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Variations of Limnological Functions in a Man-made Reservoir Ecosystem during High-flow Year vs. Low-flow Year

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We compared spatial and temporal variations of water chemistry between high-flow year (HF_y) and low-flow year (LF_y) in an artificial lentic ecosystem of Daechung Reservoir. The differences in the rainfall distributions explained the variation of the annual inflow and determined flow characteristics and water residence time and modified chemical and biological conditions, based on TP, suspended solids, and chlorophyll-*a*, resulting in changes of ecological functions. The intense rainfall and inflow from the watershed resulted in partial disruption of thermal structure in the metalimnion depth, ionic dilution, high TP, and high suspended solids. This condition produced a reduced chlorophyll-*a* in the headwaters due to low light availability and rapid flushing. In contrast, reduced inflow and low rainfall by drought resulted in strong thermal difference between the epilimnion and hypolimnion, low inorganic solids, high total dissolved solids, and low phosphorus in the ambient water. The riverine conditions dominated the hydrology in the monsoon of HF_y and lacustrine conditions dominated in the HF_y. Overall data suggest that effective managements of the flow from the watershed may have an important role in the eutrophication processes.

Key words : long-term monitoring, LTER, high flow, eutrophication, ecological monitoring, water quality

INTRODUCTION

In Korea, natural lakes are few and man-made reservoirs dominated the lentic ecosystems, unlikely in North American and European waterbodies. Previous numerous researchers pointed out that man-made reservoir ecosystem is different from natural lakes in terms of morphology (circular vs. dendritic shape), flow regime (stable vs. dynamic state), and nutrient inputs (low vs dynamic). Most dam-reservoirs in Korea were constructed for drinking water supply, electricity, and irrigation purposes since 1970s and the water quality is rapidly degradating from oligotrophic to eutrophic state (Lee *et al*., 2006; Choi *et al*., 2008). The major cause of water quality is known as eutrophication by internal and external inputs of nitrogen and phosphorus. Recently, regional reservoirs have documented excessive anthropogenic nutrient enrichment (Kim and Hwang, 2004) decreased transparency (Kim, 2003), and frequent algal blooms (Lee *et al*., 2006). Eutrophication of these systems has mainly been attributed to organic feed used in in-lake fish farms (Kim *et al*., 2000) and agricultural runoff (Kim and Jung, 2007). Especially, in the past (1990s) researches of Daechung and Soyang reservoirs demonstrated that P input from the farms was estimated at >45 percent of total P-loads (Kim, 1987), exceeded Vollenweider's (1976) dangerous loading level (Kim *et al*., 1989) and got rid of the facilities for water protection. However, still the reservoirs are eutrophied rapidly, in spite of such efforts

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and non-point source control.

Korean reservoirs potentially have unique limnological characteristics determined by summer precipitation and inflow from the watershed during June～August. Large seasonal variations in water quality are expected in Korean reservoirs because two third of the annual total rainfall occurs during the monsoon. Inflow during flood events will result in rapid flushing (An and Park, 2003) and may have a dominant influence on ionic salinity, nutrient input, and algal biomass (Soballe and Bachmann 1984; Ford, 1990), thereby modifying reservoir function. Studies of waterbodies influenced by the monsoon in South Asia demonstrated how flushing altered water chemistry such as salinity and nutrient contents (Lohman *et al.*, 1988; An *et al.*, 2006). Water quality, therefore, may be regulated by duration and intensity of the monsoon in any given year.

Daechung Reservoir was constructed in 1980 and eutrophication has proceeded quickly since 1985 (Lee *et al.*, 2000). Studies of this reservoir have emphasized impacts of a wastewater treatment plant and fish farms on nutrients, algal biomass, and transparency (Lee *et al.*, 2000; Han and An, 2008; Lee *et al.*, 2008). Despite recent work, little is known about how the unique monsoon climate and morpho-hydrodynamic characteristics influence chemical and biological processes in the reservoir. This study provides unique opportunity to evaluate how contrasting monsoon conditions influence chemical and biological processes within the system, and why an understanding the monsoon characteristics is essential to understand reservoir limnology in this part of Asia.

