**REPORT OF THE DEPARTMENT OF ENVIRONMENTAL QUALITY**

# HARMFUL ALGAE BLOOMS IN VIRGINIA

Commonwealth of Virginia
Richmond
September 2021

**This page is intentionally blank**

# Contents


Glossary of Acronyms, Abbreviations and Technical Terms ..... 4
List of Tables ..... 6
List of Figures ..... 7
Executive Summary ..... 8
Introduction ..... 9
HABs in Virginia ..... 10
Virginia HAB Task Force ..... 10
Location, Frequency, and Severity of Harmful Algae Blooms in Virginia Waters ..... 12
Marine HABs ..... 13
Freshwater Cyanobacteria ..... 17
Potentially Toxic Cyanobacteria ..... 20
Cyanobacteria Recreational Advisories ..... 23
Marine and Freshwater HAB Response Funding Gaps ..... 26
Factors that Lead to Harmful Algae Blooms ..... 27
Nutrients ..... 27
Temperature ..... 32
Light ..... 34
Low Velocity, Stable Conditions ..... 34
Turbidity ..... 34
Utilizing DEQ's Existing Monitoring Network and Resources to Understand HAB Occurrences ..... 36
Plans and Strategies for Appropriate Mitigation Efforts ..... 37
Pollution Reduction and Prevention ..... 37
HAB Treatments ..... 39
References ..... 42

## Glossary of Acronyms, Abbreviations and Technical Terms

| | |
|---|---|
| **Algae** | Ubiquitous aquatic single cell organisms that are found in all freshwater and marine habitats, carry out photosynthesis, and represent the major source of food and oxygen for many of the inhabitants present in lakes, rivers, estuaries, and oceans. Among the several thousand species of algae that exist worldwide a small number may be harmful. |
| **Algae bloom** | Occurs when environmental conditions favor the rapid growth of a species or number of species of algae. When these blooms have detrimental impact through toxin production or other mechanisms, it is known as a harmful algal bloom (HAB). |
| **Ambient Monitoring** | The monitoring of physical and chemical characteristics within the Commonwealth's rivers, streams, lakes, and estuaries. Ambient monitoring and assessment characterize ecological stressors and evaluate their potential impact on aquatic organisms and other wildlife, and on human health and recreational use of Virginia's waters. |
| **Anatoxin-a** | A neurotoxin that may be produced by cyanobacteria. |
| **CBP** | Chesapeake Bay Program |
| **CEDS** | Comprehensive Environmental Data System |
| **Cylindrospermopsin** | A hepatoxin that may be produced by cyanobacteria. |
| **CWA** | The federal Clean Water Act. The CWA, in part, describes the scope and purpose of water quality standards (WQS) and defines the authority and responsibility of the Environmental Protection Agency (EPA) and the various states in relation to the requirements for, submission of, and establishment of these standards. |
| **Cyanobacteria** | Blue-green algae; prokaryotic photosynthetic organisms that are naturally found in freshwater habitats globally. |
| **DCLS** | Division of Consolidated Laboratory Services of the Virginia Department of General Services (DGS) |
| **DEQ** | Department of Environmental Quality |
| **DGS** | Department of General Services |
| **EPA** | Environmental Protection Agency |
| **HABs** | Harmful Algal Blooms (HABs) are algae and cyanobacteria that produce toxins that may adversely affect human health through ingestion of contaminated water or shellfish. |
| **IR** | The Integrated Report (IR) is the 305(b)/303(d) Water Quality Assessment Integrated Report required by the Clean Water Act (CWA). |
| **Microcystin** | A hepatoxin that may be produced by cyanobacteria. |
| **MonPlan** | Annual Water Quality Monitoring Plan |
| **NELAP** | National Ecological Laboratory Accreditation Program |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NPS** | Non-Point Source (pollution) |
| **ODU** | Old Dominion University |
| ***Pfiesteria*** | An estuarine toxic algae. |
| **Potentially toxigenic species** | A type of algae that can produce toxins under the right conditions. Only a small number of algal species can produce toxins, and a potentially toxigenic species might not produce toxins all of the time. |
| **QA** | Quality Assurance |

| | |
|---|---|
| **QAPP** | Quality Assurance Program and Project Plan |
| **QC** | Quality Control |
| **Saxitoxin** | A neurotoxin that may be produced by cyanobacteria. |
| **SOP** | Standard Operating Procedure |
| **Toxins** | Chemicals that are poisonous to other organisms. |
| **TMDL** | Total Maximum Daily Load |
| **Turbidity** | The cloudiness of water determined by measuring how the material suspended in water affects the water's clarity. |
| **Water clarity** | How well light passes through the water column. |
| **USGS** | United States Geological Survey |
| **VDACS** | Virginia Department of Agriculture and Consumer Services |
| **VDH** | Virginia Department of Health |
| **VELAP** | Virginia Environmental Laboratory Accreditation Program |
| **VIMS** | Virginia Institute of Marine Science |
| **VMRC** | Virginia Marine Resources Commission |
| **VPDES** | Virginia Pollutant Discharge Elimination System |
| **WQM** | Water Quality Monitoring |
| **WQMA** | Water Quality Monitoring and Assessment |
| **WQS** | Water Quality Standard(s) |

# List of Tables

Table 1: Marine toxin criteria within shellfish meat for the closure of shellfish growing areas ............... 14

Table 2: Hybrid advisory approach: Cyanobacteria bloom recreational advisory thresholds using cell densities and toxin concentrations for targeted cyanotoxins (VDH 2021)............................................... 21

Table 3. Percentage of stations statewide exhibiting no statistically significant trend, improving (decreasing) total nitrogen and degrading (increasing) total nitrogen... ................................................ 28

Table 4. Total Nitrogen: basinwide summary. Numbers indicate number of monitoring stations where improving (decreased nitrogen) or degrading (increased nitrogen) were detected................................ 30

Table 5. Percentage of stations statewide exhibiting no significant trend (p> 0.10), improving (decreasing) total phosphorus and degrading (increasing) total phosphorus... ...................................... 31

Table 6. Total Phosphorous: basinwide summary. Numbers indicate number of monitoring stations where improving (decreased phosphorous) or degrading (increased phosphorous) were detected........ 32

Table 7. Percentage of stations statewide exhibiting no statistically significant trend, improving (decreasing temperature) and degrading (increasing temperature)... .................................................... 32

Table 8. Surface water temperature: basinwide summary. Numbers indicate number of monitoring stations where improving (decreased temperature) or degrading (increased temperature) were detected. ........................................................................................................................................ 33

Table 9. Percentage of stations statewide exhibiting no statistically significant trend, improving water clarity (decreasing turbidity) and degrading water clarity (increasing turbidity)...................................... 35

Table 10. Water clarity as measured by turbidity: basinwide summary. Numbers indicate number of monitoring stations where improving (decreased turbidity) or degrading (increased turbidity) were detected. ........................................................................................................................................ 36

# List of Figures

Figure 1. Routine monitoring in Virginia's marine and estuarine waters ... 13

Figure 2. Potentially toxic marine algae ... 15

Figure 3. Marine biotoxins ... 16

Figure 4. Number of potential HABs (or simply "Algal Blooms") reported annually through the online HAB reporting tool (2017 to 2021). It should be noted that while the tool is called the HAB report form, laboratory analysis is necessary to determine if the reported condition is an actual algal bloom and if the algal bloom contains toxins or toxigenic species at harmful concentrations. ... 17

Figure 5. Potential HABs (or simply "Algal Blooms") reported in each month (2017 - 2021). Laboratory analysis is necessary to confirm the presence of toxins or toxigenic species in harmful amounts. ... 18

Figure 6. Potential HABs (or simply "Algal Blooms") reported by county (2017 - 2021). Laboratory analysis is necessary to confirm the presence of toxins or toxigenic species in harmful amounts. ... 19

Figure 7. Map depicting the location and frequency of potential HAB reports in Virginia (2017-2021). Laboratory analysis is necessary to confirm the presence of toxins or toxigenic species in harmful amounts. ... 20

Figure 8. Locations in Virginia where potentially toxic cyanobacteria have been detected. ... 21

Figure 9. Locations in Virginia where microcystin was detected (2016 - 2020) ... 22

Figure 10. Locations in Virginia where cylindrospermopsin was detected (2018-2020) ... 22

Figure 11. Locations in Virginia where anatoxin-a was detected (2018-2020) ... 23

Figure 12. Locations in Virginia where saxitoxin was detected (2018-2020) ... 23

Figure 13. HAB recreational advisories issued in Virginia (2016 - 2020) ... 25

Figure 14. Map depicting the locations of HAB recreational advisories in Virginia (2016 - 2020) ... 25

Figure 15. Locations of eight Lake Anna segments where advisories are managed. ... 26

Figure 16. Statewide trends in Total Nitrogen ... 29

Figure 17. Statewide trends in Total Phosphorus ... 31

Figure 18. Statewide trends in Surface Water Temperature ... 33

Figure 19. Statewide trends in water clarity as measured by Turbidity ... 35

# Executive Summary

Item 377 P. in Chapter 552 of the 2021 Special Session I Acts of Assembly directed the Virginia Department of Environmental Quality (DEQ) to convene a workgroup, in conjunction with the Virginia Department of Health (VDH) and the Virginia Department of Agriculture and Consumer Services (VDACS), to conduct research and complete a single collaborative report that provides findings and recommendations related to:

(i) the location, frequency, and severity of harmful algae blooms in Virginia waters;
(ii) the factors that lead to the formation and occurrence of harmful algae blooms; and,
(iii) plans and strategies for state agencies to lead or support appropriate mitigation efforts.

