Are Harmful Algal Blooms Becoming the Greatest Inland Water Quality Threat to Public Health and Aquatic Ecosystems?

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Abstract—*In this Focus article, the authors ask a seemingly simple question: Are harmful algal blooms (HABs) becoming the greatest inland water quality threat to public health and aquatic ecosystems? When HAB events require restrictions on fisheries, recreation, and drinking water uses of inland water bodies significant economic consequences result. Unfortunately, the magnitude, frequency, and duration of HABs in inland waters are poorly understood across spatiotemporal scales and differentially engaged among states, tribes, and territories. Harmful algal bloom impacts are not as predictable as those from conventional chemical contaminants, for which water quality assessment and management programs were primarily developed, because interactions among multiple natural and anthropogenic factors determine the likelihood and severity to which a HAB will occur in a specific water body. These forcing factors can also affect toxin production. Beyond site-specific water quality degradation caused directly by HABs, the presence of HAB toxins can negatively influence routine surface water quality monitoring, assessment, and management practices. Harmful algal blooms present significant challenges for achieving water quality protection and restoration goals when these toxins confound interpretation of monitoring results and environmental quality standards implementation efforts for other chemicals and stressors. Whether HABs presently represent the greatest threat to inland water quality is debatable, though in inland waters of developed countries they typically cause more severe acute impacts to environmental quality than conventional chemical contamination events. The authors identify several timely research needs. Environmental toxicology, environmental chemistry, and risk-assessment expertise must interface with ecologists, engineers, and public health practitioners to engage the complexities of HAB assessment and management, to address the forcing factors for HAB formation, and to reduce the threats posed to inland surface water quality.* Environ Toxicol Chem 2016;35:6–13. © 2015 SETAC

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> “You only find what you are looking for and you only find it if it is in concentrations high enough to be detected by the method being used to analyze for it.” Dr. Tom Waller [1]

Water Quality Assessment and Management

The comment above in Waller and Allen [1] captures an important principle of water quality assessment and management and is particularly relevant to challenges presented by environmental contaminants of emerging concern (CECs). Though interpretation of the term “water quality” varies, surface water quality assessment and management programs are intended to protect and restore the integrity of inland, coastal, and marine ecosystems. Water quality problems are identified through surveillance programs that monitor specifically prioritized chemical, physical, and biological parameters in point source discharges (e.g., effluents), non–point source runoff (e.g., agricultural, urban), and ambient surface waters. In the United States, water quality standards (legal limits enforced by states and authorized tribes) and water quality criteria (recommended and developed at the federal level) provide values for specific chemicals or microorganisms that, if not exceeded, are expected to protect the designated uses (e.g., fishing, contact recreation, potable water, agriculture) of water bodies [2]. In addition to numerical standards, water quality standards can be narrative standards, such as “free from toxic substances in toxic amounts.” Similarly, in Europe, environmental quality standards represent analogous water quality thresholds for an identified list of priority substances [3]. Periodically water quality parameters are updated when necessary or are derived for new contaminants based on needs identified from the best available scientific data. For example, water quality criteria for aquatic life or human health in the United States do not exist for CECs such as pharmaceuticals, noroviruses, or algal toxins (produced by harmful algal blooms [HABs]).

Water quality standards provide a foundation of metrics on which water quality is measured, maintained, and restored. When surface water quality monitoring activities identify significant exceedances of these parameters (numerical or narrative), the ecological and human uses of a water body are considered impaired and then prioritized for restoration. In the United States, states and authorized tribes submit a list of these impaired water bodies (e.g., a 303[d] list to the US Environmental Protection Agency (USEPA) as required by the Clean Water Act). The states (or USEPA) identify these impaired ecosystems, prioritize them to identify the sources of the impairment (e.g., through a total maximum daily load), and develop watershed management or implementation plans to restore and sustain the integrity of specific aquatic systems and water uses [4]. When the cause(s) of impairments to aquatic life is not known, environmental forensic procedures (e.g., toxicity identification evaluations) can sometimes identify the causative stressor(s). Total maximum daily loads have been developed and implemented for diverse indicators of impaired water quality (e.g., copper, ammonia, atrazine, depressed dissolved oxygen, phosphorus, ambient toxicity, *Escherichia coli*) [4]; however, it remains uncommon among regulatory and resource management organizations to attribute degradation of inland surface water quality to CECs, including HABs [5], and to determine how to comprehensively address the biotoxins produced by HABs.

