Korean J. Limnol. 34 (1): 9~19 (2001)

Seasonal Patterns of Reservoir Thermal Structure and Water Column Mixis and Their Modifications by Interflow Current

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인공호에서 수온의 수직분포와 수층혼합의 계절적 변화 및 중층수 유입 현상의 영향. 안광국 (이화여자대학교, 환경학과)

본 연구는 1993년 4월부터 1994년 11월까지 대청호 17개 조사지점에서 수온 성층 및 수체 혼합 현상을 평가하였다. 조사기간 동안 하절기 장마 강도의 차이는 뚜렷한 수리 수문학적 연 변화를 가져왔다. 1993년 하절기에 이론적 평균 수체류 시간은 27일로서, 1994년 하절기 (125일)에 비해 3개월 이상 짧았다. 1993년에 수온 성층화와 수층혼합 정도를 조절하는 중요한 물리적 요인은 밀도가 높은 중층수 유입현상 (Interflow current)에 의한 것으로 평가되었다. 1993년 하절기동안 상류 유입수는 호수 중류역 (댐으로 부터 27 km 부근)에서 수직 하강되어 10~20 m 수층을 통과함으로써 표층수인 호수물과는 혼합되지않는 현상을 보였다. 중층수 유입은 수온 성층화 현상의 약화, 하류역의 중층-심층에서 평균 4°C 이상의 온도상승 효과 및 13 m 이상의 수층혼합을 가져왔다. 전자와 비교해볼 때, 1994년 하절기 중층수 유입현상은 관측되지 않았으며, 호수전체에 강한 성층이 형성되고 있음을 보였다. 1993년 온도 저항력 (Thermal resistance)은 4.0×10^5 erg로서, 1994년의 값 (8.2×10^5 erg)에 비해 절반 수준을 보임으로서, 수체의 물리적 불안정 상태를 시사하였다. 본 호수는 연중 겨울에 1회 수층혼합을 보이는 Warm monomixis 특성을 보였으나, 두해 사이의 수층혼합 시기는 차이를 보였다; 1993년 수층혼합은 1994년에 비해 약 1개월 일찍 일어났다. 하절기 동안 심층 수온 변화(Y)는 댐으로부터의 방류량(X)에 의해 98%까지 설명되었다 ($Y = 4.35 - 0.06X + 0.10X^2$, $p < 0.0001$). 총체적으로 본 수체에서 수온 안정성, 수층혼합 시기 및 수 체류시간은 1차적으로 하절기 몬순 강도에 의해 조절되는 것으로 사료된다.

Key words : Interflow, Stratification, Overturn, Monsoon, Reservoir, Korea

INTRODUCTION

Ecological processes in natural ecosystems are strongly influenced by temporal patterns of rainfall, runoff and thermal regime (Brylinsky & Man, 1973; Allan, 1995). Limnological studies in North America and European waterbodies (Dillon, 1975; Perkins & Jones, 1994; Sommer, 1985) suggest that hydrological variation occur mostly in spring and fall due to major rainfall distribution. Large hydrological fluctuations in Korean waterbodies, however, are expected during summer because over two-third of total annual precipitation occurs during summer monsoon in July~August and daily precipitation frequently exceeds > 100 mm (Kim *et al*., 1997). This situation may cause physical instability by influencing thermal stratifications and overturn in lakes and reservoirs.

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Thermal patterns may be complex when flood waters have short hydraulic retension time and enter reservoir ecosystems as an interflow or underflow current (Vincent *et al*., 1991; Soballe *et al*., 1992). Density currents often plunge subsurface of reservoirs (Ford, 1990), thereby producing an isolation of epilimnetic lake water from the meta- and hypolimnetic river water. Such events frequently modify a distribution of nutrients and suspended solids (Thorton, 1990) and phytoplankton biomass (Knowlton & Jones, 1990) as well as thermal stratification and the mixing regime (Wetzel, 1983; Ford, 1990), indicating that physical processes have major implications for controlling eutrophication in reservoirs (Vincent *et al*., 1991; Lind *et al*., 1993).

During last several decades, most reservoir studies in Korea have been conducted for evaluating nutrient dynamics (Kim *et al*., 1989; Kong, 1997), trophic state (Kim *et al*., 1997), chlorophyll-a/or primary productivity (Kim *et al*., 1985; Cho *et al*., 1989), and algal compositions (Cho *et al*., 1991; Joo *et al*., 1997). However, little is known about how hydrodynamic characteristics during the monsoon influence thermal stratification, water residence time (WRT), and mixing regime in reservoirs in Korea. The purpose of present paper was to describe monsoon hydrology and determine thermal dynamic patterns in relation to intensity of the monsoon in Taechung Reservoir.

MATERIALS AND METHODS

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 was based on the longitudinal gradients of water depth. 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). The distance from Site 1 to Site 17 is about 50 km and herein, I used the terminology of “location X” to represent the position of given site relative to the dam. For example, location 39 km indicates 39 km uplake from the dam, which is the Site 2. The reservoir map showing the sampling sites is available in An (2000). In this reservoir, temperature profiles (YSI DO-Model 51B meter) were taken from 17 sites twice a month and from the dam 2～3 times a week during 1993～1994.

Rainfall and inflow data during 1981～1994 were obtained from Taejon Meteorological Station and Taechung-Dam Management Office, Taejeon, Korea, respectively. Thermal stability was measured as a thermal resistance (unit: erg), which is the work required to completely mix a water column (after Wetzel and Likens, 1990). Theoretical water residence time (TWRT in days, after Knowlton and Jones, 1990) was calculated using the lake surface area, volume and inflow on each sampling date and season in the reservoir. The reservoir morphology used for presentation of thermal profiles was based on the hypsographic curve (Wetzel and Likens, 1990) which was calculated using the morphological variables.

