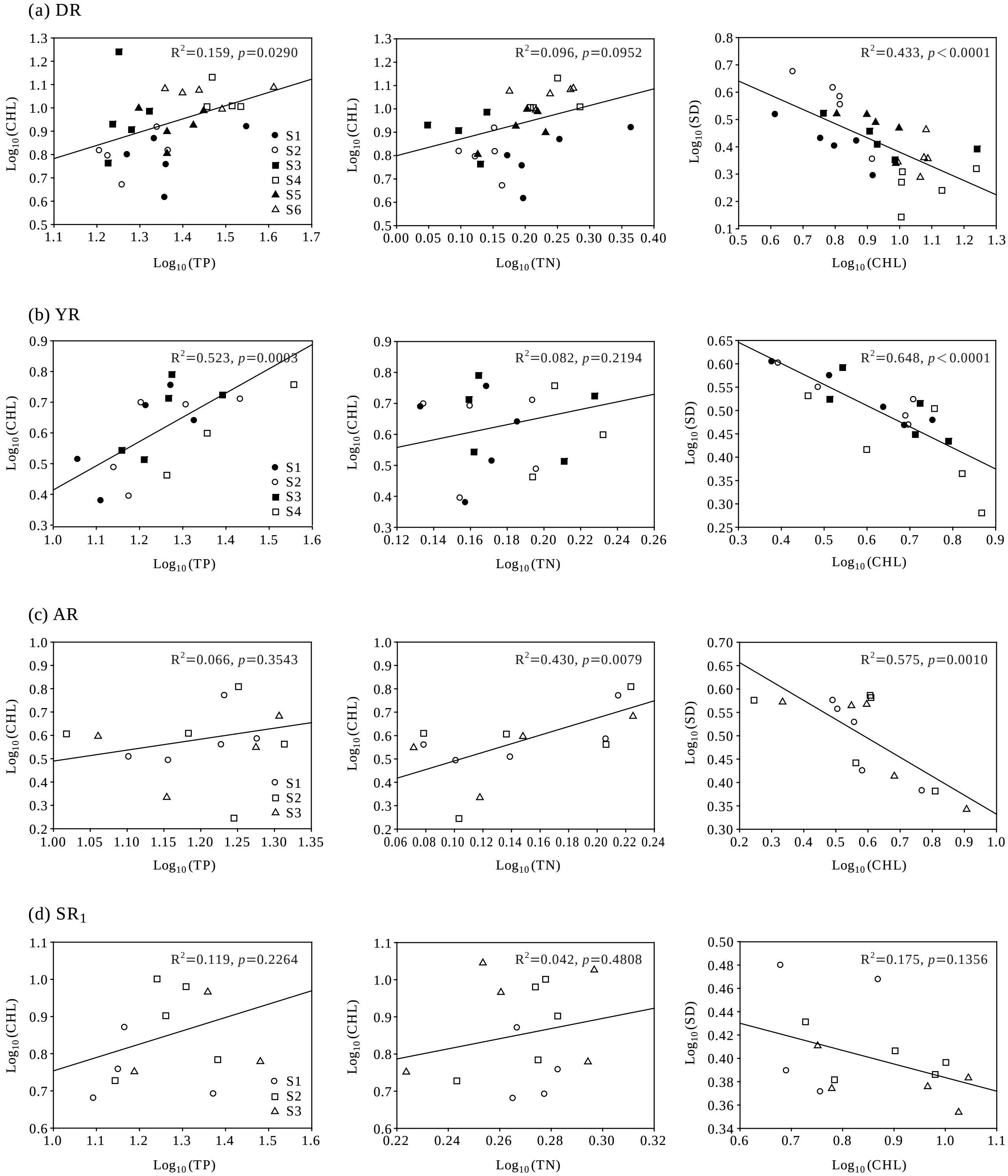

Fig. 1. Regression linear models of log-transformed total nitrogen (TN)-chlorophyll (CHL), total phosphorus (TP)-chlorophyll (CHL), chlorophyll (CHL)-Secchi depth (SD) in each reservoir. The abbreviations of reservoirs are as follows: Daecheong Reservoir (DR), Yongdam Reservoir (YR), Andong Reservoir (AR), Seomjin Reservoir (SR_1), Juam Reservoir (JR), Hwacheon Reservoir (HR), Soyang Reservoir (SR_2), Chuncheon Reservoir (CR_1), Uiam Reservoir (UR), and Chungju Reservoir (CR_2).

