Harmful Algal Blooms and Hypoxia in the Great Lakes Research Plan and Action Strategy: An Interagency Report

Product of the

National Science and Technology Council

Executive Office of the President of the United States

August 2017

EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

August 24, 2017

Dear Colleagues:

I am pleased to transmit to you *Harmful Algal Blooms and Hypoxia in the Great Lakes Research Plan and Action Strategy: An Interagency Report*, a report to Congress. The Interagency Working Group on the Harmful Algal Bloom and Hypoxia Research and Control Act of the Subcommittee on Ocean Science and Technology, organized under the National Science and Technology Council; Committee on Environment, Natural Resources, and Sustainability, produced this report.

The 2014 reauthorization of the Harmful Algal Bloom and Hypoxia Research and Control Act (P.L. 113-124) acknowledges continued concerns related to harmful algal blooms (HABs) and hypoxia. The legislation emphasizes the need for expanded and ongoing monitoring and forecasting, extends the scope of the legislation to include freshwater HABs and hypoxia, and recognizes the need for further coordinated Federal action to address these issues. Specifically, the legislation calls for a "plan, based on the integrated assessment [published February 16, 2016]… for reducing, mitigating, and controlling hypoxia and harmful algal blooms in the Great Lakes." This report is the second step and fulfills these requirements.

Sincerely,

Ted Wackler

Ted Wackler
Acting Director
Office of Science and Technology Policy

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About the Subcommittee on Ocean Science and Technology

The purpose of the Subcommittee on Ocean Science and Technology (SOST) is to advise and assist on national issues of ocean science and technology. The SOST contributes to the goals for Federal ocean science and technology, including developing coordinated interagency strategies, and fosters national ocean science and technology priorities, including implementation of the National Ocean Policy.

About the Interagency Working Group on Harmful Algal Bloom and Hypoxia Research and Control Act

In recognition of the challenges presented by harmful algal blooms (HAB) and hypoxia, the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2014 (HABHRCA 2014, P.L. 113-124) emphasizes the mandate to advance the scientific understanding and ability to detect, predict, control, mitigate, and respond to these types of events. This legislation called for the establishment of the Interagency Working Group on HABHRCA (IWG-HABHRCA). It tasked the group with coordinating and convening Federal agencies to discuss HAB and hypoxia events in the United States, and to develop action plans, reports, and assessments of these situations.

About this Document

The IWG-HABHRCA developed this document, and it was published by OSTP.

The report is intended to promote greater investment and coordination of United States government resources to address HABs and hypoxia, but it is not a budget document and does not imply approval for any specific action under Executive Order 12866 or the Paperwork Reduction Act. The report will inform the Federal budget and regulatory development processes within the context of the goals articulated in the President's Budget. All activities included in the National Strategy are subject to budgetary constraints and other approvals, including the weighing of priorities and available resources by the Administration in formulating its annual budget and by Congress in legislating appropriations.

Acknowledgements

The IWG-HABHRCA thanks Deborah Lee, Leslie Irwin, Ariana Sutton-Grier, and Kaye Lafond of the National Oceanic and Atmospheric Administration for their help with editing and designing this report.
Special thanks and acknowledgment to the following subject-matter experts who contributed significantly to the writing of this report:

- Chris Loeffler, Food and Drug Administration;
- Laura Lorenzoni, National Aeronautics and Space Administration;
- Suzanne Bricker, Quay Dortch, Alan Lewitus, Wayne Litaker, Rob Magnien, John Ramsdell, Trevor Meckley, National Oceanic and Atmospheric Administration;
- Tracy Ziegler, National Park Service; and
- Patrick Deliman, United States Army Corps of Engineers.

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Executive Summary

This report provides a research plan and action strategy for addressing the causes and impacts of harmful algal blooms (HABs) and hypoxia on stakeholders of all types within the Great Lakes region. Over the past several decades, HABs and hypoxia (low-oxygen conditions) have caught the nation's attention due to the associated negative socioeconomic, public health, and environmental impacts. Since the mid-1990s in particular, the Great Lakes region has seen an increase in the size, duration, and prevalence of these scientifically complex events.

This report responds to the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) and provides a strategy for communities, state officials, congressional leaders, and Federal agencies to address the causes and effects of HABs and hypoxia in the Great Lakes. It is the second report produced in response to the Act, the first report being *Harmful Algal Blooms and Hypoxia Comprehensive Research Plan and Action Strategy: An Interagency Report*. This current report, which complements and supports the recommendations under the Great Lakes Water Quality Agreement, discusses recent advancements in technology and conservation practices, including improved instruments, modeling, and understanding of how to manage and reduce nutrient runoff, allowing for continuous HABs and hypoxia monitoring, detection, and abatement. It reviews developments that improve understanding of what causes HABs and hypoxia; how long events last; the best methods for managing causes; and how HABs and hypoxia can affect human and animal health, the economy, and the ecology of the Great Lakes. It shows how the Federal government works with communities, resource managers, and other stakeholders to minimize impacts during an event, and to be prepared well in advance through forecasts, policies, and other means. Additionally, it takes nutrient pollution control into account, including best conservation practices and associated costs.

The report contains a number of research recommendations and actions for Federal agencies to take, as summarized below:

- Improve comprehensive conservation planning, by evaluating and implementing existing and new best management technologies and conservation practices for reducing land-derived nutrient inputs;
- Expand ecological forecasting, monitoring, and modeling for HABs and hypoxia across the Great Lakes. This will be useful in predicting HABs and hypoxia occurrences and severity, and informing decision-makers and the public about risks associated with HABs and hypoxia. This includes developing and documenting an initial prediction of the impacts of a changing climate leading to extreme weather events on HABs and hypoxia in the Great Lakes;
- Refine and develop methods for detecting HAB-related toxins found in the Great Lakes, allowing for quicker toxin detection, and earlier communication to the public. Likewise, the report recommends developing unified messages on the causes, risks, and mitigation efforts on HABs and hypoxia, along with research on the most effective communication approaches for affecting behavior and influencing decision-making processes; and
- Expand and integrate information on current and potential future social and environmental impacts of HABs and hypoxia in the Great Lakes. This includes helping communities of all scales to conduct cost-benefit and preparedness analyses to ensure they have adequate sources of drinking water, food, and revenue before a bloom or hypoxia event occurs.

Introduction

What are HABs and Hypoxia?

The Great Lakes are more than bodies of water; they are the linchpin for the region's identity. The nearshore areas of the Great Lakes are sources of drinking water for tens of millions of people. Multitudes of people each year recreate in the lake waters. Fishermen, tourism operators, and other industries depend on the Great Lakes for revenue.

Although HABs and hypoxia only occur in some areas of the Great Lakes (indicated in Figures 2 and 4), they frequently happen in areas where humans and animals commonly come into contact with the water. As a result, HABs and hypoxia can cause substantial detrimental effects to aquatic life, wildlife, humans, pets, and livestock. They also can have serious effects on a community's social health, causing lost revenue for lakefront economies that are dependent on aquatic or seafood harvests or tourism; disruption of subsistence, social, and cultural practices; or loss of community identity tied to aquatic resource use.

These impacts cause us to ask critical questions: Is it safe to drink or bathe in my tap water? Can we swim at the beach? Can I eat this fish? Are my pets at risk? How will this affect my business or job?

Defining HABs

HABs are a naturally occurring subset of microscopic or larger plant-like cyanobacteria or algal species (Appendices 1 and 2). Dominant cyanobacteria species in the Great Lakes that may become harmful (Appendices 1 and 2) include *Microcystis*, *Dolichospermum*, *Aphanizomenon*, *Planktothrix*, and *Lyngbya*. There also is a separate category of harmful algae that includes the well-documented and non-toxic benthic green alga *Cladophora* spp. (Brooks et al., 2015). When promoted by human-influenced ecosystem changes such as nutrient-loading, extreme weather events, and invasive organisms, these species can form dense overgrowths also known as "blooms" that can disrupt the environment and local economies, or can produce toxins that are harmful to people and animals (giving rise to the term "harmful algal bloom"). HAB overgrowths and toxins have the potential to kill fish directly; additionally, people may become sick if they ingest sufficient amounts of toxins through drinking water, during recreational activities, eating contaminated food, or breathing contaminated air (Wood, 2016). In contrast to marine HABs, where exposure can occur through eating seafood or inhaling aerosols, people and animals primarily have contact with HAB toxins in the freshwater Great Lakes through drinking water and recreation. Water intakes can draw in HAB toxins, leading to disruptions in the water supplies for large numbers of the population. The toxins can also sicken or kill pets, livestock, and wildlife through contaminated water and food supplies (Byappanahalli et al., 2003; Carmichael and Boyer, 2016). Pets are particularly susceptible to exposure via drinking HAB-laden water because they drink or play in nearshore waters, where certain species of HABs are likely to occur.

Algae and cyanobacteria are considered to be the cornerstones of life on Earth and form the basis of most aquatic food webs, including in the Great Lakes. Many of these species play a crucial role in maintaining healthy ecosystems. For instance, the Great Lakes are home to over 1,400 species of diatoms, a common type of algae, which represent an important and diverse part of the regional ecosystem (Stoermer et al., 1999). The annual spring diatom bloom provides an important food source for fish. Fall diatom blooms equally are important to fish and other organisms in the lakes, providing a reliable food source throughout the winter (Reavie et al., 2016).

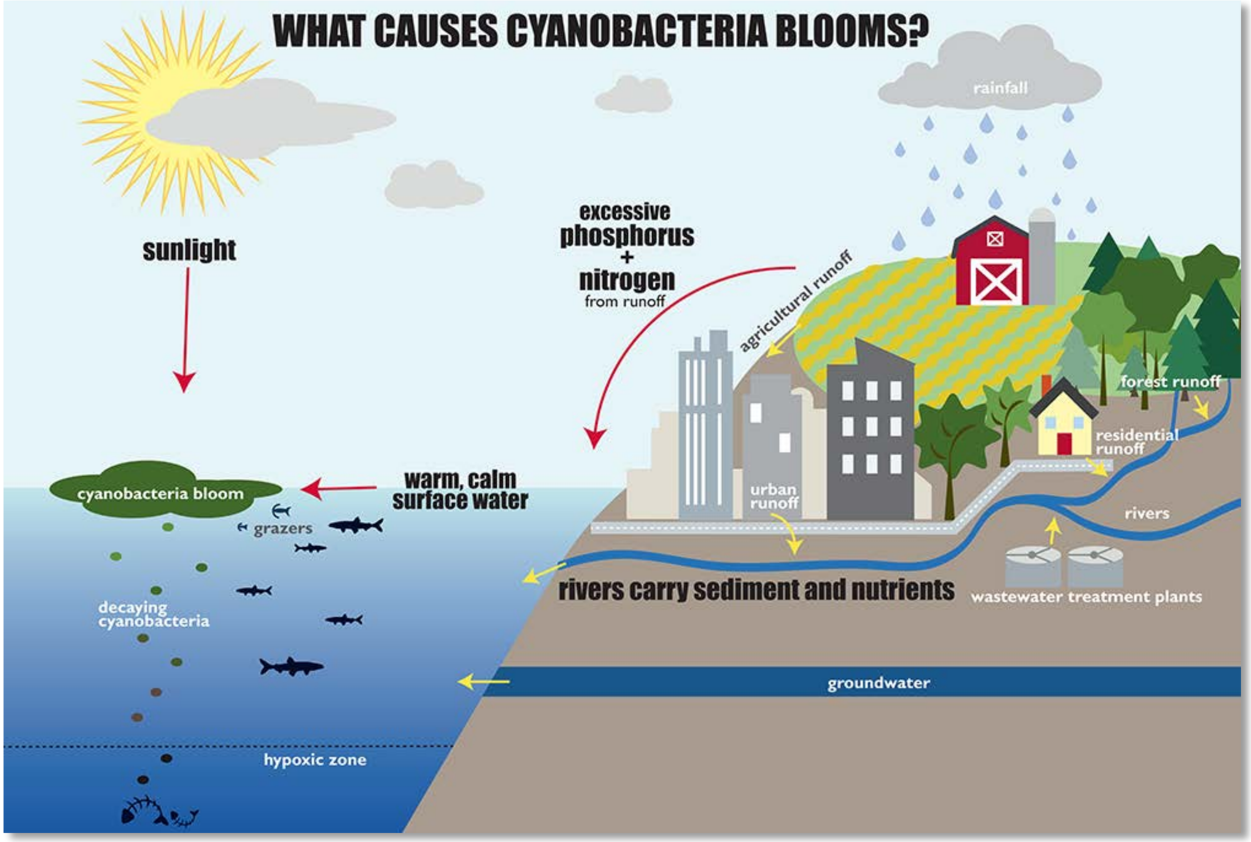

Figure 1. This figure demonstrates some of the causes and ecosystem consequences of HABs and hypoxia. Changes in precipitation patterns, including rain and snowfall; pollution and runoff due to changes in the landscape; and increased amounts of carbon dioxide in the water column, are some of the contributing factors to the development of HABs (here, represented by the cyanobacteria bloom) in a waterbody and the onset of toxin production in algal cells. Weather patterns also affect the distribution of a HAB. Additionally, while groundwater contributes nutrient inputs into waterbodies, researchers are less certain about the extent of these inputs.

This diagram also shows how HABs and hypoxia enter and affect the food web. Smaller organisms like fish or shellfish ingest algal cells, and then are eaten by larger species, such as humans or wildlife. Additionally, some organisms are unable to escape hypoxic areas and die from lack of oxygen. (Image courtesy of the Lake Champlain Basin Program.)

Figure 1 depicts factors contributing to HABs, and shows impacts that HABs may have on the ecology of an ecosystem. Currently, little is known about the movement of freshwater HAB toxins and bioactive compounds once they enter the food web (Gademann and Portmann, 2008), although microcystins have been found in the tissue and organs of freshwater fish (Schmidt et al., 2013). They also accumulate in marine shellfish and other organisms, accumulating in flesh and leading to the deaths of marine mammals (Miller et al., 2010; Gibble et al., 2016). There are challenges that arise, however, in measuring cyanotoxins in biological specimens, including a wide variability between uptake rates, half-lives, and overall concentrations of these compounds (USEPA, 2015a, 2015b, 2015c).

Blooms that are considered not toxic, such as those caused by *Cladophora* spp. and other green algae, can negatively impact ecosystems by blocking light to bottom-dwelling plants, restructuring food web dynamics, giving drinking water a bad taste or odor, and harboring pathogens (Lopez et al., 2008; Auer et al., 2010; Paerl et al., 2016). Mats of *Cladophora* and other green algae are associated with pathogens, including avian botulism, which kills fish and birds, as well as waterborne pathogens that can harm humans (Lan et al., 2015; Brooks et al., 2015; Kenow et al., 2016). The blooms can also form thick, odorous algal masses that clog water intakes, boat motors, fishing nets, and fish gills.

Cyanobacterial HABs occur throughout the Great Lakes, including in western and central Lake Erie; Saginaw Bay in Lake Huron (Fahnenstiel et al., 2008); Green Bay in Lake Michigan; and in smaller embayments, tributaries, and nearshore areas, such as Muskegon Lake, Lake St. Clair, Sandusky Bay, western Lake Superior, the Sandusky and Maumee Rivers, Little Bay du Noc, Bay of Quinte (Canada), Hamilton Harbor (Canada), Sturgeon Bay (Canada), Honey Harbor (Canada), and Sodus Bay (New York). *Cladophora* blooms are found in the Grand Traverse Bay and Sleeping Bear Dunes areas in Lake St. Clair, along the northern shorelines of Lake Erie near Ajax (Canada) and Lake Ontario (Canada), and the southern shore of Lake Ontario (Auer et al., 2010; IJC, 2013; Shuchman et al., 2013). Figure 2, below, shows known locations of cyanobacteria and *Cladophora* throughout the Great Lakes region.

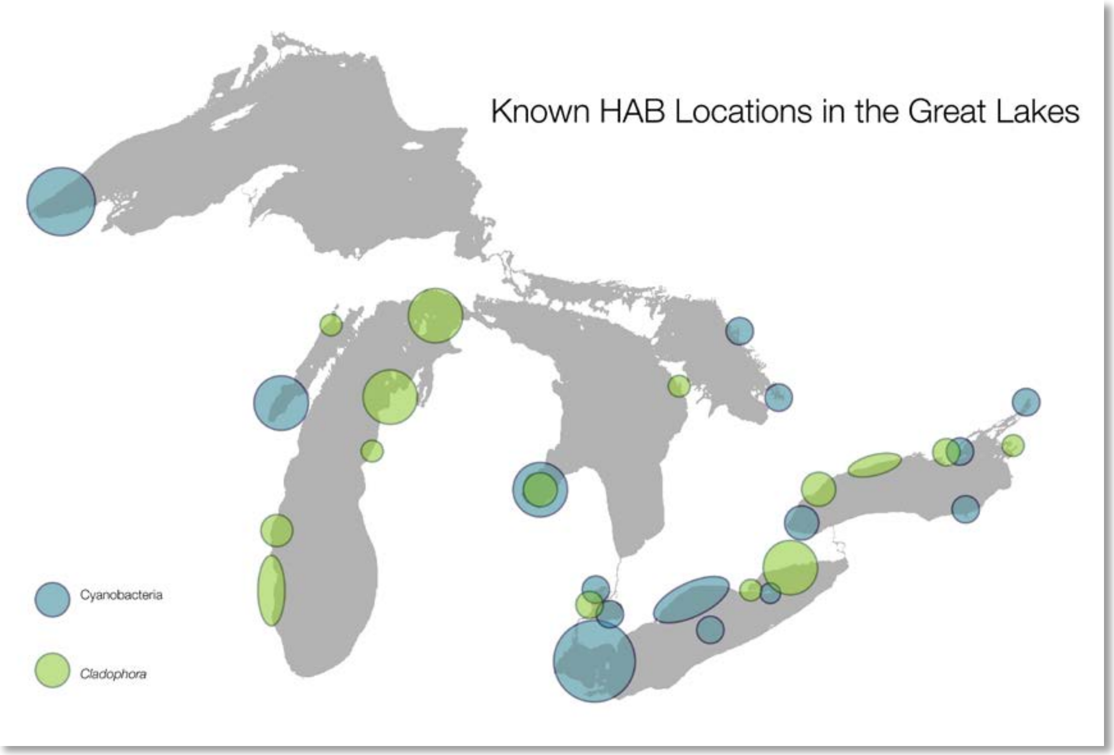

Figure 2. Map of reported cyanobacterial and Cladophora *HAB locations in the Great Lakes basin. Every lake experiences at least one type of HAB. A variety of factors impact the distribution, size, and species of HAB (Shuchman et al., 2013; Brooks et al., 2015). (Graphic courtesy of GLERL/OAR/NOAA.)*

Defining Hypoxia

Hypoxia is a naturally-occurring condition where the concentration of dissolved oxygen in a portion of the water column decreases to a level that can no longer support living aquatic organisms, typically below 2-4mg dissolved oxygen (DO)/liter (L). As with HABs, natural and human-induced environmental changes can exacerbate hypoxic conditions. Low oxygen conditions occur in waterbodies due to the confluence of physical, chemical, and biological processes.

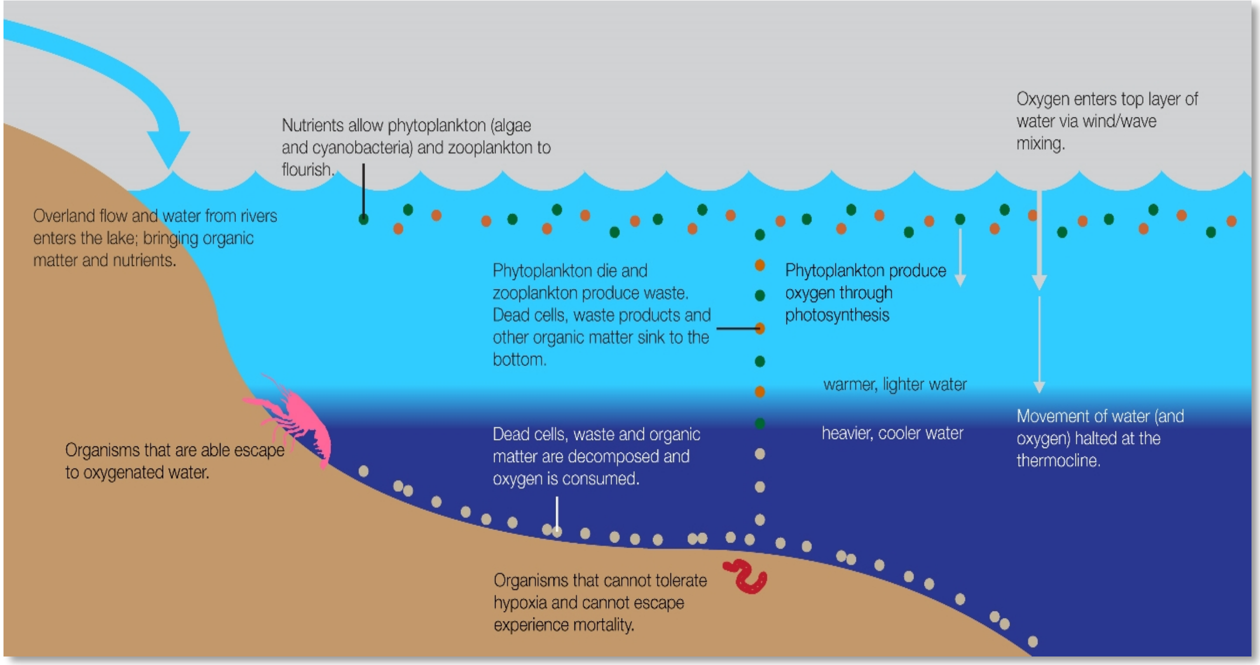

Figure 3. Hypoxia causes and consequences in the Great Lakes. Hypoxia in fresh water occurs naturally when the water column separates into warmer (light blue) and colder (dark blue) layers that do not mix. Oxygen enters warmer, upper regions of the water but cannot move into lower, colder regions beneath the warm-cold transition layer. At the same time, organisms that feed on dead organic matter consume oxygen at the bottom of the water body. Human influences can worsen the situation when excess nutrients enter the water body and cause algal blooms, which then die and sink to the bottom, thereby increasing decomposition activity and depleting even more oxygen. (Image courtesy of NOAA/OAR/GLERL.)

Warm, calm conditions in the Great Lakes (Figure 3) can promote the stratification (layering) of waters by temperature, which effectively reduces vertical circulation and can lead to oxygen-depleted bottom-waters. Hypoxia occurs most often in waters of intermediate depth, where organic matter and nutrients congregate and settle at high concentrations, versus in deeper waters where the nutrients may be diffused (Rabalais et al., 2010). Very shallow waters seldom experience hypoxia, in all but the most eutrophic conditions, because they rarely stratify. In deeper waters, stratification leaves the bottom layer isolated from the surface layer and cut off from a normal resupply of oxygen from the atmosphere. However, there usually is a sufficient level of oxygen present in this water layer, which prevents hypoxic conditions. Algal blooms can exacerbate hypoxic events, particularly in the central basin of Lake Erie, which stratifies in summer. The algal biomass ultimately settles to the lake bottom, stimulating bacterial respiration in the deep water layer (hypolimnion). It results in hypoxia that persists until the autumn, when deeper waters rise to the upper layers of a lake in a process known as “turnover” (Kraus et al., 2015; Bocaniov and Scavia, 2016). Hypoxic water subsequently can promote HABs by increasing phosphorus release from the sediments (Correll, 1998; Hawley et al., 2006). In this way, HABs and hypoxia sometimes may be self-perpetuating or exacerbating.

Currently, as shown in Figure 4, hypoxic zones occur most frequently in the central basin of Lake Erie and in Lake Michigan’s Green Bay (Burns et al., 2005; Hamidi et al., 2013), and episodically in western Lake Erie and Saginaw Bay (Bridgeman et al., 2006; Stow and Höök, 2013). Though the size of the Lake Erie hypoxic zone varies between years, it generally is approximately the size of Rhode Island and Delaware combined (EcoFore; last accessed September 2, 2016). Natural and human-influenced hypoxia events also occur in sinkhole regions of Lakes Huron and Michigan, due to the shallowness in some parts of the Great Lakes basin (Delorme, 1982; Biddanda et al., 2009; Ruberg, 2016).

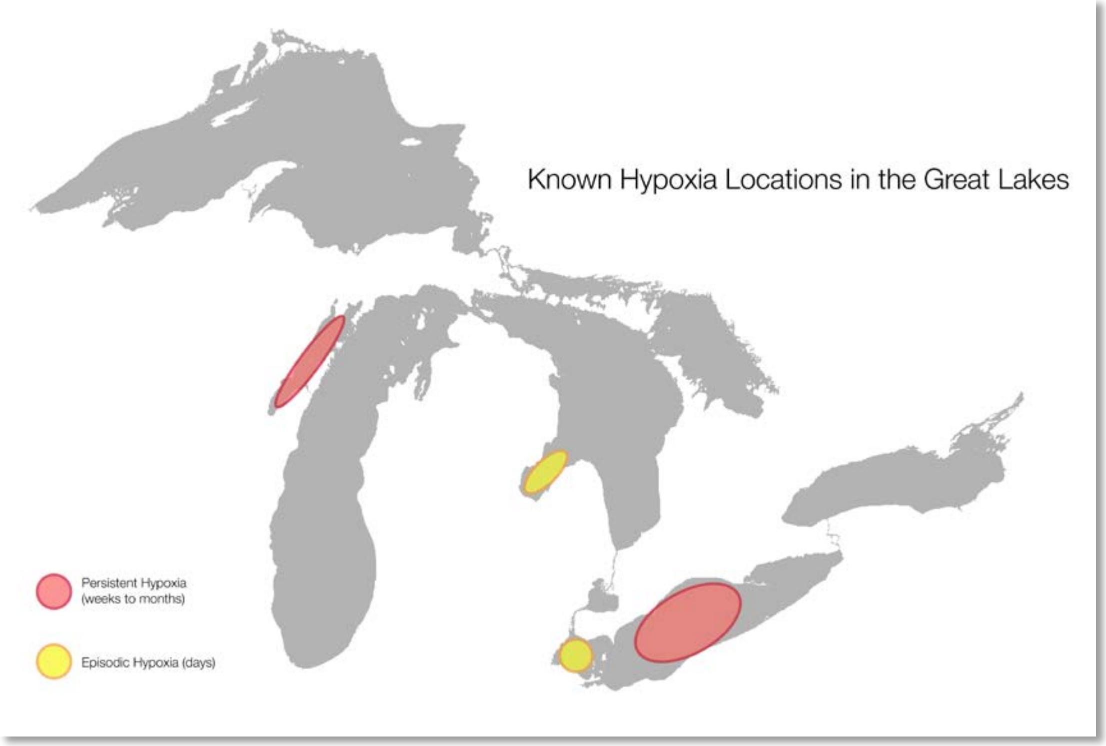

Figure 4. Known Hypoxia Regions in the Great Lakes. The two prominent hypoxic zones in the Great Lakes are the central basin of Lake Erie and Green Bay, Lake Michigan (GLEAM, 2011). The area in red experiences "persistent hypoxia" (weeks to months), whereas the areas in yellow are "episodic hypoxia" (days). (Graphic source: NOAA/OAR/GLERL.)

Report Basis

The purpose of this report is to explain the science, outline research needs, and provide an action strategy for addressing HABs and hypoxia in the United States' Great Lakes. The report recommendations are based on the most current, sound science; existing knowledge of the Great Lakes system; and stakeholder input (IJC, 2013; Scavia et al., 2014; Bingham et al., 2015; GLWQA, 2015; Keitzer et al., 2016; USDA, 2016a, 2016b). The report builds upon science reviews, as well as the strong existing foundation of other basin-wide initiatives and agreements, such as the Great Lakes Restoration Initiative (GLRI), Farm Bill-related programs, and the Great Lakes Water Quality Agreement (GLWQA).

Stakeholder Engagement Methods for this Report

Members of the Interagency Working Group on HABHRCA (IWG-HABHRCA) employed a variety of methods to communicate with academic institutions, international groups, state and local governments, nonprofits, members of the agricultural community, water resource managers, tourism groups, food and beverage providers, and the interested public. The group held a series of three discussion-focused webinars in early 2016 that engaged over 400 unique registrants, to connect with a wide variety of stakeholders in an open forum. One webinar was directed towards subject-matter experts, although it was open to all interested parties. The other two webinars were held for a broader audience. The webinars included a short presentation that informed stakeholders on HAB and hypoxia issues in the Great Lakes, explained the role of the IWG-HABHRCA, and described the focus of this report. The majority of the time during each webinar allowed for stakeholders to provide input, and to foster open discussion between interested parties and Federal representatives.

Stakeholders provided input through a few primary methods. First, they submitted feedback and asked questions via email, through an account maintained by the IWG-HABHRCA (IWG-HABHRCA@noaa.gov). Second, stakeholders submitted detailed bibliographies that focused on technology, issues related to HABs and hypoxia, and additional related topics. Finally, IWG-HABHRCA members held group and personal conversations with stakeholders, in order to delve into more detail on concerns and challenges. This included holding a workshop in 2015 at Bowling Green State University near Toledo, Ohio. The different methods of communication maximized the opportunity to receive feedback from individuals with diverse backgrounds and interests.

Image 1. Harmful algal bloom in western Lake Erie, July 2011. (Photo credit: NOAA/OAR/GLERL.)

Stakeholder Contributions

This report incorporates information submitted by stakeholders and generated during the engagement activities. Stakeholders and Federal agencies similarly expressed the needs and challenges for mitigating, managing, and responding to HABs and hypoxia. There also were numerous novel insights and ideas shared with the IWG-HABHRCA that are included in this report.

Stakeholders used engagement opportunities to discuss management measures and concerns about HABs and hypoxia. A number of common themes prevailed during the conversations. It is clear that continuing to hold and encourage conversations between Federal agencies and their stakeholders, and between state and local officials and constituents, is important to helping communities understand and limit the effects of HABs and hypoxia in the Great Lakes. The IWG-HABHRCA learned of numerous needs while speaking with stakeholders, which demonstrated the importance of improving public engagement and communications. For instance, in some states, public health offices have jurisdiction only over public beaches; they cannot monitor or provide signage at private beaches, leaving some constituents at risk of exposure to HABs. Expanding monitoring programs and requiring signage at all beaches helps to limit the risks of HAB exposure. Making individuals aware of risks by enhancing communication across all levels of government, and with the community, is essential to minimizing HAB and hypoxia impacts. Stakeholders specifically expressed the need for improved communication among all groups, including the following:

- The availability of consistent information about threats and HAB and hypoxia events throughout the region;
- The challenges of monitoring and messaging along municipal beaches;
- The lack of financial and human resources to effectively monitor and educate; and
- A general disconnect between officials and their constituent groups, as well as how different people and communities value or understand potential impacts from HABs and hypoxia.

1. Revealing the Problem: Understanding HABs, Hypoxia, and Nutrient Sources in the Great Lakes

Since the 1960s, research has shown linkages between human activities and HABs in the Great Lakes (Beeton, 1965). Prior to the enactment of the 1978 GLWQA, western Lake Erie experienced high nutrient inputs from point-source (direct) pollution. This fueled annual HAB events, although the dominant HAB species have differed over the years (Steffen et al., 2014a). Lake Erie's water quality improved after the GLWQA was established, and the United States and Canada implemented, phosphorus goals for Lake Erie. Wastewater treatment plants improved treatment methods in response to the agreement, lowering phosphorus loads. HAB events dissipated. Since the mid-1990s, however, increases in certain types of phosphorus concentrations[1] and nitrogen, attributed to nonpoint (indirect) sources, led to cyanobacterial HABs once again becoming an annual occurrence in the Great Lakes region (Richards and Baker, 2002; Fishman et al., 2009; Davis et al., 2010; Fishman et al., 2010; Daloğlu et al., 2012; Stumpf et al., 2012; Horst et al., 2014; Steffen et al., 2014a;). *Cladophora* blooms also increased during this period (Smith et al., 2015a). Increases in dissolved reactive phosphorus (DRP) concentrations appeared to promote *Cladophora* in Lake Erie, as well as cyanobacterial HABs. Researchers found that in o the Great Lakes, zebra and quagga mussels cleared the water column, leading to higher light levels at the bottom of each lake, and in effect boosting *Cladophora* growth (Auer et al., 2010; Brooks et al., 2015).

The hypoxic zone in the central basin of Lake Erie has increased in size and duration over recent years, likely due to human-influenced nutrient-loading (Zhou et al., 2013; Scavia et al., 2014; Figure 4). While HABs and hypoxia occur throughout the Great Lakes (Figs. 2 and 4), to-date, Lake Erie is the most impacted by these events; and, as it was with Lake Erie's environmental degradation in the mid-20th century, Lake Erie's conditions provide an early warning indicator of trends in the less productive lakes.

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[1] Specifically, DRP, the type of phosphorus most readily taken up by plants.

Image 2. Mats of Cladophora *washing up on the shore of Lake St. Clair, a part of the connecting river system adjacent upstream of Lake Erie. The bloom caused thick muck along the shoreline. (Photo credit: T. Joyce NOAA/OAR/GLERL.)*

Notable advancements in understanding of some of the immediate causes of Great Lakes HABs (Bullerjahn et al., 2016) and hypoxia (Scavia et al., 2014), such as nutrient inputs, have occurred in recent years. Significant questions remain, however, including:

- explaining and understanding the relative importance of the drivers of bloom toxicity and severity, including internal sources or drivers;
- understanding the impacts of current HAB and hypoxia prevention strategies, including those targeting nutrient runoff;
- enhancing knowledge of how a changing climate will influence extreme weather events, and how the changes subsequently may affect the ability to achieve nutrient reduction targets, or will influence bloom growth and toxicity (O'Neil et al., 2012; Brooks et al., 2016); and
- a better understanding of the economic costs and societal impacts in ever-changing environmental conditions, which can be used to make strategic decisions about management and investment tradeoffs.

Scientists must understand these knowledge gaps in order to make salient recommendations to address HABs and hypoxia in the Great Lakes. As a recent audit by the Government Accountability Office (GAO) demonstrated, Federal agencies are taking note of policy and research needs by increasing resources towards related work (GAO, 2016).

Lake Erie HABs and Hypoxia

HAB and hypoxia events in Lake Erie over the past several years have garnered intense public and scientific attention.

- *The 2012 drought, with extremely low water inflow from tributaries, was associated with a record-breaking dead zone in Lake Erie's central basin. Researchers forecast that there will be increased drought conditions in the future, and therefore anticipate more intense hypoxia events (Zhou et al., 2015).*
- *Hypoxic zones in Lake Erie may lead to higher catch-rates due to fish being concentrated in non-hypoxic waters. Fisheries managers may not account for this, potentially resulting in higher exploitation of certain stocks than is sustainable or accounted for by managers (Kraus et al., 2015). Hypoxia influences different fish species in different ways that can bias their habitat selection and food web dynamics in ways that are complex and difficult to ascertain (Scavia et al., 2014).*
- *In September 2013, microcystin levels in excess of WHO guidelines caused a drinking water shut down in Carroll Township, Ohio (Wynne and Stumpf, 2015). In response to the event, the city spent $125,000 in upgrades to its ozone treatment (Bingham et al., 2015).*
- *In August 2014, Lake Erie experienced a toxic cyanobacterial bloom near the intake of the drinking water treatment plant serving the city of Toledo, Ohio. Toledo issued a "do not drink or boil advisory" that affected nearly 500,000 customers that lasted just over two days due to the presence of microcystins, a class of cyanotoxins, that exceeded the lifetime safe drinking water threshold recommended by the World Health Organization (WHO) (Wilson, 2014a).*
- *In August 2015, Lake Erie experienced the largest bloom in recorded history (Stumpf et al., 2016), eclipsing the 2011 bloom that previously held that record the largest (Michalak et al., 2013).*

1.1. Harmful Algal Bloom and Hypoxia Research and Control Act

By the 1990s, researchers identified serious and large-scale water-quality problems in United States waters, including HABs and hypoxia, most prominently in the northern Gulf of Mexico, Lake Erie, Chesapeake Bay, and Long Island Sound. These problems prompted Congress to pass HABHRCA in 1998. Recognizing the ongoing nature of HABs and hypoxia, and how they continue to affect the entire U.S., Congress has reauthorized HABHRCA twice, mostly recently in 2014 (HABHRCA 2014, P.L. 113-124).

The 2014 HABHRCA reauthorization is unique for several reasons. It calls for Federal agencies to consult with stakeholders when developing action strategies, in order to develop recommendations that directly address needs and concerns related to mitigating and preventing HABs and hypoxia. It expands the focus of HABHRCA to include a specific emphasis on HABs and hypoxia in the Great Lakes and in fresh waters around the country, and recognizes the need for further coordinated action across the Federal sector to address these issues. Additionally, the legislation calls for Federal agencies to provide integrated assessments identifying the causes, consequences, and approaches to reducing HABs and hypoxia nationally, with particular emphasis on the Great Lakes. It calls for operational forecasting, observations, and modeling tools required to support forecasting, all of which are of particular relevance for the region.