RESULTS AND DISCUSSION

The major difference in rainfall between the two years of study occurred during the July ～August monsoon (Fig. 1A). Total precipitation during monsoon 1993 was 660 mm which comprised 43 % of total annual precipitation, but during monsoon 1994 it was only 251 mm. In 1993 rainfall during July～August was 164% larger than the mean value during 1981～1992, whereas rainfall in 1994 was 50% less than the long-term average (Fig. 1A). Precipitation was similar during the remaining periods of these two years (Fig. 1A).

In 1993, daily inflow ranged from 7.9×10^5 m^3 on May 27 to 3.1×10^8 m^3 on 13 July. This inflow equaled $<1\%$ and 43%, respectively, of the average volume of Taechung Reservoir in 1993. Total Inflow in 1993 and 1994 was 138% and 31%, respectively, of average inflow during 1981～1992 (Fig. 1B). Monthly outflow in both years reflected the seasonal inflow. In 1994 total outflow was only 27% of 1993 and summer outflow in 1994 was 8% of summer 1993. The frequency of water releases from the dam in 1994 was also much less relative to 1993.

The seasonal trend of theoretical water residence time (TWRT) was similar between 1993 and 1994, but mean TWRT in 1993 was 50 d shorter than in 1994 (Fig. 1d). The difference in TWRT between the two years was maximized in summer and minimized during January～April (Fig. 1D). Thus, mean TWRT during the 1994

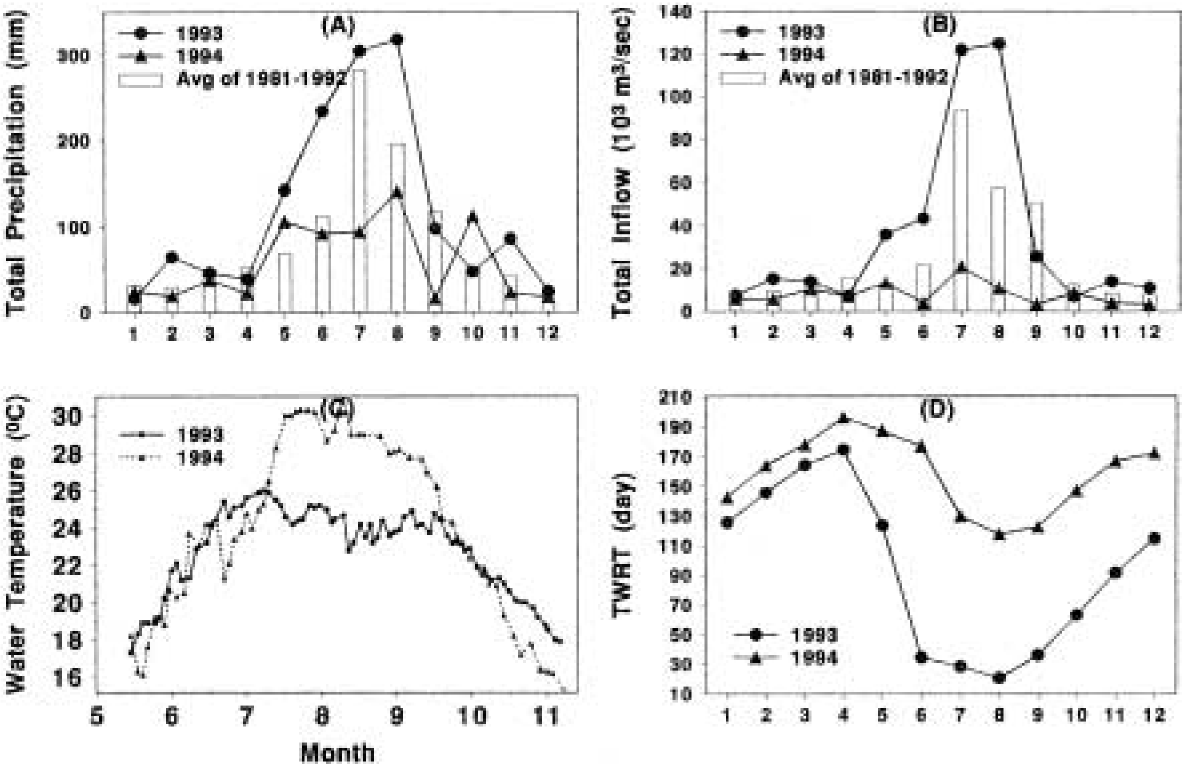

Fig. 1. Seasonal changes of monthly mean precipitation (A) and inflow (B) in 1993, 1994, and 1981~1992 and water temperature (C) and theoretical water residence time (TWRT; D) during 1993~1994. Water temperature measured at the surface near the dam wall.

monsoon (125 d) was $>$ 100 d longer than during monsoon 1993 (24 d), and the longest TWRT ($>$ 120 d) occurred during minimum rainfall in 1994 (Fig. 1D). During summer 1993 actual water residence time, however, may be longer than values calculated here because inflow water passed through the reservoir as an interflow rather than plug-through.

During 1993~1994, surface water temperature, based on data at dam site, showed a typical pattern and range (22~31°C in summer) for lakes in a warm temperate region. Seasonal patterns of water temperature were depicted by three phases (Fig. 1C): increasing phase (May~June), maximum phase (July~August), and the decreasing phase (September~December). The average temperature during July to mid-September 1993 was 24.5°C and was significantly ($p < 0.001$) lower than during the same period in 1994 (mean value = 28.3°C; Fig. 1). The lower temperature during the 1993 monsoon was likely an influence of high rainfall, inflow and short TWRT (Fig. 1). Temperatures during other seasons, however, were nearly identical between the two years (Fig. 1C). This reservoir is identified as a typical warm monomictic reservoir (Hutchinson, 1957) and this pattern is similar to the costal regions of North America and Northern Europe (Wetzel, 1983).

