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Monsoon influences on the limnology of Juam Lake, South Korea

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Introduction

Korean lakes differ from other temperate counterparts because they are artificially constructed reservoirs and experience an annual hydrologic cycle dominated by a summer monsoon (Jones et al. 1997, 2003, Kim et al. 2001). In this paper we describe how the monsoon influences the general limnology of Juam Lake, South Korea, as a contribution to the growing body of information on processes and seasonal patterns in Asian lakes.

Key words: reservoir, monsoon, phosphorus, chlorophyll, trophic state

Lake, climate and data set

Juam Lake, located in the south-central region of the South Korean peninsula (Fig. 1), is used for hydropower, water supply, and flood control. The surface area is 33 km^2 at flood level (103 MSL), and the effective storage volume is 412 MCM (mega cubic meters), but during 1992–2002 the volume averaged 235 MCM and varied by > 2-fold. Annual inflow averages about 700 MCM. Flow length within the reservoir is about 41 km. A diversion tunnel is located approximately 11.5 km from the dam (intake at 80.5 MSL) that delivers, by gravity force, some 60–70% of the outflow to an auxiliary reservoir.

During 1992–2002 hydrologic flushing in Juam Lake, estimated as annual outflow divided by storage on 1 January, averaged about 2.5 times per year, but this value ranged from < 1.5 yr^{-1} (during 1992, 1994, 1995, 1996 and 2001), to 2–2.5 yr^{-1} (during 1993, 1997 and 2000), to 3.4–3.9 yr^{-1} (during 1999 and 1998, respectively), to a maximum of 6.4 yr^{-1} (in 2002).

South Korea has a temperate, continental climate with warm, humid summers and cold, dry winters. Korea Meteorological Administration data from Sunchon during 1992–2002 show air temperature averaged 25 °C in July and August and wintertime lows averaged < 2 °C during December-February. Annual precipitation (1992–2002) averaged 1483 mm and varied from 1067 mm in 1994 to 2010 mm in 1998 (Fig. 2). The summer monsoon dominates seasonal rainfall with about 60% of annual rainfall occurring during June-August (Fig. 2). Monsoon rainfall typically peaks in August at about 400 mm, but August totals varied from 127–880 mm. Rainfall averages about 275 mm in July, about 200 mm in June and 140 mm in September. Rainfall is minimal during winter (Fig. 2), with monthly totals during December-February averaging about 30 mm.

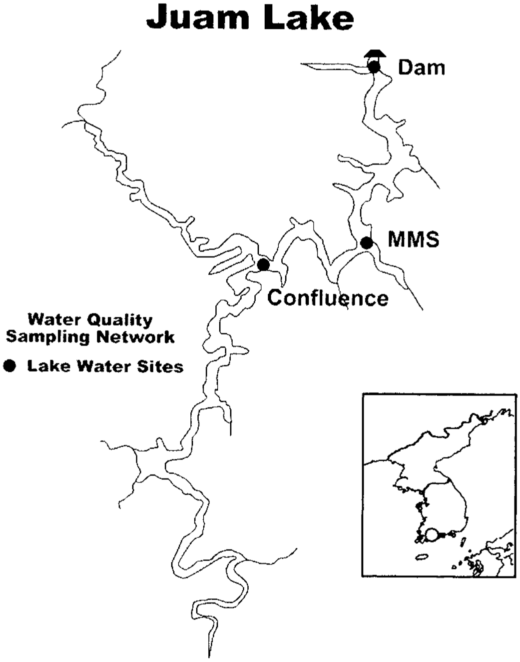

Fig. 1. Map of Juam Lake showing location of sampling sites at the Confluence, middle of the mainstem (MMS) and near the Dam.

