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Hydrological Significance on Interannual Variability of Cations, Anions, and Conductivity in a Large Reservoir Ecosystem

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대형 인공호에서 양이온, 음이온 및 전기전도도의 연변화에 대한 수리수문학적 중요성. 안광국 (이화여자대학교, 환경학과)

본 연구에서는 1993년 4월부터 1994년 11월까지, 대청호내 이온농도에 대한 하절기 강우의 영향을 파악하기 위한 일환으로 양이온, 음이온, 및 전기전도도를 분석하였다. 이온 농도의 뚜렷한 연변화는 수리수문학적 특성을 반영하였다. 1993년 이온농도의 극한 공간적 이질성은 하절기 동안 Ca^{2+} 및 HCO_3^- 농도 감소에 기인하였다. 특히, 1993년 장마기간의 중층수 유입현상은 염분농도의 호수 상~하류 구간 분포 및 수직분포(표층~심층)의 공간적 페턴을 변경시키는 주된 요인으로 작용하였다. 상류의 유입수는 댐으로부터 27~37 km의 호수 중류역에서 중층으로 유입되어 10~30 m의 수층을 통과함으로서, 표층의 높은 전기전도도를 갖는 호수물(>100 µS/cm)은 전기전도도가 낮은 하천수(>65~75 µS/cm)와 혼합되지 않음으로서 표층수 고립 현상을 가져왔다. 1993년 장마 후, 염분도를 조절하는 요인은 공간적으로 차이를 보였다; 호수의 댐근처에서 염분도는 유입수와 호수물의 혼합에 의한 희석의 결과로서 현저한 감소를 보인 반면, 호수 상류역에서 염분도는 호수로 유입되는 지하수에 포함된 $CaCO_3$ (석회암으로부터 기원) 영향으로 인해 급격한 증가를 보였다. 이런 결과는 수리수문학적 특성과 함께 유역내 지질적 특성도 이온농도에 영향을 주었음을 시사하였다. 1994년의 경우 염분도는 1993년에 비해 현저히 높았으며 ($p < 0.001$), 하절기 동안 감소된 유입수의 영향으로 이온 희석현상은 보이지 않았다. 따라서, 본 호수내 계절적 이온농도 및 성분에 영향을 주는 1차적인 요인은 하절기 몬순 강도에 의존하는 희석효과로서 사료된다.

Key words : Salinity, Cation, Anion, Reservoir, Monsoon, Korea

INTRODUCTION

Hydrodynamic fluctuations have been identified as a major source of variation of within- and inter-lakes influencing physical and chemical environments (Walker, 1982; Soballe and Threlkeld, 1985). Limnological studies in non-monsoon regions of North America and Europe have demonstrated that inflow and precipitation occur mainly in spring and fall, thus reset physical, chemical and biological conditions during summer period when rainfall is typically much reduced (Jones *et al.*, 1997). Dillon and Rigler (1974) showed a paradigm how the seasonal weather pattern is incorporated into limnological theory.

Such seasonal patterns, however, differ in waterbodies of Asian regions where rainfall and inflow distribute mainly during the summer monsoon in July-August. Lohman *et al.* (1988) emphasized that lake water volume in Asian lakes can be replaced 15 times by runoff during the monsoon, indicating that the monsoon causes

