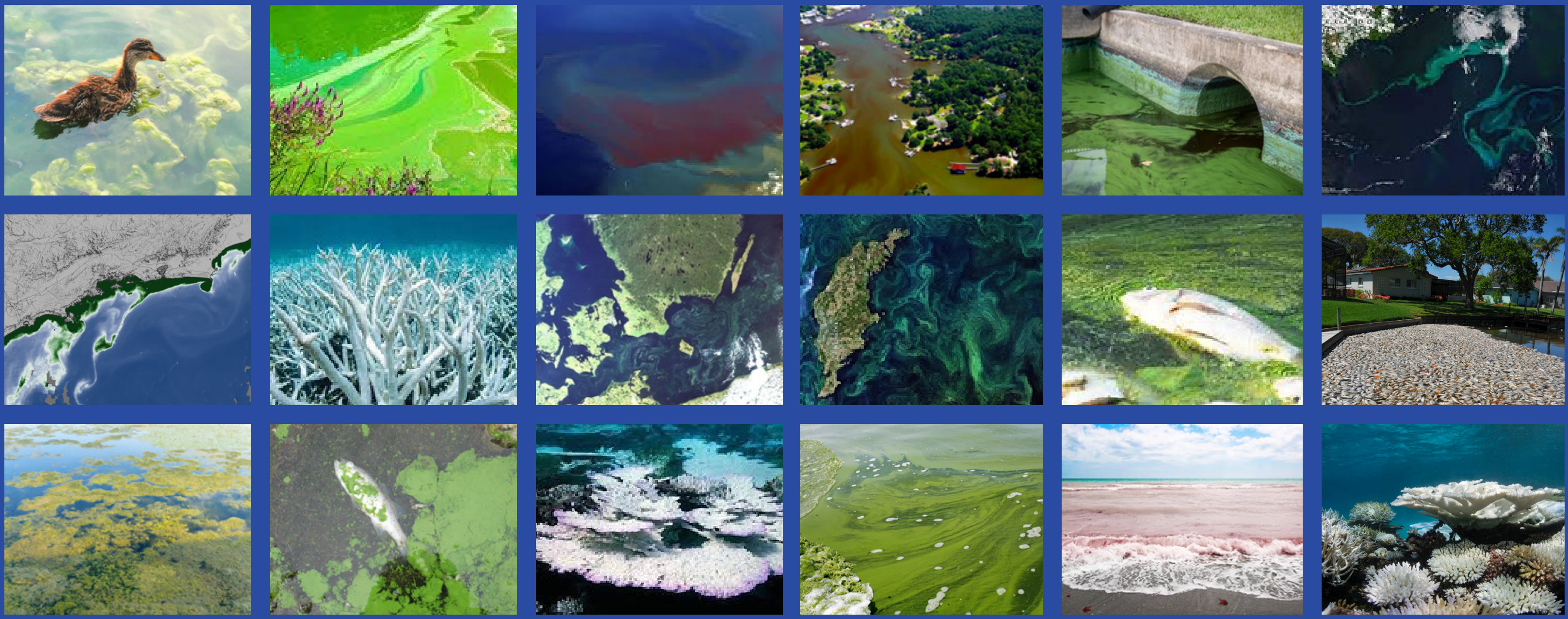
SPECIAL Report



HARMFUL ALGAL BLOOMS

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About Ocean Grants

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Dear Reader,

Thank you for being so committed to the Ocean[1] and its well-being. We capitalize the word “Ocean” and believe it deserves our ultimate respect, adoration, and glorification, so it’s our little way of paying homage. The Ocean is facing numerous challenges, and among the most pressing is the proliferation of Harmful Algal Blooms (HABs). These toxic blooms are suffocating marine life and threatening human health and economies dependent on our waters. As the Ocean battles rising temperatures, plastic pollution, and acidification, the emergence of HABs adds yet another layer of urgency to our collective efforts.

At Ocean Grants, we are dedicated to accelerating solutions to these pressing issues. In this Special Report, we delve into the world of Harmful Algal Blooms, exploring the innovative technologies, scientific research, and community-driven initiatives that are at the forefront of this fight. We have identified three leading organizations making significant strides in addressing HABs, and we are excited to share their work and impact with you. Together, we can help restore the Ocean's health and ensure its survival for generations to come.

Sincerely,
Marta Weinstock


LAKE ERIE, USA

Table of Contents

CONTENTS

01. EXECUTIVE SUMMARY

Harmful Algal Blooms (HABs) are threatening marine life and aquatic ecosystems and are negatively affecting human health and economies worldwide. Although a naturally occurring phenomenon, HABs frequency and impact are influenced by several factors, the most significant of which is the advent of fertilizers.[2] There are many byproducts to an algal bloom and some of them are highly toxic. These toxins can kill marine life and harm human health if inhaled. This report reviews the multiple causes, effects, and possible solutions to HABs.

Efforts to mitigate HABs focus on improving nutrient management through best agricultural practices, upgrading wastewater treatment systems, and implementing green infrastructure to manage stormwater. Policy interventions, such as enforcing stricter nutrient pollution regulations and promoting sustainable farming incentives, are essential in reducing the nutrient load entering water bodies. Additionally, restoration efforts, including wetland rehabilitation and the establishment of vegetative buffer zones, help filter out excess nutrients before they reach critical waterways.

A collaborative approach is crucial for addressing HABs. Government agencies, industries, and non-profits must work together to enforce regulations, adopt sustainable practices, and invest in research and technology. Innovations like natural algicides and advanced monitoring technologies offer promising solutions for early detection and mitigation. By implementing these strategies, the global community can reduce the devastating impacts of HABs on ecosystems, human health, and economies.

This report calls for urgent and coordinated action to mitigate the impacts of HABs. By implementing these recommended strategies—spanning nutrient management, policy reforms, research innovation, and collaboration across sectors—societies can protect ecosystems, safeguard public health, and secure economic stability for future generations.

02. IMPORTANT DEFINITIONS

For clarification in this report, the terms are important to understand “Red tide" and "Harmful algal blooms (HABs)" are related but not entirely interchangeable.

Red tide specifically refers to a type of Harmful algal bloom caused by the dinoflagellate *Karenia brevis* in coastal waters, particularly in the Gulf of Mexico and along the Florida coast.[3] This algae produces toxins that can kill marine life and cause respiratory problems in humans. The name "Red tide" comes from the reddish-brown discoloration of the water during a bloom, although not all red tides are actually red, and not all discolorations of water are harmful.

Harmful Algal Blooms *(HABs)* is a broader term that encompasses various types of algal blooms, not just those caused by *Karenia brevis*. HABs can occur in both marine and freshwater environments and can involve different species of algae, including Cyanobacteria (blue-green algae), Diatoms, and other Dinoflagellates. These blooms can produce a variety of toxins that affect aquatic ecosystems, wildlife, and human health, and they do not always cause water discoloration.

So while all *Red tides* are HABs, not all HABs are *Red tides*. The term "Red tide" is a specific type of HAB, whereas "HABs" is a general term for toxic algal blooms in any water body. For our special report, we will be focusing on a broader definition of Harmful Algal Blooms in encompassing as much detail as possible.

Dead zones are areas in oceans, seas, or large bodies of water where oxygen levels are so low that most marine life cannot survive. These oxygen-depleted regions, also known as hypoxic zones, typically result from nutrient pollution, particularly excess nitrogen and phosphorus from agricultural runoff, wastewater, and fossil fuel emissions. When these nutrients enter waterways, they fuel excessive algae growth, leading to Harmful algal blooms (HABs). When the algae die and decompose, the process consumes large amounts of dissolved oxygen, creating conditions that can suffocate aquatic life, including fish and shellfish.

Dead zones are a growing environmental concern globally, with one of the largest being the Gulf of Mexico Dead Zone, which forms annually due to runoff from the Mississippi River. These zones disrupt ecosystems, fisheries, and local economies, as they can span thousands of square kilometers, drastically reducing biodiversity in affected areas.

Best Management Practices (BMPs) refer to practices or strategies designed to reduce pollution, particularly from non-point sources such as agricultural runoff. BMPs aim to minimize the amount of harmful substances—like nutrients, pesticides, and sediments—that enter water bodies, thereby protecting water quality and mitigating environmental impacts. In the context of preventing HABs, BMPs are essential for managing the flow of excess nutrients, primarily nitrogen and phosphorus, which fuel algal growth. These practices are often implemented in agriculture, urban development, and wastewater management.

03. INTRODUCTION TO HARMFUL ALGAL BLOOMS (HABS)

The complexity and far-reaching consequences of HABs highlight the urgent need for continued research and effective mitigation strategies.

