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Longitudinal and Vertical Variations of Long-term Water Quality along with Annual Patterns in Daecheong Reservoir

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The objectives for this study were to evaluate spatial and temporal characteristics of water quality, based on long-term water quality monitoring data during 1993～2008. We found that physico-chemical and ecological conditions in the Daecheong Reservoir (DR) were modified by the construction of upper dam (i.e., Yongdam Reservoir). total phosphorus (TP), Secchi depth (SD), and chlorophyll-*a* (CHL) in the DR showed significant longitudinal decreases along the headwater-to-the downlake, indicating a large spatial variation, and this gradient was more intensified during the high-flow season (monsoon). Nutrient-rich water containing high nitrogen and phosphorus in the monsoon season (July～August) passed through the reservoir as a density current in the metalimnetic depth, and also high suspended solids increased in the metalimnetic depth, especially during the monsoon. According to the deviation analysis of Trophic State Index (TSI), >50% of TSI (CHL)-TSI (SD) and TSI (CHL)-TSI (TP) values were negatives, so that inorganic suspended solids (non-votatile solids) influenced the underwater light regime against phytoplankton growth. Also, ratios of CHL : TP after the dam construction evidently increased, compared to the values before the upper dam constructions, indicating a greater yield of phytoplankton in the unit phosphorus. Overall data showed that ecological and functional changes in Daecheong Reservoir occurred after the construction of upper dam (Yongdam Reservoir).

Key words: water quality, phosphorus, nitrogen, longitudinal gradient, density current, upper dam

INTRODUCTION

Lentic ecosystems including natural lakes and artificial impoundments have been eutrophied gradually as time goes by and the systems were also altered throughout changes of the structures and functions. In particular, man-made dam reservoirs have close interactions between biological community and artificial environmental changes and its relationship also may affect the nutrient cycling and energy flow in association with abiotic components.

Such changes in the dam reservoirs hardly can figure out with simple phenomena on that but only can define the effects on environmental changes based on long-term ecological researches. In the developed countries such as North America and Europe, long-term ecological researches that study the structural and functional changes of lentic ecosystems were widely applied and well developed in the regional waterbodies (Williams *et al*., 2001; Magnuson *et al*., 2004). However, little is known about long-term ecological researches due to low national investments, and moreover,

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most of the domestic researches have been focused to only water quality or amount of flow more than relations of environmental components so that showed a far difference against international research trends.

Korea was designated to one of water scarce countries by the United Nations (UN) where have used most of water resource through the dam construction. Greater parts of lake or reservoir in other country was naturally formed with its natural characteristics but domestic reservoirs about 18,000 in Korea was mainly originated through artificially constructed except a few natural reservoirs. Artificial reservoir had a significant difference to natural lake for the basin structure and hydrological characteristics so that it showed a different water quality and ecological response. in the reservoir (Ryding and Rast, 1989; Thornton, 1990; Wetzel, 1990). Therefore, it is necessary to develop empirical models through systematic study for artificial reservoir instead applicate conventional research results and models for natural lake.

Eutrophication in reservoirs usually affect to increase organic photosynthesis of algae to degrade water quality through the water resource disturbance for drinking water to also reduce the value for touristic resources (Gray *et al*., 2002). This eutrophication was usually occurred by increasing inorganic nutrients such as nitrogen and phosphorus, limiting factors of algal growth. Generally, phosphorus was the most significant factors in the freshwater but limiting nutrients were showing different in space and time so that more systematic measurement and evaluation technique should be required. Evaluation technique for lake eutrophication was usually applied by secchi depth (SD), algal biomass (individual number or chlorophyll concentration), concentration of nitrogen (N) or phosphorus (P), primary productivity, or dissolved oxygen (DO) but it also have a limitation to evaluate interrelations of eutrophication based on single (multiple) biological or chemical components. Therefore, it is important to evaluate empirically what limiting nutrients are working for the control of algal growth.

Besides, most of precipitation in Korea was mainly focused on summer season, July to August, patterned asian monsoon over 40% of entire precipitation compared to other countries (An, 2000; Jones *et al*., 2009). Summer monsoon could cause sudden changes of water level and amount so that it could also cause negative/positive changes in reservoir waterbody by such hydrological alteration, nutrient concentration variation and inorganic solid dynamics (An and Kim, 2003). Thus, it was reported that water quality characteristics and eutrophication in reservoir were closely related to seasonal precipitation pattern (Park *et al*., 2005).

Great amount of nutrients and organic matters mainly have inflow through summer season could make density current in the water depth, occurring thermal stratification to cause lack of dissolved oxygen, massive increase of phytoplankton and turbid water disturbance in the reservoir. Inflow nutrient, partly different along with seasonal changes and latitude and longitude was proceeded along with vertical stratification structure of in-lake and inflow density and generally, moved as overflow in autumn, winter, and spring and interflow or underflow in summer season (Horne and Goldman, 1994; Kalff, 2002). In addition, if artificial dam was connected in a row, serial discontinuity was occurred between upstream and downstream so that might affect to the characteristics of water quality and hydrology (Ward and Stanford, 1983; Kang and Park, 2002). Dam construction often affect to the natural flow system of reservoir so that may impact to make it ecologically disturbed such as increase of water residential time, change of primary productivity, and reduction of the biodiversity. Thus, study for water quality changes in association with dam construction in upstream region was strongly issued to minimize negative effects from dam construction but the domestic study about this topic was rare.

The purposes of the research was to analyze seasonal and interannual patterns of water quality and the characteristics of vertical and longitudinal gradients along with the determination of the trophic states, based on Trophic State Index (TSI). In addition, to analyze the major key factors among the water quality parameters, we developed empirical models such as the relations of TP-CHL, TN-CHL, SD-CHL, and TP-SD to provide effective data sources for effective water management and watershed protections.

