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Effects of Physical Characteristics on a Nutrient-Chlorophyll Relationship in Korean Reservoirs

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Abstract □ This study was performed to evaluate effects of physical characteristics of both watershed and reservoir on nutrient-chlorophyll relationship in Korean reservoirs. Simple linear models were developed with published data in Korea including 415 reservoirs and 11 multi-purpose dams, and physico-chemical parameters of reservoirs and characteristics relationship of models were analyzed. Theoretical residence time in Korean reservoirs was strongly correlated with the ratio of TA/ST (drainage area + surface area / storage volume) in the logarithmic function. As a result of monthly nutrients-chlorophyll-*a* regression analysis, significant Chl-*a*-TP relationship appeared during May ~ July. The high Chl-*a* yields per total phosphorus appeared during this time (R^2= 0.51, p<0.001, N= 1088). Chlorophyll-*a* demonstrated much stronger relationship with TP than TN. Seasonal algal-nutrient coupling were closely related with N:P ratio in the reservoir water, and it was, in turn, dependent on the monsoon climatic condition (precipitation). Based on the results of regression analysis and high N:P ratio, a major limiting factor of algal growth appeared to be phosphorus during this time. Unlikely TA/ST ratio, DA/SA ratio (drainage area / surface area) was likely to influence directly on the nutrient-Chl-*a* relationship, indicating that if storage volume and inflowing water volume were the same, algal biomass could be developed more in reservoirs with large surface area. Thus, DA/SA ratio seemed to be an important factor to affect the development of algal biomass in Korean reservoirs. With low determination coefficient of TP-Chl-*a* relationship, our findings indicated not only nutrient (phosphorus) but also other physical factors, such as DA/SA ratio, may affect algal biomass development in Korean reservoirs, where actual residence time appears to be more closely related to reservoir surface area rather than storage volume.

Keywords □ Phosphorus, Limiting factor, Korean reservoirs, Chlorophyll, N:P ratio, DA/SA ratio, Regression model

I. Introduction

Reservoir is a lentic water system where algal growth is stimulated by nutrients received from the watershed and released from the sediment. Sakamoto (1966) first demonstrated the strong empirical links among phosphorus, nitrogen, and chlorophyll. He indicated that nutrients (phosphorus and nitrogen) are important factors limiting algal growth. Most lakes and reservoirs appear to be phosphorus limited (e.g., Schindler, 1978), and the strong correlation between phosphorus and chlorophyll- *a* concentration provided a general corroboration of Liebig's Law of the Minimum applied to the phytoplankton.

In addition to nutrients, other factors affecting algal growth also were pointed out (Brylinsk and Mann, 1973; Hoyer and Jones, 1983; Brown, 1997). Richardson (1975) evaluated the effect of lacustrian morphology on primary productivity, indicating that physical factors, such as watershed ratio and lake morphometry, can deviate nutrients effect on the algal growth. Several authors proposed that riverine or lacustrine dominance of within-reservoir processes could be determined by water residence time (Thornton *et al.*, 1980; Kimmel and Groeger, 1984; Carline, 1986). Vollenweider (1975) showed that water depth as well as residence time had an impact on a degree of eutrophication in lakes.

Using the relationship between nutrients and algal biomass, many researchers have developed simple empirical nutrient-chlorophyll- *a* models to predict changes in chlorophyll- *a* concentration as a result of changes in nutrient concentration (Dillon and Rigler, 1974; Rast and Lee, 1978; Bartsch and Gakstatter, 1978; Smith, 1978; Daniel *et al.*, 1981; McCauley *et al.*, 1989; Prairie *et al.*, 1989; Canfield, 1983; Brown *et al.*, 2000). However, the troubling aspect of chlorophyll- *a*-phosphorus relationship is the substantial variability of the regression plot within and among lakes (Smith and Shapiro, 1981). Such variability may reflect the influence of other physical, chemical and biological variables on the chlorophyll- *a*-phosphorus relationship (Straskraba, 1980; Smith and Shapiro, 1981; Prepas and Trew, 1983; Canfield and Jones, 1984; Pace, 1984). The variables influencing algal growth in aquatic ecosystems were reported to be TN:TP ratio (Prairie *et al.*, 1989) and residence time (Soballe and Kimmel, 1987). These particular variables appeared to be largely affected by regional climatic condition, such as Asia monsoon (An and Park, 2002). Also, Mazumder and Havens (1998) introduced the effect of zooplankton predation on phytoplankton in various aquatic systems using nutrient-chloropyll-Secchi depth relationship.