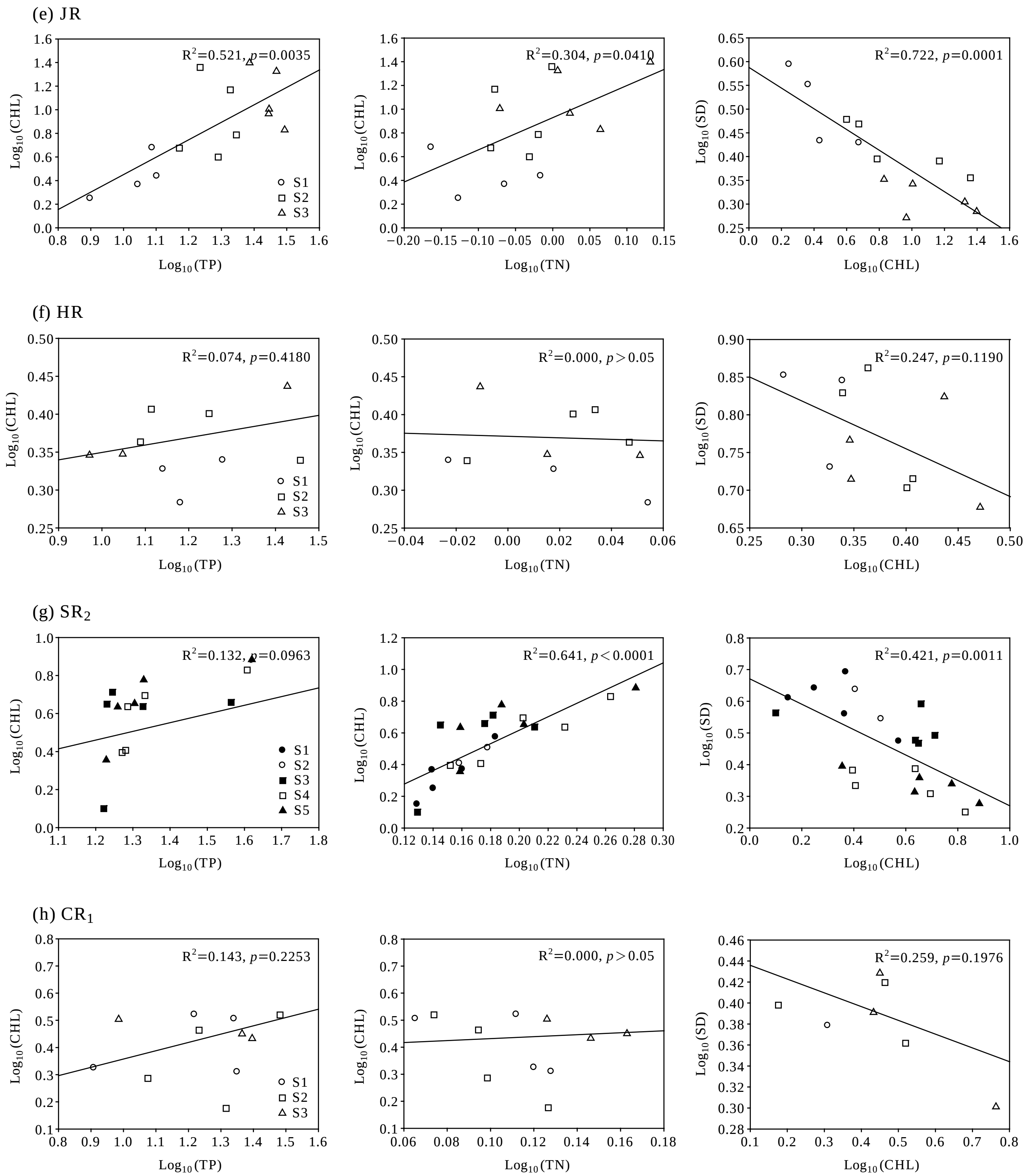

Fig. 1. Continued.

a (CHL) concentration, 250 mL water were filtered using GF/C filter paper and CHL was measured by a spectrophotometic method after extraction in ethanol.

The data of trophic variables such as TN, TP, CHL and SD were analyzed for trophic state index

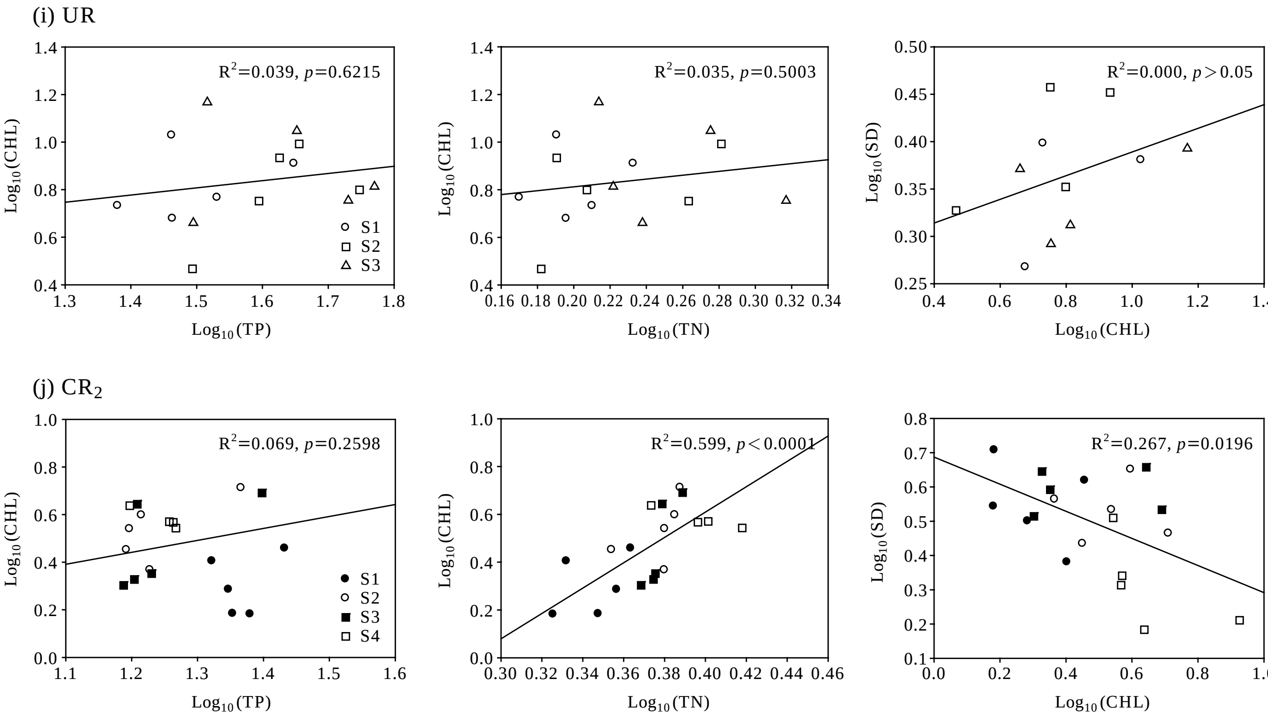

Fig. 1. Continued.

