Article

The effects of Asian summer monsoons on algal blooms in reservoirs

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Abstract

An important characteristic of lakes and reservoirs in the East Asian summer monsoon region is the dramatic seasonal difference in hydrologic inputs, with annual rainfall commonly concentrated in a few heavy rain events. In this study, we surveyed the monthly variations of phytoplankton density in 3 large deep reservoirs and 7 small shallow reservoirs and analyzed the effect of large precipitation events on phytoplankton. During heavy rains, stream phosphorus concentrations increased sharply, and phosphorus loadings into reservoirs were not continuous but episodic shock loadings. In deep stratified reservoirs, however, the concentrations of phosphorus and chlorophyll *a* were much lower than expected from the high total phosphorus levels in the storm runoff. Inflowing storm waters laden with phosphorus flowed into metalimnetic layers because deep reservoirs had strong thermal stratification and the storm water was cooler than the epilimnion. The result was the formation of an ecosystem resilient to phosphorus shock loadings during monsoon. Nutrients in the metalimnion seemed to be dispersed gradually toward the epilimnion, and phytoplankton reached maximum densities, called "monsoon blooms," after the monsoon. By contrast, shallow reservoirs with short hydraulic residence times had lower chlorophyll *a* concentrations during the monsoon season because the high flushing rate was the major limiting factor of phytoplankton growth. In conclusion, summer monsoon is the major determinant of phytoplankton density in reservoirs of the East Asian region, but their responses can vary widely depending on hydrologic characteristics.

Key words: East Asian summer monsoon, Korea, monsoon bloom, phytoplankton, reservoir

Introduction

In regions influenced by the monsoonal climate system, annual precipitation occurs in rainy seasons, which can be summer or winter. The East Asian monsoon, caused by a stagnant rain front that stays over China, Japan, Korea, and Taiwan, gives rise to typhoons, mostly in summer. The annual precipitation is therefore concentrated in summer, and these heavy rains can exert substantial effects on hydrologic conditions and biogeochemical cycles in freshwater ecosystems (Tao 1998, Kim et al. 2000, Ogawa et al. 2006, Park et al. 2007).

In Korea, half of the annual rainfall occurs during July and August. The rainy season can be divided into 2 periods; the first is a stagnant rain front occurring in July, called "Jangma" in Korean, when rains are frequent but less intense than during the second period, and the second is from August through early September when occasional typhoons pass over the Korean peninsula. Typhoons are always accompanied with heavier rainfalls than rains during the Jangma period, but the frequency and paths of typhoons are unpredictable and irregular (Chung et al. 2004, Chang and Kwan 2007).

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Given the extremely aggregated distribution of rains in summer, many reservoirs (~17 500) and weirs (>40 000) were constructed in Korea to provide water supply during dry seasons (Hwang et al. 2003). Because Korea has few natural lakes and all major lakes are artificial, hydraulic residence times in Korean lakes are much shorter than natural lakes; therefore, the variation of hydraulic residence time is large in Korean lakes and susceptible to the effects of hydrologic changes. Natural lakes have long hydraulic residence times, and the seasonal fluctuation of the nutrient loading into the lake can be moderated because the amount of storm runoff water is small compared with the lake water volume. Artificial lakes have short hydraulic residence times, and storm runoff can significantly impact the hydrological conditions of the ecosystem.

Monsoon rains are a major determining factor in many ecosystems of Asian lakes and reservoirs (An and Jones 2000, An and Park 2002, 2003, Jones et al. 2006, 2009, Xiao et al. 2011, Park et al. 2013). The effects of monsoon on phytoplankton can vary in large dams and small reservoirs, however, because of differences in hydraulic residence time, stability of stratification, and nutrient concentrations (Straškraba 1999, Lee et al. 2012). In this paper we discuss and compare the effects of East Asian summer monsoon on phytoplankton in large dams and small reservoirs.