MATERIALS AND METHODS

1. Descriptions of sampling locations and sample collection

Daechung Reservoir is located in the middle of South Korea (36° 50′N, 127° 50′E) and was formed in December 1980 by impounding the Geum River about 150 km upstream from its estuary. The selection of sampling sites in Daechung Reservoir was based on the morphometry along the longitudinal axis and the position of external nutrient loads to the reservoir. Along the main axis of the reservoir, we chose 9 mainstem sites and 8 embayment sites. In this study the riverine, transition, and lacustrine zones typically indicate sites 1～4, 5～9 and 10～17, respectively. Surface water samples were collected from these sampling sites twice each month during the study period. In addition, to measure temporal variability in some detail, surface samples were collected 2～3 times a week during the study at the dam site. Herein, we used the terms of the premonsoon (January～June), monsoon (July～August), and postmonsoon (September～December) in describing temporal conditions.

2. Physico-chemical analysis

Water samples were covered to prevent exposure to direct sunlight, stored in ice, and either preserved or analyzed in the laboratory within 12～36 hours. Secchi transparency (20 cm disk), water temperature and dissolved oxygen (YSI Model 51B meter) were measured at the time of sample collection. Specific conductance (YSI Model 33) was measured in the laboratory. Total nitrogen (TN) was measured by second derivative method after a persulfate digestion (Crumpton *et al.*, 1992). Total phosphorus (TP) was determined using the ascorbic acid method after persulfate oxidation (Prepas and Rigler, 1982). Total suspended solids were determined by filtering water through preweighted Whatman GF/C filters. Filters were weighted after drying at 103°C for 1 hour. Volatile suspended solids were determined by combustion at 550°C for 1 hour (APHA, 1985) and volatile suspended solids were determined by differences, and appropriate corrections were made for blanks. Chlorophyll-*a* (Chl) concentration was measured by using a spectrophotometer (Bechman Model DU-65) after extraction in hot ethanol (Sartory and Grobbelaar, 1984). Nutrient analyses were performed in triplicate; suspended solids and Chl were measured in duplicate.

RESULTS AND DISCUSSION

During the study, rainfall, inflow, and outflow patterns showed sharp contrasts between two monsoons of high-flow year (HF_y) and low-flow year (LF_y). Total rainfall during HF_y monsoon was 660 mm which comprised 43% of total annual precipitation, but during LF_y monsoon it was only 251 mm (Fig. 1a). The distributions of rain-

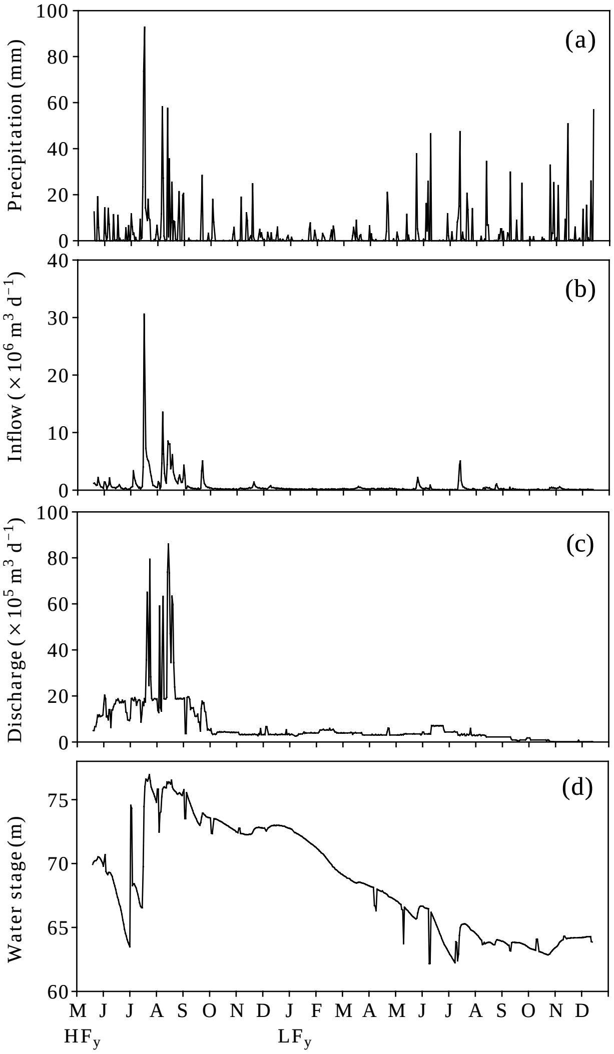


Fig. 1. Comparison of monthly change of hydrological variables among data in the HF$_y$, LF$_y$.