This item directed the workgroup to provide its findings to the Chairs of the House Agriculture, Chesapeake and Natural Resources Committee and Senate Agriculture, Conservation and Natural Resources Committee no later than September 1, 2021.

Algal blooms are natural occurrences. Human activities, including housing developments, agriculture, silviculture, road construction, etc., can increase the frequency, size, and duration of the bloom. There are many different kinds of algae, and accordingly, blooms are different and only some are considered harmful. For the purposes of this report, Harmful Algal Blooms (HABs) are a subset of algae and cyanobacteria that produce toxins that may adversely affect human health through ingestion of HAB-impacted water or shellfish. As required by Item 377 P., this report summarizes existing knowledge and provides recommendations for potential further actions related to three main topics: 1) the location, frequency, and severity of HABs in Virginia, 2) the factors that lead to HABs, and 3) plans for state agencies to lead or support mitigation of HABs. These three topics are addressed within the context of the above working definition.

The reporting and identification of potential HABs in Virginia's marine and freshwaters has increased in recent years in part because the criteria for characterizing HABs has changed. VDH and DEQ, along with academic partners, have investigated complaints of potential HAB events all over the state. While HAB events in Virginia have not yet been severe, the magnitude, frequency, and duration of cyanobacteria blooms above new VDH thresholds has led to a growing number of recreational swimming advisories across the state in recent years.

For example, in July and August 2021, DEQ investigated multiple reports of potential HABs that were submitted through the Harmful Algal Bloom Portal. Subsequent laboratory analysis indicated that algal toxins (including microcystin, cylindrospermopsin, anatoxin-a, and saxitoxin) were present within algal mats in multiple locations along the North Fork Shenandoah River. At some of those sites, toxins and potentially harmful algal cells were also detected in the water, although at the time of writing this report, all concentrations were at low levels and well below VDH advisory thresholds for recreational use. However, due to the presence of cyanobacteria in algal mats detected at sites along the river, VDH issued and subsequently extended a recreational advisory for the North Fork Shenandoah River to ensure the public was aware of the presence of these algal mats and to ensure that people, in addition to their pets and livestock, could take caution to avoid contact with visible algal mats and scum. The advisory covered approximately 52.5 miles of the North Fork Shenandoah River as of August 10, 2021.

As an illustration of other effects HABs or potential HABs may create, the Town of Strasburg and the City of Winchester adjusted their raw-water intake treatment protocols and increased monitoring since the bloom was discovered. The Town of Woodstock increased monitoring, and made plans to adjust their raw-water intake treatment protocols if necessary. As of the time this report was drafted, drinking water in the Town of Woodstock, the Town of Strasburg, and the City of Winchester was safe to use and drink, according to public statements by the localities. The three localities planned to continue active monitoring of drinking water, and to notify the public if any protective action became necessary.

An online report was created to reflect the HAB advisory status of the North Fork Shenandoah River and may be found at "North Fork of Shenandoah River Status Report (8.10.21)".

The challenges surrounding the increase in HAB events is two-fold. First, HAB events pose a challenge and potential financial burden for stakeholders, businesses, and citizens who rely on Virginia's waterways for recreation, vacation rentals, fishing charters, seafood production, and other water-tourism related activities. Second, Virginia's agencies responsible for responding to HAB events lack resources to keep up with the demand. VDH and DEQ do not currently have the funding necessary to adequately support the existing marine HAB monitoring and response program which conducts surveillance year round to protect the public and the shellfish resource on the coast of Virginia. DEQ maintains a robust monitoring network, but has no budget or staff resources to perform the additional monitoring needed to support a consistent schedule of freshwater HAB response monitoring necessary to determine causal factors and protect human health. VDH does not receive any funding to support the 100,000 miles of freshwater rivers and streams and 248 publicly owned lakes, all designated to support recreational uses throughout the state. Given the scope and complexity of HAB occurrences in Virginia, the timeline associated with this report was not sufficient to determine exact causal factors contributing to specific HAB events.

Plans and strategies for appropriate mitigation efforts include local waterbody cleanup plans for impaired waters, and the implementation of the Chesapeake Bay Watershed Implementation Plan. These strategies typically require rigorous data collection and analysis as well as significant funding for the installation of Best Management Practices and additional wastewater treatment technologies. Some of the most common in-situ treatment strategies are also reviewed in this report. This is an expanding field of study and the range of treatment strategies is broad and increasing. In addition, an analysis of the relative cost of each strategy is beyond the scope of this review, as such an analysis requires extensive information on the systems and algae types to be treated, and DEQ would need additional contractual support to perform the analysis.

## Introduction

Algae are ubiquitous single-celled or colonial organisms found in freshwater and marine habitats throughout the world. They are photosynthetic (like plants), and form the base of aquatic food webs, produce a significant portion of earth's atmospheric oxygen, and occasionally form blooms, of which a small number may be harmful. An algal bloom occurs when environmental conditions (including light, temperature, and nutrient content) favor rapid growth of one or a few types of algae such that they discolor the water or mats and scums appear. Of the 30,000 to 1 million plus species of algae estimated to exist (Guiry 2012), a small percentage have the potential to cause detrimental impacts to aquatic ecosystems due to their abundance and biomass or production of toxins. These impacts range from benign to harmful: discolored water, biofouling, reduced light penetration and consequent shading of aquatic grasses and corals, strong odors, bad tasting drinking water, reduced dissolved oxygen, fish kills and animal mortalities, and in some cases production of biotoxins that can be of public health concern. HABs include those algae that are potentially toxic to humans. In marine waters, algae of concern are generally a small number of dinoflagellates and diatoms whose compounds may contaminate shellfish growing areas, which could result in human shellfish poisoning. Within fresh waters, cyanobacteria (blue-green algae) are the primary organism of concern with the primary exposure route via the ingestion of toxins. This may occur either through the consumption of contaminated drinking water or through accidental ingestion during swimming and other recreation.

## HABs in Virginia

Over the last 20 plus years, there has been a dramatic increase in the frequency and magnitude of HABs in Virginia, throughout the US, and globally, as well as an expanded number of HAB species known to have capability to produce toxins harmful to human health (Marshall and Egerton 2009, O'Neil et al. 2012). Within freshwaters, toxic cyanobacteria blooms have become more common and have resulted in impacts to drinking and recreational waters in the US and world-wide (Backer et al. 2015, Huisman et al. 2018). While formal federal guidance from EPA on cyanotoxins in recreational waters was not released until 2019, VDH has been active in the management of toxic cyanobacteria blooms since 2012 (VDH 2012). Within the US, massive blooms in Lake Erie (Steffen et al. 2017), Florida (Schaefer et al. 2020), and the west coast (Ritzman et al. 2018) have had extraordinary impacts on drinking water, recreational use, and the seafood industry. The same toxin producing marine and freshwater species associated with these major blooms have been identified within Virginia waters (Marshall et al. 2005). Other states, including neighboring North Carolina, have also recently experienced pet (dog) mortalities after ingesting water containing toxic cyanobacteria from recreational waterbodies (Miller 2019). While in Virginia HAB impacts have not been as severe as in other parts of the country, the increasing frequency, duration, and magnitude of cyanobacteria blooms that exceed EPA's and VDH's advisory guidance have led to a growing number of recreational swimming advisories across the state in recent years. Stakeholders and citizens living near freshwater bodies where recreational swimming advisories have become a recurring event indicate losses in income related to the cancellation of vacation rental reservations, fishing charters, and other water-tourism recreational activities impacted as a result of the loss of the beneficial use. In the Chesapeake Bay and Virginia's coastal waters, marine biotoxin producers (Onofrio et al. 2021) potentially threaten the estimated $500 million annual economic impact of Virginia seafood.

