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Monsoon Inflow as a Major Source of In-lake Phosphorus

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호수내 인의 주요원으로 몬순 유입수. 안광국 (한국 화학연구소)

1993년부터 1994년 까지 대청호에서 여름몬순의 강도에 따른 인(Phosphorus)의 시 공간적 변이를 평가하였다. 연구기간동안 평균 총인은 31 μg/l 였으며, 6 μg/l에서 197 μg/l까지 변화하였다. 총인농도는 1993년 7~8월의 몬순기간동안 상류에서 가장높았으며, 주로 입자성 인으로 구성되었고, 높은 무기현탁물(NVSS)과 밀접한 관계($R^2 = 0.74$; $p < 0.001$)를 보였다. 상류에서의 호수내 총인은 유입수량과 직접적인 함수관계를 보였으며, 댐으로 내려갈수록 감소경향을 보였다. 1993년 하절기에 하류에서 총인농도는 상류 최대치의 5분의 1 수준에 불과하였고, NVSS와 낮은 상관관계를 보였다. 한편 1994년의 경우 호수내 총인은 1993년에 비해 현저히 낮았으며, 낮은 시공간적 변이를 보였다. 1994년 하절기동안 상류 및 중류에서 최대 총인농도는, 1993년 동일 두지역에서의 최대값에 비해, 72%와 52%씩 낮은 반면, 하류에서 총인은 두해사이에 유사하였다. 이런 결과는 호수내 댐부근에서 인농도의 계절적 변화는 상류에 비해 유입량에 의해 미약한 영향을 받는 것을 의미한다. 1993년에 가을 수층혼합전 평균 총인농도는 수층혼합후 보다 뚜렷하게 높은 반면, 1994년은 수층혼합후 농도가 혼합전보다 높았다. 이런결과는 1993년의 경우 호수내인의 대부분은 하절기동안 외부로부터의 인부하에 기인했으며, 1994년에 호수내 인은 자체내로부터 공급된 것을 의미한다. 결론적으로, 대청호내 인농도는 여름장마의 강도에 의해 크게 결정되며, 인공호라는 큰 공간적 이질성 때문에 호수내 댐 혹은 상류근처의 단일지점에서 측정된 인농도 자료는 호수전체의 계절적 특성을 파악할 때 고려되어야 한다고 사료된다.

Key words : Phosphorus, Monsoon, Inflow, Reservoir, Suspended solids, Korea

INTRODUCTION

Eutrophication is a major cause of water quality deterioration in many countries (Boland, 1976), including Korea. For several decades eutrophication has been considered undesirable, because it impairs human use of water for purposes such as water supply and recreation. Among elements affecting the eutrophication, phosphorus has been most frequently considered the most important limiting nutrient of temperate, inland waters (Vollenweider, 1968; Schindler, 1974; Jones and Bachmann, 1976; OECD, 1982; Vrba *et al*., 1995).

Previous studies have demonstrated that reservoirs typically have a prominent spatial heterogeneity in nutrients from the headwaters to the dam (Kennedy *et al*., 1982; Kennedy *et al*., 1985; Kimmel *et al*., 1990). Generally, phosphorus concentrations decrease from the headwaters to downlake (Jones and Novak, 1981; Thornton *et al*., 1982; Kimmel and Groeger, 1984), but this pattern varies with seasonal hydrology (Walker, 1982; Soballe and Threlkeld, 1985). Large seasonal variations in phosphorus are expected in Korean reservoirs because one third of the annual total rainfall occurs during the monsoon period. Inflow during flood events result in rapid flushing or short hydraulic residence time (Lind,

