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Temporal and spatial patterns in salinity and suspended solids in a reservoir influenced by the Asian monsoon

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Abstract

Between April 1993 and November 1994, conductivity, cations, anions and suspended solids were measured at multiple sites in Taechung Reservoir, Korea. The major mechanism regulating ionic composition was dilution by monsoon rain and a resulting interflow current; these forces caused marked spatial and temporal heterogeneity. Ionic dilution was most pronounced in the headwaters during an intense monsoon in 1993 and was accompanied by an increase in the proportion of Na^+ and Cl^-, presumably from rainwater. A decrease of >25% in conductivity and cations occurred during summer 1993 at the plunge-point due to a temperature difference between the lake water and an interflow. In contrast, the 1994 monsoon was weak, ionic dilution was not apparent, and spatial-temporal variation was modest. Overall reservoir salinity was a direct function of water residence time which is regulated by monsoon intensity. Differences in hydrology between years also influenced seston composition; inorganic suspended solids dominated total suspended solids in 1993, but in 1994 the organic fraction was the major component.

Introduction

Limnological studies of Asian lakes show that the monsoon can drastically reduce hydraulic retention time and increase mixing depth (Singh, 1985; Zafar, 1986; Jones et al., 1989; Ho, 1994; Davis et al., 1998). Lohman et al. (1988) reported that the volume in Nepalese lakes can be replaced 15 times by monsoon runoff. Under such conditions, cation concentrations and conductivity decrease due to dilution by rain water (Bjarnborg, 1983; Akhurst & Breen, 1988; Ali et al., 1988; McDowell & Asbury, 1994; Elewa, 1985; Stogner et al., 1996) and ionic composition and suspended solids are often altered (Flora & Rosendahl, 1982; Sinada & Karim, 1984; Lohman et al., 1988). Thus, the monsoon may be a major factor in determining seasonal patterns in water chemistry in many Asian waterbodies.

Little is known about how water chemistry varies in morphologically complex reservoirs influenced by the Asian monsoon. Temporal and spatial patterns in water chemistry may be complex when flood waters enter reservoirs as an interflow or underflow (Vincent et al., 1991; Davis et al., 1998). The effect of these density currents on thermal regime (Wunderlich, 1971; Carmack et al., 1986; Ford, 1990), dissolved oxygen (Cole & Hannan 1990), and nutrient distribution (Kennedy et al., 1982; Lind et al., 1993; Knowlton & Jones, 1995) has been reported in North American reservoirs. These processes are also likely important in Korean reservoirs where over half of the rainfall occurs during the summer monsoon (July–August; Watts, 1969). Inflows resulting in turbid-interflows have been observed frequently in Soyang Reservoir during summer (Kim, 1987), but the influence on salinity and solids is unknown.

This study was conducted in Taechung Reservoir, South Korea during a period when an intense monsoon in 1993 contrasted sharply with a severe drought during summer 1994. The difference between wet- and dry conditions provided a natural contrast to evaluate the role of the monsoon climate on ionic salinity

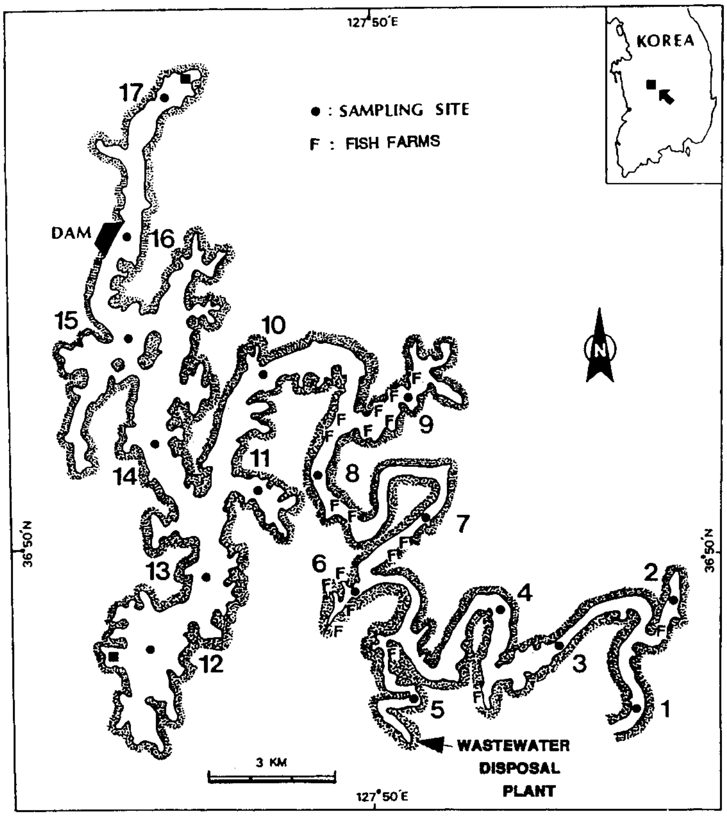

Figure 1. Map of Taechung Reservoir showing sampling sites. Sites 1–4, 7–8 and 10–16 indicate the headwaters, mid-lake and downlake, respectively.

and seston composition. In this study, we describe monsoon conditions, and spatial-temporal variability in ionic parameters and suspended solids. Our objective was to evaluate how these parameters responded to inflow during the monsoon.