## Virginia HAB Task Force

VDH has been a partner in the monitoring and management of HABs in the Commonwealth for two decades. In 1997, Virginia created a multi-jurisdictional Task Force on *Pfiesteria* (an estuarine toxic algae), to respond to blooms and associated impacts to fish and human health. Since its inception, the Task Force has continued its mission to respond to harmful algae events and monitor for potentially toxic organisms and effects to human health and aquatic life. This mission has expanded beyond the initial coastal species of concern to include all potentially harmful algae and aquatic systems in Virginia, including marine biotoxin producers and toxic cyanobacteria (VA HAB Taskforce 2018). VDH and DEQ serve as co-leads of the Task Force, along with VMRC, VIMS, and ODU. Each entity is responsible for serving the Commonwealth with defined roles respective of HAB response efforts:

- DEQ serves with VDH as a co-lead for coordinating Task Force activities. DEQ responds to suspected HAB events and fish kills that may be the result of a HAB. This includes conducting field investigations and sample collections when necessary. DEQ collects HAB samples which are analyzed by ODU and VIMS, and provides data on environmental water quality conditions associated with blooms.

- VDH serves with DEQ as a co-lead for coordinating Task Force activities and includes primary support members from the Office of Environmental Health Services (OEHS) and the Office of Drinking Water (ODW).
    - VDH OEHS-Division of Shellfish Safety and Waterborne Hazards (DSSWH) is responsible for the routine collection of samples from shellfish growing areas (marine waters), as well as bloom response sampling including shellfish collections if necessary utilizing the methods and criteria as described by their marine biotoxin contingency plan and the National Shellfish Sanitation Program Model Ordinance.

      DSSWH is also responsible for responding to health complaints related to HAB exposure, managing the public HAB reporting and outreach tools (www.SwimHealthyVA.com), supporting and facilitating HAB investigations in coordination with Task Force partners, providing the local health district (or state/federal owner of the waterbody) with recommendations based on HAB investigation results, and managing recreational swimming advisories when necessary to protect public health.

    - VDH ODW regulates waterworks with surface water intakes supplying drinking water to approximately 76% of Virginia residents. ODW will coordinate with the waterworks to confirm that an algae bloom is impacting the drinking water supply, and to determine if that algae bloom is harmful in nature. If necessary, ODW will coordinate the emergency response with the waterworks and the Virginia Department of Emergency Management (VDEM). ODW also provides technical assistance to the waterworks, and public education information to waterworks and their customers, as needed.

- VMRC serves multiple supporting roles in the Task Force, including providing access to additional boat support when necessary for the evaluation of suspected HAB events and fish kills, the enforcement of HAB waterway closures within its jurisdiction, and assistance in outreach activities.

- VIMS, in part through limited annual MOU funding from VDH, is responsible for molecular and morphological analyses of samples for HAB species, including routine marine DSSWH samples, and those collected in response to blooms and fish or shellfish kills by VIMS and other HAB Task Force members. VIMS is also responsible for pathological analyses of finfish with lesions, and animals from fish and shellfish kill events. Staff are also integral in the development of agency policy and guidance related to HAB advisory management.

- ODU (Phytoplankton analysis lab), through limited annual MOU funding from VDH, is responsible for the algal species analyses, including enumeration of all potentially toxic taxa, from routine shellfish growing area samples (marine) and additional bloom collections by DEQ and other HAB Task Force members. ODU also conducts toxin analyses of freshwater samples associated with bloom responses by the Task Force. Staff are also integral in the development of agency policy and guidance related to HAB advisory management.

To that end, the Task Force prioritizes efforts for the detection of HAB species and toxins in water supporting shellfish, drinking water, and public recreational uses within Virginia. Within shellfish waters, Virginia, as part of the National Shellfish Sanitation Program, is required to have a Marine Biotoxin Contingency Plan to protect public health as it relates to algal toxin contamination of shellfish, which includes monitoring of coastal waters for HABs throughout the year working with ODU and VIMS. This includes year round monthly collections at approximately 70 stations within shellfish growing areas (Figure 1) and toxin analyses of water and/or shellfish samples by VDH DSSWH staff, as well as maintaining MOUs with laboratories for analyses of potentially biotoxin producing species.

No such routine monitoring or funding exists for the protection of recreational freshwaters. Instead, VDH and the Task Force have managed freshwater cyanobacteria blooms through a response based management and advisory approach, co-led and supported typically by DEQ field collections and water quality data, with and phytoplankton analysis and toxin assays by the ODU lab. The increase in freshwater HAB reports in the last 10 years has led to a significant unfunded workload on Task Force partners, with more than 500 cyanobacteria toxin assays conducted in 2020 alone.

VDH, DEQ, and other HAB Task Force partners' efforts focus on responding to algal blooms that pose a potential risk to human health and the recreation and drinking water designated uses. For the purposes of the report, HABs are defined as those that are potentially toxic and threaten human health, including those events that have led to public advisories related to recreation, drinking water, or shellfish use.

## Location, Frequency, and Severity of Harmful Algae Blooms in Virginia Waters

Potentially harmful algae are a small subset of the total algal community, but can become rapidly dominant in aquatic systems with ecological imbalances such as when excessive nutrients become available or other human-based impacts have created a favorable environment for harmful algae dominance. Based on long-term monitoring data, over 1,400 algal species have been identified in the Chesapeake Bay and its tidal tributaries compared to approximately three dozen potentially harmful or toxin producing species (~2%) (Marshall et al. 2005, Marshall and Egerton 2012). The science and understanding of algal toxins is constantly evolving based on taxonomic and analytical reports worldwide, with additional toxins and potentially toxic species continuing to be identified.
For the purposes of this report, several data sources were surveyed and compiled to address the location, frequency, and severity of harmful algae blooms in Virginia waters. The period of 2015-2020 was examined, corresponding with the current DEQ assessment window. Due to the varying nature of the different monitoring programs, testing capacity, and research studies, some datasets have slightly different time periods, which are labeled accordingly. Datasets utilized in the report include the following programs in marine/coastal waters (Figure 1): Chesapeake Bay Monitoring Program (DEQ/ODU) phytoplankton monitoring (2015-2020), VDH/ODU/VIMS Shellfish growing area marine biotoxin monitoring (2016-2020), and VDH/VIMS/NOAA Sea Grant Chesapeake Bay Toxin research program (2017-2020).

