ARTICLE IN PRESS

JGLR-00844; No. of pages: 9; 4C:

Journal of Great Lakes Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

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

Review

Challenges in tracking harmful algal blooms: A synthesis of evidence from Lake Erie

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ARTICLE INFO

Article history:
Received 19 June 2014
Accepted 29 December 2014
Available online xxxx

Communicated by R. Michael McKay

Keywords:
Freshwater eutrophication
Ecosystem indicators
Aquatic ecology
Microcystis
Harmful algal blooms
Lake Erie

ABSTRACT

Harmful algal blooms (HABs) are becoming increasingly common in freshwater ecosystems globally, raising complex questions about the factors that influence their initiation and growth. These questions have increasingly been answered through mechanistic and stochastic modeling efforts that rely on historical information about HABs in a given system for development, validation, and calibration. Therefore, understanding processes that control HABs is predicated on the ability to answer much more basic questions about what has actually occurred in a given system, namely questions of HAB occurrence, extent, intensity, and timing. Here we explore the state of the science in answering these basic questions; we use Lake Erie as a case study, where nearly two decades after the resurgence of HABs, a summer 2014 event caused a mandatory three day tap water ban for Toledo, Ohio. We find that, even for well-studied systems, unambiguous answers to basic questions about HAB occurrence are lacking, raising concerns about their use as a basis for addressing mechanistic questions about controlling factors. This ambiguity is found to be caused by differences in the methods used to track HABs, the specific harm being considered, the linkage to that harm (direct or indirect), the threshold defining harm, and spatiotemporal variability in sampling. Further work is therefore needed to integrate heterogeneous types of observations in order to better leverage existing and future monitoring programs, and to guide modeling efforts toward deeper understanding of HAB causes and consequences.

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Introduction

Harmful algal blooms (HABs) in freshwater systems are quickly becoming a global epidemic. Reports of HABs in Lake Taihu in China (e.g., Qin et al., 2010), Lake Erie in North America (e.g., Michalak et al., 2013), Lake Victoria in Africa (e.g., Sitoki et al., 2012), and Lake Nieuwe Meer in The Netherlands (e.g., Johnk et al., 2008) constitute examples of an alarming trend in freshwater ecosystems worldwide that is only expected to worsen under a changing climate (Paerl and Huisman, 2009). The effects of HABs are well documented: they are associated with acute morbidity and mortality across a range of biota (including humans) (Landsberg, 2002; Van Dolah, 2005), economic impacts through ecological and human health costs (Anderson et al., 2000; Hoagland et al., 2002) and the need for additional water treatment measures for regions relying on surface water supplies (Hitzfeld et al.,

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http://dx.doi.org/10.1016/j.jglr.2015.01.001

2000; Hoeger et al., 2005). A HAB in Lake Erie during the summer of 2014 resulted in a three-day tap water ban for Toledo, Ohio (Wilson, 2014), providing an acute reminder of the impacts of HABs and the urgency of addressing their proliferation. The need for scientifically-guided policy to mitigate these impacts has never been greater.

The biogeochemical processes controlling the global increase in HABs are the topic of extensive ongoing research. Much of the debate has centered on HABs in marine ecosystems, and similar stressors apply in freshwater systems (Beeton, 2002). Four main hypotheses for the apparent increase have emerged: increased scientific awareness of toxic species, increased anthropogenic nutrient loading, increased frequency and magnitude of extreme climatic events, and increased exposure to invasive species (Hallegraeff, 2003). Understanding the role of each of these mechanisms in explaining global HAB trends is an ongoing area of research (Perovich et al., 2008).

Testing these hypotheses also involves answering questions about what causes a HAB to occur and what affects the timing, spatial extent and intensity of a HAB. Addressing these questions is a first step towards developing a predictive understanding of HAB dynamics, and therefore towards developing management strategies that limit HAB occurrence or growth. The growing effort to develop predictive mechanistic and statistical models for HABs (e.g., Walsh et al., 2001; Raine et al., 2010), and data-driven probabilistic models (e.g., Kang et al., 2011; Cha et al., 2014) relies heavily on existing data on HAB occurrence, spatial extent, and timing for model development, validation, and calibration. Using such models to answer fundamental questions about HABs is predicated, therefore, on the ability to answer much more basic questions about what has actually occurred in a given system. Chief among them:

- What is a HAB? (i.e., How do we identify blooms and whether or not they might be harmful?)
- Was there a HAB? (i.e., How do we define their occurrence?)
- How big was the HAB? (i.e., What are meaningful quantitative methods for establishing spatial extent?)
- When did the HAB occur? (i.e., When did a given HAB start, peak, and decline?)

Only when such questions are answered can a meaningful exploration of what is causing HABs begin.

We explore the state of the science in answering these seemingly basic questions through the lens of the literature available for Lake Erie, one of the Laurentian Great Lakes. Lake Erie provides a particularly appropriate test bed because it has been extensively studied over several decades, because conditions in recent years have conspired to produce some of the largest HABs ever observed in the lake (e.g. Michalak et al., 2013), and because these HABs have caused substantial harm including a mandatory tap water ban in Toledo, Ohio, in the summer of 2014. The severity of recent HABs has also led to the emergence of predictive modeling efforts in the literature (e.g., Stumpf et al., 2012; DePinto and Scavia, 2013; Obenour et al. 2014), making the need for evaluating the data used to support such efforts especially salient. To explore the questions outlined above, we present a synthesis of the evidence provided by published methods in establishing HAB occurrence, extent, intensity, and timing. We also explore whether, and to what degree, the diversity in available approaches impacts the answers to these basic questions, and implications for future monitoring and scientific inquiry.