HABs are a phenomenon where colonies of algae—simple, plant-like organisms that live in the sea and freshwater—grow out of control while producing toxic or harmful effects on people, fish, shellfish, marine mammals, and birds. These blooms are not only unsightly but can also be highly detrimental. There are various types of harmful algae, including Cyanobacteria (blue-green algae), Dinoflagellates, and Diatoms, each producing different toxins and impacts, all of which have far-reaching consequences.

Ecologically, HABs can devastate marine and freshwater ecosystems, leading to significant biodiversity loss and disruption of food webs. For human health, exposure to toxins from HABs can cause severe bacterial infection, respiratory, neurological, and gastrointestinal issues.

Economically, the repercussions are substantial, affecting industries such as fisheries, aquaculture, recreational, tourism, and the increasing costs of water treatment. Understanding the complex nature of HABs is crucial for developing effective strategies to mitigate their impact and protect both the environment and public health.

> Economically, these events can result in costs ranging from \$10 to \$100 million annually in the U.S.

04. CAUSES OF HABS

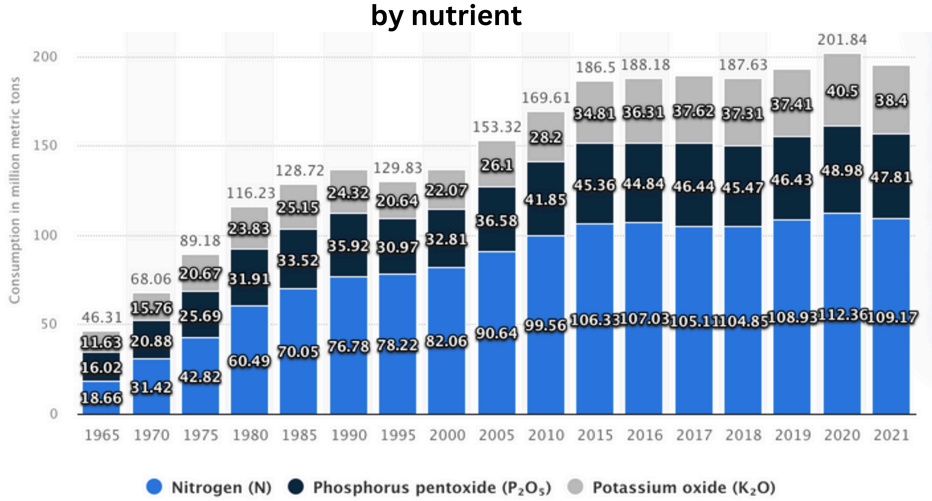
HABs result from a combination of environmental factors that favor the rapid growth of toxic algae. Excess nutrients, particularly nitrogen and phosphorus, are major contributors, often stemming from agricultural runoff, industrial discharges, and urban stormwater.

Agricultural activities, which introduce fertilizers and animal waste into water bodies, industrial wastewater, and urban rainwater runoff all infuse additional nutrients into our water sources. Climate change further exacerbates the situation by altering conditions that support algal growth. Specifically rising temperatures enhance algal metabolism and growth rates, and changes in precipitation patterns increase nutrient loading through more frequent runoff and the concentration of nutrients during droughts. Other contributing factors include human activities like dam construction and river channelization, which reduce water movement and allow for nutrient accumulation. Lastly, the introduction of invasive species can disrupt ecosystems and alter nutrient dynamics. Understanding these causes is crucial for developing targeted strategies to prevent and mitigate HABs.

Agricultural runoff is a key contributor to the formation of HABs. The use of fertilization has increased markedly over the last 50 years. Nitrogen, Phosphorus pentoxide, and Potassium oxide can all contribute to the development of HABs. These compounds are common in fertilizers, which, when washed into water bodies through runoff, provide essential nutrients that stimulate excessive algal growth. Nitrogen and phosphorus, in particular, are key drivers of HABs.[4] As algae grow uncontrollably, they can deplete oxygen in the water, creating dead zones and releasing toxins harmful to aquatic life and humans (USGS, OSU News).

Fertilizers used in agriculture often contain high levels of nitrogen and phosphorus. Efforts are being made to ensure farmers are applying fertilizers in the proper amount, at the right time of year, and with the right method which can significantly reduce how much fertilizer reaches water bodies.

Global consumption of agricultural fertilizer from 1965 to 2021, by nutrient



Climate change is also a significant driver of HABs through several interconnected factors. Warmer water temperatures accelerate the growth of algae, as many harmful species thrive in these conditions. Changes in precipitation patterns, such as more intense rainfall, increase nutrient runoff from agriculture and urban areas into water bodies, further fueling algal growth. Prolonged droughts, on the other hand, reduce water flow, creating stagnant environments ideal for bloom formation.

Additionally, rising CO2 levels can enhance photosynthesis in certain algae species, promoting their growth. Ocean acidification, a byproduct of increased CO2, may also alter marine ecosystems, allowing harmful algae to outcompete other organisms. Combined, these climate-driven changes create conditions that encourage more frequent and intense HABs, posing a growing threat to aquatic ecosystems, human health, and economies.

Regarding invasive species, non-native species can significantly alter nutrient dynamics. In this report, we provide two examples, one is the presence of Zebra Mussels (*Dreissena polymorpha*) in the Great Lakes and one in the Mississippi River Basin.

The first, Zebra mussels, were unintentionally introduced to the Great Lake region through the discharge of contaminated ballast water from ships. Zebra mussels are filter feeders that efficiently remove plankton from the water, leading to clearer water and increased light penetration. This change allows sunlight to reach deeper into the water column, promoting the growth of benthic algae. Additionally, zebra mussels excrete nutrients like phosphorus in a form that is more readily available to algae, further fueling algal blooms. Zebra mussels have been linked to increased occurrences of nearshore HABs, particularly in Lake Erie. The altered nutrient dynamics, combined with clearer water and nutrient recycling by zebra mussels, create conditions that are ideal for HAB formation.

Zebra Mussels (*Dreissena polymorpha*)
in the Great Lakes

Another example is the Asian Carp in the Mississippi River Basin. Asian carp, such as bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*), are voracious filter feeders that consume large quantities of plankton. This feeding behavior can reduce the plankton population, which is detrimental to fish species and leaves fewer plankton available to absorb nutrients, allowing excess nutrients to remain in the water column.

Asian Carp (Various Species)
in the Mississippi River Basin

These examples illustrate how invasive species can disrupt nutrient dynamics in aquatic ecosystems, often leading to conditions that favor the development of HABs. Their presence can alter the balance of nutrients, light, and other factors that are critical to maintaining healthy water bodies, making the management of both invasive species and nutrient pollution essential in mitigating HABs.

05. IMPACT OF HABS

Harmful algal blooms have far-reaching consequences that affect the environment, human health, and the economy.

Environmental Impact: HABs severely damage marine and freshwater ecosystems. The excessive growth of harmful algae depletes oxygen in the water, leading to dead zones where aquatic life cannot survive. This disrupts food webs and results in significant biodiversity loss as various species, from fish to invertebrates, perish or migrate. Additionally, the toxins produced by some algae can poison aquatic animals, further stressing these ecosystems.

Human Health Risks: The toxins produced by HABs pose serious risks to human health. These toxins can enter the human body through direct contact with contaminated water, consumption of tainted seafood, skin contact, or inhalation of aerosolized toxins. Exposure can lead to a range of health issues, including bacterial infections, respiratory illness, neurological conditions, and gastrointestinal issues with symptoms such as nausea, vomiting, and diarrhea, as well as coughing and wheezing. In some cases, exposure can lead to more serious conditions, such as liver damage, neurological impairment, and, in extreme cases, death.

Brevetoxins from *Red tides* have been linked to respiratory distress and neurotoxic shellfish poisoning, while *Saxitoxins* can cause paralytic shellfish poisoning.

Long-term exposure to these toxins is also concerning, with potential risks including chronic liver disease and an increased likelihood of neurodegenerative conditions like Alzheimer's disease. Recent studies in 2024 emphasize the growing incidence of HAB-related illnesses in the United States, where all 50 states have reported occurrences of these blooms.[5] In response to the rising threat of HABs, public health agencies like the CDC and state health departments are actively monitoring these blooms, issuing advisories, and educating the public on preventive measures. Despite these efforts, the increasing frequency and intensity of HABs, driven by climate change and nutrient pollution, underscore the urgent need for more comprehensive strategies to protect public health.

Economic Consequences: HABs have substantial economic repercussions. In fisheries and aquaculture, toxic algae can decimate fish stocks and shellfish populations, leading to significant financial losses for fishermen and seafood industries. Tourism and recreation also suffer, as polluted waters deter tourists and disrupt water-based activities. Additionally, the costs of treating contaminated water for safe human consumption increase, placing a financial burden on municipalities and water treatment facilities. The combined environmental, health, and economic impacts of HABs stress the importance of addressing this growing problem.