Site description and methods

Taechung Reservoir, located in the middle of South Korea (36° 50′ N, 127° 50′ E), was formed in December 1980 by impounding the Keum River about 150 km upstream from its estuary (Figure 1). At an elevation of 80 m MSL (Mean Sea Level), the reservoir has a surface area of 6.8×10^7 m^2 and a volume of 14.3×10^8 m^3, with a mean depth of 21.2 m and maximum depth of 69 m.

The selection of sampling sites was based on the morphometry along the longitudinal axis of the reservoir (Figure 1): 9 mainstem sites (sites 1, 3, 4, 7, 8, 10, 14, 15 and 16) and 8 embayment sites (sites 2, 5, 6, 9, 11, 12, 13 and 17). Surface water samples were collected from these 17 sites twice each month from May 1993 to November 1994 (except in winter, January–February), and subsurface samples were collected using a Van Dorn water sampler at various depths. In this study, the headwater, middle and downlake zones typically include sites 1–4, 5–9 and 10–17, respectively. Also, we used the terminology, premonsoon (January–June), monsoon (July–August) and postmonsoon (September–December) to describe temporal conditions.

Total alkalinity (sulfuric acid titration, Orion pH meter 501), sulfate (SO_4^{2-}, barium turbidimetric method) and chloride (Cl^-, mercuric nitrate titration) were measured following A.P.H.A. (1985). Cations including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+) were determined on acid preserved samples using an atomic absorption spectrophotometer (Varian AA-20; A.P.H.A., 1985). Salinity was calculated as the sum of anions ($HCO_3^- + SO_4^{2-} + Cl^-$) and cations ($Ca^{2+} + Mg^{2+} + Na^+ + K^+$) after Wetzel (1983). Water temperature was measured at the time of sample collection using DO meter (Yellow Springs Instr., Model 51B); specific conductivity (at 25 °C, YSI Model 33) and nephelometric turbidity (HACH Model 2100A) were measured in the laboratory. Total suspended solids (TSS) were determined by filtering water through preweighed Whatman GF/C filters (pore size 1.2 μm). Filters were weighed after drying at 103 °C for 1 h. Non-volatile suspended solids (NVSS) were determined by combustion at 550 °C for 1 h (A.P.H.A., 1985) and volatile suspended solids (VSS) were determined by difference; appropriate corrections were made for blanks. Cations, anions and suspended solids were measured in duplicate.

Monsoon condition and hydrology

Precipitation

Annual precipitation at the reservoir averaged 1100 mm during 1981–1994. The major difference in rainfall between the 2 study years occurred during the monsoon. Total precipitation during July–August 1993 was 660 mm which comprised 43% of the annual total, but in the same period in 1994 rainfall was only 251 mm (Figure 2a). During the monsoon, rainfall in 1993 was 164% of the mean during 1981–1992, whereas rainfall in 1994 was 50% of the long term mean. Precipitation was similar during the remaining periods of these 2 years.

Inflow and outflow

Major sources of water to Taechung Reservoir are inflows from the Keum River and direct precipitation onto the reservoir. During 1981–1992, major inflows occurred during the July–August monsoon (Figure 2b) and accounted for 64% of total annual inflow. Total inflow in 1993 was four times that of 1994 (0.83×10^9 m^3), and summer inflow in 1993 was some 8 times greater than summer 1994 (Figure 2b). These differences produced distinct interannual variation in water balance; there was a marked increase (positive value $>$ 300) in storage volume after mid-July 1993, and a consistent deficit (accumulated inflow – outflow, < -100) in 1994 because of discharge from the dam.

In 1993, daily discharge ranged between a peak flow of about 995 m^3 s^{-1} in August to a base flow of 31 m^3 s^{-1} in February. In contrast, peak instantaneous discharge in 1994 was 83 m^3 s^{-1} and the lowest was 2 m^3 s^{-1}. Thus, peak discharge differed by 12-fold between the 2 years. In 1994, total outflow was only 27% of 1993 and summer outflow in 1994 was 8% of summer 1993.