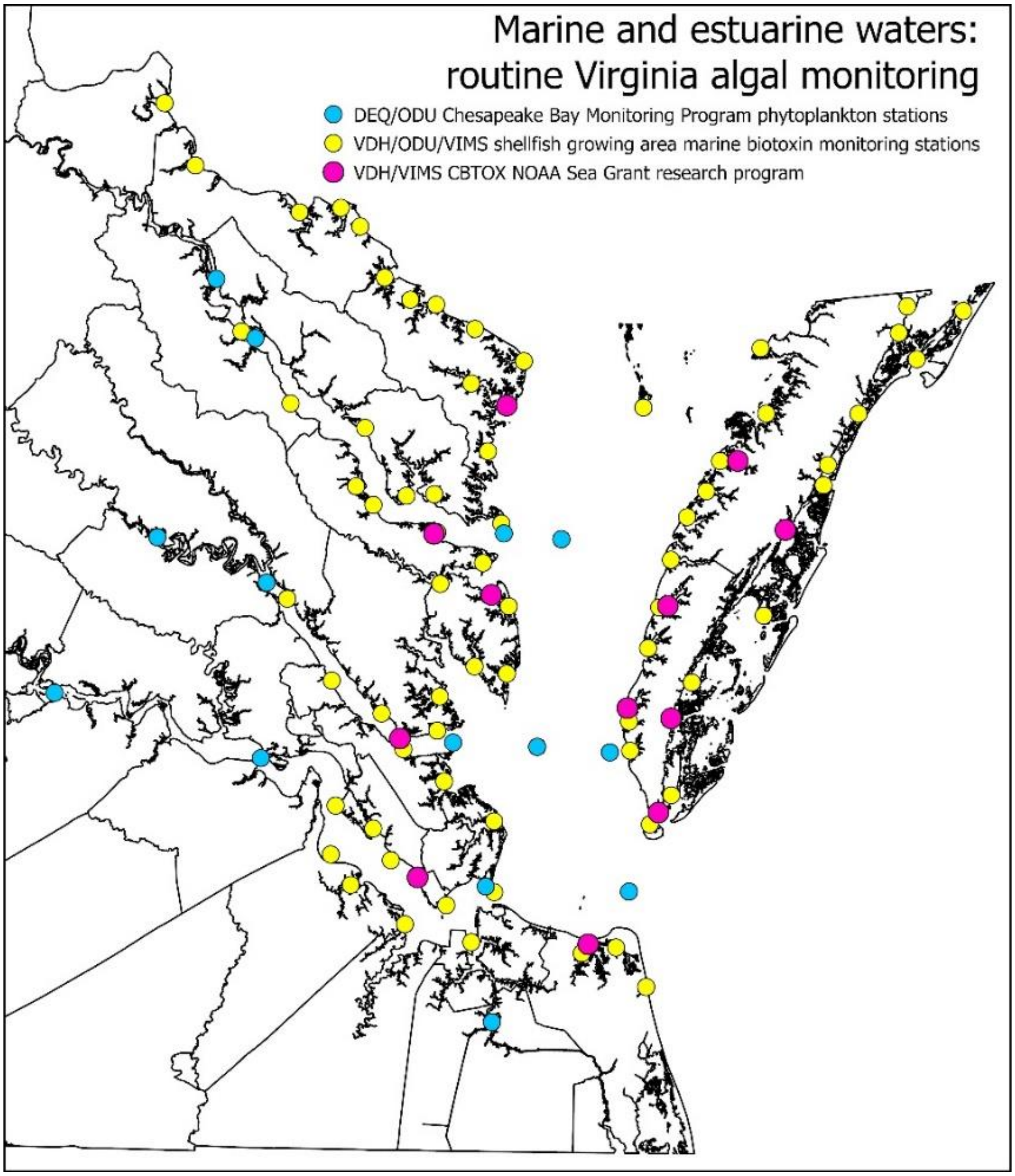


***Figure 1. Routine monitoring in Virginia's marine and estuarine waters***

Conversely for freshwaters in Virginia, funding is not available to support a routine monitoring program, therefore only response-based seasonal data (recreational swimming months May – October) constitute the information for freshwater blooms as opposed to year-round routinely-collected data in marine waters (which support trend analysis useful for evaluating and understanding HABs in these waterways). The datasets used to summarize freshwater HABs include reports to the VDH online HAB reporting tool (2017-2021), VDH/ODU algae and cyanotoxin data from freshwater HAB responses (2016-2020), and record of recreational swimming advisories issued by VDH in response to HABs (2016-2020).

## Marine HABs

The primary public health concern of marine HABs in Virginia waters is through potential contamination of seafood products which could cause shellfish poisoning. Human shellfish poisoning illness is usually associated with the presence of a bloom, although shellfish and finfish may become toxic and cause human illness in the absence of a bloom. To address the issue of biotoxins and protect the public from shellfish poisonings, VDH, following the National Shellfish Sanitation Program (NSSP), requires a Marine Biotoxin Contingency Plan, and has established standards concerning the closing and reopening of growing areas based on toxin concentrations in shellfish meats during HAB events (NSSP Model Ordinance Section II, Chapter IV@.04).

| |
|---|
| PSP (Paralytic shellfish poisoning): 80µg saxitoxin/100g shellfish meat |
| NSP (Neurotoxic shellfish poisoning): 5,000 cells Karenia brevis/L or 0.8mg brevetoxin/kg |
| AZP (Azaspiracid shellfish poisoning): 0.16mg azaspiracid/kg |
| DSP (Diarrhetic shellfish poisoning): 0.16mg okadaic acid/kg |
| ASP (Amnesic shellfish poisoning): 2 mg domoic acid/100g |

***Table 1: Marine toxin criteria within shellfish meat for the closure of shellfish growing areas***

To date there have been no HAB related human illnesses attributed to shellfish from Virginia, and no exceedances of any of the marine biotoxin concentrations listed above. Of these potential biotoxins that may contaminate shellfish, the algae that can produce DSP and ASP have been documented in Virginia waters (Figure 2). Some species belonging to the dinoflagellate genus *Dinophysis* are capable of producing okadaic acid and other dinophysistoxins. *Dinophysis* has been observed throughout the world, including toxic blooms in Europe and Asia, and US shellfish closures in Gulf of Mexico, the Pacific Northwest, and the Atlantic Northeast (Wolny et al. 2020). *Dinophysis* has been identified in the Chesapeake Bay as early as 1978, and annually since 1999, and was associated with a precautionary shellfish harvesting closure in the Potomac River in 2002 (Marshall et al. 2004, Wolny et al. 2020).

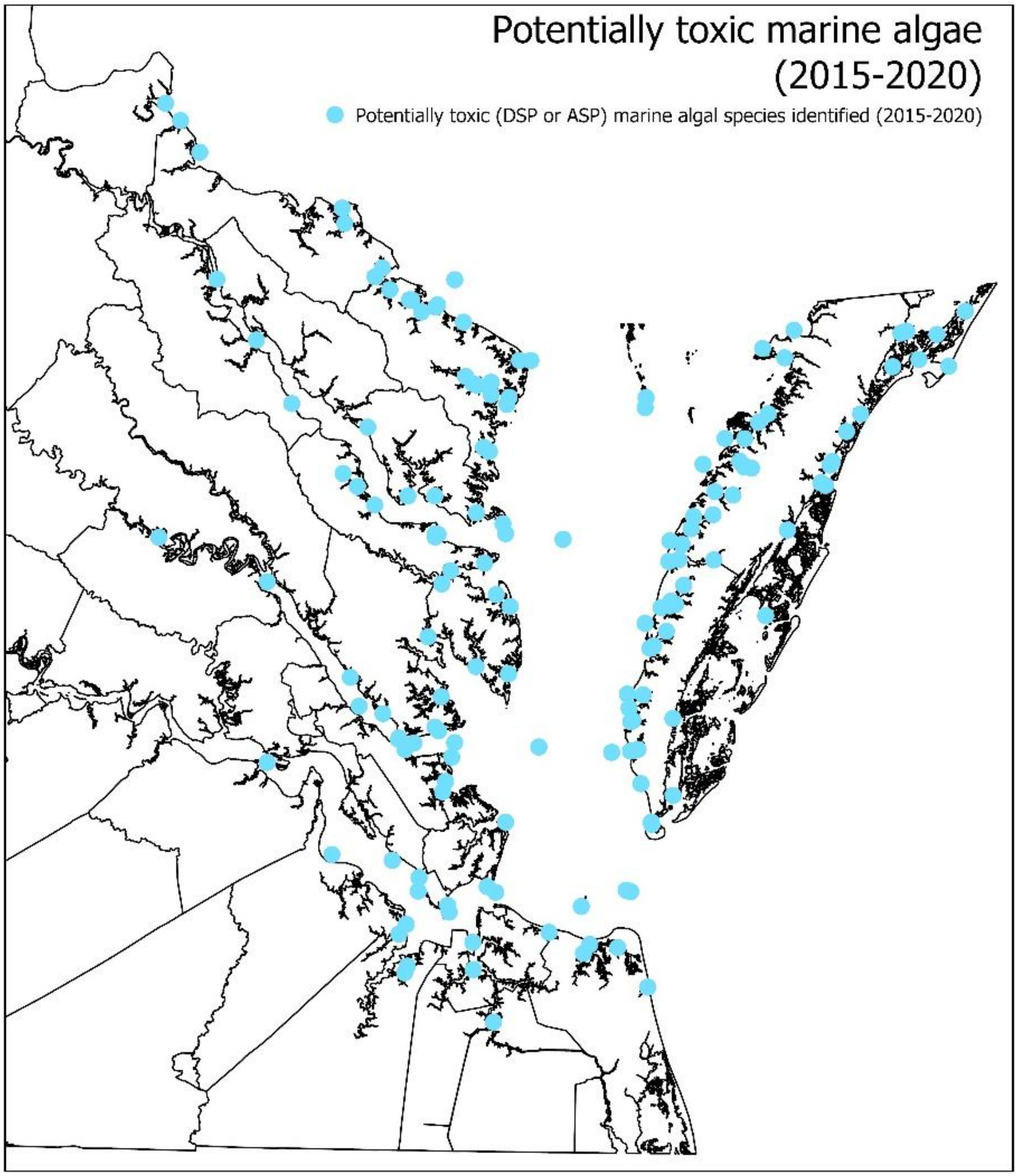


***Figure 2. Potentially toxic marine algae***

Likewise, species of the diatom genus *Pseudo-nitzschia* are known to produce domoic acid, which has led to amnesic shellfish poisoning outbreaks and fisheries closures along the US Pacific Coast (Ritzman et al. 2018) and the Atlantic Northeast (Mizuta and Wikfors 2020). Species from these two types of algae: *Dinophysis* and *Pseudo-nitzschia* have been well documented at varying densities in the brackish and marine waters of the Chesapeake Bay, all the major tributaries, as well as along the coastal Atlantic of the Eastern Shore through the multiple monitoring programs in the region over this time period (Figure 2). However, the presence of these species does not mean that toxins are produced, or that toxins are present within shellfish tissues.