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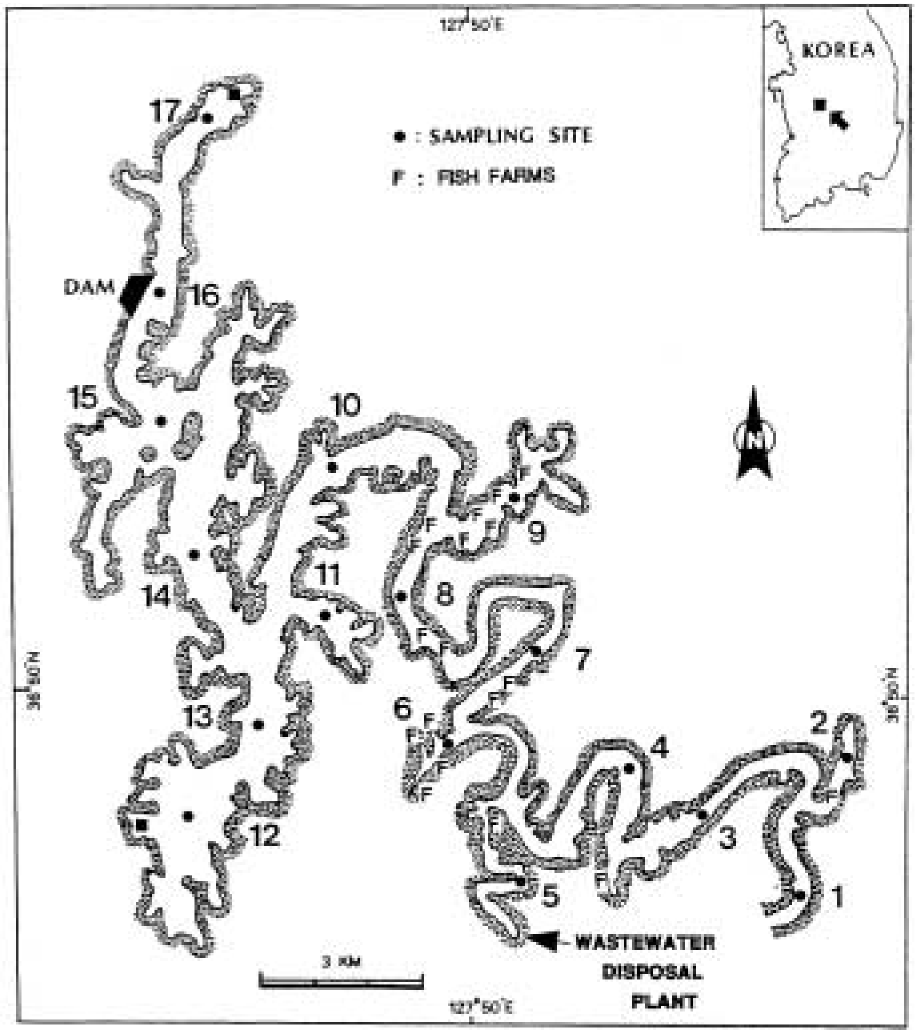

Fig. 1. Map of Taechung Reservoir showing sampling sites.

1993) and may have a dominant influence on in-lake phosphorus distribution (Hoyer and Jones, 1983; Soballe and Bachmann, 1984; Ford, 1990). Despite recent work, little is known about how the monsoon climate and morpho-hydrodynamic characteristics influence nutrient concentrations in reservoirs. This study investigates phosphorus dynamics in response to the magnitude of inflow in Taechung Reservoir during 1993 and 1994 and demonstrates some reasons why intensity of the monsoon is a key component determining the spatial distribution and seasonal patterns of in-lake phosphorus.

MATERIALS AND METHODS

Sampling Sites and Sample Collection: Taechung Reservoir is located in the middle of South Korea (36°50′N, 127°50′E) and was formed in December 1980 by impounding the Keum River about 150 km upstream from its estuary. The selection of sampling sites in Taechung 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, I chose 9 mainstem sites (Site 1, 3, 4, 7, 8, 10, 14, 15 and 16) and 8 embayment sites (Site 2, 5, 6, 9, 11, 12, 13, and 17; Fig. 1). Surface and sub-surface water samples were collected from these 17 sites twice each month from April 1993 to November 1994 (except in winter, January-February). Sub-surface samples were collected from several depths using a Van Dorn sampler (volume: 5L). In this study the headwater, middle, and downlake zone typically indicate sites 1～4, 5～9, and 10～17, respectively based on the morphometry of the reservoir. Also, the terms of premonsoon (January–June), monsoon (July–August), and postmonsoon (September–December) were used to describe temporal conditions. During the study, analyses of hydrological variables including precipitation, inflow, outflow, and water residence time are available in An and Jones (2000).