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physically unstable conditions. River inflow during flood events result in rapid flushing or short water residence time (Lind, 1993) and this conditon produces rapid replacement of lake water by river water. Studies in tropical and sub-tropical regions influenced by the seasonal monsoon (Zafar, 1986; Khondker and Kabir, 1995) found that large variation in nutrients, suspended sediments, light regime, algal biomass, and primary productivity occurred during the monsoon. Under the circumstances, ionic contents may change due to mixing processes of lake water with the monsoon rainwater and the magnitude of the variation may vary depending on locations in morphologically complex reservoirs. Dilution of lake water during the monsoon were shown in Japanese (Ohtake *et al.*, 1982), Nepalese (Lohman *et al.*, 1988; McEachern, 1996) and Indian lakes (Banerjee *et al.*, 1983; Singh, 1985). Little, however, is known in Korean waterbodies (Kim, 1987) about how the monsoon influences to ionic contents and composition in large reservoirs and lake salinity varies along the main axis of the reservoir from the headwaters to the dam. In this paper, the effect of the intensity of the monsoon on ionic contents such as cations, anions, and conductivity are evaluated in Taechung Reservoir, Korea during 1993~1994. The distinct difference in the intensity of the monsoon between 1993 and 1994 allowed me to evaluate the influence of the monsoon rainfall on lake salinity. The objectives were to document seasonal and longitudinal patterns of above ionic variables and compare ionic changes between pre-disturbance and post-distabuance in this reservoir.

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 constructed 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). The reservoir map showing sampling sites and monsoon hydrology during 1993~1994 are available in An (2000). Surface water samples were collected from these 17 sites twice each month from April 1993 to November 1994 (except in winter, January~February) with samples from several depths using a Van Dorn sampler.

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. Specific conductivity (at 25°C; YSI Model 33) were measured in the laboratory. Total alkalinity and bicarbonate (HCO_3^-; sulfuric acid titration, Orion pH meter 501), sulfate (SO_4^{2-}; barium turbidimetric method), and chloride (Cl^-; mercuric nitrate titration) were measured by A.P.H.A. (1985). Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) were determined on acid-preserved samples by using an atomic absorption spectrophotometer (Varian AA-20, A.P.H.A., 1985). Each cation and anion samples were analyzed in duplicate. Cations were estimated from the sum of calcium, magnesium, sodium, and potassium and anions from the sum of bicarbonate, sulfate, and chloride ions (Wetzel, 1983). Total salinity was estimated from the sum of the cations and anions after Wetzel (1983).

RESULTS AND DISCUSSION

Mean ionic salinity, based on monthly average by site, was 69.3 mg L^{-1} during 1993~1994 (Table 1). This value is 34% lower than the world's average (105 mg L^{-1}), and 46% lower than the Asian average (129 mg L^{-1}) for freshwater (Wetzel, 1983). Calcium (Ca^{2+}) was the predominant cation, accounting for 47% of the cations, and potassium (K^+) was the rarest (about 10% of the total). Bicarbonate (HCO_3^-) was the predominant anion accounting for 57%, and sulfate (SO_4^{2-}) and chloride (Cl^-) made up 16% and 27%, respectively. The relative order of proportion among the cations was $Ca^{2+} > Na^+ > Mg^{2+} > K^+$, indicating a typical soft waters (Lampert and Sommer, 1997) with low salinity and was similar to rivers and reservoirs in nothern Korea (Hong *et al.*, 1989). The magnitude of anonic proportion was $HCO_3^{2-} > Cl^- > SO_4^{2-}$ in the reservoir (Table 1). Overall salinity data suggest that the reservoir shows a characteristic of rock dominance (after

Table 1. Interannual and seasonal changes of major cations (Ca^{2+}, Na^+, Mg^{2+}, K^+; mg/l) and anions (Cl^-, SO_4^{2-}, HCO_3^-; mg/l) during 1993~1994. The "PRE", "MON", and "POST" indicate premonsoon (January~June), monsoon (July~August), and postmonsoon (September~November), respectively. Each data values averaged from 17 sites in each season. The values in the parenthesis indicate standard deviations.

