Korean J. Limnol. 44 (2): 214~225 (2011)

Long-term Seasonal and Interannual Variability of Epilimnetic Nutrients (N, P), Chlorophyll-*a*, and Suspended Solids at the Dam Site of Yongdam Reservoir and Empirical Models

An, Kwang-Guk*

(Department of Biological Sciences, Chungnam National University, Daejeon 305-764, Korea)

The objectives of the study were to evaluate seasonal patterns of epilimnetic water quality, and determine interannual eutrophication patterns at the dam site of Yongdam Reservoir using long-term data during 2002 ~ 2009. Ionic dilutions, based on specific conductivity, occurred in the summer period in response to the intense monsoon rain and inflow, and suspended solid analysis indicated that the reservoir was clear except for the monsoon. Seasonality of nitrogen contents varied depending on the types of nitrogen and responded to ionic dilution; Ammonia-nitrogen (NH_4-N) peaked at dry season but nitrate-nitrogen (NO_3-N) peaked in the monsoon when the ionic dilution occurred. The maxima of NO_3-N seemed to be related with external summer N-loading from the watershed and active nitrogen fixation of bluregreens in the summer. NO_3-N was major determinant ($>50\%$) of the total nitrogen pool and relative proportion of NH_4-N was minor. Long-term annual NO_3-N and TDN showed continuous increasing trends from 2004 to 2009, whereas TP and TDP showed decreasing trends along with chlorophyll-*a* (CHL) values. Empirical model analysis of log-transformed nutrients and N : P ratios on the CHL showed that the reservoir CHL had a stronger linear function with TP ($R^2=0.89, p<0.001$) than TN ($R^2=0.35, p=0.120$). Overall results suggest that eutrophication progress, based on TP and CHL, is slow down over the study period and this was mainly due to reduced phosphorus, which is considered as primary nutrient by the empirical model.

Key words : Yongdam dam, nitrogen, phosphorus, chlorophyll, seasonality, reservoir

INTRODUCTION

Yongdam Reservoir (YR) is a multi-purpose dam, which started to construct in 1990 and completed in October 2001. This dam is located in the upstream region of Geum-River and is the 5th largest in Korea, based on the water storing capacity, after Soyang, Chungju, Daechung, and Andong reservoirs in the scale of the volume. The dimension of the dam is 70 m in height, 498 m in length, and 0.815 billion tons in total water storage capacity along with watershed area of 1.164 km^2. This reservoir is located in the upper region of Daechugn Reservoir (DR), and there was a conflict in use of water resources between Jeonbuk Province and Chungnam Province when the construction was going on early stage. Yongdam dam supplies drinking water to Korea's western coast regions of Jonju, Iksan, and Kunsan cities, while Daechung dam supplies drinking water to the mid-regions of metropolitan Daejeon and Chungju cities. Previous studies of two reservoirs (Han and An, 2008) pointed out that the construction of upper dam (YR) influenced water residence time, nutrient loading of nitrogen (N) and phosphorus (P), and suspended solids to the down-reservoir (DR). Thus, algal response or lake primary pro-

---

* Corresponding author: Tel: 042) 821-6408, Fax: 042) 822-9690, E-mail: kgan@cnu.ac.kr

duction at a given ambient nutrients may be changed, resulting in modification of ecological functions in down-reservoir (Han and An, 2008; Lee *et al.*, 2008).

Eutrophication processes of newly constructed reservoirs are primarlily determined by basin morphology and landuse patterns of the watershed. In general, eutrophication is slow in deep lakes and forestry-dominant basin whereas it is rapidly accelerated in shallow lakes and agricultural and urban-dominant basin (Wetzel, 1990). In the aspect of lake morphology and land-use pattern, Yongdam Reservoir is located in the deep mountain valley and surrounded by forests, thus the eutrophication process may be slower, compared to reservoirs located in lower regions near urban and agricultural area. The studies on experimental watershed in Yongdam basin were started in 2001 (KIWE, 1998; KWRC, 2001), and showed that pH in basin soil ranged 6.9 and 7.0 and heavy metal (Cu, As, Cd, Pb, Zn) were really low. Also, land-use pattern in the Yongdam dam basin showed that agricultural land, forestry, and others were composed of 14%, 79%, and 7%, respectively (KIWE, 1998), indicating potential low inputs of nutrients from the watershed as the predominance of forestry.

Previous researches conducted in the watershed and in-lake of Yongdam Reservoir were summerized as follows. Heo *et al.* (2003) evaluated hydrological effects of water and nutrient loading to the reservoir from non-point sources, and found that total phosphorus, chemical oxygen demand (COD), and suspended solids (SS) had linear functional relations with stream inflow, but not in total nitrogen. Heo *et al.* (2006) studied limnological characteristics of Youngam Reservoir including physical (flow and mixing regime), chemical, and phytoplankton compositions, and found that the reservoir is a meso-to-eutrophic condition and chlorophyll-*a* as a measure of lake productivity had significant correlations with TP and water temperature. One year later, Heo *et al.* (2007) reported loading of total phosphorus and suspended solids in the same reservoir and estimated TP and SS loading using stream discharge volume. Recent study of Yongdam Reservoir (Kang *et al.*, 2007) tested streamflow change scenarios using G-RiBSS (Geum River Basin Systems Simulator) model to assess the sensitivity of the current river basin system to possible climate change. Yi *et al.* (2008) conducted modeling study of turbid water in Yungdam Reservoir using a linkage of HSPF and CE-QUAL-W2 and found that water quality model of the reservoir matched well with filed measurements of turbidity, water temperature and water balance. In addition, previous study of Kim *et al.* (1997) showed some influences of down-stream by construction of Yongdam Dam using index of biological integrity model, necropsy-based health assessment model and qualitative habitat evaluation index models. This study showed that flow regime and water quality of outflow water at the Yongdam dam directly influenced the downstream fish and trophic conditions (Kim *et al.*, 1997) as shown in serial discontinuity impoundment researches in other countries (Stanford *et al.*, 1988).

The previous studies indicated that the reservoir ecosystems may be change dynamically by internal factors such as availability of nitrogen and phosphorus, mixing regime, and algal response (Wetzel, 1990; An and Park, 2002; Lee *et al.*, 2008), and also external factors such as external loading of nutrients from the watershed and global climate change within the watershed (Heo *et al.*, 2003; Kang *et al.*, 2007). In spite of these studies, little is known about long-term seasonal and interannual patterns of water quality in major key limnological parameters. Also, there is no direct study how the lake productivity is regulated and what element or factor is primary source controlling the lake eutrophication. The objectives of the study were to evaluate seasonal patterns of key water quality parameters, and determine interannual eutrophication patterns using long-term data during 2002~2009. Also, Empirical models of log-transformed nutrients (TN, TP, TDP) and nutrient ratios (N : P) on chlorophyll-*a* (CHL) were described using linear regression equations in this study. This study may provide some clues and tips for long-term and seasonal efficient reservoir managements and protections in the watershed.