Analytical Methods

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. Total phosphorus (TP) were determined using the ascorbic acid method after persulfate oxidation (Prepas and Rigler, 1982) and total dissolved phosphorus (TDP) was measured like TP after filtering the water (Whatman GF/C filters; pore size: 0.45 μm). Particulate phosphorus (PP) was estimated as the difference of TP and TDP (Kagawa and Togashi, 1989) and Soluble reactive phosphorus (SRP) were measured by standard methods (APHA, 1985). 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. Non–volatile suspended solids (NVSS) were determined by combustion of filtered paper at 550°C for 1 hour (APHA, 1985) and volatile suspended solids were determined by differences, and appropriate corrections were made for blanks. Nutrient analyses were performed in triplicate and suspended solids were measured in duplicate. One–way ANOVA test was used for the statistical analyses (SAS, 1991).

RESULTS AND DISCUSSION

During the study TP concentrations averaged 31 μg/l and varied from 6 to 197 μg/l (Table 1). Mean epilimnetic TP (37 μg/l) in 1993 was higher by about 1.6 fold relative to 1994 (24 μg/l). Higher TP in 1993 was mainly attributed to greater river inflow compared to 1994; Total inflow in 1993 was four times that of 1994 (0.83×10^{9} m^{3}), and summer inflow in 1993 was 8 times greater than summer 1994. Values of TP were significantly ($p<0.001$) greater during the monsoon than other seasons and were 2～6 times greater in the headwaters (sites 1～4) than at the dam.

Table 1. Annual means and ranges of total phosphorus (TP), total dissolved phosphorus (TDP), particulate phosphorus (PP), and soluble reactive phosphorus (SRP). Each mean value is an average of all sites in 1993 (n = 188) and 1994 (n = 263), respectively.

Parameter	1993		1994	
	Mean±S.E. (μg/l)	Range (μg/l)	Mean±S.E. (μg/l)	Range (μg/l)
TP	37±2.6	6～197	24±1.7	6～77
TDP	16±1.1	2～78	11±0.4	4～56
PP	21±1.4	4～142	18±1.1	2～52
SRP	9±0.8	1～67	2±0.3	1～43

Values of TDP averaged 14 μg/l (range: 2～78 μg/l, Table 1) and was positively correlated (r = 0.87; n = 451; $p<0.001$) with TP. Particulate phosphorus (PP) averaged 20 μg/l during the study and ranged from 2 to 142 μg/l (Table 1). Soluble reactive phosphorus (SRP) ranged from 1 to 67 μg/l but was <5 μg/l except within the headwaters during monsoon 1993.

Distinct variation in dissolved and particulate fractions of TP in association with inorganic solids occurred during monsoon 1993. During all seasons in 1993 and 1994, average dissolved fractions of TP increased 15% from the headwaters (range: 28～76%) to the dam (range: 49～83%), whereas the particulate fraction decreased by 14% (Fig. 2). Maximum seasonal variation in both fractions occurred during monsoon 1993; the proportion of PP increased >25% relative to premonsoon at all sites, whereas the portion of TDP decreased by a 27% (Fig. 2). The dominance in particulate fraction was mainly attributed to inorganic particles in inflows.

Concentrations of TP in the headwaters were ditermined by the hydrograph within the watershed. In early monsoon 1993 (1 July), TP in the headwaters (>85 μg/l) increased >3 fold relative to premonsoon and peaked at 155 μg/l in mid–monsoon (17 July; Fig. 3). The marked increase may be due to an input of P–rich water from the watershed runoff (Gloss *et al*., 1980; Wetzel, 1983; Kennedy and Walker, 1990). Values of TP, however, decreased >60% during September～October (Fig. 3). Also, TP did not increase (range = 18～38 μg /l) in the headwaters even during fall overturn (November～December).

