Empirical evidence of monsoon influences on Asian Lakes

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Limited information is available on how the Asian monsoon influences contemporary lake processes, seasonal patterns and interannual variation. Data sets from Nepal (Indian monsoon region) and South Korea (East Asian monsoon region) along with published literature show a wide range in the response of Asian lakes to the seasonal monsoon. Cross-system patterns show nutrients and algal biomass peak in most lakes in response to monsoon inflow, which suggests nonpoint sources dominate external loading. This seasonal increase may be the general phenological model for nutrients and phytoplankton in lakes in monsoon regions. Major ions show dilution by surface runoff during the monsoon and post-monsoon increases. Dilution of nutrients in fertile systems during the monsoon suggests point source inputs dominate peak loads during the non-monsoon period. Peak monsoon runoff can enter the water column of large stratified lakes as a density-dependent interflow at depth in the water column with little direct influence on the mixed layer. In these water bodies nutrients in surface water can be lower during strong monsoon seasons because of sub-surface loading. Short-interval data from individual lakes show the linkage between nutrients and phytoplankton biomass can be uncoupled by physical processes and light limitation, resulting in considerable temporal variation. Collectively these mixed responses limit our ability to generalize patterns or predict conditions in individual lakes during the monsoon.

Keywords: Asian monsoon, reservoirs, nutrient loading, seasonal patterns

Introduction

Much is known about the seasonal circulation patterns and forcing mechanisms of the Indian and East Asian monsoons. Monsoon precipitation results from a seasonal shift of wind patterns caused by heating of the land mass and onshore movement of moist ocean air. Some 60% of the world population is directly influenced by this climate pattern. Depending on location, the monsoon can deliver from one to over four meters of rainfall in the span of a few months and in some locations precipitation routinely exceeds ten centimeters during individual storms. Interannual variation in monsoon intensity and patterns are tied to sea surface temperatures and atmospheric pressure. Weak and late monsoons occur with warm sea temperatures (El Niño) and floods are prevalent when surface temperatures are comparatively cool (La Niña). The Asian monsoon is expected to intensify with climate warming, resulting in both increased drought and tropical storms of greater intensity (Park and Schubert, 1997; Ronghui et al., 2000; Overpeck and Cole, 2007). Variations in the historic strength and pattern of the monsoon have been determined from proxy indices reconstructed using long-term paleoclimate records from loess deposits, lake cores, sea sediment, tree rings and speleothem formations (Huang, 1997; Xiao and An, 1999; Xiao et al., 2004; Yamada, 2004; Wang et al., 2008).

Lakes are directly influenced by both landscape and climate such that paleolimnological dating of

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sediment cores provide a basis for reconstructing biological production and species composition. As in other regions, sediment cores from Asian lakes provide inferences about climate history (e.g. Yamada 2004). There is some evidence of recent warming in Asian lakes (Shuhei, 1999) and sharp extremes in the strength of recent monsoons have been described (Park and Schubert, 1997; Ronghui et al., 2000). Surprisingly, given the importance of the climate on lake function, there is limited contemporaneous information on how the Asian monsoon influences seasonal patterns and interannual variation in lake fertility and physical processes. This paper draws on data sets from Nepal (Indian monsoon region) and South Korea (East Asian monsoon region) and presents a partial review of the contemporary literature on the response of Asian lakes to monsoon inflow to better understand monsoon-driven responses in lakes and reservoirs. Few studies describe how extreme hydrological processes affect aquatic ecosystems (Tsai et al., 2008) and this synthesis will provide a basis for anticipating the response to a changing climate in this region.

A central tenet of limnology is that lake chemistry and fertility is a direct function of edaphic factors and external loading of sediment and nutrients from the catchment (Duarte and Kalff, 1989). In turn, these inputs are modified by depth/volume, hydraulic retention time and for some constituents, sedimentation is also a factor (Edmondson, 1961; Vollenweider, 1976). Based on theory, monsoon runoff from lake catchments should dramatically alter pre-monsoon conditions and serve to re-set lake conditions in synchrony with the regional rainfall pattern.