Several extremes in rainfall during the record period (Fig. 2) allow for a comparison of water quality in

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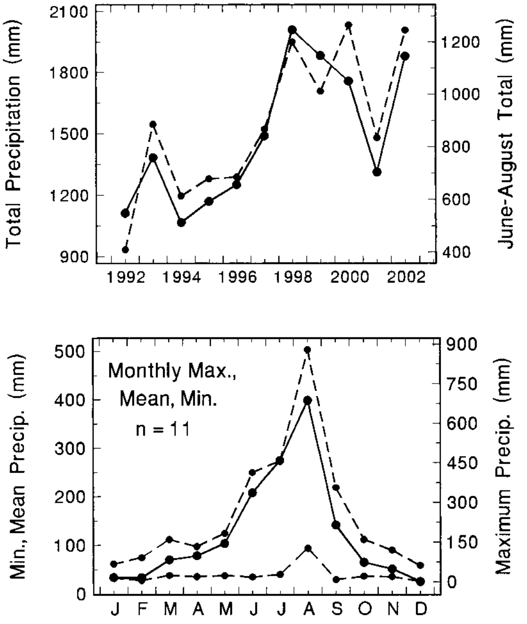

Fig. 2. Precipitation data (mm) collected from near Sunchon, South Korea. Upper panel shows total precipitation (solid line, left scale) and precipitation during the summer monsoon (dashed line, right scale) during the years 1992–2002. Lower panel shows monthly maximum (right scale), mean (left scale) and minimum (left scale) values during the period 1992–2002.

years of contrasting rainfall/inflow. During 1994–1996 both total annual rainfall and monsoon rainfall was below average, whereas during 1998–2000 rainfall was about 300 mm greater than the overall mean. Contrasts are made between these two periods to show how the lake is influenced by sequential 'dry' and 'wet' monsoon seasons/years.

Data were collected as part of a nationwide inventory compiled by the Korean Ministry of the Environment. Surface water samples were collected monthly at 3 sites during 1993–2002 (Fig. 1), and four collections were made in 1992 (included in Table 1 only). One site was in the headwater zone, near the confluence of the two principal inflowing streams (Confluence; 16,750 m uplake from the dam), another site was located near the middle of the mainstem (MMS; 6,700 m uplake from the dam), and a third site was near the dam (Dam). About 120 samples have been collected at each site during the period of record. Temperature and oxygen profiles (meter intervals) were measured during most collections after 2000. Geometric averages of water quality data were calculated to represent conditions in the entire lake (lake mean, across all sites and sampling dates), at each sampling site (across all sampling dates) and for each site monthly means were determined (across all samples within a given month over the record period). Geometric means were also calculated during the monsoon (across all seasons, and both sequential 'wet' and 'dry' monsoons). Geometric means were used to dampen the influence of extreme values on the overall analysis. Statistical analyses were conducted using SPSS software and significance was set at <0.01. LOWESS (locally weighted regression) trend lines were used to show seasonal patterns.

Results and Discussion

General characteristics

Lake mean values of total phosphorus (TP = 18 µg L^{-1}; Table 1), total nitrogen (TN = 904 µg L^{-1}), algal chlorophyll (Chl = 3.6 µg L^{-1}) and Secchi transparency (2.8 m) during 1992–2002 are within the mesotrophic range proposed for Korean reservoirs (Jones et al. 2003). The mean ratio of TN:TP (51) suggests phosphorus potentially limits phytoplankton and the mean Chl:TP ratio (0.21) matches the yield of Chl per unit of phosphorus in many mesotrophic Korean reservoirs (Jones et al. 2003). Mean values of conductivity (84 µS; Table 1) and total suspended solids (TSS = 2.5 mg L^{-1}) are within the lower quartile of inventoried reservoirs in Korea (Jones et al. 2003).

Temperature patterns

Temperature data from 2000–2002 (Fig. 3; 2000 data) show Juam Lake is a warm monomictic reservoir with stratification initiating at the Dam in spring (April-May) and persisting through fall. In early to mid-summer the mixed layer is >20 °C and is typically restricted to the upper ~ 6 m. During this time the thermal profile typically has metalimnetic temperatures of 10–18 °C and bottom temperatures of 5–6 °C. Concurrent with the monsoon peak (July-August), thermal structure of the water column is altered by both the downlake movement of monsoon inflow (positioned mid-depth within the water column) and the concurrent withdrawal of cold hypolimnetic water. Monsoon inflow, measured at the Confluence, often ranged between 20–25 °C; this water plunges

Table 1. Geometric mean values of limnological parameters in Juam Reservoir during 1992–2002 across all sites (lake mean) and at each of the sampling locations. Geometric means are also shown for the June-August samples from 1994–1996 (below average rainfall) and June-August 1998–2000 (above average rainfall).