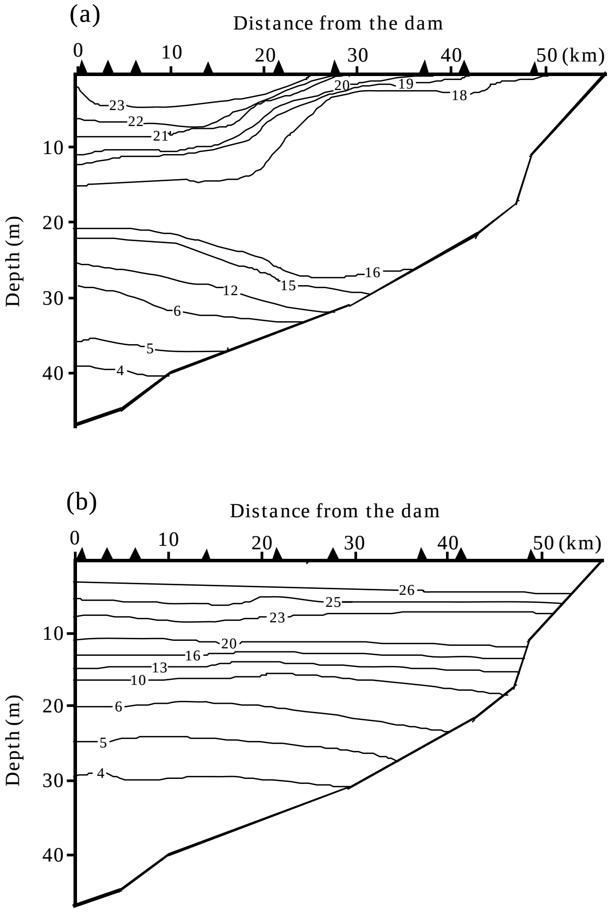


Fig. 2. Isothermal pattern along the mainstem sites from the headwaters to the dam in HF$_y$ monsoon and LF$_y$ monsoon and the hypoxia (<4 mg L^{-1} as dissolved oxygen) in the HF$_y$ monsoon and the LF$_y$ monsoon.

fall resulted in interannual variation of inflow volume and thereby altered the reservoir operation from the dam. Total inflow in HF$_y$ was 4 times that of LF$_y$ (0.83×10^9 m^3), and summer inflow in HF$_y$ was 8 times greater than summer LF$_y$ (Fig. 1b). Seasonal changes of total outflow showed a similar pattern with inflows (Fig. 1d). Seasonal pattern of outflow followed the fluctuation of inflow.

Physical processes have major implications for controlling eutrophication in reservoirs (Vincent *et al.*, 1991; Lind *et al.*, 1993). A dominant process is the influence of density currents on thermal stratification and the mixing regime (Ford, 1990). The influence of density flow on thermal structure was evident in Daechung Reservoir. During the HF$_y$ summer, river water plunged to the transition zone and traversed as a subsurface interflow (Fig. 2a). The interflow disrupted thermal stratification and produced a metalimnetic warming >4°C downlake, thereby increasing the mixing depth by >20 m. The inflow pattern directly influenced the timing of fall overturn; because of metalimnetic warming, overturn in the HF$_y$ occurred about 30 days earlier relative to that in the LF$_y$. The interflow also decreased the volume and thickness of summer hypolimnetic hypoxia as a result of rapid hypolimnetic discharge from the dam and the replacement of hypolimnetic volume by interflows. For this reason, hypoxic volume in the HF$_y$ was less compared to LF$_y$.