MATERIALS AND METHODS

Surface water at the dam site is clear (maximum transparency of 6.8 m) according to previous research of Heo *et al.* (2006) and is known as a mesotrophic-eutrophic condition depending on the season. This sam-pling site is mainly surrounded by forestry (79%) and partially influenced by agricultural land-use (14%) along with low population density within the watershed. Within the watershed with various land-use pattern, Yongdam Reservoir was constructed in October 2001. Surface water sample data collected once per month from the dam site of Yongdam Reservoir (Samrock-ri, Ancheon-meyon, Jinahn-gun, Junbuk Province) were used for the analysis and were collected as a part of a nationwide lake water quality survey by the Korean Ministry of the Environment during 1992~2009.

Several chemical parameters were analyzed the approach of Water Quality Standard Process Test, Korea (MEK, 2001). Specific conductivity at 25°C was measured in the field using conductivity meter. Water samples such as BOD, NO_3-N, and PO_4-P were measured within 48 hours after the sampling, and TN, TP, NH_4-N samples were preserved for the analysis under the condition of pH=2 using sulfuric acid (H_2SO_4). Nutrients were analyzed by standard methods of Water Quality Standard Process Test, Korea (MEK, 2001). Total phosphorus (TP) was determined using the unfiltered water digested by ascorbic acid method after persulfate oxidation and phosphate-phosphorus (PO_4-P) were analyzed without digestion using filtered water by ascorbic acid method. Total dissolved phosphorus (TDP) was determined by ascorbic acid method through the digestion of filtered water. Ammonia nitrogen (NH_4-N) was measured at 630 nm following the phenate method after filtering the water through 0.45 μm GF/C filters, and nitratenitrogen (NO_3-N) was measured by ion chromatography method after filtering the water. Dissolved inorganic nitrogen (DIN) was calculated as the sum of NH_4-N and NO_3-N. Total nitrogen (TN) was measured by UV spectrophotometric method after a potassium sulfate digestion. Total suspended solids (TSS) were determined after drying at 105°C for 1 hour (APHA, 1985). Chlorophyll-*a* (CHL) concentration was measured by Lorenzen method using spectrophotometer after extraction in acetone. Nutrient analyses were performed in triplicate; suspended solids and CHL concentrations were measured in duplicate.

RESULTS AND DISCUSSION

Monthly conductivity, corrected at 25°C, was largely varied with season in response to the monthly precipitation. The mean was 84 $\mu S\ cm^{-1}$ and ranged between 44 and 134 $\mu S\ cm^{-1}$ (Fig. 1). Maximum values in each month started to increase from January and then peaked at 134 $\mu S\ cm^{-1}$ during dry season of April ~ May when the rainfall is reduced. After the period, maximum conductivity values declined over the period of July ~ December, indicating an ionic dilution of lake water by summer rainwater and inflow from the watershed. In the mean time, monthly minimum conductivity values continued to increase from January (44 $\mu S\ cm^{-1}$) to July (68 $\mu S\ cm^{-1}$) and then declined by October (Fig. 1). Such monthly pattern in the seasonal maximum values was directly regulated by the rainfall distribution (An, 2000b; An, 2001). Such ionic dilution effect was similar to previous other reservoir study (An, 2001), but the magnitude of the variability was lower in this system, suggesting that the system experiences less changes of the lentic ecosystems in terms of water quality or more physically stable conditions seasonally.

Total suspended solids (TSS) varied little all months except for monsoon period of July ~ August when the values increased up to 25 ~ 48 mg L^{-1} (Fig. 1). About 97% of total TSS observations were < 10 mg L^{-1} (Fig. 1), indicating high water clarity in the reservoir. High solid loading during the runoff period was probably attributed to a combined effect of inputs of inorganic solids from the watershed and organic matter of algal particles within the watershed (An, 2000b; An and Park, 2006). Such phenomenon was well known in monsoon region (An and Park, 2003) and non-monsoon temperate lakes (Wetzel, 1990). The studies of Daechung Reservoir, which is located in the same watershed with Yongdam Reservoir, supported the potential influence of inorganic solids to the total solids. According to references of An (2000a) and An and Park (2003), the proportion of non-volatile suspended solids during summer monsoon were more than 10 times than the organic solids in this watersheds. Even if we did not measure the inorganic solid contents, such turbid mineral water with inorganic solids (Heuktangmul in Korean) was observed in Yeongdam Reservoir during short high-flow period, suggesting an indirect dominance of inorganic solids to total solids during the monsoon.

Seasonality of monthly nitrogen contents in the surface water varied depending on the types of nitrogen (Fig. 1). Concentrations of ammonia-nitrogen (NH_4-N) peaked at April ~ May (0.10 ~ 0.15 mg L^{-1}) when inflow and rainfall were minimum, and then as the monsoon rainfall increased, maximum NH_4-N declined continuously by December. Especially, maximum NH_4-N values decreased abruptly during June ~ August. This result indicates that ammonia nitrogen probably decreased by the rainfall and river inflow along with ionic dilutions (An, 2000a, b), as shown in conductivity values during the summer. Contents of nitrate-nitrogen (NO_3-N), however, peaked (1.701 ~ 1.733 mg L^{-1}) in the flooding monsoon season of June ~ August (Fig. 2), and then declined continuously by December as inflow and rainfall decreased (Fig. 1; Fig. 2). Nitrate-nitrogen maxima in the summer may due to external monsoon loading from point-source and non-point sources within the watershed (An, 2000a) and also may be associated with nitrate-N increases by active nitrogen fixation of bluregreen algae (*i.e.*, *Anabaena* sp.; An, 2000a; Heo *et al.*, 2006) in the summer when temperature is