Parameter and Years	Lake Mean	Dam Site	Mid-Mainstem Site	Confluence Site
1992–2002				
Total P (µg L^{-1})	18	15	17	21
Total N (µg L^{-1})	904	785	946	995
Chlorophyll (µg L^{-1})	3.6	2.6	3.7	5.0
Secchi (m)	2.8	3.6	2.8	2.2
T. Suspend. Solids (mg L^{-1})	2.5	1.9	2.6	3.2
Conductivity (µS)	84	76	85	90
1994–1996 (June-August)				
Total P (µg L^{-1})	–	22	22	25
Total N (µg L^{-1})	–	694	873	973
Chlorophyll (µg L^{-1})	–	2.5	3.9	5.8
Secchi (m)	–	4.1	3.2	2.5
T. Suspend. Solids (mg L^{-1})	–	2.2	2.6	2.8
1998–2000 (June-August)				
Total P (µg L^{-1})	–	9	16	26
Total N (µg L^{-1})	–	907	1160	1311
Chlorophyll (µg L^{-1})	–	3.0	4.8	8.9
Secchi (m)	–	3.9	2.7	1.5
T. Suspend. Solids (mg L^{-1})	–	1.7	3.9	6.2

within the water column, as determined by density characteristics, and moves downlake as an interflow. As a result, the upper 15–20 m of the water column at the Dam is > 20–25 °C. This change in thermal structure of the water column is clearly depicted in data from July-September 2000 (Fig. 3), but the pattern is similar in other years. The general shape of the temperature profile is also similar at MMS on most sampling dates (data not shown).

Interflows are well known in reservoirs, and monsoon thermal patterns in large Korean reservoirs have been described previously (An & Jones 2002). July-August temperatures in the epilimnion of Juam Lake varied between 25–30 °C (Fig. 3), and because of reduced density, this warm, mixed layer was isolated in the top 5–6 m of the water column with the cooler interflow layer positioned below. Surface samples from this isolated, mixed layer represent downlake, lacustrine conditions with little direct influence by the principal monsoon inflow. An average Secchi depth of 4 m during July-August 2000–2002, suggests the entire depth of the summer epilimnion in Juam Lake was within the photic zone. In fall, the mixed layer deepens and cools, thereby entraining the interflow layer. Complete destratification occurs in Juam Lake sometime in December-January.

During winter mixis, oxygen in the water column is often 75–90% saturated, and during stratification oxygen in the epilimnion is frequently supersaturated (Fig. 3). Under thermally stratified conditions oxygen in the aphotic zone, which includes the interflow layer and the hypolimnion, depletes over time (Fig. 3); by fall, oxygen in the lower hypolimnion declines to about 20% saturation (2–3 mg L^{-1}). During mid-summer oxygen shows a negative heterograde distribution near the middle of the water column and coincides with the interflow zone. Data from the three collection sites suggest that oxygen is depleted from the interflow layer during its downlake passage. Among years, this zone of reduced oxygen saturation (and concentration) within the interflow varies in depth and dimension during the monsoon.