Materials and methods

Study sites

Three large reservoirs and 7 smaller reservoirs were selected to compare the effects of monsoon on phytoplankton in large and small reservoirs (Fig. 1). The large reservoirs have water capacities of 1.2–1.9 × 10^9 m^3, mean depths of 20–42 m, and annual mean hydraulic residence times of 102–197 days; the smaller reservoirs have water capacities of 0.9–80 × 10^6 m^3, mean depths of 1.7–7.0 m, and residence times of 6–80 days (Table 1). The 3 large reservoirs were constructed for flood control, water resources supply, and hydroelectric power generation; the largest of the smaller reservoirs (Lake Euiam) was built for hydroelectric power, and the others were constructed for irrigation.

Lake Soyang is the largest reservoir in South Korea, based on water capacity, and was monitored during this study for a longer period than other reservoirs. Water samples were collected at the dam site at depths of 0, 2, 5, 10 m, and then at 10 m intervals to the bottom. The lake surface water was surveyed monthly. The major inflowing river into Lake Soyang (the Soyang River) was surveyed by collecting surface river water at weekly intervals on dry days but more frequently (1–3 times a day) on rainy days because water quality varies faster than on dry days. The flow rate of the Soyang River was measured by the K-Water company that manages the dam.

Lake Chungju has the second largest water capacity in Korea but the largest watershed and surface area, and Lake Daechung has the third largest water capacity. Lake Euiam has a large watershed, but it has a small water storage capacity and was classified as a reservoir of short residence time. For Lake Chungju, Lake Daechung, and Lake Euiam, chlorophyll *a* (Chl-*a*) and total phosphorus (TP) have been examined monthly by the Korean Ministry of Environment and were employed in this study. Six small reservoirs constructed for irrigation only were classified in this study as reservoirs of short residence time together with Lake Euiam. The 6 small reservoirs were monitored monthly for a period of 1 year in 2004.

Chl-*a* was measured by filtering surface water samples through a GF/C filter and applying the trichromatic spectrophotometric method (APHA 2005). TP was measured

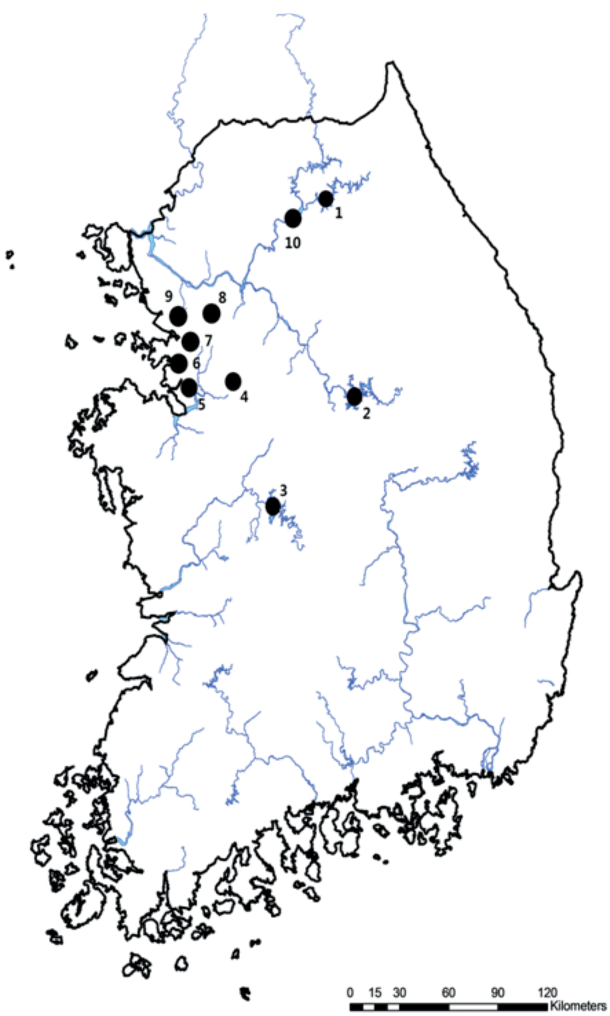

Fig. 1. Location of study reservoirs in Korea. Refer to Table 1 for lake names.

Table 1. Hydrologic characteristics of study reservoirs.