Reservoirs are a numerically predominant lentic system in Korea, with their main purposes of irrigation and water supply. It is characterized that most of them are shallow and small, and have short residence time (MAF, KOWACO, 2001). These characteristics reflect the influence of Asia Monsoon climate and fluctuation of its resultant hydrology in inflowing waters. Also, Korean reservoirs have relatively large watershed area from which they receive a large amount of nutrient loadings. As a result, they have a high potential to develop eutrophication. We suspect that these physical characteristics largely influence nutrients-chlorophyll relationship. In this study, we examined physical characteristics of broad scale Korean reservoirs comparing with U.S.A. lakes, reservoirs and rivers, and evaluated differences of regression coefficients to find a main influence on the algal growth using nutrient-chlorophyll *a*. relationship Considering various parameters correlated, evaluation of differences of regression coefficients is valuable in determining limiting factors on algal growth.

II. Materials and method

In this study, we used published data from 415 reservoirs and 11 multi-purpose dams provided by Korean Ministry of Agriculture & Forestry (MAF, 2001) and Ministry of Environment (ME, 2002). MAF data consisted of the results surveyed twice during the growing season from 1995 to 2000, and ME data surveyed every month from 1997 to 2001. Data set included monitoring results of various parameters of water quality, and about 61 of all studied reservoirs included the data of water inflow (m^3/year). Theoretical residence time (T_d, day) was calculated: storage volume (ST, cubic meter) of reservoir divided by inflowing water (Q, cubic meter per year): T_d = ST/Q.

The physical and chemical characteristics of Korean reservoirs were compared with reservoirs and lakes in U.S.A. provided by NASQUAN (National Stream Quality Accounting Network) and NES (National Eutrophication Survey) data set. NASQUAN, an active network of 345 river sites in United States, began to monitor stream flow and water quality in 1975. The NES, conducted monitoring from 1972 to 1975, and listed up trophic status of 812 lakes and reservoirs in the United States. Each site in the NES was sampled 2~4 times during the growing season.

We compared average depth, drainage area, surface area, stream flow, theological residence time, T-N, T-P, chlorophyll-a concentration, and N:P ratios between Korean reservoirs and U.S.A. lakes, reservoirs and rivers. We also plotted [storage volume] vs. [the ratio of total area (drainage area + water surface area) / storage volume] and [storage volume vs. retention time] to evaluate physical characteristics of Korean reservoirs under the similar storage volume scale.

Using the nutrient-chlorophyll- *a* models, we evaluated the effect of physical characteristics on algal biomass development. Nutrient-chlorophyll- *a* models were developed by a simple linear regression analysis with log-transformed (base 10) data of all variables.

Data set were divided into a monthly scale to evaluate seasonal effect (Monsoon climate) on algal biomass development during April ~ October. Among the results of seasonal regression analysis, we select data with only significant correlations to evaluate the effect of the ratio of total area (drainage area + surface area, TA) to storage volume (ST) and the ratio of drainage area (DA) to surface area (SA) on algal biomass development. In this process, all reservoirs were ordered by the ratios of TA/ST and DA/SA. Starting at the lower end of the TA/ST and DA/SA spectrum, we divided into 10 groups according to each ratio. Linear regressions between log-transformed values of T-P, T-N and chlorophyll- *a* were performed. Regression slopes were interpreted as a measure of the ability of the phytoplankton development to respond to change in nutrients (Margalef 1983).

Correlation coefficients can be considered as a measure of the strength of the nutrient-phytoplankton coupling (Prairie *et al.*, 1989). Thus, we hypothesize that if slopes or correlation coefficients of nutrient-chlorophyll- *a* regression equation changes systematically with other factor, it is a limiting factor on algal biomass development. All statistic analyses were conducted by SPSS10.0 (Norus, 1982).

Ⅲ. Results and discussion

1. Physico-chemical characteristics of Korean reservoirs

Generally, Korean reservoirs were shallow, had small drainage area, surface area, and short residence time compared with U.S.A lakes and reservoirs. Whereas Korean multi-purpose dams were deeper than U.S.A. lakes and reservoirs, and other factors such as drainage area, surface area, and residence time were in a similar range to that of U.S.A. reservoirs and lakes (Tables 1). The mean depth, drainage area, residence time of Korean reservoirs were 6.3±0.22m, 28±6 km^2 and 92.5±18.7days, respectively, and that of Korean multi-purpose dams were 31.5±3.4m, 1,535±469 km^2 and 270.3±34.6 days, respectively. In Korean reservoirs, there were a large difference between reservoirs and multi-purpose dams.