Are HABs Becoming the Greatest Threat to Inland Water Quality?

In *The Future of Life*, E.O. Wilson employed the acronym HIPPO to highlight major threats to global biodiversity, including habitat modification, invasive species, pollution, population growth, and overexploitation of natural resources [6]. A number of other efforts have examined stressors to surface waters from both human and ecological health perspectives [7–10]. For example, social science approaches identified research priorities for water resources [11] and for specific classes of aquatic CECs [12]. When developing standards or intervention strategies to address aquatic stressors, including CECs, it is important to recognize that patterns of the relative importance of specific stressors are perceived to be quite different among different scientists and engineers in various global regions [13] and inherently differ spatially and temporally [14].

It remains critical to specifically identify environmental protection and management goals prior to implementing restoration efforts. For example, in the United States the Harmful Algal Blooms and Hypoxia Research and Control Amendments Act includes “an integrated assessment that examines the causes, consequences, and approaches to reduce hypoxia and harmful algal blooms in the Great Lakes, including the status of and gaps within current research, monitoring, management, prevention, response, and control activities” [15]. Unfortunately, the Act focuses on the Great Lakes, though broader national-scale program development for inland water may be possible. Advancing such efforts more broadly will be critical because inland water quality impacts from urbanization, agriculture, and climate change will likely increase over the coming decades. Subsequently, the Society of Environmental Toxicology and Chemistry (SETAC) initiated the Global Horizon Scanning and Research Prioritization project [16], which aims to advance its mission toward sustainable environmental quality by identifying geographically specific research priorities based on the submission and ranking of research questions from scientists and engineers in the government, academic, and business sectors [17]. In the present column, we ask the seemingly simple question, Are HABs becoming the greatest inland water quality threat to public health and aquatic ecosystems?

The magnitude, frequency, and duration of HABs appear to be increasing at the global scale [18,19], especially in coastal and inland waters. Harmful algal blooms occur naturally and are caused by interacting factors that vary among algal species. However, key forcing factors for the development of HABs include climate change and droughts, nutrient enrichment, and other modifications resulting from anthropogenic activities such as contaminants from effluent and stormwater discharges, natural resource extraction, agricultural runoff, and salinization [20–24]. Many HAB-forming species are invasive and/or opportunistic and take advantage of altered habitat conditions in developed regions [5]. Harmful algal bloom pollution impacts are not as predictable as are those from conventional chemical contaminants; interactions among multiple factors, both natural and anthropogenic, determine the severity to which a HAB will occur in a specific water body and can affect the magnitude of toxin(s) production [5]. In the case of cyanobacterial HABs, interactions between nutrients (including, but not limited to, both N and P) and climate change may exacerbate potential impacts on water quality [25]. Cyanobacterial HABs result in a variety of water quality problems, such as impairment to recreational uses, reduced aesthetics, lower dissolved oxygen concentrations, taste and odor problems in drinking water, and the production of toxins, which can impact aquatic and terrestrial wildlife and human health. Human exposure to cyanotoxins can occur by ingestion of contaminated fish, shellfish, and drinking water; inhalation; or dermal contact. When crops are irrigated with surface waters impacted by cyanobacterial HABs, 2 significant problems may occur: 1) the spray may result in production of cyanotoxin-containing aerosols that may be inhaled by humans and other animals, and 2) cyanotoxins may be absorbed by crops [26]. Humans and other animals can subsequently be exposed to these cyanotoxins through food consumption [27,28]. It is thus also possible for algal toxins to enter terrestrial food chains through such agricultural practices. Further, wildlife, pets, and livestock illnesses and deaths are routinely attributed to cyanobacterial HABs in affected inland water bodies [29].