Reservoir	Watershed area (km^2)	Lake surface area (km^2)	Max water volume (10^6 m^3)	Mean depth (m)	Annual mean hydraulic residence time (d)	Number of data in this study
1. Soyang	2703	70	2900	42	270	1204
2. Chungju	6648	97	2385	28	102	675
3. Daecheong	3204	73	1241	20	180	972
4. Kumkwang	48.3	1.52	10.5	7.0	80	39
5. Dukwoo	22.7	1.10	4.13	3.8	66	29
6. Myukwoo	8.3	0.52	0.90	1.7	40	17
7. Dongbang	6.3	0.62	1.08	1.7	63	21
8. Wangsong	15.6	0.96	1.97	2.1	46	52
9. Hengbu	13.2	0.60	1.94	3.3	55	34
10. Euiam	7454	15	80	5.0	6	60

by ascorbic acid method after the persulfate digestion (APHA 2005). The average monthly Chl-*a* at the surface of the 3 large reservoirs was calculated from the monthly monitoring data from 2002 to 2014, selecting only 3 dry years with smaller annual precipitation in the watersheds (2005, 2007, and 2014 for Lake Soyang; 2003, 2007, and 2014 for Lake Chungju; 2008, 2010, and 2014 for Lake Daechung) and 3 wet years with more annual precipitation (2006, 2009, and 2011 for Lake Soyang; 2002, 2010, and 2011 for Lake Chungju; 2002, 2006, and 2012 for Lake Daechung). Noteworthy events were a heavy rain in 2006 in the watersheds of Lake Soyang and Lake Chungju and a nationwide severe drought in summer 2014.

To examine the seasonal variations of phytoplankton density in small reservoirs with short residence times, Chl-*a* data were collected from the 7 small study reservoirs. To directly compare data, monthly data were normalized for the annual variation of each reservoir because each had a wide range of variation and maximum Chl-*a*, depending on trophic state. The normalized scores of each of the 7 reservoirs were averaged for each month to show the relative seasonal variation of phytoplankton.

Trophic state indices were calculated according to Carlson (1977) by using the average of each month's data. Average monthly precipitation was calculated using the last 30 years of meteorological data from 73 nationwide Korean Meteorological Office stations.

Results

The variation of monthly precipitation in Korea showed extreme aggregation of precipitation in summer. The average annual precipitation was 1350 mm yr^{-1} for the last 30 years, similar to the worldwide average, but the seasonal variation was at the extreme end of uneven distribution of precipitation in the East Asian summer monsoon region. The monthly precipitation was <100 mm $month^{-1}$ during cold dry seasons from October to early June but was as high as 300 mm $month^{-1}$ in July and August (Fig. 2). Including precipitation in late June and early September, the sum of precipitation during the summer monsoon season was about 900 mm, which accounted for ~65% of the annual precipitation. In addition to higher rainfall in summer, rain was extremely aggregated in a few episodic heavy rain events per year, sometimes exceeding 100 mm d^{-1}.

According to the change in precipitation, the flow rates of streams in Korea varied dramatically. For example, the Soyang River, the main tributary into Lake Soyang, showed a flow rate of <50 m^3 s^{-1} on dry days but increased up to >2000 m^3 s^{-1} during occasional rain events that occurred a few times per year (Fig. 3). Thus, the flow rate of a river could vary annually 10- to 100-fold.

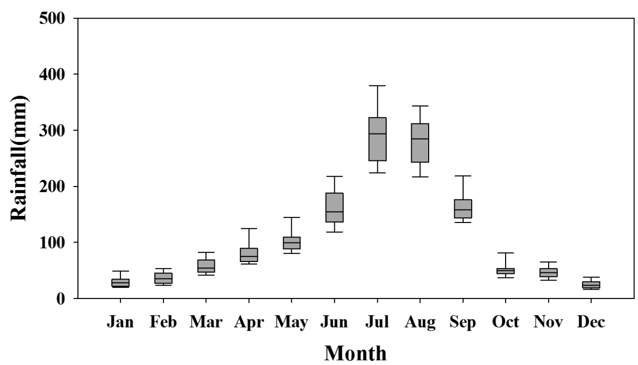

Fig. 2. Annual variation of monthly precipitation (mm $month^{-1}$) in Korea showing that rainfall is concentrated in July and August (average of 73 sites in Korea for the last 30 years).