(TSI) and converted from the ambient concentrations to TSI values by the original approach of Carlson (1977). TN was converted at the empirical equation of Kratzer and Brezonik (1981), even if the data frequently showed a potential limitation in our 10 reservoirs by the N : P ratio analysis, and TP, CHL and SD were converted at the base of Carlson (1977)'s equation. According to TSI, trophic state was divided into Oligotrophy (Ol), Mesotrophy (Me), Eutrophy (Eu) and Hypereutrophy (Hy).

$$\mathrm{TSI\,(TN)} = 54.45 + 14.43\,\mathrm{Log\,(TN)}$$

$$\mathrm{TSI\,(TP)} = 14.42\,\mathrm{Log\,(TP)} + 4.15$$

$$\mathrm{TSI\,(CHL)} = 9.81\,\mathrm{Log\,(CHL)} + 30.6$$

$$\mathrm{TSI\,(SD)} = 60 - 14.41\,\mathrm{Log\,(SD)}$$

For analyzing and predicting inter-relations of nutrients, chlorophyll-*a* and water clarity, we used empirical models of TN-CHL, TP-CHL, TP-SD and CHL-SD. For the seasonal variations of water quality, we compared three seasons of premonsoon (May ~ June), during monsoon (July ~ August), and postmonsoon (September ~ October) during the study according to the approach of An (1997). The monsoon characteristics and seasonal differences of hydrology, inflow, discharge (outflow), annual precipitation (rain fall), and water level in Korean reservoir are well described in the document of An (1997). Each water quality data was divided into annual mean and seasonal mean, and then transformed into Log_{10} and also applied regression analysis using SPSS (Window version 12.0)

RESULTS AND DISCUSSION

1. Reservoir conditions

Nutrient contents, water transparency and chlorophyll-*a*, based on 10 large dam reservoirs, were analyzed in Table 1 along with N : P ratios, trophic state, and potential limitations. Nutrient analyses at 10 reservoirs showed that phosphorus in the ambient water was low relative to nitrogen, and trophic state varied depending on the reservoir and the variables used. TP averaged 22.2 $\mu g\ L^{-1}$ and ranged between $16.4 \pm 3.2\ \mu g\ L^{-1}$ in Andong Reservoir (AR) and $39.7 \pm 10.7\ \mu g\ L^{-1}$ (Uiam Reservoir, UR), indicating a mesotrophic-eutrophic, according to the criteria of Nurnberg (1996), based on world-wide lake dataset. However, Trophic State Index, based on TP (TSI [TP]), was judged

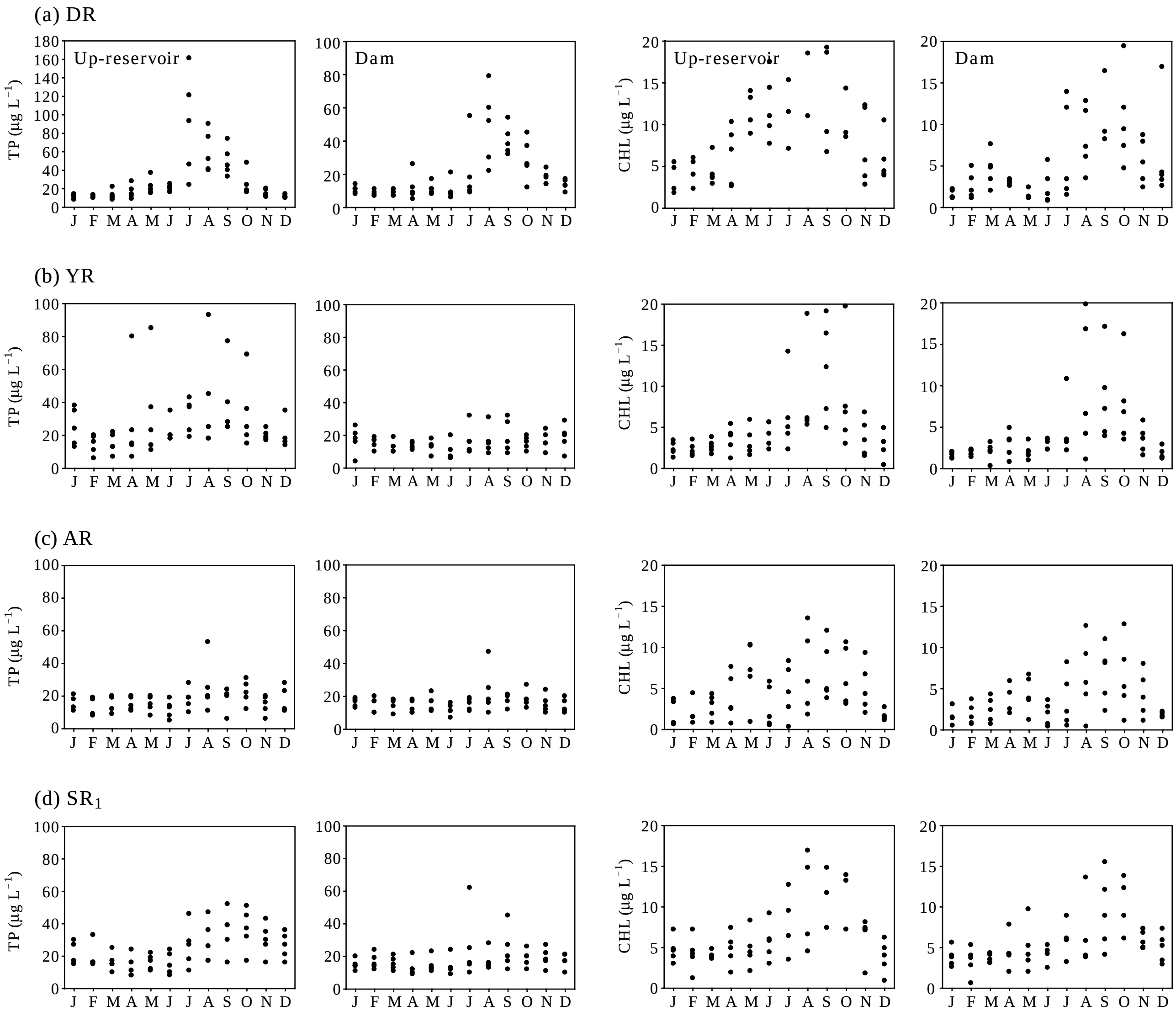

Fig. 2. Seasonal patterns of total phosphorus (TP) and chlorophyll (CHL) at the down-reservoir (dam site) vs. up-reservoir site (head water). The abbreviations of reservoir name are in Fig. 1.

