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Estimating the risk of cyanobacterial occurrence using an index integrating meteorological factors: Application to drinking water production

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ARTICLE INFO

Article history:
Received 3 October 2013
Received in revised form
7 February 2014
Accepted 9 February 2014
Available online 24 February 2014

Keywords:
Cyanobacteria
Meteorological index
Drinking water intake
Early warning systems
Wind
Nutrient mass ratios

ABSTRACT

The sudden appearance of toxic cyanobacteria (CB) blooms is still largely unpredictable in waters worldwide. Many post-hoc explanations for CB bloom occurrence relating to physical and biochemical conditions in lakes have been developed. As potentially toxic CB can accumulate in drinking water treatment plants and disrupt water treatment, there is a need for water treatment operators to determine whether conditions are favourable for the proliferation and accumulation of CB in source waters in order to adjust drinking water treatment accordingly. Thus, a new methodology with locally adaptable variables is proposed in order to have a single index, $f(p)$, related to various environmental factors such as temperature, wind speed and direction. The index is used in conjunction with real time monitoring data to determine the probability of CB occurrence in relation to meteorological factors, and was tested at a drinking water intake in Missisquoi Bay, a shallow transboundary bay in Lake Champlain, Québec, Canada. These environmental factors alone were able to explain a maximum probability of 68% that a CB bloom would occur at the drinking water treatment plant. Nutrient limitation also influences CB blooms and intense blooms only occurred when the dissolved inorganic nitrogen (DIN) to total phosphorus (TP) mass ratio was below 3. Additional monitoring of DIN and TP could be considered for these source waters prone to cyanobacterial blooms to determine periods of favourable growth. Real time monitoring and the use of the index could permit an adequate and timely response to CB blooms in drinking water sources.

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http://dx.doi.org/10.1016/j.watres.2014.02.023
0043-1354/

1. Introduction

Harmful cyanobacteria (CB) blooms have been noted worldwide. CB blooms may release toxins, which can be harmful for aquatic communities (Bartram and Chorus, 1999), limit recreational and economic activities (Steffensen, 2008) and constitute a threat to drinking water sources (Zamyadi et al., 2012a). Long-term solutions for restoring water bodies require an understanding of the factors that are contributing to the increase of CB blooms (Wongsai and Luo, 2007). Thus, considerable efforts have been made globally in order to understand the environmental factors related to these phenomena for better management of the affected water bodies (Trojanowska and Izydorczyk, 2010; Le Vu et al., 2010; Falconer, 2005). Both endogenous factors (e.g. nutrients, water temperature) and exogenous factors (air temperature, solar radiation, wind speed and wind direction) can be considered to play a role in CB bloom development (Howard, 1994). Short term fluctuations of meteorological variables play an important role with regards to CB occurrence (Wu et al., 2013).

Generally, the principal focus of past studies has been on the effects of nutrients. Thus, the mass ratio (TN/TP) of total nitrogen (TN) to total phosphorus (TP) in water and in biomass has been studied as an index for its relationship to CB blooms (Lilover and Stips, 2008; Havens et al., 2003; Smith, 1986; Schindler, 1977). However, others have had concerns (Ferber et al., 2004) or do not support the use of TN/TP mass ratio (Jayatissa et al., 2006). It has been suggested that eutrophication generated by phosphorus is the main cause of CB blooms (Christian et al., 1988), but this view has been qualified of overly simplistic and is not applicable to all water bodies (e.g. Vincent, 1981). Thus, the TN/TP mass ratio is not the only indicator to predict CB blooms and a consensus does not exist with regards to a quantitative value. Another approach related to the mass ratio of Dissolved Inorganic Nitrogen (DIN) to total phosphorus (TP) has also been proposed and was shown to be a better predictor of CB biomass than the TN/TP mass ratio with CB bloom occurrences observed when the DIN/TP mass ratio was below 2 (Bergstrom, 2010; Ptacnik et al., 2010).