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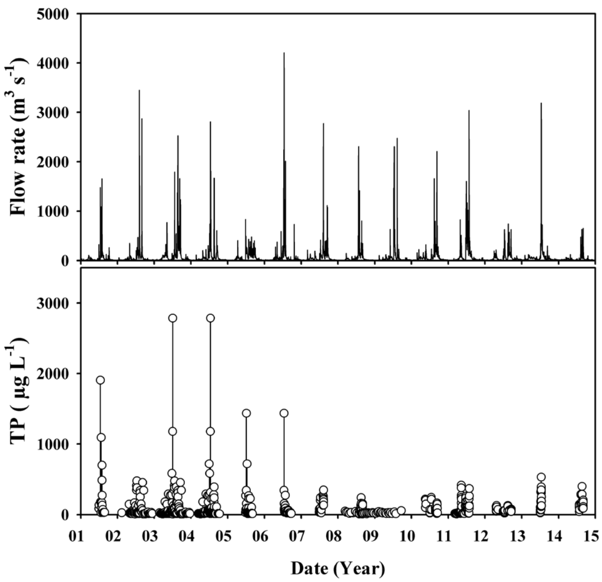

Fig. 3. The variations of flow rate and total phosphorus (TP) concentration in the Soyang River, showing dramatic changes according to rainfall (data from 2001 to 2014).

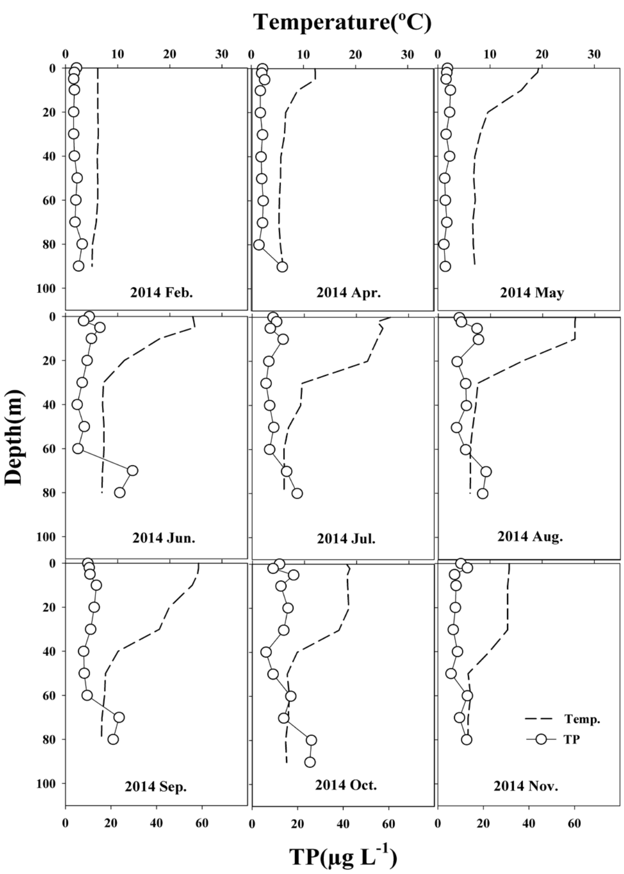

Fig. 4. Vertical profiles of temperature and total phosphorus (TP) in a dry year in a large deep reservoir (Lake Soyang) showing that a high-TP intermediate layer was not formed.