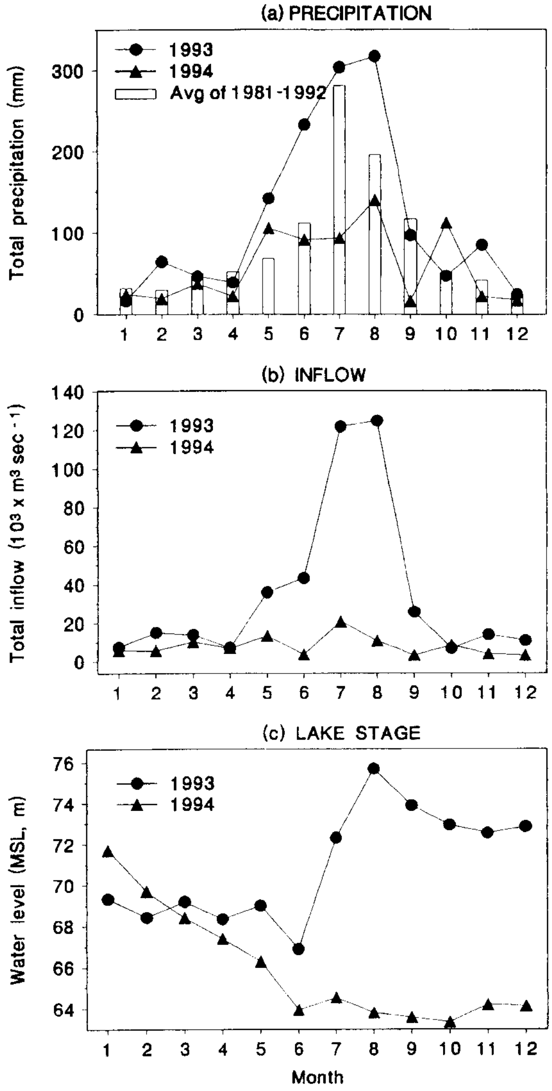

Figure 2. Seasonal fluctuation of hydrological variables ((a) precipitation, (b) inflow, and (c) lake stage) in 1993, 1994 and 1981–1992. A distinct difference in these variables occurred between monsoon 1993 and 1994.

Lake stage

Mean monthly lake stage during 1981–1992 showed a typical pattern with the highest level in September, immediately after the summer monsoon, and lowest in June before the monsoon (Figure 2c). Mean water level was 71.0 m (in MSL) in 1993 and 66.2 m in 1994. Lake stage during monsoon 1993 was $>$10 m greater than during monsoon 1994.

Table 1. Annual mean concentration of major cations, anions, conductivity, turbidity and suspended solids in Taechung Reservoir. Mean values were averaged across 17 sites and were compared with Student's *t*-test. For each variable, significant differences between the 2 years are indicated with astricks: $^{*}p < 0.001$, $^{**}p < 0.0001$, and N.S. = not significant ($p > 0.05$)

Constituent	1993	1994
	Mean±SD (Range) ($n = 17$)	Mean±SD (Range) ($n = 17$)
Ca^{2+} (meq l^{-1})	0.417±0.020 (0.124–0.691)	0.532±0.020 (0.224–0.810)**
Na^{+} (meq l^{-1})	0.261±0.009 (0.131–0.348)	0.352±0.022 (0.226–0.770$**$
Mg^{2+} (meq l^{-1})	0.181±0.008 (0.041–0.263)	0.206±0.008 (0.099–0.280)**
K^{+} (meq l^{-1})	0.046±0.003 (0.015–0.097)	0.061±0.003 (0.031–0.087)**
Cl^{-}(meq l^{-1})	0.344±0.008 (0.226–0.409)	0.398±0.025 (0.324–0.564)**
$SO_4{}^{2-}$ (meq l^{-1})	0.156±0.004 (0.073–0.327)	0.154±0.012 (0.087–0.364)^{NS}
$HCO_3{}^{-}$ (meq l^{-1})	0.395±0.020 (0.213–0.574)	0.490±0.013 (0.361–0.656)**
Conductivity (μS cm^{-1})	101.6±3.7 (65–148)	126.1±6.2 (100–199)**
Turbidity (NTU)	5.5±3.0 (1.0–51.0)*	3.1±0.9 (0.6–16.0)
TSS (mg l^{-1})	5.7±2.6 (0.9–50.6)*	4.1±1.4 (0.5–15.6)
NVSS (mg l^{-1})	3.2±2.1 (0.2–44.8)**	1.6±0.8 (0.2–11.0)
VSS (mg l^{-1})	2.3±0.7 (0.1–11.4)	2.5±0.8 (0.1–12.4)^{NS}

Results

Salinity, measured as the sum of cations and anions, averaged 1.03 meq l^{-1} or 68.5 mg l^{-1} during the study (Table 1). Calcium (Ca^{2+}) and sodium (Na^{+}) were the predominant cations, accounting for 44% and 30% of the total equivalents, respectively, and potassium (K^{+}) was the most rare (about 5%). Bicarbonate (HCO_3^{-}) accounted for 46% of the anions, and chloride (Cl^{-}) and sulfate ($SO_4{}^{2-}$) made up 38% and 16%, respectively.

Temporal variation

Salinity showed seasonal fluctuations that were tied to the hydrograph. During monsoon 1993, five major storms caused abrupt increases in river flow ($>7\times10^7$ m^3 d^{-1}), thereby decreasing water residence time (WRT) to 15 – 50 d. These flows decreased Ca^{2+} (8.8 mg l^{-1}), K^{+} (1.9 mg l^{-1}), and HCO_3^{-} (22.1 mg l^{-1}) >15% compared to the premonsoon (Figures 3 and 4). Conductivity and total cations also decreased by >20% during the monsoon (Figure 5) and the minimum values <75 μS cm^{-1} and <0.08 meq l^{-1} (or 19.9 mg l^{-1}) occurred during peak inflow (> 1.5×10^8 m^3 d^{-1}; Table 2). Subsequently, conductivity and cations increased >40% as WRT values increased to 70 d during October–December 1993 (Figure 5). In contrast, a drought during monsoon 1994 (Figure 2) resulted in conductivity >120 μS cm^{-1} and cations >1.05 meq l^{-1} when WRT was >110 d (Figure 5).