MATERIALS AND METHODS

1. Description of sampling site

Daecheong reservoir is the 3rd largest artificial reservoir in Korea and the first dam constructed in the Geum River watershed. The dam, located on Daejeon city (36°50′N, 127°50′E) composed the reservoir where supply 1.3 billion m^3 of living and industrial water resources to Chungcheongnam and bukdo including Daejeon city and some areas of Cheonrabukdo. The dam height was 72 m and watershed area and water surface area of the reservoir was 4,134 and 72.8 km^2, respectively. with $1,490 \times 10^6$ m^3 total storage showing traditional artificial reservoir characteristics and provide some recreational space near the shore. However, eutrophication was severely spreading out by the inflow of sewage from industrial complex and stock raising with residential wastes nearby the reservoirs in a recent and water quality of reservoir was going to degrading by lake farms operations and fertilizer. In addition, Yongdam reservoir was constructed on upstream region 192 km ahead of Daecheong reservoir 20 year after Daecheong dam construction to supply water resource in Jeollabukdo area. Because of this dam construction, By Yongdam dam construction, dams were serially located on up and midstream region of the Geum River watershed so that it was reported not only hydrological factors but water quality variation may influenced (Lee *et al*., 2008).

2. Sampling sites and water quality variables

We choose 4 sites representing a longitudinal gradient characteristics and appropriate distance between sites among water quality monitoring sites operating by ministry of environment, Korea (MEK). Details are following.

S1: Deokyuri, Muneuimyeon, Cheongwongun, Chungcheongbukdo
S2: Euseongri, Whoenammyeon, Boeungun, Chungcheongbukdo
S3: Daejeongri, Gunbukmyeon, Okcheongun, Chungcheongbukdo
S4: Janggyeri, Annaemyeon, Okcheongun, Chungcheongbukdo

To analyze physico-chemical water quality for each site, we collected 15 years monthly dataset from 1993 to 2008 as long term water quality data from MEK website (http://water.nier.go.kr) along with trophic states. Water quality parameters used in this study were conductivity (COND), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), total nitrogen (TN), chlrophyll-*a* (CHL), suspended solid (SS), and secchi depth (SD). All parameters from each sampling site were divided to epilimnion, metalimnion, and hypolimnion to define vertical gradient patterns and precipitation data were collected from Daejeon regional meteorological administration.

For the analysis of trophic states in Daecheong reservoir, we applied Trophic State Index (TSI) from TN, TP, CHL, and SD. TN was based on the equation of Kratzer and Brezonik (1981) and TP, CHL, SD were following by Carlson (1977).

$$TSI\,(TN) = 14.43 \times \ln TN\,(mg\ L^{-1}) + 54.45$$
$$TSI\,(TP) = 14.42 \times \ln TP\,(\mu g\ L^{-1}) + 4.15$$
$$TSI\,(CHL) = 9.81 \times \ln CHL\,(\mu g\ L^{-1}) + 30.6$$
$$TSI\,(SD) = -14.41 \times \ln SD\,(m) + 60$$

In addition, to define limiting factor was whether nutrients, or lights, we applied Trophic State Index (TSI) deviation of eutrophication index. Namely, we calculated difference value of TSI (CHL)-TSI (SD) and TSI (CHL)-TSI (TP) and then, comparatively analyzed seasonal characteristics against limiting factors. Deviation analysis of eutrophication index were well known as indirect simple method for limiting factors of algal growth (Havens, 2000).

3. Empirical models using key trophic variables

To analyze relations between N and P concentration and algal productivity, we have developed empirical models of water quality parameters such as TP-CHL, TN-CHL, SD-CHL, and TP-SD to evaluate nutrient condition and estimation. Water quality data were categorized by premonsoon, monsoon, and postmonsoon and transformed in Log10 to assum normal distribution. And, then, we applied Pearson correlation analysis and regression analysis. All statistical analyses were conducted under SPSS (version 12.0, window version). Based on these, we analyzed temporal and spatical change of water quality before and after upper dam construction.