Year	Season	Cations				Anions		
		Ca^{2+}	Na^+	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-
1993	PRE	11.5 (±0.3)	5.5 (±0.3)	2.6 (±0.1)	2.4 (±0.1)	11.2 (±0.6)	8.2 (±0.9)	27.0 (±1.4)
	MON	8.5 (±1.2)	6.2 (±0.6)	2.1 (±0.1)	2.0 (±0.1)	11.7 (±2.1)	7.2 (±0.8)	21.5 (±3.6)
	POST	7.9 (±0.3)	6.0 (±0.2)	2.1 (±0.1)	1.6 (±0.1)	12.6 (±0.2)	7.7 (±0.3)	25.2 (±1.8)
1994	PRE	10.9 (±0.5)	7.4 (±0.3)	2.6 (±0.1)	2.0 (±0.1)	14.1 (±0.8)	8.0 (±0.5)	28.9 (±1.8)
	MON	10.2 (±0.6)	7.0 (+0.4)	2.4 (±0.1)	2.7 (±0.3)	14.0 (±1.0)	7.4 (±0.8)	32.6 (±1.0)
	POST	10.0 (±0.2)	7.1 (±0.5)	2.7 (±0.1)	2.5 (±0.2)	14.6 (±0.8)	6.8 (±0.9)	31.2 (±1.6)

Table 2. Longitudinal distribution of epilimnetic mean conductivity (mean±standard error) at each sampling site (mainstem and embayment sites) in 1993 (n = 14) and 1994 (n = 13).

Mainstem Sites	1993		1994	
	Mean±SE (μS/cm)	Range (μS/cm)	Mean±SE (μS/cm)	Range (μS/cm)
Site 1	97±7	71~134	128±5	100~154
Site 3	99±6	70~132	127±5	104~152
Site 4	97±6	65~130	129±4	110~153
Site 7	106±3	94~122	129±3	115~150
Site 8	104±3	91~120	129±4	110~150
Site 10	101±3	88~123	128±3	110~153
Site 14	100±3	85~115	122±4	105~150
Site 15	100±3	87~114	119±3	102~137
Site 16	101±3	87~116	117±3	100~133
Embayment Sites				
Site 2	107±5	76~132	130±7	100~199
Site 5	133±5	90~148	144±6	120~185
Site 6	100±4	87~125	130±3	118~150
Site 9	101±3	87~122	133±3	120~150
Site 11	100±3	86~122	123±4	103~158
Site 12	98±3	83~118	120±3	105~145
Site 13	98±3	87~115	122±4	105~158
Site 17	101±3	84~115	120±3	100~142

Gibbs, 1970) in which the major proportion of salinity was calcium and bicarbonate. The basin geology is principally metamorphic rock−mostly slatey limestone and cherty dolomite−and igneous rocks (granite, Choi *et al.*, 1988; Jeong and Choi, 1991), so this ionic composition is expected.

Total salinity was some 18% greater in 1994 than 1993. The absolute concentration of mean Ca^{2+} and Mg^{2+} in 1994 was 12% and 13% greater, respectively compared to 1993 and HCO_3^{2-} in 1994 was 26% greater. The greater cations and anions in 1994 were attributed to reduced inflow.

Interannual variation in conductivity followed the pattern for salinity. Conductivity in 1993 ranged between 65 and 148 μS/cm and the annual mean was 102 μS/cm, whereas in 1994 it ranged between 100 and 199 μS/cm and the annual mean was 127 μS/cm (Table 2). The mean value in 1994 was 25% greater than that of 1993.

Seasonal changes in ionic salinity were influenced by the intensity of the Asian monsoon. During premonsoon 1993 salinity was 68.3 mg L^{-1} with Ca^{2+} and Na^+ dominating the cations (78%) and HCO_3^- the anions (40%; Table 1). Total salinity decreased by 14%, mainly resulted from a decrease in Ca^{2+} and HCO_3^- during the monsoon Total divalent cations (Ca+Mg) decreased 25%, whereas the monovalent cations (Na+K) varied little (Table 1). Decreases in HCO_3^{2-} and SO_4^{2-} were 20% and 12%, respectively, relative to premonsoon, while Cl^- increased 4%. Conductivity also decreased up to 30% (especially, in the headwaters) during this monsoon (Fig. 1). It is evident that ionic dilution of lake water occurred during the 1993 monsoon and this was due to large precipitation and river inflow. Such seasonal dilutions are similar to the finding in Japanese (Ohtake *et al.*, 1982), Nepalese (Lohman *et al.*, 1988; McEachern, 1996) and Indian lakes (Banerjee *et al.*, 1983; Singh, 1985), suggesting that the monsoon is the primary factor regulating the ionic content in these Asian lakes.