Data sources

Data from 59 reservoirs in South Korea are compiled annually by the Korean Ministry of the Environment. Jones et al. (2003) described the data base and characterized the trophic state and seasonal patterns of these reservoirs using information from 1993–2000. South Korean data used in this paper are based on nationwide survey information from 1993–2007 and from published studies

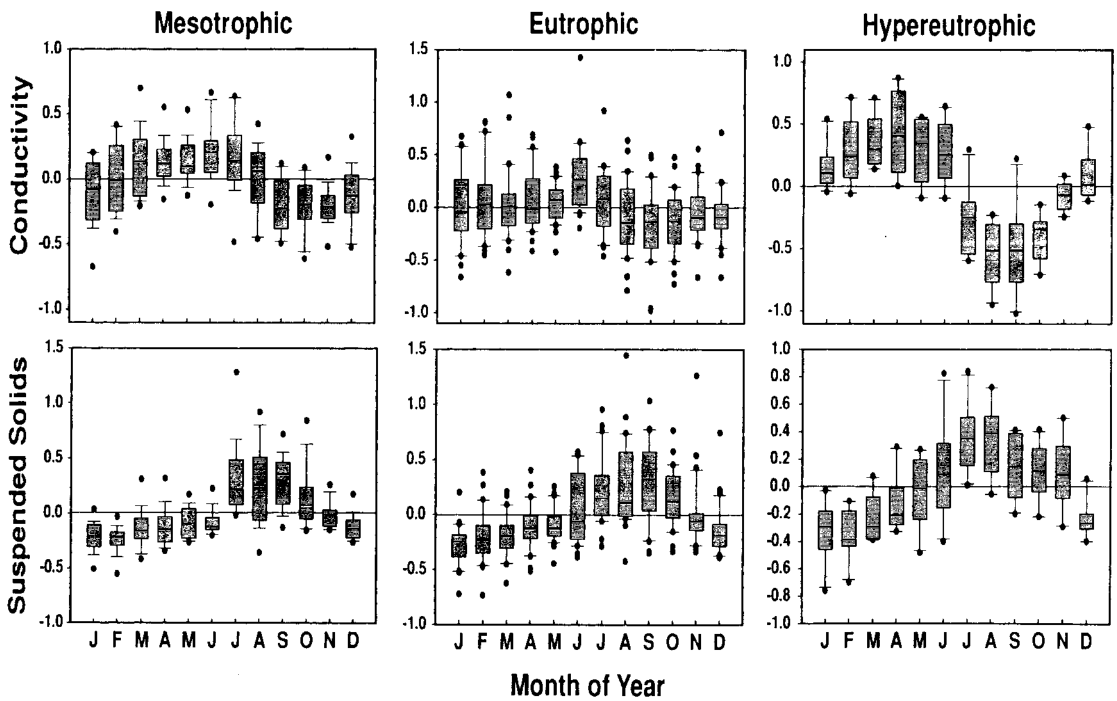

Figure 1. Box-plots of monthly mean normalized values of conductivity and total suspended solids from 59 Korean reservoirs (1993–2007) presented by trophic state (Jones et al., 2003). Individual values were normalized using the lake mean. In the box the horizontal line represents the median value, the box represents the interquartile range, and the solid lines represent a distance 1.5 times the interquartile range. Points are outliers. Yearly total precipitation averages around 1325 mm and seasonal rainfall typically peaks in July or August with a monthly total of around 300 mm.