RESULTS AND DISCUSSION

1. Long-term patters of rainfall and inflows and water quality variations

According to the 15 year precipitation analysis

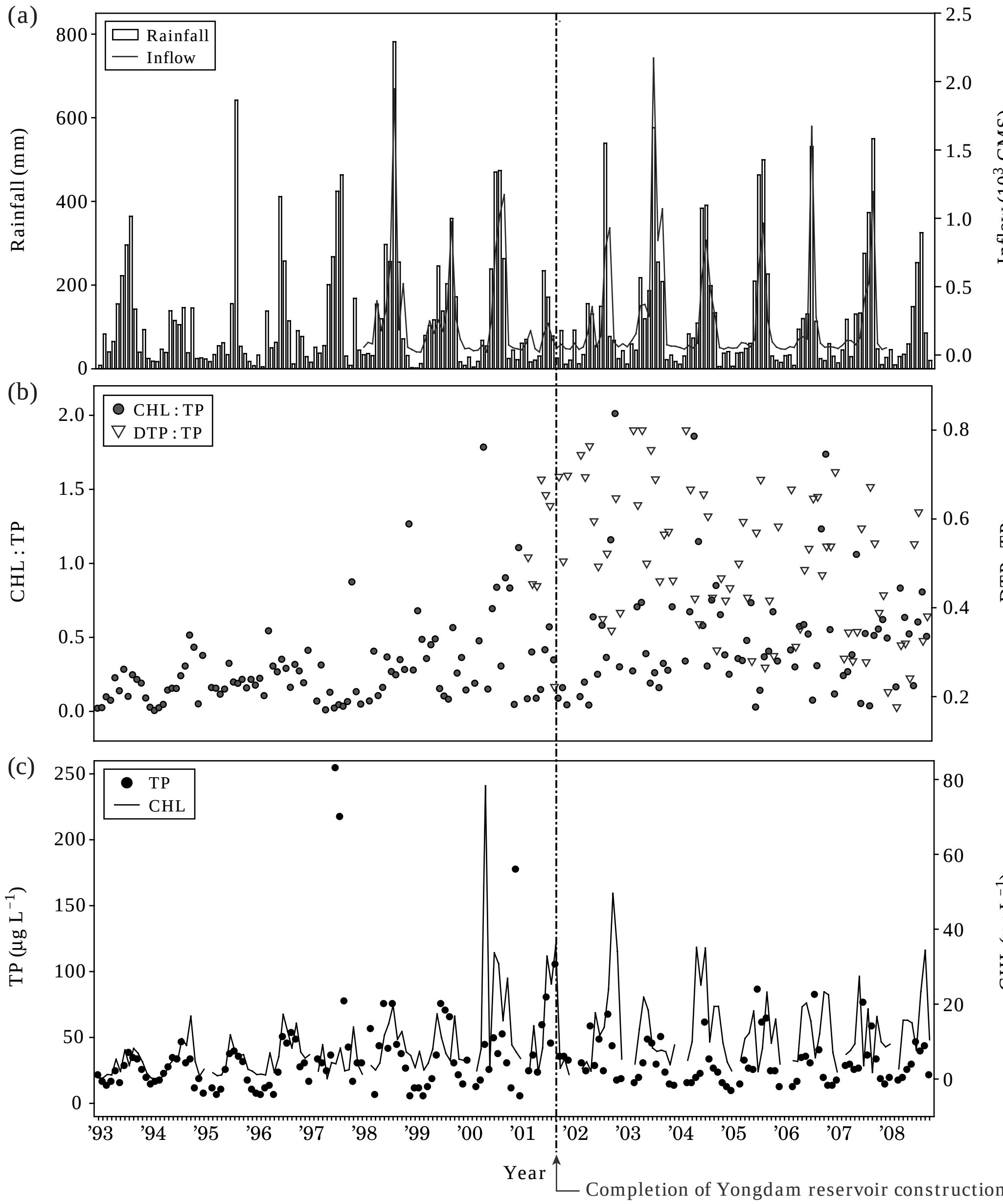

Fig. 1. Long-term interannual patterns of rainfall, inflow, CHL : TP ratios, DTP : TP ratios, TP, and CHL concentrations during 1993～2008.

from 1993 to 2008, annual mean precipitation was 1,431 mm and averaged 982 mm during asian monsoon from June to September showing over 68% of entire precipitation. Among the survey period, it showed over 1,750 mm in 1997, 1998, and 2007 showing higher rainfall intensity. However, it showed 900 mm, low precipitation intensity in 1994 and 2001. Compared to the precipitation amount between intense monsoon year and weak monsoon year, it showed the significantly higher precipitation in monsoon (July～August) than others so that we could figure monsoon precipitation was strongly influencing to the entire precipitation intensity. This result could be corresponding with the previous limnological study (An and Jones, 2002) that Korean precipitation have strong seasonal variation along with east asian monsoon climate region. In addition, from the result of long-term seasonal inflow patterns (Fig. 1a), it strongly correlated between inflow amount and rainfall distribution (R^2=0.690, $p<0.001$, n=120). It means that water residential time was getting shorter by the intense precipitation. Then, it was more inflow and outflow for external suspended solid (SS) so that may influence to the water characteristics such a hydrological water quality and eutrophication.

TP concentration, usually applied for reservoir eutrophication assessment, was averaged 33.6 μg L^{-1}, that assessed eutrophic state by standard of Forsberg and Ryding (1980). Annual TP concentration was varied, ranged from 5 to 254 μg L^{-1}. We assumed that it could be associated with heavy rainfall during summer monsoon period (Fig. 1b). From the result of nutrient inflow analysis along with upper dam construction, average TP was slightly decreased from 35.6 μg L^{-1} to 30.6 μg L^{-1}, before and after dam construction. After the Yongdam dam construction, TP concentrations of all sites during the entire survey period including premonsoon, monsoon, and postmonsoon period, were decreased. Especially, riverine zone, was decreased 20 μg L^{-1} in a maximum (Fig. 1b). In additional, algal productivity was increased by phosphorus. Thus, CHL concentration was usually applied for a representative indicator for eutrophication state in reservoirs. CHL concentration in Daecheong reservoir was also varied seasonally. Although inflow amount of TP was decreased along Yongdam dam construction, mean CHL concentration was increased from 8.1 to 13.1 μg L^{-1} (Fig. 2). Seasonal CHL analysis provided that all CHL in the entire sites were increased during premonsoon and postmonsoon period but decreased average 3.5 μg L^{-1} in all sites during monsoon period. This phenomena was related with runoff of inorganic SS during the monsoon season that could strongly reduce CHL concentration. However, annual mean data could not support this and showed only minor effects on CHL concentration along with inorganic matter. Thus, our result was different from previous report that CHL concentration, was decreased when inflowing TP were reduced (An, 2000). We regarded that this was mainly caused by increase of water residential time in reservoir through Yongdam dam construction, located in upstream region of Daecheong reservoir so that functional system among factors influencing primary productivity in Daecheong reservoir had been changed. According to CHL : TP ratio analysis, it was 0.51 after dam construction approximately over 1.8 fold higher than before

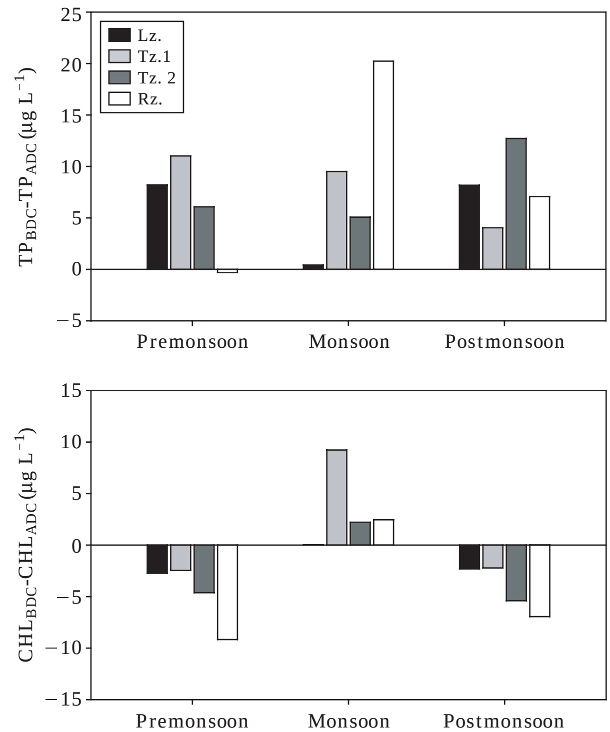

Fig. 2. Longitudinal zonal and seasonal variations of TP and CHL concentrations before Yongdam dam construction (BDC) and after Yongdam dam construction (ADC).