Major changes in ionic composition occurred during monsoon 1993 (Figures 3 and 4). The proportion of Na^{+} and Cl^{-} increased >8% relative to the premonsoon, while Ca^{2+} and $HCO_3{}^{-}$ decreased >10% (Figures 3 and 4). Relative proportions in Mg^{2+} and K^{+} changed little (<0.5%). During 1993–1994, Na^{+} values, expressed as a percentage of equivalents, were positively correlated ($r = 0.70, p < 0.01, n = 339$) with Cl^{-} and inversely correlated with ($r > -0.46$, $p < 0.01, n = 339$) with Ca^{2+} and K^{+} (Table 3).

Mean total suspended solids (TSS, 5.7 mg l^{-1}) in 1993 were significantly ($p < 0.001$, $n = 17$) greater than in 1994 (Table 1). This difference was mostly a function of non-volatile suspended solids (NVSS) being >17 mg l^{-1} in the headwaters during maximum flow in summer 1993 (Figure 5). Peak NVSS declined >80% during postmonsoon in response to reduced inflow. In contrast, volatile suspended solids (VSS) dominated total solids during all seasons in 1994 except during April. There was no seasonal peak in NVSS in 1994 and values never exceeded >2 mg l^{-1} even during the monsoon.

Spatial variation

Salinity showed a consistent longitudinal decline along the main axis of the reservoir from the headwa-

Table 2. Longitudinal difference of conductivity and cation along the mainstem axis of the reservoir in 1993. Locations 48-km, 42-km and 37-km indicate the headwaters (Sites 1, 3 and 4), locations 27-km and 22-km indicate mid-lake (Site 7 and 8), and locations of 14-km to 0-km indicate downlake (Site 10–16). The shaded area indicates the movement of low salinity water (conductivity <100 μS cm^{-1} and cations <0.90 meq l^{-1}) from the headwaters to downlake

Date	Site								
	48-km	42-km	37-km	27-km	22-km	14-km	6-km	3-km	0-km
22 May	112	117	106	108	109	110	106		
1 Jul	■	■	■	112	115	105	107	105	106
17 Jul	■	■	■	106	108	111	115	114	116
6 Aug	■	■	■	110	111	100	101	110	109
21 Aug	■	■	■	■	■	■	■	■	■
1 Sep	100	■	■	■	■	■	■	■	■
24 Sep	104	105	■	■	■	■	■	■	■
15 Oct	114	110	107	■	■	■	■	■	■
31 Oct	129	121	112	109	■	■	■	■	■
19 Nov	122	121	112	106	102	■	■	■	■
16 Dec	134	132	130	122	120	123	■	■	113
(b) Cation (meq l^{-1})									
22 May	1.121	1.117	1.102	1.080	1.060	1.057	1.057	1.061	1.060
1 Jul	■	■	■	1.141	1.161	1.084	1.084	1.083	1.111
17 Jul	■	■	■	0.885	0.934	0.864	0.864	0.959	0.913
6 Aug	■	■	■	0.900	0.910	0.845	0.845	0.919	0.920
21 Aug	■	■	■	■	■	■	■	■	■
1 Sep	0.885	■	■	■	■	■	■	■	■
24 Sep	1.005	1.024	0.890	■	■	■	■	■	■
15 Oct	0.985	1.056	1.007	0.897	■	■	■	■	■
31 Oct	1.061	1.033	0.985	0.984	0.940	■	■	■	■
19 Nov	0.989	0.820	0.940	0.962	0.960	0.869	■	■	0.846
16 Dec	0.570	0.860	0.884	0.981	0.960	0.960	0.960	0.982	0.890

Table 3. Correlation coefficients among ionic compositions expressed as a percent of equivalents (meq l^{-1}) during 1993–1994 (n = 339). If correlation coefficient (r) is $\leqslant 0.14$, then $p \leqslant 0.05$, and if r is $\geqslant 0.15$, $p \leqslant 0.01$. In the Table, 'NS' indicates 'not significant'

	Na^+	Mg^{2+}	K^+	Cl^-	HCO_3^-	$(Ca^{2+}+Mg^{2+})$
Ca^{2+}	−0.75	N.S.	0.13	−0.14	0.31	0.80
Na^+		−0.42	−0.46	0.70	N.S.	−0.97
Mg^{2+}			0.28	N.S.	N.S.	0.40
K^+				N.S.	N.S.	0.24
Cl^-					N.S.	−0.14
HCO_3^-						0.17