The magnitude, frequency, and duration of HABs in inland surface waters are poorly documented. However, identification of these factors related to HABs is increasingly of interest to the federal government (see Harmful Algal Bloom and Hypoxia Research and Control Amendments Act), states, and drinking water utilities. The USEPA's 2007 National Lakes Assessment was the first national survey of the extent of waters with levels of cyanobacteria and microcystin above World Health Organization levels of concern for risk of exposure to algal toxins. Over 600 impoundments managed by the US Army Corps of Engineers can be found across the United States. Degradation of inland water quality by HABs is particularly important in these reservoirs [30], which provide a diversity of services (e.g., flood control, energy production, navigation) and associated uses that are protected by the Clean Water Act, including contact recreation, aquatic life, agriculture, and potable water supplies. Risk management and decision making related to HAB control, such as potential activities resulting from Harmful Algal Bloom and Hypoxia Research and Control Amendments Act implementation, must inherently balance protection of ecosystem and human health with the uses of these aquatic resources and terrestrial activities that impact the water bodies. When HAB events require restrictions on the uses of inland waters, significant economic consequences result. In the case of HABs from the invasive *Prymnesium parvum* (aka golden algae or the "Texas Tide"), devastating fish kills have become so routine that fisheries managers curtail stocking of sport fish in affected reservoirs [5]. Historical economic impacts from *P. parvum* HABs alone have been conservatively estimated in the millions of US dollars [31]. Economic impacts by cyanobacterial HABs are even more severe and widespread. For example, recent observations of unprecedented [32] cyanobacterial HABs on the western shores of Lake Erie [33] underscore the spatial scope and magnitude of this emerging challenge to inland water quality (Figure 1). Impacts of cyanobacterial HABs in Lake Erie were palpable again in 2014, resulting in suspension of drinking water intake for over 500 000 residents of Toledo, Ohio, USA.

In addition to these large lakes and reservoirs, all states are using retention/detention ponds for stormwater runoff control from non–point sources. For example, within the state of South Carolina there are >14 000 retention/detention ponds along the coastal zone, which are increasing at a rate of 13% per year [34] as a result of the high rate of urban development [35]. Harmful algal blooms are frequently detected in these shallow inland water bodies, though the diagnostic capabilities associated with detection vary from visual observation and real-time biomonitoring to remote sensing technologies. Such observations are not surprising because stormwater ponds are designed to control nutrient runoff by sequestration within the ponds [36]. In Texas, thousands of PL-566 small reservoirs were developed on private lands to reduce erosion and represent important habitats and management opportunities for HABs [37]. With rapid increases of populations in many regions of the United States, the continued increased development of and urbanization around stormwater retention/detention ponds pose additional inland habitats of concern for HABs, in addition to reservoirs and large lakes.

Whether HABs presently represent the greatest threat to inland surface water quality is debatable, though their relative importance as a transformational threat to future inland water quality assessment and management appears more certain. It is clear that HABs present the most significant threats to surface water quality in some freshwater ecosystems during certain time periods in many parts of the world. However, the prevalence of consistent site-specific HABs (e.g., *P. parvum* fish kills in Texas, cyanobacterial HABs in Lake Erie) in inland waters of developed countries appears to cause more significant acute impacts to environmental quality than conventional chemical