1.2. What Contributes to HABs, Hypoxia, and their Interactions?

There are a number of factors contributing to how, why, and for how long HABs and hypoxia occur in the Great Lakes. Some drivers include higher levels of nutrient inputs to the Lakes, such as DRP, and inorganic and organic forms of nitrogen from non-point agricultural, suburban, and urban activities. For instance, aging sewer and septic tank systems, as well as combined sewer overflows, can contribute to nutrient pollution ("eutrophication") (USEPA, 2007). Herbicides and pesticides that wash into lakes during land application or at times of high precipitation may also promote HAB species by killing their natural competitors (Peterson et al., 1997; Lürling and Roessink, 2006), or by being a potential phosphorus source (Qiu et al., 2013; USEPA, 2015d). Atmospheric pollutants—especially nitrogen from fossil-fuel combustion, volatilized fertilizer and animal waste, and industrial outputs—can be deposited via the air and precipitation onto watersheds or directly into water, leading to increased nutrient levels. In addition, accumulated or "legacy" nutrients from point and non-point sources can become newly available to organisms within a system due to resuspension of sediments, and/or releases, and/or transformations of nutrients. This can occur through natural chemical reactions that cause the release of phosphorus from the sediments, in turn further stimulating algal growth (Sharpley et al., 2013; USEPA, 2015d). On the other hand, watersheds with a higher percentage of forested acres are less likely to contribute nutrients and contaminants that cause HABs and hypoxia than those with a lower percentage of forested acres (Seilheimer et al., 2013). Figure 5 shows the diversity of land cover types in the United States Great Lakes region, all of which may contribute to instances of HABs and hypoxia through point and non-point sources.

Nitrogen and phosphorus can influence cyanobacteria growth and toxicity (O'Neil et al., 2012; Steffen et al., 2014b; Davis et al., 2015; Gobler et al., 2016). Varying levels of phosphorus and nitrogen may drive changes in HAB species composition (Harke et al., 2015). Even as total phosphorus (TP) has remained stable or decreased in recent years, DRP has increased in some watersheds, which could be one factor contributing to the increasingly large blooms and hypoxic zones in Lake Erie (Michalak et al., 2013; Scavia et al., 2014; Stumpf et al., 2016). Increased DRP-loading locations include the Maumee watershed, which is the major source of nutrients fueling hypoxic zones in Lake Erie (Michalak et al., 2013; Scavia et al., 2014; Stow et al., 2015). The relationship between DRP and blooms is well-established in the Great Lakes and beyond, and there is increased research interest in the linkages between nitrogen and HAB growth, toxin production, and bloom severity (Gobler et al., 2016; Paerl et al., 2016).

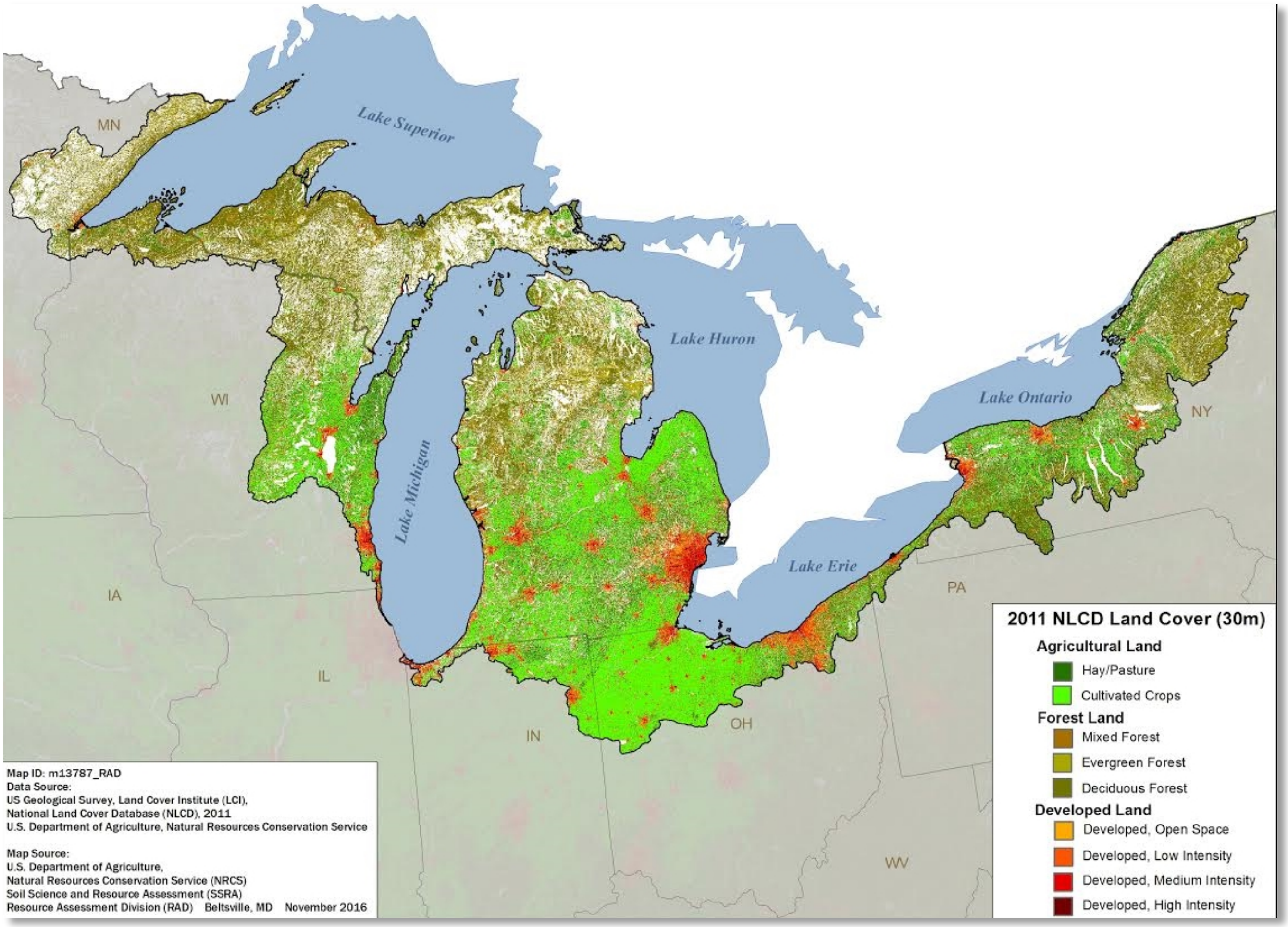

Figure 5. Land cover in the Great Lakes watershed in the United States, showing agricultural, forested, and developed land uses by area. (Graphic source: USDA/NRCS/Resource Assessment Division.)

Researchers anticipate that climate change will lead to increased incidents of extreme weather events in the Great Lakes region, including droughts and flood events, which subsequently may lead to more intense and widespread HABs and hypoxia. For instance, researchers expect precipitation patterns in the Great Lakes to change in the future, with larger numbers and more intense storms (Richards et al., 2010; Michalak et al., 2013). Increased rainfall causes more runoff from agricultural operations and storm-sewer systems, which can elevate the amount of nutrients entering the lakes (Bosch et al. 2014; Cousino et al., 2015). In turn, the influx of nutrients can promote HABs (Paerl and Huisman, 2008) and hypoxic conditions (Wilhelm et al., 2014; Zhou et al., 2015). Furthermore, larger and longer-lasting hypoxia events are associated with drought conditions (Zhou et al., 2015). Stronger winds resulting from more frequent and extreme storm events (Meehl et al., 2000) that are likely to produce changes in water stratification layers that can promote faster depletion of dissolved oxygen when tumultuous waters stir up the water column (Conroy et al., 2011; Huang et al., 2012). Conroy et al. (2011) specifically show that increased storm activity led to increased mixing of thermal layers, but also significant elevations in the depletion of hypolimnetic oxygen (Conroy et al., 2011). Rising surface water temperatures can also exacerbate low dissolved oxygen levels and water stratification (Fang and Stefan, 2009; Michalak et al., 2013).

Another aspect of how weather events may impact HAB dynamics results from the upwards trajectory of carbon dioxide in the atmosphere. Higher amounts of carbon dioxide in the atmosphere can encourage the growth of HAB species that absorb carbon dioxide for use in photosynthesis (Visser et al., 2016). High nutrient levels and increased water temperature may have a synergistic effect, promoting even more HAB growth.

1.3. How are We Monitoring and Surveilling for HABs and Hypoxia in the Great Lakes?

Image 3. A scientist collects water samples from Lake Erie on Ocean Sampling Day, June 21, 2014. (Credit: NOAA/OAR/GLERL.)

Though researchers' understanding of HABs and hypoxia has increased substantially in recent years (NSTC, 2015), additional ecological research, and expanded environmental monitoring using new technologies, are needed at a variety of spatial and temporal scales to improve understanding of how and why hypoxia and HAB events occur. Surveillance and monitoring technologies also help with protecting human and animal health.

Monitoring plays a key role in identifying the drivers of HABs and hypoxia by tracking and exploring the sources of nutrients and how they contribute to HAB and hypoxia formation. For instance, researchers can use monitoring and surveillance techniques to confirm which nutrient sources come from the watershed and atmosphere and then are delivered to the lakes via agricultural run-off; wastewater and storm water discharges; runoff from individual homes and residential gardens; groundwater; or through atmospheric deposition from burning fossil fuels containing nitrogen (Molder et al., 2015). Edge-of-field monitoring, in particular, is an important method. This refers to the point where water leaves a field and enters another field, a drainage ditch, or a waterbody, providing information on how specific nutrients move through the watershed at a particular location. Scientists may take samples from the lakes themselves, streams, groundwater sources, and tributaries. This section discusses a few key examples of agency monitoring techniques. Appendix 3 contains specific information on other current and planned agency monitoring and surveillance activities.

Expanded sampling in additional locations, and comparative work to understand how nutrients enter and cycle through ecosystems, ultimately may allow for more proactive, and location- and ecosystem-specific, HAB and hypoxia forecasts, as well as development of remediation techniques. Researchers need better monitoring information on sources of nutrients: local-scale information on the sources of nutrients would help to prioritize how to spend and target conservation dollars most effectively, and to implement conservation practices for those areas. Better monitoring programs also will help researchers understand and address the respective roles of external versus internal nutrient sources on HABs and hypoxia.

One of the key monitoring and forecasting systems for HABs in the Great Lakes is NOAA's Lake Erie HAB Forecast System, which became fully operational in July 2017. NOAA has developed this system to support management, public water suppliers, and the various recreational and other uses of the lake. It uses a combination of satellite imagery, numerical circulation models, and field observations (bloom concentration, toxicity, and other environmental parameters) to describe current bloom conditions and to forecast the likely conditions over the next several days. The primary product is a bulletin, with the main input being satellite imagery that specifically detects the presence and amount of cyanobacteria. NOAA began distributing the bulletin in 2009, with weekly distribution through 2013, and twice-weekly distribution starting in 2014. NOAA provides additional imagery to state and local partners when available during serious blooms. In 2016, almost 2,000 people subscribed to the bulletin. A complementary NOAA forecast system that tracks the horizontal and vertical movement of HABs in Lake Erie, the recently developed Lake Erie Experimental HAB Tracker (Rowe et al., 2016b), forecasts the short-term movement of blooms and produces an animation similar to a moving weather forecast.

The Federal government has a number of established monitoring programs and offices, as discussed throughout this section. For example, the USEPA created the Great Lakes National Program Office (GLNPO) in 1978 in order to carry out the responsibilities accorded to the United States under the GLWQA (discussed further in Section 2.2.1). The office manages long-term water quality and biological monitoring programs in all Great Lakes states, and a hypoxia-monitoring program in the central basin of Lake Erie. Federal and state water quality agencies use data generated from the programs to assess the trends in open lake water quality and ecological health. Additionally, USGS and USDA have extensive monitoring and data-analysis efforts, as discussed later.

New technologies for monitoring HABs and hypoxia deliver higher temporal resolution, as well as more accurate and timely information. Technologies include near-real-time toxin and organism testing methods, nutrient sensors, cabled and under-ice monitoring technologies for year-round monitoring of HABs and hypoxia; and use of satellite and hyperspectral remote sensing technologies on unmanned aircraft to help monitor for HABs. The technologies are in testing and comparison modes, and once vetted ultimately can be incorporated into future standard monitoring protocols.

The Cyanobacteria Assessment Network (CyAN) is an important interagency monitoring effort. USEPA, NOAA, NASA, and USGS are developing an early-warning indicator system that supports environmental management and public use of lakes and estuaries, including the Great Lakes, by providing capacity to detect and quantify cyanobacterial blooms and related water quality using satellite data. The goals of the project are to:

- Create a standard and uniform approach for early identification of freshwater HABs. This will involve creating new and building upon current data sets, based on existing and new sets of satellites (much of this based on methods originally developed for Lake Erie);
- Develop an information dissemination system for accelerating access to information needed for public health advisories; and
- Increase understanding of the health, economic, and environmental connections that stem from cyanobacteria and phytoplankton blooms.

As a result, CyAN aims to enhance and expand the Lake Erie Bulletin methods across all the Great Lakes. The agencies anticipate that the resulting information will help stakeholders of freshwater systems identify when one or more water bodies are experiencing or have an elevated risk for HABs or hypoxia.

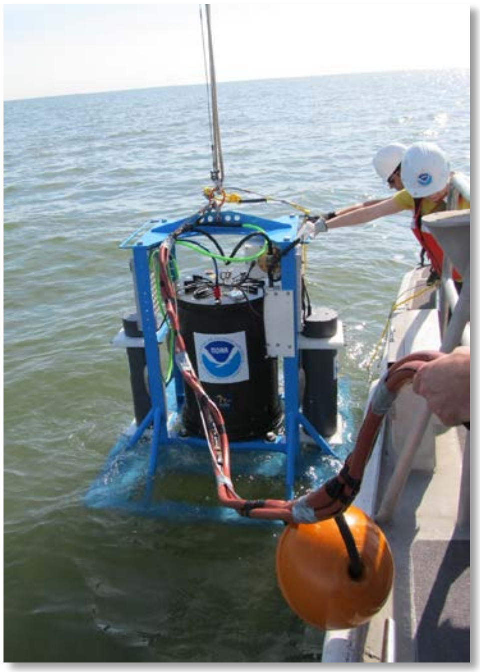

Image 4. In 2016, scientists from NOAA and the University of Michigan deployed ESPniagara for the first time in western Lake Erie. Scientists often refer to ESPs as "labs in a can" due to the technology's ability to perform multiple, ongoing experiments in the field and provide daily bloom and toxicity information to researchers in a lab. The ESPniagara sensors provide data that complements other information gleaned by field monitoring through private enterprises and municipalities (Photo credit: NOAA/OAR/GLERL).

Another example of ongoing monitoring efforts in the region is the deployment of Environmental Sample Processors (ESPs). These "labs in a can" provide researchers and managers with near-real-time information about the presence and quantity of a toxin or organism of interest in a water body. ESPs are an established technology, although researchers only recently began using them for monitoring cyanobacteria. In 2016, NOAA successfully deployed an ESP in western Lake Erie, marking the first-ever usage of this technology in any freshwater system. The ESP will provide an increased understanding of fine-scale changes in bloom toxicity. In combination with NOAA's current Lake Erie HAB forecasting tools, this should improve researchers' abilities to provide accurate forecasts of bloom location, movement, and toxicity. The results will benefit resource managers and public health officials in protecting human and animal health and helping communities to stay informed and prepared.

The Great Lakes Observing System (GLOS), a regional association of the United States Integrated Ocean Observing System (IOOS®), and certified Regional Information Coordination Entity, is another example of an interagency partnership working to coordinate observing and data-sharing activities. GLOS is a national/regional partnership that coordinates the collection and integration of ocean, coast, and Great Lakes observing data. The body helps to organize Federal and non-Federal observing activities across the region and supports operation of several nearshore buoys, including two buoys used by Cleveland, Ohio, for monitoring for dissolved oxygen levels. GLOS manages and shares data provided by Federal and non-Federal partners through the GLOS Data Portal.

Agencies and researchers need to improve upon existing, basic water quality monitoring in the Great Lakes region. Expanding current sampling frequency and spatial coverage, including year-round sampling in key locations, would help to inform researchers' understanding about nutrients sources and over-winter HAB cell-seeding (in essence, dormant algal cells that lie on the lake floor), drivers behind differences between years in size and severity of HAB and hypoxic events, and other outstanding issues (Francey et al., 2015). Coordinated Federal agency efforts include the use of remote sensing for monitoring, as is done with HABs in western Lake Erie. The remote-sensing data can complement on-site monitoring to create more spatially- and temporally-complete data sets. Currently, there is no systematic monitoring or reporting of benthic HAB taxa, including *Cladophora* or *Lyngbya* blooms, due mainly to limitations of satellite imagery. Data derived from satellite imagery, as of now, is mostly limited to the water's surface and not much further below that.[2] Additionally, current satellite-image resolution capabilities are limited and make it nearly impossible to see algae on beaches (Brooks et al., 2015).

Many monitoring programs in the Great Lakes region do not currently include monitoring of DRP. Based on sensitivity analyses, it appears that researchers need high-frequency, daily sampling to accurately detect and assess DRP loads over time, and how this relates to conservation practices and nutrient management (Williams et al., 2015). More comprehensive monitoring that better accounts for DRP ultimately can improve the effectiveness of planning and managing HAB events (Williams et al., 2016).

Western Lake Erie and the Need for Ongoing Monitoring

Researchers should conduct routine surveys in areas that have experienced HABs, to understand temporal and spatial changes in the occurrence and severity of HAB events, and why the variations occur. For example, HABs re-emerged in western Lake Erie in the mid-1990s, after the lake had not experienced HABs in some time: until that point, managers and researchers considered the lake "restored". Resource managers, scientists, and officials overlooked changing water quality conditions that contribute to the current HAB/hypoxia dynamics in the lake. Many scientists and natural resource managers were unprepared when HABs re-occurred. As researchers learned, it is important to perform continuous and frequent monitoring, even after implementing nutrient-reduction strategies, and that it is important to vary methods over time and as the aforementioned conditions change (Chapra and Dolan, 2012; Dolan and Chapra, 2012).

1.4. Modeling and Forecasting

Models and forecasts play important roles in helping the region and communities prepare for, and mitigate the impacts of, HAB and hypoxia events. The use of models can answer questions that managers may have regarding the environmental conditions that can lead to recurring HAB or hypoxia events. For instance, model simulations can suggest the main sources of nutrients polluting a water body. They also can show how nutrient dynamics change under different land-use management, or in different types of weather or ecological conditions. Some of the key questions that modeling answers, and builds upon, for all Great Lakes HABs and/or hypoxia events, include:

- How are specific nutrients in exact nutrient forms transported; and, when relevant, what chemical changes do they undergo during transport through the watershed?

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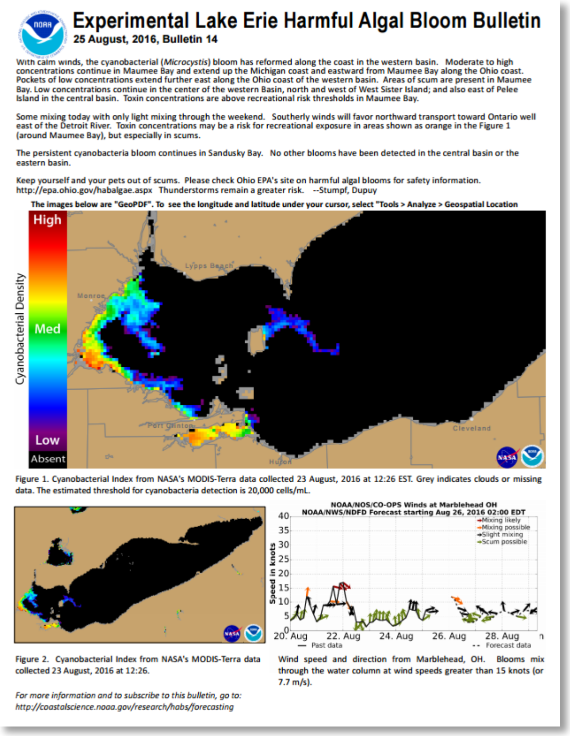
[2] Satellite ocean color sensors can "see" to one optical depth.

- Do non-nutrient factors play increasingly larger roles in bloom development over time?
- Are conservation practices improving water quality in small watersheds? In sub-basins, or basin-wide? How can we make practices more effective at different spatial and temporal scales, and achieve broader benefits?
- How can we analyze information and scenarios to inform decision-makers?

Potentially, the most important role of modeling is to protect public drinking water facilities through short-term forecasts of HAB and hypoxia events around water intake pipes. Communities can use forecast information to ensure that they have appropriate resources – including drinking water and alternative sources of income, to ensure economic stability to protect citizens in the short- and long-terms. Forecasts allow managers to plan how much treatment material they need to have available, saving funds during years with weak blooms and allowing states to focus resources on communities or water intake plants that are the most at-risk.

NOAA's operational Lake Erie forecasting products are key examples of how researchers develop models and forecasts based on a variety of factors, and use models routinely to predict the size, intensity, and location of HABs in western Lake Erie (Wynne et al., 2008; Wynne et al., 2013; Rowe et al., 2016). Similarly, real-time measurements of dissolved oxygen near the lakebed of Lake Erie give early warnings to drinking-water treatment-plant managers in Cleveland, OH. These managers then know to initiate additional water-treatment procedures to remove contaminants that tend to accumulate during hypoxic events, such as manganese and iron, which can turn drinking water yellow and affect taste or corrosion.



Experimental Lake Erie Harmful Algal Bloom Bulletin

25 August, 2016, Bulletin 14

With calm winds, the cyanobacterial (*Microcystis*) bloom has reformed along the coast in the western basin. Moderate to high concentrations continue in Maumee Bay and extend up the Michigan coast and eastward from Maumee Bay along the Ohio coast. Pockets of low concentrations extend further east along the Ohio coast of the western basin. Areas of scum are present in Maumee Bay. Low concentrations continue in the center of the western Basin, north and west of West Sister Island; and also east of Pelee Island in the central basin. Toxin concentrations are above recreational risk thresholds in Maumee Bay.

Some mixing today with only light mixing through the weekend. Southerly winds will favor northward transport toward Ontario well east of the Detroit River. Toxin concentrations may be a risk for recreational exposure in areas shown as orange in the Figure 1 (around Maumee Bay), but especially in scums.

The persistent cyanobacteria bloom continues in Sandusky Bay. No other blooms have been detected in the central basin or the eastern basin.

Keep yourself and your pets out of scums. Please check Ohio EPA's site on harmful algal blooms for safety information. http://epa.ohio.gov/habalgae.aspx Thunderstorms remain a greater risk. --Stumpf, Dupuy

The images below are "GeoPDF". To see the longitude and latitude under your cursor, select "Tools > Analyze > Geospatial Location

Figure 1. Cyanobacterial Index from NASA's MODIS-Terra data collected 23 August, 2016 at 12:26 EST. Grey indicates clouds or missing data. The estimated threshold for cyanobacteria detection is 20,000 cells/mL.

Figure 2. Cyanobacterial Index from NASA's MODIS-Terra data collected 23 August, 2016 at 12:26.

Wind speed and direction from Marblehead, OH. Blooms mix through the water column at wind speeds greater than 15 knots (or 7.7 m/s).

For more information and to subscribe to this bulletin, go to: http://coastalscience.noaa.gov/research/habs/forecasting

Image 5. An example of NOAA's Lake Erie HAB Bulletin for Lake Erie, from August 25, 2016. The weekly bulletin provides stakeholders with information about HAB formation and toxin levels. It is a good source of information for all users of the lake. (Credit: NOAA/NOS/CO-OPS.)

Experimental NOAA Runoff Risk Analysis Data for Great Lakes States – Version 2

As part of NOAA's participation in the GLRI, and the National Weather Service's (NWS) hydrologic modeling responsibility, the North Central River Forecast Center (RFC) and neighboring RFCs are working together to assemble and provide runoff risk analysis data for the Great Lakes states. The RFCs evaluate soil moisture model output to determine runoff risk based on event thresholds developed by the participating state agencies. Runoff risk analysis data for the Great Lakes states is being made available to users on an experimental basis. Runoff Risk Decision Support is in development Minnesota, Michigan, Wisconsin, and Ohio. It is planned for Illinois, Indiana, and parts of New York State.

State partners use the experimental runoff risk guidance for determining optimized nutrient application, which helps to ensure safe water quality and healthy ecosystems in the nation's streams, lakes, and coastal waters. Further, the information provided by Runoff Risk helps farmers ensure that fertilizer and manure stay on the fields, instead of washing into waterways.

Currently, HAB and hypoxia modeling and forecasts are restricted at a variety of different spatial and temporal scales due to limited data collected at the right resolution and frequency; data integration capabilities; and modeling capabilities, updates, and calibration (Daggupati et al., 2015; Brooks et al., 2016). Yet, hypoxia modeling continues to improve with the development of new statistical and modeling approaches and data sets (Zhou et al., 2013; Obenour et al., 2014; Rucinski et al., 2016). Recent modeling results show that in Lake Erie, low dissolved oxygen levels are likely to start in nearshore areas with depths less than or equal to 20 m, and that current monitoring may not capture the extent of the size of the hypoxic zones (Bocaniov and Scavia, 2016). GLOS operates the Hypoxia Warning System that NOAA built, o provide decision support for drinking water managers in Cleveland. The system gives advanced warning of hypoxic water near water intakes. Similar HAB and hypoxia models are needed for other parts of the Great Lakes, including Saginaw Bay and Green Bay. Increased monitoring and data development could greatly expand modeling capacities.

Within the Conservation Effects Assessment Project (CEAP), USDA-NRCS cooperates with USDA-Agricultural Research Service (ARS), Texas A&M University (TAMU), and Iowa State University (ISU) to apply Agricultural Policy/Environmental eXtender (APEX) and Soil and Water Assessment Tool (SWAT) models to simulate agricultural management impacts on water quality at the edge of field, in stream and rivers, and being delivered to Lake Erie. CEAP is unique in its access to farmer management decisions, which were surveyed through a National Resource Inventory-structured system by USDA National Agricultural Statistics Service in the Great Lakes region in 2003-2006, and in the western Lake Erie basin in 2012 (USDA 2011, 2016a). Simulations conducted via CEAP benefit from cross-agency knowledge sharing and mutual model enhancement. CEAP modeling efforts may better inform interagency- and university-led in-lake modeling efforts regarding feasible future scenarios by providing more realistic estimates of what is achievable through conservation solutions applied to agricultural lands. Recent results from models built to evaluate conservation practice effects, combined with monitoring data, show that among other benefits, conservation practices overall benefit stream health and fish populations in the western Lake Erie watersheds. Federal, state, and local governments should expand efforts to increase acreage receiving conservation practices substantially, in order to achieve GLWQA phosphorus-loading targets (Keitzer et al., 2016). Decision-makers also can use such models to help facilitate and prioritize conservation practice efforts to benefit stream fish communities in the watershed along with watershed water quality impacts (Keitzer et al., 2016).

Without detailed information on internal and external nutrient loading, it is difficult to determine if nutrient reduction targets are being met, and for managers to assess how to prioritize rehabilitation efforts. To help address these issues, USGS developed SPAtially Referenced Regressions On Watershed attributes (SPARROW) models for estimating loads and sources of phosphorus and nitrogen from the U.S. portion of the Great Lakes, among other freshwater bodies (Robertson and Saad, 2011). Results indicate that recent U.S. loadings to Lakes Michigan and Ontario are similar to those in the 1980s, whereas loadings to Lakes Superior, Huron, and Erie have decreased. The highest loads come from tributaries with the largest watersheds (Robertson and Saad, 2011). Agricultural areas in the region provide a significant source of nutrients, generally contributing about 33-44 percent of the phosphorus and about 33-58 percent of the nitrogen. Point sources of nutrients also are significant, contributing about 14-44 percent of the phosphorus and 13-34 percent of the nitrogen. Watersheds around Lake Erie contribute nutrients at the highest rate (similar to intensively farmed areas in the Midwest) because they have the largest nutrient inputs and highest delivery ratio (Robertson and Saad, 2011). A binational SPARROW model is in development for the entire Great Lakes watershed, with completion anticipated in 2017. Regional nitrogen and phosphorus SPARROW models are available via an interactive, online decision-support system so that water managers, researchers, and the public can access SPARROW models and map predictions of long-term average water quality conditions, track transport to downstream receiving waters, and evaluate management source-reduction scenarios.

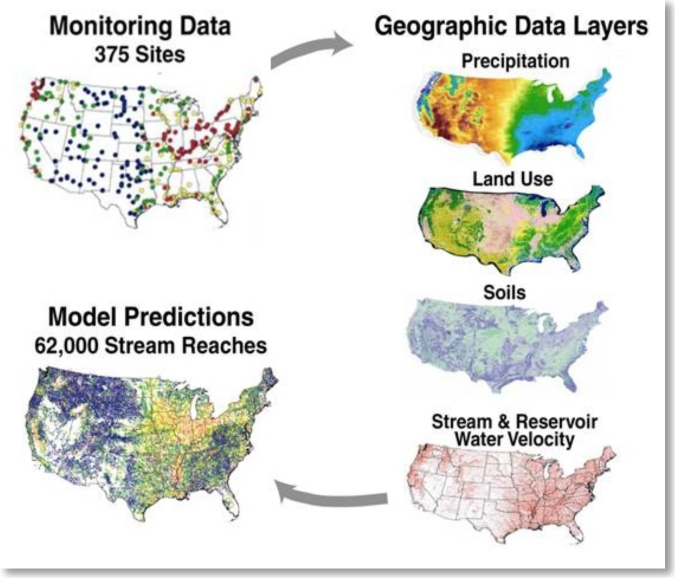


Image 6. USGS' SPARROW model uses data from a number of sources to estimate nutrient loads from streams and rivers. Models are developed at a range of scales, including national and major river basin levels. Managers can use information from the models to make informed decisions. (Credit: USGS).

Social science models may play a role in reducing public health concerns (Anderson et al., 2012), and demonstrating people's attitudes, actions, and resulting exposure to HABs and hypoxia. They also show economic trends, which can help communities prepare for potential events by helping stakeholders understand the effects of HABs and hypoxia on all aspects of the economy. Social science models also help to identify the factors that make communities economically vulnerable to current and future HAB and hypoxia events, and to help communities know what to expect during future events. This is important for identifying populations at higher risk to HAB or hypoxia impacts, including those with medical conditions that may be exacerbated by HAB toxins, vulnerable age groups, transient communities, or individuals who depend on the lakes for drinking water or food sources. Ultimately, models can help policymakers determine how to distribute resources efficiently.

Models should include area-specific calibration, account for short-term and long-term processes, and address individual and joint agency objectives. Even then, it can be a challenge to run models consistently if input data are insufficient or derive from different sources that are not always comparable. To provide the most accurate forecasts of the location, duration and intensity of a HAB or hypoxic event, researchers need standardized collection, analytics, data management methods, and defined quality control measures. A good way to accomplish this is to develop models that have the capacity to use data in whatever form it is collected, and to improve data-collection and sharing methods. Data from genetic and physiological experiments on HAB organisms, including epidemiological data and health surveillance, should be a priority, particularly any showing connections between species that produce toxins versus those that do not, ecological zones that historically are more susceptible to developing HABs or hypoxia, and human or animal sickness or death. Resulting models will need regular updates and calibrations via an established monitoring and technological infrastructure.

Challenges also arise when there is limited access to data sets from different agencies or entities, or where measured variables or locations of measurement are not congruent. As discussed in NSTC 2016, groups such as the IWG-HABHRCA can help in establishing official working relationships between Federal agencies and outside parties, such as universities and research institutions; agreeing upon standard methods; and coordinating data collection (NSTC, 2016). These actions will lead to improved models that incorporate the best data available, and can show how to improve watersheds using management practices designed for affecting nutrient levels. The list below shows issues identified by stakeholders that improved modeling could address. Stakeholders told the IWG-HABHRCA about specific models needed for the Great Lakes, as well as general models that could be adapted for the Great Lakes to improve efficiency and accuracy. As reflected in Section 3, Federal researchers and stakeholders place a greater priority or need for the models listed below:

- Microcystins nowcast and forecast models for known HAB locations in each of the lakes, based on on-site sensors and wind/current information (Francey et al., 2015).
- Relationship between microcystin and chlorophyll-*a* for application to satellite monitoring.
- Environmental impacts on HAB and hypoxia events, at a variety of scales.
- Improved physical process models appropriate for ecological and water quality forecasts.
- Improved benthic boundary layer/ nutrient diffusion models.
- Incorporation of invasive species impacts into modeling systems.
- Incorporation of the impacts of extreme weather events into modeling systems, evaluating how it affects the formation, duration, and severity of HABs and hypoxia.
- Nearshore models identifying development of HABs.
- Ecological forecasts on the formation, duration, and severity of HABs and hypoxia.

Detailed 3-D HAB events and toxicity are difficult to forecast. The next generation of forecast products that could predict subsurface HAB concentrations at the depth of drinking water intakes are under development (Rowe et al., 2016). As of this report's publication, no toxin forecast systems exist for the Great Lakes because toxins are undetectable via satellite. Researchers are therefore reliant on a two-step model that estimates proxies for toxins (algal pigments), instead of the toxins themselves. Results from the two-step model can be difficult to interpret due to the variable relationship between pigments and toxins. At the same time, because the variability appears to result from measurable environmental factors, like light and nitrogen availability, it may prove possible to develop a predictive model (Stumpf et al., 2016).

1.5. Toxicity

Some of the most critical questions about HABs include identifying which species produce toxins that are the most harmful to humans and animals, where toxins are located in a waterbody, whether researchers can predict the onset of toxicity, changes in toxicity throughout the bloom period, and how toxins affect local ecology. Advancements in technology, certified testing methods, methods to diagnose cyanobacteria-associated illness, and expanded water and health monitoring will help to answer questions regarding HAB toxicity and risk, human behavior factors, and appropriate messaging.

Furthermore, researchers need to improve understanding of the impacts of HABs on human and animal health, which will require additional research, monitoring, and disease surveillance efforts. These efforts include, but are not limited to, understanding important sources of cyanotoxin exposure, effects of low dose and episodic cyanobacterial toxin exposure, the movement of toxins through the food web, the effects of cyanobacterial toxins and associated pathogens on wildlife, and the relative toxicity and exposure risk of toxins and their variants (also known as "congeners"). Toxin research also should include the potential for new and emerging toxins in the Great Lakes region, such as saxitoxins and euglenaphycin, and their associated health effects.

Image 7. Just because you cannot see a HAB in the water clearly does not mean that a bloom is not occurring in a water body. This picture shows a bloom at Maumee Bay State Park that has a high toxin concentration of cyanobacteria (greater than 5.0 micrograms/liter), and yet the cyanobacteria are not easy to see. (Credit: USEPA).

Which toxins are most toxic to humans and animals? Federal agencies, in conjunction with university researchers, are working to improve toxin-testing methods (USEPA, 2015e; NSTC, 2016). Clinical tests for HAB toxins are primarily available within a research context and are not readily accessible to public health and healthcare practitioners. Certified toxin standards improve the validity of toxin-testing technologies, including more accurate, rapid tests for freshwater ecosystems, or animals or humans that appear sick with relevant symptoms. Standardized and rapid toxin-testing capabilities for ambient waters, treated drinking water, animal samples, and human specimens could provide a more comprehensive understanding of the species, location, and timing of HAB toxins. It is also important for veterinarians, public health officials, and clinicians to have access to tests in order to protect human and animal health, or to treat illness quickly. The following are questions for researchers to address while developing standardized and rapid toxin tests:

- Do researchers need a different detection method for each toxin? Can researchers develop a series of measures (nested protocols) for different detection methods?
- What is the validated detection range in each type of media tested?
- Do some methods produce a positive result for non-toxic breakdown products, making it seem as though a toxin is present? Does the method show cross-reactivity? Are false-negatives or false-positives more common with some testing methods, and what are the ramifications?
- Are there modifications that can improve current tests?

We have limited baseline information primarily from rodent studies on the relative toxicity of cyanobacterial toxins, which were used to support the USEPA's health advisories for microcystin and cylindrospermopsin (USEPA, 2015f). Researchers are unsure, however, how rodent toxicity translates to human health effects associated with chronic and acute exposure to cyanobacterial toxins and bioactive compounds (Gadmann and Portmann, 2008) from drinking, having contact with, or inhaling droplets of contaminated water. Researchers still need, and are attempting to glean, information to understand the relative toxicity of each toxin's variants. Having this information will help us to protect people against exposure to the most harmful toxins by aiding in setting regulatory limits for chronic and acute exposures and various exposure routes (e.g., dermal, inhalation, ingestion).

