Developing a Paradigm to Study and Model the Eutrophication Process in Korean Reservoirs

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ABSTRACT

In the task of quantifying eutrophication and its abatement, Korean limnologists and engineers have the advantage of being able to draw on the theoretical framework, comparative analyses and experimentation of colleagues in other temperate regions. Classical eutrophication theory and global models provide an appropriate framework for this evaluation but modifications may be needed to account for the Korean situation. Korean lakes differ from glacial, temperate lakes in that they are mostly artificially constructed reservoirs, and they experience an annual hydrologic cycle dominated by a summer monsoon. In this essay we address major points of distinction between reservoirs and natural lakes, and between monsoon and non-monsoon climates that should be considered in this regional assessment. Developing a paradigm to quantify how reservoir water quality responds to monsoon inflow should be an immediate concern because this seasonal event is likely a major source of variation within and among lakes. We suggest that a long-term study of Korea's reservoir resources be undertaken to provide a data base to better understand existing conditions, construct models, and position scientists to make resource decisions.

Key words : Eutrophication, Korean reservoirs, monsoon climate

INTRODUCTION

The Korean Society of Limnology celebrates its thirtieth anniversary as a tribute to past scientific accomplishments and with anticipation of forthcoming challenges. The collection of papers in this issue of the journal includes citations to previous limnological studies in Korea, and these provide the historical framework of what is known about freshwater resources on the peninsula. The titles of the contributed papers identify the major aquatic problem of concern in Korea -- that being eutrophication. It seems that rapid industrialization, urbanization and intensified agriculture have enriched surface waters in Korea resulting in troublesome algal blooms (Kim *et al.*, this issue). This worldwide problem has been addressed by many limnologists over the past several decades and reviews by Smith (1990, 1998) provide an historical evaluation and synthesis of this work. The scope of topics within this issue show that Korean limnologists are concerned with determining the effects of human-induced, nutrient enrichment on their water resources for the purpose of understanding, prediction and control.

In the task of quantifying eutrophication and its abatement, Korean limnologists and engineers have the advantage of being able to draw on the theoretical framework, comparative analyses, and experimentation of colleagues in other temperate regions. Certain findings are directly applicable to the Korean situation. Among these,

Table 1. Published observations on the influence of the Asian monsoon on lake water quality

Asian Country	Monsoon Period	Limnological features during the monsoon
India (Zafar 1986)	July-August	• 29% decreases in Chl concentrations and 34% decrease in phytoplankton abundance (compared to premonsoon). • Minimum Chl (1.5 × 2.5 gm^{-3}) and phytoplankton abundance (12.5 × 10^3 individuals L^{-1}) • Minor contribution of nutrients (NO_3-N, PO_4-P, & SiO_2) to phytoplankton growth • 15% decrease in % bluegreen algae (compared to premonsoon)
Sri Lanka (Silva & Ronald 1987)	October-December	• 32% decrease in Chl conc. and 71% decrease in primary productivity due to reduced light availability • Minimum gross primary productivity (0.378/gm O_2 m^{-2} h^{-1})
Nepal (Lohman *et al.* 1988)	June-September	• 〉50% decrease in TP in post-monsoon due to a dilution of lake water by rainfall and runoff • 〉40% decrease in Chl values (compared to premonsoon)
Bangladesh (Khondker & Kabir 1995)	June-August	• Negative correlation between Chl concentration and rainfall. • 39% decrease in Chl concentration and 47% decrease in primary productivity (compared to premonsoon) due to heavy rainfall. • 40% increase in Soluble Reactive Phosphorus (compared to premonsoon).
Korea (An 1997)	July-August	• 75% increase in TP concentration during monsoon 1993 (compared to premonsoon). • 32% decrease in Chl concentration in the headwaters due to rapid flushing and mineral turbidity. • Negative correlation between TP and Chl concentration during monsoon 1993. • Maximum TP (〉150 μg/L) during the monsoon.