Large P–inputs in the headwaters during monsoon 1993, however, was mainly composed of particulate P. During the monsoon, particulate P

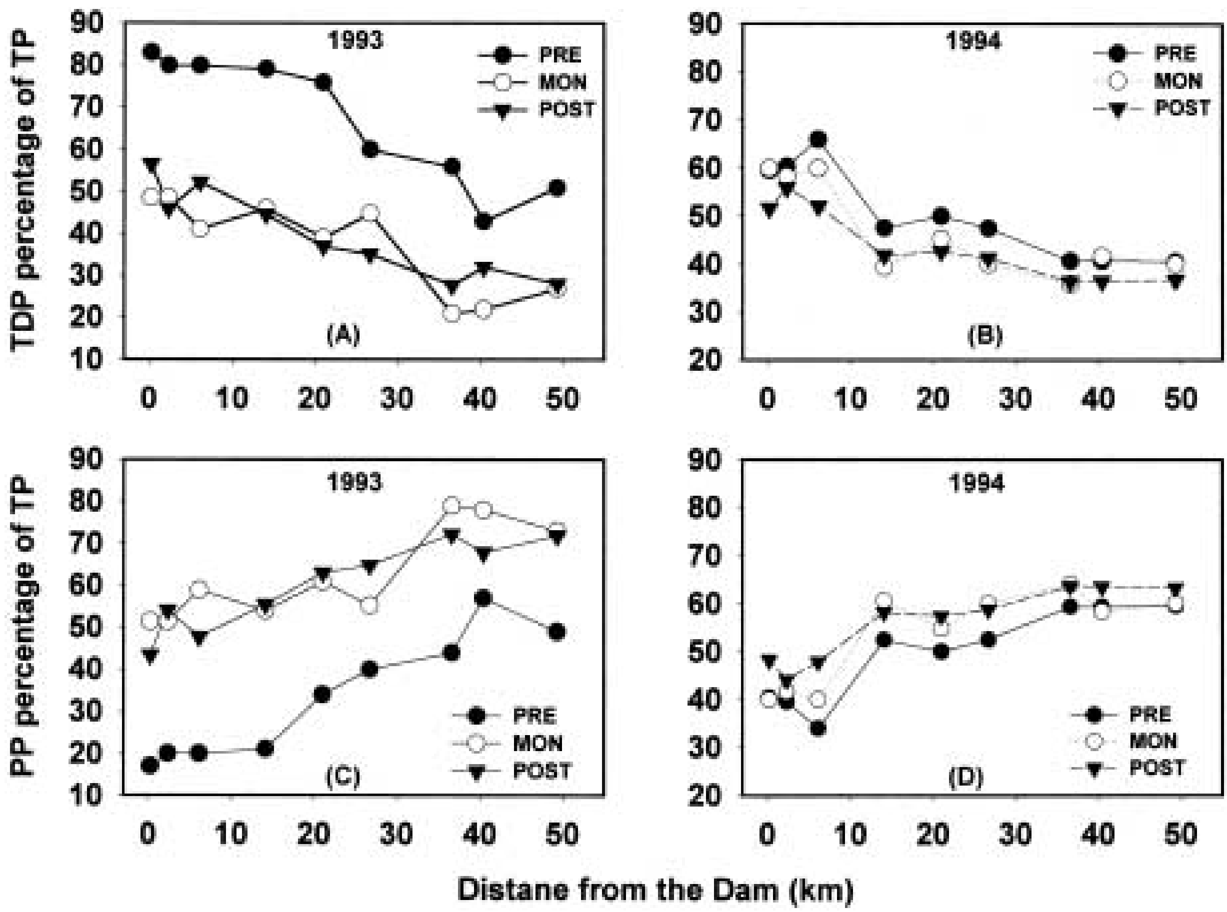

Fig. 2. The fraction of TDP (total dissolved phosphorus) and PP (particulate phosphorus) of TP (total phosphorus) along the main axis of the reservoir in 1993 and 1994; (a) premonsoon, (b) monsoon, and (c) postmonsoon. Each data point was calculated from average of each season data.

in the headwaters was >65% of TP (Fig. 2c) and inorganic solids were >20 mg/l. Thus, in the headwaters, 74% of the variation in TP was explained (n = 33; $p<0.01$) by the variation in NVSS (Table 2). Furthermore, mean water residence time in the headwaters was <5 d during this period. Under such circumstances, phosphorus might not be available for algal growth due to large contribution of particulate P, rapid flushing, and low light penetration (Hoyer and Jones, 1983; Soballe and Bachmann, 1984).