In spring 1993, surface temperature and intensity of thermal stratification, based on 9 sites at the main axis of the reservoir, increased with increasing mean depth. In May 1993, surface temperatures ranged from 22.1°C in the headwaters to 26.1°C at the dam and increased longitudinally along the length of the reservoir (Table 1). Temperature differences between the epilimnion and hypolimnion were 13, 18, and 20°C, respectively, in the headwaters, middle, and downlake (Fig. 3A), indicating a strongest thermal stratification at the downlake. It is evident that thermal regime reflected the reservoir morphology (Ford, 1990).

Development of thermal stratification in spring 1994 was similar to that of spring 1993. Surface temperatures in March 1994 were $<$ 7°C in the

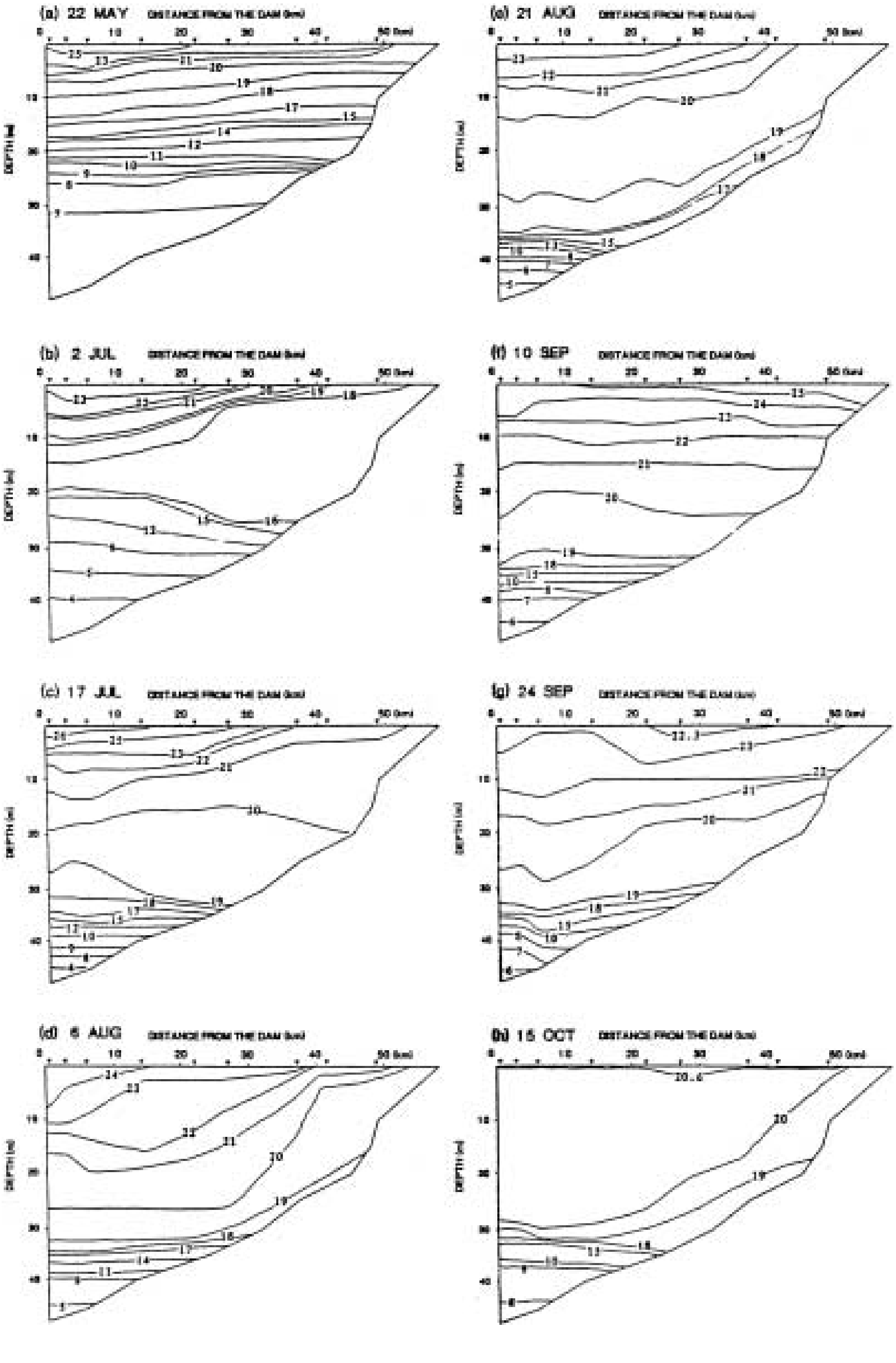

Fig. 2. Isothermal patterns along the mainstem sites from the headwaters to the dam in 1993. Interflows from the parent river were observed during July. The morphology was based on a hysographic curve in Taechung Reservoir.

Table 1. Surface water temperature (˚C) along the main axis of the reservoir from the headwaters to the dam in 1993 (A) and 1994 (B). The distance indicates the distance (km) from the dam.