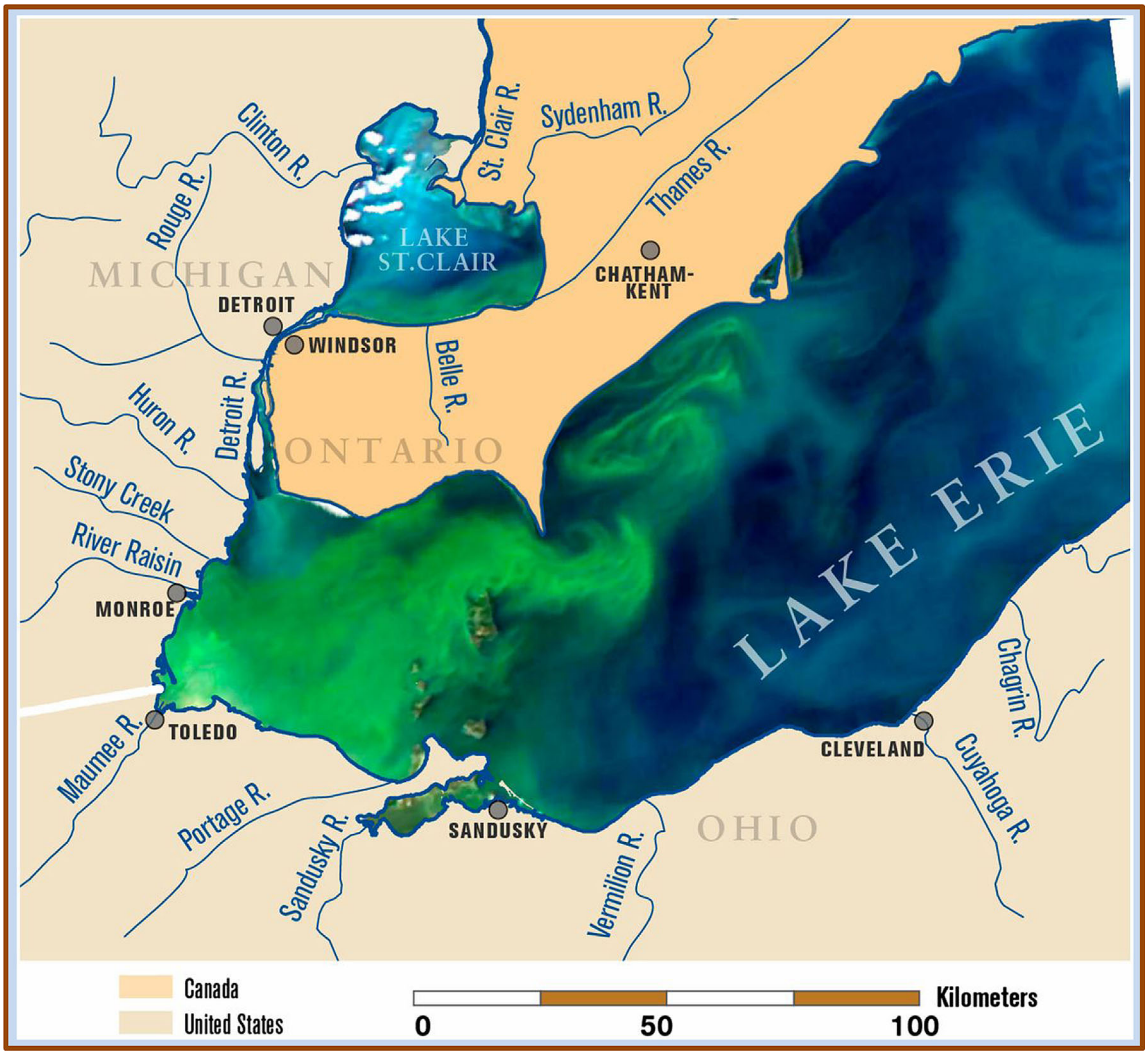

FIGURE 1: A moderate resolution imaging spectroradiometer (MODIS) satellite image indicating the extent and magnitude of a cyanobacterial harmful algal bloom (green area) in 2011 within Lake Erie, USA (modified from Michalak et al. [33]), 3 yr before the highly publicized cessation of drinking water intake for Toledo, Ohio, USA, from Lake Erie in 2014.