06. MONITORING AND DETECTION OF HABS

Monitoring and detecting Harmful algal blooms (HABs) is critical for reducing environmental and public health risks. These blooms, fueled by nutrient pollution and climate change, harm ecosystems, drinking water, and industries like aquaculture. Experts use advanced technologies to track and predict HABs in vulnerable areas such as coastal regions, lakes, and urban waterways. Monitoring helps protect the environment, human health, and the economy.

Increased monitoring is crucial in several key areas:

- Coastal Areas and Estuaries are prone to nutrient-rich runoff from agriculture and urban areas. Early detection is key to protecting tourism, fisheries, and public health.
- Major River Basins with agricultural and industrial runoff often suffer from nutrient pollution, leading to downstream HABs. Monitoring predicts blooms by tracking nutrient flows.
- Freshwater Lakes and Reservoirs, which serve as drinking water sources, face health risks and treatment cost hikes from HABs. Monitoring ensures safety for recreational activities like swimming.
- Aquaculture and Shellfish Harvesting Areas are especially vulnerable to HABs, which can devastate stock. Monitoring ensures seafood safety and supports aquaculture's economic stability.
- Urban and Suburban Waterways polluted by runoff may trigger HABs in nearby rivers, lakes, and coastal areas. Monitoring these waterways maintains public health and water quality. Protected and Sensitive Ecosystems, such as coral reefs and wetlands, need enhanced monitoring to protect against HAB impacts and conserve biodiversity.

Effective monitoring and detection use several technologies:

- Remote Sensing: Satellites and drones capture large-scale water body images, helping detect bloom locations and extent for early action.
- In-Situ Monitoring: Sensors placed in water bodies measure physical, chemical, and biological parameters, offering real-time insights into local conditions.
- Molecular Techniques: DNA and RNA analysis rapidly identifies algal species and toxins, which are critical for assessing bloom impacts.

However, challenges remain in collecting comprehensive data over large areas, analyzing this data, and developing accurate predictive models due to the complexity of environmental factors and nutrient levels. Improved models are essential for reliable forecasts and early warnings.

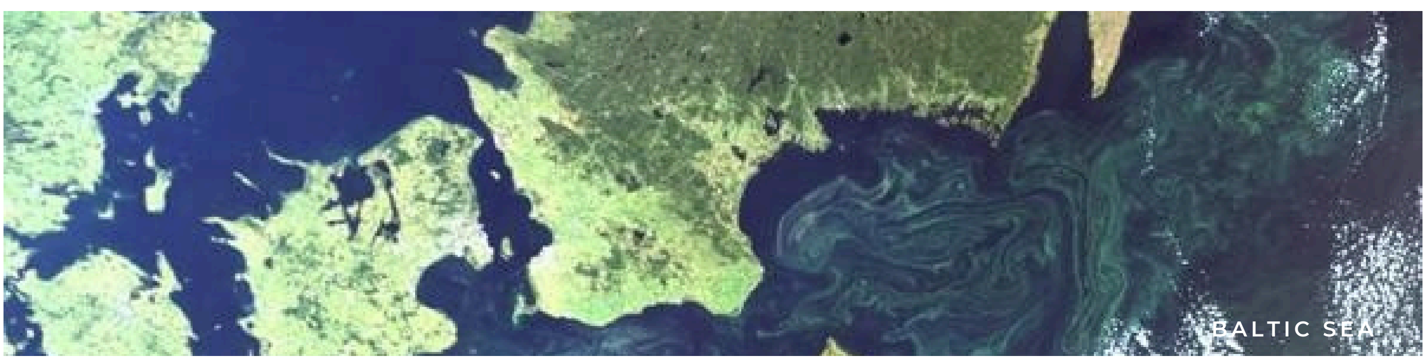
07. GLOBAL COMMUNITIES AND DATA METRICS OF HABS

To effectively combat Harmful algal blooms (HABs), it is essential to increase monitoring efforts in several key areas. Globally, specific regions are more prone to HABs, and data from these areas underscore the urgency for enhanced monitoring.

1. Coastal Areas and Estuaries

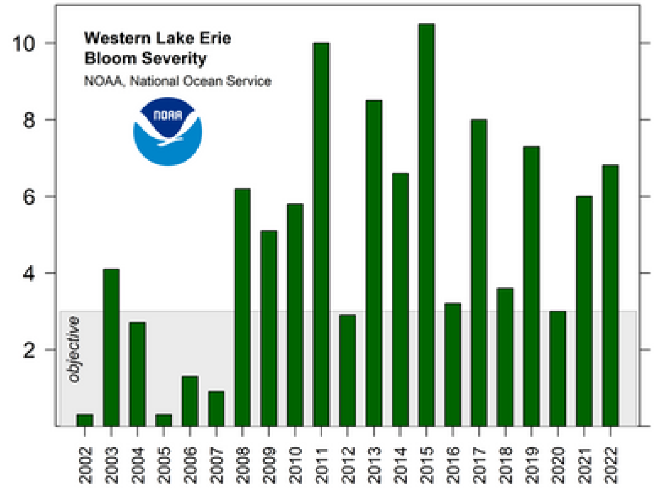
- Gulf of Mexico, USA: The Gulf experiences frequent HABs, particularly the "Red tide" caused by *Karenia brevis*. In 2018, a severe bloom lasted over a year, causing significant ecological and economic damage, including millions of dollars in losses to the tourism and fishing industries.[6]

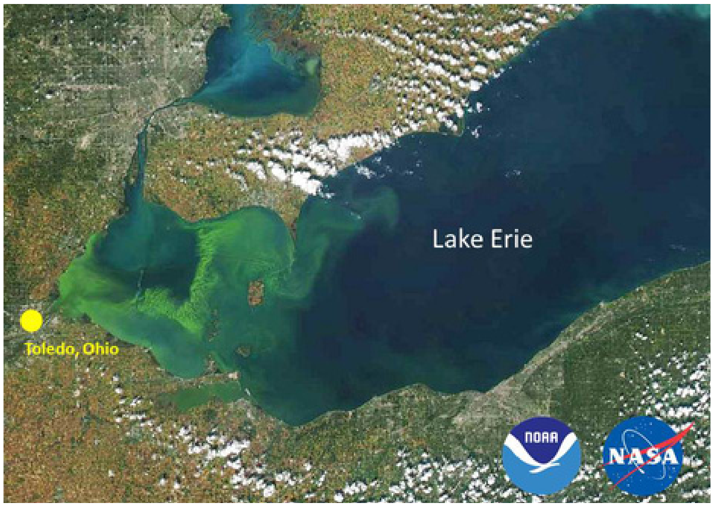
- Baltic Sea, Europe: This region faces recurrent HABs due to high nutrient inputs from agricultural runoff. A major bloom in 2010 covered 377,000 square kilometers, affecting marine life and human activities.[7]



2. Major River Basins

- Mississippi River Basin, USA: This basin is a significant contributor to nutrient pollution in the Gulf of Mexico, leading to large dead zones. In 2019, the hypoxic zone measured approximately 18,000 square kilometers.[8]
- Yangtze River Basin, China: The Yangtze River discharges large amounts of nutrients into the East China Sea, contributing to frequent HABs and hypoxic conditions. From 2000 to 2005, the Yangtze Estuary and East China Sea saw an increase in large-scale Harmful algal blooms (HABs) over 1,000 km^2, peaking at eight blooms in 2005. Smaller blooms (over 100 km^2) continued to rise, reaching a high of 16 in 2008.[9]