the concept of nutrient limitation of algal biomass by the plant nutrient phosphorus has been appreciated for decades and is based on accepted stoichiometry (Redfield, 1958). And, it is widely known that control of the phosphorus and/or nitrogen is key to eutrophication control to achieve a reduction in autotrophic processes and improve water clarity, and increase oxygen levels within stratified waters. Models have linked increases in external phosphorus loads to in-lake concentrations (Edmondson, 1961; Vollenweider, 1976; OECD, 1982) resulting in increased biomass of phytoplankton (Deevey, 1940; Sakamoto, 1966 and many others) and decreased water clarity (Edmondson, 1972). Phosphorus loading models, and the associated relations between phosphorus-chlorophyll and chlorophyll-transparency summarize and quantify limnological theory and provide a framework for judging the benefits of nutrient abatement. Improvements in Lake Washington following a reduction in phosphorus loads (Edmondson, 1994) demonstrate the potential of nutrient control schemes to improve lake water quality.

Classical eutrophication theory and global models provide an appropriate framework for developing predictive models and lake-management schemes specific to Korea. It is likely, however, that these tools will need modification before they can be applied to the Korean situation. Korean lakes differ in many ways from glacial lakes in temperate regions of Europe and North America which serve as the paradigm of how lakes function and provide the basis for the available models. Most important is that 1) most Korean lakes are artificially constructed reservoirs, not natural lakes, and 2) they experience an annual hydrologic cycle dominated by summer monsoon rains, a pattern that differs from many other temperate regions. Our purpose in this essay is to address major points of distinction between reservoirs and natural lakes, and between monsoon and non-monsoon climates that should be considered when developing limnological models that describe conditions in Korea and are used for management of Korean lakes. Reservoir examples come from limnological studies in Missouri (Jones and Knowlton 1993) and the study by An (1997) in Korea.

THE RESERVOIR PARADIGM

An obvious difference between Korea and many other temperate regions is that waterbod-

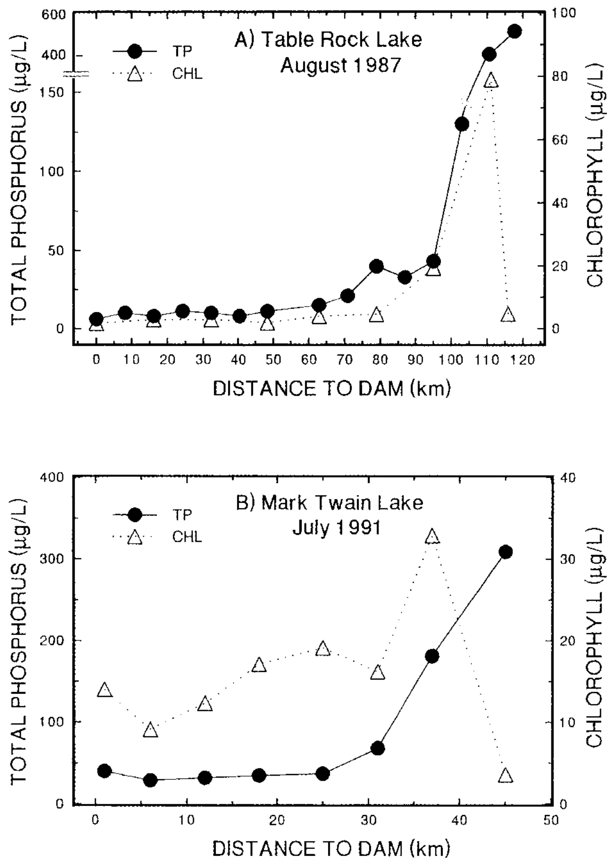

Fig. 1. Spatial variation of total phosphorus and chlorophyll in the surface layer of Table Rock Lake, Missouri, in August 1987 and Mark Twain Lake, Missouri, in July 1991. The Table Rock data represent the James River and lower White River arms of the lake and are redrawn from Knowlton and Jones 1989. The Mark Twain data represent the North Fork arm and mainstem of the lake (University of Missouri, unpublished data).