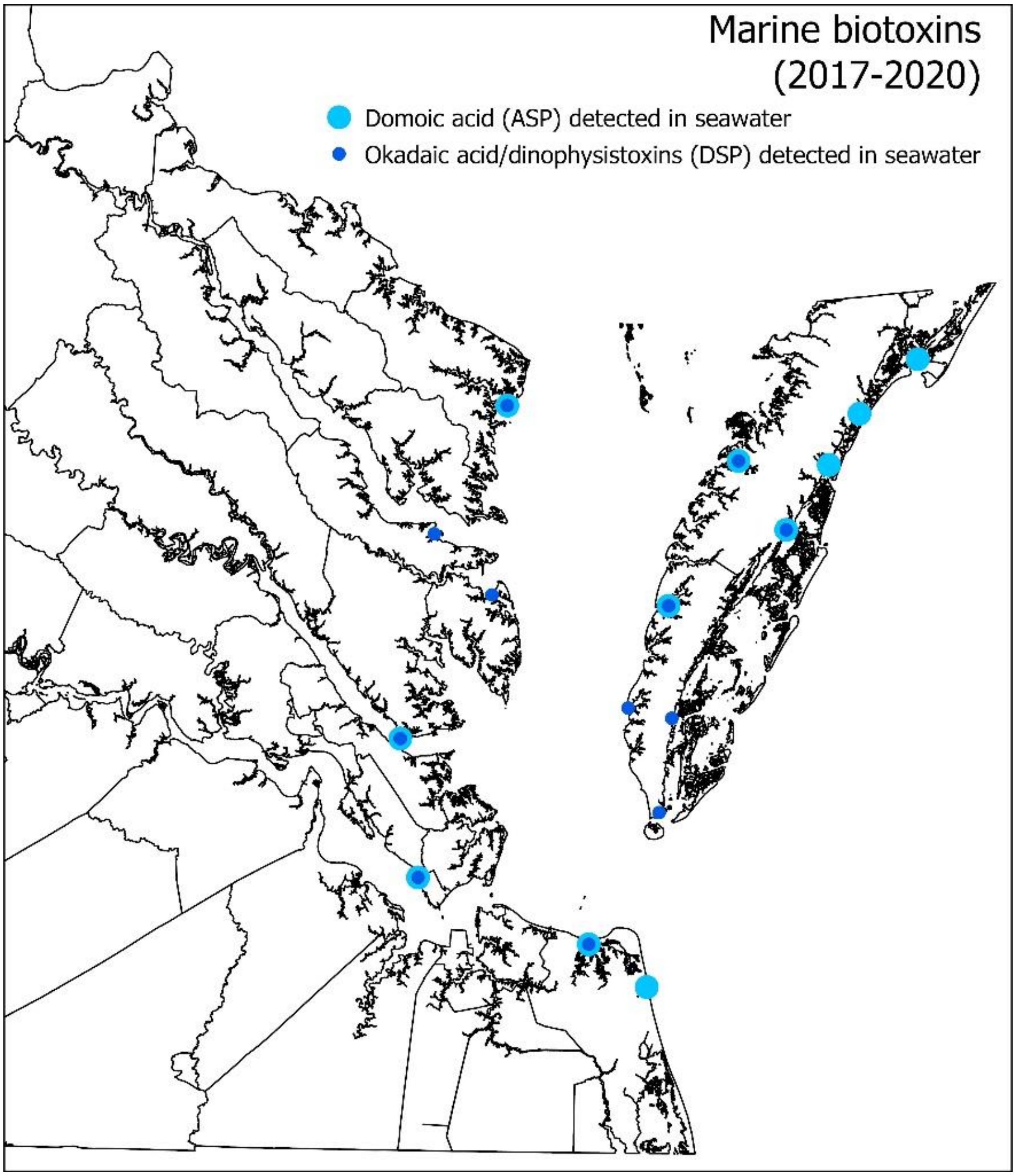


***Figure 3. Marine biotoxins***

VDH, following its marine biotoxin control plan, analyzes water samples for toxins (including DSP and ASP) when the causative algae are identified. In the majority of cases, toxin concentrations are below detection limit, although Domoic Acid (ASP) has been identified in recent years at low concentrations in the water column (Figure 3). A collaborative research project from 2017-2020 funded by NOAA Sea Grant between VIMS and VDH focused on the measurement of multiple biotoxins within Virginia waters using a number of different collection and analytical strategies. These efforts identified that multiple marine biotoxins were present throughout the Chesapeake Bay, including DSP and ASP (Onofrio et al. 2021). Locations where these toxins were identified are shown in Figure 3. These results have led to expanded efforts by VDH to analyze additional seawater and shellfish samples for toxins and utilize passive composite samplers in addition to the routine monthly collections. To date, these results have not identified any toxin concentrations within shellfish that exceed the NSSP criteria listed above. In addition, the study's detection of Azaspiracids, have led to expanded work by VDH and VIMS to do additional molecular testing for the dinoflagellate *Azadinium,* which has not been previously identified in the region.

Marine algae that are responsible for the production of PSP and NSP toxins are a significant health concern and have led to shellfish closures and advisories in other parts of the US including the Gulf of Mexico, the Pacific Coast, and the Atlantic Northeast, but to date have not been associated with blooms in this region (Marshall et al. 2005, Marshall and Egerton 2012, Anderson et al. 2021). However, as a contingency, VDH maintains capacity for testing these toxins and regularly monitors for the causative species in its routine water samples.

## Freshwater Cyanobacteria

### *HAB reports and response*

Cyanobacteria bloom recreational advisories are issued due to the potential human health risk of cyanotoxin ingestion. Activities where toxin ingestion are likely include activities where the mouth may come in contact with or be submerged in the surface of the water, such as swimming. Water activities where this contact is unlikely to occur should involve less risk, therefore, these activities may be permissible during advisories at the discretion of the waterbody manager (local health director, state park manager, etc.). For example, boating (motorized and non-motorized) involves minimal physical contact with the water and the potential for accidental ingestion of toxins is less likely.

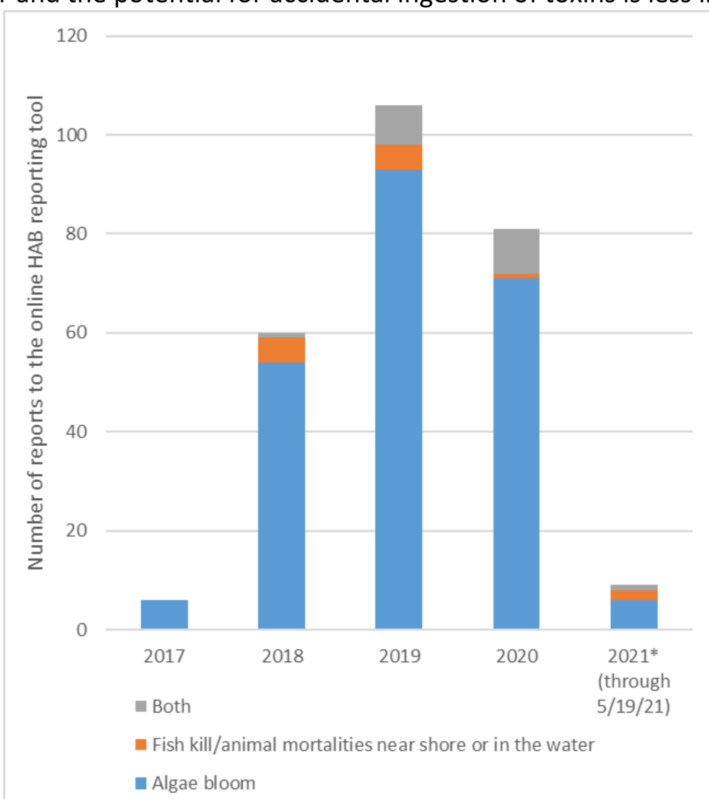


***Figure 4. Number of potential HABs (or simply "Algal Blooms") reported annually through the online HAB reporting tool (2017 to 2021). It should be noted that while the tool is called the HAB report form, laboratory analysis is necessary to determine if the reported condition is an actual algal bloom and if the algal bloom contains toxins or toxigenic species at harmful concentrations.***

Comparatively, there are no routine monitoring programs for inland waters and freshwater HABs (cyanobacteria). Instead these blooms are managed using a reporting and response plan. Reports of HABs can be made by members of the public as well as agencies (including DEQ, VDH, DCR, etc.) that observe a potential HAB through the VDH maintained HAB Hotline: 1-888-238-6154 and the HAB Online Report Form (www.SwimHealthyVA.com). The HAB Hotline was initiated in response to Pfiesteria, however the HAB Online Report Form was created in 2017 to facilitate potential HAB reporting to the website and streamline response. A total of 262 reports have been submitted to the online tool as of May 19, 2021 (Figure 4). The majority (95%) of the reports are for algal blooms, with the remainder for suspected HAB related fishkills or wildlife mortalities.

While potential HAB reports have been submitted since 2017 during all months of the year, the majority are submitted in summer, with two-thirds of all reports occurring in July-September (Figure 5). It should be noted that while the tool is called the HAB report form, laboratory analysis is necessary to determine if the reported condition is an actual algal bloom and if any algal bloom contains toxins or toxigenic species at harmful concentrations.