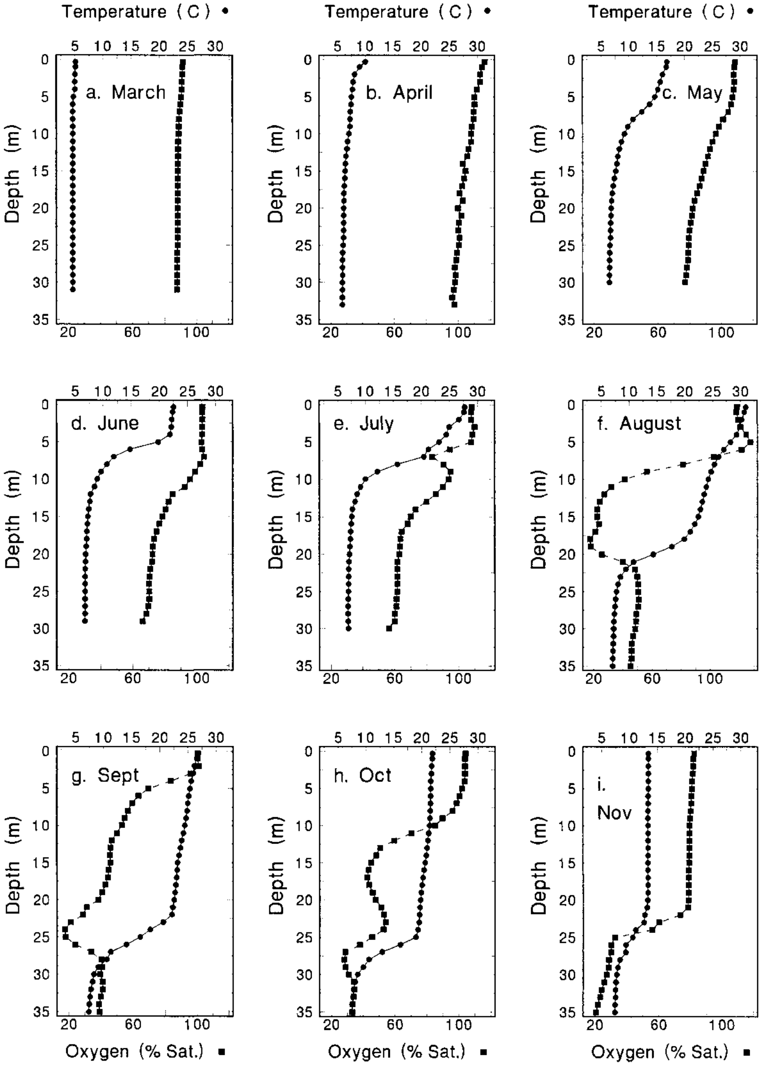

Fig. 3. Temperature (top axis, circles) and oxygen saturation (bottom axis, squares) profiles from the Dam site on Juam Lake during 2000. Panels represent conditions in March (a), April (b), May (c), June (d), July (e), August (f), September (g), October (h), and November (i).

Longitudinal gradients

Like other large reservoirs in Korea (An & Jones 2002) and elsewhere in the temperate region (Jones & Novak 1981, Thornton et al. 1990), Juam Lake shows strong longitudinal changes in limnological characteristics between the Confluence and Dam (Fig. 1; Table 1). Over the study period declines of ~25% in plant nutrients and ~45% in Chl and TSS occurred along the length of the mainstem, with a minor decrease in conductivity. Concurrently, along this distance Secchi transparency increased by over 60%.

These longitudinal gradients show a strong seasonal response to the monsoon. As is typical for mesotrophic reservoirs in Korea (Jones et al. 2003), the annual nutrient budget of Juam Lake is dominated by external inputs during the summer monsoon. Most limnological variables increase seasonally at the onset of the monsoon and peak at the Confluence during July-August (Fig. 4) in response to fluvial inputs. This seasonal inflow during the period of thermal stratification results in strong downlake gradients in water quality metrics along the mainstem (Fig. 4). During the height of the monsoon a 2-