Finally, stakeholders identified research needs pertaining specifically to drinking water treatment for HABs and cyanotoxins. Researchers and water utility managers need a better understanding of how to remove contaminants from drinking water sources using commonly available water treatment technologies. They also need to know how treatment methods affect the ability of a water treatment facility to comply with existing drinking water quality regulations. This will allow water utilities on the Great Lakes and nationwide to better prepare for and respond to HABs in source waters, and to prevent HABs from contaminating treated drinking water. For instance, research has shown that some treatment chemicals can cause algal cells to break up and release toxins (Ross et al., 2006; Ou et al., 2012; Fan et al., 2013a; Fan et al., 2013b; Fan et al., 2014). Toxins that are released by cells are more difficult to remove with common water treatment approaches, compared with removing the toxins as part of the intact cyanobacteria cell (Chorus & Bartram, 1999; Chow et al., 1999; Drikas et al., 2001; Health Canada, 2002; AWWA, 2010; Newcombe et al., 2015; Ohio EPA, 2015; USEPA, 2015h; Walker, 2015; Ohio EPA, 2016). The Federal government and utilities can develop reliable, inexpensive, easy-to-use cyanotoxin monitoring techniques to assess water treatment plant performance. Optimizing existing water treatment can help water utilities avoid costly, and perhaps unnecessary, improvements to address HABs (Chorus & Bartram, 1999; Chow et al., 1999; Health Canada, 2002; USEPA, 2004; AWWA, 2010; USEPA, 2015e; Newcombe et al., 2015; Drikas et al., 2001).

How do researchers know which blooms are producing toxins? What is the occurrence and distribution of toxins? HAB species and associated toxins can differ among locations in a water body over the course of the season. Microcystins, cylindrospermopsins, anatoxin-*a*, and saxitoxins have been found in Lake Erie. Microcystins have been found in Lake Ontario; Saginaw Bay, Lake Huron; Green Bay, Lake Michigan (Vanderploeg et al., 2001; Barrett, 2014). Beyond this, however, scientists have little information about which HAB species and associated toxins occur in blooms in the Great Lakes. Additional information at finer spatial and temporal scales for each cyanobacterial toxin, and for any given location and time during a bloom or bloom season, will help to better protect humans and other organisms from HAB toxin exposure.

Managing exposure risk plays a major role in protecting human health. At some beaches that HABs affect, there already are protocols and the infrastructure to monitor bacterial pathogens and to communicate warnings and closures to the public. Managers could leverage and expand these resources to include HAB monitoring, particularly at beaches and other areas that do not presently have monitoring or outreach efforts. Current beach monitoring efforts mainly are at municipal or state levels, which generally only cover public beaches, and therefore may not include many of the HAB-impacted recreational waters. Reducing lag times between testing samples for HAB toxins, and relaying information on risk of HAB exposure to the public, is important for improving outreach and protecting public health (Charnley and Goldstein, 1998).

Surveilling HAB-related illness will help researchers and medical professionals to gain a greater understanding of exposure risk and health outcomes. Towards that purpose, the CDC launched the web-based One Health Harmful Algal Bloom System (OHHABS: http://www.cdc.gov/habs/ohhabs.html) in 2016. OHHABS is a voluntary reporting system available to state and territorial public health departments and designated environmental health or animal health partners. It allows partners to contribute data on individual human and animal cases of illnesses from suspected HAB-associated exposures, as well as environmental data about HABs. In addition, CDC conducts health surveillance for foodborne and waterborne disease outbreaks (aggregate data on two or more cases of illness associated with a common exposure), including HAB-associated outbreaks, through the web-based National Outbreak Reporting System (NORS – Figure 6). Next steps include developing clinical tests to evaluate human and animal biological samples for evidence of exposure to cyanobacteria toxins. While currently there are no accepted case definitions of cyanobacteria-associated illness, or methods available for health care providers to recognize and diagnose cyanobacteria-associated illness, OHHABS is a first step to collecting information that characterizes the range of possible health effects associated with exposure and the most important sources and routes of HAB exposure.

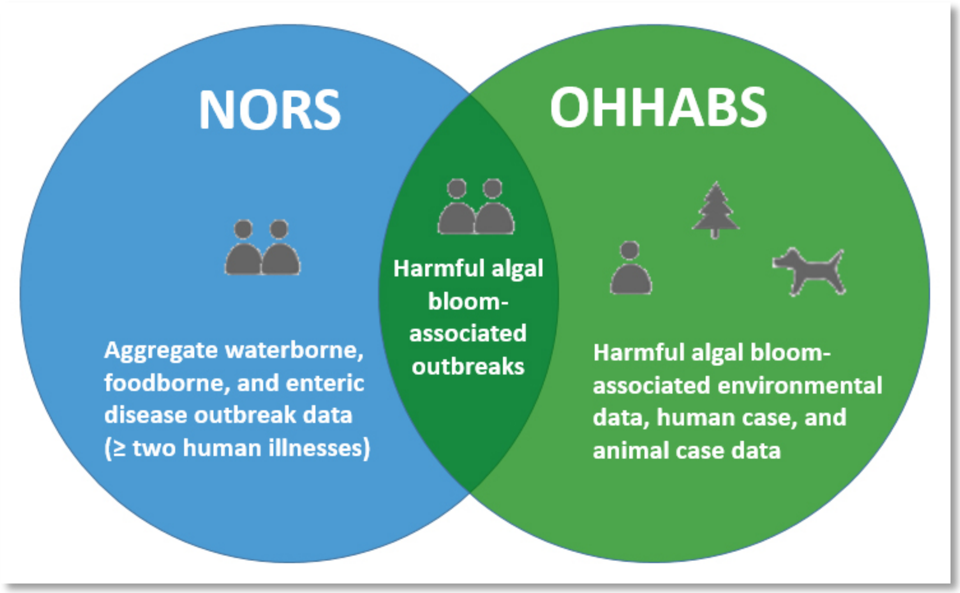


Figure 6. This image demonstrates how CDC's NORS and OHHABS programs overlap, in terms of what they track. (Credit: CDC).

Recent research shows that nutrients in the water column are likely drivers of toxin production in some HAB species (Gobler et al., 2016). However, thresholds related to the concentration of nutrients, nutrient forms that promote toxin production, and interactive effects that nutrients may have with other environmental factors may differ across HAB species, toxins, and locations in the Great Lakes. It is unclear how other environmental factors, such as water temperature or other natural chemical concentrations, could play a role in, or act synergistically with, nutrients to influence toxicity or HAB community composition at a given location or in a particular year (Davis et al., 2009; Davis et al., 2015; Harke et al., 2015; Cory et al., 2016). Additional knowledge on toxin breakdown products and pathways will help to clarify and reduce risks to aquatic organisms, humans, pets, livestock, and "non-aquatic" wildlife, such as deer. This is particularly relevant in the Great Lakes, where cyanobacteria break down (cell lysis) and then produce toxins such as microcystin-LR (Bourne et al., 1996; Dyble et al., 2008). Water treatment managers need to have forecasts and detection capabilities available in order to protect drinking water sources.

1.6. Ecological and Fisheries Management Impacts

HABs and hypoxia can affect trophic interactions (Raikow et al., 2004) and behavior in fish (Gobler et al., 2007; Kraus et al., 2015; Byappanahalli et al., 2003; Carmichael and Boyer, 2016). Researchers still do not have comprehensive understanding of how non-lethal HAB and hypoxia events affect secondary production, consumer organisms, or submerged aquatic vegetation in the lake littoral zone. There is a need to increase monitoring of blooms and fish movement, and to improve and increase toxin detection technology for cyanotoxins in flesh and viscera.

In the Great Lakes, the presence of invasive zebra and quagga mussels may promote some HAB species, although the connection is not entirely clear (Vanderploeg, 2001; Conroy et al., 2005; Bridgeman and Penamon, 2010; Fishman et al., 2010; Millie et al., 2011). Selective feeding on HAB species and nutrient excretion by the invasive zebra and quagga mussels has the potential to influence HABs and hypoxia (Bierman et al., 2005; Tang et al., 2014). Herbicides and pesticides that wash into lakes during application or times of high precipitation may promote HAB species by killing their natural competitors (Peterson et al., 1997; Lürling and Roessink, 2006; Saxton, 2011).

Fish in the Great Lakes can be particularly susceptible to hypoxia effects because they take refuge in the cool bottom-waters of the lake during the summer. Hypoxia can force fish out of these deeper refuge waters into shallower, warmer waters where the fish do not grow as well (Arend et al., 2011). In Lake Erie, increased catch rates of fish at the edges of hypoxia have important implications for fishery-management assessment models that assume that catch rates are the same, regardless of water depths, temperatures, or other conditions (Kraus et al., 2015).

Finally, the Great Lakes are an important habitat and breeding area for several species of waterbirds, including herons, egrets, gulls, and terns (Wires et al., 2010) (Figure 7, below). Many nesting colonies are located in close proximity to areas with known HAB or hypoxia zones, so there is concern that these birds may be impacted while foraging for food. Managers know little about the direct (e.g., toxicity) or indirect (e.g., reduced food) impacts of HABs and hypoxia on waterbirds breeding within the Great Lakes. Likewise, many species of waterfowl use the Great Lakes during migration; the effects of HABs and hypoxia on these species also is unknown.

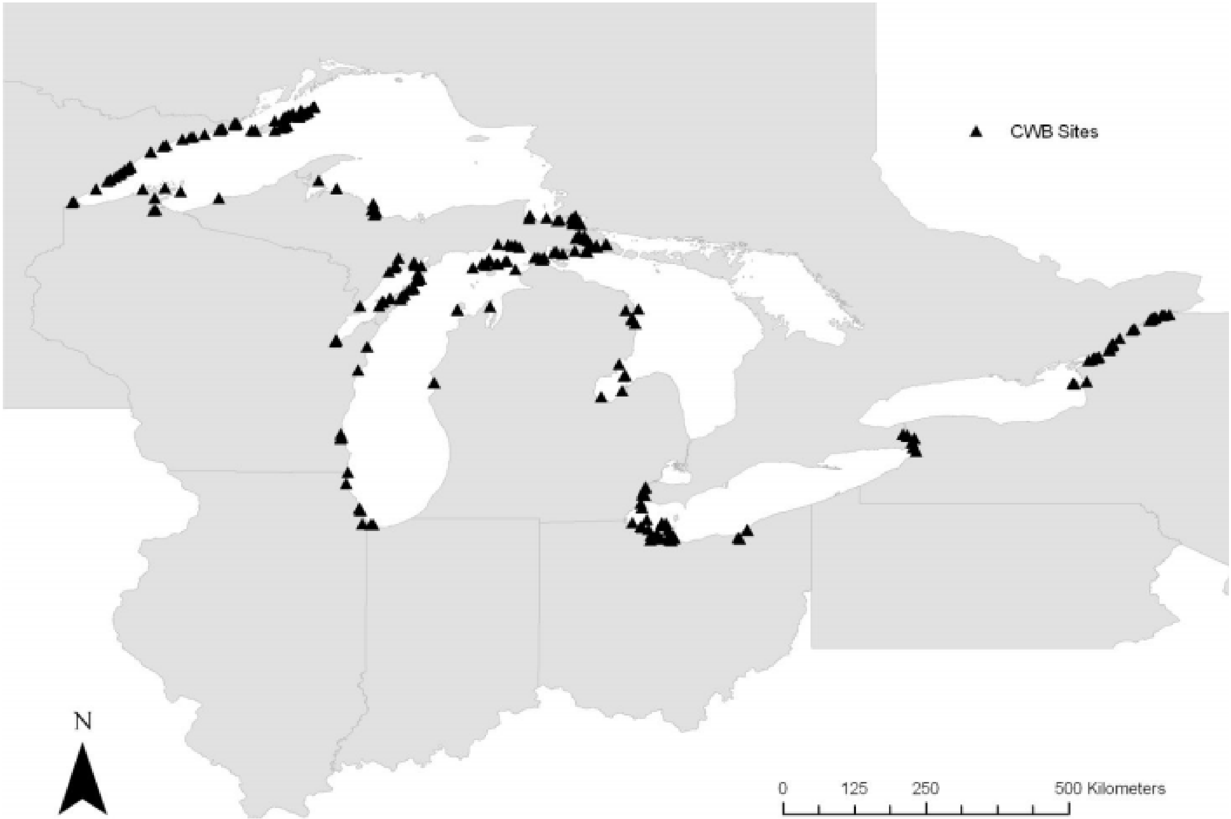


Figure 7. This figure shows the distribution of colonial waterbirds in the U.S. Great Lakes, between 2007 and 2010. As depicted by this image, almost the entirety of the Great Lakes provides habitat, breeding grounds, food, and resting areas for numerous species of waterbirds. In addition to the birds' roles in the food chain, they also provide sources of tourism revenue, and other benefits, to the region and the country as a whole. (Source: Cuthbert and Wires, 2013.)

1.7. Impacts of a Changing Climate on Extreme Weather Events, HABs, and Hypoxia

Researchers need to evaluate further the possible effects of interactions among changing air temperature, water temperature, precipitation patterns, and carbon dioxide concentrations on different HAB species or hypoxic events at different locations. How do these factors – individually, or combined – affect formation or duration? How, in turn, do climate-change-related HABs affect human and animal health, through behavior changes; water usage; or changes in how, and in what ways, exposure occurs? Further monitoring and modeling can help to show the connections between increased water temperature and water body characteristics with larger, more frequent, and more toxic blooms (Paerl and Huisman, 2009). Models and monitoring also can show how extreme weather events impact bloom growth in relation to other drivers, including differences in nutrient runoff amounts.

Resuspension of water during spring turnover and during storm or high wind events may bring nutrients and resting HAB cells from lake-bottom sediment, and has been associated with HABs in lakes that are not part of the Great Lakes (Torres and Adámek, 2013). A similar phenomenon could happen in the Great Lakes (Kutovaya et al., 2012). Impacts related to extreme weather events may exacerbate this (Jenny et al., 2016), as warming is likely to enhance stratification that leads to HABs and hypoxia (USGCRP, 2016). Timing of resuspension and cell seeding are likely to be important factors in Great Lakes HABs and hypoxic events, but scientists know few details.

2. Managing HABs and Hypoxia: What are the Options?

Managing HABs and hypoxia in the Great Lakes requires access to technology, including repurposed technology. The implementation of conservation practices often relies on new and emerging technologies. Technological needs span all spatial categories from local to basin-wide. Current technologies for estimating loads need to be adapted and applied for more accurate real-time nutrient load estimation to better identify the nutrient sources.

There are a number of HAB control or suppression techniques used in small inland lakes. This includes applying barley straw, which exudes a chemical preventing new algal growth; dredging the bottom of the lake to remove nutrient-rich sediments; or mechanical aeration and mixing of the water column to prevent stratification, reducing the conditions that many cyanobacteria prefer (USEPA, 2016a). These methods, however, are ineffective in deeper, larger ecosystems, such as the Great Lakes. Given this, the focus of efforts has been on prevention and mitigation techniques, including gaining a better understanding of the drivers of HAB and hypoxia formation, and of HAB toxicity.

2.1. Nutrient Management Opportunities and Needs: How are We Addressing Nutrient Sources, from Watershed to Lake, Contributing to Great Lakes HABs and Hypoxia?

There are many complicating factors to consider when working to reduce HAB and hypoxia events in the Great Lakes. However, scientific consensus is that properly implementing nutrient management practices and strategies that prevent excess nutrients from entering the ecosystem of the lakes can contribute to preventing HABs and hypoxia (GLWQA, 2015). Phosphorus reduction targets set forth through the 1978 GLWQA helped to eradicate HABs in Lake Erie for years. Decision-makers hope that achieving new GLWQA goals will help to lessen the severity of HABs and hypoxia (GLWQA, 2015). There is no source of basin-wide information, however, on how setting similar targets for nitrogen would impact the development and severity of these events (Elmers and Watmough, 2016), including how nitrogen contributes to toxin production (Gobler et al., 2016). Recent reports examine progress in conservation practice adoption in the region by comparing how well conservation practices in use from 2003 to 2006, and then to 2012, reduce nutrient loads entering Great Lakes tributaries and western Lake Erie (USDA, 2011; USDA, 2016a;

Image 8. Edge-of-field monitoring in practice. The pictures on the left and in the center show monitoring stations that allow NRCS to measure the amount of nutrients and sediment in water at the edge of a farm field. The picture on the right is of a calibrated flume used by USGS to measure water flow and loading of nutrients and sediment. (Credit: USDA/NRCS.)

Keitzer et al. 2016). As discussed later in this report, researchers and managers need additional analysis on the capability of conservation practices to achieve nutrient-reduction targets to minimize HABs and hypoxia, particularly under varying hydrologic and climatic conditions.

Researchers, decision-makers, and stakeholders need local- and field-scale information on the ecological costs and benefits of implementing conservation practices. Information related to the economic costs of agricultural conservation practices, and their impacts on soil and water quality, is available for numerous conservation practices in use in the region, including socio-cultural practices (e.g., nutrient management) and structural practices (e.g., erosion control structures) (NRCS, 2011; NRCS, 2016b). For instance, CEAP estimates of conservation practice impacts are valid at individual field levels – as applied in the NRCS conservation-planning tool, the Stewardship Tool for Environmental Performance (STEP) – and regional scales, as applied in CEAP-cropland assessment reports (USDA 2011, 2016a). Opportunities remain to refine interactive impacts of conservation practices, and to improve ties between conservation practice impacts and biological metrics. Keitzer et al. (2016) present novel work in western Lake Erie, in which they explored the impacts of conservation practices in use between 2003 and 2006, with scenarios of increased structural controls and nutrient management in terms of effects on fish and invertebrate biodiversity in streams (Keitzer et al., 2016). However, biological populations and biodiversity data rarely are sufficient in quantity and detail to allow similarly detailed modeling exercises. Furthermore, researchers are uncertain about how much knowledge developed in other, smaller-scale lake systems can transfer to understanding the Great Lakes system. By conducting relevant studies, researchers can improve scientific understanding while maintaining other watershed uses, such as agriculture. Section 3.2 delineates relevant research needs in more detail.

Coordinated edge-of-field, in-stream, and tributary monitoring is performed in Great Lakes priority watersheds by GLRI Regional Working Group agencies and other partners, as well as the GLQWA Annex 4 Subcommittee, to evaluate the efficacy of nutrient reduction efforts. Ongoing and expanded coordination of current nutrient management-related monitoring efforts is essential to determine the sources of nutrients and the efficacy of conservation practices, in locations most impacted by HABs and hypoxia (Betanzo et al., 2015). With additional information, researchers and policymakers can more clearly assess the successes or specific challenges and needs of current management approaches.

Researchers recommend enhancing coordination and expansion of monitoring of in-lake nutrients with an appropriate study design that allows for tributary monitoring, edge of field monitoring, and conservation practices assessments (Meals et al., 2012; Betanzo et al., 2015). The GLWQA Nutrient Annex (Annex 4) is developing binational approaches to monitor nutrient loadings to the Great Lakes as well as methods and metrics to quantify and track nearshore and open water HAB biomass and hypoxia in Lake Erie. Optimally, data-sharing between producers of data; conservation staff; and water monitoring agencies, including those at Federal, state, local, tribal, bi-national, provincial, and academic levels (Betanzo et al., 2015), will occur and follow the structure called for by Annex 4.

2.2. Key Agreements and Coordinating Bodies in the Great Lakes to Improve Water Quality

The Federal government has made substantial progress in understanding and managing Great Lakes HAB and hypoxia events through expanded, improved, and coordinated policies, and through research and management programs. Great Lakes HAB and hypoxia prevention and management requires a strong Federal coordination role in addition to state, provincial, and local oversight because Canada shares and jointly governs the waters. This section highlights some of the particular advances in Federal efforts in the Great Lakes, which are helping the region make significant advances in improving water quality and reducing the incidents of HABs and hypoxia.

2.2.1. Great Lakes Water Quality Agreement

The U.S. and Canada long have recognized the need for collaborative governance of these waterbodies, beginning with the Boundary Waters Treaty of 1909[3]. The GLWQA, first passed in 1972 and most recently amended in 2012, between the U.S. and Canadian governments commits both parties to specific responsibilities related to HABs and hypoxia.

In the 1960s and 1970s, the Great Lakes experienced large algal blooms, aesthetic issues, hypoxia, fish kills, and drinking water taste and odor problems at water intake facilities and in home faucets, among other concerns. In 1983, the U.S. and Canada (the "Parties") signed a phosphorus load supplement to the 1978 GLWQA that established phosphorus load targets and associated water quality targets for each of the lakes. Phosphorus reduction targets were set for wastewater treatment plants, and the plan suggested accelerated prevention and practice methods for the agricultural community. During the intervening years, the Parties implemented other actions such as phosphorus detergent bans and reductions of phosphorus in lawn fertilizers. Managers also tried to reduce sediment loads, as scientists believed at the time that most phosphorus was transported attached to sediment into the tributaries and Great Lakes. These actions resulted in dramatic improvements in water quality during the late-1980s and early-1990s. In the mid-1990s, however, HABs resurged in Lake Erie, and remain an issue there and in other parts of the Great Lakes.

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[3] The Treaty Between the US and Great Britain relating to Boundary Waters, and Questions Arising Between the US and Canada ("Boundary Waters Treaty"), established clear jurisdiction over and controls of the boundary waterways between the two countries. It also established the International Joint Commission (IJC), discussed in further detail in this section. Full text of the Boundary Waters Treaty is here: http://ijc.org/files/tinymce/uploaded/Boundary%20Waters%20Treaty%20of%201909_3.pdf.

Renewed binational efforts to minimize HABs and hypoxia in the Great Lakes occurred in 2012 GLWQA amendments that committed the Parties to review and update the previously established binational phosphorus-load reduction targets for each of the Great Lakes, beginning with Lake Erie. In response to this obligation, and following a robust binational science-based process and extensive public consultation, in 2016, Canada and the U.S. adopted the following phosphorus reduction targets (compared to a 2008 baseline) for Lake Erie:

- To minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie: a 40 percent reduction in total phosphorus entering the western and central basins of Lake Erie from the United States and from Canada, to achieve an annual load of 6,000 metric tons to the central basin. This amounts to a reduction from the United States and Canada of 3,316 metric tons and 212 metric tons, respectively.
- To maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie: a 40 percent reduction in spring total phosphorus and DRP loads from the following watersheds where algae is a localized problem: in Canada, the Thames River and Leamington Tributaries; and in the U.S., the Maumee River, River Raisin, Portage River, Toussaint Creek, Sandusky River, and Huron River (Ohio).
- To maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the waters of the western basin of Lake Erie: a 40 percent reduction in spring total phosphorus and DRP loads from the Maumee River, which equates to 860 metric tons per year of total phosphorus, and 186 metric tons per year of DRP in conditions of high spring discharge.

Consistent with the GLWQA, the U.S. and Canada currently are developing joint initiatives such as the GLRI and Domestic Action Plans (DAPs) that will describe the actions necessary to meet the new phosphorus reduction targets. In the United States, developing and implementing DAPs primarily is a state-led effort. Federal partners will assist states in carrying out the DAPs and developing a coordinated monitoring strategy to track progress. In addition, under the GLRI (see next section) Action Plan 1 and the first year of Action Plan 2, more than $60 million dollars were invested in the Lake Erie Basin from 2010 through 2015 to reduce nutrient pollution and to support related science and monitoring work. By 2019, per Action Plan 2, the groups involved expect to reduce over 1 million pounds of phosphorus in priority watersheds.

GLWQA provides the Great Lakes region with a binational framework for coordination and setting priorities regarding water quality issues, including those related to HABs and hypoxia under Annex 4 (Nutrients). The GLWQA organizational structure includes oversight by the Great Lakes Executive Committee, representing over 50 Federal, state, provincial, non-indigenous, municipal, and watershed groups (Figure 6). Environment and Climate Change Canada and the USEPA co-chair the GLWQA Annex 4 Subcommittee. Other GLWQA Annexes that are pertinent to HABs and hypoxia are Annexes 2 (Lakewide Management), 7 (Habitat and Species), 9 (Climate Change), and 10 (Science). Enhanced monitoring will support nutrient reduction plans and adaptive management solutions for reducing nutrient loads.

2.2.2. Great Lakes Interagency Task Force and Great Lakes Restoration Initiative

Created by a May 2004 Executive Order, and chaired by USEPA, the Great Lakes Interagency Task Force (IATF) convenes 11 U.S. Government cabinet and Federal agency heads to coordinate the restoration of the Great Lakes. The IATF manages the development of consistent Federal policies, strategies, projects, and priorities pertaining to the restoration and protection of the Great Lakes. The Great Lakes Regional Working Group (RWG), composed of administrators and directors of regional offices, supports the IATF. Since 2009, the IATF has overseen the implementation of the Great Lakes Restoration Initiative (GLRI) and the development of comprehensive multi-year Action Plans that identify goals, objectives, measurable ecological targets, and specific actions for five GLRI focus areas. The Federal government has allocated significant expenditures since 2010 for a wide array of projects aimed at reducing nutrient- and sediment-loading into the Great Lakes, including broader restoration goals beyond HABs and hypoxia, thereby directly addressing a driver of HABs and hypoxia. As an example, in response to the 2014 drinking water do not use/do not boil advisory in Toledo, Ohio, Federal and state agencies quickly received nearly $12 million in GLRI funds for projects intended to reduce and monitor HABs in western Lake Erie.

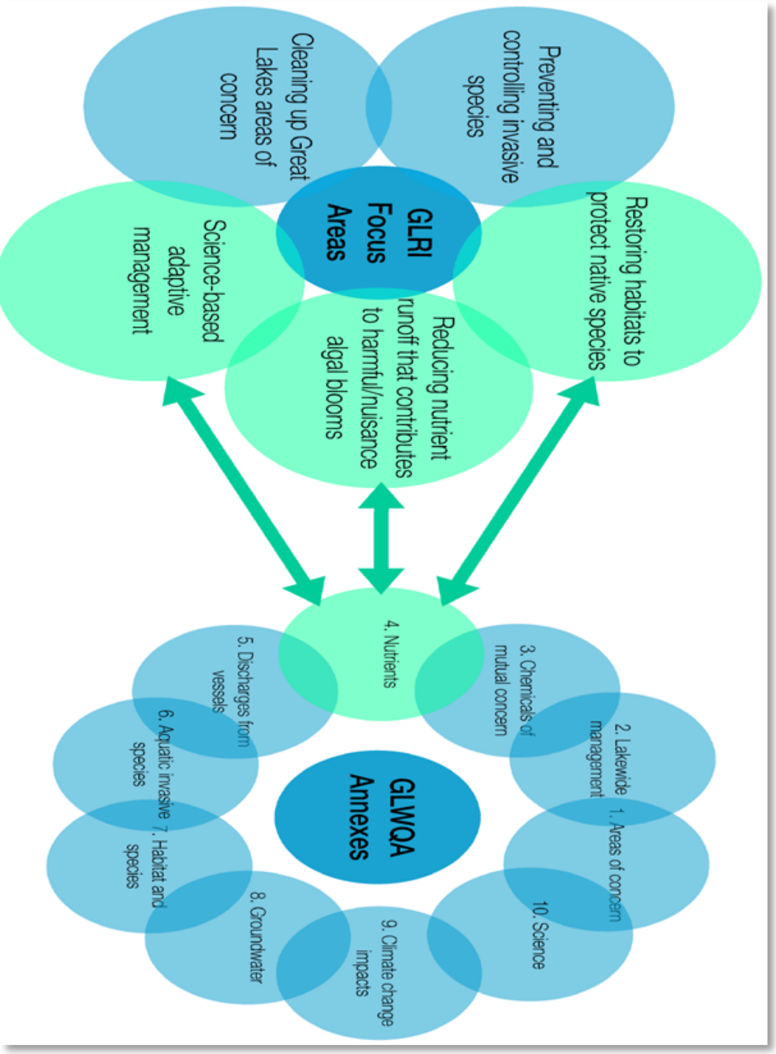

Figure 8. GLRI and GLWQA are coordinated domestic and binational efforts designed to protect and restore the Great Lakes. GLRI science enables the attainment of GLWQA goals. As it pertains to HABs and hypoxia, funding and results from GLRI Focus Area 3: "Reducing Nutrient Runoff that Contributes to Harmful/Nuisance Algal Blooms", Focus Area 4: "Habitats and Species", and Focus Area 5: "Science-based Adaptive Management", all support work in GLWQA's Nutrient Annex (4), which is charged in part with developing a nutrient reduction strategy to help mitigate HABs and hypoxia in the Great Lakes. Attainment of GLWQA Annex 4 targets also will contribute to GLRI goals.

GLRI has five focus areas (Figure 8): Toxic Substances and Areas of Concern, Invasive Species, Nonpoint Source Pollution Impacts on Nearshore Health, Habitat and Species, and Foundations for Future Restoration Actions. The GLRI targets high-priority watersheds and receiving waters that have high potential or known risk for experiencing HABs and/or hypoxia events, including the Fox River-Green Bay, Saginaw River-Saginaw Bay, and Maumee River-western Lake Erie. The programs also provide funding for nutrient-abatement projects in other high-concern areas.

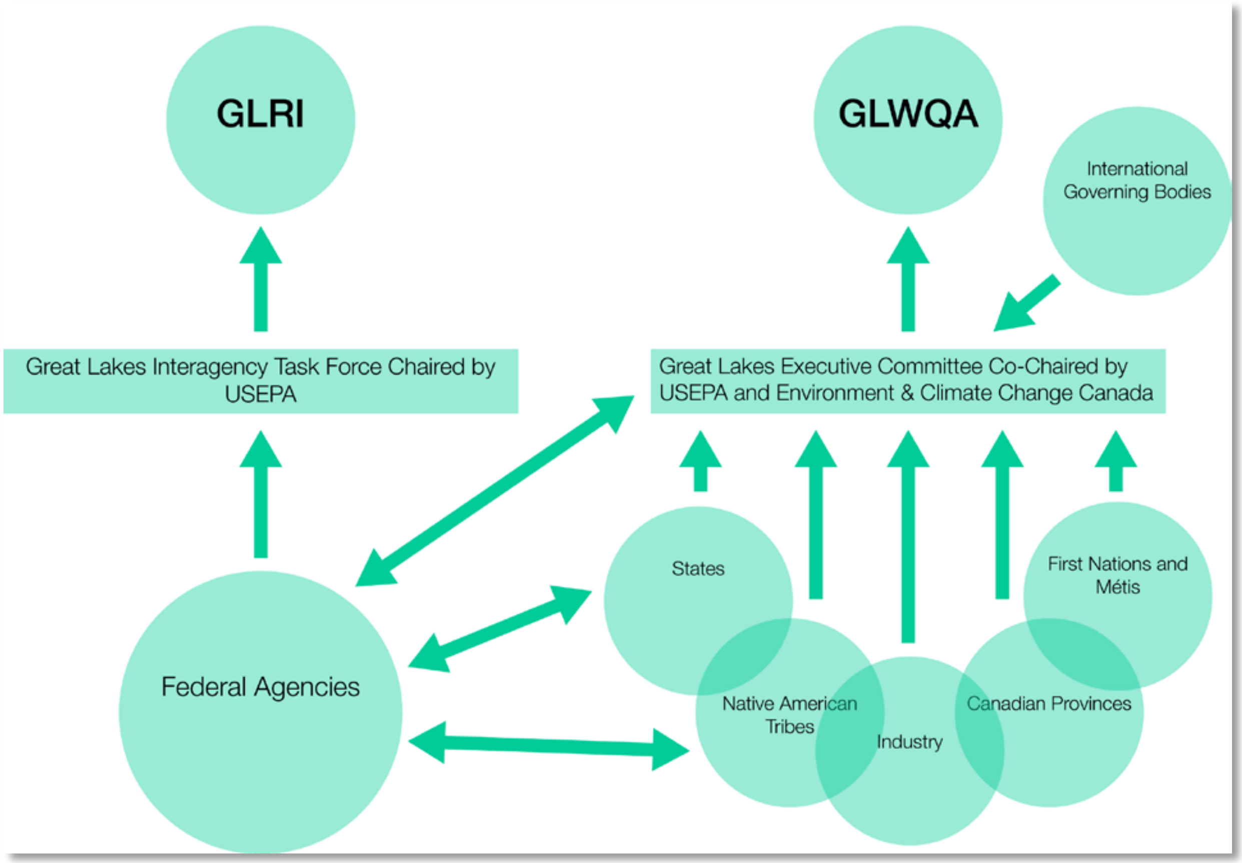

Figure 9. This chart shows the complex relationships between GLRI and GLWQA, and how they interact with stakeholders. Though the GLRI and GLWQA function independently, there are crossovers between the member bodies (Federal agencies), as well as the intent of each organization. The GLRI is not a part of the GLWQA governance structure, but it is a tool that provides information used to implement the annexes composing the GLWQA.

In partnership with NRCS, the Environmental Quality Incentives Program (EQIP) and Conservation Technical Assistance Program (CTA) deliver GLRI funds. EQIP is a voluntary conservation program that provides financial and technical assistance to agricultural producers to plan and implement conservation practices that improve soil, water, plant, animal, air, and related natural resources on agricultural land and non-industrial private forestland. CTA supports comprehensive conservation planning and innovative outreach efforts in the region. NRCS addresses some of the key strategies and management actions for reducing HABs and hypoxia, targeting GLRI Priority Watersheds in the Great Lakes basin; and any Phosphorous Priority Watersheds that are within those, including implementing nutrient management plans, controlled drainage systems, livestock waste-management facilities and related practices reduced or no-tillage practices, and planting cover crops, among other prevention strategies (GLRI, 2014; Francesconi et al., 2014). NRCS demonstrates and supports on-farm innovative, new practices, such as blind inlets, phosphorous removal structures, and two-stage ditches, for other producers to see and learn of the benefits. Demonstration farms include field-scale water-quality monitoring by USGS and USDA ARS to document the effects of the conservation practices and to provide producers with more local results on water quality and soil health benefits, and to support conservation adoption. Additionally, innovative partnership efforts, such as the Great Lakes Commission-led Fox River Phosphorous Trading Program, recently achieved the first trade involving an agricultural producer.

2.2.3. The Farm Bill

Since 2008, $371.5 million in funding provided through the Food, Conservation, and Energy Act of 2008 (P.L. 110-246; “2008 Farm Bill”), and the Agricultural Act of 2014 (P.L. 113-79; “2014 Farm Bill”), has supported conservation efforts on over 2.5 million acres of private land throughout the Great Lakes region to help address nutrient and sediment loading resource concerns. The 2014 Farm Bill, passed in February 2014, retained and expanded many existing programs designed to reduce nutrient and sediment loads into the Great Lakes basin. A new, major program authorized under this legislation is the Regional Conservation Partnership Program (RCPP), which encourages public-private partnerships in order to increase the conservation and sustainable use of soil, water, wildlife, and related natural resources. Former Secretary of Agriculture Tom Vilsack designated the Great Lakes region as a Critical Conservation Area for RCPP, providing more conservation funding (nearly 35 percent of the program) to new or existing partnerships in the region, including in the western basin of Lake Erie and Saginaw Bay. The RCPP’s collaborative approach leverages tools, technologies, and technical assistance for agricultural producers to improve nutrient and sediment management on agricultural land. For example, the Tri-State Western Lake Erie Basin Phosphorus Reduction Initiative rallies together more than 40 partners to spur voluntary conservation practices aimed at reducing phosphorus losses. NRCS dedicated $17.5 million to this major project, which other groups matched by $36 million. Saginaw Bay RCPP project is another major conservation effort based on science that is new to the region and supports targeted conservation and outcome assessments.

In 2016, NRCS announced a new 3-year “Western Lake Erie Basin Initiative” to accelerate conservation assistance delivery to agricultural producers in Indiana, Michigan, and Ohio. Along with the aforementioned projected $36 million in funds, this will bring an additional $41 million to the region, leading to $77 million in financial assistance from 2016-2018 available to support conservation on private agricultural land in the western Lake Erie basin (USDA, 2016b). The initiative’s four elements are to avoid excess nutrient application, control nutrient and sediment movement, trap nutrient and sediment losses and manage hydrological pathways to reduce nutrient and sediment losses. NRCS prioritizes financial assistance on highly vulnerable soils, particularly in areas draining directly into Lake Erie tributaries.

2.2.4. Other Federally-Led Efforts

Related to some of the objectives laid out in the 2014 Farm Bill, the Federal government established a number of challenges and prizes that seek solutions for affordable management and monitoring tools. The Nutrient Water Sensor Challenge, implemented by the Alliance for Coastal Technologies with sponsorship from NOAA and USEPA, provides funding to develop new, affordable, real-time nitrogen and phosphorus sensors. This challenge ultimately intends to develop and deploy sensors that cost less than $5,000 to purchase; are accurate over commonly-observed concentration ranges; are easy to use in maintenance-free, autonomous, remote, three-month deployments; and can be commercially-available by 2017. The George Barley Water Prize, sponsored by the Everglades Foundation, provides funding to identify cost-effective, innovative solutions to remove excess phosphorus contamination from freshwater bodies and to produce high added-value by-products. The USEPA-led Nutrient Recycling Challenge supports creating methods to recycle nutrients from livestock manure to generate products with environmental and economic benefits that farmers can use and sell. The Visualizing Nutrients Challenge, sponsored by USGS, USEPA, and Blue Legacy International, led to the development of inventive ways to organize and analyze existing data on nutrient levels in water. The Tulane Nutrient Reduction Challenge will develop innovative, in-field solutions that will maintain crop productivity and economics, while reducing nutrient run-off.