Ionic dilution did not occur during monsoon 1994. There was no significant ($p = 0.21$) difference in salinity between monsoon 1994 (76.2 mg/l) and premonsoon 1994 (73.9 mg/l; Table 1). In fact, conductivity was highest (>130 μS/cm) among seasons during monsoon 1994 (Fig. 1).

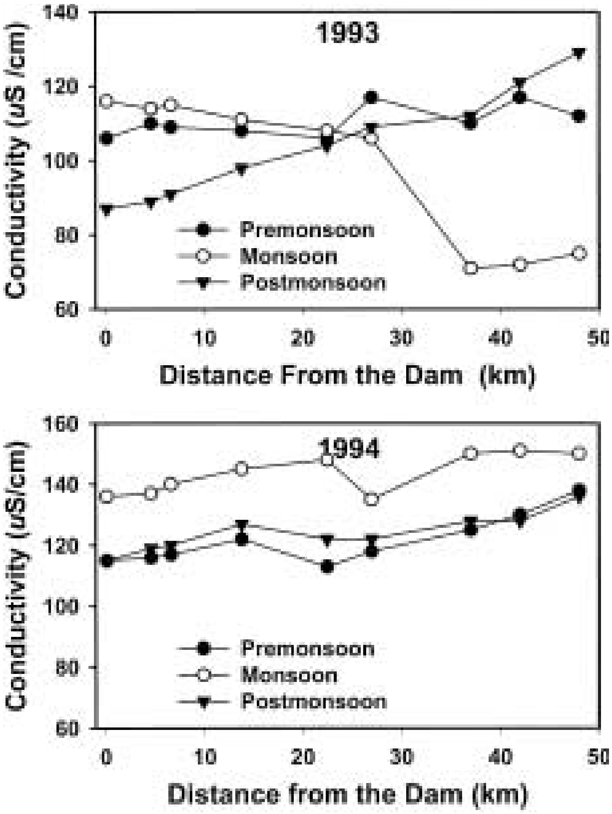

Fig. 1. Seasonal changes of epilimnetic conductivity at each sampling site in 1993 and 1994. Conductivity in 1993 was sampled in premonsoon (22 May), monsoon (17 July), and postmonsoon (31 October) and in 1994 conductivity was sampled in premonsoon (9 May), monsoon (13 July), and postmonsoon (30 September).

Values of K^+ and HCO_3^{2-} during the monsoon increased 35% and 13%, respectively while Ca^{2+} and Mg^{2+} decreased slightly ($<7\%$; Table 1).

Major inflows during monsoon 1993 diluted ionic salinity and the degree of dilution differs from the headwaters to the dam. During premonsoon 1993, there was a weak longitudinal gradient in conductivity; values changed little from the headwaters (117 µS/cm) to downlake (106 µS/cm; Fig. 1).