Variation of TP downlake was least among the three zones in 1993 (Fig. 3). Values of TP downlake varied from 10 to 32 μg/l and the maximum TP was only one-fifth of the peak (162 μg/l) in the headwaters. Also, even during monsoon 1993, mean TP (29 μg/l) downlake was >70% lower than the mean (103 μg/l) in the headwaters. The difference (>100 μg/l) in TP between downlake and the headwaters was most pronounced in July 1993 (Fig. 3). Also, TP downlake had no linear relationship (R^2 = 0.21, p = 0.21) with NVSS (Table 2). This result suggests that temporal variation downlake is much less influenced by seasonal inflow, compared to the headwaters.

In 1994, temporal variation in TP was low compared to 1993 and low P concentration (<13 μg/l TP) was continued downlake during strong stratification (Fig. 3). In 1994, monthly mean TP in the headwaters and mid-lake ranged from 22 ~51 μg/l and 22~44 μg/l, respectively (Fig. 3). The two maximum values in both zones were 72% and 52% lower, respectively, than in those two zones in 1993. The marked interannual variability in both zones was likely a result of the difference in external P-input caused by a contrasting flow regime. In contrast, seasonal patterns in TP downlake in 1994 were similar to

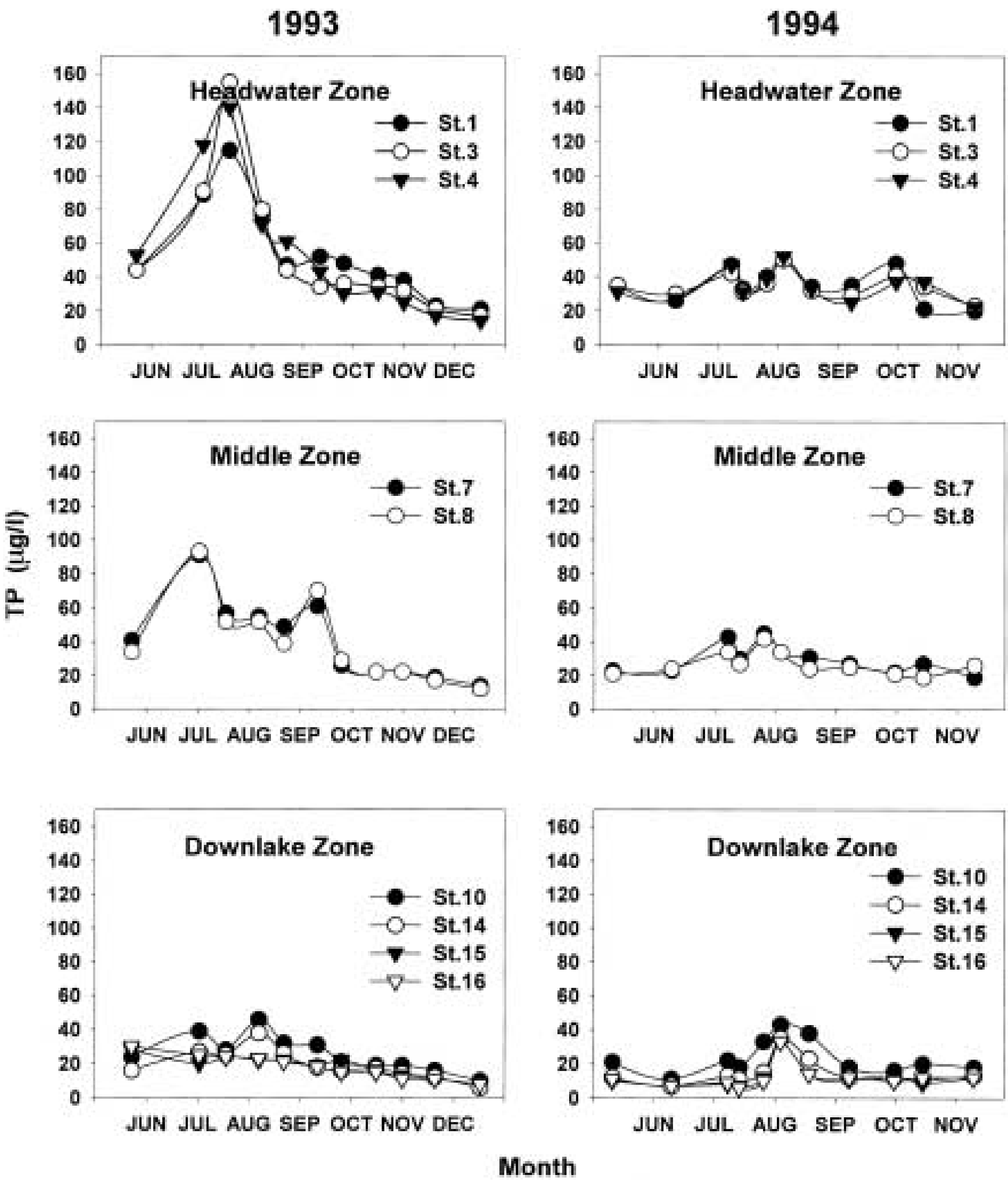

Fig. 3. Seasonal changes of total phosphorus (TP) in the headwaters, middle, and downlake zone in 1993 and 1994. Vertical dot lines indicate the intense monsoon period in both years.