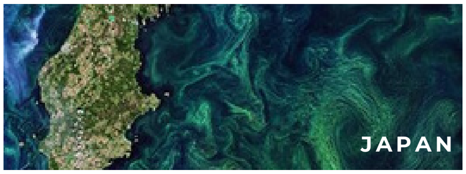


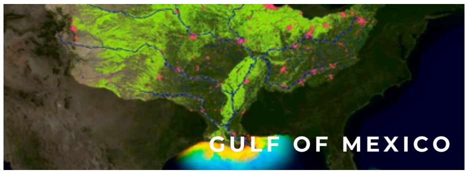
3. Freshwater Lakes and Reservoirs

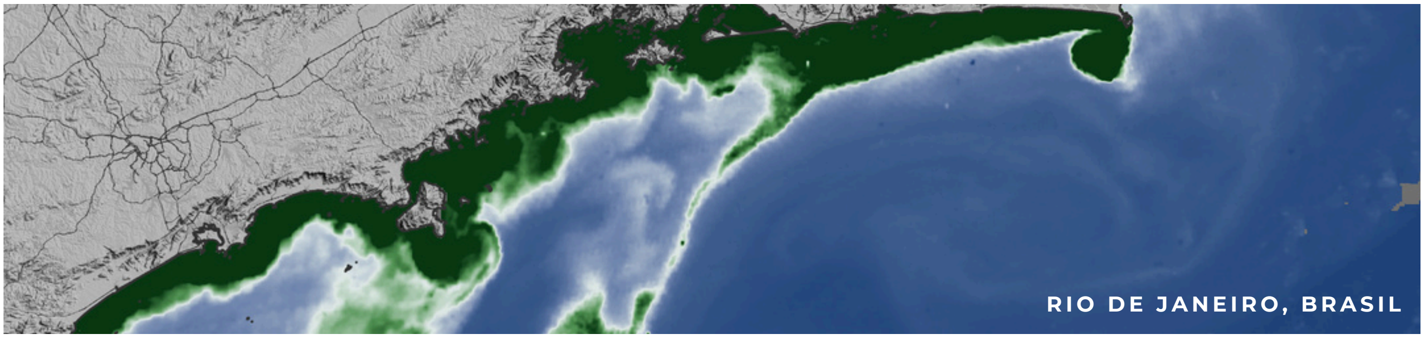
- Lake Erie, USA/Canada: Lake Erie suffers from severe HABs regularly. A bloom began forming in the western basin of Lake Erie on June 24, 2024, the earliest on record. The bloom was still present in early September. The bloom was caused by runoff pollution from fertilizer and manure washed into streams that flow into the lake. The 2014 bloom affected the drinking water supply for over 400,000 residents in Toledo, Ohio. The bloom covered more than 2,000 square kilometers. [10]
- Lake Victoria, Africa: This large freshwater lake is prone to HABs due to nutrient runoff from surrounding agricultural areas. Lake Victoria has experienced progressive eutrophication which has exacerbated the proliferation of Cyanobacterial Harmful algal blooms (cHABs). Fueled by anthropogenic nutrient loadings and climate change, these HABs are increasing in distribution, duration, and frequency, particularly in areas such as the Winam Gulf. [11]

4. Aquaculture and Shellfish Harvesting Areas

- Chesapeake Bay, USA: The bay frequently experiences HABs that impact shellfish safety and aquaculture. In 2019, HABs caused significant oyster mortality, affecting the local economy. [12]
- Hokkaido, Japan: The island's coastal waters face HABs that disrupt scallop aquaculture. A major bloom in 2021 led to losses exceeding USD 100 million. [13]







5. Urban and Suburban Waterways

- Florida, USA: Urban runoff contributes to frequent HABs in Florida's waterways, including the Indian River Lagoon. The 2016 bloom caused extensive fish kills and impacted local tourism and recreation. [14]
- Sydney, Australia: The city's urban waterways, including the Parramatta River, experience HABs due to stormwater runoff. In mid-December 2014, a bloom occurred in Calabash Bay (site 061) of a species of Alexandrium. At the time, *Alexandrium minutum* cell numbers were above the cell count threshold for "closure of harvest area pending flesh testing results" and were also considered to be above the threshold to trigger a recreational warning. A recreational warning was released. [15]

6. Protected and Sensitive Ecosystems

- Great Barrier Reef, Australia: Nutrient runoff and climate change contribute to HABs that threaten this iconic reef. A 2016 bloom caused significant coral bleaching and mortality. [16]
- Amazon Basin, South America: Wetlands are among the most fragile and threatened ecosystems on earth as they are subject to the impact of human activities. Algal blooms are frequently observed during low water periods because of nutrient enrichment by decomposing organic material and animals that concentrate in and around remaining water bodies. Many algal species can occur simultaneously thus making the basin's wetlands vulnerable to HABs from nutrient runoff and deforestation. [17]

By focusing increased monitoring efforts on these critical areas and utilizing specific global data, we can better predict, detect, and manage HABs, ultimately protecting environmental health, public safety, and economic stability.


INDIAN RIVER LAGOON, FLORIDA


LAKE VICTORIA, AFRICA


CASPIAN SEA


GREAT VARRIER REEF

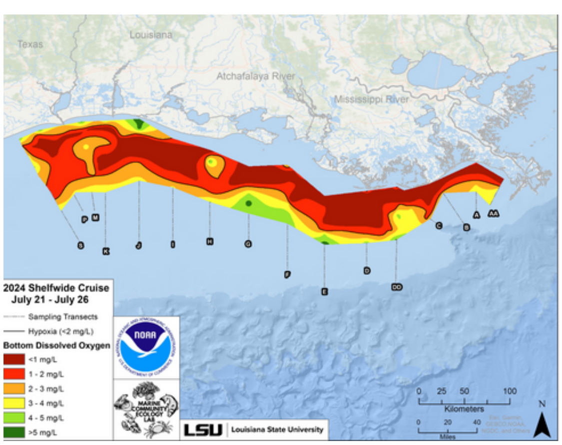
08. STRATEGIES TO REDUCE HABS

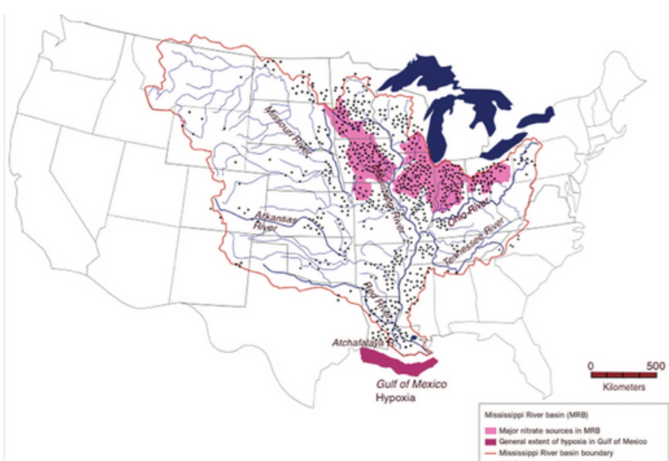
To effectively mitigate HABs, a multifaceted approach is essential. Key strategies include improved nutrient management, robust policies and regulations, and targeted restoration and mitigation efforts.

Nutrient management involves establishing agricultural practices that minimize the runoff of nitrogen and phosphorus into waterways. By developing nutrient management plans, farms can optimize fertilizer use, ensuring that nutrients are applied efficiently and excess application is avoided. In urban areas, nutrient management takes the form of **Stormwater Management**, where green infrastructure solutions such as permeable pavements, green roofs, and rain gardens help reduce and treat stormwater runoff. These systems decrease the amount of nutrients flowing into water bodies, mitigating the risk of Harmful algal blooms.

Strengthening and enforcing existing **Policies and Regulations** related to nutrient pollution, such as the Clean Water Act in the United States and the European Union's Water Framework Directive, can help control nutrient levels and prevent HABs. Plus, introducing new policies aimed at reducing nutrient pollution, such as nutrient trading programs, stricter agricultural runoff controls, and incentives for sustainable practices, can further curb HAB formation. Successful nutrient management policy implementations include the Chesapeake Bay Program and the European Union's initiatives in the Baltic Sea both are examples of coordinated policy efforts that made significant progress in reducing nutrient pollution.

In addition to policies and active nutrient management, **Restoration and Mitigation** efforts are critical strategies for reducing HAB formation. Restoring wetlands helps filter nutrients from runoff before they enter larger water bodies as wetlands act as natural buffers and improve water quality, reducing the likelihood of HABs. Other mitigation efforts include establishing vegetative buffer zones along waterways that can trap and absorb nutrients from agricultural and urban runoff. These buffer zones prevent excess nutrients from reaching water bodies and reduce the risk of HABs. In some geographical areas, Bioremediation Techniques, such as introducing microorganisms or plants that can absorb or degrade pollutants, help remove excess nutrients from the waterways and environment and can mitigate HAB formation.