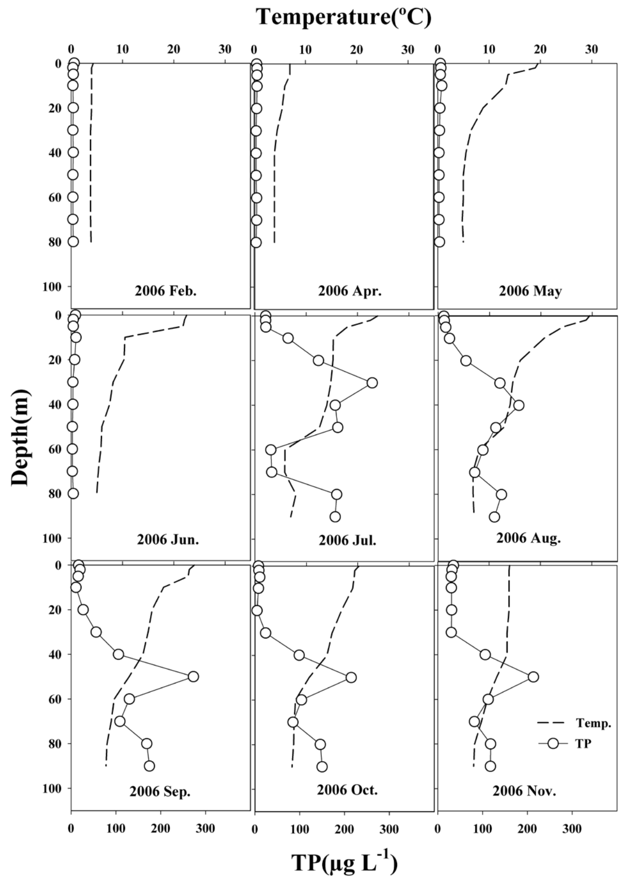

Fig. 5. Vertical profiles of temperature and total phosphorus (TP) in a wet year in a large deep reservoir (Lake Soyang) showing the formation of turbid intermediate layer with high phosphorus concentration.

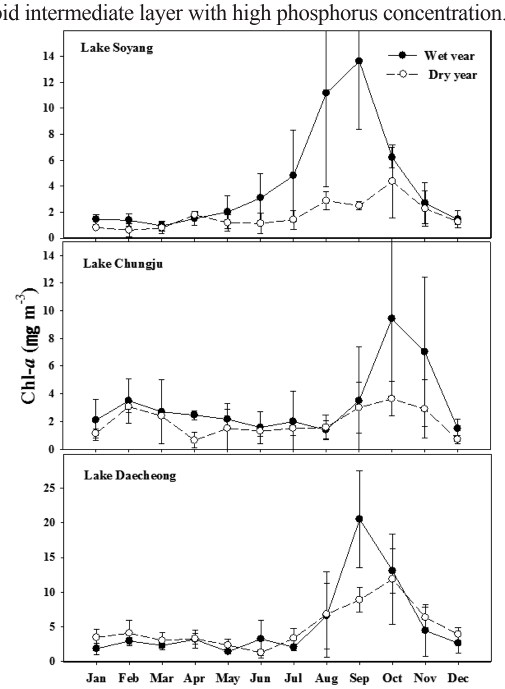

Fig. 6. The annual variations of monthly median and standard deviation of chlorophyll *a* (Chl-*a*) concentration in 3 deep stratified reservoirs in wet years (solid line) and dry years (dashed line).

When the flow rates of rivers increase during rain events, the concentrations of phosphorus and suspended particles also increase dramatically in Korean rivers (Park et al. 2010). Topsoil erosion from agricultural fields is a common problem that impairs water quality in Korea, and turbid runoff waters are usually laden with phosphorus adsorbed onto fine soil particles. In the Soyang River, TP was <20 μg L^{-1} on dry days, whereas it increased to >100 μg L^{-1} on rainy days (Fig. 3). Therefore, phosphorus loading to Lake Soyang, calculated as the flowrate multiplied by the TP, can increase during rain events >100-fold. Although the peak TP during rain events has shown a decreasing tendency in recent years, possibly because of governmental management of topsoil erosion in the watershed, TP was still much higher than during dry days (Fig. 3).

The high flow rate multiplied by high phosphorus concentration on rainy days showed that daily phosphorus loadings into reservoirs were not continuous but intermittent episodic events. Most of the annual phosphorus loading into the reservoir was contributed by only a few episodic shock loadings that occurred during heavy rain events. Phosphorus loadings on dry days were mostly negligible because both the flow rate and phosphorus concentration were low.