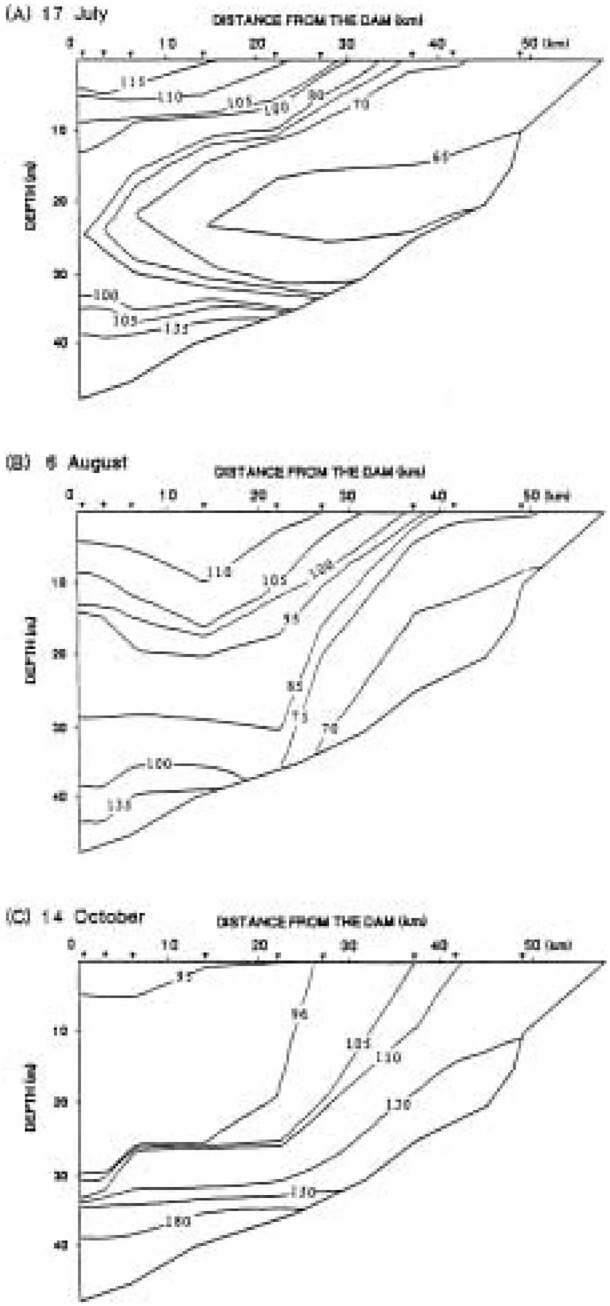

Fig. 2. Vertical distribution of conductivity along the main axis of the reservoir from the headwaters (location−50 km) to the dam in July 17 (A), 6 August (B), and October 14, 1993 (C). The dark triangles indicate the sampling locations along the main axis of the reservoir.

One of the dominant processes modifying the spatial pattern in salinity was ionic dilution by an interflow current during monsoon 1993 (Fig. 2). The degree of dilution differed longitudinally as water mass passed through the reservoir; the dilution was most pronounced in the headwaters during monsoon 1993 with a less influence on downlake. As shown in Fig. 2A, conductivity values in surface water were <70 µS/cm in the headwaters (location 37∼50 km) and were almost vertically homogeneous within the interflow. In contrast, values in the reach between the plunge

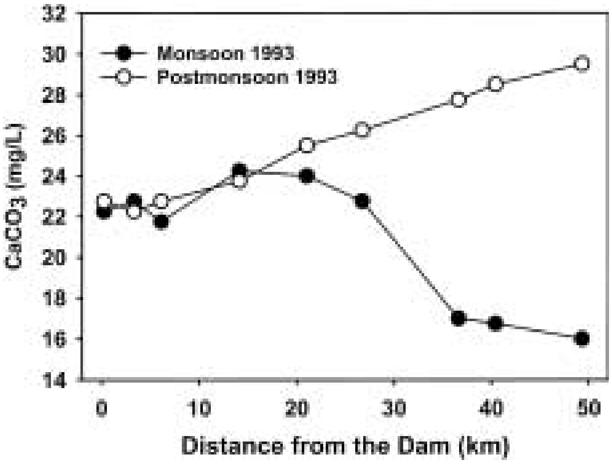

Fig. 3. Longitudinal distribution of $CaCO_3$ mg/L during monsoon 1993 and postmonsoon 1993. Each data point indicates an average by site during the monsoon (n = 4) and postmonsoon (n = 4).