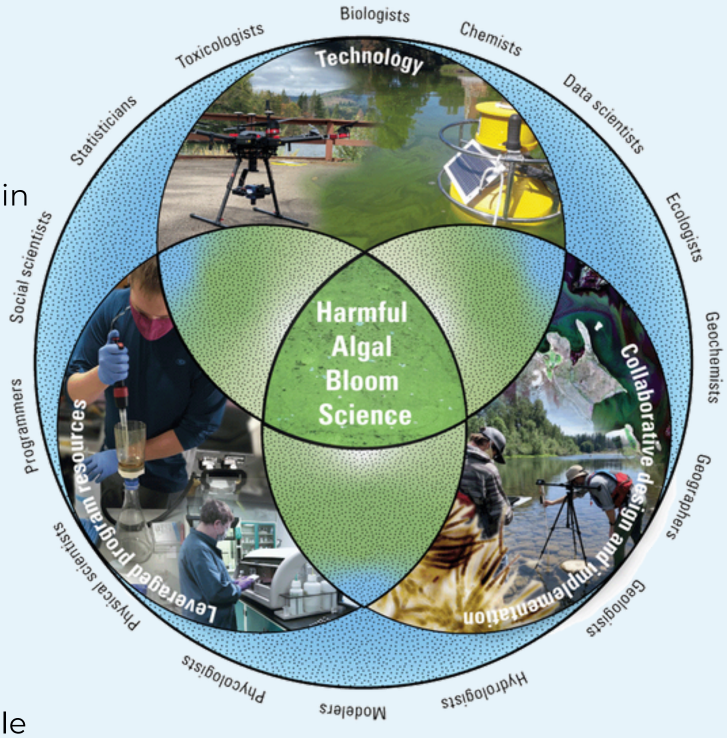
Specific examples of Best Management Practices to prevent HAB formation include:

1. **Precision Agriculture**: By using data and technology (such as GPS and soil sensors), farmers can apply fertilizers more efficiently, targeting areas that need nutrients and reducing excess application. This reduces nutrient runoff into nearby water bodies.
2. **Cover Cropping**: Planting cover crops during off-seasons helps to reduce soil erosion and absorb excess nutrients, preventing them from being washed away into water systems. For example, legumes or grasses are often used to cover the soil between crop seasons, capturing leftover nitrogen.
3. **Sustainable Farming Incentives**: Provide financial incentives or grants for farmers who implement sustainable practices and technologies that minimize nutrient runoff.
4. **Buffer Zones and Riparian Strips**: Vegetated buffer zones are planted between agricultural land and waterways. These areas absorb excess nutrients before they can enter water systems. Trees, shrubs, and grasses along riverbanks or lakes can act as a natural filter to reduce nutrient pollution.
5. **Conservation Tillage**: Reducing the intensity of tillage practices helps minimize soil erosion and runoff. By leaving crop residue on the fields, the soil's structure remains intact, and nutrients are less likely to be washed into streams and rivers.
6. **Nutrient Management Plans**: Developing a nutrient management plan for farms involves calculating the precise amount of fertilizer needed based on soil testing, crop needs, and weather conditions. This ensures that only the required amount of nutrients is applied, preventing overuse and runoff.
7. **Green Infrastructure in Urban Areas:** Techniques such as permeable pavements, green roofs, and rain gardens allow urban stormwater to filter through the ground, trapping nutrients before they reach waterways. This reduces the flow of nutrients from city areas into rivers and lakes, where they could otherwise promote HABs.
8. **Advanced Wastewater Treatment:** Upgrading wastewater treatment plants to remove nutrients more effectively (e.g., biological nutrient removal) helps reduce nutrient discharge into water bodies. For instance, processes like denitrification and phosphorus removal help reduce the amount of nutrients reaching lakes and oceans.

By adopting nutrient management protocols, managing urban stormwater, restoring wetlands and buffer zones, implementing mitigation strategies, and encouraging best management practices, we can significantly reduce the factors that contribute to HAB formation, protecting ecosystems, human health, and economic interests.

09. AGENCY, INDUSTRY-SPECIFIC, AND POLICY RECOMMENDATIONS TO REDUCE HAB FORMATION

Effectively reducing HABs requires a collaborative effort between local, state, and federal government agencies, industries, and policymakers. By implementing industry-specific best practices, strengthening policy regulations, and supporting research and innovation, we can address the root causes to reduce the likelihood of HAB formations in the future.



Agency Recommendations

International collaboration is key, as HABs are a global issue. Agencies like the United Nations Environment Programme (UNEP) can spearhead global efforts to share knowledge and establish policies for nutrient management, fostering cross-border partnerships. NOAA (National Oceanic and Atmospheric Administration) should continue expanding its monitoring and forecasting systems to improve the early detection of HABs in vulnerable coastal regions.

On the public health front, the *World Health Organization (WHO)* can take the lead by developing guidelines to mitigate human health risks from HAB toxins. *The Nature Conservancy (TNC)* can bolster its efforts in wetland restoration and buffer zone creation to curb nutrient runoff into waterways, while the *European Environment Agency (EEA)* can promote regional policies for nutrient reduction across Europe. Locally, water management districts must adopt tailored strategies, focusing on stormwater management and encouraging sustainable agricultural practices in high-risk regions. Agencies such as the *U.S. Geological Survey (USGS)* can advance research to understand nutrient sources better and improve HAB monitoring technologies.

Industry-Specific Recommendations

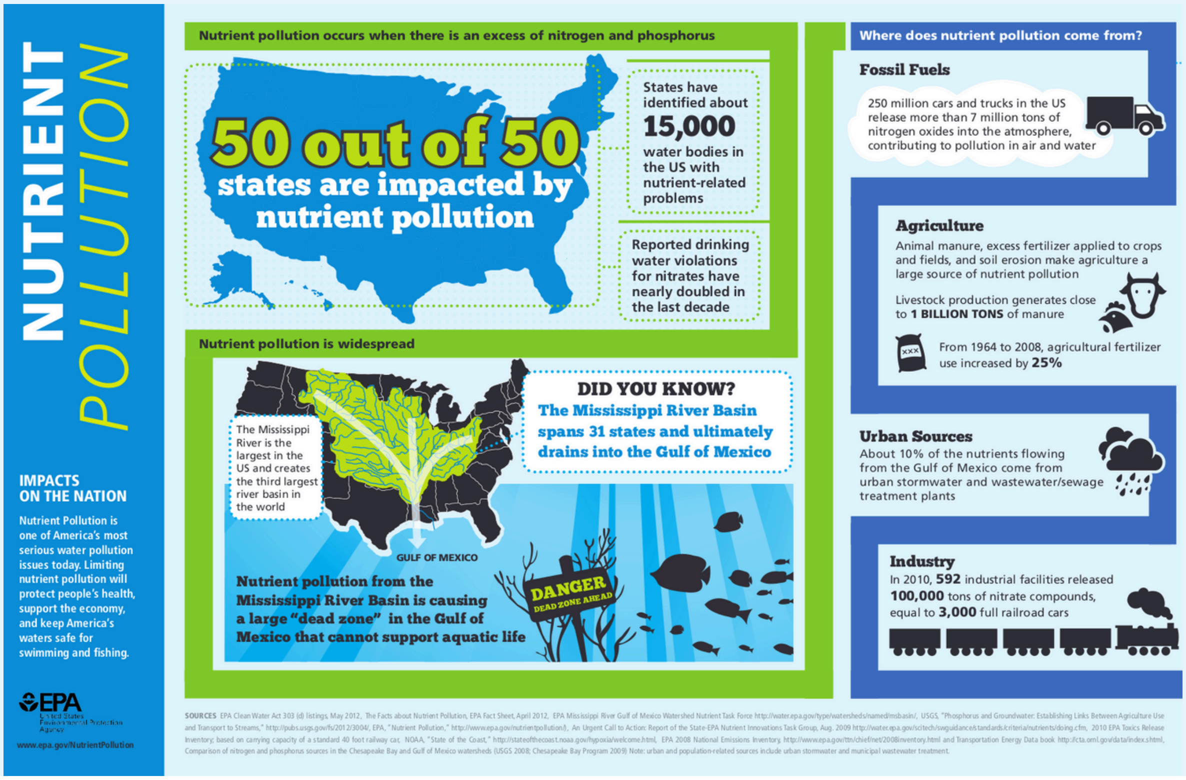
Industries contributing to nutrient pollution must adopt protocols to mitigate their environmental impact. Textile and apparel companies must reduce harmful chemical usage and improve wastewater treatment systems to curb pollution. Similarly, energy, mining, and industrial sectors should adopt sustainable practices that limit nutrient runoff and ensure compliance with environmental standards. Fisheries and aquaculture operations should regularly monitor water quality and employ sustainable methods to minimize their environmental footprint. In agriculture, precision farming techniques should be implemented to optimize fertilizer use, while offering strong financial incentives to encourage sustainable farming.

As previously stated, wastewater treatment facilities need to upgrade technologies for nutrient removal and incorporate green infrastructure to manage wastewater sustainably. These sector-specific efforts are crucial for reducing nutrient pollution and mitigating the adverse effects of Harmful algal blooms.

Global Policy Recommendations

This multi-tiered approach backed by government policies emphasizes nutrient management, advanced wastewater treatment, and international collaboration. These recommendations outline crucial strategies for reducing nutrient loads, enhancing enforcement, and promoting innovation to protect global water quality and global public health from the persistent threat of HABs.

- Promote Low-Impact Development (LID) in new construction projects to minimize runoff and nutrient discharge.
- Implement Nutrient Trading Programs by developing and supporting nutrient trading programs that incentivize reductions in nutrient pollution through market-based approaches.
- Support Research and Data Collection on HAB prevention and nutrient management technologies, and collect data to inform policy decisions and track progress.
- Funding for Research and Innovation is critical to finding long-term solutions to HABs. On a global scale, it is critical to fund research on the life cycle of harmful algae, toxin production, and the environmental conditions that contribute to HAB formation, to invest in emerging technologies such as natural algicides, genetic research, and nanobubble ozone technology (NBOT) to mitigate blooms and encourage public-private partnerships to bridge the gap between research and practical applications for HAB prevention.