The Clean Water Act (P.L. 107-303; "CWA") establishes the legal authority and basic structure for regulating pollutant discharge into United States waters, including the Great Lakes, and for protecting and regulating surface water quality standards. The CWA provides funding to states and communities to help them meet their clean water infrastructure needs, and it protects valuable wetlands and other aquatic habitats through a permitting process that ensures development and other activities are conducted in an environmentally-sound manner. The CWA prohibits discharge of pollutants via point sources unless authorized by National Pollutant Discharge Elimination System Permits (NPDES). While the CWA does not require nonpoint sources to obtain permits, it encourages states through funding and technical assistance to address the effect of nonpoint sources of pollution on water quality.

It also requires states and authorized tribes, with USEPA oversight, to establish water quality goals that include designated water uses (e.g., support of aquatic life, support of recreation), as well as water quality criteria to protect these uses. Groups then use these standards to determine which waters must be cleaned up, how much pollution can be discharged, and what is needed for protection. Numeric nutrient criteria identify ambient levels of nitrogen and phosphorus that, if met, ensure the protection of a waterbody's designated uses. The criteria can serve as benchmark values when conducting monitoring of a waterbody to assess whether it is attaining its designated uses; facilitating the formulation of nitrogen and phosphorus limits in NPDES discharge permits; and simplifying development of total maximum daily loads (TMDLs) for restoring waters not attaining their designated uses (i.e., impaired waters).

The Beaches Environmental Assessment and Coastal Health Act (P.L. 106-284; "BEACH Act") is an amendment to the CWA, designed to reduce the risk of disease to users of the nation's coastal recreation waters. The BEACH Act authorizes the USEPA to award program development and implementation grants to eligible states, territories, tribes, and local governments to support microbiological testing and monitoring of coastal recreational waters, including the Great Lakes and waters adjacent to beaches or similar points of access used by the public. BEACH Act grants also provide support for developing and implementing programs to notify the public of the potential for exposure to disease-causing microorganisms in coastal recreation waters. One source of these pathogens may be rotting HABs biomass, which can produce high bacteria counts. Furthermore, the act authorizes USEPA to provide technical assistance to states and local governments for assessing and monitoring floatable materials.[4]

One of the requirements of BEACH Act grantees is to submit beach data to USEPA annually, and for USEPA to maintain state beach data and make it publicly available. To meet this requirement, USEPA developed the Beach Advisory and Closing On-line Notification (BEACON) system to house the beach data (https://watersgeo.epa.gov/beacon2/). Beginning with the 2016 beach season reporting, beach management entities now must list sources of contamination causing beach advisories and closings, including algae.

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[4] The term "floatable material" means any foreign matter that may float or remain suspended in the water column. This includes plastic, aluminum cans, wood products, bottles, and paper products (BEACH Act, 2000).

Former President Obama signed the Drinking Water Protection Act (P.L. 114-45) into law on August 7, 2015, effectively amending the Safe Water Drinking Act (P.L. 93-523) to provide additional protection to the public against cyanobacterial toxins. The Drinking Water Protection Act mandates that USEPA:

- Develop steps and timelines to assess human health effects from drinking water contaminated with algal toxins,
- Develop and maintain a list of algal toxins that may have adverse human health impacts,
- Determine whether to publish health advisories for those listed toxins and publish subsequent health advisories,
- Provide bloom treatment options and analytical and monitoring approaches,
- Summarize the causes of harmful algal blooms,
- Recommend source water protection activities to reduce blooms,
- Enter into cooperative agreements and provide technical assistance to affected states and public water systems,
- Identify any information gaps, and
- Publish completed and ongoing work from all Federal agencies on public health concerns related to harmful algal blooms affecting drinking water.

USEPA submitted the Algal Toxin Risk Assessment and Management Strategic Plan for Drinking Water to Congress in November 2015. USEPA has published drinking water health advisories for microcystins and cylindrospermopsin, released recommendations for public water systems to manage cyanotoxin risks including treatment options, and released analysis and treatment methods for multiple cyanotoxins. The agency currently is working on recreational water advisories.

Stakeholders and Federal Agencies Respond to HABs and Hypoxia:
Great Lakes HABs Collaboratory

Reaching the nutrient targets recommended by GLQWA Annex 4 requires coordination among researchers to help select conservation practice strategies, as well as to monitor progress. The Great Lakes HABs Collaboratory (collaboration + laboratory) is a collaboration between the Great Lakes Commission and the USGS-Great Lakes Science Center to promote HABs-related information-sharing among scientists and decision-makers. Participants include academics, state agencies, Federal employees, and nonprofits.

2.3. Conservation Practice and Social Planning, Implementation, and Efficiency to Reduce the Severity of HABs and Hypoxia

While there is no single solution for addressing HABs and hypoxia, researchers have found that combining management strategies is effective in limiting the severity of these events. This section discusses a number of agricultural and non-agricultural programs and regional conservation practices used to reduce runoff and nutrient inputs, address water quality, and overall improve the efficiency of communities' water-management facilities.

2.3.1. Agriculture-Related Practices

Research shows that specific agricultural conservation practices, including nutrient management, using no-till farming to prevent soil erosion, and planting cover crops, among other methods, can reduce phosphorus and nitrogen runoff from farm fields (Richards et al., 2009; USDA, 2011; Osmond et al., 2012a; Francesconi et al., 2014; Tomer et al., 2014; Her et al., 2016; Keitzer et al., 2016; Scavia et al., 2016; USDA, 2016a). For example, one such study showed that no-till farming practices reduced losses of all water-quality pollutants except DRP (Smith et al., 2015a). It should be noted that no-till can, in some cases, increase infiltration and leaching of nutrients to tile drains or shallow water tables (Williams et al., 2016). USDA NRCS CEAP assessments have found that it is important to utilize systems of conservation practices to fully treat conservation concerns and address nutrient transport in various hydrologic pathways (Osmond et al., 2012a; Smith et al., 2015a; USDA 2016a). Therefore, NRCS recommends and focuses local conservation planning on determining if conservation practices systems are needed to fully treat conservation concerns. Conservation programs often prioritize use of systems of conservation practices, when appropriate, in application screening and ranking for this reason. Recent studies have shown successes of specific conservation practices in reducing nutrient runoff. Other studies show that an innovative conservation practice called a "blind inlet" provides greater filtration of surface water from potholes (closed depressions on agricultural land), decreasing losses of total phosphorus, DRP, and total suspended sediment by significant amounts (Smith and Livingston, 2013; Feyereisen et al., 2015). In 2012, EQIP established the blind inlet as a modification of a conservation practice standard.

Image 9. Construction of a blind inlet. Septic tiles are placed on top of a layer of coarse limestone gravel, covered in a second layer of gravel, encased in landscape fabric, and backfilled with coarse soil to facilitate infiltration. (Credit: USDA).

Researchers and managers need to consider nutrient transport pathways in effectively treating sources. Agricultural infrastructures may influence the implementation of conservation practices. For instance, while only less than 2 percent of applied phosphorous is lost in drainage (Christianson et al. 2016), drainage tile networks contribute approximately 50 percent or more of DRP that is lost from farm fields into nearby rivers and streams (King et al., 2015a; Smith et al., 2015b). Environmental factors may disproportionately influence the effectiveness of conservation practices, such as increased water flow over the soil surface during the winter thaw (Van Esbroeck et al., 2016). Incorporating this type of knowledge into conservation practice plans is important at a variety of spatial scales: for instance, small watershed information is, spatially, more closely linked to nutrient management and thus more informative for prevention.

Researchers need additional information for other conservation practices used throughout the Great Lakes region that are susceptible to HABs and hypoxia, and that may have different soil types (Calhoun et al., 2002; USDA, 2016a) and therefore have different nutrient-leaching risk-levels (Dayton et al., 2014) and nutrient run-off risk levels. Animal agriculture in the United States portion of the Great Lakes includes high-density operations in Northeast Indiana, Northwest Ohio, and the Grand River watershed that empties into Lake Michigan. It is important to understand the relative contribution of animal agriculture, especially manure handling practices, to the nutrients that drive Great Lakes HABs and hypoxia.

States also have an important role to play in managing nutrient inputs to water sources by working with homeowners and businesses to adjust fertilizer application and yard maintenance practices. Commercially-available fertilizers contain phosphorus and nitrates, in ratios that are not always a match for the soils on which they are applied, contributing to nonpoint source pollution into the Great Lakes through runoff or leaching into the water column. Recognizing this, many Great Lakes states have policies in place that limit or control the use of phosphorus or nitrogen in retail fertilizers. Michigan, for instance, banned phosphorus use on most residential and commercial lawns (SOM, 2010). Pennsylvania has similar policies in place, including one for retail fertilizers that, among other things, restricts application on turf, which largely bans the use of phosphorus, and limits the nitrogen content percentage (COP, 2015). In May 2014, Ohio Governor John R. Kasich signed into law Senate Bill 150, requiring fertilizer applicators to undergo education and certification by the Ohio Department of Agriculture (ODA); encouraging agricultural producers to adopt nutrient management plans; and allowing ODA to better track the sales and distribution of fertilizer. In April 2015, Governor Kasich signed Senate Bill 1, which included restrictions on fertilizer and manure application on frozen, snow-covered, or saturated ground in the western Lake Erie basin watershed, among other measures aimed at improving Lake Erie water quality.

Recent papers highlight local-scale information gaps with regard to best conservation practice option(s) for various locations and soil types and their effects on nutrient loss into nearby water bodies. They account for different spatial scales, and among different seasonal or interannual environmental conditions (Kröger et al., 2013; Cousino et al., 2015). More local-scale, in-stream nutrient source tracking methodologies and information about appropriate sampling design will help characterize the efficacy of individual conservation practices, strategic timing of fertilizer application, and creation of riparian buffer zones, on reducing nutrient output into nearby water bodies, including all of the Great Lakes (Bentrup, 2008; Vidon et al., 2010; USDA, 2011; Syswerda et al., 2012; Smith et al., 2015a, b; USDA, 2016b). Decision-makers can use this information to make targeted conservation actions.

Strategic selection of watersheds to monitor, and long-term, regional coordination of monitoring efforts, are essential for the most effective conservation practice implementation. Regional monitoring should ensure consistency in variables measured and method of sampling, allowing for more effective data aggregation. Aggregated data sets can provide comprehensive information about HABs and hypoxia, in effect improving ecological understanding, as well as a greater capacity to generate models and predictions that are more robust. Management efforts improve with easily aggregated and shared data. Those conducting monitoring over the long-term must also ensure temporal consistency of datasets by calibrating procedures as methodologies or data collection techniques change (Meals et al., 2012).

Lag times and legacy loads are characteristics of land that contribute to the time it takes for agricultural conservation practices to provide measureable benefits to the environment (Meals et al., 2012). Lag-times between the establishment of mitigating conservation practices and measurable impacts on water quality are well documented. Principle components of lag-time that need clarification include the time needed for an adopted practice to produce an intended impact, for that impact to reach the water body for which it was intended, and the time for the water body to respond in a measureable way (Meals et al. 2010). Understanding lag-times is important when planning conservation practice implementation, in interpreting water quality monitoring results, and in managing stakeholder expectations.

Image 10. Examples of Variable Rate Irrigation Technology (left) and precision farming (right). (Credit: USDA/ARS.)

Legacy nutrients, or those that accumulate in the water or soils within a field and also within a stream bank or bed load, or even in lake sediments, can play a role in HAB and hypoxia development (Sharpley et al. 2013). Legacy load impacts on sediment and nutrient dynamics must be considered in the evaluation of the cumulative effects of conservation practices, spatially and temporally, and be given consideration in evaluation of conservation treatment options to ensure successful application of those strategies (Meals et al., 2010; Osmond et al., 2012b; Sharpley et al. 2013). When sediment and nutrients settle out of flowing water, they become a part of "legacy" sediment and nutrients. Resuspension and redistribution may occur days, years, or decades later, contributing to a lag-time before conservation benefits are discernable (Kleinman et al., 2011; Sharpley et al., 2013; Chen et al., 2014). In several cases, stream banks and beds are frequently contributing 50 percent or more of the sediment load in streams, for example, so assessment of pollutant sources is valuable information for effectively targeting conservation practices if load reduction is the goal (Wilson et al., 2014b; Bertani et al., 2016). Edge-of-field or in-stream monitoring measurements taken today integrate current management and the legacy of prior management actions, potentially masking benefits of conservation practices on the ground today. Stream gauge data include a mixture of nutrients of different "ages" of application (e.g., "live" and "legacy" loads) (Meals et al., 2010).

Precision farming practices provide previously unavailable opportunities to improve nutrient reduction and soil loss. NRCS (USDA, 2016a) found that agricultural producers farmed the vast majority of cropland acres in the western Lake Erie basin under conservation practices. The model simulations used to derive impact estimates of these practices at the field scale in CEAP-cropland assessments do not account for variability in soil type within a field, however, which affects the simulated outcome of the management measures. However, that does not mean that farmers are unaware of and manage for soil variability; this complexity highlights the difficulty of modeling systems, and in basing management suggestions on models simulating at large scales that do not capture soil variabilities within fields. Adopting comprehensive conservation plans and improved precision-farming techniques are necessary to enable farmers to treat the mosaic of soils in their fields, e.g. treating leaching-prone soils with leaching-specific practices, or treating soils vulnerable to erosion with appropriate erosion-control practices (USDA, 2016a). As of 2012, 71 percent of western Lake Erie basin farmers had a soil test in the last five years as of 2012 (USDA, 2016a), which help to determine nutrient input needs and develop a conservation plan.

Advanced technologies using GPS interfaces and precision soil mapping enable farmers to tailor nutrient application and conservation management to particular soils, improving production efficiencies while mitigating environmental impacts. GPS mapping of soil properties increased from being in use on 8 percent of western Lake Erie basin cropland acres in 2003-2006, to being in use on 36 percent of cropland acres in 2012. Variable rate irrigation systems can tailor water applications to rates that the different soils in an individual field can accept without runoff and deep percolation losses. Variable Rate Technologies (VRTs), which allow farmers to integrate GPS technologies with farming equipment such that they can tailor nutrient applications to the needs of various portions of their fields based on yield and soil maps, increased from being in use on 4 percent to 14 percent cropland acres between 2003-2006 and 2012. Clearly, interest in these technologies is growing, but there is room for improvement.

2.3.2. Non-Agricultural Practices

Conservation and nutrient management practices extend beyond reducing runoff from agricultural sources. This section discusses a few of the many types of actions that communities and managers can take to reduce nutrients, including wastewater and storm water management, the use of forests and vegetation as buffers, and addressing the role of air pollutants.

There are many methods of managing nutrient inputs related to wastewater. Septic tanks are part of the infrastructure of rural areas of the Great Lakes region and commonly leak effluent as they age. Discharge from poorly maintained septic tanks has the potential to contribute to water quality problems, despite reductions in nutrient inputs from wastewater treatment plants following the enactment of the Clean Water Act (CWA) (IJC, 2014). Advanced septic systems are now available, which provide more effective nutrient removal. Additional information about the age and location of each septic system can help managers prioritize and replace problem systems, leading to better nutrient management for the Great Lakes and Great Lakes tributaries.

CWA-authorized NPDES permits regulate nutrient discharges in storm water as point source pollution. During storms and in cities with combined sewer overflow (CSO), where the sewage collection system connects to the storm-water collection system, increased water volume can cause untreated sewage water and nutrients to enter nearby water bodies that feed into the Great Lakes. The USEPA issued the CSO Control Policy of April 19, 1994, to ensure that all levels of management, permitting, and monitoring bodies work together to protect public health and environmental objectives by maintaining the integrity of storm water containment systems, and developing a long-term plan for maintaining CSOs (USEPA, 2016b). Similarly, wastewater treatment facilities can remove nitrogen and phosphorus from waste through a number of methods, including through adding chemicals to solidified matter (USEPA, 2015g). The Metropolitan Water Reclamation District of Greater Chicago instituted the Tunnel and Reservoir Plan System (TARP), the intent of which is to transmit CSOs via tunnels into storage reservoirs until after a storm. At that point, water in the reservoirs is pumped to a water treatment plant, where it is treated (Kay, 2016). Despite these management options, however, researchers need exact geographic information about the location of storm-water nutrient sources to ascertain if additional strategies are necessary for these locations, to help mitigate storm water-related nutrient contributions. Additional monitoring can provide this data.

Reforestation and prairie filter strips are other non-agricultural practices in watersheds used to reduce nutrient inputs that promote HABs and hypoxia. Prairie filter strips are effective in reducing runoff from cropland by using native prairie plant species (e.g., grasses and other species with long root systems) to create a natural buffer and filter between the field and a waterway (Zhou et al., 2014). Similarly, studies have shown that forested areas and reforestation are useful in reducing nitrogen runoff, particularly in agricultural areas (Bastrup-Birk and Gundersen, 2004; Hansen et al., 2007). Forested areas slow down storm water runoff, which can help to reduce nutrient removal and hypoxia-promoting conditions (Paul and Meyer, 2001; Mallin et al., 2006). Mayer et al. (2007) found that wide buffers are more effective at removing nitrogen, as are buffers made of plants that tend to provide more vegetative cover (e.g., low trees, bushes, and ground-cover plants) (Mayer et al., 2007). Lowrance (1998) states that this conservation method is a particular success, given the ease in implementing the practice and its economic benefits associated with limiting runoff (Lowrance, 1998). Researchers also have discovered that deforestation can cause changes in the distribution of fish populations. Some fish species that are relatively tolerant to hypoxia are more likely to exist in deforested areas than in forested places. As fish populations move between habitats, how fish species feed and what they feed upon may lead to potential shifts in the food web (Teresa et al., 2015).

Targeted wetland restoration efforts can play an important role in nutrient reduction and improvement in water-quality. Restoring riparian wetlands provides numerous benefits, including water storage and filtration. Floodplain wetlands allow floodwaters to spread out and slow down, while the vegetation within floodplain wetlands help filter nutrients and provide habitat for fish and wildlife. Storm water wetlands, in particular, remove nutrients by dispersing the nutrients (OH EPA, 2013). States use wetland creation and restoration as a nutrient reduction strategy, specifically. For instance, the 2013 Ohio Nutrient Reduction Strategy (OH EPA, 2013) lists wetland creation and restoration as two of several methods for improving drainage-water management. This type of conservation practice can help to reduce the rate and amount of runoff, while also increasing the treatment of field runoff. While wetland drainage may decrease water storage and treatment capacity of a landscape, it also helps to improve water quality by storing and filtering water, while also providing benefits to fish and wildlife. Furthermore, wetlands' natural beauty can have positive aesthetic and economic benefits to communities. USDA also offers incentive programs for wetland restoration and creation programs (OH EPA, 2013).

Researchers often consider watershed sources of nutrient runoff the primary drivers of HAB and hypoxic events in the Great Lakes. However, there also is evidence that atmospheric deposition of nutrients such as air pollutants (nitrogen and phosphorus) may have an impact (McDonald et al., 2010; Brown et al., 2011; Han et al., 2011; USEPA SAB, 2011; Dolan and Chapra, 2012; NADP, 2015; Rowe et al., 2014). A more local-scale understanding of both atmospheric phosphorus and nitrogen loads to the Great Lakes would help to better elucidate any connection with HABs and hypoxia.

2.4. Planning for Economic and Social Impacts of HABs and Hypoxia within Great Lakes Communities

Although economic impact assessments to date are limited in scope, researchers estimate that HABs and hypoxia-related impacts on Great Lakes communities amount to millions of dollars annually (Bingham et al., 2015; USEPA, 2015h). This includes losses in income from commercial fishing, recreation, and tourism; public health costs due to human and animal illness; expenses related to monitoring and management; and drinking water treatment (Bingham et al., 2015). More specifically, approximations of loss in property value to the western Lake Erie shoreline during the 2011 and 2014 HAB events were around $10 million, though impacts potentially were as high as $242.1 million, depending on how researchers calculated valuations (Bingham et al., 2015). With estimated tourism dollars during any given year in Ohio ranging between $66 million to $305 million (2015 dollars), and in Michigan around $25 million (Bingham et al., 2015), there is a clear potential for substantial economic losses, even if a small percentage of businesses are affected for part of the year. While the costs of hypoxia have not been quantified specifically, resultant fish kills are common knowledge. Individuals and communities at all levels clearly have a lot to lose financially, as illustrated in the box below. Understanding economic impacts could help a community ensure citizens have sufficient resources to overcome the impacts of a bloom or hypoxic event.

Water-Dependent Industries in the Great Lakes Feel the Financial Impacts of HABs

Few industries may be as aware of potential impacts by a HAB as those that rely on water from the Great Lakes. While the exact economic impacts are only estimates, numerous examples and studies show the potential for industries to lose millions of dollars during HAB events. One example of this is the over 1,800 breweries that are found throughout the Great Lakes states. These businesses are in a unique position, relying almost equally upon water and agricultural resources to make their product. Many of the Great Lakes breweries get the water for their beer from the lakes themselves, making this industry highly vulnerable to water quality issues. A single toxic HAB event affecting drinking water intakes around the region could cause breweries to lose millions of dollars over a short amount of time, through canceled or delayed sales, spoiled product, or other situations. Similarly, tour boat operators in the Great Lakes have noticed decreased profits due directly to HABs (Carmichael and Boyer, 2016; Maher and McWhirter, 2016). HABs may have unpleasant odors or can clog motors, making it difficult for operators to attract customers or be able to operate.

Image 11. The Great Lakes are inviting to day-trippers, vacationers, boaters, and fishermen, bringing in significant revenue to the region. This image shows beachgoers taking advantage of a beautiful summer day in Grand Haven, MI, on Lake Michigan (Photo credit: Rodney E. Rouwhorst/Travel Michigan and courtesy of NOAA/OCM).

Feedback that the IWG-HABHRCA received from stakeholders indicates that many individuals in the Great Lakes region and around the country are unaware of potential effects of HABs and hypoxia. For instance, one stakeholder from Wisconsin mentioned that while her community is aware of the hypoxic dead zone in Green Bay, they are unconcerned with annual algal blooms that their part of Lake Michigan experiences. She remarked that she often sees her neighbors boating, fishing, playing, and even bathing in the water, despite the visible presence of a bloom. However, there is limited published research that demonstrates how individuals perceive human and animal health, economic, and social risks, as well as how HABs or hypoxia affect communities and general perception of water safety after events (McCarty et al., 2016).

Social science helps to address and evaluate community and regional preparedness for HAB and hypoxia events. For instance, studying regional tourism or water-dependent economies can ultimately help to create mitigation measures, such as emergency funds or water supplies. It also helps to demonstrate collective needs. Social science research is essential for bolstering the need for policies and incentives for implementing conservation practices. For example, communities may have well-established traditions, such as an annual water festival, or attitudes regarding how to farm land. They may value resources differently; are willing to take different types of risks, such as not saving money in case of a HAB event; or may value conservation practices differently (Wilson et al., 2014c; Daloğlu et al., 2014; Burnett et al., 2015). Social science research provides place-based information to agricultural producers that can help them make the most effective decisions, and demonstrates the economic importance of preparedness. Appendix 4 lays out the core questions that social scientists and managers need to examine and answer, in order to assess individual, community, or regional preparedness.

Social science disciplines provide decision-makers with important information for contributing to community knowledge about HABS and hypoxia, creating policies and mitigating economic and socio-cultural effects on communities. Understanding social and economic behavior and impacts due to HABs and hypoxia is critical to prioritizing research and adaptive management strategies. There currently is limited research that evaluates how HABs and hypoxia affect communities' traditions, lifestyles, planning, and policy decision-making. Additionally, ecosystem valuation studies are important; examining the financial, social, and aesthetic benefits ecosystems bring to a location; how communities emotionally value an ecosystem or conservation of the ecosystem in question; and the actual cost that individuals are willing to pay for conservation measures.

Cost-benefit analyses are an important part of the conservation process. Currently, some information exists on the ecological (USDA, 2011) and economic benefits (Stonehouse, 1999; Forster, 2000; Forster et al., 2000; Forster, 2002; Forster and Rausch, 2002) of selected conservation practices. Researchers must investigate the ecological and economic costs and benefits of a broader range of conservation practices, adjusting for different locations and environmental conditions (Nakao and Sohngen, 2000; Napier, 2011). In particular, community and public health leaders need information at smaller-watershed scales to help address more localized HAB and hypoxia problems. While researchers are aware of immediate impacts on communities - including fishing, tourism, recreation, public health, local and state government, homeowners, and the public – they are uncertain of the true value of resources and costs of a HAB or hypoxia at local, state, tribal, and regional levels. Likewise, cost-benefit and economic analyses help agricultural producers, decision-makers, and other resource officials evaluate types of conservation or nutrient management practices (Stonehouse, 1999; Napier, 2011). Without this knowledge, it is difficult to demonstrate to communities the need to prepare, let alone how they need to prepare. With this type of information, practitioners can answer questions about risk assessment and establish priorities for future mitigation efforts. Economic research on HABs and hypoxia is necessary to understand the value of the water and related resources, and how this may vary with changes in HABs, hypoxia, or water levels.

HAB and hypoxia events, and event-response efforts, can be expensive. Bingham et al. (2015) estimated that a repeat of the 2014 toxin contamination of drinking water in Toledo, Ohio, would cost approximately $750,000 in related expenditures (e.g. monitoring and providing clean drinking water). However, the study showed also that overall economic impact would be significantly higher when considering all potential factors (e.g., loss of restaurant revenue, discarded foodstuffs in grocery stores, and shut-downs of food manufacturing factories). Low dissolved oxygen can impact corrosion control efforts in drinking water systems that have cold, acidic water, when hypoxic water is transported from bottom-waters to the surface by coastal upwellings[5] in the Great Lakes (Ruberg et al., 2008). This consequently leads to increased costs associated with drinking water purification.

One must also consider the costs of conservation, nutrient reduction, and HAB and hypoxia mitigation to the Federal, state, and local governments, and therefore to national taxpayers. In the late-1980s and into the 2000s, the Federal government paid millions of dollars to agricultural producers in the Maumee and Sandusky watersheds as nutrient reduction incentives, including approximately $143 million from 1987-1997 (Forster and Rausch, 2002). As discussed in Section 1.3, in 2016, NRCS invested $41 million in a three-year initiative to support the work of farmers in Ohio, Michigan, and Indiana, to improve water quality in the Western Lake Erie Basin. The investment helps farmers implement science-based conservation measures to reduce runoff from farms entering the region’s waterways.

Related to conservation costs, fish tend to aggregate on the very edge of hypoxic zones because those are the areas with the highest density of prey. Thus, slight changes in hypoxic zone extent and location could bias catch estimates in the stock assessments used by fishery managers. This could impact the Great Lakes fishing economy. Knowing where the fish are, and adequately accounting for their spatial variability in stock assessment models, can also help prevent overexploitation of economically and ecologically important fish species (Belore et al., 2014; Kraus et al., 2015). Additionally, as Figure 9 shows, hypoxic conditions can reduce the size of commercially important fish, and lead to losses in fishing revenue.

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[5] Upwelling is the process by which offshore currents draw away warm, less-dense surface water from along a shore, and cold, denser water brought up from the subsurface replaces the warmer water. Upwelling of offshore bottom-waters that are permanently depleted of oxygen can lead to hypoxia.

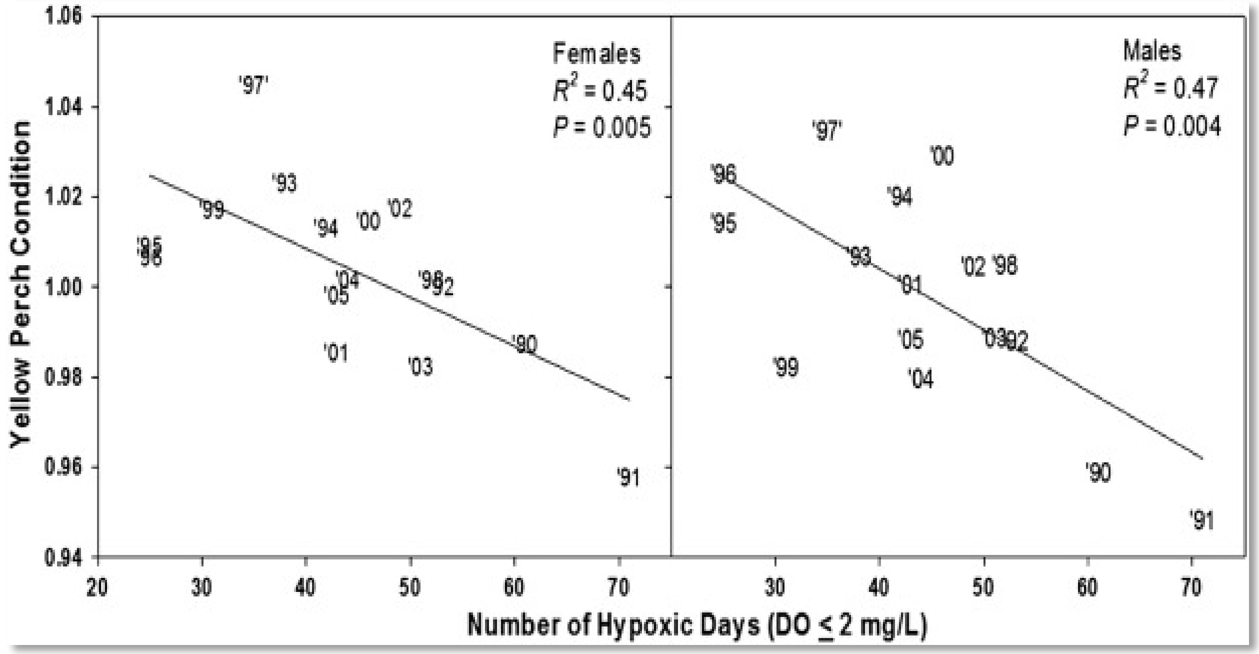

Figure 9. This graph shows how longer-duration hypoxic events in the central basin of Lake Erie can affect the mean relative weight of yellow perch, a fish species that supports a thriving tourist trade and forms the backbone of the Great Lakes fishing industry. The points on the graph represent a year. The number of days in which Lake Erie experienced hypoxic conditions correlates with the average weight of female and male yellow perch caught during those periods. As hypoxic conditions increase, perch size decreases (graph courtesy of Scavia et al., 2014).

2.5. Communication and Engagement Challenges

It is important for decision-makers to connect with the public and businesses that contribute to, and are affected by, HABs and hypoxia when creating and implementing management measures. Open conversation facilitates long-term engagement and education efforts involving a diverse stakeholder base that has different needs and expectations. Federal and state officials are able to demonstrate the importance and benefits of conservation practices. This more robust process allows people to contribute to decision-making in a way that sustains interest in implementing ongoing conservation practices, or so that citizens understand risks presented by HABs and hypoxia. For example, water utilities play a critical role in protecting human health by keeping their customers informed about the safety of their drinking water, while optimizing water treatment facilities to prepare for and address HAB and hypoxia events. Resource and utility managers may interface with researchers, officials, and the public, testing for the presence of HAB biomass or toxins, and monitoring for certain levels of toxicity in drinking water sources (CDC, 2016). Communicating with the public about a utility's preparedness for treating water during HAB events is likewise important for fostering confidence in the quality of their drinking water.

Beach, water resource, utility, and other types of managers and officials can consider the following questions to help with preparedness:

- Do we have the appropriate procedures and contact with community members, resource-users, and other stakeholders to alert them to issues/problems? Do we have communications materials (e.g., general information flyers or signage discussing impacts) that empower the public to understand the risks? Do we have a presence on social media, television, and/or radio that allow us to reach different audiences?
- Are messages from different sources consistent and coordinated?

- How can we convey information regarding toxicity of fish to humans during times when HABs historically occur?
- What are best ways to communicate what researchers know/do not know about HAB and hypoxia prevention, control, and mitigation through management actions?
- Are people, businesses, and healthcare facilities prepared for a HAB or hypoxia event, with alternative financial, socio-cultural, drinking water, recreation, and employment/revenue resources?
- How long before a bloom occurs should managers warn the public? What are effective and ineffective communication strategies during a tap water advisory (e.g., to avoid a potential public health scare)?
- Are we effectively communicating conservation practice successes to stakeholders and funders? What are the most effective ways to communicate or help managers start and continue effective use of conservation practices?
- Are expectations for the roles of various parties clear; and are expectations for conservation practices implementation clear? How prepared is the local drinking water utility for adjusting or optimizing their treatment facility to avoid contamination of drinking water, when faced with a HAB?
- Have we included local experts and community members in implementing conservation practices, and how might we improve?

Raising public awareness of HABs and hypoxia is a key component not only for addressing public health concerns, but also to make people aware of these events. Federal agencies have programs in place to address some aspects of this – notably, by increasing public health and communications efforts through webinars and public meetings, or by introducing information services like the National Park Service's Harmful Algal Blooms in National Parks website or CDC's Harmful Algal Bloom-Associated Illness website. These examples reach two sets of populations: those who are not already explicitly seeking out information about HABs but are interested in visiting national parks, and those who are interested in the health impacts caused by HAB events. Additionally, the IWG-HABHRCA heard from agencies from numerous Great Lakes states about how they try to message threats or concerns of an event. Some states rely on color-coding systems, posting colored signs at beaches or on their websites. Others use social media and hold public meetings. Ultimately, though, all levels of stakeholders agree that without consistent messaging methods, it is difficult to maximize the effectiveness of early warnings and prevention strategies.

3 – Research Recommendations and Action Strategy Opportunities

This section summarizes research needs and recommendations, along with an action strategy for addressing HABs (planktonic and benthic, and including *Cladophora*) and hypoxia in the Great Lakes. The Federal agencies that currently are conducting research on each topic are listed after each recommended action or need. It is important to note that these lists do not include several academic institutions, non-profit organizations and state agencies that also conduct research in these areas.

3.1. Research Needs

The following are the research needs identified throughout this report. The authors of this report list nutrient reduction efforts first, as the related recommendations are a primary mitigation necessity. Recommendations otherwise are in no particular order of priority.

Water and Nutrient Management Practices

- Determine the effectiveness of current HAB and hypoxia prevention strategies, including the efficacy of best management conservation and land-use practices for reducing watershed sources of nutrient inputs.
- Refine the methodologies and estimation procedures for tributary nutrient-loads with an emphasis on location, gauging streamflow based on nutrient sampling, and statistical uncertainty;
- Determine the relative effects of legacy sediment and nutrient loads, and lag-times, on HABs and hypoxia events, including from streams and tributary systems.
- Refine the atmospheric load methodologies for phosphorus and nitrogen with respect to mass budgets. Investigate the internal cycling of phosphorus and nitrogen in the Great Lakes and understand the role that legacy nutrients might play in bloom development or toxicity and how this nutrient source may impact bloom severity once external nutrient loads reach target levels.
- Look at the relative contributions by lake of septic systems, wastewater treatment plants, and CSOs to nutrient-loading in the lakes, relative to other major sources.
- Support research and outreach efforts on water management that results in methods that prevent nutrient movement off the landscape. For example, examine variable rate irrigation technology and management, including the development of decision support systems to guide applications.
- Develop control technologies to mitigate nitrogen and phosphorus movement in agricultural production systems and devise models to assess nitrogen and phosphorus life cycles in actively managed agricultural systems (USDA NIFA, NRCS, ARS).

Monitoring and Surveillance

- Conduct human and animal illness surveillance, and integrate health data with environmental monitoring data to better understand exposure risk, health outcomes, and inform mitigation efforts;
- Monitor the relation between TP and DRP loads, as well as HAB and hypoxia extent, onset, frequency, and duration, using this information to evaluate effectiveness of load reduction efforts and the lake response(s) over time;
- Determine specific roles of HAB and hypoxia drivers, including phosphorus and nitrogen, and their associated forms and dynamics. Determine the role of nutrient cycling and long-term versus short-term internal cycling;
- Continue to develop detection technologies, including genomic detection techniques, real-time sampling techniques; methods and techniques for in-place sensors for TP and DRP, in-stream and at edge-of-field; and satellite remote-sensing techniques;
- Expand monitoring to better understand benthic-sediment interactions for HABs and hypoxia within and between years, including studying the role of benthic HAB cells or cell-seeding. Use expanded monitoring to better understand the linkages between nutrient-release in the onset/timing, size, severity, and toxicity of blooms over time;
- Examine the influence of algal biomass, and winter and spring diatom blooms, on the extent and timing of hypoxic events;
- Assess legacy sediment and phosphorous loads in-stream and in-lake (internal loading, and how long this can sustain blooms even after external loads have been reduced), to better understand the relative sources and better inform more effective management actions; and
- Prioritize data from genetic and physiological experiments, and demonstrate any connections between ecological hot spots and human or animal sickness or death.

