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The relative importance of water temperature and residence time in predicting cyanobacteria abundance in regulated rivers

YoonKyung Cha [a], Kyung Hwa Cho [b], Hyuk Lee [c], Taegu Kang [d], Joon Ha Kim [e,*]

[a] Department of Environmental Engineering, University of Seoul, Seoul, Republic of Korea
[b] School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea
[c] Water Quality Assessment Research Division, National Institute of Environmental Research, Incheon, Republic of Korea
[d] Yeongsan River Environment Research Center, National Institute of Environmental Research, Gwangju, Republic of Korea
[e] School of Environmental Science and Engineering, Gwangju Institute of Science and Technology, Gwangju, Republic of Korea

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A B S T R A C T

Despite a growing awareness of the problems associated with cyanobacterial blooms in rivers, and particularly in regulated rivers, the drivers of bloom formation and abundance in rivers are not well understood. We developed a Bayesian hierarchical model to assess the relative importance of predictors of summer cyanobacteria abundance, and to test whether the relative importance of each predictor varies by site, using monitoring data from 16 sites in the four major rivers of South Korea. The results suggested that temperature and residence time, but not nutrient levels, are important predictors of summer cyanobacteria abundance in rivers. Although the two predictors were of similar significance across the sites, the residence time was marginally better in accounting for the variation in cyanobacteria abundance. The model with spatial hierarchy demonstrated that temperature played a consistently significant role at all sites, and showed no effect from site-specific factors. In contrast, the importance of residence time varied significantly from site to site. This variation was shown to depend on the trophic state, indicated by the chlorophyll-a and total phosphorus levels. Our results also suggested that the magnitude of weir inflow is a key factor determining the cyanobacteria abundance under baseline conditions.

1. Introduction

Recurring cyanobacterial blooms are prevalent in freshwater ecosystems globally (Paerl and Huisman, 2008; Pick, 2016). Cyanobacteria often form unsightly scum, can produce toxins, and taste and odor compounds, that may negatively impact drinking water supplies and recreational activities (Codd et al., 2005; Srinivasan and Sorial, 2011). These blooms therefore have adverse ecological and economic impacts, and are a major concern in water quality management (Dodds et al., 2008; Paerl and Otten, 2013).

Over several decades, efforts have been made to identify the drivers of cyanobacterial blooms. Traditionally, the link between nutrient inputs and eutrophication has been considered a key process controlling algal productivity and cyanobacteria dominance (Schindler, 1978; Smith, 1982). It is generally agreed that excess nutrient inputs from urban, industrial, and agricultural watersheds create an environment susceptible to proliferation of cyanobacteria (Conley et al., 2009; Downing et al., 2001; Lewis et al., 2011.

An increasing number of studies have focused on the role played by temperature (Elliott, 2010; Kosten et al., 2012; Ndong et al., 2014; Trolle et al., 2015). Increases in the frequency and distribution of cyanobacterial blooms over time have been attributed, in part, to global warming (Carey et al., 2012; Deng et al., 2014; Ma et al., 2016; Vilhena et al., 2010; Zhang et al., 2012). Empirical evidence suggests that warmer, stratified waters are more susceptible to cyanobacteria dominance, because the optimal temperatures for cyanobacteria growth are generally higher than those for eukaryotic phytoplankton, and some cyanobacteria can control buoyancy in stratified water columns (Carey et al., 2012; Jönk et al., 2008; Wagner and Adrian, 2009).

A number of empirical models have been developed in the attempt to assess the relative importance of the factors driving cyanobacterial blooms in lakes and reservoirs (Kosten et al., 2012;

* Corresponding author.
E-mail address: joonkim@gist.ac.kr (J.H. Kim).

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Rigosi et al., 2014, 2015; Taranu et al., 2012). Most have identified nutrients and temperature as the factors that play the most significant role in promoting cyanobacteria abundance or dominance (Rigosi et al., 2014). Linear regression model results from 2007 U.S. National Lakes Assessment data, covering more than 1000 U.S. lakes, suggested that nutrient levels, measured by total nitrogen (TN) and/or total phosphorus (TP), were more important predictors than temperature (Beaulieu et al., 2013; Rigosi et al., 2014). In contrast, an analysis using a Bayesian network model suggested that, in 20 lakes distributed globally, cyanobacteria abundance was more sensitive to changes in water temperature than to TP (Rigosi et al., 2015). Kosten et al. (2012), using logistic regression with a quasi-likelihood function to model 143 lakes distributed around the globe, also identified temperature as the most important predictor of percent cyanobacteria abundance.

Interestingly, several studies have suggested that the relative importance of nutrients and temperature may be a product of lake-specific factors (Rigosi et al., 2014; Taranu et al., 2012). Findings derived from mixed-effect regression modeling of five lakes in Alberta, Canada showed that the relative importance of these factors depended on the mixing status of the lake. TP played an important role only in lakes that exhibited a polymictic state, while water column stability, positively correlated with temperature, was only important in hypereutrophic dimictic lakes (Taranu et al., 2012). An alternative view was presented by Rigosi et al. (2014). When the U.S. lakes were categorized into subsets by trophic state, they found that nutrient levels were the most important predictor of cyanobacteria dominance in oligotrophic lakes, whereas temperature was the most important predictor in mesotrophic lakes. In eutrophic and hypereutrophic lakes, the interaction between the two factors was a better predictor than either factor on its own.