10. NEW RESEARCH AND INNOVATIONS

To address the challenges posed by HABs, ongoing innovation and the adoption of new technologies are crucial. Key monitoring tools such as remote sensing technologies, satellite and drone imagery, and in-situ sensors that track nutrient levels and algal concentrations in real-time are instrumental. Machine learning and predictive modeling can further enhance early detection and forecasting of HAB events.

Innovative water treatment methods are crucial for managing HABs. Advanced oxidation processes (AOPs) like ozone and UV light effectively degrade toxins, while bioremediation technologies use microorganisms or plants to remove nutrients and pollutants. Electrochemical treatments, which employ electric currents for pollutant removal, also may help.

Two promising HAB control methods currently under development are worth highlighting in this special report: natural algicides and nanobubble ozone technology.

Natural Algicide Discovery: Funded by the NCCOS, University of Delaware marine scientist Dr. Kathryn Coyne's team has characterized an algicidal compound produced by the bacterium Shewanella that selectively kills harmful marine Dinoflagellates, which are known to produce HABs. This compound induces programmed cell death in the targeted dinoflagellates without harming other phytoplankton, fish, or shellfish, making it an effective and environmentally safe natural algicidal agent. With additional funding from the Delaware Sea Grant, the team is testing a novel delivery method by embedding the bacteria in gel-like alginate beads. These beads, packaged in mesh bags, can be temporarily deployed in coastal waters to prevent or mitigate algal blooms.[18]

Nanobubble Ozone Technology (NBOT): Validated by an independent quality control testing laboratory, NBOT has shown high effectiveness in controlling algae, bacteria, and motile zooplankton in ship ballast water, a known vector for spreading invasive species. For HAB remediation, NBOT has proven successful in eliminating algae during pilot tests at Lake Okeechobee, Lake Newport, and Constitutional Gardens. Nanobubbles can retain ozone for extended periods, allowing for prolonged water treatment with low ozone levels.[19]

Unlike traditional biocidal treatments, NBOT leaves no harmful chemical residues, instead enhancing the water's oxygen levels, making it a "green" and sustainable solution for algae management.

While these and other technologies offer promising solutions, it's important to note that many are not a panacea. Implementing these treatments on a large scale requires careful planning, regulation, and monitoring to ensure they are both effective and safe for aquatic ecosystems. Without such measures, there is a risk of merely shifting the problem rather than solving it.

To move beyond just identifying the problem and warning people, it is crucial to:

- Develop and scale these technologies with a focus on safety and environmental impact.
- Integrate these solutions with existing water management practices.
- Monitor treated areas to ensure that the treatments are not causing new problems.
- Promote ongoing research to refine these technologies and ensure they are safe for all forms of aquatic life.

Effective use of AOPs, bioremediation, and electrochemical treatments, combined with preventive measures like nutrient management, offers the most comprehensive approach to managing and mitigating the effects of HABs. Ongoing studies on algae life cycles and toxin production, as well as genetic research and bioengineering, are key to developing strategies for HAB prevention. Innovations like natural algicides and nanobubble ozone technology (NBOT) show potential for selectively targeting harmful algae without harming other aquatic life. For instance, NBOT has successfully eradicated algae in pilot tests, providing a sustainable and environmentally friendly option for water treatment.

Community engagement is also important for effective HAB management. Public awareness campaigns educate communities on HAB impacts and prevention, while community-based monitoring programs involve residents in tracking water quality and detecting blooms. These combined efforts of technology, research, and community participation are important pieces of managing and mitigating the impacts of HABs.

Community and Stakeholder Engagement

Public Awareness Campaigns: Launch educational campaigns to raise awareness about HABs, their impacts, and prevention measures. Engage the public through various media channels, community events, and partnerships with local organizations.

Community-Based Monitoring Programs: Establish programs that involve local communities in monitoring water quality and detecting HABs. Empower citizens with training and tools to contribute to data collection and reporting, fostering greater community involvement in water management.

These cutting-edge technologies represent significant advances in the fight against HABs, offering effective, environmentally friendly methods for both prevention and remediation. By leveraging these emerging technologies and fostering active community engagement, we can enhance our ability to predict, manage, and mitigate the impacts of Harmful algal blooms. These innovative approaches offer promising solutions for protecting water quality and ensuring a healthier environment.

11. NON-PROFIT ORGANIZATIONS MAKING A DIFFERENCE

Environmental nonprofits also play a vital role in supporting local and global research, development, and implementation of Advanced Oxidation Processes (AOPs), despite the technology's complexity and costs. **Calusa Waterkeeper** primarily focuses on water quality advocacy, but they collaborate with government agencies and private companies on initiatives that may involve AOPs to mitigate water pollution. **Puget Soundkeeper Alliance** engages in pollution monitoring and enforcement, potentially supporting pilot projects or awareness campaigns related to AOPs to reduce harmful pollutants. **Ocean Research & Conservation Association (ORCA)**, with its strong research focus, contributes to developing and testing AOPs as part of its mission to protect marine environments.

CALUSA WATERKEEPER®

40 PUGET SOUNDKEEPER® Established in 1984

ORCA

Harmful algal blooms have been at the center of Calusa Waterkeeper's science-based advocacy initiatives exploring the impacts of water quality on human health, our economy, and quality of life.

Originally founded as the Caloosahatchee River Citizen's Association in 1995, this grassroots not-for-profit organization rechartered as Calusa Waterkeeper in 2016-2017 to become a member of the global Waterkeeper Alliance. Calusa Waterkeeper's jurisdiction includes over 1,000 square miles of water bodies, including Lake Okeechobee, the Caloosahatchee River, and estuary, and the nearshore Gulf waters of Lee County stretching from Boca Grande to Bonita Beach.

One of the linchpins of Calusa Waterkeeper's efforts has been the volunteer Ranger program, which invites community members to join the organization as boots on the ground and fins in the water protecting and restoring the watershed. Through a series of classes, the Ranger Training Academy teaches the basics of water quality parameters, common pollution concerns, advocacy, and restoration initiatives. The citizen scientists enabled by the Ranger program greatly increase the amount of monitoring and advocacy the organization can achieve.

There are many serious challenges in the work to protect and restore the Caloosahatchee River and Estuary system, including harmful discharges from Lake Okeechobee, nutrient-laden stormwater runoff from agriculture and land uses of all types, and local and state policies allowing for rampant development and ineffective enforcement against water pollution.

Taking Action in a Crisis

Poor water quality conditions have been on display in increasing scope and frequency in Lake Okeechobee and Southwest Florida, including unprecedented conditions in the summer and fall of 2018. That year, Lee County became ground zero for double states of emergency for both a massive blue-green algae (*Microstyis aeruginosa*) bloom making its way down the Caloosahatchee River from Lake Okeechobee, and a terrible and prolonged red tide (*Karenia brevis*) event that killed millions of pounds of sea life, including dolphins, manatees, sea turtles, fish and invertebrates.

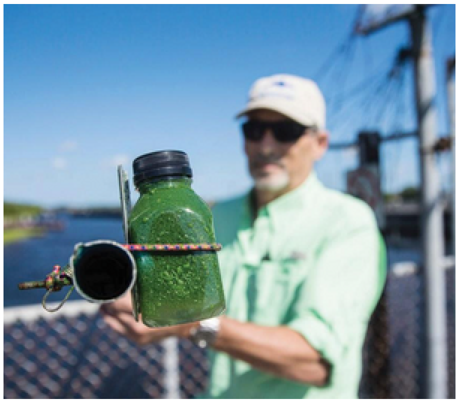
Toxin-producing *Cyanobacteria* blanketed huge swaths of the Caloosahatchee River and residential canals in Lee County, Florida. 2018

Calusa Waterkeeper was one of the first to sound the alarms of the approaching cyanobacteria bloom and sprang into action making observations as it spread across the more densely populated areas of the river and estuary. Volunteers tracked the bloom's scope and severity, aided in water samples for toxicology analysis, engaged with local, national, and international media inquiries, and organized public civic meetings to address the states of emergency.

At Fire Marshall capacity for a civic meeting with Army Corps, Lee County and Cape Coral public officials. (2018)

Advancing Research & Awareness

Because of Southwest Florida's unique and close relationship to the water, the proximity of homes and businesses to toxin-producing Harmful algae blooms became a keen point of interest.