(A) 1993

Distance (km)	MONTH						
	MAY	JUL	AUG	SEP	OCT	NOV	DEC
49	22.1	20.2	22.0	24.7	17.9	14.0	10.1
40	23.3	20.7	21.4	24.3	18.3	14.2	10.3
37	24.1	21.0	22.9	24.4	18.8	14.8	10.3
27	24.3	23.6	23.1	24.5	19.6	15.5	11.8
21	24.6	24.4	23.4	24.6	19.3	15.7	12.1
14	25.8	24.5	23.1	24.3	19.4	15.7	12.1
6	26.5	24.4	23.3	25.3	19.5	15.8	12.5
3	26.1	24.6	23.6	23.8	19.5	15.8	13.1
0	26.1	24.7	23.8	23.7	19.6	15.6	13.2
Mean	24.8	23.1	23.0	24.2	19.1	15.2	11.7

(B) 1994

Distance (km)	MONTH							
	MAR	APR	JUN	JUL	AUG	SEP	OCT	NOV
49	6.0	13.8	24.4	29.2	28.7	23.9	18.3	10.0
40	6.0	13.3	23.3	29.2	28.9	24.3	19.0	11.1
37	6.3	13.2	23.0	29.9	28.6	24.6	20.0	12.5
27	5.7	11.5	22.5	29.2	28.5	24.1	20.7	13.0
21	5.4	11.5	21.9	29.1	28.4	24.7	20.7	13.2
14	4.9	11.7	21.6	28.5	28.3	25.1	20.2	14.5
6	4.9	10.3	21.6	28.5	28.1	24.9	19.8	14.0
3	4.7	10.2	21.4	28.3	28.2	25.0	19.5	14.0
0	4.9	10.7	22.0	28.7	28.4	24.5	19.8	14.0
Mean	5.4	11.7	22.4	29.0	28.4	24.5	19.8	12.9

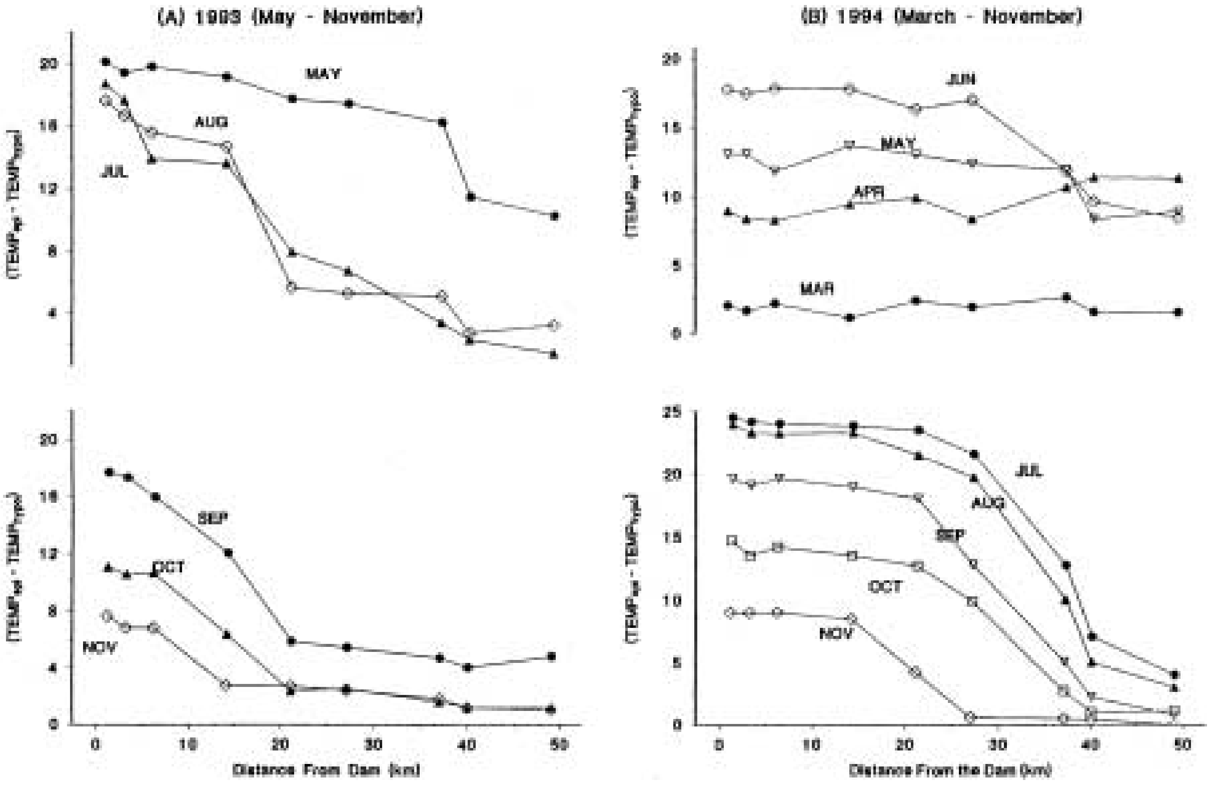

Fig. 3. Seasonal patterns in temperature differences between epilimnetic ($TEMP_{epi}$) and hypolimnetic water ($TEMP_{hypo}$) along nine mainstem sites of the reservoir from the headwaters (location ~ 50 km) to the dam (location − 0.2 km) in 1993 (May ~ November; A) and 1994 (March ~ November; B).

entire reservoir and were slightly greater in the headwaters than downlake (Table 1). Thermal stratification was established in the headwaters in late April 1994 when the difference between surface and bottom water was > 10˚C (Fig. 3B). By May, however, stratification was stronger downlake than in the headwaters (Fig. 4A). The temperature difference between surface and bottom water in June was > 15˚C (Fig. 3B, Fig. 4B).