Modeling and Forecasting

- Develop, enhance, couple, and link models that help predict the development, intensification, and spread of a bloom's toxicity levels;
- Develop improved forecast models that integrate and identify relationships among nutrient concentration information, bloom timing, algal biomass, species composition, chlorophyll-*a*, pigments, algal growth, genomics, and toxicity with regard to hypoxic extent, duration, frequency and intensity;
- Integrate and link agricultural and watershed process-based models and in-lake water quality models for greater watershed-level understanding and forecasting. Use coupled models to begin to evaluate the impacts of land-use shifts, changing demographics and climate, and genetic and technological improvements in agricultural systems;
- Improve models of the timing, spatial movement, and intensity of low-oxygen events for drinking-water management;
- Refine models of hypoxia and fish populations interactions, including dynamics and behavior of fish, predators, and fishing practices;
- Compute whole-lake and basin/bay specific mass-budgets of phosphorus and nitrogen.
- Improve ecosystem models to assist in understanding the relationship between external and internal phosphorus loads and the occurrence of HABs and hypoxia;
- Expand HABs and hypoxia forecast modeling to Saginaw Bay and Green Bay, among other sites, as needed; and
- Improve coordinated management and data-sharing, and leverage non-Federal data sources for use in research and model verification:
    - Utilize existing data management and sharing capacity within the GLOS; and
    - Where appropriate, direct the adoption of data management standards and best practices.

Toxins and Toxicity

- Expand toxin monitoring throughout the Great Lakes, with specific emphasis on areas that are known to experience HABs, and potential or suspected regions where cyanobacteria are known to bloom;
- Determine the drivers of HAB toxin production;
- Expand research on the effects of toxins on humans, aquatic life, livestock, and wildlife, including clinical toxin test method development and/or training for state or clinical use; and
- Expand the analytic methods, detection limits, breakdown products (including those that occur naturally in the field, as well as during the treatment process), and range of cyanobacterial toxins.

Ecological and Fisheries Management

- Investigate how HABs and hypoxia affect Great Lakes fish populations and fisheries, including dynamics and behavior of fish, predators, and resource managers;
- Investigate how HABs and hypoxia affect Great Lakes breeding and migratory waterbirds;
- Expand research on nutrient loading, and toxicity to other affected areas of the Great Lakes, including Saginaw Bay and Green Bay;
- Develop models with biological endpoints to better inform conservation practice and land-management impacts on fish and other aquatic organisms, in both the lake and the tributaries;
- Conduct further research how invasive species in the Great Lakes affect bloom growth and toxicity and how invasive species respond to hypoxia;

- Investigate how nutrient-loading impacts the aquatic-plant community-structure, specifically ecosystem shifts from rooted plants to phytoplankton-driven systems;
- Investigate how the aquatic plant community structure can serve as a biological indicator, demonstrating the levels at which, and how at those levels, certain nutrient concentrations impact the ecosystem; and
- Investigate how dressenid mussels cause and exacerbate *Cladophora* bloom growth, including interactions with other drivers.

Climate Change and Extreme Weather Events

- Conduct further research on how factors related to climate change and extreme weather events may influence bloom growth and toxicity, as a consequence of variations, timing, and magnitude in precipitation, air temperature, water temperature, wave height, and water movement; and
- Examine how a changing climate and extreme weather events may impact efforts to achieve nutrient reduction targets across a variety of sectors, with consideration given to water management.

Drinking Water Treatment

- Understand chemical and physical reactions associated with cyanotoxins and common water treatment chemicals;
- Conduct further research on cyanobacteria cell reactions to common water treatment chemicals;
- Evaluate the potential consequences of cyanobacteria and cyanotoxin treatment techniques on the ability of a water treatment facility to comply with existing drinking water quality regulations;
- Evaluate short-term options for water treatment plants to adjust their existing treatment technologies and operational practices to respond to HABs, as well as collateral impacts on non-target plant and animal communities associated with the source-water body; and
- Understand source-water treatment options and how they impact drinking water treatment.

Social Science

- Conduct cost-benefit analyses to determine potential economic costs of algal blooms that can be compared to the costs of conservation practices;
- Conduct more studies on human health impacts of HABs and hypoxia, including drinking water, beach and recreational exposures and documented illnesses associated with HABs; and
- Further develop local and regional cost-benefit analyses and other models to determine impacts on social well-being and the community, and to inform policy and management options.
- A better understanding of what motivates farmers to adopt conservation systems – monetary and non-monetary factors – and that lead to more effective programs for achieving concentrations of effort necessary to meet water quality goals.

Engagement and Communication

- Develop preparedness plans, including rapid response, warning systems, and communication networks for public, management, and officials involved in response activities.

3.2. Recommended Actions

The following are the recommended actions for the Federal government and stakeholders. Please note that the actions related to nutrient reduction should be coordinated with State-led implementation plans, such as the forthcoming DAPs for Lake Erie and any future DAPs developed for other parts of the Great Lakes to address HABs and hypoxia (Section 2.2.1).

Water and Nutrient Management Practices

- Reduce nutrients and sediment from non-point sources within contributing basins and watersheds; and
- Continue and expand ongoing complementary programs that provide planning, knowledge dissemination, tools, and technical and financial assistance for nutrient and sediment pollution reduction and improved water management by:
    - Conducting additional, comprehensive, field-scale to watershed-scale agricultural conservation planning (Implement within 5 years). (USDA NRCS; and external partners);
    - Expanding efforts to integrate new and innovative approaches into farm implementation and conservation plans, including enhanced or precision nutrient management and nutrient-trapping conservation practices (Implement within 5 years). (USDA NRCS);
    - Conducting more effective outreach on the benefits of agricultural conservation practices, and facilitate and support producer-to-producer networks for information exchange, such as done at the demonstration farm networks in the Blanchard River Watershed in Ohio and the Lower Fox River Watershed in Wisconsin (Implement within 1-3 years). (USDA, USGS, NOAA, and external partners);
    - Using landscape prioritization tools and partnerships to identify the locations and designs for potential constructed/restored wetlands that maximize phosphorous reduction in priority watersheds. (USACE; USDA ARS, NRCS; USGS; and external partners);
    - Pursuing opportunities to construct demonstration wetlands, monitor wetland efficacy for nutrient and sediment reduction, and fully evaluate wetland performance, including the comparison of costs and benefits. (USACE, USGS, USFWS, EPA and external partners);
    - Evaluating stormwater best management practices and agricultural conservation practices for their efficacy in reducing land-derived nutrient pollution in the Great Lakes region; incorporate practice effects assessments, as necessary (Implement within 5 years). (USDA NRCS, ARS, NIFA; USGS; NOAA; EPA; USFWS; and external partners); and
    - Implementing green infrastructure in urban areas that experience significant impacts by stormwater runoff. Share knowledge and success stories regarding implemented green infrastructure to gain support from additional urban communities. (EPA).

Monitoring and Surveillance

- Improve understanding of HABs, HAB toxins, and hypoxia distribution and drivers in the Great Lakes by:
    - Expanding and coordinating in-lake HAB and hypoxia monitoring that includes frequency, location, toxicity, and seasonal coverage (Implement within 5 years). (NOAA, USGS, EPA);
    - Determining the most effective monitoring design for successful detection of HABs, hypoxia, toxins, and drivers over the long-term, and in areas where this is already required for the GLWQA. Fill any need gaps with new efforts and coordination (Implement within 5 years). (NOAA, USGS, EPA);
    - Coordinating monitoring within strategically selected small watersheds in the basin designed to detect and assess multi-scalar effects (link edge-of-field with small and larger watersheds) of conservation implementation. Monitoring should be designed to inform more effective action and adaptive management (Implement within 5 years). (USDA NRCS, ARS; NOAA; USGS; EPA);

    - Continuing pilot testing of at least one ESP annually in Western Lake Erie, and expand to other parts of the Great Lakes, as possible and necessary (Implement within 5 years). (NOAA);
    - Using hyperspectral and other remote sensing monitoring techniques to advance operational ecological forecasting of HAB events in coastal areas (Implement within 5 years). (NOAA, NASA); and
    - Increasing the use of health surveillance data for making decisions, by reporting out on surveillance data, improving the ability to link existing health systems such as OHHABS and NORS with environmental monitoring data for analysis and data visualization, and expanding multidisciplinary collaboration on activities that directly impact health surveillance (e.g., detection of HABs and detection of HAB-associated illnesses) (Implement within 5 years). (CDC).

Modeling and Forecasting

- Improve prediction and forecasting of HABs, hypoxia, and the onset of HAB toxicity by:
    - Fully operationalizing NOAA's Lake Erie HAB Forecast (Implement within 1-3 years). (NOAA);
    - Enhancing and refining the existing ecosystem-based models in use, to meet Annex 4 phosphorus reduction goals, to account for changing factors in the western Lake Erie basin watershed (Implement within 5 years). (NOAA, USGS, EPA);
    - Building initial HAB and hypoxia models for Saginaw Bay and Green Bay (Implement within 5 years). (NOAA);
    - Monitoring for phosphorus and nitrogen at whole-lake and basin scales to help model and predict HABs. (Implement within 2-3 years). (NOAA, USGS, EPA); and
    - Building cooperative modeling relationships across Federal and state agencies, universities, and think tanks to improve capacity to simulating land-use management impacts on water quality across all sectors (Implement within 5 years). (NOAA, USGS, EPA, NASA, USDA).

Toxins and Toxicity

- Better understand the distribution of toxins, and to help predict the onset of toxicity:
    - Developing robust rapid test kits for all forms of microcystin found in the Great Lakes;
    - Developing at least two models and/or forecast techniques that aid in the detection of the onset of toxicity (Implement within 5 years). (NOAA, USGS);
    - Developing clinical testing abilities of state health departments and clinicians for microcystins, saxitoxins, anatoxin-a, and cylindospermopsins to aid in the detection and confirmation of human and animal illness (Implement within 5 years). (CDC); and
    - Improving methods to identify HAB-associated illness in humans, animals and wildlife (Implement within 5 years). (CDC).

Ecological and Fisheries Management

- Determine how HABs and hypoxia impact fisheries and other ecosystem variables or organisms by
    - Conducting annual research on fish population size in the Great Lakes at areas that are known HAB or hypoxia locations, or that experience HAB or hypoxia events. Develop models that show changes in fish populations and behavior in relation to HAB and hypoxia events, including for times when there are no water quality issues, and accounting for

    - other factors (Implement within two years, with research intended to continue out at minimum 5-7 years.) (NOAA);
    - Investigating how HABs and hypoxia affect natural fish populations and fisheries, including dynamics and behavior of lower levels of the food web (phytoplankton and invertebrates), fish, predators, and humans (Implement within 3 years.) (All Federal agencies involved in the IWG-HABHRCA); and
    - Expanding ecological research, nutrient loading, and toxicity to other affected areas of the Great Lakes, including Saginaw Bay and Green Bay (Implement within 2 years.) (NOAA, USGS, EPA).

Climate Change and Extreme Weather Events

- Better understand current and potential future influences of extreme weather events on HABs, HAB toxicity, hypoxia, legacy loads, and conservation management practices in the Great Lakes by incorporating variables related to extreme weather events into the five ecosystem-based models mentioned above. Produce a document that provides an initial prediction of impacts related to extreme weather events on HABs and hypoxia in the Great Lakes (Implement within 5 years). (NOAA); and
- Evaluate the impacts of changes in climate on land use, and how these may have complex and concurrent impacts on water quality (e.g., shifts in agricultural crop selection and production strategies; opportunity for reserving floodplain areas to enhance nutrient cycling as communities move out of increasingly flood-prone riparian areas). (USDA NRCS, USGS).

Drinking Water Treatment

- Conduct studies and evaluations with Great Lakes stakeholders and water utilities to understand the types of cyanobacteria present in each lake/region/area, and how existing treatment infrastructure performs at removing cyanotoxins. Understand limitations of Great Lakes water treatment plants in removing cyanotoxins and develop strategies for addressing those limitations (Implement within 5 years). (EPA).

Social Science

- Understand the economic and social impacts of HABs and hypoxia in the Great Lakes by conducting an initial cost-benefit analysis that accounts for the economic impact of HABs and hypoxia on the Great Lakes, as well as the costs and benefits of current reduction strategies (Implement within 5 years.) (NOAA);
- Improve methods to identify HAB-associated illness in humans, animals and wildlife (Implement within 5 years). (CDC); and
- Conduct an economic and policy assessment on the feasibility of implementing water quality trading models and other novel incentive programs, at scales that match objectives. (EPA).
- Evaluate and incorporate multi-sector ecosystem services to encourage cost-effective design and configuration of green infrastructure and nutrient management practices, and that expand the impact of practices for wildlife, renewable energy, and other social values beyond water quality.

Engagement and Communication

- Better inform impacted communities about the causes and consequences of HABs and hypoxia in general, or about specific events in the Great Lakes by
    - Creating a unified message on HAB and hypoxia causes, consequences, and mitigation in the Great Lakes. Work with stakeholder groups and Federal agencies to identify the best

    strategies for increasing social awareness, attitudes, and public understanding and behavior regarding HABs and hypoxia (Implement within 1-3 years). (All Federal agencies involved in the IWG-HABHRCA);
  - Creating a unified method of informing the public about risks, and about current HAB and hypoxia events (Implement within 1-3 years). (All Federal agencies involved in the IWG-HABHRCA); and
  - Communications strategies that directly involve peer-to-peer and technology transfer through conduits who are trusted and accessed by agricultural producers.
- Partner with stakeholders in developing guides, documents, and literature syntheses on water treatment strategies for cyanotoxins to provide to Great Lakes water utilities and nationwide. (All Federal agencies involved in the IWG-HABHRCA); and
- Conduct workshops, and host training opportunities, for water-treatment-plant operators and supervisors for monitoring, sampling, and optimizing water treatment for HABs and cyanotoxins. (All Federal agencies involved in the IWG-HABHRCA).

Conclusion

A great deal of progress has been made in the Great Lakes on partnership efforts to address nutrient pollution and other stressors to the Great Lake ecosystem, as well as on the science of HABs and hypoxia. Some of the most important advances include researchers' ability to provide accurate HAB forecasts, to detect the presence of toxins in water, and to communicate better with the public. Particularly in recent years, however, HABs and hypoxia have varied widely in frequency, duration, effects, and toxicity. Several key research gaps remain in the understanding of, and ability to respond to, HABs and hypoxia, such as the drivers of toxicity, how to forecast events even more quickly, human and animal health impacts, climate change and extreme weather event impacts, and the best mitigation efforts to minimize economic and public health impacts.

The variability of these events, in conjunction with their uncertainty, makes the ecological, economic, human and animal health, and sociological impacts of HABs and hypoxia hard to predict and prevent. The challenges and recommendations outlined in this report represent a framework for future efforts to better understand and address HABs and hypoxia in the Great Lakes ecosystem. Adaptive management is a key element in all of the recommendations. Drawing from past experience, researchers know that improving water quality into the foreseeable future and long-term requires continued and even increased monitoring and management efforts. While Federal agencies and stakeholders are making progress on reducing HABs and hypoxia in the Great Lakes, there continue to be key uncertainties and research challenges that, as they are addressed, will help improve predictive abilities, management options, and the ability to protect the short- and long-term health of communities in the Great Lakes through mitigation efforts. This strategic document promotes effective collaboration between Federal and non-Federal organizations, and efficient use of resources now and in the future to reduce HABs and hypoxia in the Great Lakes.

Appendix 1

Great Lakes HABs, Toxins, and Bioactive Compounds and their Effects

HAB Taxa	**Toxin/Bioactive/ Nuisance Compound**	**Human Health Effects**	**Animal Impacts**	**Environmental Effects**	**Economic Impact**
Cyanobacteria (e.g., *Microcystis, Dolichospermum, Aphanizomenon, Cylindrospermopsis, Planktothrix, Lyngbya*, and others)	Microcystins, Cylindrospermopsins, Anatoxin-a, Saxitoxins, geosmins, methylisoborneol	Liver and kidney toxicity, neurotoxicity, paralysis, gastrointestinal illness, dermatitis	Pets, farm animals, and wildlife morbidity and mortality, fish kills	Water discoloration, drinking-water contamination, foul odors, loss of benthic aquatic vegetation, changes in food web structure, bioaccumulation in fish	Loss of tourism, contamination of drinking water requiring additional expensive water treatment or alternate water sources, make farmed and wild-caught freshwater fish inedible (including bad taste)
Macroalgae (e.g., *Cladophora*)		Bad taste and odor	Associated with outbreaks of avian botulism	Fouls water intakes, creates a bad odor, and piles up on beaches, localized hypoxia	Loss of recreational use and clean-up costs, clogged water intakes, bad odor
Euglenophytes (*Euglena sanguinea*)	Euglenophycin	Not characterized	Fish kills	Water discoloration	Loss of aquaculture operations
Diatoms			Possible contributor to fish kills	Blooms contribute to hypoxia	Possible negative impact on fishery

Appendix 2

Great Lakes HAB-Related Human Illnesses

Toxin	Vector	Occurrence of outbreak	Acute Toxicity	Long-Term Health Impacts	Susceptible Populations
Anatoxin-a, Homoanatoxin-a	Drinking water, Recreational waters, Dietary supplements	Low	Tingling, burning, numbness, drowsiness, incoherent speech, respiratory paralysis leading to death	Unknown	Recreational water users
Cyanobacterial LPS	Drinking water, Recreational Waters	Medium	Abdominal pain, vomiting and diarrhea, acute dermatitis	Unknown	Recreational water users
Cylindospermospins	Drinking water, recreational waters, dietary supplements	Medium	Abdominal pain, vomiting and diarrhea, liver inflammation and hemorrhage, acute pneumonia, acute dermatitis	Malaise, anorexia, liver failure leading to death	Children, dialysis patients, liver disease, recreational water users
Microcystins	Drinking water, recreational waters, dietary supplements, fish consumption	High	Abdominal pain, vomiting and diarrhea, liver inflammation and hemorrhage, acute pneumonia, acute dermatitis, seizures leading to coma and death	Hepatocellular carcinoma, liver failure leading to death	Children, dialysis patients, pre-existing liver disease, recreational water users
Saxitoxins (i.e. Paralytic Shellfish Toxins)	Unknown	Medium	Paralytic Shellfish Poisoning: tingling, burning, numbness, drowsiness, incoherent speech, respiratory paralysis leading to death	Unknown	Unknown
BMAA (β-Methylamino-L-alanine)	Consumption of fish and other organisms (i.e. biomagnification through the food web)	Unknown	Unknown	Neurodegenerative: Possible link to amyotrophic lateral sclerosis (ALS) and Alzheimer's disease.	Unknown

Appendix 3

HABHRCA Federal Agency HABs and Hypoxia Program Activities

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DHHS	Great Lakes Restoration Initiative, CDC	HABs	HAB-associated case and outbreak surveillance	CDC initiated waterborne and foodborne-disease outbreak surveillance systems in the 1970s. United States states and territories voluntarily report to these systems via the electronic NORS, which receives aggregate data on human cases and their exposures, including exposures to harmful algal blooms (HABs) or HAB toxins. The One Health Harmful Algal Bloom System (OHHABS) launched in June 2016 and collects single case-level reporting of human and animal illness, and relevant environmental data. OHHABS will inform restoration activities in the Great Lakes but is accessible to all states via NORS.
DHHS	CDC	HABs	Great Lakes State Health Surveillance Capacity	CDC partnered with the Council of State and Territorial Epidemiologists (CSTE) since 2013 to place and provide technical support for epidemiology fellows in Great Lakes states, including Indiana, Illinois, Michigan, Minnesota, New York, Ohio, and Wisconsin. The GLRI supports this activity. Fellows focus on waterborne disease detection, investigation, response and reporting. The fellowship has expanded state waterborne disease reporting and analytic capacity; improved state health surveillance for harmful algal blooms; and ensured dedicated staff time for waterborne disease surveillance and coordination activities.
DHHS	CDC	HABs	Health Communications	CDC's health communications activities related to HABs include the launch of a HAB-Associated Illness website with information for public health practitioners, clinicians, and the general public, and the expansion of the Drinking Water Advisory Communications Toolbox (DWACT) to include information about HAB-related drinking water advisories. The DWACT was created through a collaborative effort among CDC, USEPA, the American Water Works Association, the Association of State and Territorial Health Officials, the Association of State Drinking Water Administrators (ASDWA), and the National Environmental Health Association (NEHA).

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DHHS	CDC	HABs		Method development, refinement, and validation for detecting human exposures to HAB toxins through the detection of toxins and specific biomarkers in clinical samples. Current methods approved for use include the detection of saxitoxin, neosaxitoxin, tetrodotoxin, and gonyautoxins (1-4), which have been applied to individual cases to confirm suspected HAB exposures.
DHHS	FDA	HABs		Method development, refinement, and validation for detecting HAB toxins; Improving understanding of HAB toxin sources and vectors that impact seafood and dietary supplement safety
DOC	NOAA	HABs	National Phytoplankton Monitoring Network (PMN)	The intent of the PMN is to monitor phytoplankton and harmful algal blooms and promote environmental stewardship though the use citizen volunteers. The NOAA PMN in partnership with USEPA Office of Water expanded the use of citizen scientist to monitor HABs into Lake Erie. Volunteer monitors on the west coast of Lake Erie are currently monitoring potentially toxic cyanobacteria biweekly and reporting results back to NOAA through an online data portal. An internet map service can depict environmental conditions and HAB species information. NOAA staff train PMN volunteers on sampling techniques and identification methods for over 50 genera, including 10 potentially toxin-producing genera, of dinoflagellates and diatoms on the volunteers' watch list. Currently, 250 sites in 22 states and American territories including 52 schools, 15 universities, 298 civic groups and 40 state and Federal agencies collect phytoplankton and environmental data. Since the inception of the program in 2001, PMN volunteers have reported more than 275 algal blooms and 15 toxic events.
DOC	NOAA	HABs		The National Centers for Coastal Ocean Science (NCCOS) has provided base funding (labor and operational funds) for development of HAB forecasts for Lake Erie. NOAA NCCOS develops an annual HAB severity forecast for Lake Erie distributed in early July. Also, the twice-weekly Lake Erie Harmful Algal Bloom Bulletin transitioned to operations in July 2017. NOAA NCCOS will continue to improve the Lake Erie bulletin and will develop similar products for other HAB impacted regions of the Great Lakes including Saginaw Bay, Lake Huron and Green Bay, Lake Michigan. Furthermore, NOAA NCCOS will begin to develop a Lake Erie HAB toxicity-forecasting model in collaboration with NOAA GLERL.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOC	NOAA	HABs		NOAA GLERL, in collaboration with NOAA NCCOS will continue to develop a three-dimensional lagrangian particle transport-model to effectively predict HAB advection (HAB Tracker) as part of the Lake Erie Operational Forecasting System, which is set to go operational in fiscal year 2015. NOAA plans to fully operationalize the Lake Erie Experimental HAB Tracker by 2018. Furthermore, the HAB Tracker will continue to be improved to incorporate vertical mixing. Furthermore, NOAA GLERL plans to develop this bloom forecasting system in other HAB-impacted areas, including Saginaw Bay, lake Huron and Green Bay, Lake Michigan.
DOC	NOAA	HABs		NOAA Sea Grant programs have funded research, outreach, and education programs to understand the causes of HABs and to help the public understand the risks associated with them. Sea Grant's Great Lakes programs collaborate with GLERL to support research, and transfer research results to stakeholders in the region and were integral to public understanding of the Toledo water crisis. Website learning pages, HAB webinars, and stakeholder meetings are among the tools used by Sea Grant to inform decision-makers, and other publics on HAB topics of relevance to their lives.
DOC	NOAA	HABs	Ecology and Oceanography of Harmful Algal Blooms (ECOHAB)	Developing a better understanding of HAB causes and impacts that form the basis for better management to reduce HABs and their impacts throughout the US regions, including the Great Lakes.
DOC	NOAA	HABs	Monitoring and Event Response for Harmful Algal Blooms (MERHAB)	National, competitive extramural research program that builds capacity for enhanced HAB monitoring and response in state, local, and tribal governments, including the Great Lakes.
DOC	NOAA	HABs	Prevention, Control, and Mitigation of Harmful Algal Blooms (PCMHAB)	National, competitive extramural research program that develops new methods of HAB prevention, control, and mitigation. It also addresses the socioeconomic impact of HABs and efforts to reduce HAB impacts.
DOC	NOAA	HABs	Event Response	Provides immediate assistance for managing HAB events and advancing the understanding of HABs when they occur, including the Toledo water crisis.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOC	NOAA	Hypoxia	Coastal Hypoxia Research Program (CHRP)	National, competitive extramural research program that develops understanding of hypoxia causes and impacts that form the basis for better management to reduce hypoxia and its ecological and socioeconomic impacts. Through CHRP, NOAA hopes to develop a hypoxia warning system for the central basin of Lake Erie. It includes all coastal systems except the large hypoxic zone along the northern Gulf of Mexico continental shelf.
DOC	NOAA	Hypoxia/ HABs	Outreach and Education	Continue to work with Sea Grant and other partners to engage stakeholders to drive research prioritization and disseminate advanced knowledge and tools for HAB and hypoxia mitigation to regional managers, fishing industry, state and Federal leadership and citizens to name a few.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOC	NOAA	HABs	NOAA's Great Lakes HAB monitoring and experiment program	Studies molecular ecology of HABs in the Great Lakes to improve understanding of the drivers of bloom growth and toxin production as well as the interaction of HAB-forming species with other microbes to understand bloom impacts on western Lake Erie ecosystem services. Key regions of focus include Lake Erie, Saginaw Bay, Lake Huron and Green Bay, Lake Michigan. GLERL monitors eight routine stations in the western basin of Lake Erie and five sites in Saginaw Bay while collaborating with academic and state partners to study Green Bay. GLERL samples Lake Erie and Saginaw Bay on a weekly and bi-weekly basis, respectively, during blooms season. At four sites in Lake Erie, GLERL deploys real-time water quality monitoring instrumentation that measure several key parameters including pigments, temperature, dissolved oxygen, nitrate and dissolved reactive phosphorus. GLERL supplies critical data, including toxicity, to stakeholders via the GLERL HABs and hypoxia website and that supports NCCOS and GLERL predictive HAB models in Lake Erie and elsewhere in the Great Lakes (described above). Using monitoring data, GLERL works with Federal, state, and academic partners to conduct experiments on the response of HAB communities to future environmental conditions (i.e. extreme weather events). GLERL, in collaboration with NOS and academic partners, deployed the first-ever Environmental Sample Processor in Lake Erie during the 2016 field season to begin to develop an autonomous, high-frequency bloom toxicity monitoring network. Finally, GLERL, in collaboration with NASA, state, and academic partners, will continue to use hyperspectral flyovers intended to further develop the resolution of remote sensing imaging to distinguish phytoplankton functional groups which will allow for more accurate forecasting products.

Office/ Dept.	**Agency**	**HABs/ Hypoxia/ Both**	**Program Title (brief description)**	**Program Activities**
DOC	NOAA	HABs and hypoxia	GLRI	Investigating links between land-use changes and in-lake algal blooms: GLRI-funded research led by NOAA's Great Lakes Environmental Research Lab, in collaboration with partners from the University of Michigan's Cooperative Institute for Limnology and Ecosystems Research, is investigating impact of land use changes and algal bloom development in the western basin of Lake Erie and in Lake Huron's Saginaw Bay. Measurements of total phosphorus, total dissolved phosphorus, and dissolved reactive phosphorus will contribute to the GLRI's goal of reducing algal bloom growth through reductions in phosphorus.
DOC	NOAA	Both	United States Integrated Ocean Observing System (IOOS) and Great Lakes Observing System (GLOS)	GLOS is a certified Regional Information Coordination Entity under IOOS. GLOS aggregates data from Federal and non-Federal data sources and makes it more easily discoverable and accessible to a broader stakeholder audience including researchers, policy-makers, and resource managers. This is evidenced most directly through the GLOS Data Portal as well as the customized HABs Portal: http://habs.glos.us/map/ As a regional association of IOOS, GLOS also helps coordinate Federal and non-Federal observing activities across the region and supports operation of several nearshore buoys, including two buoys used for hypoxia monitoring by Cleveland, Ohio.
DOD	USACE	HABs		Responding to HABs in response to public reports/complaints in close coordination with state water quality/public health agencies. Response programs developed by individual USACE Divisions/Districts. USACE Engineer Research and Development Center available to support Divisions/Districts in assessing HAB impacts to USACE Civil Works Projects (e.g., water quality modeling, remote sensing, and technical assistance). General water quality monitoring and HAB response to meet authorized project purposes and recreation mission requirements.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOD	USACE	HABs and Hypoxia		USACE is currently involved in modeling inthe two of the three GLRI priority watersheds (Saginaw, MN and Maumee, OH). The goals of thise modeling and forecasting efforts include identifying potentialthe highest impact locations in these watersheds that may be suitable for establishingfor wetlands forcreation and phosphorous absorption,; and facilitating interagency and stakeholder partnerships to collect data for such an effortto implement phosphorous optimal wetland creation when possible.
DOD	USACE	HABs		The USACE Energy Research and Development Center (ERDC) provides support for the Great Lakes and Ohio River Division’s water quality monitoring program. Assess hyperspectral and other imagery to identify water quality indicators of HABs.
DOD	USACE	HABs		ERDC researches and develops activities for reducing eutrophication and the prevalence of harmful algal blooms from USACE reservoir systems.
DOI	FWS	HABs/ hypoxia	North American Wetlands Conservation Act	The DOI- U.S. Fish & Wildlife Service is working with partners throughout the Great Lakes Basin to protect, restore, and enhance wetland habitats through the North American Wetlands Conservation Act grant programs, the GLRI, and other grant programs. While most grant activities through these programs are not designed to directly mitigate HAB/hypoxic concerns, the thousands of acres of wetland and associated habitats protected, restored, and enhanced through these programs helps to provide habitat for birds and other wildlife that may be displaced by HAB/hypoxic zones, as well as help mitigate/lessen the effects through increased nutrient filtration, etc.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOI	NPS	HABs and hypoxia	Outreach and Education	Of the 411 NPS units, 88 units are considered ocean, coastal, or Great Lake parks, in addition to other park units that have extensive surface water bodies. HABs have the potential to influence all of these park units at various levels, and it is therefore important to prepare for these events in order to preserve resources. The National Park Service is creating a website containing a public health and ecological HAB events reporting system. It also provides a point of contact for park managers to collaborate with local, state, and Federal health and environmental agencies that can provide park personnel with technical assistance for the management of HAB events. Outreach materials (brochures, interpretive displays, and materials) on HABs, their causes, the effects on the ecosystem, and the many ways to reduce or stop nonpoint source pollution, are being created by the NPS. NPS participates in detection of HAB events that negatively affect wildlife and visitor experiences, and actively manages natural resources to prevent and respond to HAB events.
DOI	USGS	HABs and hypoxia	National Water Quality Program/National Water Quality Assessment and Cooperative Matching Funds	USGS conducts long-term monitoring of nutrients and other water quality characteristics in surface and groundwater networks, nationally. USGS monitors the sources and quantities of nutrients delivered by streams and groundwater to the Great Lakes and estuaries at several sites and locations throughout the Great Lakes watersheds. The agency makes annual updates from monitoring sites available to the public, including nutrient concentrations, loads, and yields. Researchers use these data, along with data aggregated from numerous other agencies, to evaluate trends in critical water quality parameters including nutrients and sediment. USGS is pioneering new field sensor methods and systems for monitoring and delivering real-time nutrient data through the Nutrient Sensor Challenge.
DOI	USGS	HABs and hypoxia	National Water Quality Program/National Water Quality Assessment	USGS collects fish-, aquatic macroinvertebrate-, and algae-community samples, and conducts stream physical habitat surveys to assess the effects of multiple stressors—including algal toxins—on aquatic organisms in streams in several ecoregions.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOI	USGS	HABs	National Water Quality Program/ Cooperative Matching Funds	At least 20 USGS Water Science Centers conduct HABs research, working closely with state, local, and Federal partners. Studies include both short- and long-term projects focused on quantifying blooms and associated toxins and taste-and-odor compounds, and understanding causal factors. Many studies employ new and developing sensor technology to detect algal pigments. For example, in a study in Ohio, scientists are developing real-time and comprehensive models to estimate microcystin concentrations at 7 drinking-water intakes and 4 recreational sites.
DOI	USGS	Hypoxia	National Water Quality Program/National Water Quality Assessment	The USGS SPARROW model quantifies nutrient and sediment sources and loads to the Great Lakes. SPARROW models link to an online Decision Support System, which allows direct exploration of the potential benefits of nutrient management for the Great Lakes. USGS is modeling groundwater/surface water interactions at the hydrologic unit code (HUC) 8 scale throughout the US part of the Great Lakes Basin, which will provide key information on travel times for recharging water to flow to a receiving surface water.
DOI, USDA	USGS, USDA-NRCS	HABs and hypoxia	GLRI	USGS GLRI projects are assessing HABs and hypoxia control, prevention, and mitigation from a landscape perspective, and in close consultation with NRCS, monitoring at edge-of-field (22 sites) and small watershed (6 sites) locations in the GLRI priority watersheds to help quantify phosphorus, nitrogen, and sediment reductions from GLRI projects on agricultural lands. Rapid sharing of edge-of-field monitoring results with local stakeholders allow adaptive management processes to occur. Additional monitoring near the mouths of 24 tributaries helps to assess the impacts of management practices, extreme weather events, and land use change on the timing and magnitude of delivery of nutrients and sediments to the Great Lakes. Finally, USGS works collaboratively with NOAA, USEPA, states, universities, and NGOs on several projects to better understand how nutrient and sediment loading from Great Lakes watersheds affect hypoxia, HABs, and biological communities in the river mouths and open lake environments.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOI	USGS	HABs	Toxic Substances Hydrology Program	USGS investigates the origins, occurrence, transport/fate, effects, and mitigation of HABs and associated toxin mixtures. These investigations have transfer value to the Great Lakes. In doing so, the agency pioneers new methods, including toxin-specific analytical methods and development of targeted and non-targeted ground-to-space field and laboratory methods. Current and planned research, which includes investigations of metabolites and related biota, characterizes the spatial/temporal extent of understudied aspects of toxins associated with HABs; evaluates environmental controls responsible for HAB proliferation and associated toxin production; and evaluates environmental health implications and impacts. In addition to contributing to basic understandings of the biogeochemical underpinnings of algal toxin occurrence and associated environmental health threats, researchers can use this information to assist with standardization of study designs, field, laboratory, and interpretative techniques and to inform mitigation activities. Current and planned collaboration is ongoing with multiple Federal and state agencies and tribes as well as through outreach efforts such as participation on the Inland HAB Discussion Group. USGS fosters industry collaborations to facilitate acquisition of lower cost, higher throughput screening assays and more advanced interpretative capabilities where the program provides validation support for the benefit of program research and stakeholder collaboration.
DOI	USGS	HABs	Environmental Health/Toxic Substances Hydrology Program	Pioneer new field monitoring methods (sensors), assessment techniques, and laboratory methods needed to address harmful algal bloom issues in freshwaters. New methods include a multi-toxin method that can quantify cyanotoxin mixtures, and DNA- and RNA-based molecular methods for detecting microcystin and microcystin producers.
DOI	USGS	HABs and hypoxia	Ecosystems	USGS has ongoing research characterizing ecological and food web impacts of cyanotoxins and hypoxia. For example, USGS studies in Lake Erie are exploring fish behavior mediated by effects of western basin HABs. Research conducted in and around the central basin of Lake Erie to measure effects of hypoxia on prey and game fish recruitment.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
DOI	USGS	HABs and hypoxia	GLRI	Edge of field monitoring stations: The USGS has installed GLRI-funded edge-of-field monitoring stations on farms in the Maumee River basin, the Fox River basin, the Saginaw River basin and the Genesee River basin. These stations will gather weather data and sample runoff water during storm events. Researchers plan to analyze the water samples for their phosphorus, nitrogen, and sediment content. USDA-Natural Resources Conservation Service (NRCS) staff will assist the cooperating farmer with installing conservation practices in the field above the stations. This analysis will help quantify the value of conservation practices in reducing sediment and nutrient delivery from these fields, under these conditions, in order to improve water quality.
Multiple agencies	Multiple agencies	HABs and hypoxia	GLRI	Nutrient and sediment reduction projects in targeted watersheds: Through the GLRI, Federal agencies and their partners are reducing nutrient loads into the Great Lakes. During FY 2015, Federal agencies and their partners funded nutrient and sediment reduction projects on over 100,000 acres of targeted watershed in the Great Lakes Basin using GLRI funding which are projected to prevent over 160,000 pounds of phosphorus from entering the Great Lakes annually. During FY 2015, Federal agencies and their partners also funded urban runoff projects that are anticipated to capture an average annual volume of more than 37 million gallons of untreated urban runoff per year. These projects reduce flooding, increase green space in urban areas, and return vacant properties to productive use.
Multiple agencies	Multiple agencies	HABs and hypoxia	GLRI	Conservation demonstration farms for watershed farmers: The GLRI is funding the implementation of conservation practices including cover crops, silage leachate containment areas, a waste storage structure, and nutrient management on conservation demonstration farms in the Fox River basin. The farms are open for annual tours where other farmers in the watershed can view the installed practices, hear farmers' opinions on the value that conservation farming practices can add to their farming operations, and ask questions.