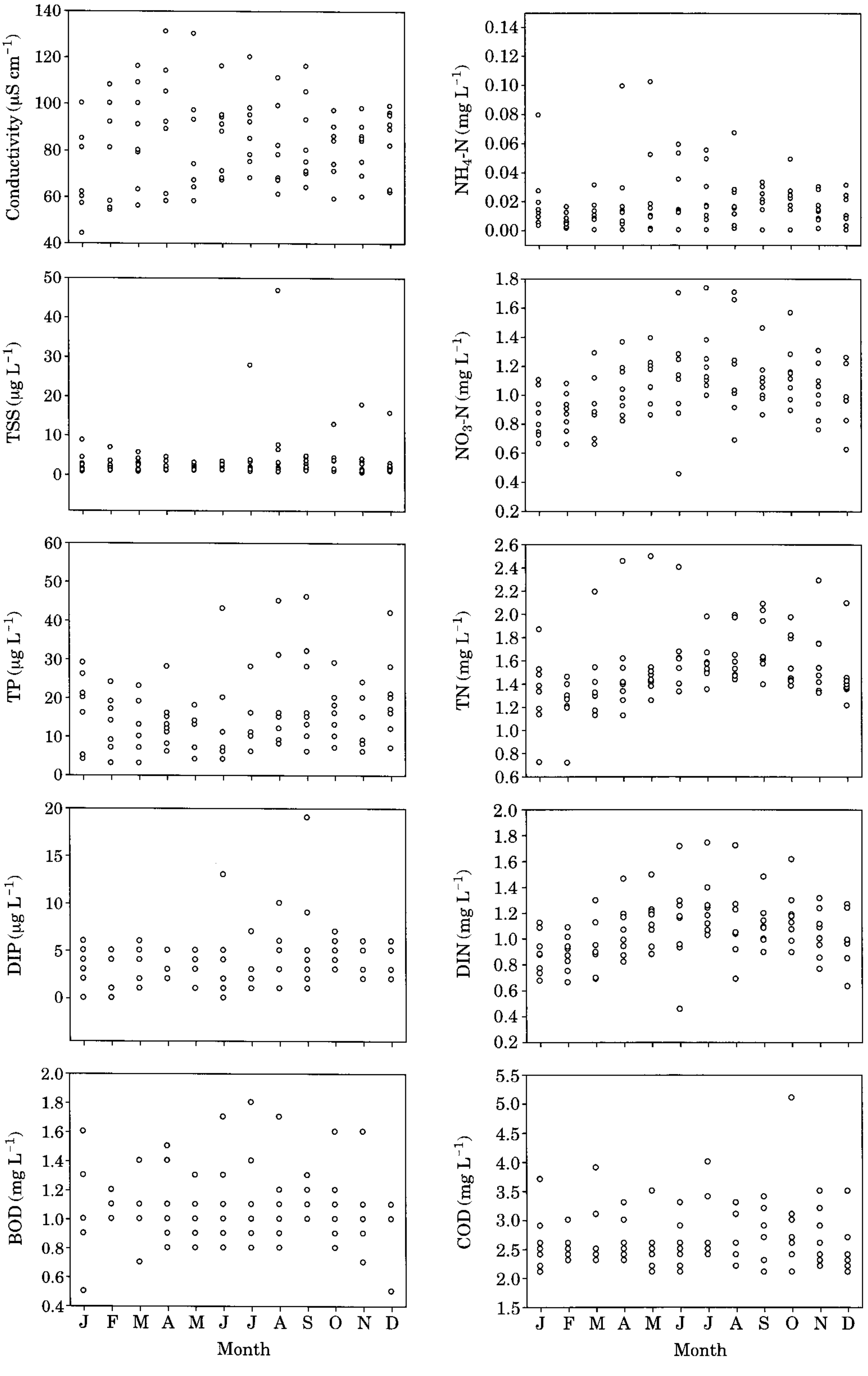

Fig. 1. Monthly mean values of specific conductivity (at 25°C), ammonia-nitrogen (NH_4-N), total suspended solids (TSS), nitrate-nitrogen (NO_3-N), total phosphorus (TP), dissolved inorganic phosphorus (DIP as PO_4-P), total nitrogen (TN), dissolved inorganic nitrogen (DIN), biological oxygen demand (BOD), and chemical oxygen demand (COD) at the dam site during the study period. Top and bottom values in each month indicate maximum and minimum of chemical parameters, respectively.