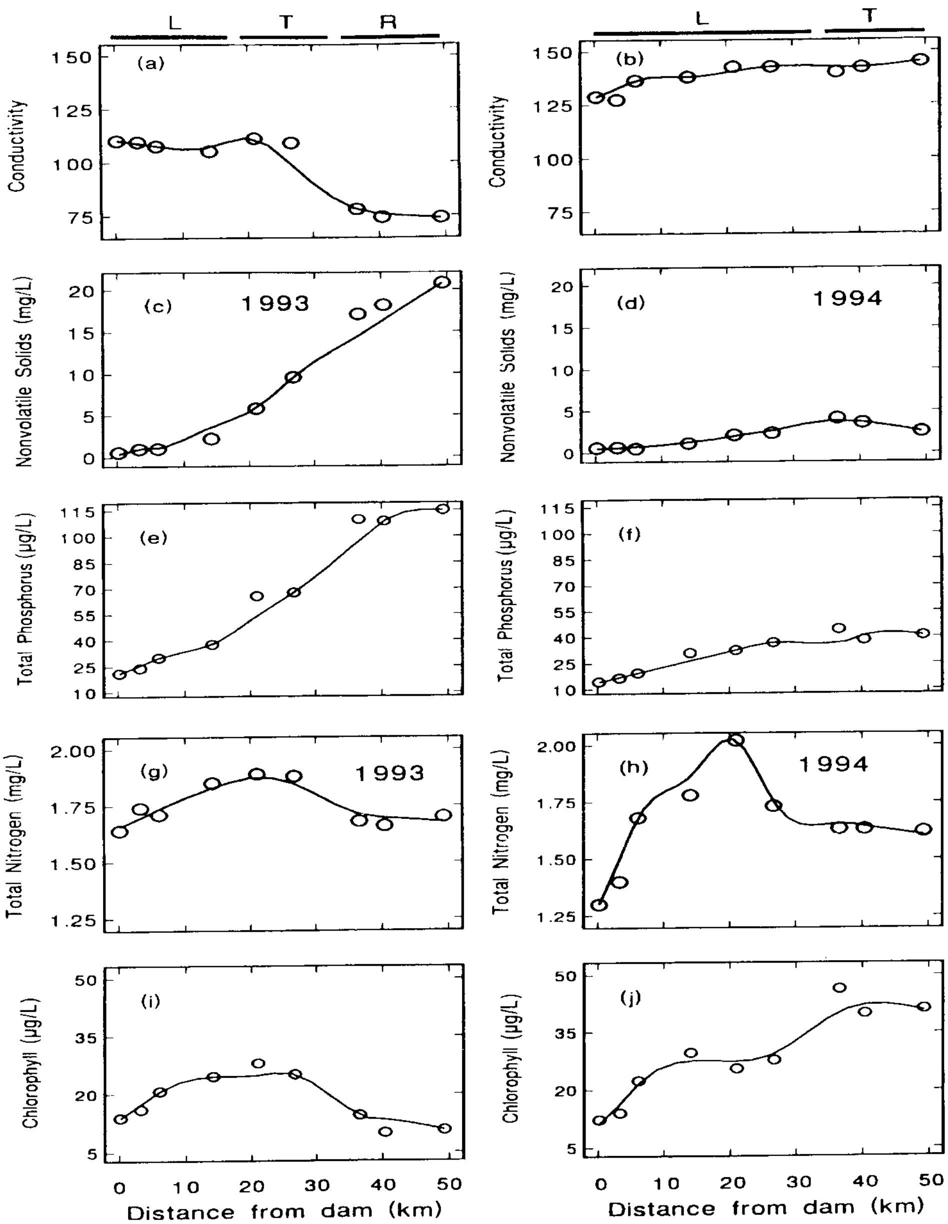

Figure 2. Longitudinal gradients of water quality variables along the mainstem of Daechung Lake, South Korea during 1993 (near normal monsoon) and 1994 (weak monsoon). Each date point indicates the seasonal mean. The longitudinal gradient was characterized using locally weighted sequential smoothing. Letters R, T and L indicate the extent of riverine, transition and lacustrine functional zones in this reservoir, respectively. During the weak monsoon in 1994 there was no detectable riverine zone in the sampled reach and the lacustrine zone occupied most of the reservoir surface. The figure was redrawn after An and Jones (2002).

of Daechung Lake and Juam Lake. Data from Nepal come from various published sources and the seasonal study of 9 natural lakes and reservoirs by McEachern (1996). All data were generated with standard methodology and cross-system comparisons were based on normalizing individual measurements to the mean for that water body (Jones et al., 2003). When citing literature on lake response to the monsoon we also include papers detailing the response to typhoon storms; this is done with recognition of the distinction in the underling atmospheric factors.

