Journal of Great Lakes Research xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Review

Status, causes and controls of cyanobacterial blooms in Lake Erie

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ARTICLE INFO

Article history:
Received 4 July 2013
Accepted 2 October 2013
Available online xxxx

Communicated by Joseph Makarewicz

Keywords:
Lake Erie
Microcystis
CyanoHAB
Eutrophication
Climate change

ABSTRACT

The Laurentian Great Lakes are among the most prominent sources of fresh water in the world. Lake Erie's infamous cyanobacterial blooms have, however, threatened the health of this valuable freshwater resource for decades. Toxic blooms dominated by the cyanobacterium *Microcystis aeruginosa* have most recently been one of primary ecological concerns for the lake. These toxic blooms impact the availability of potable water, as well as public health and revenues from the tourism and fishery industries. The socioeconomic effects of these blooms have spurred research efforts to pinpoint factors that drive bloom events. Despite decades of research and mitigation efforts, these blooms have expanded both in size and duration in recent years. However, through continued joint efforts between the Canadian and United States governments, scientists, and environmental managers, identification of the factors that drive bloom events is within reach. This review provides a summary of historical and contemporary research efforts in the realm of Lake Erie's harmful cyanobacterial blooms, both in terms of experimental and management achievements and insufficiencies, as well as future directions on the horizon for the lake's research community.

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Introduction

The Laurentian Great Lakes are arguably one of the most valuable natural resources in North America, if not the world. This system represents roughly 20% of the Earth's available surface freshwater, a resource that is expected to become increasingly limited in the near future (Schottler and Eisenreich, 1994). Lake Erie alone provides over 7 billion dollars in revenue each year from tourism and fishery industries (United States Department of Agriculture, 2005). For the last two decades, however, Lake Erie has again been threatened (as it was in the 1960s and 1970s) by annual blooms of toxic cyanobacteria during summer months. Despite intensive research and management efforts, the duration and toxicity of blooms appear to be expanding in recent years (Stumpf et al., 2012).

Proliferation of undesirable plankton, whether in freshwater or marine environments, has long plagued the world's waters (Table 1). Among the Laurentian Great Lakes, Lake Erie is most susceptible to recurring large-scale blooms due to the morphology of the lake, its location in a temperate climate with warm summer temperatures, and extensive anthropogenic inputs. At an average depth of 19 m, Lake Erie has a relatively short retention time (<3 years) and consistently reaches temperatures above 25 °C during summer months (Burns et al., 2005; Stumpf et al., 2012; National Weather Service, www.wbuf.noaa.gov/laketemps/laketemps.php, accessed Dec 2, 2013). The lake continues to receive extensive input from agricultural and industrial runoff, despite decades of international efforts to reduce nutrient loading (Waples et al., 2008). Phosphorus (Dolan and Chapra, 2012; Dolan and McGunagle, 2002; Han et al., 2012) and nitrogen (Solomon et al., 2010) are key components in detergents, fertilizers, industrial chemicals, and common herbicides. These compounds and others are increasingly being applied within watersheds, resulting in the delivery of nutrients to the lakes through tributaries, rivers, and non-point

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http://dx.doi.org/10.1016/j.jglr.2013.12.012

Table 1
A brief selected historical overview of freshwater toxic algal blooms.

Year	Observation	Reference
~1000	General Zhu Ge-Ling reports illness in troops who drank from a river in the south of China that was green.	Chorus and Bartram (1999)
~1200	Locals aware of the toxicity of algae near *Monasterium Viridis Stagni* (Monastery of the Green Loch), located near the eutrophic, freshwater Soulseat Loch near Stranraer in south west Scotland.	Codd (1996)
1648	Paintings by Dutch Master Artist Salomon van Ruysdael (1648) show water bodies that are visibly green with a blue sky background.	Paerl (2009)
1878	Domestic animal poisonings in Australia	Francis (1878)
1931	Lower than normal rainfalls in Ohio cause a bloom which is washed down the river leading to a cascade of gastroenteritis that could not be attributed to any infectious disease.	Miller and Tisdale (1931)
1959	*Microcystis* blooms first reported in Lake Tai (Taihu) China. Regions that experience blooms have been reported to also have the highest incidence of cancer.	Qin et al. (2007)
1981	Extensive bloom in Australia associated with illness and hepatotoxicity	Chorus and Bartram (1999)
1995	*Microcystis* blooms first reported on large scales in Lake Erie	Brittain et al. (2000)
1996	50 deaths in Brazil due to microcystins in a dialysis unit's intake filters	Azevedo et al. (2002)
2007	Blooms in *Taihu* force government to supply bottled water to *Wuxi*.	Qin et al. (2010)
2011	The largest ever recorded *Microcystis* bloom in Lake Erie occurs and persists into September.	Michalak et al. (2013)
2012	*ABC News* and the *Food & Environmental Reporting Network* report 10 dog deaths nationwide over the past 2 years and 98 reports of illness in Wisconsin in last three years.	Avila (2012)

source runoff. As in the past, constraining these two macronutrients remains a particular focus for both scientists and ecosystem stewards.