ies on the Korean peninsula are mostly constructed reservoirs with few lakes formed by natural processes. Early eutrophication studies demonstrated that there were differences between these two lake types and that limnological theory needed modification to account for the unique morphological and hydrological features of reservoirs (Jones and Bachmann, 1978a, b). It seems that reservoirs have lower in-lake nutrient levels than natural lakes at a given level of external nutrient loading (Canfield and Bachmann, 1981). This difference results from greater sedimentation processes in reservoirs than natural lakes. Reservoirs are typically constructed in erosional topography on the mainstem of large streams; in such situations, nutrient inputs are often associated with suspended materials that enter the "riverine" zone in the upper reach of the reservoir. As a result of reduced turbulence, these materials rapidly sediment upon entry into the water column of impoundments. In contrast, most glacial lakes occur in depressional landscapes and nutrient loading associated with particulate materials is typically not a major feature.

Reservoirs constructed within major river valleys with inflows from one or more large streams typically show a longitudinal pattern in water quality from upstream to the dam (Jones and Novak, 1981). Light attenuation, nutrient concentrations, and suspended sediment typically decline from a headwater riverine zone to a lacustrine zone downreservoir. This longitudinal gradient is the result of sedimentation of particulate materials and dilution during advective flow through the impoundment. Often, algal biomass and areal oxygen depletion rates peak at some intermediate location in response to improved light and available nutrients and this reach is considered the transition zone. These zones vary in relative size and position along the downreservoir axis in response to hydrologic conditions. Examples of this longitudinal pattern, using total phosphorus and algal chlorophyll, from two large reservoirs in Missouri are shown in Fig. 1. In many large reservoirs this spatial gradient can be remarkable; in fact, the variation among sampling sites within Table Rock Lake, Missouri is so large that it nearly matches the magnitude of lake-to-lake variation within the state (Knowlton and Jones, 1989; Jones and Knowlton, 1993). This level of spatial variation makes it difficult to generalize about reservoir water quality without being specific about particular lake segments or arms. Many natural lakes are well-mixed and their responses to nutrient loads are modeled as spatially averaged, mixed tank reactors, but reservoirs with strong longitudinal gradients require use of spatially segmented models (Chapra and Reckhow, 1983). The book by Thornton *et al.* (1990) documents reservoir function, and is a valuable general reference to the physics and chemistry of these engineered systems and is good starting point for modifying eutrophication models to account for their unique hydrology and morphology.

The timing of turbid, nutrient laden inflows relative to seasonal stratification can be critical