dam construction (0.27) (Fig. 1c). In addition, it was showed mono-modal peak pattern before dam construction but no patterns with increasing value only after the construction. Besides, algal growth and reproduction was only controlled through P existence type and concentration in water so that to expect internal origin organic matter changes scientifically, dissolved P, directly useful to living biota was necessary to study further. Generally, organic matter was inflow to the reservoir as dissolved or particle types. From the result of DTP : TP ratio analysis to configure relationship among those factors, DTP : TP ratio average was 0.5 after Yongdam dam construction. We could not figure out the ratio before dam construction because of no data for DTP but could assume less than 0.5 because DTP was directly or indirectly influencing CHL growth (Fig. 1c).

2. Temporal and zonal variations of water quality

Monthly concentration variations of water qual-

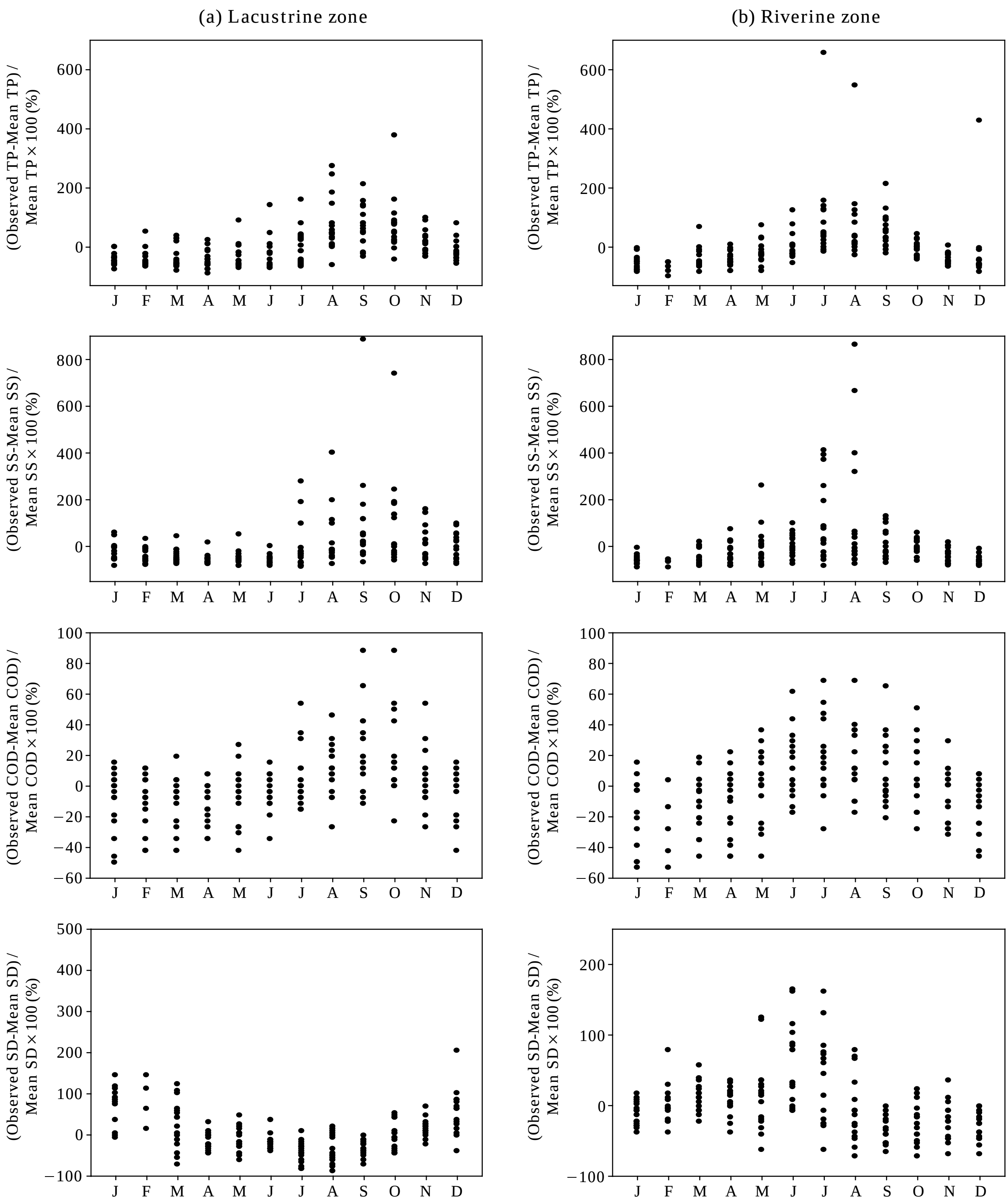

Fig. 3. Analysis of observed parameter against mean value in water quality between lacustrine and riverine zone.

ity along with hydrological changes were applied with ratio of measured value against entire average value (Fig. 3). According to the monthly variation of TP, it showed distinct characteristics of

Table 1. Pattern analysis (Type I ~ Type IV) of Trophic State Index (TSI) deviation along the longitudinal gradients of lacustrine zone (L_z), transition zones (T_{z1}, T_{z2}), and the riverine zone (R_z). The numbers in the table indicate the number of observations in the each section.