TP in storm runoff waters was much higher than the threshold level for eutrophication; however, in the epilimnion of Lake Soyang, phosphorus concentrations after storms were not as high as expected from the high phosphorus concentrations in storm runoff. We found that the turbid storm runoff waters during summer monsoon flowed into the metalimnion because the temperatures of storm runoffs were lower (10–15 °C) than the lake surface temperature (20–25 °C). The density flow formed an intermediate layer of high phosphorus concentration not easily dispersed into the epilimnion because of a stable stratification. The effect of storm runoff was obvious when the vertical TP profiles were compared between a year without a major storm runoff (2014; Fig. 4) and a year of a heavy storm runoff (2006; Fig. 5). In 2014, TP was <20 μg L^{-1} in both epilimnion and metalimnion throughout the year, whereas TP increased >200 μg L^{-1} in the metalimnion after monsoon rains in 2006. It is noteworthy that the TP in the epilimnion remained <20 μg L^{-1}, whereas the metalimnion had high TP. After the monsoon, phosphorus in the metalimnion seemed to gradually disperse into the epilimnion according to the descending thermocline and entrainment.

The patterns of seasonal change in phytoplankton standing crop in deep large reservoirs and in small reservoirs varied. In the 3 large reservoirs (Lake Soyang, Lake Chungju, and Lake Daechung), phytoplankton density showed a unique seasonal variation pattern different from those of typical natural lakes. In this study we compared Chl-*a* in 3 dry years with lower precipitation and 3 wet years with significant monsoon rains (Fig. 6). In dry years, the seasonal variation of Chl-*a* was not as prominent as during wet years, although small blooms were observed in autumn or spring. In wet years, the median Chl-*a* of ~2 mg m^{-3} in Lake Soyang and Lake Chungju before the monsoon increased to >10 mg m^{-3} after the monsoon, and in Lake Daechung from <5 before the monsoon to 20 mg m^{-3}. Although most temperate lakes have 2 phytoplankton blooms per year, one in spring and another in autumn, large reservoirs in Korea had the highest blooms in late August and September, 1–2 months after the onset of the summer monsoon.

By comparison, in reservoirs of shorter hydraulic residence time, Chl-*a* decreased during summer monsoon, mainly due to hydrologic flushing. Phytoplankton standing crop seems to decrease when the residence time is <5 days, as clearly seen in Lake Euiam (Fig. 7). The residence time in Lake Euiam was about 10 days during dry seasons, and phytoplankton thrived, but decreased to <5 days after the summer monsoon, and

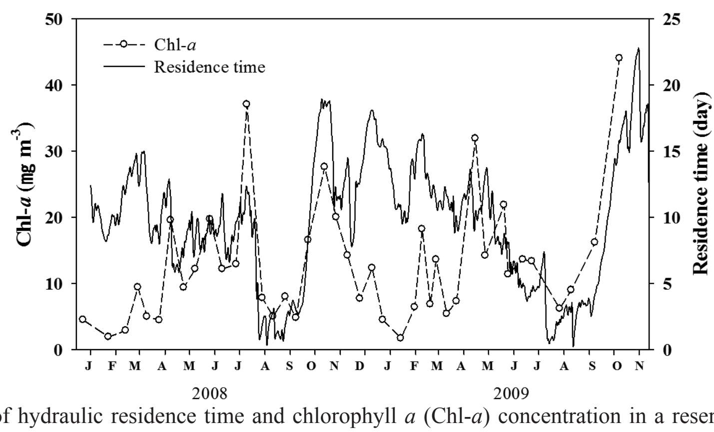

Fig. 7. The annual variations of hydraulic residence time and chlorophyll *a* (Chl-*a*) concentration in a reservoir with a short residence time (Lake Euiam), showing the sharp decrease in residence time and phytoplankton after the monsoon season.

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phytoplankton subsequently decreased dramatically.