as mesotrophy as shown in Table 1. TN, based on 10 observations of 10 reservoirs, averaged 1.530 mg L^{-1} and the all values were >0.680 mg L^{-1}. Minimum mean values (0.945 mg L^{-1}) were shown in Juam Reservoir (JR) and the maximum value (2.386 ± 0.155 mg L^{-1}) were shown in Chungju Reservoir (CR_2), resulting in a nitrogen difference of >2-fold in the ambient water. Nitrogen data indicate that this system is hypereutrophic, based on the Nurnberg's criteria, and the dissolved nitrogen dominates the nitrogen pool in Korean dam reservoirs. Under the circumstances, nitrogen was not likely limiting phytoplankton growth regardless of season and location (Morris and Lewis, 1988).

Mass ratio of TN : TP, a measure of the potential P or N limitation, averaged 77.8 (n=177) in the ten reservoirs and varied between 44.9 in Uiam Reservoir (UR) and 124.9 in Chungju Reservoir (CR_2) depending on the reservoir (Table 1). All 10 reservoirs showed mass ratios of >17N : 1P (Forsberg and Ryding, 1980) and atomic ratio (16N : 1P) of Redfield (1934), indicating a potential of phosphorus limitation for phytoplankton growth. The potential analysis of nutrient limitation showed that reservoirs of SR_1 and CR_2 were greater than 100, indicating a severe potential P-limita-

Table 3. Empirical models of CHL-TP in the seasonal mean. The abbreviations of reservoir name are in Table 1.

Parameter	Site	Seasonal means	Linear model (equation)	R^2	P value	n
CHL vs. TP	DR	P_r	Log (CHL)=1.533* Log (TP)−1.081	0.510	<0.001**	60
		M_o	Log (CHL)=0.504* Log (TP)+0.151	0.159	0.002**	60
		P_o	Log (CHL)=0.262* Log (TP)+0.737	0.033	0.174	57
	YR	P_r	Log (CHL)=0.104* Log (TP)+0.351	0.022	0.385	36
		M_o	Log (CHL)=0.711* Log (TP)+0.190	0.250	0.001**	40
		P_o	Log (CHL)=0.453* Log (TP)+0.257	0.132	0.021*	40
	AR	P_r	Log (CHL)=1.408* Log (TP)−1.097	0.328	<0.001**	30
		M_o	Log (CHL)=1.246* Log (TP)−0.954	0.371	<0.001**	28
		P_o	Log (CHL)=0.778* Log (TP)−0.235	0.143	0.039*	30
	SR_1	P_r	Log (CHL)=0.656* Log (TP)+0.054	0.024	0.506	20
		M_o	Log (CHL)=0.639* Log (TP)+0.181	0.076	0.138	30
		P_o	Log (CHL)=0.801* Log (TP)+0.012	0.483	<0.001**	28
	JR	P_r	Log (CHL)=0.925* Log (TP)−0.367	0.228	0.008**	30
		M_o	Log (CHL)=0.788* Log (TP)−0.199	0.247	0.005**	30
		P_o	Log (CHL)=1.227* Log (TP)−0.660	0.546	<0.001**	30
	HA	P_r	Log (CHL)=0.306* Log(TP)−0.287	0.084	0.119	30
		M_o	Log (CHL)=0.158* Log (TP)+0.138	0.037	0.308	30
		P_o	Log (CHL)=0.558* Log (TP)−0.179	0.278	0.003**	30
	SR_2	P_r	Log (CHL)=0.621* Log (TP)−0.340	0.091	0.051	42
		M_o	Log (CHL)=0.400* Log (TP)+0.025	0.150	0.009**	42
		P_o	Log (CHL)=0.282* Log (TP)+0.227	0.041	0.185	44
	CR_1	P_r	Log (CHL)=0.142* Log (TP)+0.217	0.025	0.399	30
		M_o	Log (CHL)=0.329* Log (TP)+8.664	0.045	0.367	21
		P_o	Log (CHL)=0.450* Log (TP)+0.029	0.233	0.007**	30
	UR	P_r	Log (CHL)=0.815* Log (TP)−0.830	0.133	0.373	8
		M_o	Log (CHL)=4.036* Log (TP)−5.353	0.683	0.084	5
		P_o	Log (CHL)=0.482* Log (TP)+0.043	0.071	0.563	7
	CR_2	P_r	Log (CHL)=1.020* Log (TP)−1.047	0.312	<0.001**	40
		M_o	Log (CHL)=0.635* Log (TP)−0.364	0.119	0.034*	38
		P_o	Log (CHL)=0.506* Log (TP)−0.033	0.055	0.173	35

tion, while reservoirs of UR and JR were less than 100, indicating a low potential P-limitation.

2. Regression linear models of TP-CHL, TN-CHL, and CHL-SD

Regression linear models of total phosphorus-chlorophyll (TP-CHL), total nitrogen-chlorophyll (TN-CHL), and chlorophyll-Secchi depth (CHL-SD) were analyzed for elucidations of the empirical relations between the variables (Fig. 1; Table 1). Regression analysis of log-transformed nutrients showed that algal biomass, measured as CHL, were more associated with phosphorus (70%) than nitrogen (30%). In three reservoirs of DR, YR and JR chlorophyll-*a* was linearly ($R^2 > 0.159$, $p < 0.05$) increased with an increase of ambient phosphorus but in DR, YR not with TN (range of $R^2 = 0.082 \sim 0.096$; $p > 0.05$, Fig. 1). This fact agrees with the finding that CHL values have higher correlation with TP than TN (Downing and McCauley, 1992; An, 1997). In these reservoirs, the weaker correlation of CHL with N seems to be attributed to the richness and less variability of nitrogen relative to phosphorus, based on previous references of Grobbelaar (1992), An (1997), and An *et al.* (2006). In the mean time, three reservoirs of AR, SR_2, and CR_2, CHL were linearly ($R^2 > 0.430$, $p < 0.05$) had a positive linear functions with TN, but not with TP ($p > 0.05$, Fig. 1). The higher relations of N with CHL in the three reservoirs were not accord with the diagnosis of potential limitation by N : P. Such phenomena should be elucidated in the future, even if the reason is not explained in this research due to the experimental limitations. Also, empirical model analysis of CHL-SD showed that water clarity, measured as Secchi depth, in most reservoirs were mainly determined by ambient

Table 4. Empirical models of SD-CHL in the seasonal mean. The abbreviations of reservoir name are in Table 1.