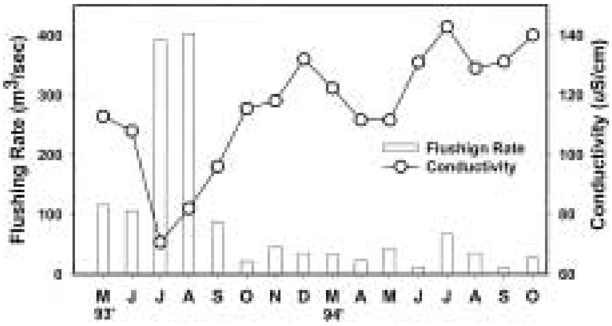

Fig. 4. The influence of the flushing rate on monthly mean epilimnetic conductivity. Each data point indicates monthly average values in 1993 and 1994.

-point and dam (0～27 km) were > 105 μS/cm. For this reason, maximum longitudinal difference (> 30 μS/cm) in conductivity occurred at the plunge point (Fig. 2A). These outcomes imply that physical factor (i.e., interflow) may be a key component for influencing spatial pattern of salinity in reservoirs (Vincent *et al.*, 1991). A similar result was found in Soyang Reservoir during summer when high inflows and turbid water dominated (Kim, 1987). These findings suggest that the process of interflow is likely an important factor causing the spatial variation of ionic contents in many Korean reservoirs.

Major factors regulating salinity during postmonsoon 1993 differed between the headwaters and downlake. Conductivity during the postmonsoon (30 September) markedly decreased some 14% at downlake (location 0～8 km) compared to the monsoon (Fig. 1). Conductivity in the headwaters, however, increased during postmonsoon 1993 (Fig. 1); conductivity was greater by 39% than the values during monsoon 1993, resulting in a longitudinal decline from the headwaters to the dam. This situation was opposite to that of the monsoon when salinity increased from the headwaters to downlake. The decline in epilimnetic salinity at downlake during the postmonsoon was a result of dilution by vertical mixing of high salinity epilimnetic water (> 105 μS/cm in conductivity at 0～5 m) and low salinity metalimnetic flood water (< 80 μS/cm at 6～20 m, Fig. 2C). In contrast, increases of salinity in the headwaters may be attributed to groundwaters entering the reservoir (Wetzel, 1983). This suppossition may be supported by marked increases (> 70%) of calcium carbonate ($CaCO_3$) in the headwaters during the postmonsoon compared to the 1993 monsoon (Fig. 2). These processes produced a weak downlake gradient in salinity.

In premonsoon 1994 (9 May), mean conductivity (121 μS/cm) was slightly greater relative to premonsoon 1993 (111 μS/cm). In this period, conductivity decreased along the main axis from the headwaters (131 μS/cm) to downlake (115 μS/cm, Fig. 1). The declining pattern toward the downlake was similar to that in premonsoon 1993.

Conductivity during monsoon 1994 showed a downlake decrease, contrary to monsoon 1993. Reduced inflow (< 100 m^3/sec) during monsoon 1994 produced mean conductivity > 125 μS/cm in all locations (Fig. 1) and values declined from the headwaters to the dam. This pattern was continued during postmonsoon 1994. As shown in Fig. 4, seasonal conductivity had an inverse relation with flushing rate during 1993～1994; conductivity values were < 85 μS/cm when flushing rate was > 350 m^3/sec, while values were > 100 μS/cm when flushing rate was < 80 m^3/sec. This outcome suggests that the high conductivity during all seasons in 1994 and the minimum during monsoon 1993 reflected water retention time.

Large inflows in 1993 also caused a horizontal heterogeneity in salinity between mainstem and embayment sites. In premonsoon 1993, mean conductivity in the mainstem sites (110 μS/cm) was similar to that in the embayments (111 μS/

Table 3. Horizontal heterogeneity of surface mean conductivity (μS/cm) between mainstem sites (Site 1, 3 and 4) and embayment site (Site 2 and 5) in the headwater zone in 1993 and 1994.