Results

Cross-system seasonal patterns

During the monsoon the major cations and anions of Asian lakes are diluted by surface runoff from the catchment and direct rainfall on the water surface. In the data set from South Korea (Figure 1) this seasonal decrease in ion content, measured as conductivity, was most pronounced among hypereutrophic reservoirs, presumably from surface runoff dilution of municipal point source inputs and estuary water in enriched coastal impoundments. Seasonal dilution of the major salinity ions has been documented previously in South Korea (Hong et al., 1989) and was apparent in Daechung Lake in years of sharply contrasting monsoon intensity (Figure 2, An and Jones, 2000). Similarly, among Nepalese lakes cations and bicarbonate peak at the end of the dry season and decline sharply during the monsoon in response runoff; subsequent increases in fall are largely attributable to internal loading during overturn, evaporation during the dry season and groundwater inputs, which are considered particularly important in shallow lowland lakes (Figure 3). Monsoon dilution was documented previously in Nepal (Lohman et al., 1988), Japan (Ohtake et al., 1982), and India (Banerjee et al., 1983; Singh, 1985; Ramanathan, 2007).

External loading from monsoon inflow is a major influence on the nutrient budget of Asian lakes. Nutrients peaked during the monsoon concurrent with seasonal inflow in the Nepalese lakes and among mesotrophic reservoirs in South Korea (Figure 3 and 4). This pattern is consistent with limnological theory which suggests nonpoint source inputs largely determine annual nutrient loads to lakes responding to seasonal rainfall. In contrast, nutrients decreased during the monsoon among hypereutrophic reservoirs in South Korea, with decline in nitrogen being stronger than phosphorus (Figure 4). This pattern suggests that during the non-monsoon period municipal point source inputs provide the principal nutrient load to hypereutrophic systems. So, rather than being a major nutrient source, monsoon surface flow from the watershed dilutes in-reservoir nutrient concentrations in severely polluted systems. Dilution by monsoon rainfall directly on the surface of lakes and reservoirs would also be a factor, particularly during extremely wet years. Nutrients in eutrophic South Korean reservoirs are probably influenced by both point and nonpoint inputs, so when taken in aggregate the seasonal pattern was less apparent (Figure 2).

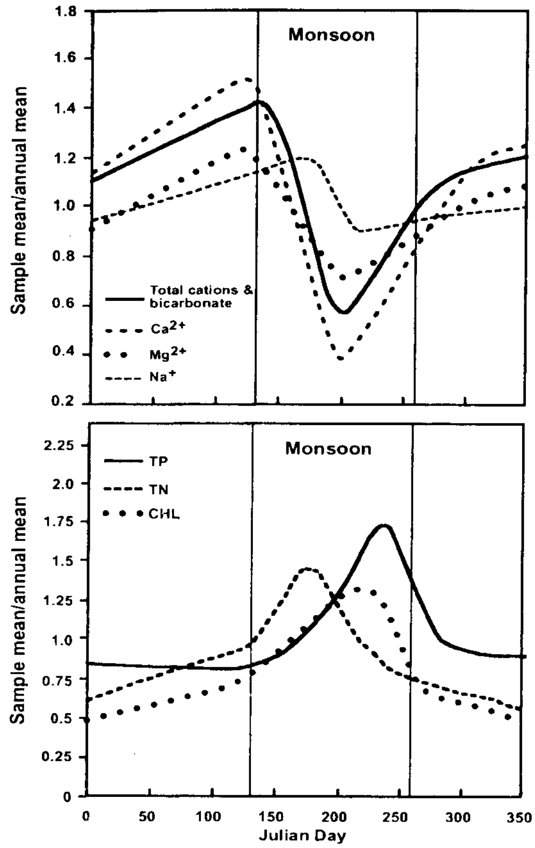

Figure 3. Locally weighted sequential smoothing plots showing cross-system seasonal fluctuation in (a) mean total cations and bicarbonate (meq L^{-1}) and (b) nutrients and total chlorophyll in nine lakes and reservoirs in Nepal (1993–1995) representing low altitude lakes which were all shallow (3–4 m) and mid-altitude lakes/ reservoirs of much greater (8–90 m) depth. Data were normalized by the lake mean (McEachern, 1996).

As expected, suspended solids increased in South Korean reservoirs during the monsoon as a result of delivery of terrigenous particulate materials in surface flow (Figure 1). Algal response to monsoon nutrients was detected in the Nepalese lakes and meso-eutrophic reservoirs in South Korea. Despite considerable variation in the cross-system pattern (Figure 3 and 4) it may be a general phenological model of for phytoplankton in the same sense of spring and fall blooms in temperate lakes (Marshall and Peters, 1989). The seasonal response, however, was less apparent among the nutrient rich hypereutrophic reservoirs in South Korea which tend to be shallow and at low elevation (Figure 4).