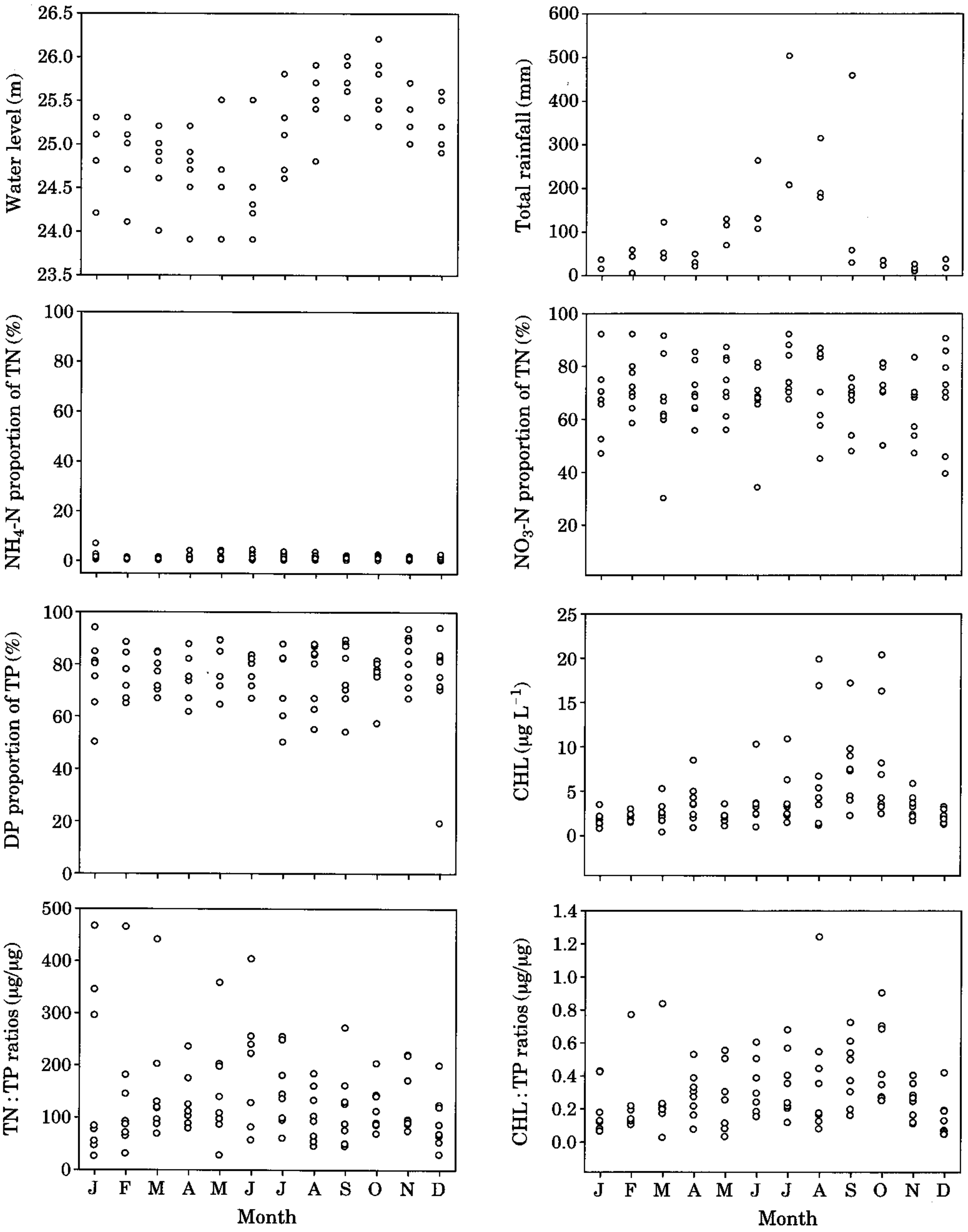

Fig. 2. Monthly mean values of water level, rainfall, the proportions of NH_4-N and NO_3-N to total nitrogen, dissolved phosphorus (DP), the proportion of TP, chlorophyll-*a* (CHL), TN : TP ratios, and the CHL : TP ratios during 2002~2009.

best for the growing.

In the mean time, total pools of N and P behaved differently each other. Monthly total nitrogen (TN) peaked in May and then declined during the monsoon of July~August (Fig. 1). Generally total nitrogen pool is mainly composed of dissolved inorganic nitrogen (DIN); values of DIN were more than 80% of the total nitrogen. DIN : DIP ratios was frequently used for the evaluation according to Downing and McCauley (1992). Mean DIN : DIP ratios calculated in Yongdam Reservoir were 451 (n=97) and ranged between 57.2 and 1740, thus DIN : DIP ratios were 9 times greater than the mass ratios of TN : TP. In this reservoir, reduced TN in the flow-dominant period indicated that particulate N may not contribute largely to the total N pool, as shown in previous researches of the same watershed (An, 2000a) and other Korean watersheds (An and Park, 2003), and some proportions of total nitrogen may be diluted by rainwater as shown in previous reservoir studies (An, 2000b). In contrast, total phosphorus (TP) showed maximum in the high runoff period of August ~ September (Fig. 1), indicating that large parts of in-reservoir phosphorus come from watershed (external loading) and the phosphorus fractions may be more contributed by particulate forms rather than dissolved forms. The relative contributions of dissolved inorganic phosphorus (DIP) to in-reservoir P differed from nitrogen pool. As shown in Fig. 1, DIP values were less than 10 $\mu g\ L^{-1}$ except for three observations, indicating that low contributions to the total phosphorus pool. Monthly maximum TP observed at the dam site was low in July and this was probably due to difference of water residence time between the headwater (riverine zone) and dam site (lacustrine zone) throughout delayed lacustrine-zone arrivals of phosphorus-rich inflow water occurred in July in the headwaters as shown in other monsoon reservoirs (An, 2000b; An and Park, 2002). In fact, as shown in Fig. 2, rainfall peaked in July ~ August when major river inflow occurred, whereas water level (reservoir stage) peaked in September ~ October. This result suggests that spatial distributions of phosphorus may be closely influenced by the river runoff pattern, especially in this monsoon-dominant reservoir.

All observations of biological oxygen demand (BOD) were $<1.9\ mg\ L^{-1}$ (Fig. 1) and monthly mean was 1.06 $mg\ L^{-1}$ (range=0.5 ~ 1.8 $mg\ L^{-1}$), indicating low organic matter pollution and low seasonal variation. This condition was judged as "Ib" by the criteria of Lake/reservoir-water quality by the Ministry of Environment (MEI), Korea. Chemical oxygen demand (COD) ranged between 2.10 and 5.10 $mg\ L^{-1}$ and averaged 2.67 $mg\ L^{-1}$ (Fig. 1). Except for one outlier of $>5\ mg\ L^{-1}$ all monthly maximum and minimum values varied little, indicating that organic matter pollution is less influenced by seasonal flow than nutrients (N, P).

Relative contribution (RC) of nitrogen fractions to total pool differed as shown in Fig. 2. The RC of NH_4-N was $<10\%$ at all season but the RC of NO_3-N was $>50\%$ except for few data (Fig. 2). So, the contribution of ammonia-N to the total was minor in this system. Also, the proportion of monthly minimum NO_3-N in July was $>60\%$ (Fig. 2), which was greater than any other month. The higher dissolved proportion of nitrate-N in the flow season indicates that high total N in the monsoon is not largely influenced by particulate nitrogen fraction which comes from the watershed. Relative proportion of dissolved phosphorus (DP) of total pool was generally 65 ~ 95% except for few data (Fig. 2). When we excluded one outlier in December, minimum proportion of dissolved phosphorus occurred in July when inflow and precipitation dominated the system (Fig. 2), indicating that relative particulate P fraction occurred in July. Therefore, total phosphorus in the flow period was more contributed by particulate fractions than dissolved fraction.

Concentrations of monthly chlorophyll-*a* (CHL) showed large variations with season. The values of CHL ranged between 0.7 and 23.7 $\mu g\ L^{-1}$ and averaged 4.26 $\mu g\ L^{-1}$ (n=96; Fig. 2). Algal maxima in this reservoir occurred in August ~ October when monthly maximum CHL were peaked. Thus, there was no bimodal peak of CHL in Yongdam Reservoir. Our mono-modal pattern differed from the temperate lakes and reservoirs of North America and Europe, as shown by Marshall and Peters (1989). The CHL maxima during three months may be associated with phosphorus (high TP of $>43\ \mu g\ L^{-1}$) rather than nitrogen. In fact, mass ratios of TN : TP averaged 140 (range=25 ~ 466; n=96) and more than 95% of the total N : P observations were >17N : 1P, which is suggested as low limit of phosphorus on phytoplankton growth by Forsberg and Ryding (1980). Most TN : TP observations were >50, indicating a severe phosphorus limitation as shown in Fig. 2. This outcome in the ambient water suggests that phosphorus is potentially a primary limiting nutrient and nitrogen may not be limited as mentioned by An and Park (2002) in the same watershed due to high ambient average NO_3-N of 1.04 $mg\ L^{-1}$ at all seasons. Seasonal patterns of TN, NH_4-N, and NO_3-N did not follow the CHL pattern. Mean ratio of CHL : TP in Yeongdam Reservoir, as an indicator of algal bloom, was 0.311 and showed peak as 1.317 in October when dissolved P and underwater light was highly available along with high water column stability (physically). This result suggests that algal blooms occurred in the fall according to the criteria of An and Park (2002).