Trophic state index (TSI)	L_z	T_{z1}	T_{z2}	R_z	Overall mean
Type I	5 (41.7%)	7 (58.3%)	5 (41.7%)	9 (75.0%)	26 (54.2%)
Type II	3 (25.0%)	1 (8.3%)	3 (25.0%)	1 (8.3%)	8 (16.7%)
Type III	0 (0%)	0 (0%)	3 (25.0%)	2 (16.7%)	5 (10.4%)
Type IV	4 (33.3%)	4 (33.3%)	1 (8.3%)	0 (0.0%)	9 (18.8%)

longitudinal gradient. Riverine zone showed almost 5 fold higher than the least 12.3 μg L^{-1} on February compared to the highest 64.9 μg L^{-1} on July. Whereas, lacustrine zone showed about 3 fold difference between April (11.8 μg L^{-1}) and October (36.9 μg L^{-1}). Riverine zone had showed precipitation effects through nutrient increase in a short terms periods but lacustrine zone had showed interflow current by density flow to less affect to the direct downstream water quality and showed the maximum on October because of water residential time. SS was showed as similar as TP's pattern that gradually increasing in monsoon periods and then, sharply decreased in October. Namely, SS was increased until September through volatile solids increase (i.e. phytoplankton) and non-volatile suspended solids inflow (i.e. silt) from the watersheds during the summer season (An and Jones, 2002) and then, suddenly decreased by the reduction of inorganic particulate matter inflow and temperature drops to decrease algal growth after October. Such inorganic matter increase during monsoon season was corresponding with stream discharge analysis in spring season, strong precipitation period in North America as similar as previous report (Perkins and Jones, 1994). Inorganic SS increase was caused to increase turbidity in reservoir shortly and also increase chemical oxygen demand (COD), represented indicator for organic pollution (Fig. 3). It also might impact to light limitation for several phytoplanktons and periphytons usually have important roles for primary producers.

Besides, regarding COD maximum value was corresponding with intensive precipitation period in riverine and lacustrine zone, allochthonous organic matters were increased by organic matter increase from point and non-point sources inflow from neighbor watershed along with precipitation. Secchi depth (SD) was getting increased from riverine zone (mean: 1.8 m, range: 0.2 ~ 5.6 m) to lacustrine zone (mean: 3.3 m, range: 0.9 ~ 8.6 m) in a different patterns with TP, SS, and COD's (Fig. 3). This result came from the algal growth to inhibit light penetration and light limitation in lacustrine zone. Comparing to precipitation intensity also, SD was getting higher when precipitation was lower and lower in monsoon season. That means inflow increase to reservoir might be affect to decrease SD in monsoon periods.

3. Deviation analysis of Trophic State Index (TSI)

The deviation analysis of Trophic State Index (TSI), based on TP, CHL, and SD data (Carlson, 1977) indicated that inorganic suspended solids influenced the phytoplankton growth during the monsoon period and phosphorus was key factor controlling the algal growth in the reservoir during the major periods. In this study, we analyzed trajectary trophic state index deviation, based on monthly data of TP concentration which parameters for limiting nutrients to algal growth in freshwater, CHL, representative parameter for algal biomass, and SD and then, categorized 4 different types (Table 1) with its longitudinal gradients. For type I, it was a case in TSI (CHL) ≪ TSI (SD) and TSI (CHL) ≪ TSI (TP) so that small size of particles are one of the most component in SS of reservoirs and light limited algae were provided. Type II was in TSI (TP) ≪ TSI (CHL) ≪ TSI (SD) case that might be increasing phosphorus limitation with smaller particle predominance. Type III was TSI (CHL) ≫ TSI (SD) and TSI (CHL) ≫ TSI (TP) values that increasing phosphorus limitation with larger particle predominance. Type IV was case for TSI (TP) ≫ TSI (CHL) ≫ TSI (SD) that larger particle was predominant to scatter light in the water and also zooplankton glazing to be an limiting for phytoplankton growth (Havens, 2000). According to the monthly TSI deviation