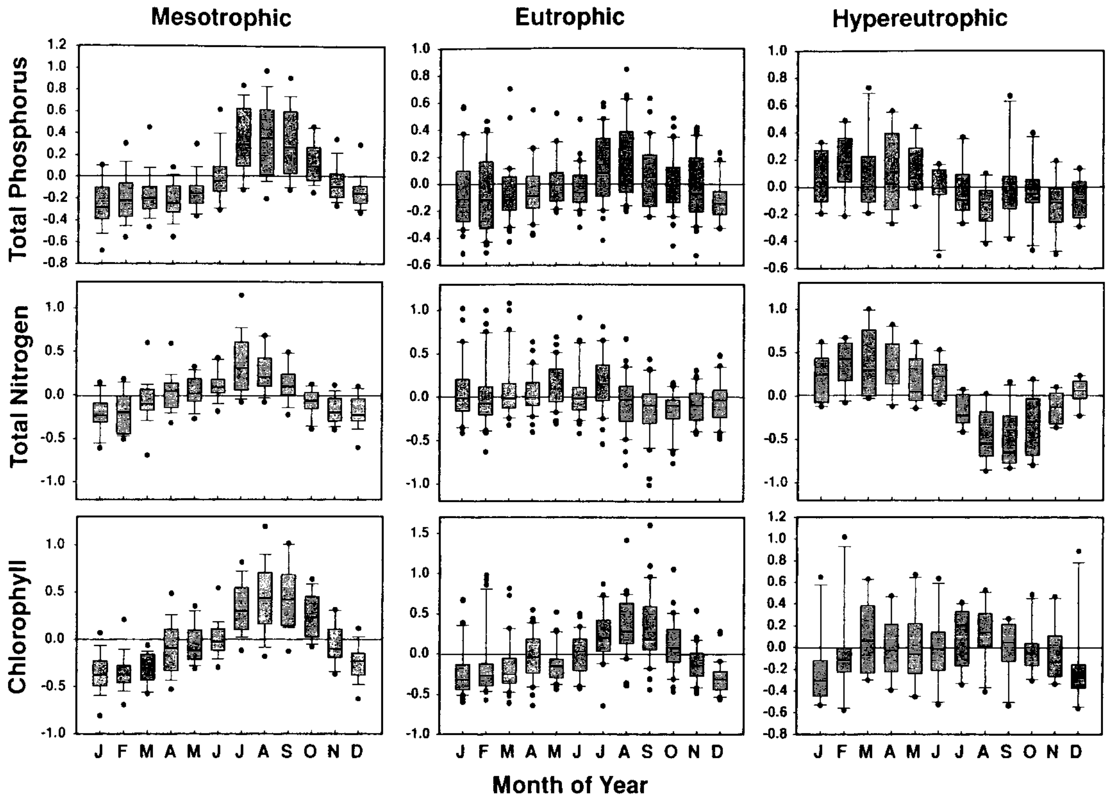

Figure 4. Box-plots of monthly mean normalized values of total phosphorus, total nitrogen and chlorophyll from 59 Korean reservoirs (1993–2007) presented by trophic state (Jones et al., 2003). Individual values were normalized using the lake mean. Box plots and rainfall patterns are described in Fig. 1.

Within lake conditions and interannual comparisons

Thermal stratification in Asian lakes can be influenced by the strength and timing of monsoon inflows and intensity of rainfall on the lake surface (Davis et al., 1998; An and Jones, 2002; Satoh et al., 2001; Jones et al., 2006; Tsai et al., 2008). Typically, monsoon storms cool surface temperatures and deepen the mixed layer of stratified lakes, and may destratify shallow basins. In some cases, peak monsoon runoff can enter large stratified lakes as a density-dependent interflow at some depth in the water column. Depending on inflow volume and stratification characteristics, interflows can disperse deep in the water column with little direct influence on the mixed epilimnion. Data from Juam Lake (South Korea, Figure 5) illustrate changes in temperature and oxygen in the water column during the summer monsoon. In June the water column was stratified with some deep water oxygen depletion, in July a notch in the oxygen profile at the epilimnion-metalimnion interface suggests a minor interflow and the positive heterograde oxygen peak immediately below suggests a mid-column algal peak. By August the oxygen profile showed a strong negative heterograde pattern associated with a $\sim$ 23°C interflow below the warm epilimnion. Data from Lake Phewa, Nepal illustrate that interflows can directly influence algal biomass in the water column – the lake can support large metalimnetic algal layers (Lohman, 1988) that can be completely eliminated by turbid monsoon interflows (Figure 6) only to re-form during storm-free periods (Davis et al., 1998). A cage-culture fishery in this lake depends on this rich organic layer for increased yields.