Long-term annual water quality of ionic variable, organic matter, and nutrients varied largely depending on the year. Total annual rainfall showed that the maximum occurred in 2007, and minimum occurred in 2008. This rainfall were not accord with annual water level (as MSL), which had maximum in 2003 and minimum in 2008. Annual mean conductivity was the lowest (62 $\mu S\ cm^{-1}$) in 2003 with lowest variability and was highest (117 $\mu S\ cm^{-1}$) in 2009 (Fig. 3). The minimum in 2003 reflected the highest water level, which were directly influenced by upstream runoff. The highest conductivity variation with minimum 45 $\mu S\ cm^{-1}$ and maximum 134 $\mu S\ cm^{-1}$ occurred in 2005. Annual BOD and COD values in two years of 2002 and 2003 were higher than any other years, and after that, mean values were relatively low and constant (BOD=0.90~1.12 mg L^{-1}; COD=2.3~2.6 mg L^{-1}), even if slight variations happened year-to-year (Fig. 3). This result indicates that the annual organic matter input from the watershed is low except for early years after the completion of Yongdam Reservoir in 2001. Also, annual NO_3-N and total dissolved nitrogen (TDN) were higher in two years of 2002 and 2003 than other years, and then the mean values were consistently increased from 2004 to 2009 (Fig. 3), indicating soluble nitrogen increased over the period. In contrast, annual TN did not show increasing trend through 2004~2009 (Fig. 3). In this system, TP showed a consistent declining trend from 25 μg L^{-1} in 2002 to in 6 μg L^{-1} in 2009 and also annual TDP showed a same declining pattern with TP. Annual mean PO_4-P, however, were <6 μg L^{-1} in the all years and the variations were low (Fig. 3).

Annual means of TN : TP mass ratios were >50 in all observed years (Fig. 4), indicating severe phosphorus limitation in the reservoir by the criteria of Wetzel (2001). Also, when nutrient limitation are judged by ambient water, DIN : DIP ratios was frequently used for the evaluation according to Downing and McCauley (1992). Mean DIN : DIP ratios calculated in Yongdam Reservoir were 451 (n=97) and ranged between 57.2 and 1740, thus DIN : DIP ratios were 9 times greater than the mass ratios of TN : TP. This outcome suggests that nutrient limitation, based on the dissolved N : P ratios, were even much more severe than that, based on TN : TP ratios. Both results of soluble ratios of DIN : DIP and total ratios of TN : TP support the phosphorus limitation for chlorophyll-*a*. Previous criteria on dissolved N : P ratios, based on the criteria of Downing and McCauley (1992) supported the evidence of P-limitation in Yongdam Reservoir. Annual N : P ratios showed increasing trend over the study years with higher values of >200 in two years of 2008 and 2009 than other years. The trend of N : P ratios were opposite with annual TP and TDP (Fig. 4), but did not match with TN (Downing and McCauley, 1992). This result suggests that N : P ratios are directly regulated by phosphorus rather than nitrogen (An and Park, 2002). So, Yongdam Reservoir is a typical phosphorus limiting system and the N : P ratios are a function of P-loading, not by N due to consistent high ambient N with regardless of the year sampled. Thus, magnitude of phosphorus limitation on phytoplankton growth increased from 2002 to 2009.

Relative proportion of annual dissolved phosphorus declined slightly over the periods from 2002 to 2009, while the proportion of DN decreased from 2002 to 2005, and then increased again (Fig. 4). Annual mean CHL values were <7 μg L^{-1} in all observed years (Fig. 4), indicating a mesotrophy by the criteria of Forsberg and Ryding (1980), and were higher in two years of 2002 and 2003 than other years. Thus, eutrophication process, based on CHL-*a*, did not show in the reservoir, but maximum values of CHL (as outliers) were >15 μg L^{-1} in 2002, 2005, and 2006 (Fig. 4), indicating a slight algal bloom by the criteria of Wetzel (1990). Also annual mean CHL : TP varied little, indicating a slight change in the algal response at a given phosphorus.

Various empirical models on interrelations of annual chlorophyll-*a* (CHL), nutrients (TN, TP, TDP), TSS, ratios of TN : TP, and COD were analyzed as shown in Fig. 5. Linear regression analysis showed that concentrations of annual CHL were directly regulated by phosphorus (Wetzel, 2001) rather than nitrogen, COD, or suspended solids. As shown in Fig. 5, Log_{10} (CHL) had a strong positive linear functions (R^2=0.89, $p<0.001$) with Log_{10} (TP), indicating that the variation of TP accounted for 89% of the CHL variation. Similar regression coefficient (R^2=0.35, $p<0.001$) is shown in log-transformed annual CHL-TDP equation (Fig. 5). Also, log-transformed annual CHL had an inverse relations ($p<0.05$, R^2=0.67) with mass ratios of annual TN : TP, and the equation was Log_{10} (CHL)=2.507 −0.910 Log_{10} (TN : TP), indicating that annual CHL concentrations decrease with higher N : P ratios. Thus, greater N:P ratios decreased phytoplankton production according to Downing *et al.* (1992). In the mean time, the annual variation of COD, which was reported as close relations with chlorophyll in Korean reservoir ecosystem (Kim *et al.*, 1995), accounted for (p=0.19, F=2.18, R^2=0.267) only 26.7% for the CHL variation as shown in equation of Log_{10} (CHL)=−4.339+1.630 Log_{10} (COD). Kim *et al.* (1995) demonstrated that variation of COD was accounted up to 50% of the chlorophyll-*a*, indicating a high relation between the two variables. The relation of CHL-COD in Yongdam Reservoir, however, was not statistically significant (Fig. 5), indicating that major products of COD may not be originated from refractive chlorophyll or algal particles. In contrast, TN had no significant statistical relations (R^2=0.35, p=0.120) with long-transformed CHL and at the mid-level (0.4) of log-transformed TN the variation was largest in the analysis (Fig. 5), indicating no relation of nitrogen (N) on CHL. This was may be enough nitrogen contents in the reservoir regardless of seasons and year in the reservoir system.