Table 1 Comparison of physico-chemical characteristics of Korean reservoirs and U.S. reservoirs, natural lakes and rivers (K.R= Korean reservoirs, K.M.D= Korean multi-purpose dams)

System type	Number	Depth (m)	Drainage area (km^2)	Surface area (km^2)	Stream flow (m^3/s)	Residence Time (d)
K. R	413	6.3±0.22	28±6	0.8±0.1	0.3±0.04	65.4±4.5
K. M. D.	11	31.5±3.4	1,535±469	33.04±7	35.6±11.1	270.3±34.6
U.S. lakes	149	8.6±0.9	1,680±360	51.6±14.3	16.3±3.9	1073.5±185
U.S. reservoirs	366	8.9±0.4	9,168±932	42.5±3.5	63.7±8.7	528.5±85

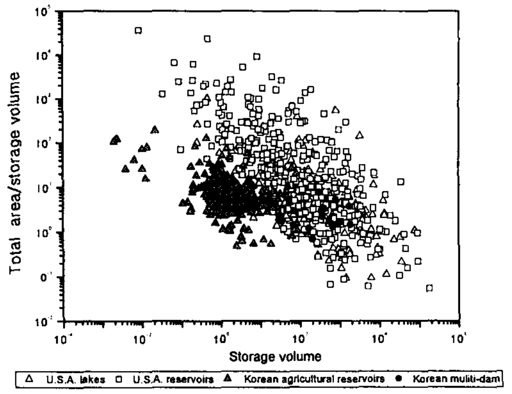

Fig. 1 Comparison of storage volume (10^6m^3) with the ratio total area (drainage area + water surface area, km^2) to storage volume (10^6m^3)

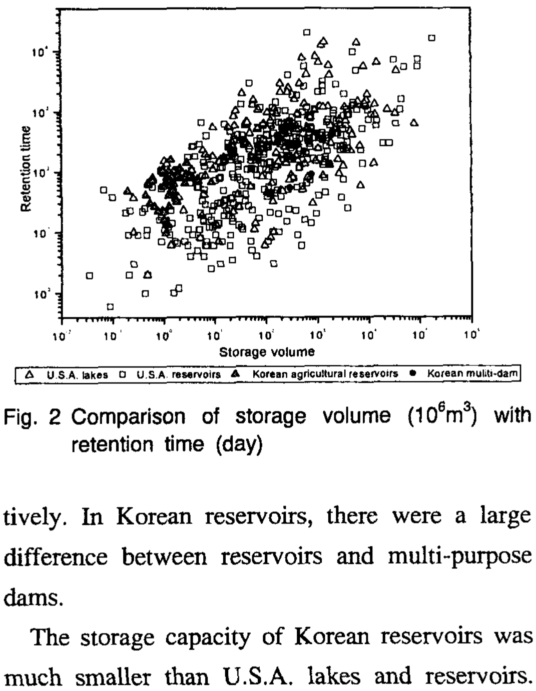

Fig. 2 Comparison of storage volume (10^6m^3) with retention time (day)

The storage capacity of Korean reservoirs was much smaller than U.S.A. lakes and reservoirs. The ratio of TA/ST of Korean reservoirs was smaller, with being located at the point of similar storage volume, indicating that inflowing water from the watershed was less than U.S.A. lakes and reservoirs so that residence time was longer even in a similar scale (Fig. 1, 2). However, those in Korean multi-purpose dams were in a similar range of U.S.A. lakes and reservoirs (Fig. 2).

Theoretical residence time in Korean reservoirs was strongly correlated with the ratio of TA/ST in the logarithmic function [Log (t_d) = 2.69 + 1.05 Log (TA/ST) ($R^2 = 0.93$, SD = 0.10, $P < 0.0001$)]. Bartsch and Gakstatter (1978) showed that residence time was dependent on drainage area/surface area ratio (DA/SA) in the North American lakes and reservoirs, but in this study, the ratio of TA/ST was more closely correlated with theoretical residence time than was the ratio of DA/SA. We had only 62 theoretical retention time data among the 429 reservoirs so we used the ratio of TA/ST to evaluate the effect of theoretical residence time on the relationship of nutrients- chlorophyll *a* based on strong correlation of theoretical residence time and the ratio of TA/ST.