contamination events, with few exceptions (e.g., Deepwater Horizon oil spill). The duration of these HAB events varies among species and environmental conditions. Impacts of freshwater HABs may threaten limited drinking water supplies at a time when future climate models are predicting more droughts in many parts of the United States [38], which may subsequently affect public health [39]. It is also important to note that despite some environmental monitoring and surveillance, albeit minimal, in developed countries, HAB observations from large geographic regions with many countries in transition (e.g., Africa, Asia, Latin America) are occasionally reported in the literature but may be more severe in regions where environmental assessment and management programs are less developed than the recent high-profile reports from North America. Further, international patterns of commerce, urbanization, development, climate change, and stresses to the water–energy–food nexus [40], which inherently influence the primary forcing factors of HABs, highlight the global importance of this threat to inland water quality.

Challenges to Environmental Management and Water Quality Research Needs

Despite the widespread and potential increase in the occurrence of cyanobacterial and other HABs in water bodies throughout the United States and the documented ecological and health risks these blooms present, many states, tribes, and territories do not have formal HAB species or algal toxin monitoring programs for surface waters. The lack of established monitoring programs for HAB–related CECs consistently applied by all states, tribes, and territories makes it difficult to assess risks to human health and the environment when water quality is degraded by blooms. The United States' National Oceanic and Atmospheric Administration (NOAA) developed the National Phytoplankton Monitoring Program, which is staffed primarily by volunteers who conduct the monitoring; it was initially developed in coastal states to monitor for marine HABs [41]. More recently, this program has begun to focus on freshwater HABs in the Great Lakes and other regions. Satellite imagery has been developed to identify surface cyanobacteria events in near real time to monitor large lakes (>100 ha) [42]. The USEPA's National Aquatic Resource Surveys [43] provide a well-developed program that could be expanded to support more robust monitoring efforts for cyanobacterial and other HABs; however, the scope of this program presently does not allow for frequent monitoring of algal toxins in inland surface waters.

Such limited formal monitoring and surveillance efforts, which represent an essential service of environmental public health [44], have likely occurred for several reasons. Lack of water quality criteria for algal toxins and inconsistent implementation of standards among regions limit regulatory incentives for identification and prioritization of impaired water bodies by HABs for restoration efforts (Figure 2). However, reliable standardized analytical methods for algal toxins are not widely available, which inherently results in nonroutine monitoring of surface waters. Lack of analytical standards, reference materials, and analytical methods were previously identified by an expert panel to NOAA in addressing impediments to marine HAB research [45,46]; thus, it is not surprising that we see a similar issue with freshwater HABs today. Similarly, toxicity information for most inland HAB toxins is not presently robust enough to develop water quality criteria for the protection of aquatic life, recreation, or drinking water supply uses, and ideally essential ecosystems functions and services. Unfortunately, the majority of federal funding for HABs research in the United States has focused on coastal and marine systems instead of inland surface waters, where impacts to fisheries, agriculture, and potable water supplies are routinely observed. It may be that the historically high costs of analytical toxin standards have limited monitoring, aquatic toxicity, and bioaccumulation studies. Fortunately, rapid enzyme-linked immunosorbent assays (though these kits have limited specificity because of numerous toxin congeners), more robust analytical approaches (e.g., liquid chromatography–tandem mass spectrometry), and less expensive toxin standards have become more readily available in recent years, at least for a number of cyanotoxins. Broader availability of analytical standards and analytical capacity would facilitate environmental toxicology and chemistry research (Figure 2), though access to these toxins must be sufficiently controlled when safety concerns exist for select agents. Clearly, expanding existing programs and recently developed monitoring efforts, strategies, and technologies is necessary to understand and manage this threat to inland surface waters.