Overall, this research suggests that chlorophyll is primarily regulated by phosphorus rather than nitro-

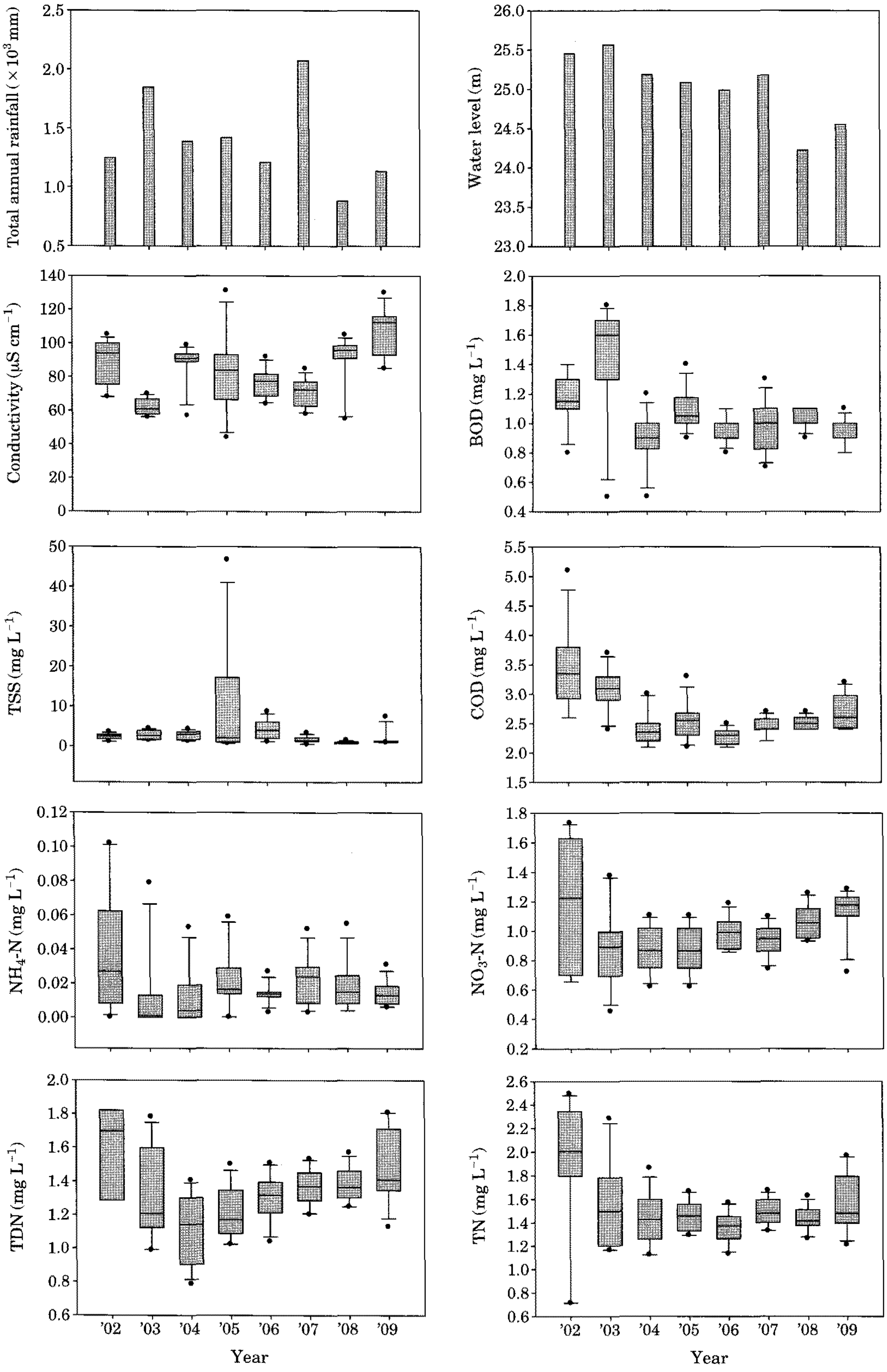

Fig. 3. Annual means of total annual rainfall, water level (as mean sea level, MSL), specific conductivity, BOD, TSS, COD, and various forms of nitrogens (NH_4-N, NO_3-N, TDN, and TN) during 2002 ~ 2009. The horizontal line in each rectangular box indicates a mean of the year and the dark circle indicates outlier from the data analysis.