A marked interannual difference in surface temperature occurred during summer monsoon. Overall mean surface temperature during mon-

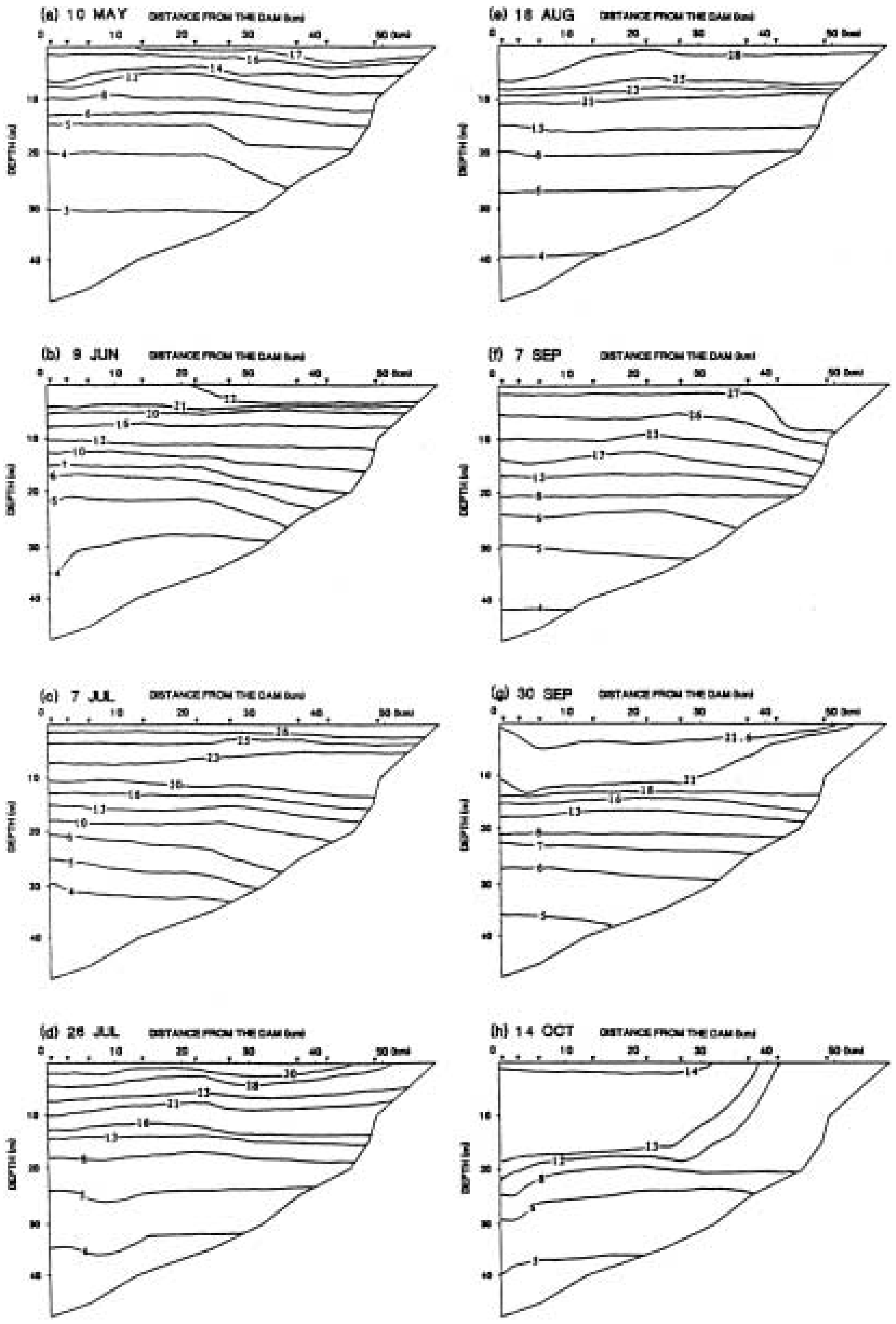

Fig. 4. Isothermal patterns along the mainstem sites from the headwaters to the dam in 1994. Ditto with Fig. 5.

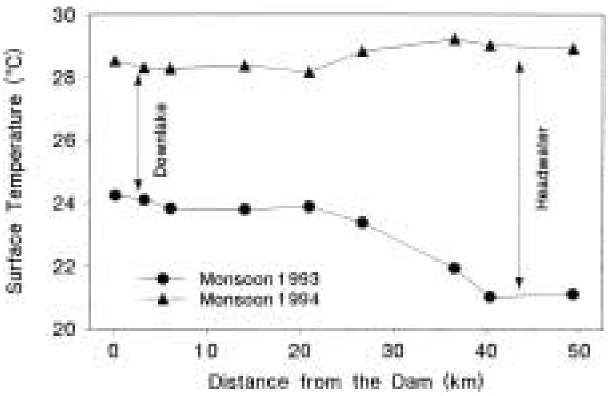

Fig. 5. Surface temperature differences between monsoon of 1993 and 1994 along the longitudinal gradients from the headwaters to downlake. Each data point indicates averages by site during monsoon.

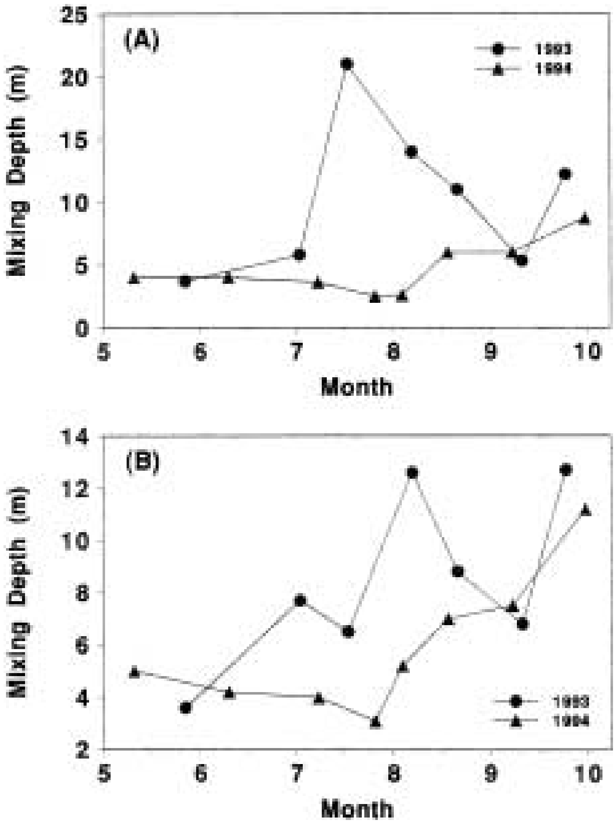

Fig. 6. Interannual variation of mixing depth (epilimnetic thickness; Z_m) in the headwaters (upper panel) and downlake (lower pannel) during the study. Each data point in the headwaters and downlake indicate averages of sites 1~4 and 15~17, respectively in each sampling period.