In addition to nutrients, meteorological conditions are required to explain CB bloom occurrences. Meteorological variables are known to have a significant influence on CB development (Elliott, 2012; Reichwaldt and Ghadouani, 2012; Liu et al., 2012a). Many authors have explored the relationships among meteorological variables and CB (e.g. Lilover and Stips, 2008; Bormans et al., 2005; Kanoshina et al., 2003; Liu et al., 2012a,b). Various weather variables have been related to CB blooms such as air temperature (Elliott, 2012; Reichwaldt and Ghadouani, 2012; Zhang et al., 2012), rainfall (Reichwaldt and Ghadouani, 2012), wind (Liu et al., 2012a,b; Zhang et al., 2012) and sunshine hours (Zhang et al., 2012). Wind in particular may play both direct and indirect roles in determining cyanobacterial densities (Falconer et al., 1999). Wind can generate complex physical processes, such as internal waves or seiches, which produce periodic motion of the water layers in stratified lakes (e.g. Lemmin and Mortimer, 1986). These internal waves affect the spatial distribution of phytoplankton in the epilimnetic layer (Marcé et al., 2007). In deep lakes, they have a great impact on the distribution of cyanobacteria proliferating in the metalimnion and on their growth though a direct influence on light availability (Cuypers et al., 2011). As CB are buoyant, wind can result in accumulation of cyanobacteria at specific locations during a bloom (Cao et al., 2006; Ostos et al., 2009; Kanoshina et al., 2003), but it may also indirectly influence nutrient availability through mixing processes of the water column (e.g. MacIntyre et al., 1999; Livingstone, 2003; Schmittner, 2005).

Other meteorological variables such as the relative humidity, minimum daily air temperature and the amount of solar radiation (sunspots) have also been related to CB density (Hu et al., 2009). It has been hypothesized that the increase in the number of CB blooms is at least partly related to global climate change and increasing air temperatures (Zhang et al., 2012; Wagner and Adrian, 2009; Mooij et al., 2007). Although the effect of water temperature on growth is species-specific (Mehnert et al., 2010) some generalizations can be made for the CB native to temperate environments. Seaburg et al. (1981) found that the majority of CB have an optimal growth temperature of 25 °C. However, many bloom forming CB show optimal growth rates at temperatures of 25 °C or higher (Robarts and Zohary, 1987). Tang et al. (1997), in studying the predominance of CB in freshwater in polar environments, showed that the growth was undetectable when the temperature of the aquatic environment in which the CB live was less than or equal to 5 °C or greater than 35 °C.

Consideration of meteorological variables is important when implementing an early warning system for the proliferation of CB in drinking water sources (Hu et al., 2009). In the United States, NOAA issues weekly harmful algal bloom reports based upon satellite imagery and meteorological conditions (Wynne et al., 2013). Early warning systems are needed for drinking water treatment plant operators who must adjust treatment according to the biovolume and species of CB present, including such measures as changing coagulant, or adjusting the doses of treatment chemicals to be added (Zamyadi et al., 2013). For drinking water treatment, in sources highly impacted by cyanobacteria, operational decisions must be made in real time. Thus, weekly forecasts can provide useful information, but higher resolution forecasts are required (i.e. daily or sub-daily).

For the development of a reliable index which can serve as a ‘universal threshold’ for the occurrence of CB blooms in the aquatic environment, the effects of endogenous factors and exogenous parameters must be investigated. It is anticipated that the threshold for CB bloom occurrence will be based on the coupled effects of these external and internal factors. Thus, the objectives of this study are to: (1) through a new approach, propose an index in the form of a unique factor that integrates the effects of exogenous factors such as meteorological variables and water temperature on CB occurrence at a drinking water treatment plant intake, (2) evaluate this index to determine the probability of CB occurrence as an aid to operational decision making for water treatment plants, and (3) assess the role of nutrient limitation and the DIN/TP mass ratio as additional variables to be monitored along with phycocyanin at drinking water intakes. This paper proposes a novel index approach integrating meteorological factors and