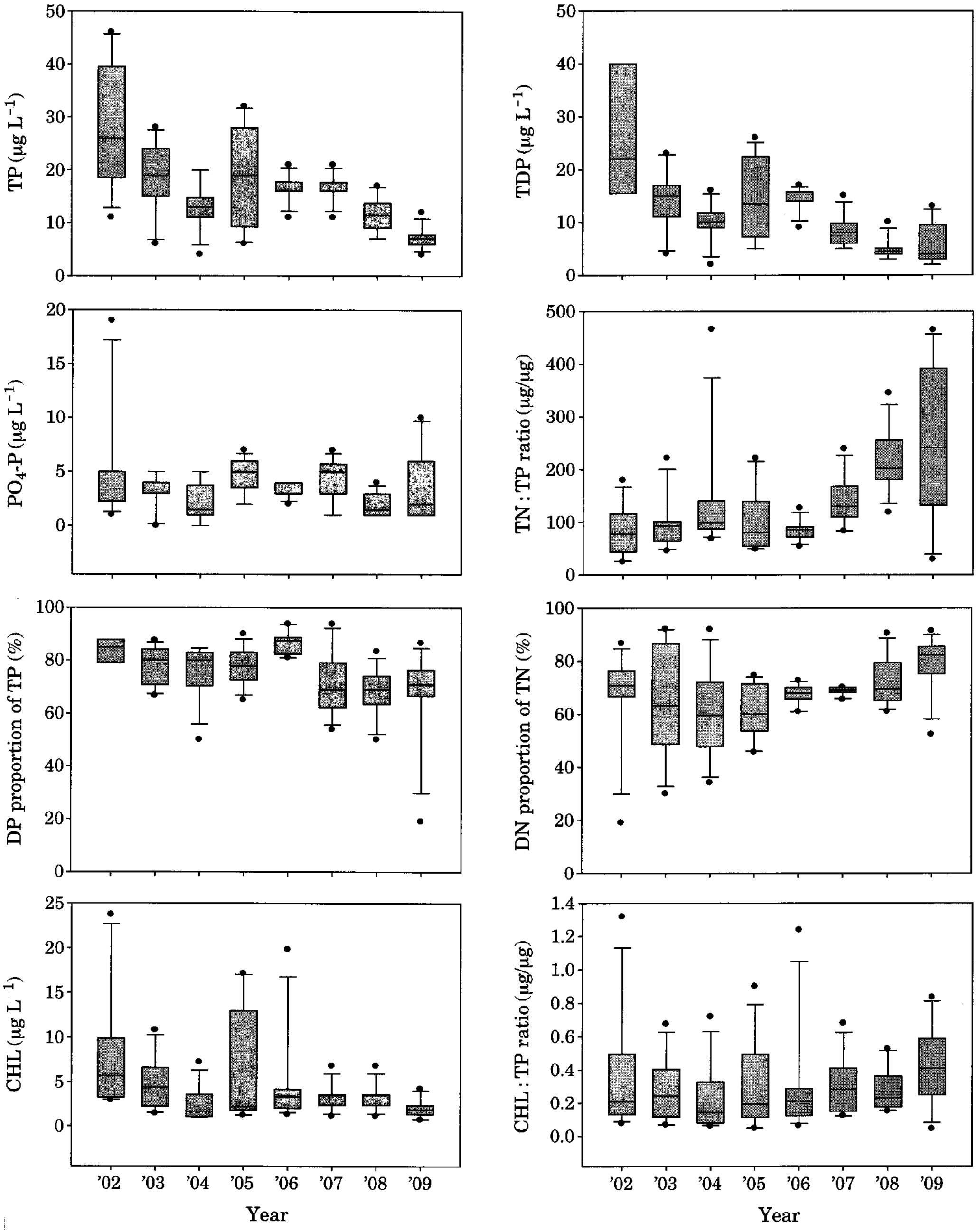

Fig. 4. Annual means of various phosphorus forms (TP, TDP, PO$_4$-P), TN : TP ratios, DP proportions of TP, DN proportions of TN, chlorophyll-*a* (CHL), and CHL : TP ratios. The box plot analysis is ditto with Fig. 3.

gen and N : P ratios also had a close relation with CHL as shown in other temperate lake ecosystems (Downing *et al.*, 1992; Wetzel, 2001). Non-algal particles also partially influenced light attenuation in the water column. This phenomenon is explained by simple calculation of Carson's Trophic State Index (TSI) in Yongdam Reservoir; Values of TSI (CHL)-TSI (TP) were less than zero, suggesting a partial light limitation by inorganic particles according to the approaches of Carlson (1991) and Havens (2000). The data with below zero occurred in the intense monsoon period, indicating that sporadic high mineral turbidity is caused from the monsoon runoff in the watershed. Similar trophic state deviation effects of inorganic solids were found in Daechung Reservoir (An and Park, 2003), which is located in the same watershed with Yongdam Reser-

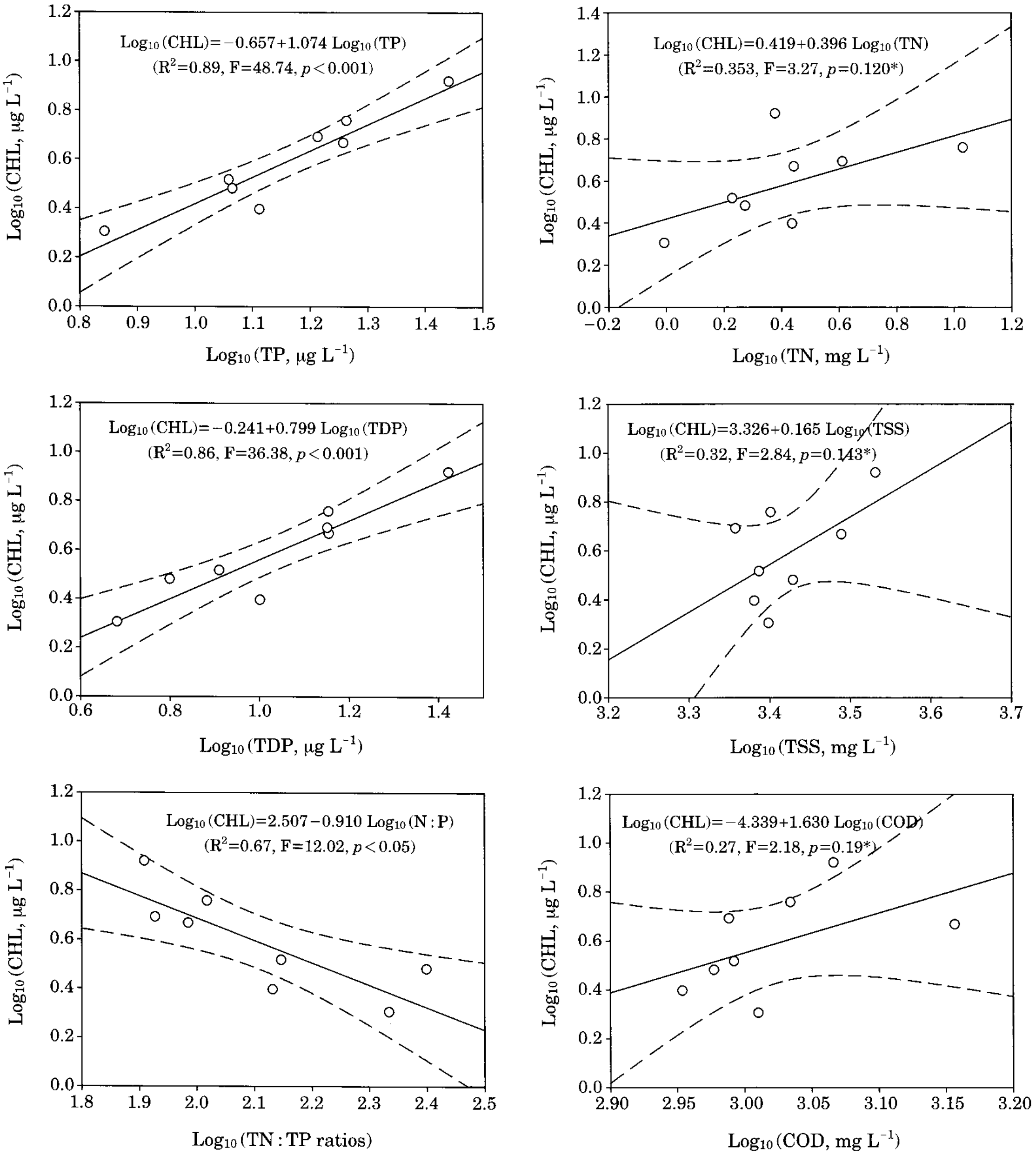

Fig. 5. Empirical models of log-transformed TP-CHL, TN-CHL, TDP-CHL, TSS-CHL, TN : TP-CHL, and COD-CHL relations. The models were expressed as simple linear equations and the data were $\log_{10}$-transfromed for the statistical normality. Asterisk in the *p*-value indicate no statistical significance.