soon was >5°C greater in the low-inflow year, 1994, than the high-inflow year, 1993. The temperature difference (mean = 7.4°C) between these two monsoon seasons was most pronounced in the headwaters (Fig. 5). In 1993 temperatures in the headwaters were significantly ($p < 0.01$) lower than downlake (about 21 vs. 24°C). Whereas, in 1994 temperature was slightly greater in the headwaters than downlake (Fig. 5). This outcome supports the finding that thermal structure is influenced by the magnitude of inflow (Ford, 1990).

During summer monsoon, a large difference in mixing depth (i.e. epilimnion thickness, Z_m) between the two years was attributed to a modification of thermal structure by the contrasting inflow. Mean Z_m during monsoon 1993, based on all sites, was 13 m and was 3 fold greater than during monsoon 1994 (4.1 m; Fig. 6). In 1993, maximum Z_m occurred during monsoon (mid-July) in the headwaters, whereas downlake it occurred after the monsoon (Fig. 5). In 1994 the minimum Z_m (2.5 m) occurred in mid-July in the headwaters. In contrast, the maximum (13 m) downlake occurred in early August 1993 (Fig. 5), and was attributed to an arrival of peak inflow ($>3\times10^8$ m^3 d^{-1}) in mid-July from the headwaters. This result suggests that regional climate is a dominant factor influencing mixing processes of lakes (Brylinsky & Mann 1973), thereby determining thermal patterns.

One of the dominant physical processes modifying the thermal structure and mixing regime was an interflow during monsoon 1993, resulting in changes of reservoir functions. Early in the monsoon (1 July), flood water from the parent river partially disrupted thermal stratification in the headwaters with little influence on surface temperature mid-lake and downlake (Fig. 2B). Interflow water was observed at the plunge-point near location 27~37 km and was >2~3°C colder relative to lake surface temperature (Fig. 2B). The wide band of 16~18°C water marking this interflow passed through the 10~20 m stratum of the reservoir, resulting in an isolation of epilimnetic water from advected river water (Fig. 2B). Thus, mean temperatures in the metalimnion (approximately, 10~25 m) declined >3°C relative to the premonsoon. This observation support the finding that thermal stratifications are largely modified when flood waters have short TWRT and enter reservoirs as a density current like an interflow or underflow (Vincent *et al.*, 1991).

The interflow in Taechung Reservoir caused a progressive metalimnetic warming downlake by entrainment (Ford, 1990), with a corresponding lowering of the thermocline level (Mortimer 1961). In mid-monsoon 1993 (17 July), the density current resulted in a warming > 4°C of the metalimnion (10 ~ 30 m) downlake (0 ~ 21 km) and decreased the thickness (35 m-bottom) of hypolimnion (Fig. 2C). During this period, metalimnetic water with temperatures of 19 ~ 21°C comprised > 60% of total reservoir volume (Fig. 2C). During late monsoon (6 ~ 21 August), metalimnetic temperatures in the headwaters and downlake increased > 2°C and 7°C, respectively, compared to the early monsoon (Fig. 2D, E). The metalimnetic warming in the headwaters was a result of a reduced river inflow, whereas downlake it was the influence of the interflow. An and Jones (2000) found that metalimnetic interflow in Taechung Reservoir was nutrient-rich (total phosphorus > 150 μg/L), low ionic (conductivity < 80 μS/cm), and highly turbid water (non-volatile suspended solids > 20 mg/L). These results suggest that interflow may be a dominant physical process modifying physical and chemical conditions in the water column, thereby influencing eutrophication processes (Vincent *et al.*, 1991)

In contrast, during monsoon 1994 strong thermal stratification was present in the whole system and density currents were not observed. In early monsoon 1994 (7 July), average surface temperatures were about 6°C greater relative to early monsoon 1993 (Table 1). A difference of > 22°C between epilimnion and hypolimnion water was measured downlake (Fig. 3B) with differences of > 10°C in the headwaters (Fig. 4C). In mid-monsoon (26 July), surface temperature was > 30°C, and thermal stratification was intense in the whole system (Fig. 4D). Thus, the metalimnion rose from 10 ~ 13 m in early monsoon to 5 ~ 7 m in mid-monsoon. Sharp stratification persisted until late monsoon (18 August) in spite of surface cooling of > 2°C (Fig. 4E). Thus, metalimnetic temperature was > 9°C greater in summer 1994 than summer 1993 due to the absence of an interflow.

Thermal stability, measured as thermal resistance (the work required to completely mix a water column, Wetzel and Likens 1990), was significantly ($p < 0.001$) greater in monsoon 1994 (8.2 $\times 10^5$ erg) than monsoon 1993 (mean by sites: 4.0 $\times 10^5$ erg), while it was > 7 fold greater in the downlake (3 ~ 15 km; mean = 11.5×10^5 erg) than the headwaters (35 ~ 50 km; 1.2×10^5 erg; Fig. 7). The stronger stability in 1994 was attributed to a marked reduction of inflow and discharge and the continued surface heating of the reservoir from early monsoon.