Current capacity to model HAB initiation and termination events is extremely limited. However, recent modeling efforts, made possible by a multiyear collaborative effort involving laboratory experiments, in situ studies, and spatially and temporally explicit field monitoring, have successfully predicted bloom formation of a relatively understudied and invasive mixotrophic (i.e., acquire energy through autotrophy and heterotrophy) HAB–forming species in inland waters [47]. Such advances and sustained research support may provide a template for developing future modeling efforts to predict HAB occurrence and severity. Harmful algal bloom forecasting has been identified as a major focus of NOAA in the development of its coastal and marine ecosystem forecasting capabilities, and current HAB forecasts are developed in certain regions of the United States, such as the west coast of Florida [48]. These advances are particularly relevant for mixotrophic harmful algal species, which are increasing in eutrophic inland and coastal waters as a result of subsequent increases of microbial prey availability [49]. It is unlikely that HABs can be eliminated because they are naturally occurring. However, because the causes of HABs

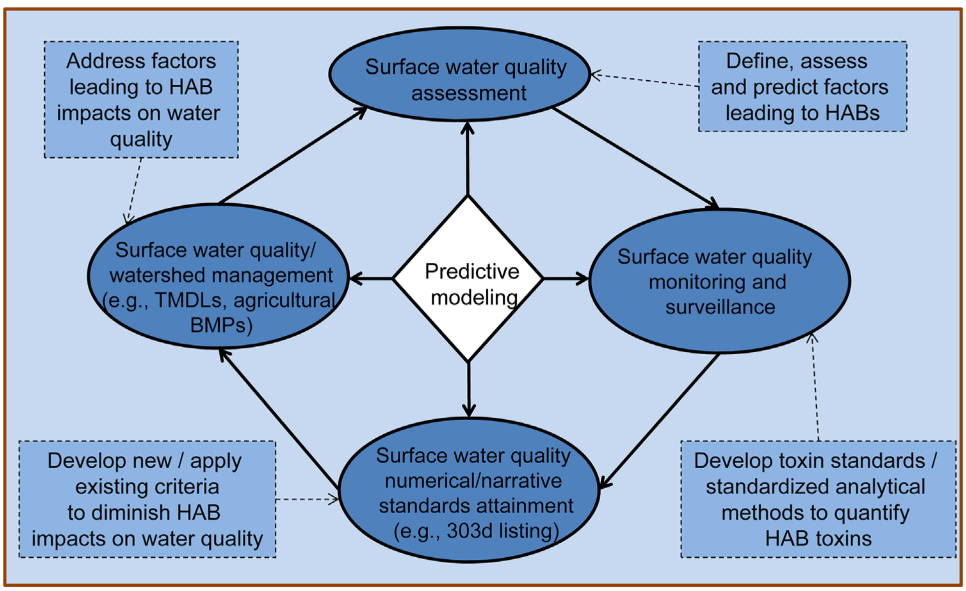

FIGURE 2: Conceptual model of research (dashed rectangles) and management (solid ellipses) of harmful algal blooms in inland waters exemplified within an existing regulatory framework of the US Clean Water Act. HAB = harmful algal bloom; TMDL = total maximum daily load; BMP = best management practice.

have been associated with changes in land use, climate, and water resource management, an improved ability to predict HABs coupled with regional watershed management and planning may enable reduction of adverse outcomes caused by inland HABs (Figure 2). Here again, it remains critical to clearly identify ecosystem and human health protection goals prior to initiating risk-assessment and management efforts.

The incidence of inland HABs may increase as a result of interactions with inorganic (e.g., salinity, nutrients) and organic (e.g., pesticides) contaminants associated with urbanization and agricultural practices, especially if the changing environment contributes to community reorganizations among HAB–forming species and their competitors and predators. More resilient strains of HAB species may be developing through natural selection under increased anthropogenic pressures. For example, salinity thresholds for *P. parvum* HABs are demonstrated to be lower in downstream reservoirs relative to upstream impoundments of the Brazos River in Texas, USA [23]. Further, the introduction of nonnative organisms to surface waters may promote HAB formation, as illustrated in the recent resurgence of cyanobacterial HABs in the Great Lakes, which is probably partially associated with the invasion of Asiatic mussels (*Dreissena*) that may selectively filter-feed nontoxic phytoplankton [50].

