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Original article

Major nutrients and chlorophyll dynamics in Korean agricultural reservoirs along with an analysis of trophic state index deviation

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ABSTRACT

The main objectives of this study were to determine how Asian monsoon influences nutrient regime, suspended solids, and algal chlorophyll (CHL) in 182 agricultural reservoirs, and then to develop the empirical models of nutrients-chlorophyll. The intensity of summer monsoon directly determined the ambient concentrations of nitrogen (N) and phosphorus (P). Regression analysis of empirical model showed that CHL had a high linear relation ($R^2 = 0.716$, $p < 0.01$) with total phosphorus but a weak relation ($R^2 = 0.041$, $p < 0.01$) with total nitrogen. Seasonal empirical models of TP-CHL showed that the regression coefficients in premonsoon ($R^2 = 0.605$) and postmonsoon ($R^2 = 0.554$) were greater than that of the monsoon. Values of trophic state index (TSI) implied that phosphorus limitation was severe in the Korean agricultural reservoirs. Overall, our study of 182 reservoirs suggested that phosphorus was key nutrient regulating the phytoplankton growth. This phenomenon was supported by the analysis of trophic state index deviation relations of “TSI (CHL)–TSI (SD) < TSI (CHL) − TSI (TP)”.

Introduction

Eutrophication is a world-wide problem on the water quality for drinking waters and agricultural irrigations and the processes is faster in the artificial lakes than the natural lakes (Sutcliff and Jones 1992). Eutrophication, therefore, is one of the major challenging issues for limnologists and ecologists (Kalff 2001). Most of the reservoirs are located in low-rainfall regions (low runoff) due to the imbalanced rate of precipitation versus evaporation throughout the year, and especially, the agricultural reservoirs are true in Korea. Agricultural reservoirs in Asian regions are shallow in depth, eutrophic, and have unstable hydrodynamics and the major source of nutrients are allochthones (Hwang et al 2003; MAF and KOWACO 2001). By contrast, reservoirs in North America and Europe are deeper, have more drainage area, and had longer water residence time. In Asian regions including Korea, small or medium-size reservoirs were made for irrigation in paddy farming (Hwang et al 2002). Also, the reservoirs are used for supplying the drinking water, flood control, electricity generation, and fish culture in the Asian region (Hwang et al 2003).

In Korea, high amounts of fertilizers have been used in the paddy fields which is the important source of nutrients [nitrogen (N) and phosphorus (P)] in streams and reservoirs (Yoon et al 2006). Nitrogen and phosphorus are the key elements for the growth of phytoplankton in the reservoir waterbodies. The excess level of nutrients (N and P) is responsible for the eutrophication in the reservoirs. Concerns associated with eutrophication such as blue-green algae include discolored water, reduced light penetration, taste and odor problems, and dissolved oxygen depletions during die-off (i.e. summer fish kill) and toxin production (i.e. microcystin). When blue-green algae reach bloom densities, they can actually reduce light penetration, which can adversely affect other aquatic organisms both directly such as other phytoplankton and aquatic plants and indirectly such as zooplankton and fish that depend on phytoplankton and plants (Kotak et al 1994). Such water quality problems in reservoirs are common in North America (Tran et al 2013), Europe (Svircev et al 2008), Oceania (Pridmore et al 1985), and Asia (Xu et al 2012). In Korean eutrophic reservoirs, cyanobacterial blooms frequently occurred, and the toxin of microcystin has been frequently detected in the water (Kim et al 1999).

Loading of N and P are rapidly incrementing in agricultural reservoirs due to intense agricultural activities and wastewater disposal plants near farmland. Seasonal differences in the rainfall (monsoon *vs.* nonmonsoon region) between the continents

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influence time of N and P loadings and the seasons in the response of phytoplankton communities. Summer total phosphorus (TP) influences the fall chlorophyll (CHL) in Asian reservoirs, whereas the spring TP influences summer chlorophyll in North America. The growing season of algae is during the summer period of July–August) in Korean reservoirs. On the contrary, most of the rainfall occurs in spring (May and June) in North America, Therefore, the spring TP increased from stream runoff influences the summer chlorophyll, which is a typical growing season of algae in the reservoirs. In Korea, about one-half of the rainfall occurs during the summer monsoon period, increased phosphorus and inorganic suspended solids, and affects the phytoplankton growth in the reservoirs. Similarly, in China located in the monsoon-region, the highest monthly inputs of N and P occur in the reservoir water during the summer monsoon period (Joseph et al 2007).

Previous studies of agricultural reservoirs in North America (Carlson 1991) and Europe (Ekholm and Mitikka 2006) have shown that trophic states based on CHL had a positive linear relationship with concentrations of TP in P-limited systems. This paradigm, however, may be modified in the Asian reservoirs due to monsoon seasonality. The importance of the monsoon on the reservoir water quality dynamics and functional relations among the trophic variables have been well discussed for the Asian water bodies (An and Park 2002). The summer monsoon produces short water residence times in Korean reservoirs and has a dominant influence on seasonal nutrients, high inorganic suspended solids, low light availability (An 2000), and reduced algal chlorophyll (An 2000; Kim et al 1999; Heo et al 1999). These researches indicate that the monsoon is a key determinant for limnological characteristics such as physical, chemical, and biological conditions in the reservoirs. A similar phenomenon is frequently observed in other tropical and subtropical Asian reservoirs, including reservoirs in India (Barinova et al 2012), Nepal (Raut et al 2015), and Bangladesh (Khan et al 2007).This implies that the monsoon may be a critical component modifying the water quality of the reservoirs and the functional relations among limnological variables.