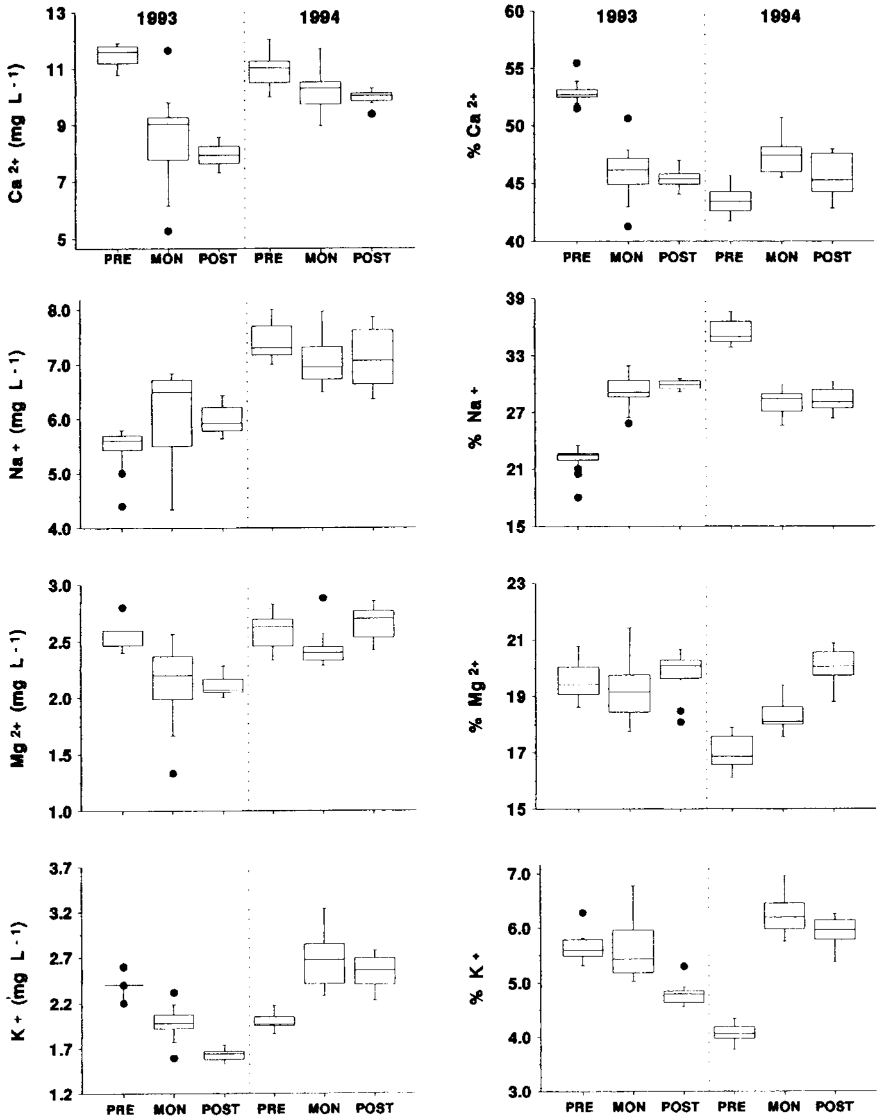

Figure 3. Temporal variation in absolute concentration (left column) and the proportion of cations (right column, expressed as %) between 1993 and 1994. The 'PRE', 'MON' and 'POST' indicates premonsoon (January–June), summer monsoon (July–August) and postmonsoon (September–November). In the box plot, the dark point indicates outliers and the horizontal line within the box indicates the mean value. The box indicates interquartile range and the vertical line indicates a distance 1.5 times the interquartile range.

ters to downlake during all seasons except monsoon 1993. Typically, conductivity and cations were 5–15% greater in the headwaters than downlake (Table 2) and values at mid-lake (sites 5–9) were intermediate. An increase of ~15% in conductivity was evident in mid-lake embayments (sites 5 and 6) where intense fish farms and/or the wastewater disposal plant influence water quality.

The longitudinal pattern in salinity was largely modified by density currents (Figure 6). Early in the monsoon (2–17 July 1993), flood water >2–3 °C cooler than lake surface temperature partially disrupted thermal stratification in the headwaters and plunged as an interflow mid-lake between location 27 and 37 km (Figure 6). During this period, conductivity and cations in the headwaters (location 37–50 km) were <75 μS cm^{-1} and <0.85 meq l^{-1}, respectively, whereas values were > 100 μS cm^{-1} and >0.90 meq l^{-1} downlake (0–27 km, Figure 6). A change of >30 μS cm^{-1} in conductivity occurred at the inter-