Parameter	Site	Seasonal means	Linear model (equation)	R^2	P value	n
SD vs. CHL	DR	P_r	Log (SD) = −0.456*Log (CHL) + 0.781	0.730	< 0.001**	60
		M_o	Log (SD) = −0.406*Log (CHL) + 0.645	0.191	< 0.001**	60
		P_o	Log (SD) = −0.213*Log (CHL) + 0.526	0.115	0.010*	57
	YR	P_r	Log (SD) = −0.482*Log (CHL) + 0.735	0.287	< 0.001**	36
		M_o	Log (SD) = −0.350*Log (CHL) + 0.682	0.395	< 0.001**	40
		P_o	Log (SD) = −0.438*Log (CHL) + 0.745	0.387	< 0.001**	40
	AR	P_r	Log (SD) = −0.465*Log (CHL) + 0.711	0.723	< 0.001**	30
		M_o	Log (SD) = −0.273*Log (CHL) + 0.616	0.387	< 0.001**	28
		P_o	Log (SD) = −0.433*Log (CHL) + 0.768	0.508	< 0.001**	30
	SR_1	P_r	Log (SD) = −0.041*Log (CHL) + 0.487	0.011	0.648	15
		M_o	Log (SD) = −0.143*Log (CHL) + 0.346	0.287	0.002**	30
		P_o	Log (SD) = −0.258*Log (CHL) + 0.473	0.208	0.015*	28
	JR	P_r	Log (SD) = −0.280*Log (CHL) + 0.560	0.618	< 0.001**	30
		M_o	Log (SD) = −0.327*Log (CHL) + 0.632	0.368	< 0.001**	30
		P_o	Log (SD) = −0.136*Log (CHL) + 0.479	0.143	0.039*	30
	HR	P_r	Log (SD) = −0.119*Log (CHL) + 0.684	0.037	0.316	29
		M_o	Log (SD) = −0.046*Log (CHL) + 0.667	0.046	0.361	20
		P_o	No data			
	SR_2	P_r	Log (SD) = −0.149*Log (CHL) + 0.470	0.060	0.154	35
		M_o	Log (SD) = −0.361*Log (CHL) + 0.611	0.167	0.009**	40
		P_o	Log (SD) = −0.056*Log (CHL) + 0.476	0.016	0.410	44
	CR_1	P_r	Log (SD) = −0.051*Log (CHL) + 0.402	0.013	0.642	18
		M_o	Log (SD) = −0.082*Log (CHL) + 0.466	0.183	0.164	12
		P_o	Log (SD) = −0.092*Log (CHL) + 0.340	0.165	0.094	18
	UR	P_r	Log (SD) = −0.502*Log (CHL) + 0.462	0.200	0.266	8
		M_o	Log (SD) = −0.103*Log (CHL) + 0.228	0.080	0.643	5
		P_o	Log (SD) = −0.996*Log (CHL) + 1.079	0.299	0.204	7
	CR_2	P_r	Log (SD) = −0.463*Log (CHL) + 0.614	0.357	< 0.001**	38
		M_o	Log (SD) = −0.127*Log (CHL) + 0.488	0.050	0.189	36
		P_o	Log (SD) = −0.119*Log (CHL) + 0.572	0.045	0.217	35

contents of algal phytoplankton. The regression coefficients were > 0.267 in the reservoirs of DR, YR, AR, JR, SR_2, and CR_2, indicating a direct influence of water clarity by the organic solids not by non-volatile solids, based on previous references (Grobbelaar, 1992; An, 1997). In other reservoirs (SR_1, HR, CR_1 and UR), the relations of SD with CHL were weak or no relations (R^2 range: 0.000 ~ 0.259).

3. Seasonal patterns of nutrients, and CHL at the Dam vs. Up-Reservoir

1) Monthly variations of water quality

Seasonal TP, based on monthly data at the dam site, showed diverse shapes depending on the types of the reservoirs, but a mono-modal peak during July ~ October were evident in most reservoirs (Fig. 2). This results suggest that the phosphorus loading mainly comes from the watershed of the up-reservoir, and that the internal loading may be less effect than the external loading (An and Kim, 2003).

The magnitude and time of the TP peak differed between the dam site and up-reservoir site among the reservoirs; As shown in Fig. 2, highest peak of > 150 μg L^{-1} at the up-reservoir site occurred during July of the monsoon in Daecheong Reservoir (DR), and declined as a value of < 80 μg L^{-1} in the August at the dam site. However, the highest peak of > 160 μg L^{-1} at the up-reservoir site did not influence phytoplankton growth as shown in monthly CHL fluctuations. This result may be attribute to combined effects of greater fractions of particulate phosphorus rather than dissolved P of the total phosphorus, reduction of phytoplankton biomass by high flushing rate during the monsoon, and decrease of underwater light avail-