Most of the Korean agricultural reservoirs showed P-limitation, whereas N-limitation occurred in the reservoirs with low-latitude region (i.e. Nepal) due to geological activities of a tectonic plate. Previous research pointed out that an empirical model is a good predictor to determine the relations of water quality parameters such as CHL-TP, CHL-total nitrogen (TN), and ratios of TN:TP-TP in reservoirs. Also, the empirical realtions were frequently used to evaluate nutrient regime process and eutrophication in the reservoirs. In Japan, Sakamoto (1966) first demonstrated the strong empirical links among P, N, and CHL who indicated that nutrients of N and P are important factors limiting algal growth. Previous studies of temperate and subtropical reservoirs have demonstrated that mean summer CHL is a function of spring or summer mean TP (Dillion and Rigler 1974; Canfield and Bachmann 1981; Forsberg and Ryding 1980; Nurnberg 1996). These studies showed that CHL had a positive linear relationship in North American and European reservoirs (Smith 1982; McCauley et al 1989) with the concentrations of TP and TN. Such research is necessary in the Korean agricultural reservoirs to elucidate the eutrophication processes.

In this study, we investigated how nutrients (N or P) and solid dynamics vary among the seasons and the chemical elements of N and P influence the CHL concentrations and water clarity in 182 agricultural reservoirs. For the research, the effects of nonalgal light attenuation on nutrients, nutrient ratios, and trophic state index (TSI) were analyzed using a two-dimensional approach of trophic state index deviations (TSIDs). Finally, empirical models were developed to determine the key nutrients regulating the CHL content in the reservoirs.

Materials and methods

Sampling sites and sample collection

We selected 182 reservoirs from four major watersheds (Geum River, Nakdong River, Han River, and Yeongsan/Seomjin River), which are located in the west part of South Korea. Surface water samples were collected from these reservoirs on a monthly basis from February 2013 to December 2013 Water samples were immediately transferred to the environmental ecology laboratory for further analysis.

Water quality parameters and data analysis

Nutrient data of TN and TP in Korean reservoirs were analyzed along with total suspended solids (TSS) and CHL. TP was determined using the ascorbic acid method after persulfate oxidation (Prepas and Rigler 1982), and TSS were filtered by GF/C filters and measured by the American Public Health Association (1999). CHL concentration was measured by using a spectrophotometer after extraction in hot ethanol (Sartory and Grobbelaar 1984). Secchi transparency [i.e. Secchi depth (SD)] was estimated from the empirical equation of total suspended solids [$\mathrm{Log}_{10}(\mathrm{SD}) = 0.76–\mathrm{Log}_{10}(\mathrm{TSS})$]. The use of the chemical data enabled seasonal patterns to be evaluated by classifying the months as premonsoon (January–June), monsoon (July–August), and postmonsoon (September–December). Monthly and seasonal mean data were log-transformed in order to follow the regression analysis requirements. Statistical analyses were performed using Sigma Plot version 10 (Systat Software Inc; USA).The calculations of TSI were followed by the approach of Carlson (1977), and the values of trophic parameters were calculated in the three periods using the three equations as follows:

$$\mathrm{TSI}\left(\mathrm{CHL},\ \mu\mathrm{gL}^{-1}\right) = 10*[6 - (2.04 - 0.68\ \ln\ (\mathrm{CHL}))/\ln 2\,]$$

$$\mathrm{TSI}\ (\mathrm{TP},\ \mu\mathrm{g/L}) = 10*[6 - \ln(48/\mathrm{TP})/\ln 2]$$

$$\mathrm{TSI}\ (\mathrm{SD},\ \mathrm{m}) = 10*[6 - \ln\ (\mathrm{SD})/\ln 2]$$

Nonalgal light attenuation coefficient (K_{na}) was estimated in order to evaluate the mechanisms controlling light attenuation in the water column (Walker 1982). Nonalgal light attenuation was calculated using the following formula:

$$K_{na} = \text{Secchi depth}\ (1/\mathrm{SD}) - 0.025*\mathrm{CHL}$$

Results and discussion

Seasonal dynamics of nutrients, chlorophyll, and suspended solids

Values of CHL increased during the monsoon, especially in July (173 μg/L) and August (227 μg/L) due to nutrient supplies by high runoffs from intense rain (Figure 1). By contrast, monthly means of CHL decreased in the premonsoon and then increased during the postmonsoon (December) because of late turn-over of the reservoir waters. Concentrations of TP showed a stable pattern with low value from February to June but increased abruptly in the summer monsoon. This indicates that P loading increased from the watershed and contributed to algal growth in the reservoirs. These results agree well with the viewpoint that the monsoon is a major