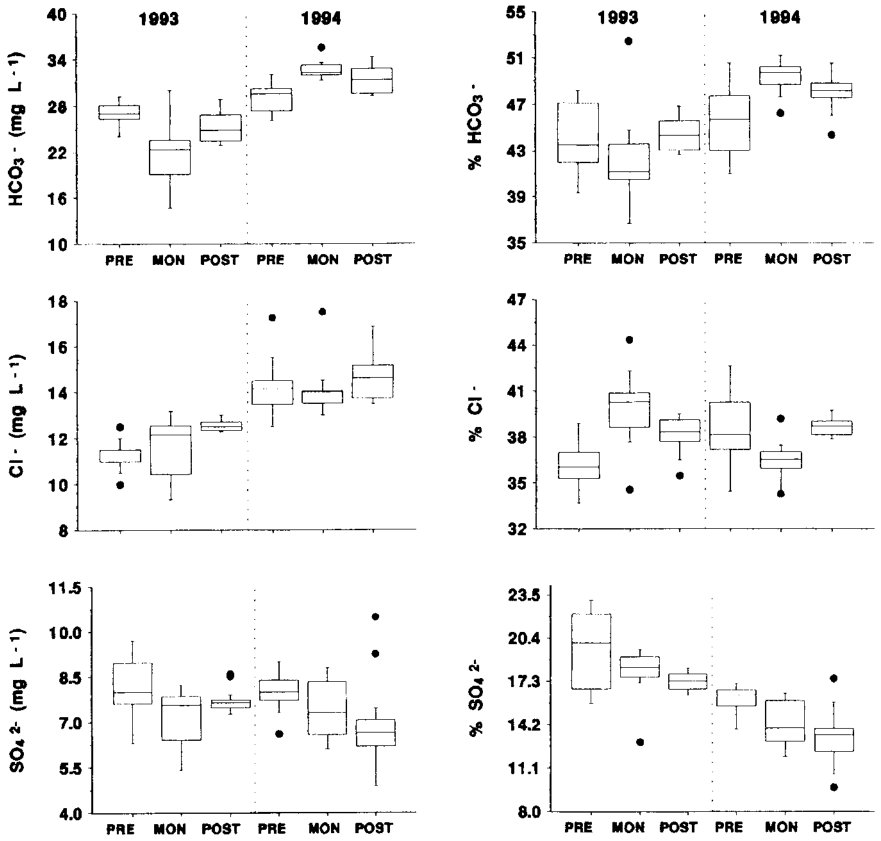

Figure 4. Temporal variation in absolute concentration (left column) and the proportion of anions (right column) between 1993 and 1994. Ditto with Figure 3.

flow (Figure 6a) and coincided with sharp decline in cations (25% as meq l^{-1}, Figure 6b). For this reason, conductivity in the water column showed vertical differences near mid-lake and downlake; values were >100 μS cm^{-1} near the surface vs. <80 μS cm^{-1} at the 15–30 m stratum of the reservoir, suggesting the interflow movement through the metalimnion.

Inflows also caused differences in salinity between mainstem and embayment sites (Figure 7). During premonsoon 1993, no difference in conductivity was observed between mainstem (111 μS cm^{-1}) and embayment sites (112 μS cm^{-1}, Figure 7). In early monsoon 1993, however, conductivity markedly declined by <70 μS cm^{-1} in the mainstem while it increased in the embayments, resulting in a difference of >60 μS cm^{-1} between the two zones. This difference was attributed to an isolation of embayment water from the monsoon runoff in the mainstem.

In contrast, the weak monsoon in 1994 resulted in little spatial variation in ionic variables. During premonsoon 1994 (May), conductivity decreased longitudinally from the headwaters (131 μS cm^{-1}) to downlake (115 μS cm^{-1}, Figure 8). Cations and anions also showed a slight downlake-decrease during the premonsoon. This longitudinal gradient continued during postmonsoon 1994. No interflow was observed during monsoon 1994.

Discussion

Water in Taechung Reservoir is of the bicarbonate type, characterized by a predominance of Ca^{2+} among the cations and HCO_3^- among the anions. The basin geology is principally composed of metamorphic rock – mostly slatey limestone and cherty dolomite – and igneous rock (Jeong & Choi, 1991; Choi et al., 1988), so this ionic composition is expected. At 68.5 mg l^{-1}, total salinity in this reservoir is about two-thirds of the world's average (105 mg l^{-1}), and about half the Asian average (129 mg l^{-1}) for freshwater (Wetzel, 1983). These values of total dissolved solids are

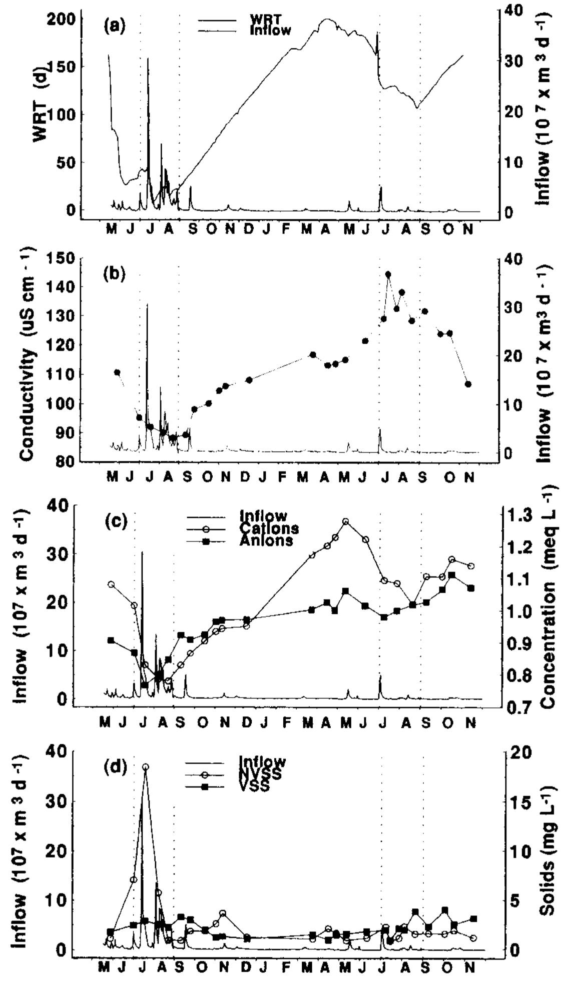

Figure 5. Seasonal co-variation of ionic salinity and suspended solids with the hydrograph in the headwaters during 1993–1994. (a) WRT (water residence time), (b) conductivity, (c) cations and anions, (d) NVSS (non-volatile suspended solids) and VSS (volatile suspended solids). Water residence time (WRT) was estimated after Knowlton & Jones (1990).