those in 1993 (Fig. 3). In 1994, however, one of the prominent characteristics downlake (sites 14 ~16) was severe P limitation during May~July; during this period, mean TP was 9 μg/l (range = 7 ~12 μg/l, Fig. 3) and TN : TP ratios were >140. Also, SRP values were under detection limits. The consistent low P downlake may be attributed to an uptake by phytoplankton, subsequent sedimentation to the hypolimnion, strong stratification even during summer, and water release through the hypolimnetic outlet (Kimmel *et al*., 1990; Sterner, 1994).

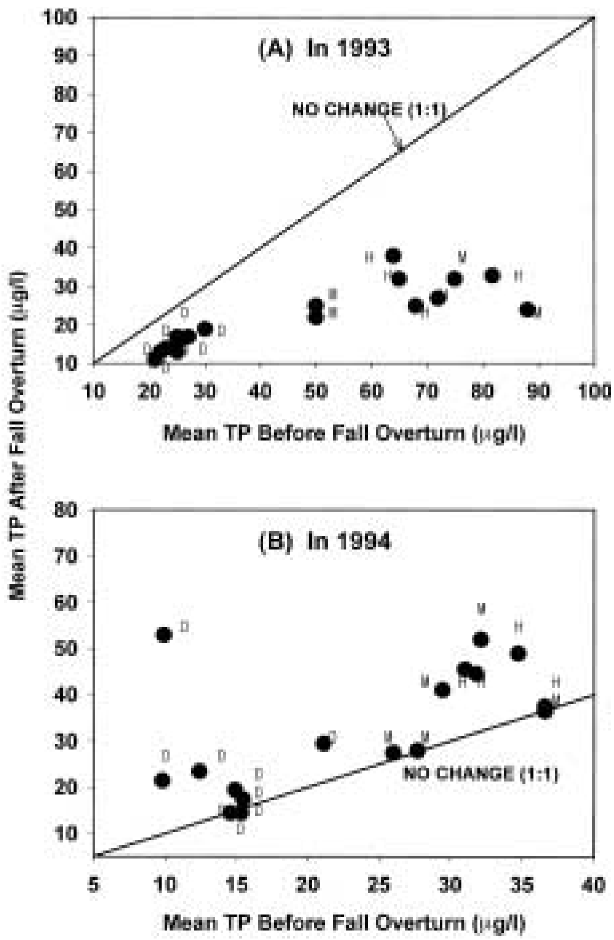

Fig. 4. Contrast of phosphorus loading in the reservoir between the two years. In the figure, "H", "M", and "D" indicates the headwaters (sites 1-4), mid-lake (sites 5-9), and downlake (sites 10-17), respectively.

The annual mean P-budget was mainly influenced by the intensity of summer monsoon. Mean lake TP was significantly ($p < 0.001$) greater in 1993 (mean = 38 μg/l; range = 6~197 μg/l) than 1994 (mean = 25 μg/l; range = 6~77 μg/l). Thus, trophic state based on TP criteria of Nurnberg (1996) was greater in 1993 (eutrophic) than in 1994 (mesotrophic). The marked difference between the two annual means was attributed to summer P-input during July~August (Fig. 3); the summer mean in 1993 was greater by >50 μg/l than the value in summer 1994.