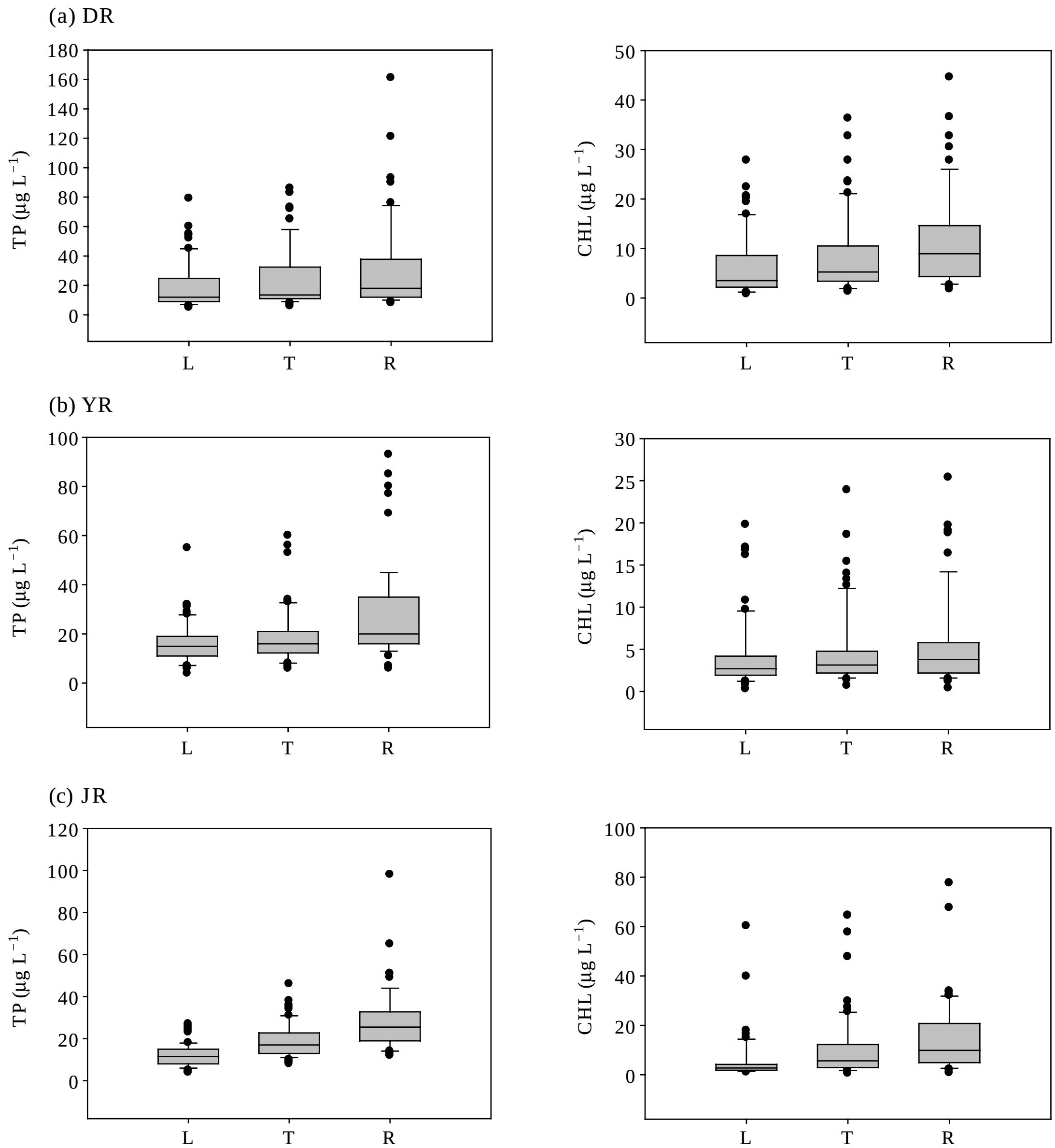

Fig. 3. Spatial gradients of TP and CHL along the lacustrine zone (L), transition zone (T), and riverine zone (R). The graph is based on all individual data of 10 reservoirs.

ability by high inorganic solids (Chapra and Tarapchak, 1976; Walker, 1982). For this reason, the maixmum CHL at the up-reservoir site did not differ with the maixmum CHL at the dam site. As the up-reservoir water pass through the lake, TP at the dam site was reduced by nearly 2-fold and the gap was approximately 30 days (1 month) between the peaks of TP at the dam and the up-reservoir. For this reason, the peak of TP occurred in July at the up-reservoir and August at the dam site. In the up-reservoir site of DR, maximum TP increased consistently by July from January and then dropped down rapidly, whereas the peak at the dam site increased by 100% on August (Fig. 2). Thus, seasonal peaks of TP at the dam site occurred one month later than that in the up-reservoir site. The disparity in TP seasonality was probably attributed to differences in the water residence time between the two sites. This phenomenon is well demonstrated by previous researches of Grobbelaar (1992), An (1997), and An *et al.* (2006). Such declining pattern in TP along the main axis of