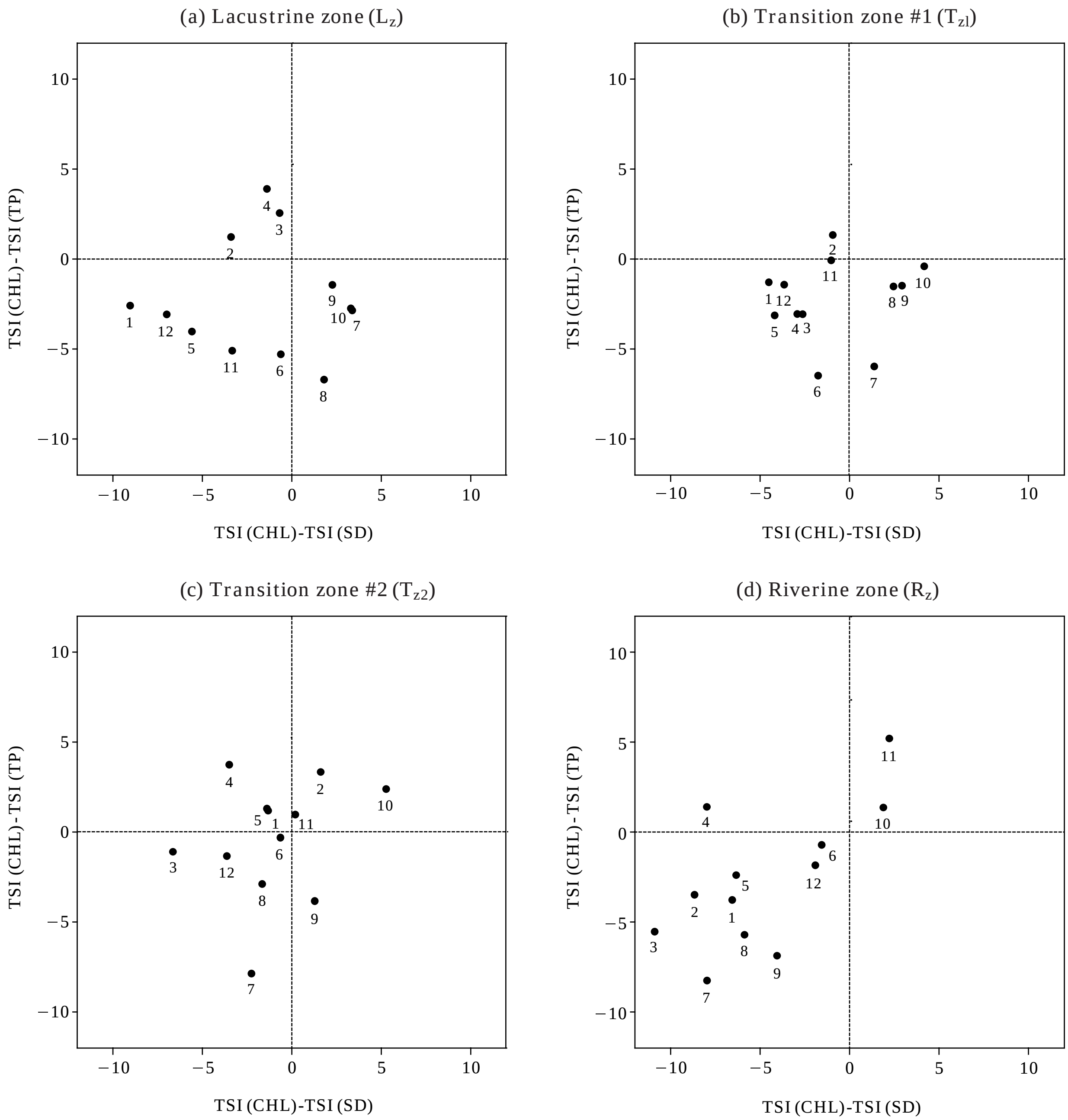

Fig. 4. Monthly trajectory analysis on the deviation of Trophic State Index (TSI) in the various longitudinal zones.

analysis, over 54% of the entire (26 times) were in type I. Namely, light limitation by phytoplankton was distinct during most seasons in Daecheong reservoir. In the riverine zone, TSI (CHL)-TSI (SD) value were ranged from −10.8 to 2.3 and over 83% were shown as negative values (Fig. 4). There was no type 4 in riverine zone but values in monsoon and post monsoon period, July to October were type 4 as going to move lacustrine zone. Thus, phytoplankton growth was mainly controled through light limitation and then, changed to grazing effects of upper predation such as fish and zooplankton along with summer monsoon.

4. Thermal profiles and density current

Though most dam reservoirs in Korea is known to have a slight thermal difference depending on