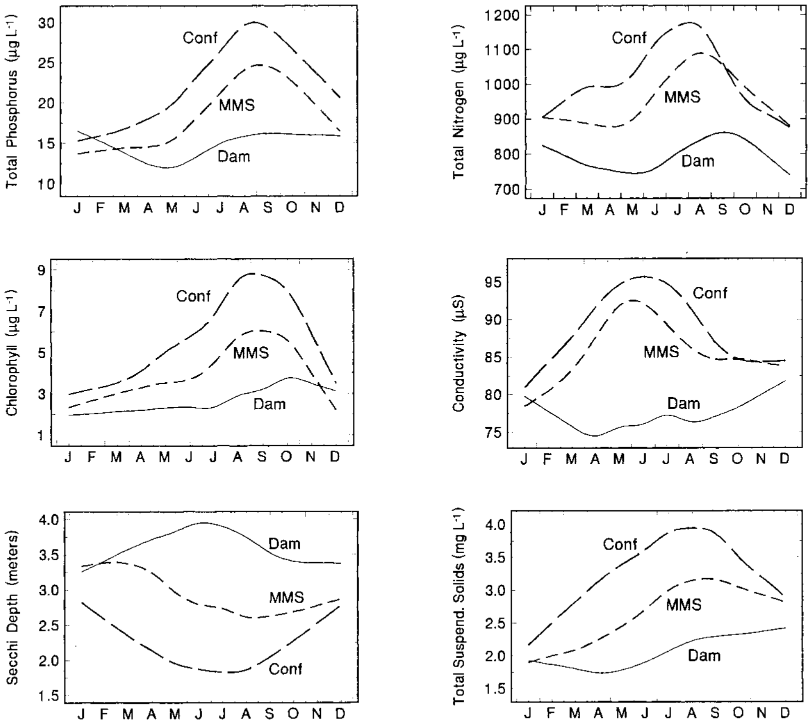

Fig. 4. LOWESS (locally weighted regression) plots fitted through data collected monthly between 1993–2002 at the Dam, middle of the mainstem (MMS), and uplake at the Confluence site (Conf). The panels show the average seasonal response at the various sampling sites to the pre-monsoon, summer monsoon and subsequent post-monsoon periods.

to 3-fold decrease in TP is typical between the Confluence and the Dam (Fig. 5), and on several occasions the reduction was 5- to 7-fold. Declines in TN at the downlake site were proportionally smaller than for TP. Measurements of TN at the Dam were usually <20% smaller than at the Confluence, but some 15% of the samples showed declines of 2- to 3-fold (amounting to >800 µg L^{-1}). Differences in longitudinal patterns in these two plant nutrients are expected because most N in lake water is dissolved whereas most P is particulate and more strongly influenced by sedimentation processes. The seasonal pattern in TSS closely matched that of TP, and monsoon declines of 3-fold were common along the mainstem (Fig. 5). Monsoon Chl values at the Confluence are typically 3-times those at the Dam while average Secchi depth nearly doubles across this distance (Fig. 4); however, longitudinal changes of twice this magnitude have been measured in both variables. Worth noting, seasonal increases in Secchi transparency at the Dam coincide with the onset of thermal stratification in early summer and subsequent isolation of the mixed layer from monsoon inflow.

Post-monsoon Chl values characteristically decline in fall, particularly at the two uplake sites (Fig. 4). During the subsequent winter months when the lake is homothermal, longitudinal gradients in most limnological features are modest (Figs. 4 and 5). Averaged over the study period, monthly mean nutrient and seston values were highly correlated at the Confluence and MMS sites (r = 0.91 for TP; 0.78 for TN; 0.82 for TSS; and 0.93 for Chl; n = 12) thereby reflecting the synchrony in the seasonal movement of inflowing water downlake. Correlations between monthly averages at the Dam and values at the other two sites were weak or not

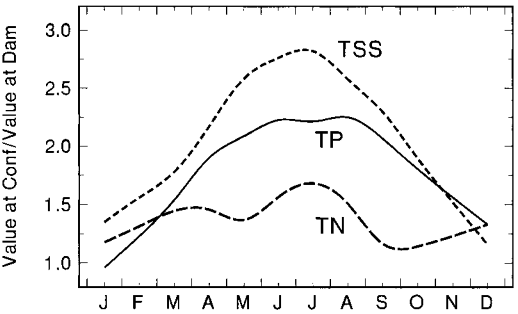

Fig. 5. LOWESS (locally weighted regression) plots fitted through the monthly average ratio (during 1993–2002) of the value measured at the Confluence site divided by the value measured at the Dam. Measurements of total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) are routinely greater at the Confluence site than at the Dam, particularly during the peak of the monsoon.

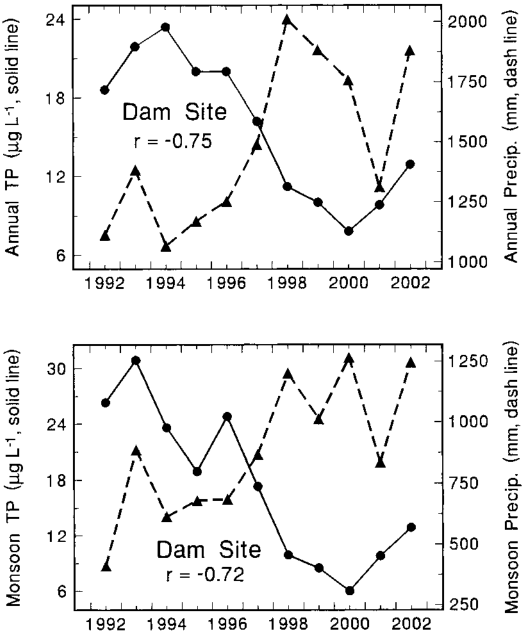

Fig. 6. The upper panel shows the annual total phosphorus value at the Dam during the period of record and the annual total precipitation. The two values are negatively correlated (r = –0.75, n = 11). The lower panel shows average total phosphorus and rainfall at the Dam during the monsoon season. The two values are negatively correlated (r = –0.72, n = 11).

significant because of the lacustrine nature of the downlake surface layer during the monsoon.