Office/ Dept.	**Agency**	**HABs/ Hypoxia/ Both**	**Program Title (brief description)**	**Program Activities**
Multiple agencies	Multiple agencies	HABs and hypoxia	GLRI	Real-time continuous water quality observation buoys and forecasting: During FY 2015, GLRI partners established a network of four real-time continuous observing buoys to track detailed water quality conditions to support modeling, forecasting, and public warnings of HAB conditions throughout western Lake Erie. The observing buoys are capable of tracking water quality and bloom conditions and measuring dissolved phosphorus concentrations at hourly intervals. During the 2015 bloom season, these buoys collected over 7,000 in-lake nutrient and water quality measurements, providing unprecedented spatial and temporal details of internal lake dynamics and bloom development. In addition to providing real-time tracking of HABs conditions for water intake managers and recreational users, the observing data will be used to improve ongoing forecasting efforts covering a range of spatial and temporal scales including seasonal HABs forecasts, 5-day forecasts, and vertical distribution forecasts.
Multiple	CDC, USEPA, NOAA	HABs	Interagency Analytic Workgroup	Additional research is necessary to characterize and understand fully the health risks from drinking water provided by public water systems when cyanobacterial toxins contaminate that water. There is a need to establish standardized biological sample collection and analysis protocols to support assessment of toxin-associated health effects. Multiple Federal agencies are working together to assess sampling and analytical capabilities related to analysis of biological specimens collected from human and animals exposed to cyanobacteria toxins via contaminated water, including drinking water. The goal is to combine expertise to develop robust analytic methods to detect biological evidence of exposure to cyanobacterial toxins, to optimize laboratory and emergency response capacity in the collection, analysis, and response to harmful algal bloom-related illnesses.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
Multiple agencies	Multiple agencies and partners, including but not limited to USEPA, FWS, NOAA, NPS, USACE, USDA, USGS	HABs and hypoxia	Water Quality Portal	Participants in the Water Quality Portal, a cooperative data service that makes data publically available. The data are derived from the USGS National Water Quality Information System (NWIS), the USEPA Storage and Retrieval data warehouse (STORET), and the USDA ARS Sustaining the Earth's Watersheds - Agricultural Research Database System (STEWARDS). With data from over 400 Federal, state, tribal, and local agencies, this effort will improve understand progress in nutrient reduction efforts.
Multiple agencies	Multiple agencies and partners , including but not limited to USDA ARS, NOAA, NPS, NSF, USEPA, USFS, USGS	HABs and hypoxia	National Atmospheric Deposition Program (NADP)	The NADP, a consortium of Federal and non-Federal partners, monitors precipitation chemistry and publically provides information on atmospheric nitrogen deposition.
Multiple agencies	Multiple agencies: CDC, NASA, NOAA, NSF, USDA, and USGS	HABs	Exposure Science (ES)21 Federal Working Group on Exposure Science	Exposure assessment is instrumental in helping to forecast, prevent, and mitigate exposure that leads to adverse human health or ecological outcomes. This vision expands exposures from source to dose, over time and space, to multiple stressors, and from the molecular to ecosystem level. ES21 Working Groups on Biomonitoring, Citizen Engagement/Citizen Science and Sensors/Dosimeters addresses HAB exposure assessments.
Multiple agencies	Multiple Agencies, USEPA and NOAA	HABS	Volunteer Freshwater Phytoplankton Monitoring Program	Volunteer monitoring program that collects baseline data on harmful algal species and builds capacity by providing data to NOAA Phytoplankton Monitoring Network and USEPA. Agencies train volunteers to identify algae, collect water samples, conduct basic water quality analyses, and preserve samples for further analysis NOAA Analytical Response Team. The network went operational in 2015, with stations in the western basin of Lake Erie and in seven lakes in USEPA Region 8, with plans to expand to Lakes Michigan, Superior, Huron, and Grand Lake St. Mary in 2016.

Office/ Dept.	**Agency**	**HABs/ Hypoxia/ Both**	**Program Title (brief description)**	**Program Activities**
NASA	NASA	HABs	The Ocean Biology and Biogeochemistry Program	Basic HABs research resulting in publications and new retrieval algorithms.
NASA	NASA	HABs	Applied Sciences Program - Health and Air Quality Applications Program	Monitoring and surveillance of cyanobacterial harmful algal blooms in drinking and recreational water supplies. Satellite derived products developed for western Lake Erie are analyzed for their use in other regions (e.g., Chesapeake Bay and inland lakes in Ohio and Florida). This project establishes methods to identify environmental thresholds that indicate the potential for cyanobacterial blooms to form or persist, and these data sets are available to CDC.
NSF	Joint initiative between NSF and NIEHS	HABs	Oceans and Human Health (OHH) Initiative and the NSF's Division of Ocean Sciences	The NIEHS supports multiple studies focused on the effects of HAB toxins on human and mammalian physiology, development of biomarkers for chronic toxin exposure, and the design and testing of novel technologies for *in situ* detection of algal toxins in fresh and saltwater environments. For example, a number of supported, ongoing studies analyze the effects of domoic acid on neurotoxicity as well as cognitive impacts in human cohorts, non-human primates and rodent models. In addition, NIEHS is accepting unsolicited applications for support and use of time sensitive mechanism to allow research support for unanticipated bloom events.
NSF	NSF	HABs and hypoxia	Ocean Observatories Initiative and the National Ecological Observatory Network	Provides environmental data for studies of HABS (both marine and freshwater) and hypoxia.
NSF	NSF	HABs	Division of Ocean Sciences (OCE), NSF Ocean Observatories Initiative	Observational capabilities for research in marine systems.
NSF	NSF	HABs	Directorate for Geosciences, Prediction and Resilience Against Extreme Events (PREEVENTS)	Focused interdisciplinary research projects.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
NSF	NSF	HABs	Division of Biological Infrastructure, National Ecological Observatory Network (NEON)	Observational capabilities for ecological research.
NSF	NSF	HABs	Division of Ocean Sciences	Research Support, unsolicited proposal in marine ecology.
NSF	NSF	HABs and hypoxia	Collaboration between NSF GEO, SBE, and ENG directorates, as well as USDA NIFA.	Program supporting interdisciplinary research to understand and predict the interactions between the water system and extreme weather events, land use, the built environment, and ecosystem function and services though research and models. Several research projects focus on nutrient movement and hypoxia mitigation strategies.
NSF	NSF	HABs	Ocean and Human Health Initiative, a collaboration between NSF's Division of Ocean Sciences, and the National Institute for Environmental Health Sciences	Studies of the effects of HAB toxins on human and mammalian physiology, development of biomarkers for chronic toxin exposure, and the design and testing of novel technologies for *in situ* detection of algal toxins in fresh- and salt-water environments. Also accepting unsolicited applications for support and use of time sensitive mechanism to allow research support for unanticipated bloom events.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USDA	USDA/Multiple agencies, led by USDA NRCS, Partner with ARS, NIFA, FSA, and NASS. Also includes USGS, NOAA, FWS, USEPA, BLM, NASA, USDA Economic Research Service and US Forest Service	HABs and hypoxia	CEAP-1, Analyses of Agricultural Practices in 2003-06	The Conservation Effects Assessment Project (CEAP) is a collaborative, multi-agency effort to quantify the environmental effects of conservation practices and programs and develop the science base for managing the agricultural landscape for environmental quality. Project findings guide USDA conservation policy and program development, and help conservationists, farmers, and ranchers make more informed conservation decisions. USGS will incorporate conservation data collected by CEAP into their surface water quality monitoring. The National Cropland Assessment combines information from NASS producer surveys and conservation practice data as inputs into two models, the APEX (Agricultural Policy EXtender) field-scale model and the Soil and Water Assessment Tool (SWAT) watershed model, to estimate the environmental impacts of conservation practices and conservation treatment needs within major drainage basins of the United States. These include sub-basins of the Mississippi River Basin, Chesapeake Bay and Great Lakes. In addition, the Watershed Assessment Component of CEAP conducts small watershed scale studies across the United States to quantify water and soil resource outcomes of conservation practices and systems and enhance understanding of processes. Interactions among practices are investigated as well as modeling enhancements, watershed targeting approaches, and socioeconomic factors. Practice standards are developed or updated to improve effectiveness and address gaps.
USDA	Multiple agencies, led by USDA NRCS. Partner with ARS, NASS and FSA	HABs and hypoxia	CEAP	In 2012, NASS worked with NRCS to administer a “Special Study” CEAP-Cropland survey focused in the western Lake Erie basin. Data from 2003-06 and 2012 cropland surveys and other sources was used to assess conservation effects in the Western Lake Erie Basin and compare trends and progress in conservation as well as evaluate additional treatment needs in that region. The agencies released the edge-of-field assessment report in March 2016, with the SWAT modeled delivery estimations’ anticipated release in 2017.

Office/ Dept.	**Agency**	**HABs/ Hypoxia/ Both**	**Program Title (brief description)**	**Program Activities**
USDA	USDA NIFA and NRCS	Hypoxia	CEAP	As part of the CEAP Watershed Assessment Studies, USDA's NIFA and NRCS jointly funded 13 projects to evaluate the effects of cropland and pastureland conservation practices on spatial and temporal trends in water quality at the watershed scale. In some projects, participants also investigated social and economic factors that influence implementation and maintenance of practices. The NIFA-CEAP projects occurred from 2004 to 2011. They were mainly retrospective, in that they focused on conservation practices and water quality monitoring efforts that had been implemented before the NIFA-CEAP projects began.
USDA	USDA	Hypoxia	Small Business Innovation Research program (SBIR)	The USDA SBIR program supports the research and development of technologies that contribute to the protection and conservation of air, water and soils resources. This program has supported (among others) the development of technologies involved in the monitoring and measurement on nutrients such as N and P. The USDA SBIR Program provided support to the Nitrate Elimination Company, Inc., which has developed a portable nitrate biosensor system for quantitative nitrate detection. This will be the first portable kit certified by the USEPA and will be used by the USGS.
USDA	NIFA	Hypoxia	Agriculture and Food Research Initiative (AFRI) Water for Agriculture Challenge Area	This program focuses on solutions for conserving higher quality water and understanding the human behavior and its influence on decision making for agricultural water use. The program will focus on developing solutions for water management that link food, water, climate, energy, and environmental issues.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USDA	NIFA	Hypoxia	Agriculture and Food Research Initiative (AFRI) Foundational	Bioenergy, Natural Resources and Environment (BNRE): This program area supports research on healthy agro-ecosystems and their underlying natural resources. Program areas focuses on the physical and biogeochemical processes affecting the flow, fate and transport, transformation, movement, and storage of nitrogen (N) and phosphorus (P) and innovative agro-ecosystem management practices with the potential to enhance ecosystems services. Agricultural Economics and Rural Communities (AERC): This program support projects related to interactions between agriculture, environment and communities in rural areas; demographic changes and impacts; consumer preferences or behavior; decision-making under uncertainty; market structure and performance; policy design and impact; or agricultures impact on the environment. Critical Agricultural Research and Extension (CARE): This program area addresses critical challenges and opportunities to improve the Nation's agricultural and food systems. It focuses on critical problems that despite prior investments in basic and applied research, it continuous to impede the efficient production of agriculturally-important plants and animals, producing safe and nutritious foods, and to meet environmental challenges for agriculture. Projects are expected to produce results that lead to practices that are rapidly adopted by end-users.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USDA	NIFA	Hypoxia	Climate and Corn-based Cropping Systems CAP (CSACP) (also known as the Sustainable Corn Project	This USDA-NIFA funded project gathers data from 35 field sites and thousands of farmers in 9 Midwestern states, with the goal of creating a suite of practices for corn-based systems that: a. Retain and enhance soil organic matter and nutrient and carbon stocks b. Reduce off-field nitrogen losses that contribute to greenhouse gas emissions and water pollution c. Better withstand droughts and floods d. Ensure productivity under different climatic conditions. This program has developed a vast number of tools and resources that can be helpful for researchers, farmers, extension agents and policy makers. Examples include the Nitrogen Rate calculator, Decision Support Tools, and several reports, videos, a YouTube Channel, blogs and publications in all topics related extreme weather events, nutrient management, water and soil quality, crop production, resiliency and others. It received $4 million USD per year up to 2015 (it is in a no-cost extension in 2016).
USDA	NIFA	Hypoxia	Sustainable Agriculture Research and Education (SARE)	A significant portion of the broad research and extension portfolio funded by the SARE program contributes to hypoxia solutions. Significant topic areas where SARE has provided funding include cover crops, nutrient management, and systems diversification to include use of more perennial forage crops. The SARE Professional Development Program is a train the trainer program that has focused on training agricultural professionals, especially in the Midwest about using cover crops to improve soil health. The SARE program funds multiple grant types and sizes ranging from Research and Extension Grants, which go primarily to academic institutions to smaller research grants that go directly to farmers. Funding for the overall SARE program is $22.667 million per year.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USDA	NIFA	Hypoxia	Hatch Multi-State Projects	Through capacity (Hatch) funds, NIFA provides financial assistance to multistate projects addressing issues with Hypoxia. Some project examples are: • Framework for Nutrient Reduction Strategy Collaboration: The Role for Land Grant Universities (SERA-46); • Organization to Minimize Nutrient Loss from the Landscape (SERA-17); • Drainage Design and Management Practices to Improve Water Quality (NCERA-217); • Enhancing Nitrogen Utilization in Corn-Based Cropping systems to Increase Yield (NC-1195); • Southern Region Integrated Water Resources Coordinating Committee (SERA-43); and • Catalysts for Water Resources Protection and Restoration: Applied Social Science Research (NC-1190).
USDA	NRCS	Hypoxia	Regional Conservation Partnership Program (RCPP) and Conservation Innovation Grants (CIG)	• RCPP: This NRCS-funded program promotes coordination between NRCS and its partners to deliver conservation assistance to producers and landowners. RCPP combines the authorities of four former conservation programs – the Agricultural Water Enhancement Program, the Chesapeake Bay Watershed Program, the Cooperative Conservation Partnership Initiative and the Great Lakes Basin Program. Around $14.6 million USD has been invested in programs along the Mississippi River Basin. • CIG: These are competitive grants that stimulate the development and adoption of innovative approaches and technologies for conservation on agricultural lands. CIG uses Environmental Quality Incentives Program (EQIP) funds to award competitive grants to non-Federal governmental or nongovernmental organizations, American Indian Tribes, or individuals.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USDA	ARS and NRCS	HABs	St. Joe Watershed CEAP Study	Nested (edge-of-field to headwater stream-scale) research to quantify the effects of conservation practices on surface runoff and subsurface (tile) drainage nutrient transport. Develop novel conservation practices (i.e., blind inlets) to minimize the water quality impacts of agricultural management.
USDA	ARS and NRCS	HABs	Western Lake Erie Basin	CEAP and Long-Term Agro-Ecosystem Research (LTAR) edge-of-field research to quantify effects of in-field conservation practices (e.g. 4Rs) as well as novel field edge practices (e.g. drainage water management, blind inlets and steel slag filters) on nutrient transport in surface and subsurface (tile) drainage pathways.
USDA	NIFA and ARS	HABs		Support of extramural and intramural research on the effects of HABs and HAB toxins on food safety, aquaculture, and livestock.
USDA	ARS	HABs and hypoxia		Research on nutrient management, nutrient contribution to hypoxia, and aquaculture. Long-Term Agro-Ecosystem Research (LTAR) and Watershed Research Centers.
USDA	NIFA and ARS	HABs and hypoxia		Supports research on best management practices for nutrient management, aquaculture, and plant breeding, among others. Specific concerns addressed by this research include manure management from animal feeding operations and water use and conservation on cropland.
USDA	NRCS, ARS (partnership with The Nature Conservancy)	HABs and hypoxia	CEAP— Wildlife — Western Lake Erie Basin	The Nature Conservancy-led Western Lake Erie Basin CEAP-Wildlife project was conducted to assess and forecast benefits of NRCS conservation practices to stream fish communities, to help advance strategic conservation of riverine ecosystems. A similar project was completed for the Saginaw Bay. This project used pre-existing water quality and stream fish community data alongside CEAP-Cropland data and treatment scenarios adjusted for use at smaller scales. It links SWAT modeling with fish community condition at small watershed scales (NHD+ scale) to reveal relationships between conservation practice implementation and fish community response within the streams. The effort provides science-based estimates of the priorities, scope and costs of restoring stream fish communities throughout the Western Lake Erie Basin watershed. Coordination with other groups is evaluating connections to Lake Erie water quality.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USDA		HABs and hypoxia	Nonpoint Education for Municipal Officials (NEMO)	The National NEMO Network is a collection of outreach programs across the United States that educate local (town/city/county) land use decision makers about protecting water quality as communities grow. There are currently NEMO program in 30 states, most led by either University-based Extension and/or Sea Grant programs.
USEPA	USEPA	HABs and hypoxia	Water Quality Management	Diversified approach to better understand cyanobacterial HABs ecology and the development of watershed and source water management techniques, including the development of models for nutrients loadings, the optimization of watershed placement of phosphorus and sediment BMPs, and the use of water quality trading (WQT) to cost-effectively reduce nutrient loadings. It also includes an assessment of the impact of land use and infrastructure on watershed changes, and the evaluation of ecological contributors to cyanobacterial HAB development and toxin production. This research program also includes the use of molecular methods to characterize the risk for toxin and algal blooms, and the analysis of the impact of HABs on creating disinfection by-products (DBPs) precursors.
USEPA	USEPA	HABs	Human and Ecological Health	Research support to address data gaps associated with health, ecosystem, and economic effects of HABs. Research activities include the characterization of cyanobacteria and their toxins and allergic components, the evaluation of the toxicity of multiple congeners of microcystins, and identification of biomarkers of exposure for human health risk assessments. USEPA is also assessing occurrence and health information for the inclusion of cyanotoxins in the Contaminant Candidate List (CCL) and the Unregulated Contaminant Monitoring Rule (UCMR) program. In addition, USEPA is developing Human Health Water Quality Criteria (HHWQC) for cyanotoxins in recreational waters.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USEPA	USEPA	HABs	Monitoring and Analytical Methods Development (CyAN, NARS)	A collaborative effort of USEPA, NASA, NOAA, and USGS to provide an approach for mainstreaming satellite ocean color capabilities into United States fresh and brackish water quality management decisions. The Cyanobacteria Assessment Network (CyAN) for freshwater systems will develop approaches to relate nutrient loads and land use to the frequency, location, and severity of cyanobacterial blooms in lakes of the United States. It will include assessing risk to human health from satellite multispectral data to assess biological conditions and risk to human health in lakes and reservoirs in the United States. USEPA also provides nationally consistent and scientifically defensible assessments of aquatic resources through the National Aquatic Resource Surveys (NARS), including indicators associated with cyanotoxin exposure. USEPA and its regions are also working on monitoring efforts including the Great Lakes Restoration Initiative projects and Phosphorus Reduction Strategy. USEPA is also working on monitoring projects to improve identification and removal of HAB toxins in drinking water, and evaluating the impact of temperature on bloom development. USEPA is developing analytical tools including the use of real-time sensors, quantitative polymerase chain reaction and fluorescence based technologies of micro spectrophotometer and flow cytometry to detect cyanobacteria organisms in source water.
USEPA	USEPA	HABs	Drinking Water Treatment	USEPA is working collaboratively with regional offices to assess the presence of HABs-related organisms and toxins in drinking water treatment plant intakes nationally, characterize the effectiveness of drinking water treatment techniques in reducing toxin concentrations, and assist drinking water treatment facilities in optimizing their existing facilities for toxin control while maintaining compliance with other SDWA finished water quality standards
USEPA	USEPA	HABs	Outreach	USEPA conducts webinars and provides online resources to promote public awareness and information sharing.

Office/ Dept.	Agency	HABs/ Hypoxia/ Both	Program Title (brief description)	Program Activities
USEPA	USEPA	Hypoxia	Monitoring	The USEPA GLNPO annually monitors the DO concentration at ten sampling stations in the central basin of Lake Erie throughout the stratified season. This program began in order to monitor and track hypoxic conditions in response to the phosphorus reduction programs implemented by the 1978 GLWQA. Oxygen and temperature profiles help to determine the annual corrected oxygen depletion rate. Researchers also can use data from these surveys to assess the extent and/or duration of hypoxia/anoxia in the Central Basin of Lake Erie. GLNPO has been conducting this program since 1991 (with several short breaks), and the procedures used have been successfully employed with minor variations since 1983 by two other collaborators [Ohio State University (1983-1986) and U.S. Fish and Wildlife Service (1987-1990)].

Appendix 4

Great Lakes HABs and Hypoxia Toolkit

The prevalence and duration of harmful algal blooms (HABs) and hypoxia (low-oxygen conditions) in the marine waters and freshwaters of the United States, including the Great Lakes, are generating public concern. From extended shellfish closures on the west coast in 2015, to a larger-than-predicted hypoxic zone in the Gulf of Mexico, these events negatively impact resources across thousands of miles of the Nation's coastal and inland waters, and represent some of the most scientifically complex and economically damaging aquatic issues.

HABs and hypoxia have serious effects on a community's social and public health. They may threaten the safety of seafood, drinking water, and air quality. They may also result in lost revenue for lakefront and coastal economies that are dependent on aquatic/seafood harvest or tourism, disruption of subsistence activities, loss of community identity tied to aquatic-resource use, and disruption of social and cultural practices. The impacts cause us to ask critical questions: Is it safe to drink the water? Can we swim at the beach? Can we eat this fish? Are my pets and ecological resources at risk? How will this affect my business or job? These questions became apparent for many Great Lakes basin residents when almost 500,000 people in the Toledo, OH, metro area were advised not to drink their tap water for three days in 2014 due to HAB toxins.

It is important to note that most algal and cyanobacterial species are not toxic, and that they play an important role in maintaining healthy ecosystems. Scientists consider algae and cyanobacteria to be the cornerstones of life on Earth and form the basis of the food chain as food for zooplankton and fish. Given human and environmental health impacts, however, it is important for communities to be aware and prepared.

The intent of this toolkit is to help communities, big and small, to have a central source of information on HABs and hypoxia. It includes information and a worksheet to help communities better understand and prepare for these events and their impacts.

What is a HAB?

HABs are a naturally occurring, small subset of microscopic, or larger and plant-like cyanobacteria or algal species. When promoted by human-influenced ecosystem changes such as nutrient-loading, extreme weather events, and invasive organisms, these naturally occuring species can form dense overgrowths that can disrupt the environment and local economies, or can produce toxins that are harmful to people and animals. These blooms can cause damage by blocking light from bottom-dwelling plants, restructuring food web dynamics, reducing oxygen availability during decay, and promoting pathogens (Lopez et al., 2008; Auer et al., 2010; Paerl et al., 2016). Some HAB species can harbor waterborne pathogens or produce toxins that are harmful to humans and wildlife.

What is hypoxia?

Hypoxia is a naturally-occurring condition where the concentration of dissolved oxygen in the water column decreases to a level that can no longer support living aquatic organisms, typically at or below 4 mg/L. Areas of hypoxia are commonly called "dead zones" because of their inability to support fish and other organisms. Hypoxia can force fish out of refuge into waters where the fish do not grow as well (Arend et al., 2011). Hypoxia also affects drinking water, causing taste and odor problems due to high manganese and iron levels.

What causes HABs and hypoxia?

HABs and hypoxia occur from several factors acting together, and indeed, the two types of events often are linked. Although they are both naturally occurring, natural and human-induced environmental changes can exacerbate the issues. Low-oxygen conditions, for instance, occur in waterbodies due to the confluence of physical, chemical, and biological processes. Algal blooms also reduce water clarity and prevent sunlight from penetrating into the water and reaching submerged aquatic vegetation and seafloor microalgae, causing them to release less oxygen that would normally help to replenish the water's oxygen supply. In these ways, HABs can contribute to hypoxia (CENR, 2010). Nutrient pollution that stimulates algal blooms can result in much more organic matter reaching bottom waters, effectively driving hypoxic conditions to much more severe levels than would occur naturally.

Where do HABs and hypoxia occur? We haven't had them – should I be worried?

Every state in the United States now experiences some kind of HAB or hypoxia event, in many cases annually. The incidence of hypoxia globally has increased tenfold over the past 50 years, and by almost thirtyfold in the United States since 1960, with more than 300 aquatic systems recently experiencing hypoxia (Diaz and Rosenberg, 2008; CENR, 2010). Previously unrecognized HAB species have emerged in some locations.

This increase largely occurs due to ecological changes, food-web alterations, and the introduction of HAB species into new regions due to international commerce, water-flow modifications, and increased water temperatures. Another important driver of HABs and hypoxia events is the export of large quantities of nutrients, such as phosphorus and nitrogen, and organic matter into coastal waters in areas of high population density or near developed watersheds (CENR, 2010). Excess nutrients and organic matter can stimulate harmful algal growth. Nutrient pollution can come from both direct ("point") and indirect ("nonpoint") sources, including agriculture; municipal, and industrial wastewater; urban and suburban storm water runoff; and aquaculture. In addition, atmospheric pollutants—especially nitrogen from fossil-fuel combustion, volatilization of fertilizer and animal waste, and industrial outputs—can be deposited from the air to watersheds or directly into water, leading to increased nutrient levels. Overall, the greater the input of nutrients and organic matter into a body of water, then the greater the chance of hypoxic conditions developing and continuing.

In the Great Lakes, the presence of invasive zebra and quagga mussels may promote some HAB species, although the connection is not always clear (Vanderploeg, 2001; Conroy et al., 2005; Bridgeman and Penamon, 2010; Fishman et al., 2010; Millie et al., 2011). Selective feeding on HAB species and nutrient excretion by the invasive zebra and quagga mussels has the potential to influence HABs and hypoxia (Tang et al., 2014). Herbicides and pesticides that wash into lakes during application or times of high precipitation can also promote Great Lakes HAB species by killing their natural competitors (Peterson et al., 1997; Lürling and Roessink, 2006; Saxton, 2011).

A changing climate may lead to or exacerbate HABs and hypoxia in many environments (Paerl and Huisman, 2008; Davis et al., 2009; O'Neil et al., 2012; Paerl and Otten, 2013; USGCRP 2016; Visser et al., 2016) by raising air and water temperatures that increase algal growth and reduce water-column mixing, and by causing changes in precipitation patterns that increase stream discharge, and promote phosphorus- and nitrogen-loading into nearshore waters (Paerl and Paul, 2012; Michalak et al., 2013; Scavia et al., 2014; Visser et al., 2016). Extreme weather events also may lead to warmer bottom water temperatures that could lead to higher respiration rates and faster oxygen depletion (Bouffard et al., 2013).

What can I do to protect my community?

Remember some of these basic guidelines:

- Don't:
    - Swim, wade, or otherwise recreate in; drink; or cook with water that has a smell or strange color, or that has dead fish floating in it.
    - Eat fish or other types of seafood that come from these waters.
- Do:
    - Tell your local health department if you see a dog, bird, or other type of wildlife behaving strangely.
    - Follow the news before you plan to go swimming or fishing, and listen for reports of HABs in your area.
    - Speak up! Tell your friends about HAB events that may affect them.

The below worksheet is designed to help communities be aware and prepare, regardless of whether you've experienced a HAB or hypoxic event. Understanding the risks to human, economic, and environmental health is the most important step to minimizing how you and your community are impacted.

- What is/are my community's primary industry(ies)? What do each produce in annual revenue? What is the value of each?
    -
    -
    -
- Are any of our industries/sources of employment or revenue dependent upon water resources?

- Have we experienced a HAB or hypoxic event before (of which we are aware)? ___________
    - *If yes:*
        - Did anyone get sick? If so, how many people/animals? Was it reported to the health department?
        - Did we lose revenue?
            - If so, how much?
        - What happened?
- What did/would a HAB or hypoxia event cost us?
    - Potential lost revenue: ____
    - Social impacts: ____
    - Cost to clean up HAB, treat or remove affected wildlife: ______________________________
    - Cost of water treatment: ____
    - Cost for monitoring/detection methods: ______________________________________
    - Cost of medical care for sick humans: _______________________________________
    - Cost of medical care for sick animals: _______________________________________
    - Type of water such as drinking water or source water treatment? ___________________
- Am I connected to my local Chamber of Commerce?
    - If so, do we have a strategy for reducing HABs and hypoxia in our area
    - Are there any gaps that we have identified?
    - Are there other groups, such as academics, that I could connect with convey that information?

- In the event of a HAB or hypoxia event, do citizens have alternative resources….
    - Financially, for employment/revenue? (Tourism, fishing, etc.)
    - Emotionally/culturally?
    - For a drinking water supply?
    - For food?
    - For recreation?
- Do we have emergency funds for this type of event? If so, how much? How do they need to be disbursed? How quickly can we access them>
- How can we use this information to reach constituents, to help reduce personal, bodily harm as well as economic harm?
    - For example, can communications about a hypoxic event allow recreational fishermen to plan their fishing time in a way that maximizes the fishing experience?
    - Is there a similar activity that makes the fishermen similarly happy and that does not require excessive additional resources?
- Do we have protocols for divers and other recreation users?
- Do we have presences on social media, television, and/or radio that allow us to inform audiences of the presence of a HAB or hypoxia?
- Do we have local signage at waterbodies, in the event of a HAB?
- Do we have general information flyers or signage discussing how to detect a HAB, or be aware of HAB or hypoxia impacts?
- How can we convey information regarding toxicity of fish during HAB season?

For additional questions or resources, please visit these sites:

- *Marine HABs, hypoxia; the Great Lakes:* *http://oceanservice.noaa.gov/hazards/hab/*
- *HAB and hypoxia forecasting:* *https://tidesandcurrents.noaa.gov/hab/*
- *Harmful Algal Bloom and Hypoxia Research and Control Act:* *https://coastalscience.noaa.gov/research/habs/habhrca*
- *Freshwater HABs:* *https://www.epa.gov/nutrientpollution/harmful-algal-blooms*
- *Monitoring nutrient inputs:* *http://water.usgs.gov/nawqa/sparrow/*
- *Conservation programs and nutrient reduction strategies:* *http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/ceap/*
- *National Sea Grant College Program:* *http://seagrant.noaa.gov/*
- *Harmful Algal Bloom (HAB)-Associated Illness:* *http://www.cdc.gov/habs/index.html*
- *Drinking Water Advisory Communication Toolkit:* https://www.cdc.gov/healthywater/emergency/pdf/dwact-2016.pdf

In recognition of the challenges presented by harmful algal blooms and hypoxia, the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2014 (HABHRCA 2014, P.L. 113-124) emphasizes the mandate to advance the scientific understanding and ability to detect, predict, control, mitigate, and respond to these types of events. This legislation established the Interagency Working Group on HABHRCA (IWG-HABHRCA). It tasked the group with coordinating and convening Federal agencies to discuss HAB and hypoxia events in the United States, and to develop action plans, reports, and assessments of these situations.

References

American Water Works Association (AWWA). 2010. *Algae: Source to Treatment, Manual of Water Supply Practices M57*. First Edition. Denver, CO. ISBN: 9781583217870.

Anderson, D.M., P.M. Glibert, and J.M. Burkholder. "Harmful Algal Blooms and Eutrophication: Nutrient Souces, Composition, and Consequences." *Estuaries* 25(4B/2002): 704-726. http://www.jstor.org/stable/1353028. Last accessed: October 18, 2016.

Anderson, D.M., A.D. Cembella, and G.M. Hallegraeff. "Progress in Understanding Harmful Algal Blooms: Paradigm Shifts and New Technologies for Research, Monitoring, and Management." *Annual Review of Marine Science* 4(2012): 143-176. DOI: 10.1146/annurev-marine-120308-081121.

Arend, K.A., D. Beletsky, J.V. DePinto, S.A. Ludsin, J.J. Roberts, D.K. Rucinski, D. Scavia, D.J. Schwab, and T.O Höök. "Seasonal and Interannual Effects of Hypoxia on Fish Habitat Quality in Central Lake Erie." *Freshwater Biology* 56(2011): 366-383.

Auer, M.T., L.M. Tomlinson, S.N. Higgins, S.Y. Malkin, E.T. Howell, and H.A. Bootsma. "Great Lakes *Cladophora* in the 21st Century: Same Algae-Different Ecosystem." *Journal of Great Lakes Research* 36, no. 2 (2010): 248-255. DOI: 10.1016/j.jglr.2010.03.001.

Barrett, N.J. "Effects of Toxic Cyanobacteria (*Microcystis aeruginosa*) on the Feeding and Reproduction Ecology of the Copepod *Eurytemora affinis* from Green Bay, Lake Michigan." (2014). Lawrence University Honors Projects. Paper 60. http://lux.lawrence.edu/luhp/60.

Bastrup-Birk, A., and P. Gundersen, "Water Quality Improvements from Afforestation in an Agricultural Catchment in Denmark Illustrated with the INCA Model." *Hydrology and Earth System Sciences Discussions* 8(4/2004): 764-777. http://www.hydrol-earth-syst-sci.net/8/764/2004/. Last accessed: November 11, 2016.

Beaches Environmental Assessment and Coastal Health Act of 2000 (BEACH Act; P.L. 106-284). (2000). Last accessed October 26, 2016. https://www.epa.gov/sites/production/files/2015-04/documents/beaches-act-2000.pdf.

Beeton, A.M. "Eutrophication of the St. Lawrence Great Lakes." *Limnology and Oceanography* 10(2/1965): 240-255. DOI: 10.4319/lo.1965.10.2.0240.

Belore, M., A. Cook, T. Hartman, K. Kayle, C. Knight, J. Markham, C. Murray, M. Thomas, M., and L. Witzel. *Report of the Lake Erie Yellow Perch Task Group to the Great Lakes Fishery Commission*. Windsor, Ont. (2014). http://www.glfc.org/lakecom/lec/YPTG_docs/annual_reports/YPTG_report_2014.pdf. Last accessed: May 31, 2016.

Bentrup, G. "Conservation Buffers: Design Guidelines for Buffers, Corridors, and Greenways." General Technical Report SRS-109 for the Southern Research Station, Forest Service, United States Department of Agriculture. http://www.srs.fs.usda.gov/pubs/gtr/gtr_srs109.pdf. Last accessed: November 3, 2016.

Bertani, I., D.R. Obenour, C.E. Steger, C.A. Stow, A.D. Gronewold, and D. Scavia. "Probabilistically Assessing the Role of Nutrient Loading in Harmful aAlgal Bloom Formation in Western Lake Erie." *Journal of Great Lakes Research* (2016). DOI: 10.1016/j.jglr.2016.04.002.

Betanzo, E.A., A.F. Choquette, K.H. Reckhow, L. Hayes, E.R. Hagen, E.R., Argue, D.M., and A.A. Cangelosi. "Water Data to Answer Urgent Water Policy Questions: Monitoring Design, Available Data and

Filling Data Gaps for Determining the Effectiveness of Agricultural Management Practices for Reducing Tributary Nutrient Loads to Lake Erie." Northeast-Midwest Institute Report. (2015). ISBN: 978-0-9864448-0-7.

Biddanda, B. A., S.C. Nold, S. A Ruberg, S. T. Kendall, T.G. Sanders, T. G., and J.J. Gray. "Great Lakes Sinkholes: A Microbiogeochemical Frontier. *Eos*, *90*(8/2009): 61-68. DOI: 10.1029/eost2009EO08.

Bierman, Jr., V.J., J. Kaur, J.V. Depinto, T.J. Feist, and D.W. Dilks. "Modeling the Role of Zebra Mussels in the Proliferation of Blue-Green Algae in Saginaw Bay, Lake Huron." *Journal of Great Lakes Research* 31(1/2005): 32-55. DOI: doi:10.1016/S0380-1330(05)70236-7.

Bingham, M., S.K. Sinha, and F. Lupi. *Economic Benefits of Reducing Harmful Algal Blooms in Lake Erie.* Environmental Consulting and Technology, Inc., Report. (2015). http://ijc.org/files/tinymce/uploaded/Publications/Economic-Benefits-Due-to-Reduction-in-HABs-October-2015.pdf. Last accessed: May 18, 2016.

Bocaniov, S.A., R.E.H. Smith, C.M. Spillman, M.R. Hipsey, and L.F. Leon. "The Nearshore Shunt and the Decline of the Phytoplankton Spring Bloom in the Laurentian Great Lakes: Insights from a Three-Dimensional Lake Model." *Hydrobiologia* 731(1/2014): 151-172. DOI: 10.1007/s10750-013-1642-2.

Bocaniov, S.A., and D. Scavia. "Temporal and Spatial Dynamics of Large Lake Hypoxia: Integrating Statistical and Three-Dimensional Dynamic Models to Enhance Lake Management Criteria." *Water Resources Research* (2016). DOI: 10.1002/2015WR018170.