Beyond the site-specific water quality degradation caused directly by HABs, the presence of HAB toxins can influence routine surface water quality monitoring, assessment, and management practices. In fact, HABs can present significant challenges for achieving water quality protection and restoration goals when these toxins confound interpretation of monitoring results and standards implementation efforts for other chemicals and stressors. For conventional contaminants (e.g., copper, ammonia), a water quality criteria is derived for an individual stressor from laboratory toxicity studies with multiple aquatic species. Extrapolating this ecological threshold information from the laboratory to be protective, and ideally predictive, of water quality integrity in the field has received extensive attention. Water quality impairment still occurs because of complex mixtures of stressors, ineffective implementation of water quality standards, historical contamination, accidental chemical spills, and so forth. When the intended uses of surface waters are impaired, toxicity identification evaluation techniques can be employed when the causative stressor is not known. However, toxicity identification evaluations procedures were not designed to identify HAB toxins [51].

Anecdotal reports from practitioners suggest that algal toxins may be causative stressors when ambient water and sediment toxicity is observed in inland and coastal surface waters. As noted above, algal toxins are not routinely monitored in surface water or sediments of the United States, which is captured by 1 of the water quality principles highlighted by Waller's quote [1] at the beginning of the present article. Thus, it appears that without the inclusion of algal toxins in toxicity identification evaluation protocols, the presence of HABs could be overlooked and lead to incorrect identification of water quality stressors. This could result in false negatives and costly misapplication of restoration-based management activities. The extent of the problem is not presently understood [52], but the apparent increased magnitude, frequency, and duration of HABs and their impacts to public health, aquatic and terrestrial ecology, and biogeochemistry have the potential to, in the absence of coordinated and advanced adaptive management, challenge the foundations of historical water quality assessment and management programs (Figure 2).

Many of the water quality challenges presented by HABs in inland waters have resulted from Wilson's HIPPO threats to global biodiversity [6]. These threats create conditions resulting in HAB impacts that are not consistently "looked for" in inland waters, a practice that inherently ignores Waller's principle for water quality assessment and management [1]. Herein, the "SETAC sciences" are needed to engage the complexities of HAB assessment and management, to address the forcing factors for HAB formation, and thus to reduce the threats posed to inland surface water quality. Historically, inland HAB topics have appeared sporadically at SETAC meetings and in its journals. According to a recent (October 2014) Web of Science search with the terms "harmful algal bloom," "harmful algae," "microcystin," and "cylindrospermopsin," only 39 manuscripts have been published in *Environmental Toxicology and Chemistry*. However, over 50% (20 of 39) of these manuscripts were published in the past 5 yr. Further, technical sessions on inland

HABs. . .in Focus

- Harmful algal blooms (HABs) represent a transformational threat to inland water quality.
- Formal monitoring and surveillance programs for HABs are limited in developed and developing nations.
- Site-specific HAB events degrade water quality to a greater extent than many chemicals.
- Harmful algal blooms confound routine surface water quality assessment and management practices.
- Strategic engagement by environmental toxicology, chemistry, and risk assessment is necessary.

HABs have been held during each of the most recent annual meetings of SETAC North America, and HAB presentations have been increasing at recent SETAC Europe meetings. Clearly, there remains a need for more robust interfaces among environmental toxicology, environmental chemistry, and hazard and risk-assessment professionals with ecologists, engineers, medical professionals, and public health practitioners on this topic. In fact, such integration and engagement of environmental toxicology, environmental chemistry, and hazard and risk assessment is critical to implement and expand goals articulated in the Harmful Algal Blooms and Hypoxia Research and Control Amendments Act. We call on SETAC to develop more concentrated efforts on the topic of inland HABs through the development of advisory groups, workshops, and focused topic meetings.

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