Monsoon intensity

Longitudinal gradients in Juam Lake, driven by the intensity of monsoon inflow, are more pronounced during years of above-average rainfall than during weak monsoons. Using TP to illustrate this point, when monsoon intensity was below average (June-August 1994–1996) TP at the Confluence was only ~10% greater than at the Dam, whereas during years of above average monsoon rain (June-August 1998–2000) TP showed nearly a 3-fold decline along the mainstem (Table 1).

Interestingly, during the 'wet' monsoons TP at the Dam averaged less than half the value during the 'dry' monsoons (9 vs. 22 µg L^{-1}; Table 1). Across all years, the correlation between annual total precipitation and mean annual TP at the Dam was negative (r = –0.75, n = 11; Fig. 6) and the same pattern held during the monsoon season (Fig. 6). This outcome is counterintuitive relative to the expected response to external loading, which would suggest greater values during years of high inflow. Three factors may contribute to the observed pattern. First, surface samples from the Dam represent lacustrine conditions in a thermally isolated layer, relatively uninfluenced by monsoon interflow (Fig. 3). Thermal data suggest large monsoon inflows pass through the reservoir as a deep interflow current without direct influence on downlake surface water. In years of moderate to weak rainfall, interflows are likely less pronounced and may have greater direct influence on downlake TP. Also, diversion of water to the auxiliary reservoir may differentially influence downlake flow patterns in 'wet' and 'dry' monsoons. Second, intense monsoon rainfall directly on the reservoir surface may serve to dilute nutrient and dissolved solids levels in the epilimnion. Third, inflow TP concentrations may be lower during wet years than dry ones because of greater surface runoff/dilution, thereby resulting in a reduced unit load to the lake and lower in-lake TP. Complete temperature, hydrology and loading records, however, are not available to directly test these hypotheses.

Algal chlorophyll

Within the context of lake management and water supply, Chl values > 10 µg L^{-1} are associated with reduced water clarity, increased potential for Cyanobacteria dominance, and nuisance algal blooms (Bachmann & Jones 1974, Downing et al. 2001). In Juam Lake only about 10% of the Chl samples from all sites were within this category (n = 38 of 369). The frequency of Chl > 10 µg L^{-1} doubled between the Dam and MMS, and again between MMS and the Confluence (n = 5%, 10%, and 23% of samples at each site, respectively).

Chl commonly peaked in September (Fig. 4), particularly at the uplake sites. This time period marks the end of the monsoon and is concurrent with the initial stages of destratification and entrainment of metalimnetic/hypolimnetic water into the mixed layer. Across all sites and years, maximum Chl values averaged 2.9 times the annual mean Chl (median = 2.4), which is consistent with other reservoirs in Korea (Jones et al. 2003). Ratios of Chl:TP showed seasonal peaks in spring/early summer and again in fall, particularly at uplake sites; this pattern matches the general model for seasonal phytoplankton growth in temperate lakes (Marshall & Peters 1989). Only about 5% of all samples had ratios of Chl:TP greater than unity, which is the ratio considered indicative of bloom conditions. Many of these maximal Chl:TP events occurred during 2002 concurrent with *Peridinium* dominating the lake phytoplankton, and during a time when hydrologic flushing rate was at its maximum.

Comparison with other Korean reservoirs

Based on nutrients and algal Chl, data from Juam Lake fall within the lower quartile of major reservoirs in South Korea, and in the top quartile based on Secchi (Jones et al. 2003). The reason for these comparatively low nutrient levels is that the watershed is primarily forested (80%) with relatively small areas of agriculture (8%) and urban development (0.6%). Also, with a dam height of 58 m, it is one of the deepest reservoirs in the country. Among the major Korean reservoirs, plant nutrients show a strong negative correlation with dam height and a strong positive correlation with both the proportion of urban and agricultural area in their respective catchments (unpublished data). Data from Juam Lake fit within this cross-system pattern.

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