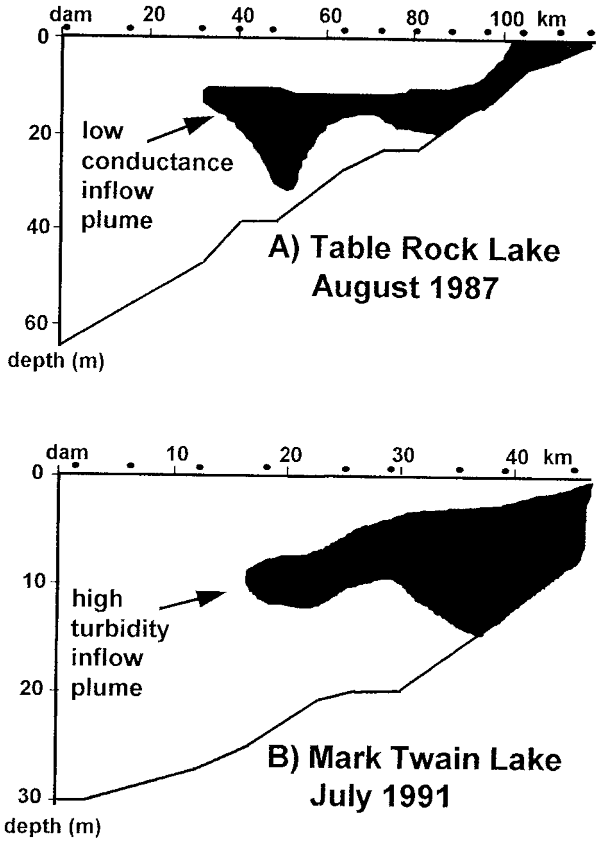

Fig. 2. Examples of large-scale interflow currents. A) White River Arm of Table Rock Lake, Missouri, August 1987. The shaded area represents low conductance inflows from an upstream reservoir as determined from vertical profiles at locations indicated by dots above the horizontal axis. Redrawn from Knowlton and Jones 1989. B) Middle Fork Arm and mainstem of Mark Twain Lake, Missouri, July 1991. The shaded area represents turbid inflow from the Middle Fork of the Salt River as determined as determined from vertical profiles at locations indicated by dots above the horizontal axis. Redrawn from Knowlton and Jones 1995.

in controlling phosphorus loading to the photic zone of reservoirs. Cool inflows entering a reservoir during winter or early spring mix directly with lake water and influence nutrient and suspended sediment values. The same magnitude of inflow entering in late spring or summer, after thermal stratification has established, will often enter the water column as under-or interflows having little influence on the nutrient or suspended solids content of surface water. Under these conditions, thermal stratification "protects" the surface layer from these external loads. Outlet structures located deep in the water column are a common feature of impoundments, and subsurface outlets can enhance the passage of cool inflow through the water column by functioning to "pull" water from upreservoir through this deep stratum. This phenomenon occurs when plunging inflows are drawn through the length of the reservoir as interflow or underflow currents. Examples of interflows in two Missouri reservoirs, using conductance and turbidity as measures of water quality, are shown in Fig. 2. These sub-surface flows "short circuit" inputs so that nutrient and suspended sediment levels in the biogenic zone of the water column are not directly influenced by runoff. The timing and passage of these inflows must be considered when quantifying external loading to reservoirs; simple application of loading data can easily overestimate phosphorus inputs to the biogenic zone of artificial lakes (Knowlton and Jones, 1995). These density flows are amplified when reservoirs are built in a series and the deep water withdrawal from an upstream structure is released to a downstream waterbody. Models linking external loads to in-lake concentrations generally do not account for subsurface water movements.

Subsurface outlets also affect internal lake processes such as thermal stratification and oxygen depletion. Most natural lakes and some reservoirs have surface outlets that draw water from the euphotic zone; in these waterbodies, temperature and density gradients below the seasonal thermocline are typically stable during stratification and oxygen depletion varies with some relation to productivity in the euphotic zone (Thornton *et al.*, 1990). Discharge of hypolimnetic water from subsurface outlets, however, can reduce the volume of the hypolimnion and cause it to be replaced by the interflow currents which weaken thermal stratification. When interflows are tied directly to watershed runoff, they can deliver particulate and dissolved organic materials and these allochthonous materials increase oxygen demand within the deep strata beyond levels expected based on autotrophic production. The overall result of subsurface release is an increase in hypolimnetic temperatures and increased oxygen depletion rates within the hypolimnion. In Table Rock Lake, Knowlton and