Former Calusa Waterkeeper John Cassani takes a cyanobacteria sample from W.P. Franklin Lock & Dam for toxin analysis. Photo Credit: Fort Myers News-Press

Through a partnership with Brain Chemistry Labs, Calusa Waterkeeper helped spearhead research into the unprecedented intersection of blue-green algae and red tide blooms that took place near the mouth of the Caloosahatchee River and in Pine Island Sound. Findings were first published in the journal Neurotoxicity Research, <u>Toxin Analysis of Freshwater Cyanobacterial and Marine Harmful Algal Blooms on the West Coast of Florida and Implications for Estuarine Environments</u> and found that "the potential for multiple, potentially toxic blooms to co-exist and the possible implications for human and animal health," including "the possibility of long-term exposure of residents to BMAA," a compound linked with neurological diseases such as Parkinson's and ALS.

Calusa Waterkeeper Codty Pierce demonstrates ADAM in North Fort Myers, Florida. Photo Credit: Fort Myers News-Press

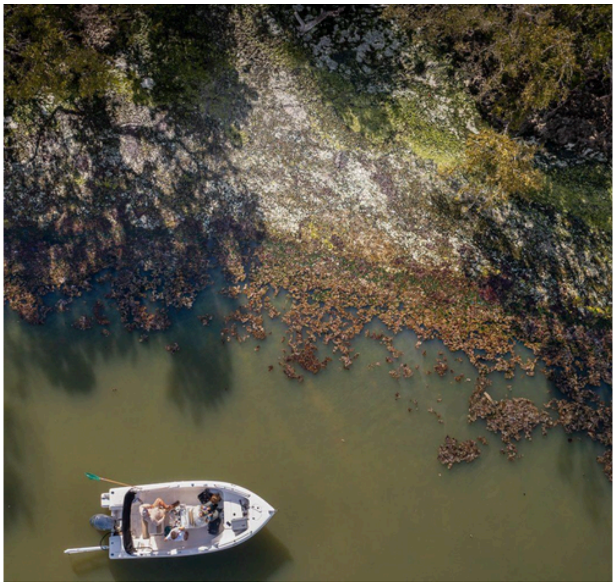
Calusa Waterkeeper also produced and premiered the first in a series of documentaries, Troubled Waters, which examined the possible health impacts of Harmful algal blooms in our community, including new airborne research from Florida Gulf Coast University scientists that found toxins present in the air many miles away from blooms.

On the advocacy front, Calusa Waterkeeper volunteers engaged in local, state, and national efforts to affect policy changes, including water management changes for Lake Okeechobee, advocating the strengthening of local fertilizer ordinances and the re-establishment of Florida's Blue-Green Algae Task Force.

In 2020/21, Calusa Waterkeeper volunteers set out to engineer their own novel research kit to capture air samples and measure them for aerosolized toxins related to blue-green algae and red tide. After months of research, planning, and iteration, the Aerosol Detector for Algae Monitoring (ADAM) was born.

How it works: Over the course 24-hours, an air pump cycles and equivalent to what an adult's lungs would process, and the microscopic particles are captured in air and water samples for lab analysis. Six ADAM units were ultimately constructed and are prepared for rapid deployment along the Caloosahatchee watershed. This pioneering research sets out to document the range of aerosolized toxins and concentrations from sites in Southwest Florida. Read more about the programs first findings: Collaborative Research on Airborne Toxins from Harmful Algal Blooms in Southwest Florida.

HAB and associated fish kill whilst the community is still repairing after Hurricane Ian in Matlacha, Fl. August 14, 2024.



Calusa Waterkeeper Captain Codty Pierce utilizes a boat and drone to document algal bloom activity in Pine Island Sound.

The Long Haul

While it is difficult for the public to ignore or deny the neon-green signals sent by blue-green algae blooms, unfortunately, the underlying and degraded water quality attributes persist year-round even when a bloom is not visible.

At the heart of Calusa Waterkeeper's advocacy approach is the belief that it is always more effective and economical to stop pollution at its source, rather than settle for expensive remediation efforts or cleanup technologies; prevention is superior to treatment. Thus, we believe policy reform remains the most effective way to prevent harmful algal blooms and protect the public interest. Unfortunately, Florida leaders are enabling poor water quality conditions by their own policy and planning decisions, and then spending unprecedented sums of public money on addressing the symptoms instead of the cause.

Where the "rubber meets the road" in efforts to stop nutrient pollution (and other water quality impairments) in Florida is via its Basin Management Action Plans and Total Maximum Daily Load programs, designed to limit the amount of pollution entering a given waterbody. These plans, devised by the legislature and implemented by the Florida Department of Environmental Protection, have largely failed to reduce overall nutrient loading, let alone restore an impaired waterbody. Key policy and enforcement changes must be made in Florida for us to be successful at preventing the pollution that fuels Harmful algal blooms and endangers human health, wildlife and our economy.

The increase in Harmful algal blooms (HABs) presents serious implications for ecosystems, human health, and the economy. As blooms become more frequent and widespread, they can devastate aquatic ecosystems by depleting oxygen levels in the water, leading to mass fish die-offs and creating dead zones where marine life cannot survive. The toxins released by certain algae species pose direct health risks to humans, livestock, and pets, causing respiratory problems, skin irritation, and in severe cases, liver and neurological damage

2016 Toxic algae bloom in the St Lucie Estuary

through water contact, consumption of contaminated seafood, or inhalation of aerosolized toxins. Economically, these blooms disrupt fisheries, reduce tourism, lower real estate values, and damage water-dependent industries, while costly mitigation efforts strain public resources. Additionally, the environmental damage can have long-lasting effects, further exacerbated by climate change, creating a feedback loop of warmer temperatures and stormwater nutrient runoff that accelerates bloom formation. This rising trend represents a multifaceted threat that demands improved data gathering for science-driven solutions.

Based in Florida, the **Ocean Research & Conservation Association (ORCA)** plays a significant role in addressing harmful algal blooms (HABs) through innovative research, technology development, and community engagement. Their efforts are focused on both understanding the causes of algal blooms and mitigating their impacts on Florida's ecosystems and communities.

Key Initiatives by ORCA to Address Harmful Algal Blooms

1. Pollution Mapping and Monitoring:
ORCA uses advanced technologies like the Kilroy Continuous Water Quality Monitoring System, which is the largest real-time monitoring network in Florida to map pollution sources and monitor water conditions in Florida's coastal and inland waterways.

These systems help identify key contributors to nutrient pollution, such as stormwater runoff and muck, which fuel HABs. By pinpointing pollution hotspots, ORCA can work with local governments and stakeholders to develop targeted strategies to reduce nutrient inputs into the waterways.

By regularly measuring parameters like turbidity, pH, temperature, dissolved oxygen, nutrient levels, and blue-green algae, ORCA's Kilroys can detect changes that may indicate pollution, habitat degradation, or the onset of Harmful algal blooms.

ORCA's Kilroy Water Monitoring System

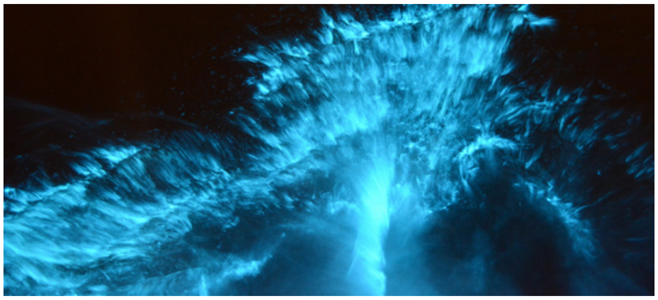
2. Citizen Science Programs:

ORCA actively engages the local community through initiatives like the Citizen Science Pollution Mapping Program. This program trains volunteers to collect water samples and measure pollution levels in local water bodies. The data collected by these citizen scientists supplements ORCA's monitoring efforts and helps create a broader understanding of the geographic and seasonal patterns of harmful algae blooms, empowering local communities to take part in environmental conservation.

Volunteer citizen scientists collecting sediment samples.

3. Research and Data Collection:

ORCA conducts scientific research to understand better the biological, chemical, and physical processes that lead to Harmful algal blooms. Their research focuses on the complex interactions between nutrient pollution, climate change, and water management practices that contribute to the growth of toxic algae. ORCA also investigates how some HABs go from being nontoxic to toxic.



The dinoflagellate Pyrodinium bahamense is a bioluminescent dinoflagellate that produces the potent neurotoxin, saxitoxin (STX), which if consumed by humans can produce paralytic shellfish poisoning. P. bahamense bloomed in the Indian River Lagoon (IRL), along the east coast of Florida, for years with no known record of STX production until the mid-2000s.

4. Restoration Projects:

ORCA participates in habitat restoration projects, such as living shorelines and the installation of buffered shorelines, which help filter out excess nutrients before they reach the ocean. By enhancing natural filtration systems, these projects can mitigate the nutrient pollution that drives HAB formation, improving water quality and reducing the frequency of blooms. Monitoring pre- and post-mitigation projects provides much-needed data on the relative effectiveness of different methodologies.