Bosch, N.S., M.A. Evans, D. Scavia, and J.D. Allan. "Interacting Effects of Climate Change and Agricultural BMPs on Nutrient Runoff Entering Lake Erie." *Journal of Great Lakes Research* 40(3/2014): 581–589. DOI: 10.1016/j.jglr.2014.04.011.

Bouffard, D., J.D. Ackerman, and L. Boegman. "Factors Affecting the Development and Dynamics of Hypoxia in a Large Shallow Stratified Lake: Hourly to Seasonal Patterns." *Water Resources Research* 49(5/2013): 2380-2394. DOI:10.1002/wrcr.20241. http://onlinelibrary.wiley.com/doi/10.1002/wrcr.20241/full. Last accessed: May 13, 2016.

Bourne, D.G., G.J. Jones, R.L. Blakeley, A. Jones, A.P. Negri, and P. Riddles. "Enzymatic Pathway for the Bacterial Degradation of the Cyanobacterial Cyclic Peptide Toxin Microcystin LR." *Applied and Environmental microbiology* 62(11/1996): 4086-4094. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC168230/. Last accessed: July 25, 2016.

Bridgeman, T.B., D.W. Schloesser, and A.E. Krause. "Recruitment of Hexagenia Mayfly Nymphs in Western Lake Erie Linked to Environmental Variability." *Ecological Applications* 16(2/2006): 601-611. http://www.jstor.org.proxy.lib.umich.edu/stable/40061680. Last accessed: May 18, 2016.

Bridgeman, T.B., and W.A. Penamon. "*Lyngbya wollei* in Western Lake Erie." *Journal of Great Lakes Research* 36(1/2010): 167-171. DOI: 10.1016/j.jglr.2009.12.003.

Brooks, C., A. Grimm, R. Shuchman, M. Sayers, and N. Jessee. "A Satellite-Based Multi-Temporal Assessment of the Extent of Nuisance *Cladophora* and Related Submerged Aquatic Vegetation for the Laurentian Great Lakes." *Remote Sensing of Environment* 157(2015): 58-71. DOI: 10.1016/j.rse.2014.04.032.

Brooks, B.W., J.M. Lazorchak, M.D.A. Howard, M.V.V. Johnson, S.L. Morton, D.A.K. Perkins, E.D. Reavie, G.I. Scott, S.A. Smith, and J.A. Steevens. "Are Harmful Algal Blooms Becoming the Greatest Inland Water Quality Threat to Public Health and Aquatic Ecosystems?" Environmental Toxicology and Chemistry 35(2016): 6–13. DOI: 10.1002/etc.3220.Brown, L.J., V. Taleban, B. Gharabaghi, and L.

Weiss. “Seasonal and Spatial Distribution of Atmospheric Phosphorus Deposition to Lake Simcoe, ON.” *Journal of Great Lakes Research* 37(2011): 15-25. DOI: 10.1016/j.jglr.2011.01.004.

Bullerjahn, G.S., R.M. McKay, T.W. Davis, D.B. Baker, G.L. Boyer, L.V. D’Anglada, G.J. Doucette, J.C. Ho, E.G. Irwin, C.L. Kling, R.M. Kudela, R. Kurmayer, A.M. Michalak, J.D. Ortiz, T.G. Otten, H.W. Pearl, B. Qin, B.L. Sohngen, R.P. Stumpf, P.M. Visser, and S.W. Wilhelm. “Global Solutions to Regional Problems: Collecting Global Expertise to Address the Problem of Harmful Cyanobacterial Blooms. A Lake Erie Case Study." *Harmful Algae* 54(2016): 223-238. DOI: 10.1016/j.hal.2016.01.003.

Burnett, E.A., R. S. Wilson, B. Roe, G. Howard, E. Irwin, W. Zhang, and J. Martin. “Farmers, Phosphorus and Water Quality: Part II. A Descriptive Report of Beliefs, Attitudes and Best Management Practices in the Maumee Watershed of the Western Lake Erie Basin.” (2016). Columbus, OH: The Ohio State University School of Environment and Natural Resources. DOI: 10.13140/RG.2.1.3317.0805.

Burns, N.M., D.C. Rockwell, P.E. Bertram, D.M. Dolan, and J.J.H. Ciborowski. “Trends in Temperature, Secchi Depth, and Dissolved Oxygen Depletion Rates in the Central Basin of Lake Erie, 1983-2002.” *Journal of Great Lakes Research* 31(Supplement 2/2005): 35-49. DOI: 10.1016/S0380-1330(05)70303-8. DOI: 10.1016/S0380-1330(05)70303-8.

Byappanahalli, M.N., D.A. Shively, M.B. Nevers, M.J. Sadowsky, and R.L. Whitman. “Growth and Survival of Escherichia coli and Enterococci Populations in the Macro-Alga *Cladophora* (Chlorophyta)." *FEMS Microbiology Ecology* 46(2/2003): 203-211. DOI: 10.1016/S0168-6496(03)00214-9.

Byrne, D.G., G.J. Jones, R.L. Blakeley, A. Jones, A.P. Negri, and P. Riddles. “Enzymatic Pathway for the Bacterial Degradation of the Cyanobacterial Cyclic Peptide Toxin Microcystin LR.” *Applied and Environmental Microbiology*, 62(11/1996): 4086–4094. http://aem.asm.org/content/62/11/4086.full.pdf. Last accessed: April 22, 2016.

Calhoun, F.G., D.B. Baker, and B.K. Slater. “Soils, Water Quality, and Watershed Size: Interactions in the Maumee and Sandusky River Basins of Northwestern Ohio.” *Journal of Environmental Quality* 31(1/2002): 47–53. DOI: 10.2134/jeq2002.4700.

Carmichael, W.W., L. Backer, L.M. Billing, S. Blais, J.B. Hyde, L. Merchant-Masonbrink, M. Palmer, J.M. Reutter, S. Watson, M. Sanborn, P. Allen, J. Boehme, T. Buchanan, V. Serveiss. “Human Health Effects from Harmful Algal Blooms: A Synthesis.” International Joint Commission. (2013). http://www.ijc.org/files/publications/Attachment%202%20Human%20Health%20Effects%20from%20Harmful%20Algal%20Blooms.pdf. Last accessed: November 2, 2016.

Carmichael, W.W. and G.L. Boyer. “Health Impacts from Cyanobacteria Harmful Algal Blooms: The North American Great Lakes.” *Harmful Algae* 54 (2016): 194-212. DOI: 10.1016/j.hal.2016.02.002.

Centers for Disease Control and Prevention. “Drinking Water Advisory Communication Toolbox.” (2016). http://www.cdc.gov/healthywater/pdf/emergency/drinking-water-advisory-communication-toolbox.pdf. Last accessed: November 2, 2016.

Chaffin, J. D., T. B. Bridgeman, and D. L. Bade. “Nitrogen Constrains the Growth of Late Summer Cyanobacterial Blooms in Lake Erie.” *Advances in Microbiology* 3(2013):16-26. DOI: 10.4236/aim.2013.36A003.

Chapra, S.C., and D.M. Dolan. “Great Lakes Total Phosphorus Revisited: 2. Mass Balance Modeling.” *Journal of Great Lakes Research* 38(4/2012): 741-754. DOI: http://dx.doi.org/10.1016/j.jglr.2012.10.002.

Charnley, G., and B.D. Goldstein. “A Public Health Context for Residual Risk Assessment and Risk Management Under the Clean Air Act.” *Environmental Health Perspectives* 106(9/1998): 519-521. DOI: 10.2307/3434224.

Chen, D. J., H. Huang, M. P. Hu, and R. A. Dahlgren. “Influence of Lag Effect, Soil Release, and Climate Change on Watershed Anthropogenic Nitrogen Inputs and Riverine Export Dynamics.” *Environmental Science and Technology* 48(2014): 5863-5690. DOI: 10.1021/es500127t.

Chorus, I., and J. Bartram, eds. 1999. *Toxic Cyanobacteria in Water: A Guide to their Public Health Consequences, Monitoring and Management*. World Health Organization. http://www.plannacer.msal.gov.ar/images/stories/ministerio/intoxicaciones/cianobacterias/toxcyanobacteria.pdf. Last accessed: November 6, 2016.

Chow, C.W.K., M. Drikas, J. House, M.D. Burch, and R.M.A. Velzeboer. “The Impact of Conventional Water Treatment Processes on Cells of the Cyanobacterium *Microcystis aeruginosa*.” *Water Research* 33(15/1999): 3253-3262. DOI: http://dx.doi.org/10.1016/S0043-1354(99)00051-2.

Christianson, L.E., Harmel, R.D., Smith, D.R., Williams, M.R., and King, K.W. “Assessment and Synthesis of 50 Years of Published Drainage Phosphorus Losses.” *Journal of Environmental Quality* 45(2016):1467-1477. DOI: doi:10.2134/jeq2015.12.0593.

Commonwealth of Pennsylvania. Senate Bill No. 563, Session of 2015. General Assembly of Pennsylvania. http://www.legis.state.pa.us/cfdocs/legis/PN/Public/btCheck.cfm?txtType=PDF&sessYr=2015&sessInd=0&billBody=S&billTyp=B&billNbr=0563&pn=0603. Last accessed: May 19, 2016.

Committee on Environment and Natural Resources (CENR). *Scientific Assessment of Hypoxia in US Coastal Waters*. Washington, DC: Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. 2010. https://www.whitehouse.gov/sites/default/files/microsites/ostp/hypoxia-report.pdf. Last accessed: May 18, 2016.

Conroy, J. D., D.D. Kane, D.M. Dolan, W.J. Edwards, M.N. Charlton, and D.A. Culver. “Temporal Trends in Lake Erie Plankton Biomass: Roles of External Phosphorus Loading and Dreissenid Mussels.” *Journal of Great Lakes Research* 31(2005): 89-110. DOI:10.1016/S0380-1330(05)70307-5.

Conroy, J.D., L. Boegman, H. Zhang, W.J. Edwards, and D.A. Culver. “‘Dead Zone’ Dynamics in Lake Erie: The Importance of Weather and Sampling Intensity for Calculated Hypolimnetic Oxygen Depletion Rates.” *Aquatic Sciences* 73(2/2011): 289-304. DOI: 10.1007/s00027-010-0176-1.

Correll, D.L. “The Role of Phosphorus in Eutrophication of Receiving Waters: A Review.” *Journal of Environmental Quality* 27(1998): 261-266. http://nature.berkeley.edu/classes/espm-120/Website/correll1998.pdf. Last accessed: May 19, 2016.

Cory, R.M., T.W. Davis, G.J. Dick, T. Johengen, V.J. Denef, M.A. Berry, S.E. Page, S.B. Watson, K. Yuhas, and G.W. Kling. “Seasonal Dynamics in Dissolved Organic Matter, Hydrogen Peroxide, and Cyanobacterial Blooms in Lake Erie.” *Frontiers in Marine Science* 3 (54/2016). DOI: 10.3389/fmars.2016.00054.

Cousino, L.K., R.H. Becker, and K.A. Zmijewski. “Modeling the Effects of Climate Change on Water, Sediment, and Nutrient Yields from the Maumee River Watershed.” *Journal of Hydrology: Regional Studies* 3(1/2015): 762-775. DOI: http://dx.doi.org/10.1016/j.ejrh.2015.06.017.

Cuthbert, F.J. and L. Wires. “The Fourth Decadal U.S. Great Lakes Colonial Waterbird Survey (2007-2010): Results and Recommendations to Improve the Scientific Basis for Conservation and Management.” Electronic PDF.

Daggupati, P., H. Yen, M.J. White, R. Srinivasan, J.G. Arnold, C.S. Keitzer, and S.P. Sowa. "Impact of Model Development, Calibration and Validation Decisions on Hydrological Simulations in West Lake Erie Basin." *Hydrological Processes* 29(26/2015): 5307–5320. DOI: 10.1002/hyp.10536.

Daloğlu, I., K.H. Cho, and D. Scavia. "Evaluating Causes of Trends in Long-Term Dissolved Reactive Phosphorus Loads to Lake Erie." *Environmental Science and Technology* 46 (19/2012): 10660-10666. DOI**:** 10.1021/es302315d.

Daloğlu, I., J.I. Nassauer, R. Riolo, and D. Scavia. "An Integrated Social and Ecological Modeling Framework—Impacts of Agricultural Conservation Practices on Water Quality." *Ecology and Society* 19(3/2014): 12. DOI: 10.5751/ES-06597-190312.

Davis, T.W, D.L. Berry, G.L. Boyer, and C.J. Gobler. "The Effects of Temperature and Nutrients on the Growth and Dynamics of Toxic and Non-Toxic Strains of *Microcystis* During Cyanobacteria Blooms." *Harmful Algae* 8(2009): 715-725. DOI: 10.1016/j.hal.2009.02.004.

Davis, T. W., M. J. Harke, M. A. Marcoval, J. Goleski, C. Orano-Dawson, D. L. Berry, and C. J. Gobler. "Effects of Nitrogenous Compounds and Phosphorus on the Growth of Toxic and Non-Toxic Strains of *Microcystis* During Cyanobacterial Blooms." *Aquatic Microbial Ecology* 61(2010): 149-162. DOI: 10.3354/ame01445.

Davis, T.W., G.S. Bullerjahn, T.T. Tuttle, R.M. McKay, and S.B. Watson. "Effects of Increasing Nitrogen and Phosphorus Concentrations on Phytoplankton Community Growth and Toxicity During *Planktothrix* Blooms in Sandusky Bay, Lake Erie." *Environmental Science and Technology* 49(2015): 7197-7207.DOI: 10.1021/acs.est.5b00799. http://www.glerl.noaa.gov/pubs/fulltext/2015/20150039.pdf. Last accessed: March 4, 2016.

Dayton, E.A., S.D. Whitacre, and C.H. Holloman. "Demonstrating the Relationship Between Soil Phosphorus Measures and Phosphorus Solubility: Implications for Ohio Phosphorus Risk Assessment Tools. *Journal of Great Lakes Research*, 40(3/2014): 473–478. DOI: 10.1016/j.jglr.2014.04.001.

Delorme, L. D. "Lake Erie Oxygen: The Prehistoric Record." *Canadian Journal of Fisheries and Aquatic Sciences* 39(1982): 1021–1029. DOI: 10.1139/f82-137.

Diaz, R.J., and R. Rosenberg. "Spreading Dead Zones and Consequences for Marine Ecosystems." *Science* 321(5891/2008): 926-929. DOI: 10.1126/science.1156401.

Dolan, D.M., and S.C. Chapra. "Great Lakes Total Phosphorus Revisited: 1. Loading Analysis and Update (1994-1998)". *Journal of Great Lakes Research* 38(2012): 730-740. DOI: 10.1016/j.jglr.2012.10.001.

Drikas, M., C.W.K. Chow, J. House, M. Burch. "Using Coagulation, Flocculation, and Settling to Remove Toxic Cyanobacteria." *Journal of the American Water Works Association* 93(2/2001): 100-111.

Drinking Water Protection Act (P.L. 114-45). https://www.congress.gov/114/plaws/publ45/PLAW-114publ45.pdf. Last accessed: November 11, 2016.

Dyble, J., G.L. Fahnenstiel, R. Wayne Litaker, D.F. Millie, P.A. Tester. "Microcystin Concentrations and Genetic Diversity of *Microcystis* in the Lower Great Lakes." *Environmental Toxicology* 23(4/2008):507-516. DOI: 10.1002/tox.20370.

"Ecological Forecasting: Hypoxia Assessment in Lake Erie." (EcoFore.) http://ecofore.org/hypoxia/. Last accessed September 2, 2016.

Eimers, M.C., and S.A. Watmough. “Increasing Nitrate Concentrations in Streams Draining into Lake Ontario.” *Journal of Great Lakes Research* 42(2/2016): 356-363. DOI: 10.1016/j.jglr.2016.01.002.

Fahnenstiel, G.L., D.F. Millie, J. Dyble, R.W. Litaker, P.A. Tester, M.J. McCormick, R. Rediske, and D. Klarer. “Microcystin Concentrations and Cell Quotas in Saginaw Bay, Lake Huron.” *Aquatic Ecosystem Health & Management* 11 (2/2008): 190-195. DOI: 10.1080/14634980802092757

Fan, J., R. Daly, P. Hobson, L. Ho, and J. Brookes. “Impact of Potassium Permanganate on Cyanobacterial Cell Integrity and Toxin Release and Degradation.” *Chemosphere* 92(5/2013a): 529-534. DOI: http://dx.doi.org/10.1016/j.chemosphere.2013.03.022.

Fan, J., L. Ho, P. Hobson, and J. Brookes. “Evaluating the Effectiveness of Copper Sulphate, Chlorine, Potassium Permanganate, Hydrogen Peroxide and Ozone on Cyanobacterial Cell Integrity.” *Water Research* 47(14/2013b): 5153-5164. DOI: http://dx.doi.org/10.1016/j.watres.2013.05.057.

Fan, J., P. Hobson, L. Ho, R. Daly, and J. Brookes. “The Effects of Various Control and Water Treatment Processes on the Membrane Integrity and Toxin Fate of Cyanobacteria.” *Journal of Hazardous Materials* 264(2015): 313-322. DOI: 10.1016/j.jhazmat.2013.10.059.

Fang, X., and H.G. Stefan. “Simulations of Climate Effects on Water Temperature, Dissolved Oxygen, and Ice and Snow Covers in Lakes of the Contiguous United States Under Past and Future Climate Scenarios.” *Limnology and Oceanography* 54(6/2009): 2359–2370.

Feyereisen, G.W., W. Francesconi, D.R. Smith, S.K. Papiernik, E.S. Krueger, C.D. Wente. “Effect of Replacing Surface Inlets with Blind or Gravel Inlets on Sediment and Phosphorus Subsurface Drainage Losses.” *Journal of Environmental Quality* 44(2/2015): 594-604. DOI: 10.2134/jeq2014.05.0219.

Fishman, D.B., S.A. Adlerstein, H.A. Vanderploeg, G.L. Fahnenstiel, and D. Scavia. “Causes of Phytoplankton Changes in Saginaw Bay, Lake Huron, During the Zebra Mussel Invasion." *Journal of Great Lakes Research* 35 (4/2009): 482-495. DOI: 10.1016/j.jglr.2009.08.003.

Fishman, D.B., S.A. Adlerstein, H.A. Vanderploeg, G.L. Fahnenstiel, and D. Scavia. “Phytoplankton Community Composition of Saginaw Bay, Lake Huron, During the Zebra Mussel (*Dreissena polymorpha*) Invasion: A Multivariate Analysis.” *Journal of Great Lakes Research* 36 (1/2010): 9-19. DOI: 10.1016/j.jglr.2009.10.004.

Food, Conservation, and Energy Act of 2008. (P.L. 110-234). https://www.gpo.gov/fdsys/pkg/PLAW-110publ234/pdf/PLAW-110publ234.pdf. Last accessed: November 11, 2016.

Forster, D.L. “Public Policies and Private Decisions: Their Impacts on Lake Erie Water Quality and Farm Economy.” *Journal of Soil and Water Conservation* 55(3/2000): 309–327.

Forster, D.L. “Effects of Conservation Tillage on the Performance of Lake Erie Basin Farms.” *Journal of Environmental Quality* 31(1/2002): 32–37. DOI: 10.2134/jeq2002.3200.

Forster, D.L., and J.N. Rausch. “Evaluating Agricultural Nonpoint-Source Pollution Programs, in Two Lake Erie Tributaries.” *Journal of Environmental Quality* 31(1/2002): 24–31. DOI: 10.2134/jeq2002.2400.

Forster, D.L., E.C. Smith, and D. Hite. “A Bioeconomic Model of Farm Management Practices and Environmental Effluents in the Western Lake Erie Basin.” *Journal of Soil and Water Conservation*, 55(2/2000): 177–182.

Francesconi, W., C. O. Williams, D. R. Smith, J. R. Williams, and J. Jeong. “Phosphorus Modeling in Tile Drained Agricultural Systems Using APEX.” *Journal of Fertilizers and Pesticides* 7 (166/2016). DOI: 10.4172/2471-2728.1000166.

Francey, D.S., J.L. Graham, E.A. Stelzer, C.D. Ecker, A.M.G. Brady, P. Struffolino, and K.A. Loftin. "Water Quality, Cyanobacteria, and Environmental Factors and their Relations to Microcystin Concentrations for Use in Predictive Models at Ohio Lake Erie and Inland Lake Recreational Sites, 2013–14: U.S. Geological Survey Scientific Investigations Report 2015-5120. 2015. DOI: 10.3133/sir20155120.

Gademann, K., and C. Portmann. "Secondary Metabolites from Cyanobacteria: Complex Structures and Powerful Bioactivities." *Current Organic Chemistry* 12(4/2008): 326-341. DOI: https://doi.org/10.2174/138527208783743750.

Gibble, C.M., M.B. Peacock, and R.M. Kudela. "Evidence for Freshwater Algal Toxins in Marine Shellfish: Implications for Human and Aquatic Health." *Harmful Algae* 59(2016): 59-66.

Gobler, C.J., J.M. Burkholder, T.W. Davis, M.J. Harke, T. Johengen, C.A. Stow, and D.B. Van de Waal. "The Dual Role of Nitrogen Supply in Controlling the Growth and Toxicity of Cyanobacterial Blooms." *Harmful Algae* 54 (2016): 87-97. DOI: 10.1016/j.hal.2016.01.010.

Gobler, C. J., T.W. Davis, K. J. Coyne, and G. L. Boyer. "Interactive Influences of Nutrient Loading, Zooplankton Grazing, and Microcystin Synthetase Gene Expression on Cyanobacterial Bloom Dynamics in a Eutrophic New York Lake." *Harmful Algae* 6(1/2007): 119-133. DOI: 10.1016/j.hal.2006.08.003.

Great Lakes Environmental Assessment and Mapping Project (GLEAM), and S. Ruberg, personal communication. "Hypoxia: Mapping Hypoxia as a Great Lakes Stressor." (2011.) http://greatlakesmapping.org/great_lake_stressors/6/hypoxia. Last accessed July 13, 2016.

Great Lakes Restoration Initiative (GLRI). "Great Lakes Restoration Initiative Action Plan II." (2014). http://greatlakesrestoration.us/actionplan/pdfs/glri-action-plan-2.pdf. Last accessed: May 19, 2016.

Great Lakes Water Quality Agreement (GLWQA) Annex 4 Objectives and Targets Task Team. "Recommended Phosphorus Loading Targets for Lake Erie." (2015). https://www.epa.gov/sites/production/files/2015-06/documents/report-recommended-phosphorus-loading-targets-lake-erie-201505.pdf. Last accessed: January 29, 2016.

Hamidi, S.A., H.R. Bravo, and J.V. Klump. "Evidence of Multiple Physical Drivers on the Circulation and Thermal Regime in the Green Bay of Lake Michigan." *World Environmental and Water Resources Congress 2013: Showcasing the Future.* (2013): 1719-1726. DOI: 10.1061/9780784412947.169.

Han, H., N. Bosch, and J.D. Allan. "Spatial and Temporal Variation in Phosphorus Budgets for 24 Watersheds in the Lake Erie and Lake Michigan Basins." *Biogeochemistry* 102(2011): 45-58. DOI 10.1007/1s0533-10 0-9420-y.

Hansen, K., L. Rosenqvist, L. Vesterdal, and P. Gundersen. "Nitrate Leaching from Three Afforestation Chronosequences on Former Arable Land in Denmark." *Global Change Biology* 13(6/2007): 1250-1264. DOI: 10.1111/j.1365-2486.2007.01355.x.

Harke, M.J., T.W. Davis, S.B. Watson, and C.J. Gobler. "Nutrient-Controlled Niche Differentiation of Western Lake Erie Cyanobacterial Populations Revealed via Metatranscriptomic Surveys." *Environmental Science and Technology* 50(2015): 604-615. DOI: 10.1021/acs.est.5b03931.

Harmful Algal Bloom and Hypoxia Research and Control Act (P.L. 113-124). (2014). [https://www.gpo.gov/fdsys/pkg/PLAW-113publ124/pdf/PLAW-113publ124.pdf.

Hawley, N., T.H. Johengen, Y.R. Rao, S.A. Ruberg, D. Beletsky, S.A. Ludsin, B.J. Eadie, D.J. Schwab, T.E. Croley, and S.B. Brandt. "Lake Erie Hypoxia Prompts Canada-U.S. Study." *EOS Transactions* 87(32/2006): 313-324. DOI: 10.1029/2006EO320001.

Health Canada. “Guidelines for Canadian Drinking Water Quality: Supporting Documentation – Cyanobacterial Toxins — Microcystin-LR. Federal-Provincial-Territorial Committee on Drinking Water.” (2002). http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/sum_guide-res_recom/index-eng.php. Last accessed: November 6, 2016.

Her, Y., I. Chaubey, J. Frankenberger, and D. Smith. “Effect of Conservation Practices Implemented by USDA Programs at Field and Watershed Scales." *Journal of Soil and Water Conservation* 71(3/2016): 249-266. DOI:10.2489/jswc.71.3.249.

Horst, G.P., O. Sarnelle, J.D. White, S.K. Hamilton, R.B. Kaul, and J.D. Bressie. “Nitrogen Availability Increases the Toxin Quota of Harmful Cyanobacterium, *Microcystis aeruginosa*.” *Water Research* 54(2014): 188-198. DOI: 10.1016/j.watres.2014.01.063.

Huang, A., Y.R. Rao, and W. Zhang. “On Recent Trends in Atmospheric and Limnological Variables in Lake Ontario." *Journal of Climate* 25 (17/2012): 5807-5816. DOI: 10.1175/JCLI-D-11-00495.1.

International Joint Commission (IJC 2013). *Human Health Effects from Harmful Algal Blooms: A Synthesis.* 9 (2013). http://www.ijc.org/files/publications/Attachment%202%20Human%20Health%20Effects%20from%20Harmful%20Algal%20Blooms.pdf. Last accessed: May 19, 2016.

International Joint Commission (IJC 2014). *A Balanced Diet for Lake Erie: Reducing Phosphorus Loadings and Harmful Algal Blooms.* Report of the Lake Erie Ecosystem Priority. 2014. http://www.ijc.org/files/publications/2014%20IJC%20LEEP%20REPORT.pdf. Last accessed: May 19, 2016.

Jenny, J.-P., P. Francus, A. Normandeau, F. Lapointe, M.-E. Perga, A. Ojala, A. Schimmelmann, and B. Zolitschka. “Global Spread of Hypoxia in Freshwater Ecosystems During the Last Three Centuries is Caused by Rising Local Human Pressure.” *Global Change Biology* 22 (2016): 1481–1489. DOI: 10.1111/gcb.13193.

Kay, R.T. “Hydrogeology and Groundwater Quality at Monitoring Wells Installed for the Tunnel and Reservoir Plan System and Nearby Water-Supply Wells, Cook County, Illinois, 1995–2013: (ver. 1.1, May 2016).” U.S. Geological Survey Scientific Investigations Report (2016): 2015–5186. DOI: http://dx.doi.org/10.3133/sir20155186.

Keitzer, S.C., S.A. Ludsin, S.P. Sowa, A.M. Sasson, G. Annis, J.G. Arnold, A. Brennan, P. Daggupati, A.M. Froehlich, M.E. Herbert, C. Vollmer-Sanders, M.J. White, C. J. Winslow, and H. Yen. “Quantifying the Potential Water Quality Benefits of Agricultural Conservation Practices for Stream Fish Conservation in the Western Lake Erie Basin. Final Report submitted to NRCS Conservation Effects Assessment Project.” 2016. http://lakeerieceap.com/wp-content/uploads/2016/09/Final_Report_with_Appendices.pdf. Last accessed: September 27, 2016.

Kenow, K.P., Z. Ge, L.J. Fara, S.C. Houdek, B.R. Lubinski. “Identifying the Origin of Waterbird Carcasses in Lake Michigan Using a Neural Network Source Tracking Model.” *Journal of Great Lakes Research* (2016). https://doi.org/10.1016/j.jglr.2016.02.014.

King, K.W., M.R. Williams, and N.R. Fausey. “Contributions of Systematic Tile Drainage to Watershed-Scale Phosphorus Transport.” *Journal of Environmental Quality* 44(2015b): 486-494. DOI: doi:10.2134/jeq2014.04.0149.

Kleinman, P.J.A., A.N. Sharpley, R.W. McDowell, D.N. Flaten, A.R. Buda, L. Tao, L. Bergstrom, and Q. Zhu. "Managing Agricultural Phosphorus for Water Quality Protection: Principles for Progress." *Plant and Soil* 349(2011): 169-182. DOI: 10.1007/s11104-011-0832-9.

Knoll, L.B., O. Sarnelle, S.K. Hamilton, C.E.H. Kissman, A.E. Wilson, J.B. Rose, and M.R. Morgan. "Invasive Zebra Mussels (*Dreissena polymorpha*) Increase Cyanobacterial Toxin Concentrations in Low-Nutrient Lakes." *Canadian Journal of Fish and Aquatic Sciences* 65(2008): 448-455. DOI: 10.1139/F07-181.

Kraus, R.T., C.T. Knight, T.M. Farmer, A.M. Gorman, P.D. Collingsworth, G.J. Warren, P.M. Kocovsky, and J.D. Conroy. "Dynamic Hypoxic Zones in Lake Erie Compress Fish Habitat, Altering Vulnerability to Fishing Gears." *Canadian Journal of Fisheries and Aquatic Sciences* 72(2015): 797-806. DOI: DOI/10.1139/cjfas-2014-0517.

Kröger, R., E.J. Dunne, J. Novak, K.W. King, E. McLellan, D.R. Smith, J. Strock, K. Boomer, M. Tomer, and G.B. Noe. "Downstream Approaches to Phosphorus Management in Agricultural Landscapes: Regional Applicability and Use." *Science of the Total Environment* 442(2013): 263-274. DOI: 10.1016/j.scitotenv.2012.10.038.

Kutovaya, O.A., R.M.L. McKay, B.F.N. Beall, S.W. Wilhelm, D.D. Kane, J.D. Chaffin, T.B. Bridgeman, and G.S. Bullerjahn. "Evidence Against Fluvial Seeding of Recurrent Toxic Blooms of *Microcystis* spp. in Lake Erie's Western Basin." *Harmful Algae* 15(2012): 71-77. DOI: 10.1016/j.hal.2011.11.007.

Lake Erie Nutrient Targets Working Group (LENT). "A Joint Action Plan for Lake Erie." A Report of the Great Lakes Commission Lake Erie Nutrient Targets Working Group. (2015). http://glc.org/files/projects/lent/LENT-Joint-Action-Plan-FINAL-Sept-2015.pdf. Last accessed: May 19, 2016.

Lan, C.C., C.I. Kahn, A.J. Borchert, M.N. Byappanahalli, R.L. Whitman, J. Peller, C. Pier, G. Lin, E.A. Johnson, and M.J. Sandowsky. "Prevalence of Toxin-Producing *Clostridium botulinum* Associated with the Macroalga *Cladophora* in Three Great Lakes: Growth and Management." *Science of the Total Environment* 511(2015): 523-529. DOI: 10.1016/j.scitotenv.2014.12.080.

Lopez, C.B., E.B. Jewett, Q. Dortch, B.T. Walton, and H.K. Hudnell. "Scientific Assessment of Freshwater Harmful Algal Blooms." Washington, D.C.: Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. 2008. https://www.whitehouse.gov/sites/default/files/microsites/ostp/frshh2o0708.pdf. Last accessed: May 19, 2016.

Lowrance, R. "Riparian Forest Ecosystems as Filters for Nonpoint-Source Pollution." In: Michael L. Pace and Peter M. Groffman (eds.): *Successes, Limitations, and Frontiers in Ecosystem Science*. (New York, New York, USA: Springer New York, 2007): 113-141. ISBN: 978-0-387-98475-9.

Lürling, M., and I. Roessink. "On the Way to Cyanobacterial Blooms: Impact of the Herbicide Metribuzin on the Competition between a Green Alga (*Scenedesmus*) and a Cyanobacterium (*Microcystis*)." *Chemosphere* 65(4/2006): 618-626. DOI: 10.1016/j.chemosphere.2006.01.073.

Makarewicz, J.C., T.W. Lewis, M. Winslow, E. Rea, L. Dressel, D. Pettenski, B.J. Snyder, P. Richards, and J. Zollweg. "Utilizing Intensive Monitoring and Simulations for Identifying Sources of Phosphorus and Sediment and for Directing, Siting, and Assessing BMPs: The Genesee River Example." *Journal of Great Lakes Research* 41(3/2015): 743-759. DOI: 10.1016/j.jglr.2015.06.004.

Mallin, M.A., V.L. Johnson, S.H. Ensign, and T.A. MacPherson. “Factors Contributing to Hypoxia in Rivers, Lakes, and Streams.” *Limnology and Oceanography* 51(2006): 690-710. DOI: 10.4319/lo.2006.51.1_part_2.0690.

Matisoff, G., E.C. Bonniwell, and P.J. Whiting. "Soil Erosion and Sediment Sources in an Ohio Watershed Using Beryllium-7, Cesium-137, and Lead-210." *Journal of Environmental Quality* 31(1/2002): 54-61. DOI: 10.2134/jeq2002.5400.

Mayer, P.M., S.K. Reynolds, Jr., M.D. McCutchen, T.J. Canfield. “Meta-Analysis of Nitrogen Removal in Riparian Buffers.” *Journal of Environmental Quality* 36(4/2007): 1172-1180. DOI: 10.2134/jeq2006.0462.

McCarty, C.L., L. Nelson, S. Eitniear, E. Zgodzinski, A. Zabala, L. Billing, and M. DiOrio. “Community Needs Assessment After Microcystin Toxin Contamination of a Municipal Water Supply – Lucas County, Ohio, September 2014.” *MMWR Morb Mortal Weekly Report* 65(2016): 925–929. DOI: http://dx.doi.org/10.15585/mmwr.mm6535a1.

McDonald, C.P., N.R. Urban, and C.M. Casey. “Modeling Historical Trends in Lake Superior Total Nitrogen Concentrations.” *Journal of Great Lakes Research* 41(2010): 715-721. DOI: 10.1016/j.jglr.2010.07.008.

Meals, D.W., S.A. Dressing, and T.E. Davenport. “Lag Time in Water Quality Response to Best Management Practices: A Review.” *Journal of Environmental Quality* 39(2010): 85-96. DOI: 10.2134/jeq2009.0108.

Meals, D.W., D.L. Osmond, J. Spooner, and D.E. Line. “Chapter 4: Water Quality Monitoring: National Institute of Food and Agriculture–Conservation Effects Assessment Project.” In: Deanna L. Osmond, Donald W. Meals, Dana LK. Hoag, and Mazdak Arabi (eds.): *Water Quality Monitoring: National Institute of Food and Agriculture–Conservation Effects Assessment Project. How to Build Better Agricultural Conservation Programs to Protect Water Quality: The National Institute of Food and Agriculture–Conservation Effects Assessment Project Experience*. (Ankeny, Iowa, USA: Soil and Water Conservation Society, 2012): 58-83. ISBN: 978-0-9769432-9-7.

Meehl, G.A., F. Zwiers, J. Evans, T. Knutson, L. Mearns, and P.R Whetton. “Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extremes in Projections of Future Climate Change.” *Bulletin of the American Meteorological Society* 81(3/2000): 427-436. DOI: 10.1175/1520-0477(2000)081<0427:TIEWAC>2.3.CO;2.

Michalak, A.M., E.J. Anderson, D. Beletski, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, J.V. DePinto, M.A. Evans, G.L. Fahnenstiel, L. He, J.C. Ho, L. Jenkins, T.H. Johengen, K.C. Kuo, E. LaPorte, X. Liu, M.R. McWilliams, M.R. Moore, D.J. Posselt, R.P. Richards, D. Scavia, A.L. Steiner, E. Verhamme, D.M. Wright, and M.A. Zagorski. “Record-Setting Algal Bloom in Lake Erie Caused by Agricultural and Meteorological Trends Consistent with Expected Future Conditions.” *Proceedings of the National Academy of Sciences* 110.16(2013): 6448-6452. DOI: 10.1073/pnas.1216006110.

Millie, D.F., G.L. Fahnenstiel, G.R. Weckman, D.M. Klarer, J. Dyble, H.A. Vanderploeg, and D.B. Fishman. “An Enviro-Informatic Assessment of Saginaw Bay (Lake Huron, USA) Phytoplankton: Data-Driven Characterization and Modeling of *Microcystis* (Cyanophyta).” *Journal of Phycology* 47(4/2011): 714-730. DOI: 10.1111/j.1529-8817.2011.01022.x.

Miller, M.A., R.M. Kudela, A. Mekebri, D. Crane, S.C. Oates, M.T. Tinker, M. Staedler, W.A. Miller, S. Toy-Choutka, C. Dominik, D. Hardin, G. Langlois, M. Murray, K. Ward, and D.A. Jessup. "Evidence for a Novel Marine Harmful Algal Bloom: Cyanotoxin (Microcystin) Transfer from Land to Sea Otters." *PLoS One* (2010). DOI: http://dx.doi.org/10.1371/journal.pone.0012576.