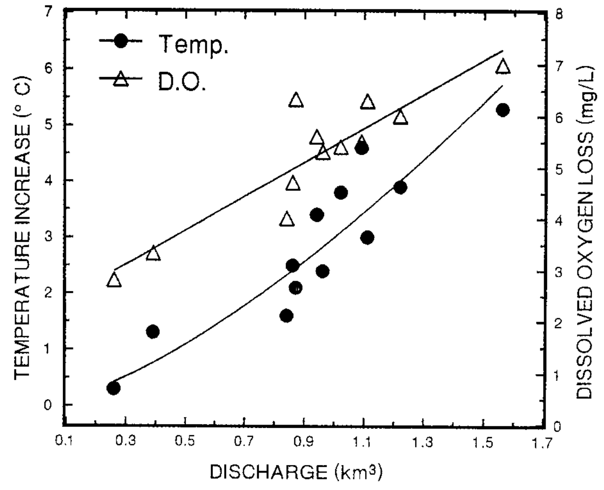

Fig. 3. June-September temperature increase and dissolved oxygen loss in the hypolimnion of Table Rock Lake, Missouri, as a function of discharge, 1976~1986. Redrawn from Knowlton and Jones 1989.

Jones (1989) found a direct relation between the increase in temperature and decrease in oxygen within the hypolimnion and the volume of discharge through the subsurface outflow (Fig. 3). The complex dynamics of subsurface flow and hydrology in reservoirs cause the hypolimnion to be more temporally variable than in natural lakes.

Canfield and Bachmann (1981) found that predictions of algal biomass and water transparency are less reliable in reservoirs than natural lakes due to the influence of nonalgal particulate materials. Non-algal turbidity can alter the relation between nutrients and algal biomass and in turbid systems the yield of chlorophyll per unit of phosphorus is greatly reduced (Jones and Novak, 1981; Carlson, 1991). Using a multi-year and multi-lake data set, Jones and Knowlton (1993) have shown that high concentrations of suspended solids and low transparency are major features of water quality in Missouri reservoirs, particularly in regions of the state dominated by agriculture. Suspended solids dominate the seston of these reservoirs and govern their transparency. Within this among lake comparison, algal chlorophyll accounted for only 30% of the variation in water clarity. In these turbid waterbodies, transparency is a poor measure of trophic state because water clarity is not closely tied to algal biomass (Carlson, 1991). They found a slight curvilenear relation between log10 transformed values of chlorophyll and phosphorus in their turbid reservoirs such that including a quadratic term improved the fit. Values of chlorophyll approached an asymptote above 50 ug/L phosphorus. Often these waterbodies had levels of suspended solids 〉10 mg/L, the point above which the relation between algal biomass and phosphorus was greatly dampened. Suspended solids alter the phosphorus-chlorophyll relation through light limitation and reduced nutrient availability, and the influence of suspended solids seems most strong in the headwater zone of reservoirs and during periods when waterbodies are not stratified. High levels of suspended solids weaken the interrelations among nutrients, algal biomass and water clarity that are central to lake management efforts. Conventional practices directed at cutting watershed phosphorus loads to reduce algal biomass and improve water clarity may not be effective without also addressing sediment loss from the catchment.

Reservoir research in Missouri has shown that phosphorus-chlorophyll and chlorophyll-transparency relations can vary from year-to-year as a function of hydrology and the amount of suspended sediment within the waterbodies. For example, data from 1993 show the same type of curvilenear, quadratic relation between phosphorus and chlorophyll found in the multi-year analysis, and the relation between chlorophyll and transparency in 1993 was weak (Fig. 4). In contrast, data from 1991 show a linear phosphorus-chlorophyll relation that is similar in form to a phosphorus-chlorophyll relation found in natural lakes with low turbidity. In 1991 the correspondence between chlorophyll and transparency was much stronger than in 1993. The difference between years was weather; 1993 was a year of record breaking rainfall, while precipitation in 1991 was below normal. Sediment loading differed between the two years; among these lakes non-volatile suspended solids averaged 5.7 mg/L in 1993 (range 0 to 107 mg/L) and in 1991 the average was 3.6 mg/L (range 0 to 44 mg/L). These data illustrate that reservoirs are responsive to the magnitude of external inputs of sediment, and that it is difficult to provide advance predictions of expected conditions in a particular waterbody in a particular year.