5. Public Education and Advocacy:

Through workshops, educational programs, and partnerships with local schools, ORCA raises awareness about the causes and consequences of Harmful algal blooms. They advocate for better policies and practices to reduce nutrient runoff, pushing for sustainable land use, improved agricultural practices, and enhanced wastewater treatment to minimize human contributions to HABs.

In summary, ORCA addresses Harmful algal blooms through a combination of cutting-edge technology, scientific research, citizen science, ecosystem restoration, and public advocacy. Their holistic approach targets the root causes of blooms while promoting environmental stewardship and sustainable solutions to improve Florida's water quality and protect marine life.

ORCA Citizen Scientists monitoring living shorelines

Puget Soundkeeper's work addressing HAB:
Many factors can contribute to and exacerbate the proliferation of HABs. Puget Soundkeeper's work on National Pollution Elimination Discharge (NPDES) permits, green stormwater infrastructure, education and outreach, and community science is central to some of the largest contributors to HABs in the Puget Sound and its watersheds:

Nutrients:
Nutrient loading contributes to HABs. Wastewater and human land-use activities are two major contributors to nutrient loading in the Puget Sound region. Soundkeeper is part of two major Clean Water Act lawsuits, fighting for comprehensive nutrient regulation required by both the Federal Clean Water Act and the State Water Pollution Control Act.

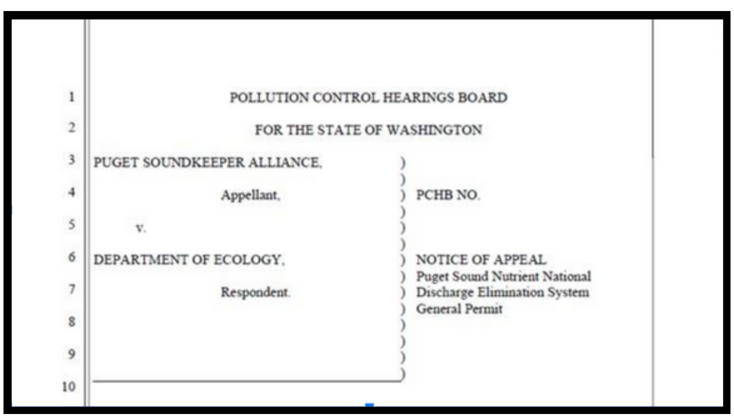
In addition, Soundkeeper is actively advocating for robust nutrient regulation at individual wastewater treatment facilities like the one at West Point in Seattle, which contributes more than 18,000 pounds of nitrogen a day to the central Puget Sound where tides and the unique geology of the Sound generate cascading impacts throughout the waterbody.[20] At the same time, Soundkeeper is actively engaged with government agencies to develop policies and programs that would better educate decision-makers about resources needed to address this problem (e.g., green infrastructure to reduce the flow volume heading to treatment facilities, low-impact development BMPs, and advanced sewage and stormwater management technologies, training and tools).

Soundkeeper is also engaged in a Clean Water Act lawsuit fighting for comprehensive regulation of Combined Animal Feeding Operations (CAFOs), including related nutrient pollution from livestock manure affecting groundwater and surface waters throughout the state.

Turbidity and pH:
Turbidity and pH can both contribute to HABs. Stormwater runoff from industrial facilities can result in increased turbidity and changes to pH. Soundkeeper actively monitors publicly available discharge data from industrial facilities that hold a NPDES permit. When those data show benchmark exceedances of turbidity or pH, Soundkeeper takes action. Sometimes Soundkeeper will reach out directly to the Department of Ecology's enforcement team. Sometimes Soundkeeper will pursue an enforcement action in the courts. In the past year, Soundkeeper has initiated several lawsuits against polluters in Skagit, King, and Pierce counties.

Temperature and Flow:

Temperature and flow are each contributing factors to HABs. Soundkeeper works to protect riparian zones and restore critical habitat. Soundkeeper works with partners on increasing tree canopy in local and regional land use plans and for projects like shading along the Ship Canal and other urban waterways like Lake Union and the Green-Duwamish River. Again, Soudnkeeper's long history of advocating for green infrastructure and low impact development (LID) in NPDES permits has been driving change in this space. Soundkeeper has regularly participated as panelists in the region's annual Green Stormwater Infrastructure Summit for the past to share knowledge with local practitioners, Soundkeeper works to remove or improve culverts and other flow-limiting structures, and Soundkeeper's advocacy on municipal stormwater management led to the state's first LID requirements. In addition, Soundkeeper conducts habitat restoration and monitoring at several key tributaries to the Sound, including Springbrook Creek (working with local youth program Unleash the Brilliance to educate and inspire the next generation of local water quality experts) and Longfellow Creek , a salmon bearing stream stressed by culvert related flow problems and human development related habitat and water quality degradation – and a site that has produced a host of data used by decision makers across the region.



POLLUTION CONTROL HEARINGS BOARD
FOR THE STATE OF WASHINGTON

PUGET SOUNDKEEPER ALLIANCE, Appellant,

v.

DEPARTMENT OF ECOLOGY, Respondent.

PCHB NO.

NOTICE OF APPEAL
Puget Sound Nutrient National Discharge Elimination System General Permit

Monitoring:

Monitoring the conditions that lead to HABs is a large part of Soundkeeper's work. Soundkeeper is a partner with the WDFW on its mussel monitoring program, collecting data from mussels that indicate the health of the Puget Sound. Soundkeeper also tracks and monitors NPDES permit compliance for years after a lawsuit has closed, standing ready to act if and when discharges exceed benchmarks for things like turbidity and pH.

12. CONCLUSION AND CALLS TO ACTION

Addressing the challenges posed by HABs requires a multifaceted approach that integrates modified industry practices, effective policy changes, advanced technological solutions, and active community engagement.

Companies across various industries must adopt sustainable manufacturing practices that prioritize water quality and minimize nutrient runoff. Agricultural companies, for example, can implement precision agriculture techniques to optimize fertilizer use and reduce excess nutrient discharge. Fertilizer manufacturers should develop slow-release fertilizers and invest in environmentally friendly products that minimize runoff into waterways. Wastewater treatment facilities need to enhance their systems to incorporate advanced nutrient removal technologies, ensuring that treated water meets stricter regulatory standards.

Additionally, industrial and chemical companies can implement best practices for wastewater management to prevent nutrient and chemical discharges. The textile and apparel industry must adopt greener production methods to reduce the use of harmful dyes and chemicals, coupled with efficient wastewater treatment systems. Energy and mining companies should focus on sustainable practices that limit sediment and nutrient runoff from their operations. Lastly, food and beverage manufacturers can improve their water management practices to reduce pollution, while automotive manufacturers can adopt advanced treatment technologies to ensure their manufacturing processes are environmentally friendly.

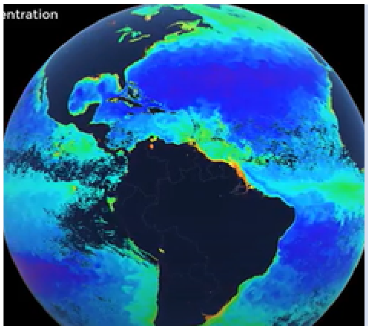
To support these efforts, comprehensive nutrient management policies, strengthened regulations, and increased funding for research and innovation are essential. Furthermore, international collaboration and knowledge sharing are vital for addressing HABs on a global scale. By implementing these strategies and leveraging technological advancements, along with proactive changes in manufacturing processes, we can better protect water quality, safeguard public health, and preserve aquatic ecosystems from the adverse impacts of HABs.

CALLS TO ACTION

We envision a world where Harmful Algal Blooms (HABs) are no longer a threat to our waters, ecosystems, or communities, achieved through cutting-edge research, collaboration, and sustainable practices.

Industry Leaders

- Adopt sustainable manufacturing practices.
- Enhance wastewater treatment and integrate cleaner production technologies.
- Immediate changes to reduce nutrient runoff, improve water quality, and support regulatory compliance.



Government and Funding Agencies

- Increase funding for HAB research and innovation.
- Prioritize studies on algae life cycles, toxin production, and new treatment technologies.
- Develop effective solutions and management strategies.

Local Governments and Community Organizations

- Launch public awareness campaigns and community-based monitoring programs.
- Educate residents about HAB impacts, and encourage involvement in water quality monitoring.
- Promote preventive actions to protect water resources.

Our vision is to create a future where Harmful algal blooms no longer threaten the health of our oceans, waterways, and communities. Through innovative research, strategic partnerships, and proactive environmental stewardship, we aim to mitigate the impacts of HABs, ensuring the resilience and sustainability of our marine ecosystems for generations to come.

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