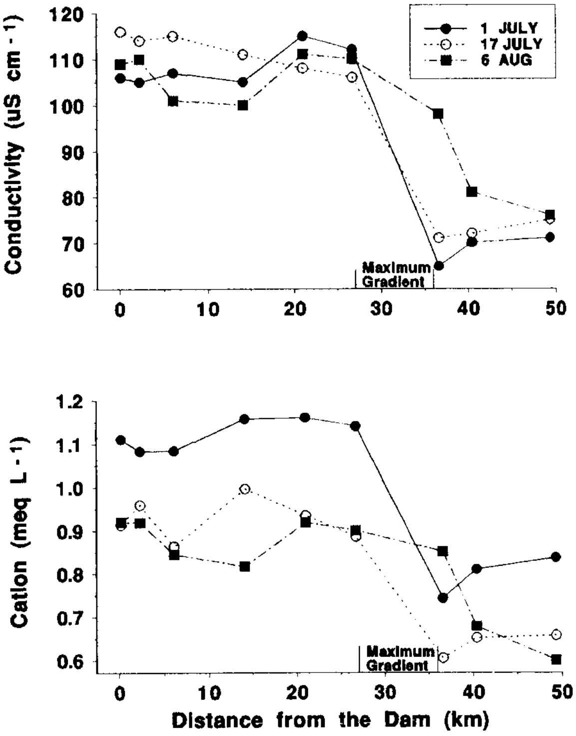

Figure 6. Spatial heterogeneity of conductivity and cations along the major axis of the reservoir (above the dam) during monsoon 1993. Maximum differences in these two variables occurred between location 27-km and 37-km due to an interflow current.

at the low end of the expected range (100–600 mg l^{-1}; Drever, 1982) for waters draining this geology. In fact, the relative proportion among cations in Taechung Reservoir showed a pattern in typical soft waters ($Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$; Lampert & Sommer, 1997) with low salinity. The cationic proportion of Ca^{2+}:Na^{+}:Mg^{2+}:K^{+} in this system was similar to values (mean = 43:35:12:10%) found in the surface waters of reservoirs and rivers in northern Korea (Hong et al., 1989).

Seasonal differences in salinity were apparent (range: 45–85 mg l^{-1}) and were largely a function of monsoon rainfall. For example, total salinity (77 mg L^{-1}) and Ca^{2+}+ HCO_3^- (40.1 mg L^{-1}) during premonsoon 1994 were > 20% greater than the overall mean, and the Langelier saturation index (>0.1 after Larson & Buswell, 1942) suggests the reservoir was oversaturated with calcium carbonate during this dry season. Whereas salinity decreased by 25% during monsoon 1993 in response to dilution. Based on precipitation and inflow, the reservoir volume was replaced 3 times during July–August 1993 and lake stage was >4 m higher during summer than spring 1993. Overall salinity showed a strong inverse relation with inflow ($r = 0.90, p < 0.01$) when WRT values were <100 d (Figure 5). This relation, however, was weak when WRT values were >100 d. Hong et al. (1989) showed Ca^{2+} values decreased by 40–70% in Korean reservoirs and rivers during July–August compared to the premonsoon . This pattern is similar to the seasonal dilution in Japan (Ohtake et al., 1982), Nepal (Lohman et al., 1988; McEachern, 1996) and Indian lakes (Banerjee et al., 1983; Singh, 1985) influenced by the Asian monsoon, and also conforms to lake chemistry in other regions showing large seasonal

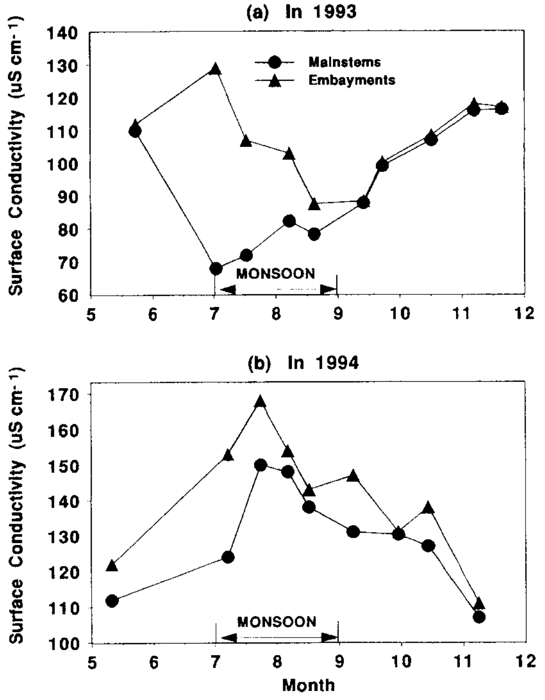

Figure 7. Difference in mean cation values between mainstem (sites 1, 3 and 4) and embayment sites (sites 2 and 5) in the headwaters during 1993 and 1994. In the early monsoon 1993, rapid dilution was observed in the mainstem sites, but cation values increased in the embayment sites.