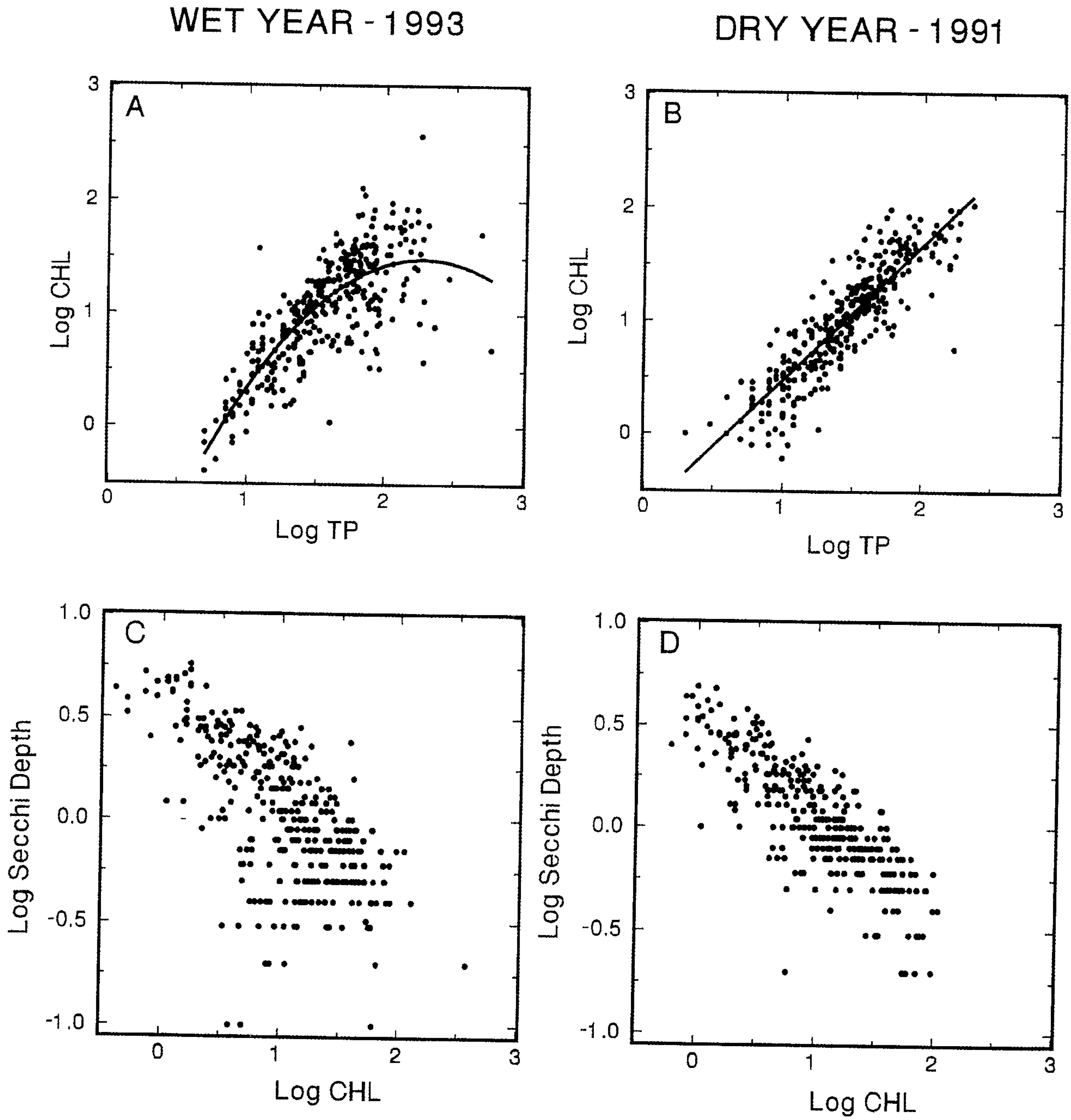

Fig. 4. Comparison of chlorophyll-total phosphorus (CHL, TP in μg/L) and chlorophyll-Secchi depth (m) relations in Missouri lakes during years with above-average rainfall (Wet Year) and below-average rainfall (Dry Year). The data shown are single day observations from state-wide lake surveys in 1993 (n=347 observations from 114 lakes) and 1991 (n=326 observations from 107 lakes). In 1993, (A), the CHL-TP regression model (solid line) is significantly non-linear ($R^2 = 0.64$). In 1991, (B), the regression model is not significantly non-linear ($R^2 = 0.77$).