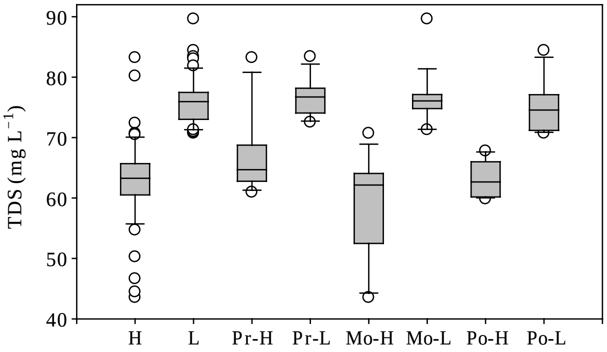


Fig. 3. Temporal variation of total salinity (mg L^{-1}) between the HF$_y$ and LF$_y$. The "PRE", "MON", and "POS" indicate premonsoon (May ~ June), monsoon (July ~ August), and postmonsoon (September ~ December), respectively.

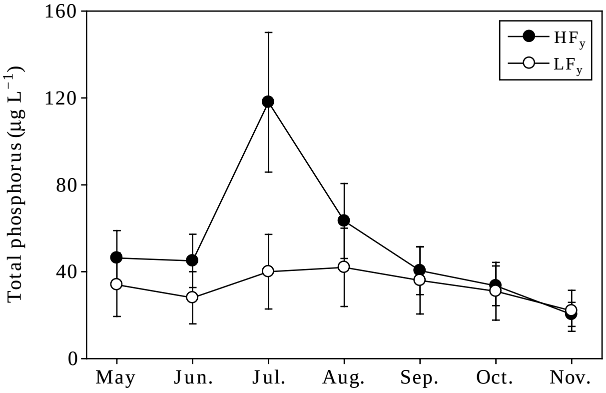


Fig. 4. Monthly distribution of mean total phosphorus (TP) in the HF$_y$ and LF$_y$.

The major mechanism regulating ionic salinity in this system was dilution by monsoon inflow. The dilution process, however, varied spatially and temporally in response to the magnitude of the monsoon rain. Seasonal patterns in salinity reflected rainfall distribution (Fig. 3); salinity, based on total disolved solids(TDS) was lowest (62.1 mg L^{-1}) during peak inflow in the HF$_y$ and highest (96.5 mg L^{-1}) during a drought period (premonsoon) in the LF$_y$. Maximum inflow in the HF$_y$ also produced large spatial heterogeneity in conductivity; this happened longitudinally ($>$30 µS cm^{-1} between the headwaters and downlake), vertically ($>$25 µS cm^{-1} between the surface and bottom), and horizontally ($>$20 µS cm^{-1} between the mainstem and embayment sites). These declines were mainly attributed to decreases in calcium and bicarbonate.

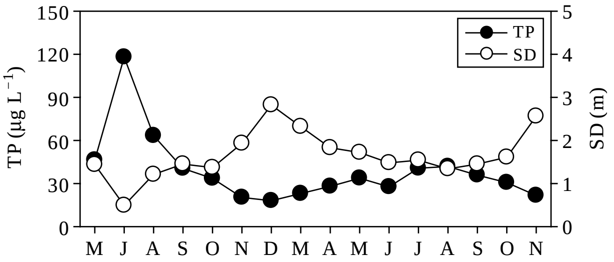
The annual in-reservoir P-budget was mainly regulated by the intensity of the summer rainfall and precipitation. Mean concentration of TP was significantly ($p < 0.001$) greater in HF$_y$ (HF$_y$=38 µg L^{-1} range=6 ~ 197 µg L^{-1}) than LF$_y$ (mean=25 µg L^{-1} range=6 ~ 77 µg L^{-1}). Thus, trophic state based on TP criteria of Nurnberg (1996) was greater in HF$_y$ (eutrophic) than in LF$_y$ (mesotrophic). The marked difference between the two annual means was attributed to summer P-input during July ~ August (Fig. 4). The summer mean in the HF$_y$ was greater by $>$50 µg L^{-1} than the value in LF$_y$ summer.