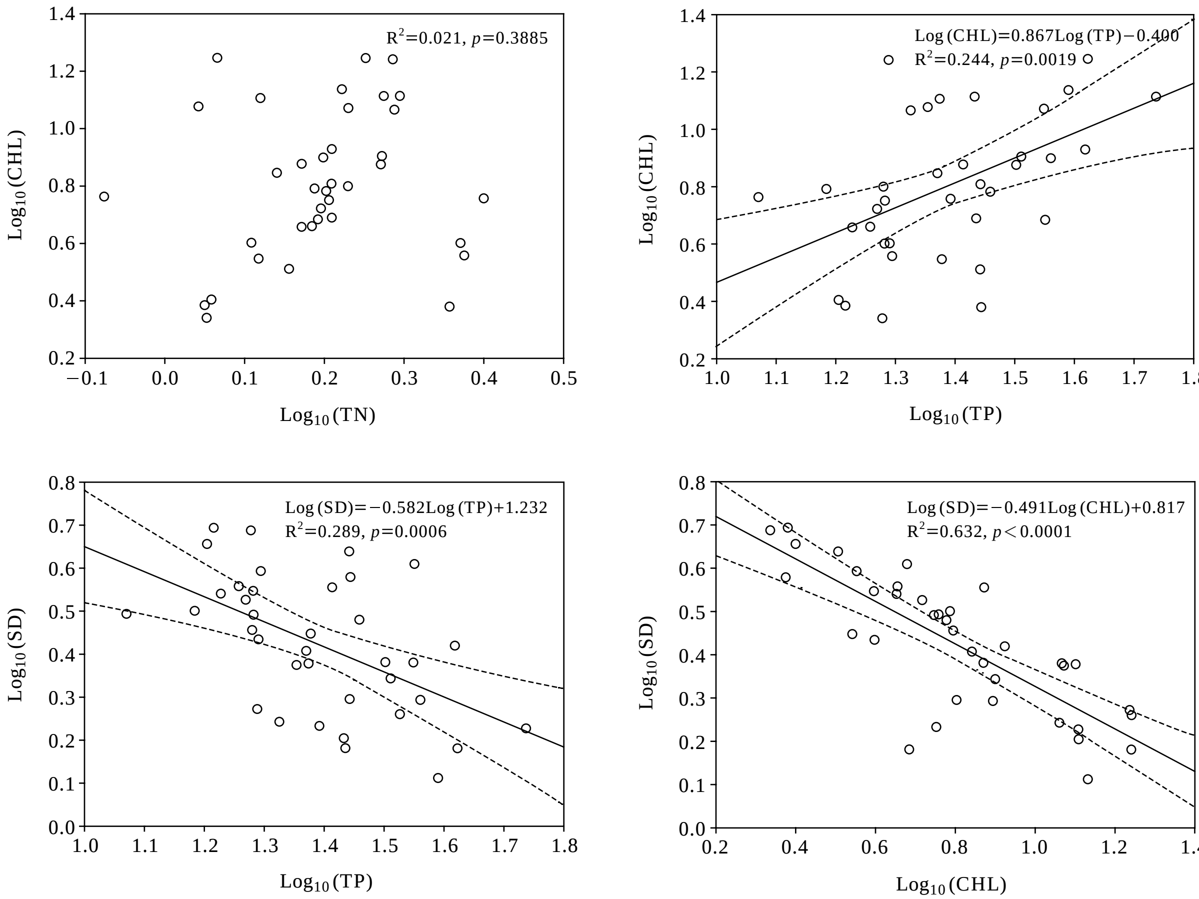

Fig. 4. Regression linear models of log-transformed TN-CHL, TP-CHL, TP-SD and CHL-SD in 10 reservoirs. The dotted line indicates 95% confidence intervals.

the reservoir was similar to TP in the reservoir of YR.

In contrast, the high disparity between the up-reservoir and the dam site was not shown in the reservoir of AR; The maximum TP in the up-reservoir was 53 μg L^{-1} and occurred in August, while the maximum in the dam site was 47 μg L^{-1} and occurred in August. Also, in the up-reservoir site of AR, maximum CHL on each month were observed in August but in the dam site of AR, the maximum occurred in October. But, there is no distinct difference between the CHL maxima in the up-reservoir and CHL maxima at the dam site in the AR.

Monthly data in the reservoirs suggest that most reservoirs had high input of phosphorus input during the Asian monsoon season of July～August, but the high TP peak did not match the contents of CHL, which may be influenced by high flushing rate, low light availability, and dominant particulate-P fractions.

2) Seasonal variations of the empirical relations by the monsoon

Seasonal effect of TP on CHL were analyzed by empirical models of TP-CHL in the premonsoon (P_r), monsoon (M_o), and postmonsoon (P_o). In the reservoir of DR, the Asian monsoon dramatically influenced the relations of CHL-TP; The regression coefficient in the P_r was 0.510 ($p<0.001$, n=60) but the value in the M_o was 0.159 ($p<0.01$, n=60; Table 3). This result indicates that the CHL values during the premonsoon was directly determined by ambient phosphorus and that CHL values did not increase under the P-limitation system, even if the TP increased in the water column. For this reason, during the P_r season, the variation of water transparency, measured as Secchi depth (SD), was largely accounted (R^2=0.73, $p<0.01$, n=60) by the variation of phytoplankton biomass, measured as CHL value. Also, during the premonsoon, similar high regression coefficients (R^2) of >0.60 in the SD vs. CHL were observed in the reservoirs of AR and JR (Table 4) where the relation of TP-CHL were statistically significant (p values <0.01, n=30; Table 3) in the premonsoon season.

In contrast, in the reservoir of YR, the relations of CHL-TP increased during the monsoon, compared to the premonsoon (Table 3); The regression coefficient in the P_r was not statistically significant ($p=0.385$, n=36) but the value in the M_o was 0.250 ($p<0.01$, n=40). This result of YR may be a result of low flushing rate during the monsoon. In the mean time, in the reservoir of SR_1, the relations of CHL-TP in the P_o ($R^2=0.483$, $p<0.01$, n=28) was greater than the any other seasons (Table 3), and the relation of CHL vs. SD in the reservoir of SR_1 was significant ($p<0.01$, n=28; Table 4).

4. Spatial gradients of TP and CHL

Longitudinal gradients of TP, which is a potential limiting nutrient based on N : P ratios (Table 1), were evident in the reservoirs of DR, YR and JR; In the reservoir of DR, mean TP was 29, 24, and 19 $\mu g\ L^{-1}$ in the riverine, transition, and lacustrine zones, respectively and in the YR, mean TP was 27, 18, and 16 $\mu g\ L^{-1}$ in the three zones, respectively. Similar trend of TP were found in the reservoir of JR. Also, maximum values of TP at each zone showed similar longitudinal gradients in the DR (L_z,=80 $\mu g\ L^{-1}$, T_z=88 $\mu g\ L^{-1}$, R_z,=162 $\mu g\ L^{-1}$) YR (L_z,=55 $\mu g\ L^{-1}$, T_z=61 $\mu g\ L^{-1}$, R_z,=93 $\mu g\ L^{-1}$), and JR (L_z,=28 $\mu g\ L^{-1}$, T_z=47 $\mu g\ L^{-1}$, R_z,=99 $\mu g\ L^{-1}$) (Fig. 3). In contrast, distinct spatial gradients were not found in other reservoirs, indicating that spatial water quality variation may not highly vary within the reservoirs.