In contrast to large reservoirs, phytoplankton standing crops in small reservoirs were lower in the monsoon season. In this study, the variation of normalized Chl-*a* in the 7 small reservoirs was incorporated into a monthly Chl-*a* variation graph, showing that the mean Chl-*a* in July was lower than the annual mean (mean − 0.4 × standard deviation), although July was a warm growing season for algae (Fig. 8). TP was higher in the small reservoirs in July during the monsoon season than it was in large reservoirs, but Chl-*a* was lower, possibly from the effect of short residence time or dilution.

To examine the effect of short residence time on the exploitation efficiency of phosphorus, measured Chl-*a* was compared with the corresponding Chl-*a* estimated from reported empirical relationships between TP and Chl-*a*. The relationship was incorporated in the trophic state index (TSI) by Carlson (1977), and the difference between TSI(Chl) and TSI(TP) can increase when short residence time or turbidity prevents complete exploitation of phosphorus. TSIs were calculated for the 7 small reservoirs, and TSI(Chl) and TSI(TP) were compared. We found that the difference (TSI(Chl) − TSI(TP)) was lowest in the season of Jangma (July), implying that hydraulic residence time can be a controlling factor of phytoplankton biomass buildup during the monsoon season (Fig. 8).

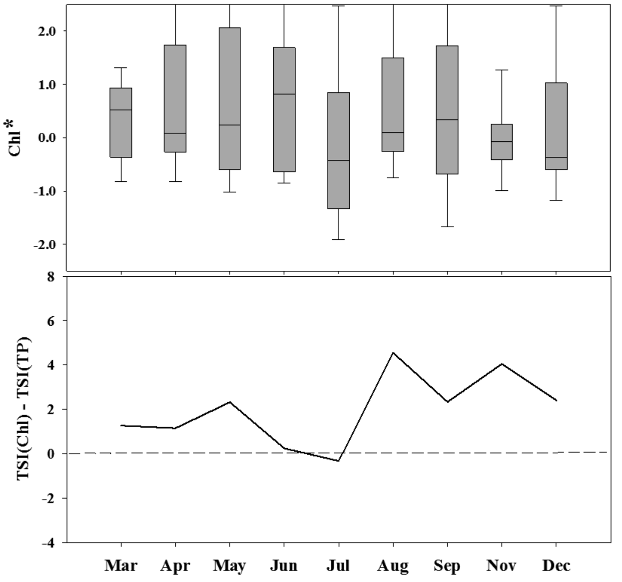

Fig. 8. The seasonal variations of monthly median and the standard deviation of normalized chlorophyll *a* concentration (Chl*) and the deviation of trophic state index of chlorophyll *a*, TSI(Chl), from the trophic state index of total phosphorus, TSI(TP), in 7 reservoirs of short residence times (data collected in 2003–2004 and normalized for the mean and standard deviation of each reservoir).

Discussion

The effects of monsoon can be exerted through both physical and geochemical factors. The main physical factor is the reduced hydraulic residence time in rainy seasons, which can have significant dilution effects on plankton in reservoirs of short residence time. Increased inorganic turbidity and reduced light penetration may be additional physical factors causing the reduction of phytoplankton primary productivity (Schagerl and Oduor 2003, Allende et al. 2009, Sobolev et al. 2009). The main geochemical factor is that storm runoff water in Korea usually is heavily laden with high concentration of phosphorus, which can increase phytoplankton production in lakes. Therefore, these 2 factors have opposite effects, and the final net effect is determined by the relative importance of each factor, depending on the hydrologic conditions and watershed conditions.

Dramatic increases in water flow rate and TP in summer are unique features of the seasonal change of aquatic environments in Korean streams and reservoirs. Phosphorus loadings into reservoirs are much larger in summer than in other seasons, and the dramatic increase of phosphorus and subsequent severe phytoplankton blooms are expected in reservoirs. The effect of phosphorus shock loadings on phytoplankton during summer monsoon, however, is not exerted as strongly in reservoirs as would be expected from the high TP in inflowing rivers. This is a common phenomenon, both in large deep reservoirs and in small reservoirs. Impacts of storm runoff on phytoplankton are weaker than expected in deep stratified large reservoirs because phosphorus concentration does not increase as much in the epilimnion, even after the monsoon. Thermal stratifications are stable in deep montane reservoirs because of the wind-sheltering effect, and storm runoff waters with high phosphorus content usually flow into intermediate layers because the temperature of river water on rainy days is lower than the surface layer of reservoirs (Kim et al. 2000, Kim and Kim 2006). The temperature of river water is at equilibrium with air temperature when water flow velocity is slow, whereas the temperature of river water is lower than air temperature during rain events because the water temperature is equilibrated with air in the high altitude upstream area, and fast-flowing water does not provide enough time to equilibrate with warming air before reaching the downstream area.