Concentrations of TP in the headwaters were directly influenced by the hydrograph within the watershed. In early monsoon of HF$_y$, TP in the headwaters ($>$85 µg L^{-1}) increased $>$3 fold relative to the premonsoon and peaked at 155 µg L^{-1} in the mid-monsoon (Fig. 5). Values of TP, however, decreased $>$60% during September ~ October of the HF$_y$. In the HF$_y$, temporal variation in TP was low compared to LF$_y$. In the LF$_y$, monthly mean TP in the headwaters and mid-lake ranged from 22 ~ 51 µg L^{-1} and 22 ~ 44 µg L^{-1}, respectively (Fig. 5). The two maximum values in both zones were 72% and 52% lower, respectively, than in those two zones in the HF$_y$. The marked interannual variability in both zones was a result of the difference in external P-input caused by a contrasting flow regime. Besides, SD was showed the reverse pattern against TP related to light limitation in association with nutrient availability.

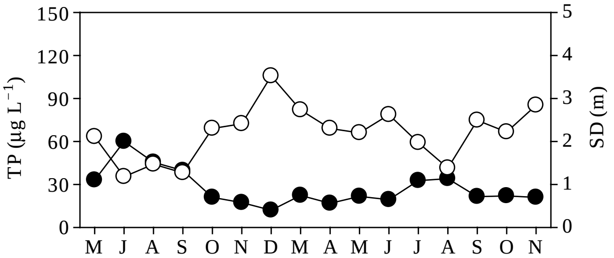
Mass ratios of TN : TP averaged 120 during the study and varied from 10 to 226. The mean ratio in the HF$_y$ was 63 and in the LF$_y$, it was 179, indicating a large temporal variation. During the study about 97% of the total observations (n=509) was $>$17. The remaining 3% of $<$17 occurred only in the headwaters during the HF$_y$ monsoon when inflows peaked, suggesting that P was a potential factor limiting algal growth in the reservoir (Forsberg and Ryding, 1980).

In July of HF$_y$, mean TSS in the headwaters reached a maximum value of 24.4 mg L^{-1} and about 81% of TSS was made up NVSS carried by flood water (Fig. 6), indicating a dominance of inorganic materials. In contrast, NVSS in the HF$_y$ never exceeded 6 mg L^{-1} and VSS : NVSS $>$1 occurred during all seasons except brief periods in August (Fig. 6), suggesting a larger contribution of algae or organic matter to total solids.

(a) Riverine zone (R_z)



(b) Transition zone (T_z)



(c) Lacustrine zone (L_z)

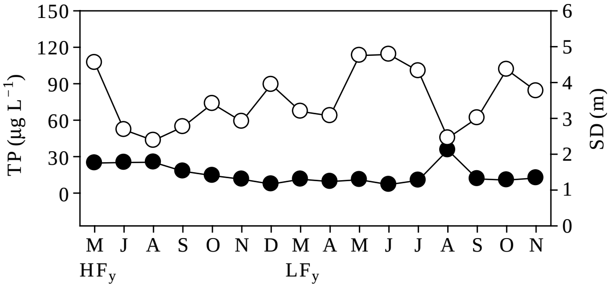
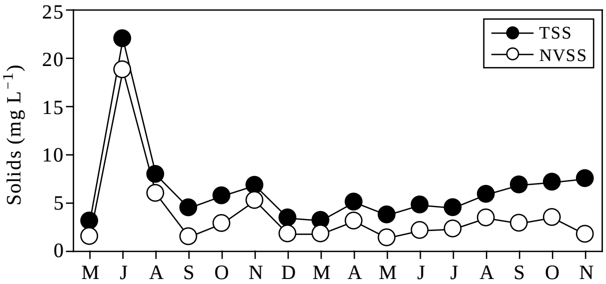
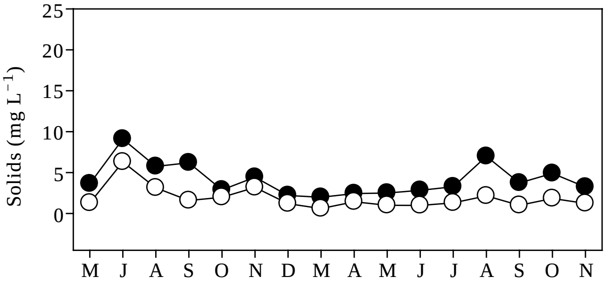


Fig. 5. Seasonal patterns of TP in the riverine zone (sites 1～4), transition zone (sites 5～9) and lacustrine zone (sites 10～17) in the HF_y and LF_y.