The formation of large swaths of cyanobacterial biomass across Lake Erie is not a new phenomenon. Beginning in the early twentieth century, a marked increase in phytoplankton biomass and a decline in dissolved O_2 were primarily thought to be a result of phosphorus loading via point sources into the system (Charlton et al., 1993). While largely comprised of diatoms, the Lake Erie phytoplankton community throughout the first half of the twentieth century also contained cyanobacteria from the genera *Microcystis* and *Anabaena* (Davis, 1958; Nicholls et al., 1977). During the 1950s, studies indicated a peak in cyanobacterial biomass during the months of September and October, referred to as the "autumnal maximum." Both filamentous genera (*Anabaena* spp., *Aphanizomenon* spp., *Lyngbya* spp., and planktonic *Oscillatoria* spp. — now reclassified as *Planktothrix* spp.) and the unicellular colony-forming *Microcystis* were observed to contribute to this autumnal maximum, with filamentous *Aphanizomenon* being reported as most abundant (Davis, 1954). A later survey of the phytoplankton community during 1956 and 1957 reported *Microcystis* as the most abundant cyanobacterium, followed in quantity by the filamentous *Aphanizomenon flos-aquae* and *Oscillatoria* (*Planktothrix*) spp. (Davis, 1962). Despite the presence of these potentially toxic organisms, the initial focus remained on reduction of overall nuisance algal biomass and restoration of dissolved O_2 levels to the hypolimnion of the lake (Charlton et al., 1993). In the mid-twentieth century, the eutrophication of Lake Erie was described by the scientific community with increasing frequency and urgency. Indeed, an article by Beeton (1961) that pointed out rapid eutrophication in Lake Erie served as a spring board for the popular press to describe the lake as suffering from "accelerated old age," to the point where the lake was declared "dead" by the popular press (Ashworth, 1986; Fortner, 1987). Ironically, the problem was that the lake was likely "too alive," at least microbiologically. Indeed so poor was the health of the lake at that time that it was referenced in a popular children's book:

> *You're glumping the pond where the Humming-Fish hummed! No more can they hum, for their gills are all gummed. So I'm sending them off. Oh their future is dreary. They'll walk on their fins and get woefully weary in search of some water that isn't too smeary. I hear things are just as bad up in Lake Erie* (Seuss, 1971).

Spurred by popular press and an outcry among scientists alike, a scientific "call to action" resulted in a flurry of studies looking to identify the cause of the eutrophication of such an ecologically and economically important water source. Phosphorus was identified as the key nutrient contributing to eutrophication (Vollenweider, 1968), which led to the implementation of the Great Lakes Water Quality Agreement of 1972 (Hasler, 1969; International Joint Commision, 1986; Schindler, 1977). This joint effort by the Canadian and American governments effectively reduced phosphorus loading from point sources into the lake by 50% within 10 years of the peak levels observed in 1968 (Charlton et al., 1993; Makarewicz and Bertram, 1991).

As predicted, total phytoplankton biomass (g/m^3) was observed to decline during the 1970s and 1980s, with reports suggesting an 89% total reduction in biomass in some areas of the lake (Makarewicz, 1993). In fact, so effective was the remediation that the above children's literature reference to Lake Erie by Dr. Suess was removed in 1985 (Morgan, 1995). Dissolved O_2 levels did not recover, however, despite substantial efforts to limit further eutrophication of the lake by regulation of phosphate loading (Charlton, 1980; Charlton et al., 1993). However, by the early 1990s, trends in fishery populations, algal biomass decline, and sediment quality suggested a possible recovery of the system. The reasons for lack of total recovery from anoxia remain unknown but have been tied tightly to the morphology of the lake and the orientation of the central basin. The combination of these physical characteristics results in a typically thin (~4 m) hypolimnion, which is supplied with carbon from primary producers in the much larger epilimnion (Rao et al., 2008; Wilhelm et al., 2006). Combined with carbon input from spring diatom growth as well as mid-winter blooms that do not appear to be totally consumed by bacteria during winter months, dissolved O_2 isolated in the hypolimnion in summer months is rapidly consumed (Twiss et al., 2012; Wilhelm et al., 2006).

Historically, the major input of nutrients into Lake Erie has been from the Maumee River, which drains productive (and well-fertilized) farmland, as well as urban centers in Michigan, Indiana, and Ohio into the western basin of the lake (Dolan and Chapra, 2012). In contrast, while there is no doubt that large volumes of water also pass down the Detroit River, nutrient inputs from the Detroit River have been much lower than from the Maumee River (Han et al., 2012), and there is no record of blooms occurring at the entrance of the Detroit River into the lake. After decades of reduction in P loading, Lake Erie reached its target external phosphorus loading of 11,000 MT per year in 1981. For the next decade, combined concentrations from point and nonpoint sources remained relatively static, as observed for example in the Maumee River which flows into the western basin of Lake Erie (Fig. 1A). Beginning in the mid-1990s, however, a return to annual increases in soluble reactive phosphorus (SRP) loading to the lake has been reported (Joosse and Baker, 2011). Measurements of SRP concentrations for at least the Maumee River contradict this observation, however, as they reflect a limited variability loading trends after 1995, with a similar overall trend from 1975 to present in