Average T-N concentration of Korean reservoirs and multi-purpose dams was a little bit higher than the U.S.A lakes and reservoirs, whereas T-P concentration was very similar between Korean and U.S.A reservoirs. T-P concentration was highest in USA lakes (Table 2). N:P ratio of Korean reservoirs was much higher than that of U.S.A lakes and reservoirs, suggesting that a major nutrient limiting algal growth in Korean reservoirs is likely phosphorus. Chlorophyll- *a* concentration of Korean agricultural reservoirs was highest, and only U.S.A lakes value was comparable to it.

Table 2 Comparison of chemical characteristics of Korean reservoirs and U.S. reservoirs, natural lakes and rivers (K.R= Korean reservoirs, K.M.D= Korean multipurpose dams)

System type	T-N (mg/l)	T-P (mg/l)	N:P ratio (mass)	Chl- *a* (μg/l)
K. R	1.38±0.02	0.069±0.003	44.5±1.33	26.7±1.04
K. M. D.	1.59±0.02	0.019±0.001	129.8±8.72	5.33±0.23
U.S. lakes	1.24±0.11	0.105±0.018	28.6±2.74	22.8±3.38
U.S. reservoirs	0.97±0.05	0.066±0.004	22.5±0.99	13.9±0.87

2. Effects of physical characteristics of reservoirs on the algal growth

As a result of monthly nutrients-chlorophyll- *a* regression analysis, strong Chl- *a*-TP relationship appeared during May ~ July (Fig. 3). The lowest slope value (0.47) appeared during April, but subsequently the slope sharply increased in May. The high Chl- *a* yields per total phosphorus

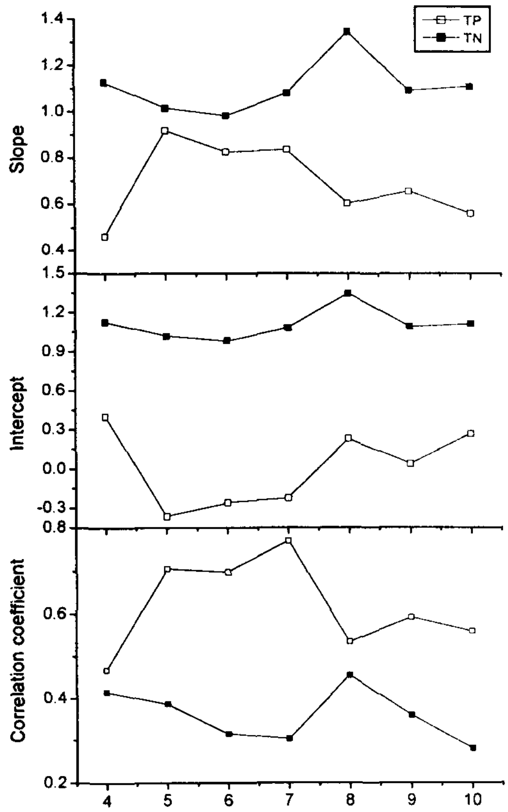

Fig. 3 Relationship of nutrients-chlorophyll- *a* according to month

appeared during this time (R^2= 0.51, p<0.001, N= 1088). A weak relationship between TP-Chl-*a* appeared again in August.

According to the result of regression analysis based on all of the collected data during May~July, chlorophyll-*a* demonstrated much stronger relationship with TP than TN (Fig. 4). It may be partly due to the phosphorus limiting condition in most of reservoirs indicated by N:P ratio (Table 2). During May~July, a second order polynomial and sigmoidal model describing the relationship between log-transformed mean Chlorophyll-*a* and TP concentration were: Log (Chl-*a*) = 0.29+0.01 Log TP +0.29 $(\text{Log TP})^2$ (R^2 = 0.53, SD = 0.35, N = 1088, P<0.0001) and Log (Chl-*a*) = 0.58-0.79 Log TP +0.92 $(\text{Log TP})^2$ - 0.15 $(\text{Log TP})^3$ (R^2 = 0.54, SD = 0.34, N = 1088, P<0.0001), respectively. The determination coefficient of second order polynomial model and sigmoidal model were similar.