Interflows can further complicate the interpretation of lacustrine water quality during the monsoon. An analysis of phosphorus values in the mixed layer near the dam of Juam Lake (South Korea) during a series of above average monsoons averaged less than half the value during a relatively dry

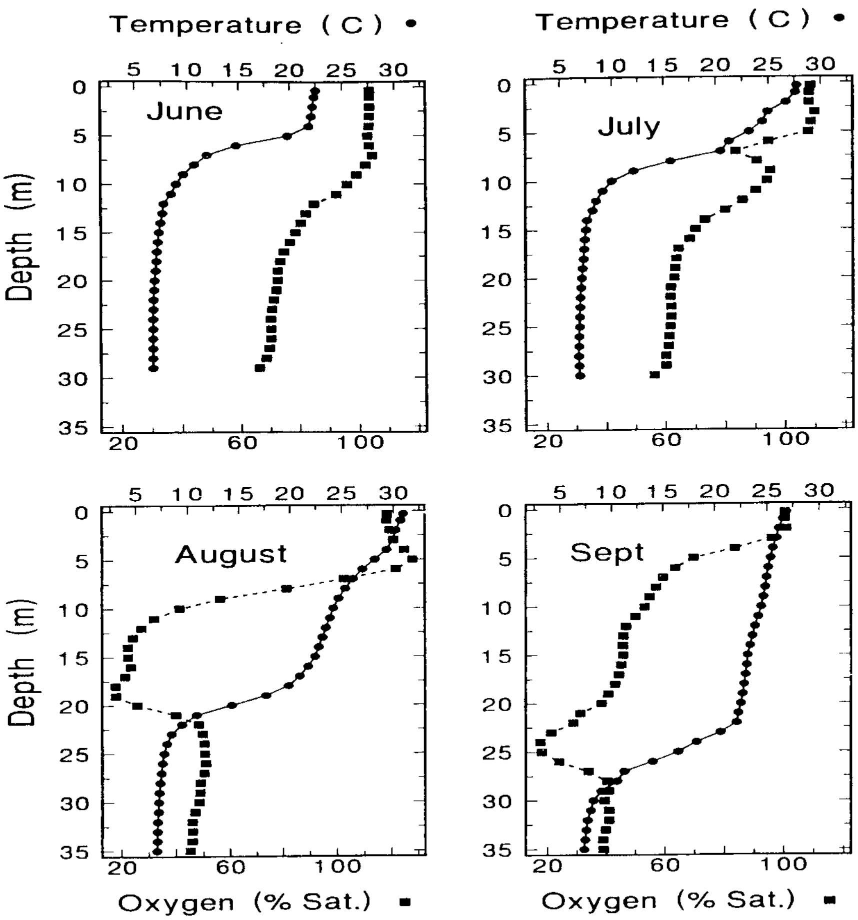

Figure 5. Temperature (top axis, circles) and oxygen saturation (bottom axis, squares) profiles from the Dam site on Juam Lake, South Korea during 2000. Months the data were collected are shown on the panels. The figure was redrawn after Jones et al. (2006).

period (9 vs. 22 $\mu g\ L^{-1}$, Jones et al., 2006). The correlation between precipitation and phosphorus was negative for both annual values and the monsoon season ($r > -0.72$, $n = 11$, Figure 7). Given the clear differences in external loading between these extreme monsoon seasons this outcome is counter-intuitive, and likely results from interflows passing through the reservoir with minimal influence on the downlake zone during strong monsoons. In contrast, during weak monsoons interflows may not form or be less pronounced, and less isolated from the mixed surface layer. Simply put, nutrient loads during a strong monsoon can be largely undetected in surface samples collected in the main body of lakes and reservoirs that experience distinct sub-surface flow. Hydropower production in many Asian impoundments can discharge inflows through the turbines and reduce their residence time and dispersal in the impoundment.