Models that rank the competing predictors of cyanobacteria abundance are therefore an indispensable tool to support management of cyanobacterial blooms. Such models are not yet available for rivers (Cha et al., 2016b; Hilton et al., 2006), although cyanobacteria are now reaching nuisance levels in many rivers, encouraged by climate change and river impoundment (Mitrovic et al., 2011; Pick, 2016).

Between 2009 and 2011, as part of the Four Major Rivers Restoration Project, 16 weirs were constructed along South Korea's four major rivers, which serve as the nation's principal source of drinking water. In recent summers, massive algal blooms have recurred along all four rivers (Park et al., 2012). These unprecedented outbreaks have led to intensive monitoring, providing data on four major rivers with distinct trophic and hydrological characteristics. The objectives of the present study were 1) to assess the relative importance of the predictors of the cyanobacterial blooms and 2) to quantify both the relationship between the major predictors and cyanobacteria abundance, and the uncertainty that is associated with those relationships. We hypothesized that, as in the case of lakes, nutrient levels and temperature would be the principal factors. However as rivers are generally more dynamic systems than lakes (Hilton et al., 2006), we expected the variation in hydrological properties to play a significant role (Mitrovic et al., 2011; Webster et al., 2000). We therefore added residence time as a candidate predictor.

Bayesian hierarchical models have been demonstrated to be suitable for quantifying the relationships between response and predictor variables in river networks, which exhibit both upstream-to-downstream interconnectivity and local idiosyncrasies (Cha et al., 2016b; Webb et al., 2010). We therefore adopted a Bayesian hierarchical approach, in which partial pooling allowed the model parameters to differ by site, while sharing a common prior distribution. This was able to accommodate the commonality and variability in the relationships between cyanobacteria and predictors (Gelman and Hill, 2007; Qian et al., 2015). Further, those model parameters that varied significantly between sites were modeled using predictors at the higher, site level, to investigate the site-specific characteristics that determine the relationships between response and predictor variables.

2. Methods

2.1. Study sites and data description

The four major South Korean rivers studied were the Han, Nakdong, Geum, and Yeongsan (Fig. 1). These rivers have lengths of 494 km, 510 km, 397 km, and 129 km, respectively. The total watershed area of the four is approximately 72,500 km^2, accounting for 72 percent of the country's land area. The rivers pass through South Korea's largest cities, including Seoul, Busan, and Daegu.

We used monitoring data sampled at 16 sites across the four rivers (Fig. 1) for the years 2012–2015. Each monitoring site was located 500 m upstream from one of the 16 weirs. The data included biological, environmental, meteorological and hydrological factors, and were obtained from multiple sources. Cyanobacterial cell counts and chlorophyll-a (Chla) data are collected by the National Institute of Environmental Research Institute on a semi-weekly to weekly basis. For the analysis of cyanobacteria cell counts, 1 mL sample taken from a well-mixed 2 L water sample was put into a Sedgwick-Rafter chamber and was analyzed by a phase-contrast microscope (Nikon Eclipse 80i) at 400–600× resolutions (Komárek, 1991). Note that cyanobacteria data were available for the years 2012 and 2013. For the Chla analysis, a glass fiber filter (GF/F, 47 mm) was used to filter 1 L of water sample. Then the filter was soaked in 10 mL of 90% acetone solution to elute Chla. A spectrophotometer was used to measure the Chla concentration of the solution. Water quality characteristics, including TP, TN, turbidity, total organic carbon, and water temperature, are monitored daily by the National Institute of Environmental Research, and were taken from the Real Time Water Quality Information

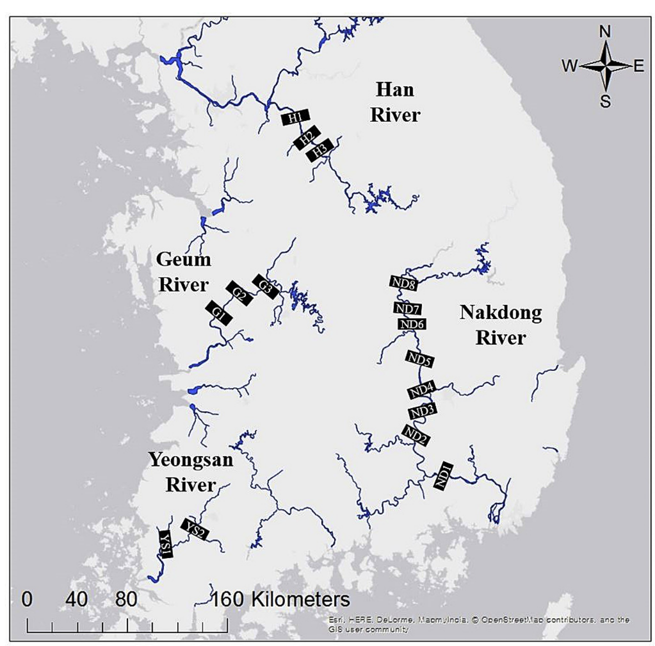

Fig. 1. Map of the four major rivers in South Korea. Weirs are marked with rectangles. The weirs along the Geum (G), Nakdong (ND), Yeongsan (YS), and Han (H) Rivers are numbered from the lower to the upper parts of the river.