Regression equation of Chl-*a* = f(TP, TN) was Log (Chl-*a*) = - 0.25 +0.83 Log TP + 0.13 Log TN (R^2 = 0.52, SD = 0.35 N = 1088, P < 0.0001). The determination coefficients of Chl-*a* = f(TP) and Chl-*a* = f(TP, TN) did not differ. Based on the results of regression analysis and high N:P ratio (Table 2) we conclude that a major limiting factor of algal growth is phosphorus during May~July in Korean reservoirs.

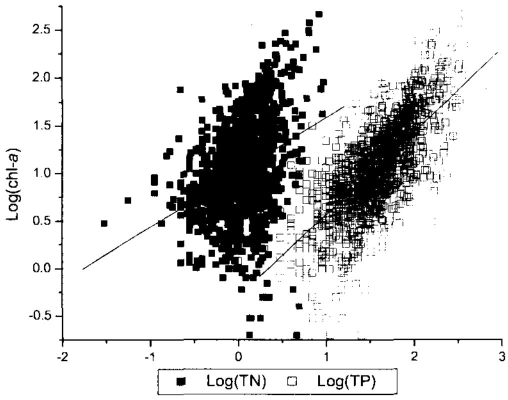

Fig. 4 Relationship of nutrients-chlorophyll-*a* in Korean reservoirs during May-July. Linear regression equation of each relationship is: Log (Chl-*a*) = 0.87 x Log(TP) - 0.30 (R^2= 0.51, N= 1088); Log(Chl-*a*) = 0.58 x Log (TN) + 1.01 (R^2= 0.12, N= 1088)

In Korea, intensive rainfall appeared during June ~ July, so called as Asian summer monsoon, and strong nutrient-Chl-*a* relationship appeared during monsoon period. In support of our finding, phosphorus limitation was consistent near the dam site (Daecheong Dam) during summer monsoon period (An, 2002). Fig. 5 shows monthly variation of TN:TP ratio in Korean reservoirs. TN:TP ratio increased during monsoon period with the highest value occurred in July (75.4±12.7), and during that period, TP-Chl-*a* relationship was much stronger (Fig. 3). Subsequently, the strong relationship of TP-Chl-*a* became weak, and instead TN-Chl-*a* relationship got stronger. Taken together, seasonal algal-nutrient coupling is closely related

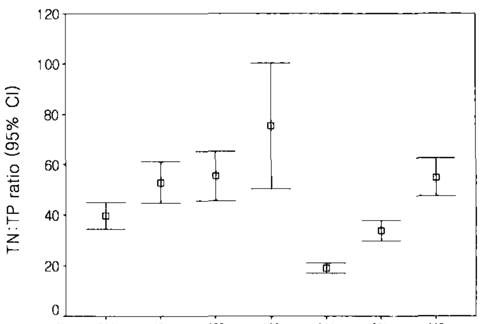

Fig. 5 Monthly TN:TP ratio (by mass) of Korean reservoirs

with TN:TP ratio in the reservoir water, and it was, in turn, dependent on the monsoon climatic condition (precipitation) in Korea. As a result of monthly analysis, it is concluded that strong phosphorus limitation was dominant during Asian summer monsoon period, but it became weak temporarily when Asian summer monsoon ended.

Theoretical residence time did not influence directly on the TP-Chl-a relationship in Korean reservoirs. As a result of linear regression analysis according to TA/ST ratio which showed a strong correlation with theoretical residence time, the slope of TA/ST $<$ 4 was lowest (0.76), that of 4$<$TA/ST$<$6 was steepest (1.00), and that of 6$<$TA/ST$<$10 and TA/ST$>$10 was similar (Table 3). However, there was no systematic pattern of changing regression coefficient according to TA/ST ratio.

Unlikely TA/ST ratio, DA/SA ratio appeared to influence directly on the nutrient-Chl-a relationship in Korean reservoirs. Regression analysis with DA/SA ratio showed that the slope of DA/SA$<$20 was steepest (1.10), and subsequently the value of slope decreased with increasing DA/SA ratio (Table 4). The regression coefficients change systematically with the DA/SA ratio: the higher the DA/SA ratio, the lower the slope and determination coefficient, and the higher the intercept. These results indicate that if storage volume and inflowing water volume were the same, algal biomass can be more developed in reservoirs with large surface area. Thus, we conclude that the DA/SA is an important factor to affect the development of algal biomass in Korean reservoirs.