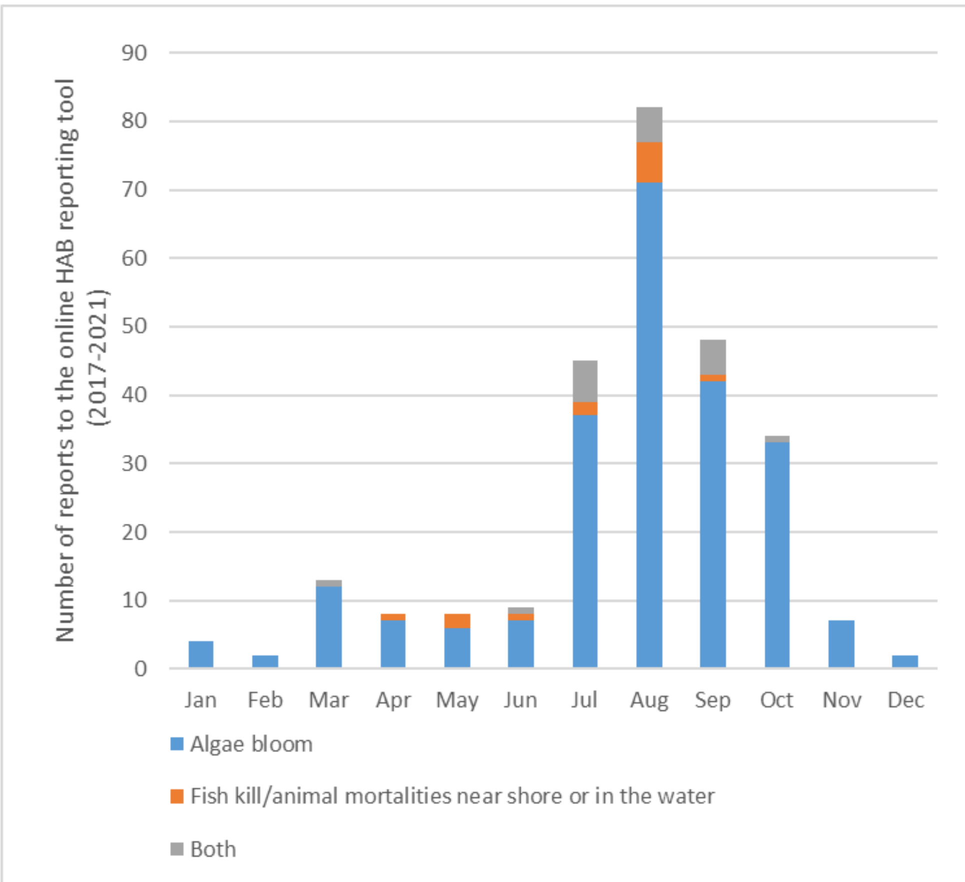


***Figure 5. Potential HABs (or simply "Algal Blooms") reported in each month (2017 - 2021). Laboratory analysis is necessary to confirm the presence of toxins or toxigenic species in harmful amounts.***

Reports of potential HABs have been submitted from across the Commonwealth, from a total of 53 counties and cities. The waterbody with the largest number of bloom reports has been Lake Anna which is split by Louisa, Spotsylvania and Orange counties (Figure 6). Figure 7 maps the location and frequency of reported algal blooms by county and city since 2017.

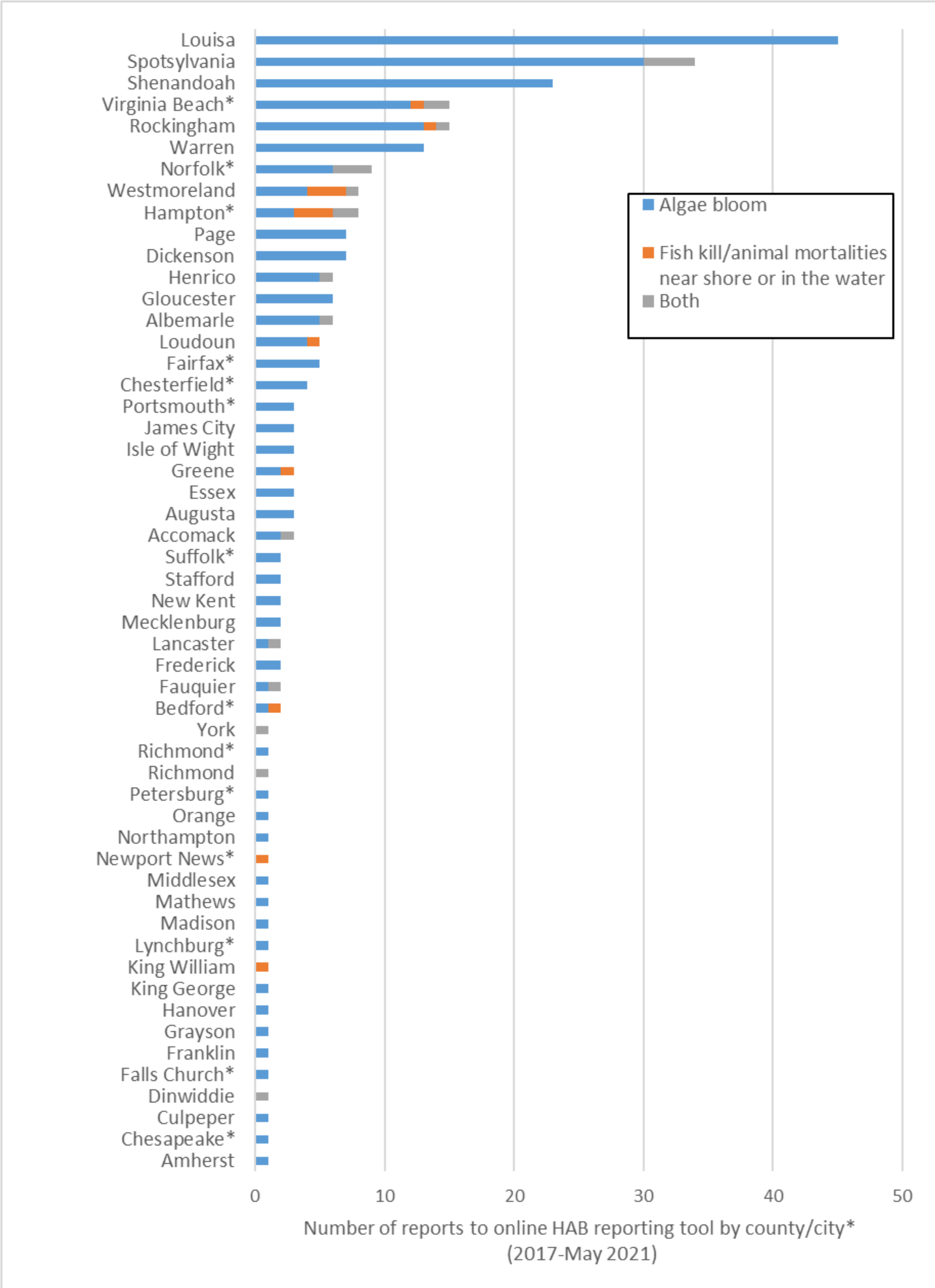


***Figure 6. Potential HABs (or simply "Algal Blooms") reported by county (2017 - 2021). Laboratory analysis is necessary to confirm the presence of toxins or toxigenic species in harmful amounts.***

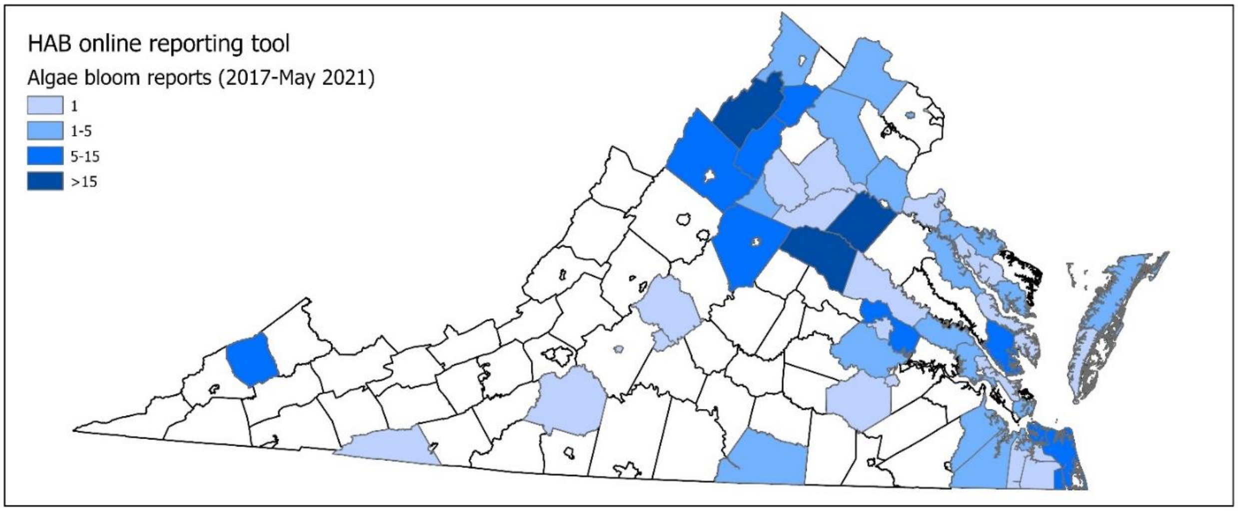


***Figure 7. Map depicting the location and frequency of potential HAB reports in Virginia (2017-2021). Laboratory analysis is necessary to confirm the presence of toxins or toxigenic species in harmful amounts.***

## Potentially Toxic Cyanobacteria

Not all cyanobacteria produce toxins, different toxins may be produced by multiple species, and some species may produce multiple types of toxins. EPA has recommended recreational water quality advisory guidelines for two hepatotoxins commonly detected in surface waters: microcystins (8 µg/L) and cylindrospermopsin (15 µg/L) (EPA 2019)[1]. Additionally, anatoxin-a and saxitoxin are recognized by the EPA and the World Health Organization (WHO) as potent neurotoxins, but neither have national health-based advisory recommendations at the time of this report (WHO 2003, EPA 2009, D'Anglada et al. 2015). In the absence of EPA/WHO advisory levels for these toxins, several states, including Virginia (VDH 2021), have developed advisory thresholds to support management strategies to protect against human and animal neurotoxin exposure, which include monitoring the cell density of organisms known to produce the toxins and/or direct measurements of toxin concentrations.