In 1993, in-lake mean TP was highest during the summer period, whereas in 1994 it was highest immediately after the fall overturn. In 1993, mean TP before overturn, based on average value for all sites, was significantly (46 μg/l; t = 5.99; $p < 0.001$) greater than the mean (22 μg/l) after fall overturn (Fig. 4A). These values in 1993 constantly declined >2.5 times from the headwaters (expressed as "H": >60 μg/l P) to downlake ("D": <30 μg/l). In contrast, in 1994, mean TP after fall overturn (32 μg/l) was greater than the mean before overturn (23 μg/l, Fig. 4B). In summer 1994, mean TP was significantly ($p <$ 0.001) greater mid-lake (43 μg/l) than elsewhere. This phenomenon was probably due to an impact of the point-sources such as the wastewater disposal plant and in-lake fish farms. These results suggest that the pattern in 1993 and 1994 was determined by external loading through the watershed runoff and point-sources, respectively.

Table 2. Regression analyses of TP (μg/l) against non-volatile suspended solids (NVSS, mg/l) in the headwater, mid-lake, and downlake zones in 1993 and 1994. The ANOVA test was used for the p-values.

Year	Zone	Sample # (n)	Slope	Intercept	p-value	R^2
1993	Headwater	48	4.14	29.9	<0.001	0.74
	Mid-lake	60	5.20	20.9	<0.01	0.48
	Downlake	96	−4.57	23.6	0.21	0.05
1994	Headwater	52	4.79	21.0	<0.01	0.30
	Mid-lake	65	2.64	21.1	0.20	0.04
	Downlake	104	1.79	10.1	0.12	0.06

In conclusion, overall data of this study suggest that in-lake phosphorus was influenced by the magnitude of monsoon inflow and the temporal effect varied among the zones of the reservoir. Most P-inputs in the headwaters occurred during July~August in 1993 and came from the watershed runoff. This outcome supports nutrient hypothesis in North American reservoirs where hydrology is a major source of variation (Walker, 1982; Hoyer and Jones, 1983; Soballe and Bachmann, 1984; Soballe and Threlkeld, 1985; Ford, 1990; Lind, 1993). The major P-loading during the short monsoon in this system, however, differed compared to mainly spring and fall in non-monsoon regions (Jones *et al*., 1997). Such regional patterns in major P-input might make differences in reservoir productivity, resulting in a modification in eutrophication processes between the monsoon and non-monsoon regions.

ABSTRACT

Spatial and temporal variation of phosphorus in response to intensity of summer monsoon was evaluated in Taechung Reservoir during 1993~1994. Total phosphorus (TP) averaged 31 μg/l during the study and varied from 6 to 197 μg/l. Concentrations of TP were highest in the headwaters during the monsoon of July~August 1993, and these values were mainly made of particulate P and were closely associated ($R^2 = 0.74$, $p < 0.001$) with high inorganic suspended solids (NVSS). In-lake TP in the headwaters was mainly influenced by the watershed runoff and declined toward the dam. Values of TP downlake was only one-fifth of the peak in the headwaters and had no correlation with NVSS. In 1994, in-lake TP was markedly lower relative to 1993 and showed low spatial and temporal variation. Maximum TP during monsoon 1994 in the headwaters and mid-lake was 72% and 52% lower, respectively, than in those two zones in 1993 whereas TP downlake was similar between the two years. These results suggest that temporal variation downlake is much less influenced by seasonal inflow compared to the headwaters. In 1993, mean TP before fall overturn, based on average value for all sites, was significantly ($t = 5.99$, $p < 0.001$) greater than the mean after fall overturn, whereas in 1994 mean TP after fall overturn (32 μg/l) was greater. This outcome indicates that in 1993 major P-input originated from the external source from the watershed during the intense monsoon, whereas in 1994 internal processes dominated during the weak monsoon. Overall data suggest that annual budget of in-lake P is regulated by intensity of the summer monsoon, and phosphorus data measured at single site near the dam or headwater zone may not be represent seasonal trends of the system due to large spatial variation of Taechung Reservoir.

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