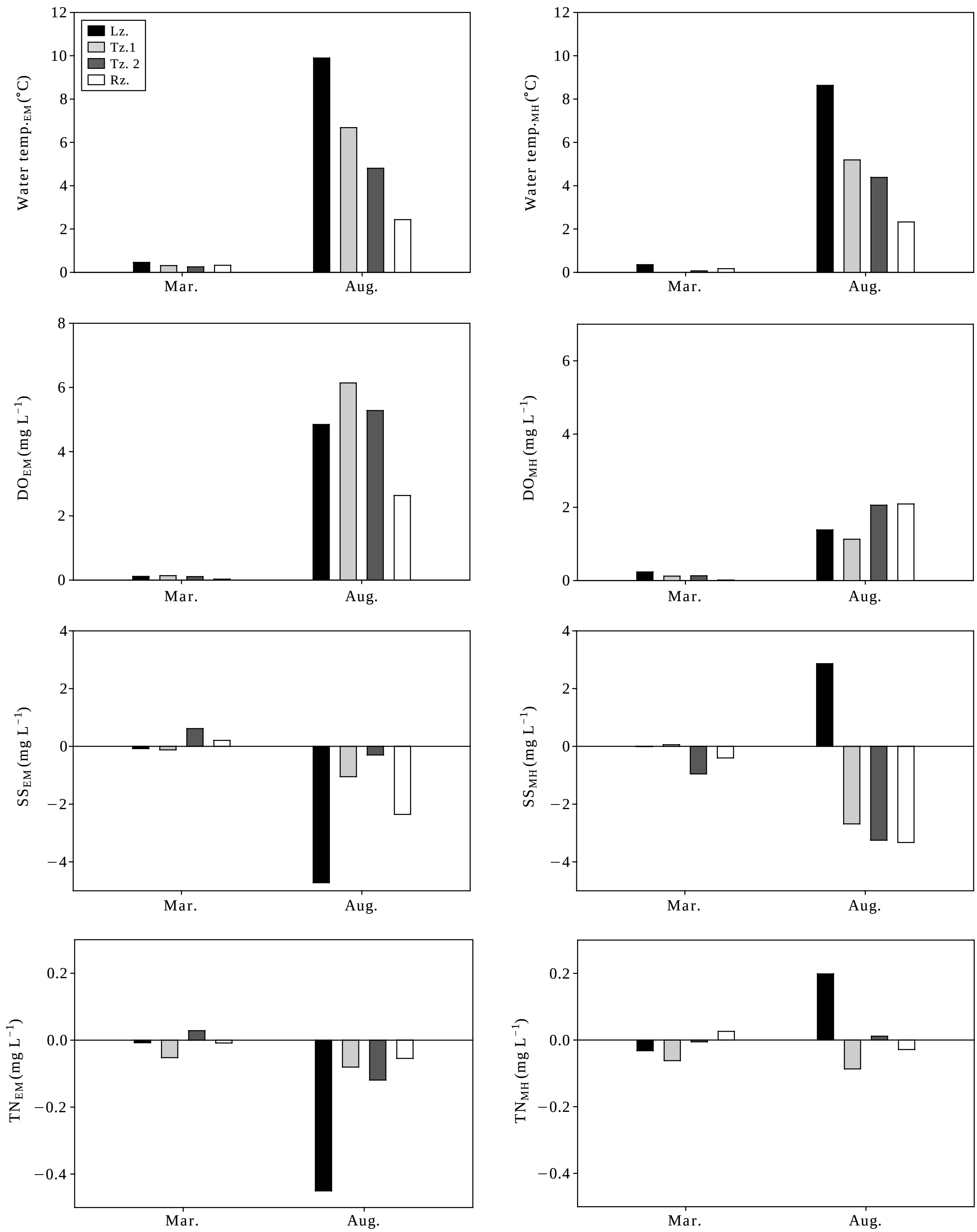

Fig. 5. Vertical variation analysis based on epilimnion, metalimnion, and hypolimnion in water quality parameter (EM= epilimnetic values minus metalimnetic values, MH=metalimnetic values minus hypolimnetic values).

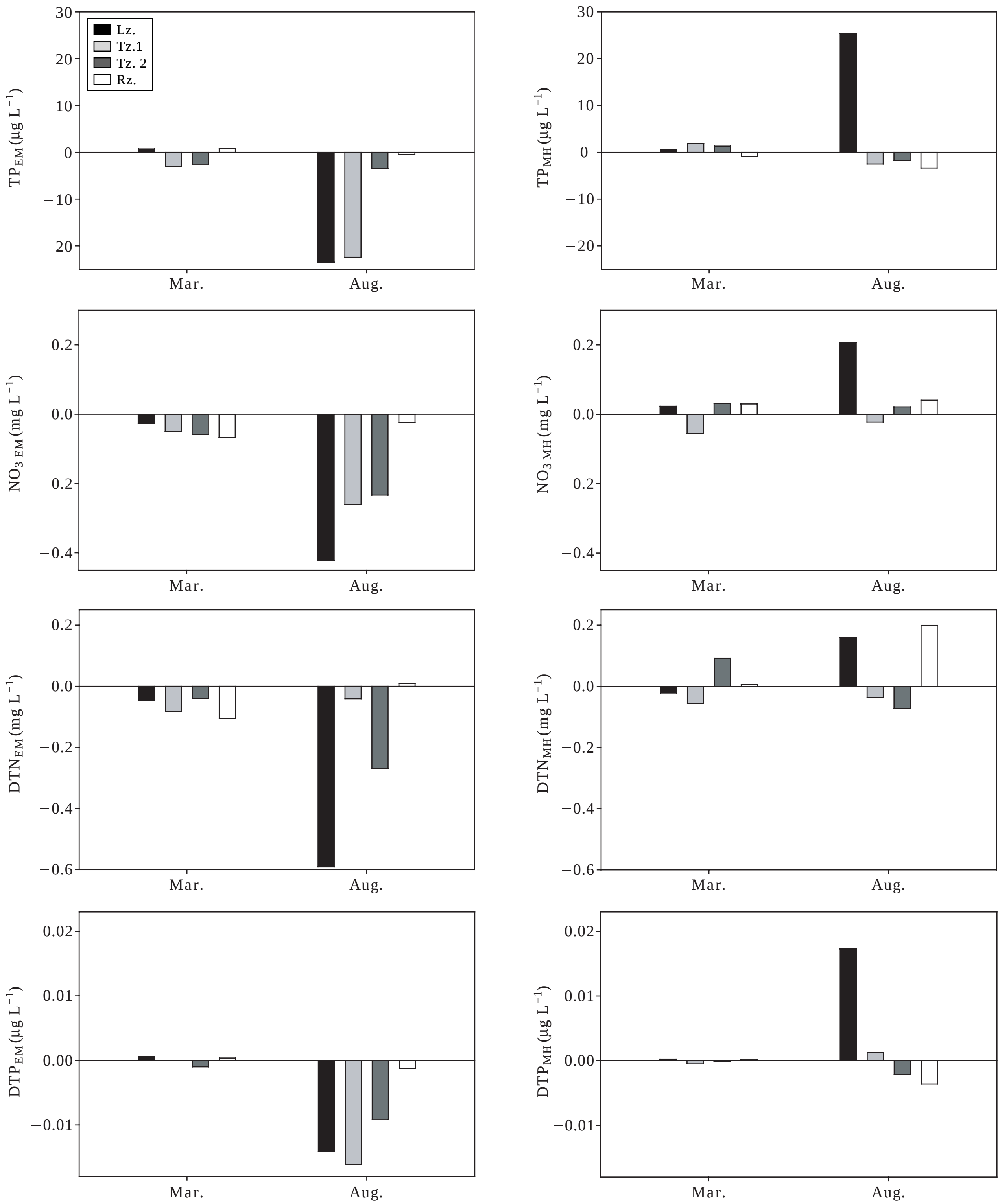

Fig. 5. Continued.

water temperature and geographical location, the reservoir was initially stratificated in April and late June through the temperature increase and showed a distinct stratification between epilimnetic and metalimnetic water column. Then, the thermocline was getting down after the fall and the thermal stratification was disappeared along with entire isothermal water column condition until next January to February. Thus, vertical distribution of temperature was varied the patterns along with formation and disappearance of stratification (Kim *et al*., 2001; park *et al*., 2005). In August with maximum sunshine amount during the entire survey period, there were 9.9 and 8.6°C respectively in epilimnion and metalimnion and metalimnion and hypolimnion region (Fig. 5). However, It was averaged less than 0.3 (range: 0∼0.5°C) in March for these variations to show least temperature changes. Also, it was less effective for stratification as far as dam (Fig. 5). It means that lacustrine zone was relatively wider and deeper to less effect to the sunshine than riverine zone. Thus, thermocline was formated after April to devide epilimnion and hypolimnion and strongly stratificated in summer season. Dissolved oxygen (DO) was one of the fundamental and conventional parameter to evaluated the degree of aquatic breath. This parameter was shown a similar pattern corresponding with temperature stratification in water. Even though it was not showing strong seasonal and regional variation, hypolimnetic oxygen deficit was obvious in hypolimnion during summer season (mean: 3.8 mg L^{-1}, range: 3.4∼4.9 mg L^{-1}).