Building on the EPA 2019 criteria, prior VDH guidance (2012), and the recommendations of the Virginia HAB Task Force, VDH developed and utilizes a hybrid advisory approach incorporating thresholds for potentially toxigenic (PTOX) cyanobacteria cell densities in addition to toxin concentrations. Advisories are initiated when PTOX densities are equal to or exceed 100,000 cells/ml (or in the case of *Microcystis* species, equal to or greater than 40,000 cells/ml) (VDH 2021).

[1] 1 µg/L = 1 part per billion (ppb)

| Metric | Concentration |
|---|---|
| *Microcystis* species | ≥40,000 (total cells/mL) |
| total potentially toxigenic (PTOX) cyanobacteria taxa* | ≥100,000 (total cells/mL) |
| microcystin toxin | ≥8 µg/L |
| cylindrospermopsin toxin | ≥15 µg/L |
| anatoxin-a toxin | ≥8 µg/L |
| saxitoxin toxin | ≥4 µg/L |

***Table 2: Hybrid advisory approach: Cyanobacteria bloom recreational advisory thresholds using cell densities and toxin concentrations for targeted cyanotoxins (VDH 2021)***

Virginia's HAB Task Force partners, in collaboration with state-partners and input from colleagues in the research field, developed the Potentially Toxigenic Cyanobacteria genera (PTOX) taxa list for use in determining the genera for cells/ml tally which is utilized in the hybrid approach for comparison of the total cells/ml. The PTOX list cautions on the conservative side to be protective of public health by including all species of a potentially toxigenic genera, since in many cases, the species-specific toxin potential may be unknown. The PTOX taxa list will be reviewed at least annually or more frequently as needed to reflect changes in taxonomy and toxin research by HAB Task Force staff. The current list of genera includes: *Anabaena, Anabaenopsis, Aphanizomenon, Chrysosporum, Cuspidothrix, Dolichospermum, Lyngbya, Microcystis, Microseira, Nodularia, Nostoc, Oscillatoria, Phormidium, Planktolyngbya, Planktothrix, Raphidiopsis, Sphaerospermopsis* and *Woronichinia*.

In response to reported algal blooms, these potentially toxic cyanobacteria have been observed throughout Virginia. Figure 8 illustrates the location and severity of PTOX cyanobacteria blooms in regard to cell density. Light blue dots indicate the location where one of the listed potentially toxic species was identified, with dark blue dots indicating where the PTOX density exceeded the 100,000 cells/ml criteria.

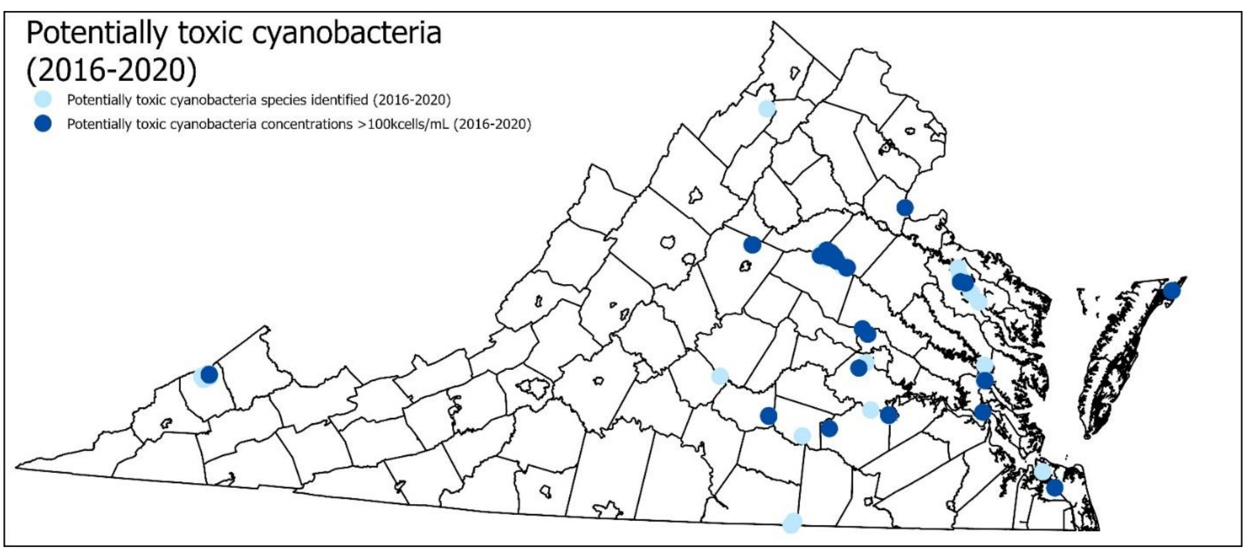


***Figure 8. Locations in Virginia where potentially toxic cyanobacteria have been detected.***

Collectively, these cyanobacteria have the potential to produce a number of both hepatotoxins (microcystin and cylindrospermopsin) and neurotoxins (anatoxin-a and saxitoxin). The maps below (Figures 9 – 12) illustrate the location of cyanobacteria bloom occurrence and severity of these HABs with respect to toxin concentration. In the case of microcystin, the most commonly detected cyanotoxin, light green dots identify the location of where microcystin was measured during a HAB response analyses above the lowest detectable limit (LDL) of the toxin test. Dark green dots represent where the concentration of microcystin exceeded the VDH and EPA advisory threshold of 8ppb (µg/L). Cylindrospermopsin, anatoxin-a, and saxitoxin have not been measured over the corresponding VDH or EPA threshold at the time of this report.