(a) Riverine zone (R_z)



(b) Transition zone (T_z)



(c) Lacustrine zone (L_z)

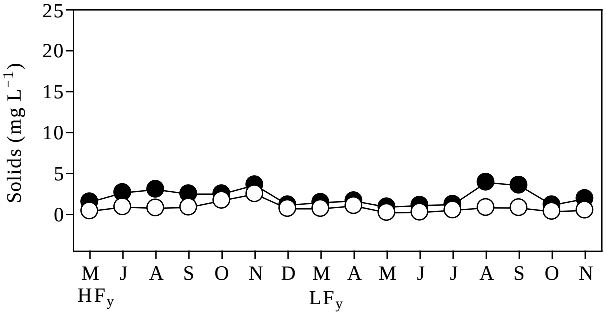


Fig. 6. Seasonal variations of suspended solids in three different zones of mainstem sites; (A): riverine zone, (B): transition zone, (C): lacustrine zone. TSS=total suspended solids, NVSS=non-volatile suspended solids, and VSS=volatile suspended solids.

During the study Chl concentration averaged 20 μg L^{-1} and varied from 1.7 μg L^{-1} to 172.7 μg L^{-1}. Mean Chl (21.8 μg L^{-1}) in the HF_y was similar to the value in the LF_y (22.7 μg L^{-1}), but distinct difference in annual mean Chl (by site) between the two years, however, occurred in the headwaters (sites 1～4); the mean in the HF_y (20.1 μg L^{-1}, range=2.2～40.4 μg L^{-1}) was 38% lower than the value in the LF_y (32.4 μg L^{-1}, range=11.8～74.8 μg L^{-1}).

During the HF_y monsoon, light condition, rapid flushing, and nutrient avaiability were dominant factors regulating algal biomass in the headwaters. During the monsoon, surface mean Chl in the riverine zone was lowest (11.7 μg L^{-1}) among seasons and was significantly ($p < 0.001$) lower than values of transition and lacustrine zones (26.6 and 18.3 μg L^{-1}, respectively Fig. 6). The minimum Chl in the riverine waters coincided with maximum NVSS (17.4 mg L^{-1}, Fig. 7). This inorganic turbidity from the watershed abruptly caused non-algal light attenuation (K_{na}), estimated as an inverse Secchi depth (1/SD) minus 0.025* chlorophyll-*a* (Walker, 1982), and its effect was most pronounced ($>$1.5 m^{-1}) in the riverine zone. Also, rapid flushing was a dominant factor regulating algal biomass during floods (Fig. 8). Values of Chl (range=10.7～28.0 μg L^{-1}) in the riverine zone and transition zone decreased with an incre-

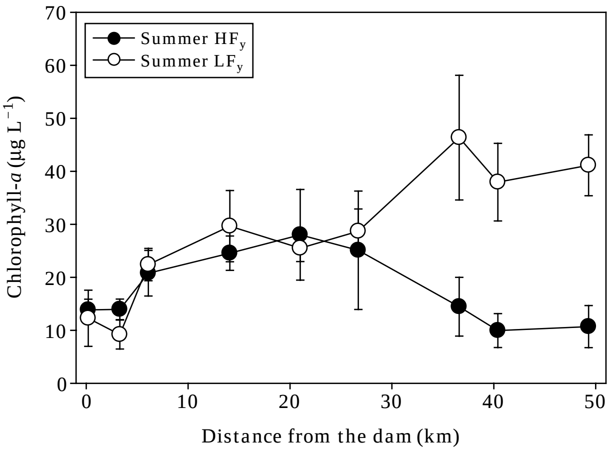


Fig. 7. Longitudinal distribution in chlorophyll-a (Chl) during the monsoon of the HF$_{y}$ and LF$_{y}$. Each data point indicates mean value (n=4) by site during summer monsoon.