1993			1994		
Month	Conductivity at mainstem site	Conductivity at embayment site	Month	Conductivity at mainstem site	Conductivity at embayment site
27 MAY	110	111	10 MAY	112	122
01 JUL	68	129	07 JUL	122	153
17 JUL	72	107	26 JUL	150	168
08 AUG	75	82	03 AUG	148	154
21 AUG	78	88	18 AUG	138	143
10 SEP	88	88	07 SEP	131	147
24 SEP	99	100	30 SEP	130	131
15 OCT	107	109	14 OCT	127	138
19 NOV	116	118	09 NOV	107	111

cm; Table 3). In early monsoon 1993 conductivity markedly declined in the mainstem but it increased in the embayments, resulting in the greatest difference ($>$60 μS/cm) between the two locations during this study. This difference disappeared in early postmonsoon (September) as a result of continued mixing of high salinity lake water and low salinity river water in embayments. Large horizontal difference of conductivity indicates that river runoff during early monsoon directly passed through the main axis (mainstem sites) of the reservoir and as water level increases, dilution expanded to the embayment sites. In contrast, during monsoon 1994 conductivity increased significantly ($p < 0.001$) in both locations compared to premonsoon 1994, indicating no dilution and little horizontal variation (Table 3).

Overall data suggest that the major component regulating ionic contents in Taechung Reservoir was a dilution process by monsoon rain and river inflow. The dilution, however, varied spatially and temporally in response to the magnitude of the monsoon rain and inflow. It is evident that density current such as interflow may be a major determinant regulating vertical, longitudinal and horizontal variation of ionic contents. This low salinity interflow was an excellent tracer of flow, and provided an opportunity to answer questions about how the interflow dilutes the lake water along the main axis of the reservoir (Ford, 1990). These processes are likely important in Korean reservoirs because over half of the rainfall and inflow occurs during the summer monsoon when thermal stratification is usually strong. Rigorous regional comparisons of this dilution are not possible because few spatial and temporal measurements in salinity have been published for Asian reservoirs. According to reservoir studies of non-monsoon regions, interflow current also can modify mixing regime (Wunderlich, 1971; Ford, 1990), dissolved oxygen content (Cole and Hannan, 1990), and nutrient distribution (Kennedy *et al*., 1982; Lind *et al*., 1993), suggesting that physical processes have major implications for controlling eutrophication in reservoirs (Vincent *et al*., 1991; Soballe *et al*., 1992; Lind *et al*., 1993). Further studies are required to elucidate the roles of interflow current on other water quality variables as well as ionic contents of reservoirs in Korea.

ABSTRACT

During April 1993 to November 1994, cations, anions, and conductivity were analyzed to examine how summer monsoon influences the ionic content of Taechung Reservoir, Korea. Interannual variability of ionic content reflected hydrological characteristics between the two years (high-flood year in 1993 vs. draught year in 1994). Cations, anions and conductivity were lowest during peak inflow in 1993 and highest during a drought in 1994. Floods in 1993 markedly decreased total salinity as a result of reduced Ca^{2+} and HCO_3^- and produced extreme spatial heterogeneity (i.e., longitudinal, vertical, and horizontal variation) in ionic concentrations. The dominant process modifying the longitudinal (the headwaters-to-downlake) and vertical (top-to-bottom) patterns in salinity was an interflow current during the 1993 monsoon. The interflow water plunged near a 27∼37 km-location (from the dam) of the mid-lake and passed through

the 10～30 m stratum of the reservoir, resulting in an isolation of epilimnetic high conductivity water (>100 μS/cm) from advected river water with low conductivity (65～75 μS/cm). During postmonsoon 1993, the factors regulating salinity differed spatially; salinity of downlake markedly declined as a result of dilution through the mixing of lake water with river water, whereas in the headwaters it increased due to enhanced $CaCO_3$ (originated from limestone/metamorphic rock) of groundwaters entering the reservoir. This result suggests an importance of the basin geology on ion compositions with hydrological characteristics. In 1994, salinity was markedly greater ($p < 0.001$) relative to 1993 and ionic dilution did not occur during the monsoon due to reduced inflow. Overall data suggest that the primary factor influencing seasonal ionic concentrations and compositions in this system is the dilution process depending on the intensity of monsoon rainfall.

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