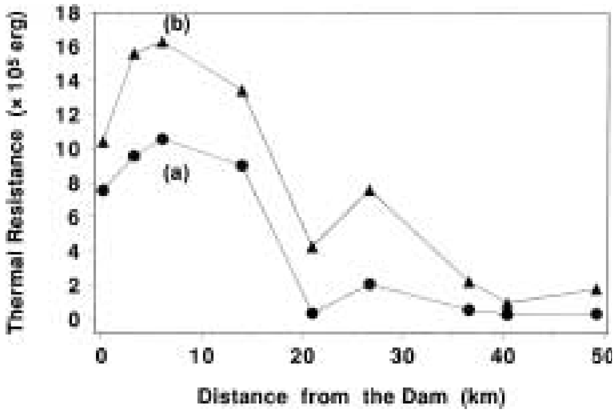

Fig. 7. Thermal resistance (unit: erg, after Wetzel and Likens, 1990) along the axis of the reservoir during summer in 1993 (a) and 1994 (b).

Thus, the pattern of longitudinal zonation, based on temperature differences between epilimnion and hypolimnion, differed between two monsoons of 1993 and 1994. Herein, the vertical thermal differences in the riverine and lacustrine zone were defined as < 10°C and > 20°C, respectively. In summer 1993 the riverine zone was observed in the reach between 20 and 50 km, while the lacustrine zone occurred only in the reach between 0 and 0.2 km (Fig. 8), indicating a riverine dominance (Kimmel *et al.*, 1990). This result does not agree with the suggestion that transition zone starts from a plunge point in reservoirs (Thornton, 1980), which means the riverine zone was in the headwaters (above the plunge point). In contrast, in 1994 the riverine zone was confined to the headwaters (location 40 ~ 49 km) while the lacustrine zone occurred between 0 and 30 km (Fig. 8), indicating a lacustrine dominance (Kimmel *et al.*, 1990). This observation suggests that the reservoir function changed from the riverine dominance in 1993 to the lacustrine conditions in 1994.

Summer hypolimnetic warming in the both years followed a predictable pattern, in spite of the dynamic nature in thermal structure. During

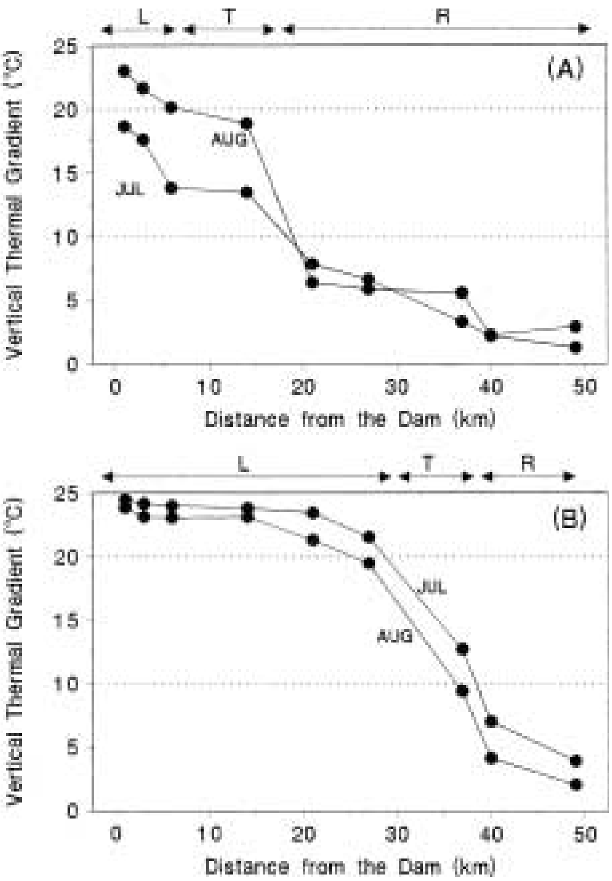

Fig. 8. The change of longitudinal zonation based on the vertical thermal gradient (i.e., difference of epilimnetic and hypolimnetic temperature in each sampling site) in summer 1993 (A) and summer 1994 (B). Capital characters of "R", "T", and "L" indicate the riverine, transition, and lacustrine zone, respectively.

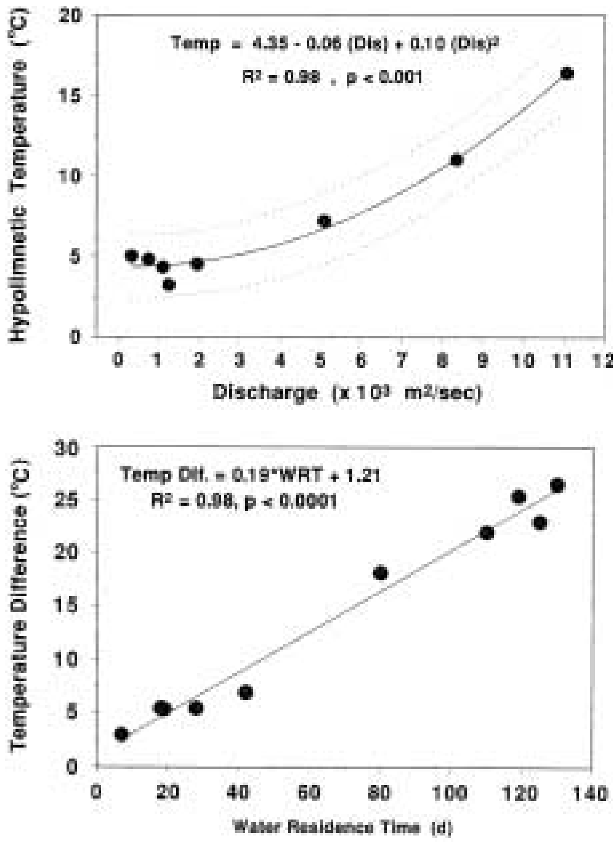

Fig. 9. Regression analyses of hypolimnetic temperature (HT; expressed as 25~45 m) against monthly discharge (upper panel) and temperature difference (between < 0.5 m and 30m depths) against water residence time (lower pannel) during May~August of 1993 and 1994.