Definitions: What is a HAB?

A *harmful* algal bloom is defined by its potential to harm humans and/or ecosystems, but defining harm has proven challenging. Earlier work has explored the criteria that algal species need to meet to be characterized as harmful, the abundance thresholds that define a HAB, and the diversity of pathways that can lead to the occurrence of a HAB of a particular species (Smayda, 1997; Zingone and Enevoldsen, 2000). Some groups have also made a distinction between "harmful" blooms as ones having health impacts and "nuisance" blooms as ones that are linked to a more general class of harm (Watson and Boyer, 2013). The main conclusion from earlier analyses is that the definitions of HABs implied in the literature are subjective, stemming from differences in the harmful impacts being considered (Richardson, 1989; Smayda, 1997; Zingone and Enevoldsen, 2000).

We argue here that the question of what constitutes a HAB is more subtle still, by exploring a case where the target species is known and known to lead to at least some impacts that have been qualified as being harmful. In the case of Lake Erie, the primary species of concern is *Microcystis aeruginosa*, known for its secretion of the hepatotoxin microcystin and its use of buoyancy to out-compete other species (Steffen et al., 2014). Although other harmful species have also been observed in Lake Erie, e.g., *Aphanizomenon* spp., *Anabaena* spp., *Cylindrospermopsis* spp., and *Planktothrix* spp. (Allinger and Reavie, 2013; Conroy et al., 2007), *Microcystis* has been the dominant species in HABs at least since the mid-1990s (Brittain et al., 2000). HABs dominated by cyanobacteria (a.k.a. cHABs or cyanoHABs) such as *Microcystis* are especially relevant for study as they are rapidly proliferating globally (Paerl and Huisman, 2009). We explore how HABs have been defined through the lens of the metrics used in monitoring the lake, the types of harm considered, the nature of the linkage between metrics and harm (direct/indirect), and the degree to which that linkage is explicit. Note that here and in subsequent sections, we use the terms HAB and bloom interchangeably when discussing Lake Erie HABs.

The occurrence of blooms has been defined in Lake Erie using various *types of metrics* (Fig. 1 and Electronic Supplementary Material (ESM) Appendix S1). An in-depth review of the methodologies associated with these metrics and their advantages/disadvantages is available in Srivastava et al. (2013), and a timeline of studies making use of these metrics for Lake Erie is provided in ESM Table S1. Biomass and/or biovolume abundance has been reported in terms of total phytoplankton, total cyanobacteria, and/or individual species abundance (Bridgeman et al., 2013; Brittain et al., 2000; Conroy et al., 2005; Davis et al., 2012; DeBruyn et al., 2004; Dyble et al., 2008; Millie et al., 2009), and chlorophyll a (*chl a*) concentration has also been used as a proxy for total abundance (Becker et al., 2009; Conroy et al., 2005; Davis et al., 2012; DeBruyn et al., 2004; Millie et al., 2009; Ouellette et al., 2006; Rinta-Kanto et al., 2005). *Microcystis*-specific DNA analyses have been reported to confirm presence (Dyble et al., 2008; Ouellette et al., 2006; Rinta-Kanto et al., 2005; Rinta-Kanto and Wilhelm, 2006), and cell counts combined with the other metrics listed here have been used to quantify the relative abundance of *Microcystis* within the total cyanobacterial or phytoplankton population (Brittain et al., 2000; Conroy and Culver, 2005; Millie et al., 2009; Ouellette et al., 2006; Rinta-Kanto et al., 2009). Presence and concentrations of microcystin, a toxin secreted by some cyanobacteria including *Microcystis*, have been reported as a measure of the toxicity associated with blooms (Boyer, 2008; Brittain et al., 2000; Dyble et al., 2008; Millie et al., 2009; Rinta-Kanto et al., 2005; Rinta-Kanto et al., 2009) although the concentration of microcystin is not necessarily proportional to the amount of *Microcystis*. Remote sensing has also been invoked to identify blooms, based on different biotic and abiotic metrics that use algorithms to relate satellite reflectance data with in situ observations (Budd et al., 2002; Dash, 2005; Vincent et al., 2004; Becker et al., 2009; Wynne et al., 2010). More qualitative depictions of blooms use reports of surface scums appearing in the peer-reviewed literature, in news outlets, (e.g. "a thick slick of green paint" (Taylor, 1997)), in governmental reports ("surprising *Microcystis* blooms of 1998" (LaMP Work Group, 2002)), and in anecdotal reports ("reports of *Microcystis* by anglers" (Budd et al., 2002)). The presence of surface scum is dependent on in situ hydrodynamic conditions, however, and is therefore not a definitive identifier of HABs.

How these various metrics differ in their analytical approach and their applicability for regular monitoring is detailed elsewhere (Srivastava et al., 2013). For this discussion, we focus on how they differ in their relationship to harmful impacts. First, the metrics differ in the