5. Empirical relationship of trophic variables

Empirical models of all reservoirs, based on growing seasonal mean of $\log_{10}$-transformed trophic variables, showed that mean CHL was determined by phosphorus, even though the regression coefficient was low, but not by nitrogen ($p>0.05$, n=37).

$$\mathrm{Log_{10}(CHL)}=0.867\,\mathrm{Log_{10}(TP)}-0.400 \quad (R^2=0.244,\ p=0.0019) \qquad \text{(A)}$$

The model of TN-CHL, however, did not show any statistical significance ($p=0.388$, n=37) in the analysis. In contrast, regression analysis of mean CHL vs. SD (Fig. 4) showed a stronger linear fit than the relation of TP-CHL and the variation of CHL explained 47% of variance in the log-transformed CHL.

$$\mathrm{Log_{10}(SD)}=-0.491\,\mathrm{Log_{10}(CHL)}+0.817 \quad (R^2=0.632,\ p<0.001) \qquad \text{(B)}$$

Based on the results, the water clarity, as a transparency of SD was more accounted by the variation of CHL, compared to the relation of TP vs. CHL. Previous models, based on annual mean of 59 Korean reservoirs, showed high regression coefficients in the TP-CHL models, but our model of TP-CHL, based on 10 large dam reservoirs, did not show a strong linear fit. Also, TN-CHL model was not significant ($p=0.388$, n=37), as shown in other reservoir studies (Park and An, 2007; Han and An, 2008). When we compared our data with previous references, reduced responses of chlorophyll-*a* to the phosphorus in these large dam reservoirs may be influenced by monsoon run-off or low light availability, based on Secchi transparency values, during the intense monsoon, as shown in other reservoir researches of Grobbelaar (1992), An (1997), and An *et al.* (2006), resulting in low TP-CHL relations. In spite of the low regression coefficients in the TP-CHL model, the TP-CHL relationships reported here support the view that phytoplankton in lentic ecosystems responds to phosphorus enrichment (Schindler, 1978) and not to nitrogen.

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LITERATURE CITED

An, K.G. 1997. Influence of the Asian monsoon on the limnology of Taechung Reservoir, Korea, The dissertation of University of Missouri, Columbia. p. 361.

An, K.G. and D.S. Kim. 2003. Response of reservoir water quality to nutrient inputs from streams and in-lake fishfarms. *Water, Air, and Soil Pollution* **149**: 27-49.

An, K.G., J.K. Kim and S.J. Lee. 2008. Reservoir trophic state and empirical model analysis, based on nutrients, transparency, and chlorophyll-*a* along with their relations among the parameters. *Korean J. Environ. Biol.* **26**(3): 252-263.

An, K.G., S.J. Park, S.M. Choi and J.S. Park. 2006. Comparative analysis of long-term water quality data monitored in Andong and Imha Reservoirs. *Korean J. Limnol.* **39**(1): 21-31.

Carlson, R.E. 1977. A trophic state index for lakes. *Limnology and Oceanography* **22**: 361-369.

Charpra, S.C. and S.J. Tarapchak. 1976. A chlorophyll-*a* model and its relationship to phosphorus loading plots for lakes. *Water Resour. Res.* **12**: 1260-1264.

Dettmers, J.M. and R.A. Stein. 1996. Quantifying linkage among gizzard shad, zooplankton, and phytoplankton in reservoirs. *Transactions of the American Fisheries Society* **125**: 27-41.

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

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

Grobbelaar, J.U. 1992. Nutrient versus physical factors in determining the primary productivity of water with high inorganic turbidithy. *Hydrobiologia.* **238**: 177-182.

Han, J.H. and K.G. An. 2008. Water quality variation dynamics between artificial reservoir and the effected downstream watershed: the case study. *Korean J. Limnol.* **41**(3): 382-394.

Kim, B.C. and Y.H. Kim. 2004. Phosphorus cycle in a deep Reservoir in Asian monsoon area (Lake Soyang, Korea) and the modeling with a 2-D hydrodynamic water quality model [CE-QUAL-W2]. *Korean J. Limnol.* **37**(2): 205-212.

Kratzer, C.R. and P.L. Brezonik. 1981. A Carlson-type trophic state index for nitrogen in Florida lakes. *Wat. Res. Bulletin* **17**: 713-715.

Lee, E.H., J.W. Choi, J.H. Lee and K.G. An. 2007. Ecological health diagnosis of Sumjin River using fish model metric, physical habitat parameters, and water quality characteristics. *Korean J. Limnol.* **40**(2): 184-192.

Morris, D.P. and W.M. Lewis. 1988. Phytoplankton nutrient limitation in Colorado mountain lakes. *Freshwater Biology* **20**: 315-327.

Nurnberg, G.K. 1996. Trophic State of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. *J. of Lake and Reserv. Manage.* **12**: 432-447.

Ohtake, H., K. Kondo, Y. Seike and Y. Date. 1982. Seasonal and areal features of the lagoonal environment in lake Nakanoumi, a shallow coastal lagoon in Japan. *Hydrobiologia.* **97**: 15-26.

Park, H.J. and K.G. An. 2007. Trophic State Index (TSI) and empirical models, based on water quality parameters, in Korean Reservoirs. *Korean J. Limnol.* **40**(1): 14-30.

Redfield, A.C. 1934. On the proportions of organic derivatives in a sea water and their relation to the composition of plankton, p. 177-192. *In*: James Johnstone Memorial Volume (Daniel, R.J., ed.). University Press of Liverpool, United Kingdom.

Schindler, D.W. 1978. Factors regulating phytoplankton production and standing crop in the world's freshwater. *Limnol. Oceanogr.* **23**: 478-486.

Walker, W.W. Jr. 1982. An empirical analysis of phosphorus, nitrongen, turbidity effects on reservoir chlorophyll-*a* levels. *Can. Water Resour. J.* **7**: 88-107.

Zafar, A.R. 1986. Seasonality of phytoplankton in some South Indian lakes. *Hydrobiologia.* **138**: 177-187.

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