the study monthly mean hypolimnetic temperature (HT) varied from 3.2 to 16.4°C (Fig. 9). Mean HT (11.5°C) in 1993 was significantly ($p < 0.001$) greater than in 1994 (4.4°C). It was a result of a withdrawal of cooler water and rapid replacement by warmer water from the layers of interflow above during 1993. Thus, HT was strongly correlated ($r = 0.99$; $p < 0.001$) to summer discharge volume, and the variation in discharge accounted for 98% of the interannual variation in the HT. This feature is similar to patterns in deep temperate reservoirs with subsurface outlets (Knowlton & Jones, 1989; Cole & Hannan, 1990).

In 1993, overturn started in late autumn and was continued until early spring of the next year. In early postmonsoon (10 September), as rainfall and inflow decreased, thermal stratification was re-established and isothermal contour lines were parallel from the headwaters to the dam (Fig. 2F). In this period, temperature differences between surface and bottom water in the headwaters, middle, and downlake were 6, 11, and 18°C, respectively (Fig. 3A). By mid-postmonsoon (24 September), however, surface cooling increased convective mixing (Wetzel 1983), resulting in vertical gradients of < 5°C within the 14~49 km reach (Fig. 2G). In late autumn (30 October), overturn occurred throughout the reservoir (Fig. 2H), and in winter (December), surface temperature dropped to 7~10°C.

In 1994, cold metalimnetic temperatures (MT) influenced the timing of fall overturn. In autumn 1994 (September), epilimnetic water (0~15 m) ranged from 21 to 22°C, similar to that in autumn

1993 (Fig. 4F, G). Metalimnetic water (20~30 m), however, was 6~8°C (Fig. 4F, G), whereas the values in autumn 1993 were 19~20°C at the 20~30 m stratum (Fig. 2F, G). Thus, mean MT in autumn 1994 was colder >10°C than in autumn 1993. Lower MT in autumn 1994 was the consequence of greater water column stability resulting from reduced inflow and meta-hypolimnetic withdrawal from the dam during monsoon. Thus, overturn in 1994 was delayed >30 days compared to in 1993, indicating that intensity of the monsoon can shift the time of overturn by one month.

Overall data suggest that the intensity of thermal stratification and mixing pattern varied among the major zones in response to river inflow and withdrawal from the dam. The intensity of the monsoon rain accounted for the most of the annual inflow and discharge and determined flow characteristics (like an interflow current) and TWRT values.

The interannual contrasts in hydrological characteristics produced distinct differences in thermal resistance (weak in 1993 vs. strong in 1994). For this reason, the reservoir based on thermal dynamics and TWRT had river-like characteristics during monsoon 1993 vs. lake-like conditions during monsoon 1994. One of the important findings in this study was the influence of density current on thermal structures. Thermal profiles during monsoon 1993 indicated that epilmnetic lake water was isolated from the metalimnetic river interflow water. Reservoir studies (Kennedy *et al*., 1982; Lind *et al*., 1993; Jones *et al*., 1997; An and Jones, 2000) have demonstrated that such phenomenon can be critical in controlling loading of nutrients (N, P) and suspended solids to a photic zone of reservoirs, thereby modifying the reservoir processes. About 50~70% of annual total precipitation occurs during thermal stratification in summer and turbid, nutrient-laden inflow water were frequently observed in the metalimnion Kim 1987. Based on these facts, interflow current may frequently occur during intense monsoon in Korean reservoirs. Under the situations, the influences of density currents on water quality should be considered in evaluating eutrophication processes in Korean reservoirs.

ABSTRACT

Seasonal thermal structure and mixing regimes were evaluated at 17 sites of Taechung Reservoir during April 1993~November 1994. A contrasting monsoon between 1993 and 1994 produced an interannual difference in hydrology. Theoretical water residence time (TWRT) in monsoon 1993 averaged 27 d, which was >3 months shorter compared to the TWRT in monsoon 1994. A dominant physical process influencing thermal stratification, water movement, and mixing regime was an interflow current in 1993. During summer 1993, river water plunged to mid-lake (location 27 km) and passed through the 10~20 m stratum of the reservoir, resulting in an isolation of epilimnetic lake water from advected river water. The interflow disrupted thermal stratification and produced a meta-hypolimnetic warming of >4°C downlake, thereby increased a mixing depth (>13 m). In contrast, during monsoon 1994 density currents were not observed and strong thermal stratification occurred in the entire reservoir, resulting in >2 fold greater thermal resistance (8.2×10^5 erg) compared to 1993 (4.0×10^5 erg). This reservoir was identified as a typical warm monomictic reservoir which showed one mixis during early winter. The timing of overturn, however, differed between the two years as a result of distinct contrast in TWRT and thermal regime; overturn in 1993 occured about one month earlier relative to that in 1994. Hypolimnetic warming was predictable in this system; the variation in discharge accounted ($Y = 4.35 - 0.06X + 0.10X^2$, $p < 0.0001$) for 98% of the interannual variation in hypolimnetic temperature. Overall data suggest that thermal stability, the timing of fall overturn, and water residence time in this system are primarily regulated by the intensity of monsoon.

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(Received 30 Nov. 2000, Manuscript accepted 5 Mar. 2001)