Our TP-Chl-a model used growing season

Table 3 Results of regression analyses of chlorophyll-a-nutrients models according to TA/ST

	Category of TA/ST	Regression values: Intercept	Error	Slope	Error	R^2	SD	Number
TP	〈 4	-0.23	0.08	0.76	0.05	0.40	0.39	295
	4~6	-0.50	0.10	1.00	0.06	0.52	0.35	260
	6~10	-0.20	0.08	0.83	0.05	0.51	0.35	282
	〉 10	-0.16	0.08	0.80	0.05	0.53	0.30	244
TN	〈 4	0.81	0.03	0.12	0.11	0.00	0.50	295
	4~6	1.06	0.03	0.71	0.10	0.17	0.57	260
	6~10	1.11	0.03	0.80	0.05	0.28	0.42	282
	〉 10	1.11	0.03	0.61	0.08	0.20	0.39	244

Table 4 Results of regression analysis of chlorophyll-a-nutrients models according to DA/SA

	Category of DA/ST	Regression values: Intercept	Error	Slope	Error	R^2	SD	Number
TP	〈 20	-0.69	0.10	1.10	0.05	0.63	0.33	242
	20~40	-0.25	0.07	0.84	0.04	0.50	0.36	405
	40~60	-0.24	0.11	0.82	0.08	0.38	0.34	179
	〉 60	-0.10	0.08	0.73	0.05	0.42	0.36	254
TN	〈 20	1.09	0.03	1.14	0.11	0.33	0.45	242
	20~40	1.00	0.04	0.61	0.08	0.12	0.48	405
	40~60	0.93	0.03	0.25	0.10	0.04	0.43	179
	〉 60	0.97	0.03	0.33	0.08	0.06	0.46	254

Table 5 Comparison of TP-Chl-a models during growing season

	Season	Intercept	Slope	R^2
Florida model (Brown *et al.*, 2000)	Jul.~Aug.	-0.30	1.03	0.72
Northern model in U.S.A. (Jones & Bachmann, 1976)	Jul.~Aug.	-1.09	1.46	0.90
Korean model (this study)	May.~Jul.	-0.30	0.87	0.51

(May~July) data was somewhat different from those in other studies (Table 5). The slope of our model was less than 1, and the determination coefficient much less than those of other studies. In Korean reservoirs, not only nutrient (phosphorus) but also other factors may affect algal biomass development.

Generally, reservoirs have one or two main inflows. When inflowing river water is warmer than surface water of reservoir, this inflowing water flows to epilimnion, so called as "overflow" (Kimmel and Groeger, 1984). Reservoir system often shows plug flow characteristics where horizontal water movement is distinct. Inflowing water temperature is higher than temperature of reservoir surface water during the growing season, and thus density flow in reservoirs is dominated by overflow.

In such system, actual residence time which stresses algal biomass development directly differs with theological residence time. Actual residence time is shorter than theological residence time, but actual residence time in reservoirs having shallow and large surface area may approach actual residence time. In plug flow reservoir system, actual residence time is dependent on surface area rather than storage volume. This may be the reason why regression coefficients did not systemically change with TA/ST, which was correlated with theological residence time, but systemically change with DA/SA, which reflects density flow in Korean reservoirs.

Ⅳ. Conclusions

Our results show that DA/SA ratio appears to be an important factor to affect the development of algal biomass in Korean reservoirs. Considering relatively low determination coefficient of TP-Chl- *a* relationship in comparison with that of natural lakes, not only nutrient (phosphorus) but also other physical factors, such as DA/SA ratio, may affect algal biomass development in Korean reservoirs, where actual residence time is more closely related to reservoir surface area rather than storage volume.

Significant chlorophyll- *a*-TP relationship appeared during May ~ July, and during this period, chlorophyll- *a* demonstrated much stronger relationship with TP than TN. Seasonal algal-nutrient coupling were closely related with N:P ratio in the reservoirs, and it was, in turn, dependent on the monsoon climatic condition (precipitation). Based on the results of regression analysis and high N:P ratio, a major factor limiting algal growth appeared to be phosphorus during May~July in Korean reservoirs. Unlikely TA/ST ratio, DA/SA ratio appeared to influence directly on the nutrient-Chl- *a* relationship in Korean reservoirs, indicating that if storage volume and inflowing water volume were the same, algal biomass could be more developed in reservoirs with large surface area.

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