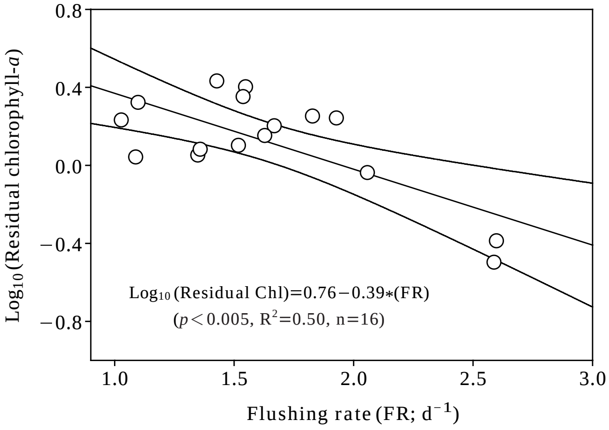


Fig. 8. Seasonal variation of residual chlorophyll [measured log-transformed Chl minus predicted log-transformed Chl] and the relation with monthly flushing rate.

ase of flushing rate (range=32 ~ 121 yr^{-1}) and were strongly correlated (r=0.90; $p < 0.05$) to water residence time. Fig. 8 shows the plot of flushing rate against residual Chl values [Log-observed Chl minus Log-predicted Chl] calculated using the previous TP-Chl model. The negative values in residual Chl during the monsoon suggest that the Chl-TP relation was affected by short water residence time < 10 d (Lind *et al.*, 1993). Also, during the HF$_{y}$ monsoon, particulate P accounted for > 60% of TP, and inorganic solids (NVSS) were made up > 90% of TSS. This result suggests that ambient nutrient content was sufficient but bioavailable P decreased due to phosphorus adsorption reactions with suspended particles.

It is evident that in-reservoir productivity during the HF$_{y}$ monsoon did not increase in spite of major P-input from the watershed. External P supply in the HF$_{y}$ monsoon was over twice that of the LF$_{y}$ monsoon (Fig. 5). Overall in-reservoir mean Chl (17.8 μg L^{-1}) during the HF$_{y}$ monsoon, however, was significantly ($p < 0.01$) lower than during the LF$_{y}$ monsoon (28.1 μg L^{-1}, Fig. 8). Lesser biomass in the HF$_{y}$ was mainly attributed to decreases in the mainstem headwater sites (Fig. 8). Also, ratios of overall in-reservoir mean Chl to TP-input from the watershed were minimal in the HF$_{y}$ monsoon. This phenomenon was explained by interflow (Lind *et al.*, 1993) as well as several factors mentioned above. During the HF$_{y}$ monsoon, river water entered the reservoir as an interflow (Fig. 1; Ford, 1990; Soballe *et al.*, 1992), and the water mass moved in the stratum below the photic zone (approximately, 2.3 m, Secchi depth; 1.4 m in the headwaters to 8.2 m downlake). Thus, nutrient-rich water was isolated from the trophgenic epilimnion due to a density difference between lake and inflow water (Kennedy and Walker, 1990; Cooke *et al.*, 1993), resulting in little contribution to reservoir productivity (Ford 1990; Soballe *et al.*, 1992).

In contrast, Chl values in the LF$_{y}$ were a function of P during all seasons. Monthly mean Chl was < 20 μg L^{-1} in spring (March ~ June) and peaked 42.2 μg L^{-1} in August. The maximum was 2.3 times greater than the mean in spring. During the massive algal blooms (> 40 μg L^{-1} Chl, Maceina 1993; Havens *et al.*, 1995) in August, Chl : TP ratios were > 1.0, indicating high Chl yields at a given P. During the intense rainfall, NVSS values were < 6 mg L^{-1}, indicating a low flushing rate and mineral turbidity. Thus, nonalgal light attenuation (k$_{na}$) never exceeded 0.5 m^{-1} at all sites during the LF$_{y}$ monsoon, indicating that light availability was enough for algal growth. Under such circumstances, the key factor controlling algal growth was ambient P concentration.

Overall data suggests that the key factor regulating ecological functions and processes in this system clearly is the seasonal component of the summer monsoon. The intense monsoon acts a "pulse effect or deterministic instability" (Straskraba *et al*., 1993) in the reservoir environment. Thus, the whole system may be reset during summer monsoon and the magnitude of change is determined by the intensity of the monsoon.

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