Studies in Asian lakes show that disruption, or collapse of stratification during strong monsoon storms can provide an internal source of limiting nutrients from layers deep in the water column. These changes in stratification patterns often coincide with sediment re-suspension and inflow of allochthonous materials that can reduce light penetration and depress, at least temporally, lake fertility (Davis et al., 1998; Robarts et al., 1998; Frenette et al., 1996; Tsai et al., 2008). Deep mixing and mineral turbidity are known to weaken the relation between nutrients and algal biomass (Jones et al., 1998; Jones and Knowlton, 2005) but with photoadaptive adjustments phytoplankton communities can rebound quickly once light scattering materials have sedimented. These findings suggest physical, chemical and light conditions can be dynamic within the water column of lakes influenced by monsoon inflow. Short-term variation in these conditions would be

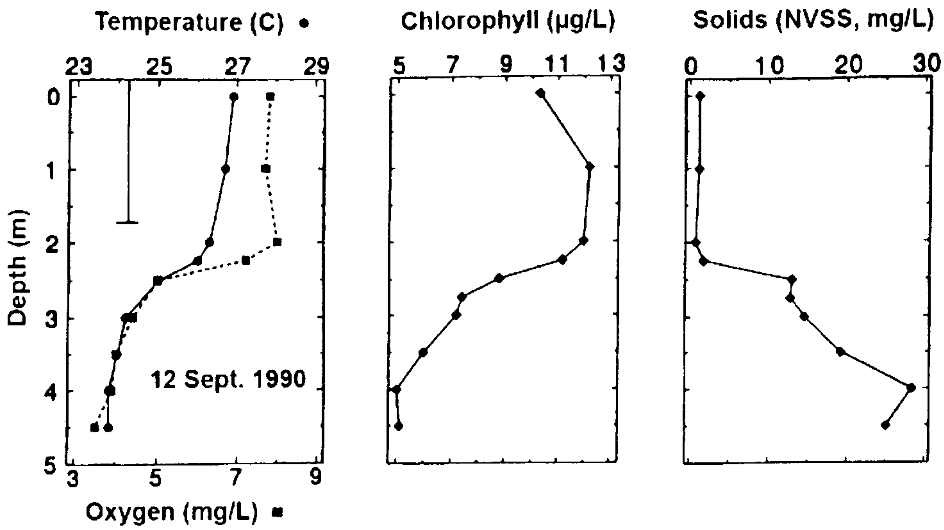

Figure 6. Limnology data from Lake Phewa, Nepal in 1990. Vertical line represents Secchi depth, temperature (top axis, circles), oxygen (bottom axis, squares), chlorophyll (middle panel) and non-volatile suspended solids as a measure of inorganic turbidity (right panel) are shown. The figure was redrawn after Davis et al. (1998).

more extreme in years of above-average rainfall and during intense storm events. Data from South Korea show chlorophyll values in the surface layer were larger by ~ 45% during a weak monsoon despite lower nutrient levels (Figure 2). This difference is attributed to more favorable conditions for phytoplankton growth during the weak monsoon.

Longitudinal gradients along the mainstem of Asian reservoirs can show a strong seasonal response to monsoon inflow. Nutrients and suspended solids increase in response to fluvial inputs and decline along the mainstem with a concomitant increase in transparency. During the height of the monsoon changes of several fold along the reservoir mainstem are not uncommon (An and Jones, 2002; Jones et al., 2006). Concentrations and the magnitude of this longitudinal decline depend on monsoon intensity. Data from Daechung Lake (South Korea) show low nutrients and suspended solids and weak spatial gradients during a year of widespread drought (Park and Schubert, 1997) relative to a near normal monsoon (Figure 2). Spatial patterns in reservoirs with monsoon influence will be expected to show both sharp seasonal and interannual contrasts.