MONSOON CLIMATE

Limnologists in Korea should also be prepared to modify theory and exiting models to account for the impact of the Asian monsoon on lake processes and seasonal patterns. In North America and Europe principal inflows and nutrient loading often occur in spring and fall and coincide

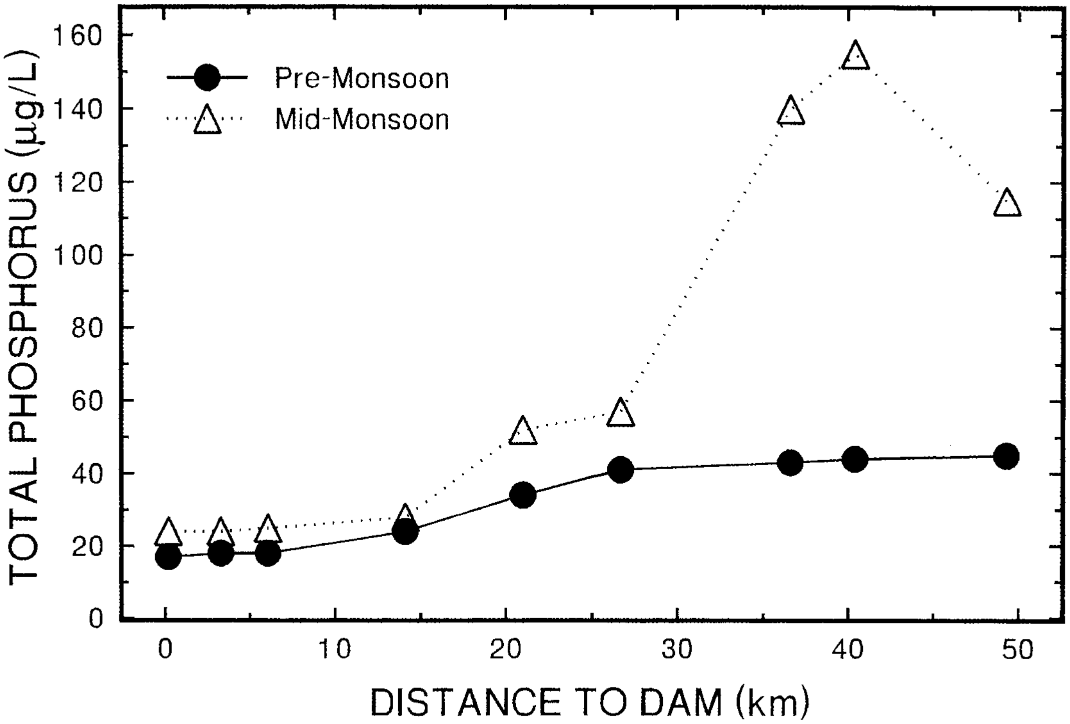

Fig. 5. Spatial variation of total phosphorus in the surface layer of Taechung Reservoir during pre-monsoon (May) and mid-monsoon (July) periods in 1993.