Molder, B., J. Cockburn, A. Berg, J. Lindsay, and K. Woodrow. "Sediment-Assisted Nutrient Transfer from a Small, No-Till, Tile Drained Watershed in Southwestern Ontario, Canada." *Agricultural Water Management* 152(2015): 31-40. DOI: 10.1016/j.agwat.2014.12.010

Nakao, M., and Sohngen, B. "The Effect of Site Quality on the Costs of Reducing Soil Erosion with Riparian Buffers." *Journal of Soil and Water Conservation* 55(2/2000): 231–237.

Napier, T.L., "Human Dimensions of Conservation Adoption Behaviors: The United States Experience." in Ted L. Napier (ed.) *Human Dimensions of Soil and Water Conservation: A Global Perspective*. (Hauppauge, NY: Nova Science Publishers, Inc., 2011).

National Atmospheric Deposition Program (NADP). "Critical Loads of Atmospheric Deposition Science Committee: 2015 Summary of Critical Load Maps." (2015). http://nadp.sws.uiuc.edu/lib/CLAD/Cladreport14.pdf. Last accessed: November 10, 2016.

National Science and Technology Council (NSTC). Harmful Algal Blooms and Hypoxia Comprehensive Research *Plan and Action Strategy: An Interagency Report*. (2016). Pub.: Office of Science and Technology Policy. https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/habs_hypoxia_research_plan_and_action_-_final.pdf. Last accessed: May 19, 2016.

Newcombe, G., J. Dreyfus, Y., Monrolin, C. Pestana, P. Reeve, E. Sawade, L. Ho, C. Chow, S.W. Krasner, and R.S. Yates. "Optimizing Conventional Treatment for the Removal of Cyanobacteria and Toxins." Water Research Foundation: Order Number 4315. 2015. http://www.waterrf.org/ExecutiveSummaryLibrary/4315_ProjectSummary.pdf Last accessed: November 6, 2016.

Obenour, D.R., A.D. Gronewold, C.A. Stow, and D. Scavia. "Using a Bayesian Hierarchical Model to Improve Lake Erie Cyanobacteria Bloom Forecasts." *Water Resources Research* 50(2014/10): 7847-7860. 10.1002/2014WR015616.

Ohio Environmental Protection Agency (OH EPA). "Ohio Nutrient Reduction Strategy." (2013.) http://epa.ohio.gov/Portals/35/wqs/ONRS_final_jun13.pdf. Last accessed: February 10, 2017.

Ohio Environmental Protection Agency (OH EPA). "Public Water System Harmful Algal Bloom Response Strategy." (2015.) http://epa.ohio.gov/Portals/28/documents/HABs/PWS_HAB_Response_Strategy.pdf. Last accessed: November 6, 2016.

Ohio Environmental Protection Agency (OH EPA). "Generalized Cyanotoxin Treatment Optimization Recommendations." (2016). http://epa.ohio.gov/Portals/28/documents/habs/Generalized%20Cyanotoxin%20Treatment%20Optimization%20Recommendations.pdf. Last accessed: November 6, 2016.

O'Neil, J.M., T.W., Davis, M.A. Burford, and C.J. Gobler. "The Rise of Harmful Cyanobacteria Blooms: The Potential Roles of Eutrophication and Climate Change." *Harmful Algae* 14(2012): 313-334. DOI: 10.1016/j.hal.2011.10.027.

Osmond, D., D.W. Meals, D.L.K. Hoag, and M. Arabi (eds.) (2012a): *Water Quality Monitoring: National Institute of Food and Agriculture–Conservation Effects Assessment Project. How to Build Better Agricultural Conservation Programs to Protect Water Quality: The National Institute of Food* *and Agriculture–Conservation Effects Assessment Project Experience*. (Ankeny, Iowa, USA: Soil and Water Conservation Society, 2012a): 58-83. ISBN: 978-0-9769432-9-7.

Osmond, D., A. Sharpley, C. Bolster, M. Cabrera, S. Feagley, B. Lee, C. Mitchell, R. Mylavarapu, L. Oldham, F. Walker, and H. Zhang. "Comparing Phosphorus Indices from Twelve Southern US States Against Monitored Phosphorus Loads from Six Prior Southern Studies." *Journal of Environmental Quality* 41(6/2012b): 1741-1749. DOI: 10.2134/jeq2012.0013.

Ou, H., N. Gao, W. Chaohai, D. Yang, and J. Qiao. "Immediate and Long-Term Impacts of Potassium Permanganate on Photosynthetic Activity, Survival and Microcystin-LR Release Risk of *Microcystis aeruginosa*." *Journal of Hazardous Materials* 219-220(2012): 267-275. DOI: http://dx.doi.org/10.1016/j.jhazmat.2012.04.006.

Paul, M.J., and J.L Meyer. "Streams in the Urban Landscape." *Annual review of Ecology and Systematics* (2011): 333-365. DOI: 10.1146/annurev.ecolsys.32.081501.114040.

Paerl, H.W., and J. Huisman. "Blooms Like It Hot." *Science* 320(2008): 57-58. DOI: 10.1126/science.1155398.

Paerl, H.W., and J. Huisman. "Climate Change: A Catalyst for Global Expansion of Harmful Cyanobacterial Blooms." *Environmental Microbiology Reports* 1(1/2009): 27-37. DOI: 10.1111/j.1758-2229.2008.00004.x.

Paerl, H.W., and V.J. Paul. "Climate Change: Links to Global Expansion of Harmful Cyanobacteria." *Water Research*. 46(2012): 1349-1363. DOI: 10.1016/j.watres.2011.08.002.

Paerl, H.W., T.G. Otten. "Blooms Bite the Hand that Feeds Them." *Science* 342(6157/2013): 433-434. DOI: 10.1126/science.1245276.

Paerl, H.W., W.S. Gardner, K.E. Havens, A.R. Joyner, M.J. McCarthy, S.E. Newell, B. Qin, and J.T. Scott. "Mitigating Cyanobacterial Harmful Algal Blooms in Aquatic Ecosystems Impacted by Climate Change and Anthropogenic Nutrients." *Harmful Algae* 54 (2016): 213-222. DOI: 10.1016/j.hal.2015.09.009.

Peterson, H.G., C. Boutin, K.E. Freemark, and P.A. Martin. "Toxicity of Hexazinone and Diquat to Green Algae, Diatoms, Cyanobacteria and Duckweed." *Aquatic Toxicology* 39(1997): 111-134. DOI:10.1016/S0166-445X(97)00022-2.

Qiu, H., J. Geng, H. Ren, X. Xia, X. Wang, and Y. Yu. "Physiological and Biochemical Responses of *Microcystis aeruginosa* to Glyphosate and its Roundup® Formulation." *Journal of Hazardous Materials* 248(2013): 172-176. DOI: 10.1016/j.jhazmat.2012.12.033.

Rabalais, N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang. "Dynamics and Distribution of Natural and Human-Caused Hypoxia." *Biogeosciences* 7(2010): 585-619. DOI: doi:10.5194/bg-7-585-2010.

Raikow, D.F., O. Sarnelle, A.E. Wilson, and S.K. Hamilton. "Dominance of the Noxious Cyanobacterium *Microcystis aeruginosa* in Low-Nutrient Lakes is Associated with Exotic Zebra Mussels." *Limnology and Oceanography* 49(2/2004): 482-487. http://www.jstor.org.proxy.lib.umich.edu/stable/3597857. Last accessed: May 19, 2016.

Reavie, E.D., M. Cai, M.R. Twiss, H.J. Carrick, T.W. Davis, T.H. Johengen, D. Gossiaux, D.E. Smith, D. Palladino, A. Burtner, and G.V. Sgro. "Winter–Spring Diatom Production in Lake Erie is an Important Driver of Summer Hypoxia." *Journal of Great Lakes Research* 42 (3/2016): 608-618. DOI: 10.1016/j.jglr.2016.02.013.

Richards, R.P., and D.B. Baker. "Trends in Water Quality in LEASEQ Rivers and Streams (Northwestern Ohio), 1975–1995." *Journal of Environmental Quality* 31 (1/2002): 90-96. DOI: 10.2134/jeq2002.9000.

Richards, R.P., D.B. Baker, and J.P. Crumrine. "Improved Water Quality in Ohio Tributaries to Lake Erie: A Consequence of Conservation Practices." *Journal of Soil and Water Conservation* 64(3/2009): 200-211. DOI: doi:10.2489/jswc.64.3.200

Richards, R.P., D.B. Baker, J.P. Crumrine, and A.M. Stearns. "Unusually Large Loads in 2007 from the Maumee and Sandusky Rivers, Tributaries to Lake Erie." *Journal of Soil and Water Conservation* 65(6/2010): 450-462. DOI: 10.2489/jswc.65.6.450.

Robertson, D.M. and D.A. Saad. "Nutrient Inputs to the Laurentian Great Lakes by Source and Watershed Estimated Using SPARROW Watershed Models." *Journal of the American Water Resources Association (JAWRA)* 47(5/2011): 1011-1033. DOI: 10.1111/j.1752-1688.2011.00574.x

Ross, C., L. Santiago-Vásquez, and V. Paul. "Toxin Release in Response to Oxidative Stress and Programmed Cell Death in the Cyanobacterium *Microcystis aeruginosa*." *Aquatic Toxicology* 78(2006): 66-73. DOI: 10.1016/j.aquatox.2006.02.007.

Rowe, M.D., D.M. Dolan, and R.G. Kreis Jr. "Reactive Nitrogen Mass Budget for Lake Michigan. Journal of Great Lakes Research." 40(1/2014): 192-201. DOI: 10.1016/j.jglr.2013.11.005. http://www.sciencedirect.com/science/article/pii/S038013301300172X. Last accessed: August 1, 2016.

Rowe, M.D., E.J. Anderson, T.T. Wynne, R.P. Stumpf, D.L. Fanslow, K. Kijanka, H.A. Vanderploeg, T.W. Davis. "Vertical Distribution of Buoyant *Microcystis* Blooms in a Langrangian Particle Tracking Model for Short-Term Forecasts in Lake Erie." *Journal of Geophysical Research – Oceans* 121(2016). DOI: doi:10.1002/2016JC011720.

Ruberg, S.A., E. Guasp, N. Hawley, R.W. Muzzi, S.B. Brandt, H.A. Vanderploeg, J.C. Lane, T.C. Miller, and S.A. Constant. "Societal Benefits of the Real-Time Coastal Observation Network (ReCON): Implications for Municipal Drinking Water Quality." *Marine Technology Society Journal* 42(3/2008): 103-109. DOI: 10.4031/002533208786842471.

Ruberg, S. Personal email communication. Great Lakes Environmental Research Laboratory. April 25, 2016.

Rucinski, D.K., J.V. DePinto, D. Beletsky, and D. Scavia. "Modeling Hypoxia in the Central Basin of Lake Erie Under Potential Phosphorus Load Reduction Scenarios." *Journal of Great Lakes Research* (2016). DOI: 0.1016/j.jglr.2016.07.001.

Saxton, M.A., E.A. Morrow, R.A. Bourbonniere, and S.W. Wilhelm. "Glyphosate Influence on Phytoplankton Community Structure in Lake Erie." *Journal of Great Lakes Research* 37(2011): 683-690. DOI: 10.1016/j.jglr.2011.07.004.

Scavia, D., J.D. Allan, K.K. Arend, S. Bartel, D. Beletsky, N.S. Bosch, S.B. Brandt, R.D. Briland, I. Daloğlu, J.V. DePinto, D.M. Dolan, M.A. Evans, T.M. Farmer, D. Goto, H. Han, T.O. Höök, R. Knight, S.A. Ludsin, D. Mason, A.M. Michalak, R.P. Richards, J.J. Roberts, D. K. Rucinski, E. Rutherford, D.J. Schwab, T.M. Sesterhenn, H. Zhang, and Y. Zhou. "Assessing and Addressing the Re-Eutrophication of Lake Erie: Central Basin Hypoxia." *Journal of Great Lakes Research* 40 (2/2014): 226-246. DOI: 10.1016/j.jglr.2014.02.004.

Scavia, D., M. Kalcicl, R. Logsdon Muenich, N. Aloysius, J. Arnold, C. Boles, R. Confesor, J. DePinto, M. Gildow, J. Martin, J. Read, T. Redder, D. Robertson, S. Sowa, Y.-C. Wang, M. White, and H. Yen. "Informing Lake Erie Agriculture Nutrient Management via Scenario Evaluation." Graham Sustainability Institute, University of Michigan. 2016. http://graham.umich.edu/media/pubs/InformingLakeErieAgricultureNutrientManagementviaScenarioEvaluation.pdf. Last accessed: May 19, 2016.

Schmidt, J.R., M. Shaskus, J.F. Estenik, C. Oesch, R. Kidekel, and G. Boyer. "Variations in the Microcystin Content of Different Fish Species Collected from a Eutrophic Lakes." *Toxins* 5(5/2013): 992-1009. DOI: http://doi.org/10.3390/toxins5050992.

Seilheimer, T.S., P.L. Zimmerman, K.M. Stueve, and C.H. Perry. "Landscape-Scale Modeling of Water Quality in Lake Superior and Lake Michigan Watersheds: How Useful are Forest-Based Indicators?" *Journal of Great Lakes Research* 39(2/2013) 211-223. DOI: http://dx.doi.org/10.1016/j.jglr.2013.03.012.

Sharpley, A., H.P. Jarvie, A. Buda, L. May, B. Spears, and P. Kleinman. "Phosphorus Legacy: Overcoming the Effects of Past Management Practices to Mitigate Future Water Quality Impairment." *Journal of Environmental Quality* 42(2013): 1308-1326. DOI:10.2134/jeq2013.03.0098.

Shuchman, R.A., M.J. Sayers, and C.N. Brooks. "Mapping and Monitoring the Extent of Submerged Aquatic Vegetation in the Laurentian Great Lakes with Multi-Scale Satellite Remote Sensing." *Journal of Great Lakes Research* 39(2013): 78-89. DOI: http://dx.doi.org/10.1016/j.jglr.2013.05.006.

Smith, D.R., and S.J. Livingston. "Managing Farmed Closed Depressional Areas Using Blind Inlets to Minimize Phosphorus and Nitrogen Losses." *Soil Use and Management* 29(1/2013): 94-102. DOI: 10.1111/j.1475-2743.2012.00441.x.

Smith, D.R., W. Francesconi, S.J. Livingston, and C.-H. Huang. "Phosphorus Losses from Monitored Fields with Conservation Practices in the Lake Erie Basin, USA." *Ambio* 44(2/2015a): 319-331. DOI: 10.1007/s13280-014-0624-6.

Smith, D.R., K.W. King, L. Johnson, W. Francesconi, P. Richards, D. Baker, and A.N. Sharpley. "Surface Runoff and Tile Drainage Transport of Phosphorus in the Midwestern United States." *Journal of Environmental Quality* 44(2015b): 495-502. DOI: 10.2134/jeq2014.04.0176.

Sohngen, B., K.W. King, G. Howard, J. Newton, and D.L. Forster. "Nutrient Prices and Concentrations in Midwestern Agricultural Watersheds." *Ecological Economics* 112(2015): 141–149. DOI: 10.1016/j.ecolecon.2015.02.008.

"State of Knowledge of *Cladophora* in the Great Lakes Workshop: Executive Summary." (2016). Workshop held January 26-28, 2016, NOAA-Great Lakes Environmental Research Laboratory, Ann Arbor, MI.

State of Michigan (SOM). Act No. 299, Public Acts of 2010. Enrolled House Bill No. 5368. https://www.legislature.mi.gov/documents/2009-2010/publicact/pdf/2010-PA-0299.pdf.

Steffen, M.M., B.S. Belisle, S.B. Watson, G.L. Boyer, and S.W. Wilhelm. "Status, Causes, and Controls, of Cyanobacterial Blooms in Lake Erie." *Journal of Great Lakes Research* 40(2/2014a): 215-225. DOI: 10.1016/j.jglr.2013.12.012.

Steffen, M.M., S.P. Dearth, B.D. Dill, Z. Li, K.M. Larsen, S.R. Campagna, and S.W. Wilhelm. "Nutrients Drive Transcriptional Changes that Maintain Metabolic Homeostasis but Alter Genome Architecture in *Microcystis*." *The ISME journal*, 8(10/2014b): 2080-2092. DOI: 10.1038/ismej.2014.78.

Stoermer, E.F., R.G. Kreis, Jr., N.A. Andresen. "Checklist of Diatoms from the Laurentian Great Lakes II." *Journal of Great Lakes Research* 25(1999/3): 515-566. DOI: 10.1016/S0380-1330(99)70759-8.

Stonehouse, D.P. “Economic Evaluation of On-Farm Conservation Practices in the Great Lakes Region of North America.” *Environmetrics* 10(4/1999): 505–520. DOI: 10.1002/(SICI)1099-095X(199907/08)10:4<505::AID-ENV371>3.0.CO;2-X.

Stow, C.A. and T. Höök, Eds., with D. Beletsky, R. Beletsky, A. Burtner, J.H. Bredin, J. Cavaletto, Y. Cha, C. De Marchi, J.V. DePinto, J. Dyble, D.Fanslow, S. Francoeur, D. Gossiaux, N. Hawley, C. He, T.H. Johengen, D.R. Kashian, M.D. Kaplowitz, W. Keiper, P.J. Lavrentyev, F. Lupi, D.F. Millie, N. Morehead, T.F. Nalepa, T.J. Newcomb, D. Palladino, S.D. Peacor, S.A. Pothoven, T. Redder, M. Selzer, H.A. Vanderploeg, E. Verhamme, and K.Winslow. “Saginaw Bay Management Report.” *NOAA Technical Memorandum GLERL* 160(2013). Ann Arbor, Michigan: NOAA, Great Lakes Environmental Research Laboratory. http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-160/tm-160.pdf. Last accessed: May 19, 2016.

Stow, C.A., Y. Cha, L.T. Johnson, R. Confesor, and R.P. Richards. “Long-Term and Seasonal Trend Decomposition of Maumee River Nutrient Inputs to Western Lake Erie.” *Environmental Science & Technology* 49 (6/2015): 3392-3400. DOI: 10.1021/es5062648.

Stumpf, R.P., L.T. Johnson, L.T., T.T. Wynne, and D.B. Baker. “Forecasting Annual Cyanobacterial Bloom Biomass to Inform Management Decisions in Lake Erie.” *Journal of Great Lakes Research* (2016). DOI: 10.1016/j.jglr.2016.08.006

Stumpf, R.P., T.T. Wynne, D.B. Baker, and G.L. Fahnenstiel. “Interannual Variability of Cyanobacterial Blooms in Lake Erie.” *PLoS One* 7 (8/2012): e42444. DOI: 10.1371/journal.pone.0042444.

Stumpf, R.P., and T.T. Wynne. “Experimental Lake Erie Harmful Algal Bloom Bulletin.” National Oceanic and Atmospheric Administration National Centers for Coastal Ocean Science and Great Lakes Environmental Research Laboratory. Bulletin 27. November 10, 2015.

Stumpf, R.P., L.T. Johnson, T.T. Wynne, and D.B. Baker. “Forecasting Annual Cyanobacterial Bloom Biomass to Inform Management Decisions in Lake Erie.” *Journal of Great Lakes Research* (2016). DOI: 10.1016/j.jglr.2016.08.006.

Syswerda, S.P., B. Basso, S.K. Hamilton, J.B. Tausig, and G.P. Robertson. “Long-Term Nitrate Loss Along an Agricultural Intensity Gradient in the Upper Midwest USA." *Agriculture, Ecosystems & Environment* 149 (2012): 10-19. DOI: 10.1016/j.agee.2011.12.007.

Tang, H., H.A. Vanderploeg, T.H. Johengen, and J.R. Liebig. “Quagga Mussel (*Dreissena rostriformis bugensis*) Selective Feeding of Phytoplankton in Saginaw Bay.” *Journal of Great Lakes Research 40(2014): 83-94.* DOI: 10.1016/j.jglr.2013.11.011.

Teresa, F.B., L. Casatti, M.V. Cianciaruso. “Functional Differentiation Between Fish Assemblages from Forested and Deforested Streams.” *Neotropical Ichthyology* 13(2/2015): 361-370. DOI: http://dx.doi.org/10.1590/1982-0224-20130229.

Thomas, Mridul K., and Elena Litchman. “Effects of Temperature and Nitrogen Availability on the Growth of Invasive and Native Cyanobacteria.” *Hydrobiologia* 763 (2016): 357-369. DOI: 10.1007/s10750-015-2390-2.

Tomer, M.D., E.J. Sadler, R.E. Lizotte, R.B. Bryant, T.L. Potter, M.T. Moore, T.L. Veith, C. Baffaut, M.A. Locke, and M.R. Walbridge. “A Decade of Conservation Effects Assessment Research by the USDA Agricultural Research Service: Progress Overview and Future Outlook.” *Journal of Soil and Water Conservation* 69(2014): 365-373. DOI: 10.2489/jswc.69.5.365.

Torres, G.S., and Z. Adámek. “Factors Promoting the Recruitment of Benthic Cyanobacteria Resting Stages: A Review.” *Croatian Journal of Fisheries* 71(2013): 182-186. DOI: 10.14798/71.4.696.

United States Department of Agriculture Natural Resources Conservation Service (USDA, 2011). "Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Great Lakes Region." (2011). http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1045480.pdf. Last accessed: May 15, 2015.

United States Department of Agriculture Natural Resources Conservation Service (USDA 2016a). "Effects of Conservation Practice Adoption on Cultivated Cropland Acres in Western Lake Erie Basin, 2003-06 and 2012." (2016a). http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd889806.pdf. Last accessed: April 14, 2016.

United States Department of Agriculture Natural Resources Conservation Service (USDA 2016b). "Western Lake Erie Basin Initiative." (2016b). http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/newsroom/releases/?cid=NRCSEPRD892606. Last accessed: April 14, 2016.

United States Environmental Protection Agency (USEPA 2004). "Optimizing Water Treatment Plant Performance Using the Composite Correction Program." EPA-625-6-91-027. Office of Water, Office of Research and Development. Cincinnati, OH.

United States Environmental Protection Agency (USEPA 2007). "Report to Congress: Combined Sewer Overflows to the Lake Michigan Basin." (2007). EPA-833-R-07-007. https://www.epa.gov/sites/production/files/2015-10/documents/cso_reporttocongress_lakemichigan.pdf. Last accessed: April 8, 2016.

United States Environmental Protection Agency (USEPA 2015a). "A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution." (2015a). EPA 820-F-15-096. http://www2.epa.gov/sites/production/files/2015-04/documents/nutrient-economics-report-2015.pdf. Last accessed: May 15, 2015.

United States Environmental Protection Agency (EPA 2015b). "Health Effects Support Document for the Cyanobacterial Toxin Microcystins." (2015b). EPA-820R15102. https://www.epa.gov/sites/production/files/2015-06/documents/microcystins-support-report-2015.pdf. Last accessed: April 28, 2016.

United States Environmental Protection Agency (EPA 2015c). "2015 Drinking Water Health Advisories for Two Cyanobacterial Toxins." (2015c). 820F15003. https://www.epa.gov/sites/production/files/2015-06/documents/cyanotoxins-fact_sheet-2015.pdf. Last accessed: March 4, 2016.

United States Environmental Protection Agency (EPA 2015d). "Preventing Eutrophication: Scientific Support for Dual Nutrient Criteria." (2015d). EPA-820/S-15-001. https://www.epa.gov/sites/production/files/documents/nandpfactsheet.pdf. Last accessed: February 10, 2017.

United States Environmental Protection Agency (EPA 2015e). "Health Effects Support Document for the Cyanobacterial Toxin Microcystins." (2015e). EPA-820R15102. https://www.epa.gov/sites/production/files/2015-06/documents/microcystins-support-report-2015.pdf. Last accessed: April 28, 2016.

United States Environmental Protection Agency (EPA 2015f). "Health Effects Support Document for the Cyanobacterial Toxin Cylindrospermopsin." (2015f). EPA-820R15103.

https://www.epa.gov/sites/production/files/2015-06/documents/cylindrospermopsin-support-report-2015.pdf. Last accessed: April 28, 2016.

United States Environmental Protection Agency (EPA 2015g). “Case Studies on Implementing Low-Cost Modifications to Improve Nutrient Reduction at Wastewater Treatment Plants.” (2015g). Draft, version 1.0. EPA-841-R-15-004. https://www.epa.gov/sites/production/files/2015-08/documents/case_studies_on_implementing_low-cost_modification_to_improve_potw_nutrient_reduction-combined_508_-_august.pdf. Last accessed: November 11, 2016.

United States Environmental Protection Agency (EPA 2015h). “Health Effects Support Document for the Cyanobacterial Toxin Anatoxin-A.” (2015h). EPA-820R15104. https://www.epa.gov/sites/production/files/2015-06/documents/anatoxin-a-report-2015.pdf. Last accessed: April 28, 2016.

United States Environmental Protection Agency (EPA 2015i). “Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water.” (2015i). EPA-815R15010. Washington, DC. http://www.epa.gov/sites/production/files/2015-06/documents/cyanotoxin-management-drinking-water.pdf. Last accessed: November 6, 2016.

United States Environmental Protection Agency (EPA 2016). “Control and Treatment.” https://www.epa.gov/nutrient-policy-data/control-and-treatment. Last accessed: June 10, 2016.

United States Environmental Protection Agency (EPA 2016a). “Report to Congress: Combined Sewer Overflows into the Great Lakes Basin.” file:///C:/Users/caitlin.gould/Downloads/Report%20to%20Congress%20-%20CSOs%20into%20the%20Great%20Lakes%20Basin%20.pdf. Last accessed: October 20, 2016.

United States Environmental Protection Agency Science Advisory Board (USEPA SAB). “Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options.” EPA-SAB-11-013. (2011). https://yosemite.epa.gov/sab/sabproduct.nsf/WebBOARD/INCFullReport/$File/Final%20INC%20Report_8_19_11(without%20signatures).pdf. Last accessed: November 10, 2016.

United States Global Change Research Program (USGCRP). “The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.” (2016). Crimmins, A., J. Balbus., J.L. Gamble, C.B. Beard, J.E., Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha., M.C. Sarofim., J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC. DOI: 10.7930/J0R49NQX.

Vanderploeg, H.A., J.R. Liebig, W.W. Carmichael, M.A. Agy, T.H. Johengen, G.L. Fahnenstiel, and T.F. Nalepa. “Zebra Mussel (*Dreisssena polymorpha*) Selective Filtration Promoted Toxic Microcystis Blooms in Saginaw Bay (Lake Huron) and Lake Erie.” *Canadian Journal of Fisheries and Aquatic Sciences* 58(2001): 1208-1221. DOI: 10.1139/cjfas-58-6-1208.

Vanderploeg, H.A., A.E. Wilson, T.H. Johengen, J. Dyble Bressie, O. Sarnelle, J.R. Liebig, S.D. Robinson, and G.P. Horst. “Role of Selective Grazing by Dreissenid Mussels in Promoting Toxic *Microcystis* Blooms and Other Changes in Phytoplankton Composition in the Great Lakes.” In: Nalepa, T.F., and D.W. Schloesser (eds), *Quagga and Zebra Mussels: Biology, Impacts, and Control. Second Edition.* (Boca Raton, FL: CRC Press, 2012). DOI: 10.1201/b15437-40.

Van Esbroeck, C.J., M.L. Macrae, R.I. Brunke, an dK. McKague. “Annual and Seasonal Phosphorus Export in Surface Runoff and Tile Drainage from Agricultural Fields with Cold Temperate Climates.” *Journal of Great Lakes Research*. (2016). DOI: 10.1016/j.jglr.2015.12.014.

Vidon, P., C. Allan, D. Burns, T.P. Duval, and N. Gurwick. “Hot Spots and Hot Moments in Riparian Zones: Potential for Improved Water Quality Management.” *Journal of the American Water Resources Association* 46(2/2010): 278–298. DOI: 10.1111/j.1752-1688.2010.00420.x.

Visser, P.M., J.M.H. Verspagen, G. Sandrini, L.J. Stal, H.C.P Matthijs, T.W. Davis, H.W. Paerl, and J. Huisman. "How Rising CO_2 and Global Warming May Stimulate Harmful Cyanobacterial Blooms." *Harmful Algae* 54(2016): 145-159. DOI: 10.1016/j.hal.2015.12.006.

Walker, H. W. *Harmful Algae Blooms in Drinking Water: Removal of Cyanobacterial Cells and Toxins.* 2015. CRC Press. Boca Raton, FL. ISBN: 9781466583054.

Williams, M.R., K.W. King, M.L. Macrae, W.I. Ford, C.V. Esbroeck, R.I. Brunke, M.C. English, and S.L. Schiff. “Uncertainty in Nutrient Loads from Tile Drained Landscapes: Effect of Sampling Frequency, Calculation Algorithm, and Compositing Strategies.” *Journal of Hydrology* 530(2015):306-316. DOI: http://dx.doi.org/10.1016/j.jhydrol.2015.09.060.

Williams, M.R., K.W. King, W. Ford, and N.R. Fausey. “Edge-of-Field Research to Quantify the Impacts of Agricultural Practices on Water Quality in Ohio.” *Journal of Soil and Water Conservation* 71(1/2016): 9A-12A. DOI: 10.2489/jswc.71.1.9A.

Wilson, C. G., R. A. Kuhnle, S. M. Dabney, R. N. Lerch, Chi Hua Huang, K. W. King, and S. J. Livingston. “Fine Sediment Sources in Conservation Effects Assessment Project Watersheds.” *Journal of Soil and Water Conservation* 69 (5/2014b): 402-413. DOI: 10.2489/jswc.69.5.402.

Wilson, E. K. “Danger from Microcystins in Toledo Drinking Water Unclear.” *Chemical Engineering News*, 92(32/2014a). DOI: 10.1021/cen-09232-notw8.

Wilson, R.S., G. Howard, and E.A. Burnett. “Improving Nutrient Management Practices in Agriculture: The Role of Risk-Based Beliefs in Understanding Farmers’ Attitudes Toward Taking Additional Action.” *Water Resources Research*, 50(8/2014c): 6735–6746. DOI: 10.1002/2013WR015200.

Wilhelm, S.W., G.R. LeCleir, G.S. Bullerjahn, R.M. McKay, M.A. Saxton, M.R. Twiss, and R.A. Bourbonniere. “Seasonal Changes in Microbial Community Structure and Activity Imply Winter Production is Linked to Summer Hypoxia in a Large Lake.” *FEMS Microbiology Ecology* 87 (2/2014): 475-485. DOI: dx.doi.org/10.1111/1574-6941.12238.

Wires, L.W., S.J. Lewis, G.J. Soulliere. S.W. Matteson, D.V. Weseloh, R.P. Russell, F.J. Cuthbert. “Upper Mississippi Valley/ Great Lakes Waterbird Conservation Plan.” http://pwatol.us/mibci/fileadmin/user_upload/ResearchMonitoring/UMVGLWaterbirdPlan5-26-10.pdf. Last accessed: July 27, 2017.

Wood, R. “Acute Animal and Human Poisonings from Cyanotoxin Exposure—A Review of the Literature.” *Environment International* 91(2016): 276-282. DOI: 10.1016/j.envint.2016.02.026.

Wynne, T.T., R.P. Stumpf, M.C. Tomlinson, R.A. Warner, P.A. Tester, J. Dyble, and G.L. Fahnenstiel. “Relating Spectral Shape to Cyanobacterial Blooms in the Laurentian Great Lakes.” *International Journal of Remote Sensing* 29 (12/2008): 3665-3672. DOI: 10.1080/01431160802007640.

Wynne, T.T., and R.P. Stumpf. “Spatial and Temporal Patterns in the Seasonal Distribution of Toxic Cyanobacteria in Western Lake Erie from 2002-2014.” *Toxins* 7(5/2015): 1649-1663. DOI: 10.3390/toxins7051649.

Wynne, T.T., R.P. Stumpf, M.C. Tomlinson, G.L. Fahnenstiel, J. Dyble, D.J. Schwab, and S.J. Joshi. “Evolution of a Cyanobacterial Bloom Forecast System in Western Lake Erie: Development and Initial Evaluation.” *Journal of Great Lakes Research* 39 (2013): 90-99. DOI: 10.1016/j.jglr.2012.10.003.

Zhou, X., M.J. Helmers, H. Asbjornsen, R. Kolka, M.D. Tomer, and R.M. Cruse. “Nutrient Removal by Prairie Filter Strips in Agricultural Landscapes.” *Journal of Soil and Water Conservation* 69(2014): 54-64. DOI: 10.2489/jswc.69.1.54.

Zhou, Y., D.R. Obenour, D. Scavia, T.H. Johengen, and A.M. Michalak. “Spatial and Temporal Trends in Lake Erie Hypoxia, 1987–2007.” *Environmental Science and Technology* 47 (2/2013): 899-905. DOI: 10.1021/es303401b.

Zhou, Y., A.M. Michalak, D. Beletsky, Y.R. Rao, and R.P. Richards. “Record-Breaking Lake Erie Hypoxia during 2012 Drought.” *Environmental Science and Technology* 49 (2/2015):800-807. DOI: 10.1021/es503981n.

Acronyms

Below are acronyms that are used for the purposes of organizing the activities in this report. They are non-statutory in nature.

APEX	Agricultural Policy/Environmental eXtender
ARS	Agricultural Research Service
BMP	Best management practice
CDC	Centers for Disease Control and Prevention
CEAP	Conservation Effects Assessment Project
CWA	Clean Water Act
DHHS	Department of Health and Human Services
DOC	Department of Commerce
DOD	Department of Defense
DOI	Department of the Interior
EQIP	Environmental Quality Incentives Program
FDA	Food and Drug Administration
GLRI	Great Lakes Restoration Initiative
GLOS	Great Lakes Observing System
GLWQA	Great Lakes Water Quality Agreement
HABs	Harmful Algal Blooms
HABHRCA	Harmful Algal Bloom and Hypoxia Research and Control Act
HAB-OFS	Harmful Algal Bloom Operational Forecast System
IOOS	Integrated Ocean Observing System
IWG-HABHRCA	Interagency Working Group on the Harmful Algal Bloom and Hypoxia Research and Control Act
LEOFS	Lake Erie Operational Forecast System
NASA	National Aeronautics and Space Administration
NCCOS	National Centers for Coastal Ocean Science (NOAA)
NIEHS	National Institute of Environmental Health Sciences
NIFA	National Institute of Food and Agriculture
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NORS	National Outbreak Reporting System
NPS	National Park Service
NRCS	Natural Resources Conservation Service
OHHABS	One Health Harmful Algal Blooms
OSTP	Office of Science and Technology Policy
PCM	Prevention, Control, and Mitigation
PCMHAB	Program that transitions promising PCM technologies and strategies to end-users and is authorized by the Harmful Algal Bloom and Hypoxia Research and Control Act (1998, 2014)
PMN	Phytoplankton Monitoring Network
RCPP	Regional Conservation Partnership Program
RRAF	Runoff Risk Advisory Forecast
SPARROW	SPAtially-Referenced Regression on Watershed attributes mode
SOST	Subcommittee on Ocean Science and Technology
SDWA	Safe Drinking Water Act

USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WLEB	Western Lake Erie Basin

Glossary

Below are definitions the IWG-HABHRCA used for the purposes of organizing the activities in this report. They are non-statutory in nature.

Congener: When referring to HAB toxins, a congener is toxin of the same type (e.g., microcystin-LR and microcystin-LA) or within the same group, but with a different chemical structure that may affect how toxic it is and what methods can be used to differentiate between the forms.

Control (or suppression): Strategies that directly kill HAB cells or destroy their toxins, physically remove cells and toxins from the water column, or limit cell growth and proliferation. These strategies aim to reduce the impacts of HABs and hypoxia events on people and commerce by targeting the immediate causative agents of these events.

Dissolved Reactive Phosphorus: A form of phosphorus that is more biologically available to organisms, such and algae and cyanobacteria, and therefore can more readily promote growth.

Lysis: Breaking of the cell wall or membrane

Mitigation: Responding to an existing or ongoing bloom by taking steps to restrict, inhibit, or prevent associated undesirable impacts on the environment, human health, or human economies and communities. Prohibiting seafood that is contaminated with HAB toxins from entering commerce is an example of a management strategy to mitigate human-health impacts. Mitigation is the area of HAB management where the most immediate potential exists to reduce impacts, given that many such activities are already underway.

No-Till: No-till is a farming practice that aims to minimize soil disturbance and maintain as much crop residue on the soil surface as possible.

Nowcast: A description of present conditions.

Prevention: Environmental-management actions taken to reduce the incidents and extent of HABs and hypoxia events.

Resuspension: Water movement that stirs up the sediments and associated nutrients and organisms that then become suspended in the water column.

Stratification: Formation of a layer of warm surface water above colder water, which limits exchange of nutrients and oxygen and favors some algal groups over others