Stream water inflowing reservoirs have declined to water column with same density and moved horizontally. SS was the highest as 14.9 mg L^{-1} in hypolimnion of riverine zone and moved to hypolimnion of transition zone. It was the highest 6.4 mg L^{-1} in metalimnion of lacustrine zone. Thus, SS was inflowing at metalimnion than epilimnion and hypolimnion than metalimnion but tend to inflow metalimnion as close as the dam. Mean SS difference between metalimnion and hypolimnion was all negative but only positive (2.9 mg L^{-1}) in lacustrine zone (Fig. 5). It was all similar patterns for TN, TP, NO_3, DTN, and DTP with SS (Fig. 5) There were not any vertical variation among all parameters in winter season with lower temperature and all nutrient inflow during monsoon period might be the least effective to epilimnion of lacustrine zone through metalimnion inflow by density flow. Water density in reservoir was usually decided by water temperature or concentrations of dissolved matters but mostly water temperature. Water temperature was closed related with density that interflow was occurring when inflow temperature was lower than epilimnion temperature and higher than hypolimnion temperature that reported most of Korean reservoir was so (Kim *et al*., 2001). Interflow current appeared in monsoon period usually contained organic matters and nutrients and these one could occur oxygen deficiency through sudden assumption and eutrophication. In addition, SS with lower density was not sedimented and reported that moved through density layer to front of the dam (Frink, 1969; Hyne, 1978).

5. Empirical models using key trophic parameters

Generally speaking, eutrophication of Korean reservoirs and lakes were primary occurred through the P limitation stimulating eutrophication by the P concentration instead of N which enriched in waterbody. Also in Daecheong reservoir, P increase was directly influencing primary productivity and impact to increase of CHL concentration. However, after the upper Yongdam dam construction, TP was reduced but CHL concentration increased (Fig. 6). Namely, ecological function have been changed in reservoir. Especially in riverine zone, this phenomena was distinct so that it was appeared the wash out effects for primary producer, algae because of heavy amount of inflow and fast water current and showed worse light condition by increase of inorganic SS. In addition, TN : TP ratio in waterbody could estimate CHL biomass and be useful as indirect estimation indicator how to figure limiting nutrients against

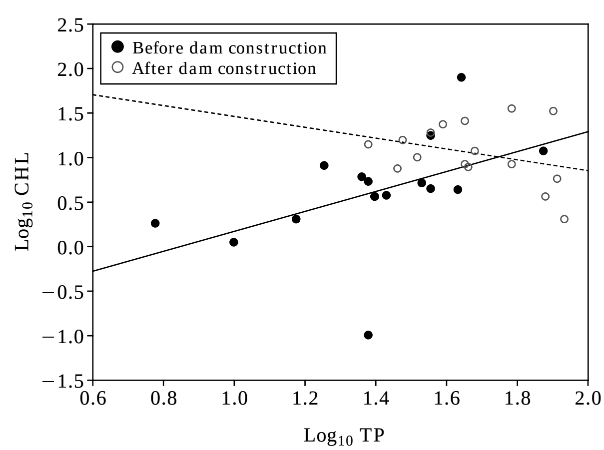

Fig. 6. Empirical model between TP and CHL before and after the Yongdam dam construction.

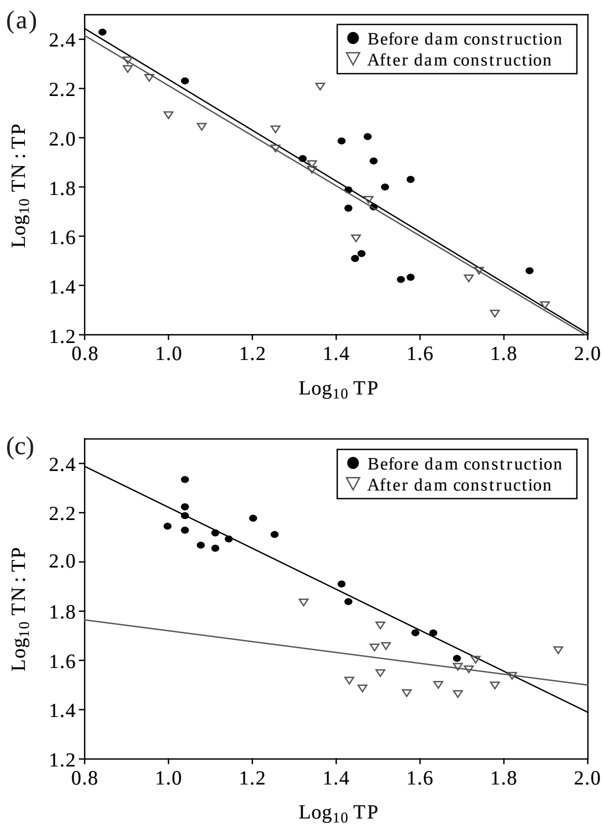

Fig. 7. Empirical models of log-transformed TN : TP ratio and TP before and after the dam construction along the longitudinal zonations (a): lacustrine zone, (b) (c): transition zones (T_{z1}, T_{z2}), and (d): riverine zone.

CHL so that also could estimate reservoir limiting nutrients and eutrophication. According to regression analysis of TN : TP ratio against TP before upper dam construction, R^2 was maxmized 0.88 (slope: -0.83, $p<0.001$, $n=17$) that showed highly correlated in entire sites. After the dam construction, however, R^2 value was ranged 0.01∼0.12 that showed less correlated with order of lacustrine zone, transition zone, and then, riverine zone so that we could confirm again the ecological function have been changed after the dam construction (Fig. 7).

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