In deep reservoirs, turbid storm runoff laden with high phosphorus loads plunge into an intermediate layer of the reservoir, and the stable thermal stratification prevents the turbid middle layer from mixing completely. Because large dams usually have discharge outlets at the middle depth that coincide with the depth of the turbid intermediate layer, the middle layer water can be discharged from dams before being completely mixed with the surface layer, and the high phosphorus content in the turbid storm runoff does not impact the epilimnion. Because of the combined effects of strong stratification in summer and cold storm runoff water, deep reservoirs in Korea can form ecosystems resilient to phosphorus shock loadings that occur during summer monsoon.

Even in stratified deep reservoirs, however, phytoplankton blooms regularly occurred after summer monsoon, resulting from the gradual dispersion of intermediate layer water toward the epilimnion. In most natural lakes, the annual peak algal bloom occurs in spring and a smaller bloom follows in autumn; by contrast, maximum algal blooms occur in late summer in this summer monsoon region and can be called “monsoon blooms” rather than spring and autumn blooms common in other climate regions.

The density of phytoplankton, however, was much lower than the density expected from high phosphorus concentrations in storm runoffs. For example, in Lake Soyang, TP in the inflowing river sometimes exceeded 300 μg L^{-1}, and TP in the intermediate layer was >100 μg L^{-1}, which can result in a corresponding Chl-*a* concentration of 70 mg m^{-3} if exposed to sunlight at the lake surface. TP in the epilimnion, however, remained 30 μg L^{-1} and Chl-*a* <20 mg m^{-3}. Most phosphorus transported by the storm runoff remains in the intermediate layer, and surface TP was <10% of TP in the storm runoff waters; therefore, Lake Soyang and Lake Chungju could remain in the range of oligo-mesotrophic lakes, but they would be eutrophic lakes if the storm runoff water were completely mixed with the surface layer.

Reservoirs of short hydraulic residence times showed lower phytoplankton density in rainy periods than in dry seasons (Fig. 8), in contrast to the deep stratified reservoirs, possibly because of flushing effects by storm runoff. Residence times in small reservoirs sometimes can be <5 days during storm periods in Korea, when flushing becomes the primary limiting factor of phytoplankton growth. Chl-*a* was lower than the annual average, even when TP and temperature were higher in the monsoon season, implying lower exploitation efficiency of phosphorus by algae due to short residence time.

Inorganic turbidity sometimes becomes a suppressing factor for phytoplankton during monsoon. Clay particles can coagulate with phytoplankton cells by adhering to the cell surface, resulting in increased settling velocity of phytoplankton cells (Avnimelech et al. 1982, Soballe and Threlkeld 1988, Sengco et al. 2001, Beaulieu et al. 2005). Turbidity also can reduce primary production of phytoplankton by reducing light availability under water. In small reservoirs, turbid storm runoff water can be completely mixed with the surface layer or the whole reservoir. Small reservoirs in Korea always appear highly turbid just after a heavy rain event, and the primary productions of both phytoplankton and macrophytes can be lower in the summer monsoon season than in clear dry periods. By contrast, deep stratified reservoirs appear clear even after a heavy rain event because turbid storm runoff flows into a middle layer without having a direct impact on the transparency of the epilimnion.

In conclusion, summer monsoon is the major determinant factor of phytoplankton biomass in reservoirs of the East Asian region, but the response can vary widely depending on hydrological characteristics. In deep stratified reservoirs, monsoon blooms occur after the summer monsoon, whereas phytoplankton are washed out of small reservoirs with short residence times.

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