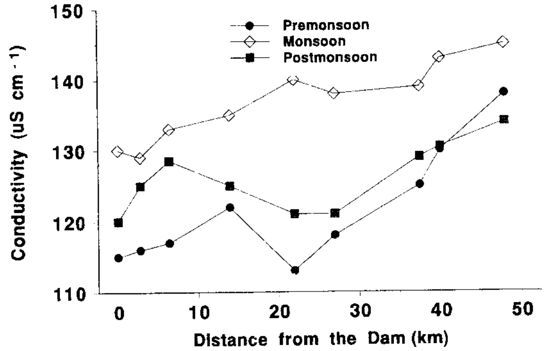

Figure 8. Longitudinal gradient in conductivity along the main axis of the reservoir (above the dam) during premonsoon, monsoon and postmonsoon 1994.

fluctuation in precipitation and discharge (Bjarnborg, 1983; Akhurst & Breen, 1988; Ali et al., 1988; Stogner et al., 1996).

Increases in Na^+ and Cl^- during monsoon 1993 may be a combined effect of terrestrial input and atmospheric transport. Reduced equivalent ratios of Ca^{2+}:Na^+ (1.63) and HCO_3^-:Cl^- (1.07) during monsoon 1993, compared to the premonsoon (2.40 and 1.43, respectively) suggest the shift of ionic composition by surface runoff. A similar result was found in Soyang Reservoir, Korea (Hong et al., 1989) where the proportion and absolute concentration of Na^+ increased >50% during the monsoon. During 1993–1994, mean Na^+:Cl^- (0.85 as μeq l^{-1}) in Taechung Reservoir was similar to the typical value in sea water (0.86; Eilers et al., 1993), and Na^+ values co-varied ($r = 0.70$; $p < 0.01$) with Cl^-, indicating a potential influence from sea salt. Tyler (1984) found that monsoon rains in Thailand had an ionic character of seawater and total dissolved salts shifted slightly from rock dominance during dry periods to dominance by atmospheric precipitation during monsoon due to increases of Na^+ and Cl^- originating from the Indian Ocean. The influence of sea salt on lake water is often shown in other peninsula regions (Eilers et al., 1993; Pienitz et al., 1997).

An interflow was the dominant physical process modifying the spatial pattern in salinity. Our field observation suggests that longitudinal, vertical and horizontal heterogeneities in conductivity during major inflows (Figures 6 and 7) were caused by density differences between the lake water and interflow at the plunge point (between location 27 and 37 km) during strong thermal stratification. At the plunge point, the metalimnetic interflow was >2–3 °C cooler than the lake surface and passed through the 15–30 m stratum of the reservoir, resulting in an isolation of epilimnetic water with conductivity of >100 μS cm^{-1} from river water with conductivity of <70 μS cm^{-1}, in this respect conductivity measurements provided a tracer of storm flow (Kennedy et al., 1981). This isolation of epilimetic water is also explained by a 65–75% increase in NVSS and turbidity and a 25% decline in cations at the plunge point. Turbid-interflows (>20 NTU) have often been observed in reservoirs in Asia (Kim, 1987; Davis et al., 1998) and North America (Nix, 1987; Knowlton & Jones, 1995) during peak inflow. These findings suggest spatial heterogeneity in ionic variables and suspended solids coupled with hydrology (Flora & Rosendahl, 1982; Knowlton & Jones, 1989; Thornton, 1990).

Major factors regulating salinity during postmonsoon 1993 differed spatially within the reservoir. Ionic dilution in the downlake zone was maximized during postmonsoon 1993 because lake-water with conductivity of 110–135 μS cm^{-1} was continuously discharged from the dam during July–August and was replaced with uplake river-water with conductivity <80 μS cm^{-1}, resulting in a dilution process during major inflow periods (Bjarnborg, 1983; McDowell & Asbury, 1994; Stogner et al., 1996). Postmonsoon salinity in the headwaters increased due to groundwater entering the reservoir, as shown by >35% increases in calcium and bicarbonate ions in this reach. A comparable result was found in floodplain lakes (Akhurst & Breen, 1988); groundwater elevated conductivity during the period between floods. This pattern suggests as rainfall and river inflow decrease, groundwater inputs dominates in the headwaters, resulting in an increase of ionic salinity. Rigorous regional comparisons in ionic patterns, however, are not possible because few spatial measurements in salinity have been published for Asian reservoirs.

These results suggest that an intense monsoon acts as a "pulse effect or deterministic instability" (Straskraba et al., 1993) in reservoirs. During the study, the intensity of the monsoon rain accounted for most of the annual inflow (Figure 2) and determined flow characteristics (Figure 6) and water residence time (Figure 5). These hydrological conditions directly influenced thermal structure and water movement which, in turn, modified the ionic content and suspended solids (Figure 5), and their distribution and composition (Figures 3, 4, 6 and 7), suggesting a physical and chemical resetting of the whole system. Such hydrological disturbances during the monsoon are considered a consistent environmental pattern (Songqiao, 1986) because of cyclic climate characteristic (Reynolds, 1993; Straskraba et al., 1993) in Asia. Jones et al. (1997) emphasized the importance of the monsoon in determining lake processes and seasonal patterns in Asian lakes because principal rainfall and inflows in Asian regions occur in summer monsoon, in contrast to major inflows during in spring and fall in North America and Europe. We believe the intensity of seasonal monsoon is a forcing factor explaining spatial-temporal variation in ionic salinity, thereby determining regional limnological patterns in Asian waterbodies.

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