with mixis. Under this situation external loads are mixed within the water column and these inputs set the stage for summertime conditions when rainfall is typically much reduced. An example of how this seasonal weather pattern is well-incorporated into limnological theory is that Dillon and Rigler (1974) suggested that springtime phosphorus measurements could be used to predict summertime chlorophyll. In contrast, the Korean peninsula receives nearly half of its rainfall during the summer monsoon in July and August. This peak load of water, nutrients and sediment during the summer growing season deserves consideration and may require adjustments to conventional water quality models developed in non-monsoon regions. Inputs during the summer monsoon will likely be a major source of variation within and among lakes. The magnitude of monsoon rains and their timing will be important factors in determining longitudinal zonation in reservoirs and the pattern of flow through reservoirs. In Taechung Reservoir, An (1997) quantified a major change in the size and phosphorus content of the riverine zone during the monsoon relative to the pre-monsoon (Fig. 5) and this is consistent with longitudinal patterns driven by inflow events in other temperate reservoirs. It is obvious, however, hydrologic influences from the monsoon will likely be sufficient to invalidate the approach of using measurements from spring turnover to predict summertime conditions in Korean reservoirs. The seasonal changes in water quality would be too great to make this approach valid. Surprisingly little is known, however, about the how monsoon inflow affects in-lake conditions and functional relations. Data in Table 1 summarize the published observations on the influence of the Asian monsoon on lake water quality. The general theme from these finding is that during the monsoon there is a reduction in algal levels, likely in response to suspended sediments and reduced water residence time, and an increase in phosphorus in response to inflow. The impact of the monsoon on reservoir water quality needs additional attention. Developing a paradigm to quantify how reservoirs respond to summertime inflow, and its intensity, should be an immediate concern to Korean limnologists. The influence of the monsoon is a topic that will likely require adaptation of exiting models to fit the regional condition.

THE NEED FOR A DATA BASE

The extent to which eutrophication theory and global models must be adjusted by Korean limnologists to account for reservoir dynamics and seasonal patterns resulting from the monsoon is unknown. Potential modifications can only be considered when lake resources in Korea are understood well enough to evaluate their present condition. This task can be characterized as a regional assessment and it will require an extensive data base. In other temperate regions major breakthroughs in our understanding of lake function have come from large-scale, systematic efforts to sample lake resources. Examples of such studies are the National Eutrophication Survey (used by Canfield and Bachmann, 1981) and the OECD (1982) project. In both efforts, a large number of lakes were sampled over several years to facilitate comparative analyses and generalizations. The emphasis of both these studies was to intensively sample a large number of lakes over several years and draw comparisons among them. These large-scale comparative studies provide general information about variation deriving from internal and external sources. In Missouri, much has been learned about reservoir limnology from sampling our reservoir resources each summer to determine present conditions, regional patterns, interannual variation and changes over time. We have used these data to construct empirical models specific to conditions in our state (Jones and Knowlton, 1993). These models describe cross-sectional patterns between variables within the population of lakes in our study (Jones *et al.*, 1998); the curvilinear relation between chlorophyll and phosphorus (Fig. 4) is an example of this type of model. Over time we have gathered data on each study lake, and from this long-term information we have identified atypical patterns in certain lakes where the cross-sectional response does not apply. This information prompts subsequent work on explanatory theory about lake function in our region.

Long-term data are required to identify and evaluate the effects of unusual or extreme events on lake processes that are often obscured in short time series by interannual variation (Likens, 1984; Goldman, 1988). These disturbances can be considered whole-lake, natural experiments. Long-term studies have typically centered on individual waterbodies (Edmondson, 1994) but protracted collections from a diverse suite of lakes within a geographic region would better position scientists to construct models and make resource decisions. The Korean Limnological Society, perhaps in conjunction with the Korea Research Foundation, should consider taking the lead on designing a rigorous long-term study of Korea's reservoirs for the purpose of answering the resource questions raised in this issue of the Society's journal. Particular attention should be given to quantifying the influence of the monsoon on temporal variability and lake processes. A study of this type would parallel the goals and scope of work encompassed in long-term ecological research efforts currently underway in other regions (Magnuson *et al.*, 1997).

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