voir. Also, values of TSI (CHL)-TSI (SD) were greater than zero, suggesting that zooplankton grazing on chlorophyll-*a* occurred in the system. It is evident that phosphorus is the key nutrient regulating chlorophyll-*a*, but also partially inorganic particles and zooplankton grazing were factors influencing chlorophyll-*a* concentration. In Yongdam Reservoir, nitrogen contents were rich all the year round, in spite of some seasonal and interannual variation. This outcome is consistent with the seasonality of TP-CHL shown in other research of An and Park (2002) in the same watershed. The response of CHL to phosphorus contents in Yongdam Reservoir (YR) are differed from previous TP-CHL empirical model of An and Park (2002) in Daechung Reservoir (DR) where were shown quadratic asymptote pattern of CHL on high TP. This result indicates that the trophic condition is lower in the Yongdam Reservoir than Daechung Reservoir. Thus, maximum TP and CHL levels in the Yongdam Reservoir were lower than the Daechung Reservoir. If the trophic levels increase in the Yongdam Reservoir, the pattern of CHL-TP model may follow the empirical patterns of Daechung Reservoir. These outcomes suggest that external phosphorus loading from the watershed should be reduced for maintaining the reservoir water and seasonal nutrient management is so important because phosphorus is mainly loaded in summer season.

ACKNOWLEDGEMENTS

This research was supported by 2011' Korea Long-Term Ecological Research (KLTER) of the Ministry of Environment, Korea.

REFERENCES

An, K.G. 2000a. An influence of point source and flow events on inorganic nitrogen fractions in a large artificial reservoir. *Korean Journal of Limnology* **33**: 350-357.

An, K.G. 2000b. The impact of monsoon on seasonal variability of basin morphology and hydrology. *Korean Journal of Limnology* **33**: 342-349.

An, K.G. 2001. Hydrological significance on interannual variability of cations, anions, and conductivity in a large reservoir ecosystem. *Korean Journal of Limnology* **34**: 1-8.

An, K.G. and S.S. Park. 2002. Indirect influence of the summer monsoon on chlorophyll-total phosphorus models in reservoirs: A case study. *Ecological Modelling* **152**: 191-203.

An, K.G. and S.S. Park. 2003. Influence of seasonal monsoon on the trophic state deviation in an Asian reservoir. *Water, Air, and Soil Pollution* **145**: 267-287.

APHA. 1985. Standard methods for the examination of water and waste water (16th ed). American Public Health Association, New York. pp. 874-1133.

Carlson, R.E. 1991. Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs, Enhancing the States's Lake Management Programs, pp. 59-71.

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

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

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

Havens, K.E. 2000. Using Trophic State Index (TSI) values to draw inferences regarding phytoplankton limiting factors and seston composition from routine water quality monitoring data. *Korean Journal of Limnology* **33**: 187-196.

Heo, J., Y.S. Kim, Y.H. Park and T.G. Kim. 2003. Quantification of non-point source materials of Yongdam Reservoir using non-point source model (AnnAGNPS). *Kor. Soc. of Enviro. Eng.* Spring meeting (1-3 May). pp. 681-684.

Heo, W., S. Kwon, Y. Kim, W. Yih and B. Kim. 2005. Phosphorus and suspended solid loading in Lake Yongdam. *Korean Journal of Limnology* **38**(3): 322-333.

Heo, W., S. Kwon, Y. Kim, W. Yhi, B. Lim and B. Kim. 2006. Spatial and temporal variations of environmental factors and phytoplankton community. *Korean Journal of Limnology* **39**(3): 366-377.

Jang, J.H., C.G. Yoon, K.W. Jung and J.H. Jeon. 2006. Pollutant loading estimate from Yongdam watershed using BASINS/HSPF. *Korean Journal of Limnology* **39**(2): 187-197.

Kang, B., S.-J. Lee, D.-H. Kang and Y.-O. Kim. 2007. A flood risk projection for Yongdam dam against future climate change. *Journal of Hydro-environment Research* **1**(2): 118-125.

Kim, B.C., K.S. Hwang, D.S. Kim and K.S. Choi. 1995. Organic matter production of phytoplankton in Yeongsan Lake. *Korean Journal of Limnology* **28**(4): 514.

Kim, J.H., J.W. Seo, Y.E. Na and K.G. An. 2007. Ecological health assessments on turbidwater in the downstream after a construction of Yongdam dam. *Korean Journal of Limnology* **40**(1): 130-142.

Kimmel, B.L., O.T. Lind and L.J. Paulson. 1990. Reservoir primary production. *In*: Reservoir Limnology-Ecological Perspectives. Wiley Interscience. pp. 133-199.

KIWE (Korea Institute of Water and Environment). 1998. Experimental Watershed in Yongdam Dam Basin (http://www.ydew.or.kr).

KWRC (Korea Water Resource Cooperation). 2001. Hydrological analysis methodology of water resource experimental watershed: case study of Yongdam watershed.

Lee, S.C., J.H. Han and K.G. An. 2008. Functional modifications of Deachung Reservoir eutrophication by upper dam construction. *Korean Journal of Limnology* **41**(3): 348-359.

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.

MEK (Ministry of Environment, Korea). 2001. Water Quality Standard Process Tests. pp. 220.

Stanford, J.A., F.R. Hauer and J.V. Ward. 1988. Serial discontinuity in a large river system. *Internationale Vereinigung fuer Theoretische und Angewandte Limnologie* **23**(2): 1114-1118.

Wetzel, R.G. 1990. Reservoir ecosystems: conclusions and speculations. *In*: Reservoir Limnology: Ecological Perspectives (Thornton, K.W. *et al.*, eds.). John Wiley and Sons, New York.

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems, 3rd Ed. Academic Press, USA. pp. 998.

Yi, H.S., S.A. Jeong, S.Y. Park and Y.S. Lee. 2008. Modeling study of turbid water in the stratified reservoir using linkage of HSPF and CE-QUAL-W2. *Journal of Korean Society of Environmental Engineers* **30**(1): 69-78.

(Manuscript received 11 March 2011,
Revision accepted 9 June 2011)