Discussion

Climate change is expected to result in greater extremes in droughts (El Niño) and floods (La Niña). Water quality data collected from lake systems in Asia show a wide range in response to monsoon intensity in all factors except the consistent seasonal dilution of major ions by surface flow. Cross-system seasonal patterns in Nepal and among mesotrophic reservoirs in South Korea are consistent with nutrients being controlled by nonpoint sources. The dilution of nutrients by monsoon inflow in hypereutrophic South Korean reservoirs is consistent with point source inputs being responsible for peaks in the annual load during the non-monsoon period. The lack of a clear seasonal pattern among eutrophic South Korean reservoirs suggests a highly variable response to monsoon inflow in individual water bodies of moderate depth. The isolation of interflows from the mixed surface layer also complicates the in-lake response to nutrient loads carried by monsoon inflow. The seasonal cycle of phytoplankton biomass peaking with nutrients during the monsoon may be a phenological model for the region but with considerable variation within individual lakes; available data suggest it is strong enough to stand out against most within lake variation and may be most pronounced in small lakes. At a different temporal and spatial scale, short-interval data from individual lakes show disruption or collapse of stratification during severe storms by wave induced shear stress, locally heavy rainfall and inflow. These forces can serve as an internal and external source of limiting nutrients while concurrently create an unfavorable

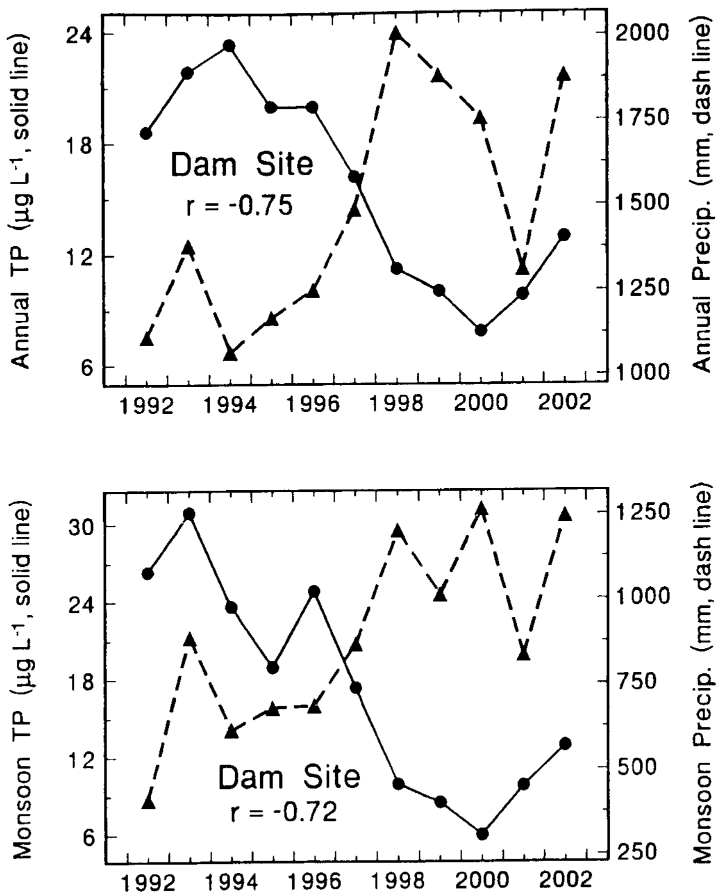

Figure 7. The upper panel shows the annual total phosphorus value at the Dam site in Juam Lake, South Korea during the period of record and the annual total precipitation. The two values are negatively correlated. The lower panel shows average total phosphorus and rainfall at the Dam during the monsoon. The two values are negatively correlated. The figure was redrawn after Jones et al. (2006).

light environment resulting from sediment inputs and deep mixing, in both the surface waters and the metalimnion. In response to physical processes the linkage between nutrients and phytoplankton biomass can be briefly uncoupled in monsoon influenced lakes.

Conclusions

Available data suggest the frequency of storm events and the strength of the monsoon in a given season, or over a series of seasons, can influence the direction and magnitude of response of individual lakes. Collectively these mixed responses limit our ability to predict what happens in a given lake or reservoir during the Asian monsoon or generate a holistic seasonal pattern that is broadly applicable. Likewise, conditions during the dry season leading up to the monsoon, which are influenced by evaporation, water withdrawal and nutrient loading from local and municipal sources, are of equal importance in understanding the generalized seasonal pattern. Additional studies, such as the long-term monitoring program in South Korea and similar studies in Japan, are required throughout the region to better quantify the broad continuum of responses to extreme hydrological processes, and seasonal phenology in Asian lakes to anticipate changes as the monsoon intensifies with climate warming.

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