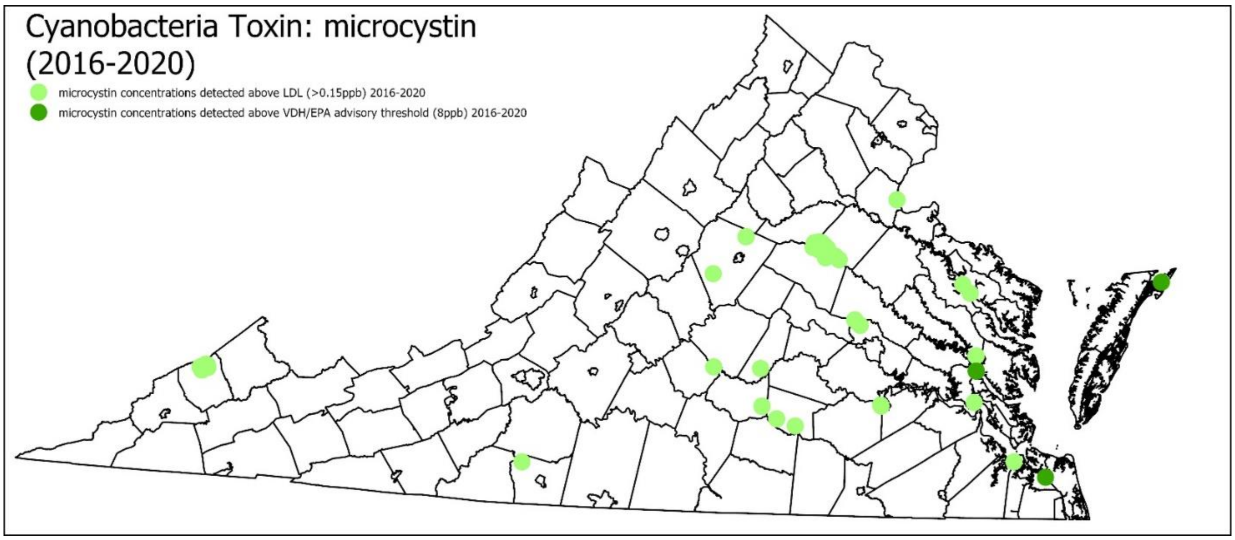


***Figure 9. Locations in Virginia where microcystin was detected (2016 - 2020)***

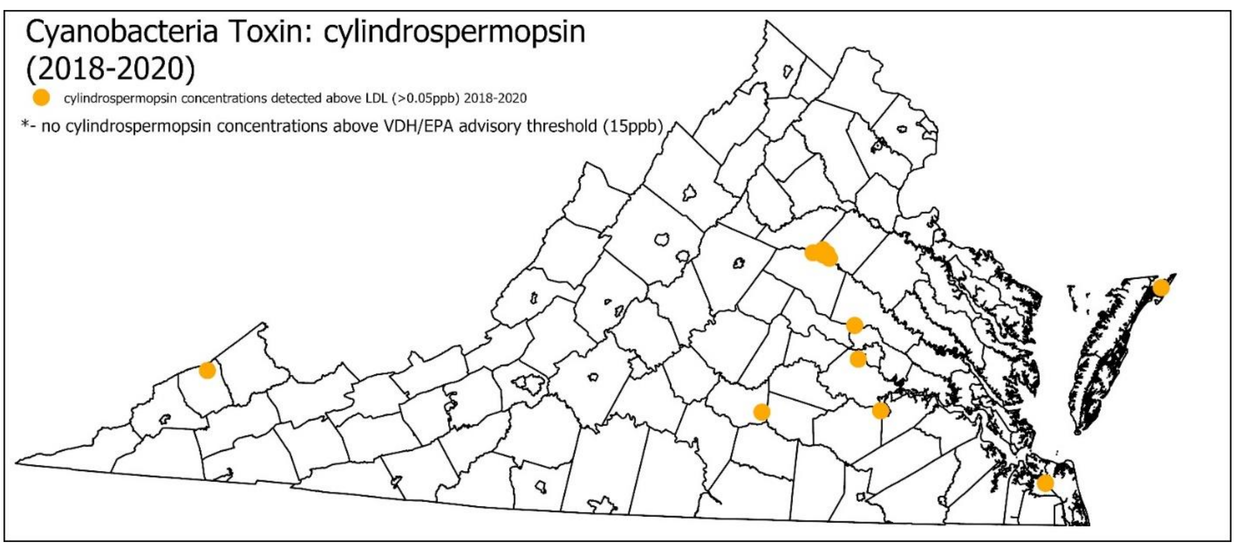


***Figure 10. Locations in Virginia where cylindrospermopsin was detected (2018-2020)***

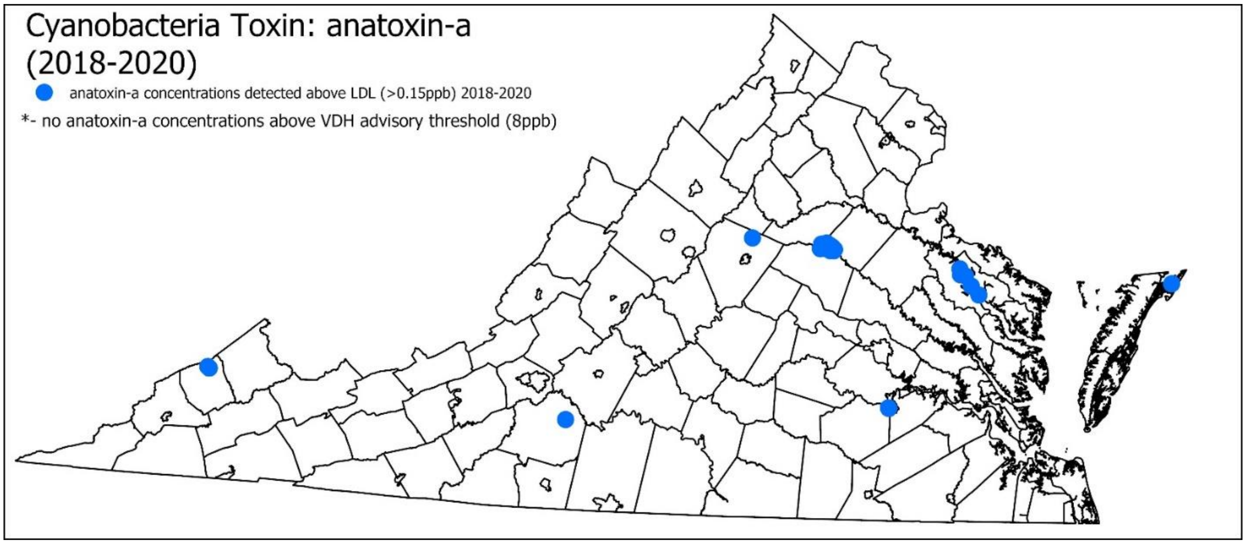


***Figure 11. Locations in Virginia where anatoxin-a was detected (2018-2020)***

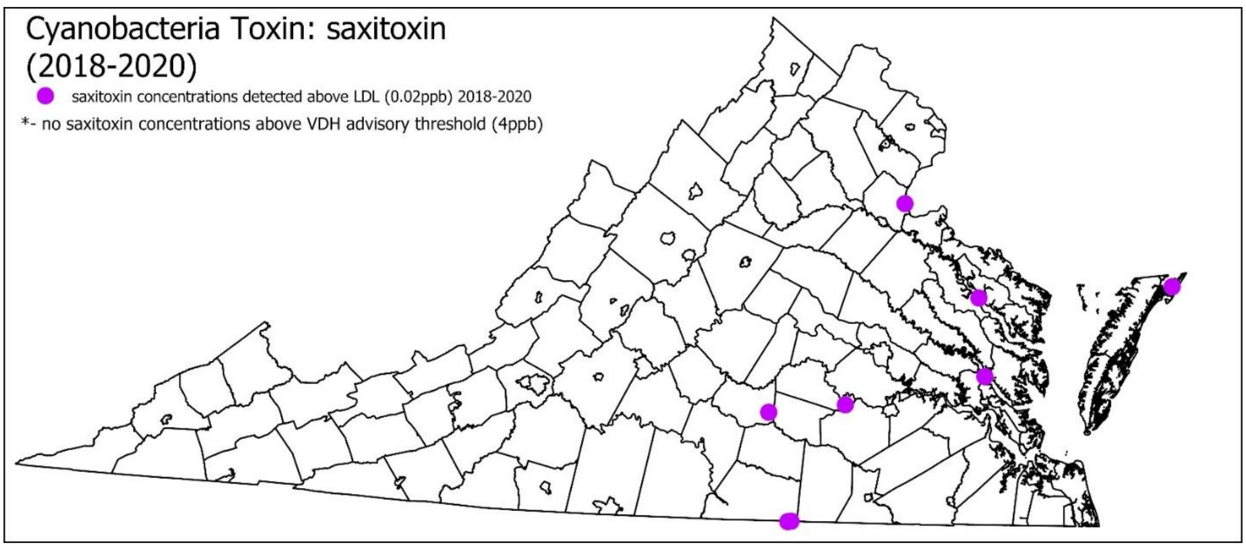


***Figure 12. Locations in Virginia where saxitoxin was detected (2018-2020)***

## Cyanobacteria Recreational Advisories

### *Issuing a recreational swimming advisory:*

To protect public health, recreational swimming advisories are issued due to the potential human health risk of cyanotoxin ingestion. The VDH regulatory authority to issue advisories in response to HAB events lies in Code of Virginia § 32.1-248. *Closing of waters; modification or revocation of regulation or order.* Should laboratory results of bloom samples for either the enumeration and identification of PTOX densities exceed 100,000 cells/ml or exceed any of the four cyanotoxin concentrations, as seen in Table 2, above, advisory recommendations are made by VDH: DSSWH to the local health director or other waterbody manager to issue an advisory for the waterbody. Advisories cover the spatial extent of the waterbody impacted by the bloom and are subject to the information available on the bloom at the time, but may change as conditions change and as more information about the bloom and its extent becomes available through follow-up monitoring.

*Follow-up Monitoring for a recreational swimming advisory*

Once an advisory is in place, DEQ and sometimes other partners conduct follow up monitoring of appropriate spatial coverage and sample frequency to adequately inform VDH on the need to extend or reduce the spatial extent, and, when it is appropriate, to lift the advisory. In accordance with sampling protocols established by DEQ and other members of the HAB Task Force, monitoring sites should be selected so they are representative of the waterbody extents and target high recreational use areas in order to be protective of public health. The spatial coverage and sample frequency of follow-up monitoring is subject to the availability of monitoring staff (primarily provided by DEQ), resources, and lab capacity on a per-case basis. Monitoring every two weeks is ideal if personnel and resources are available but this frequency is not essential in every case and may not be possible based on resource and personnel availability. Efforts to target monitoring temporally and spatially may be enhanced with NOAA/National Aeronautics and Space Administration supported remote sensing and weather forecasts; however, DEQ does not currently have resources or protocols in place for such activities.

*Lifting a recreational swimming advisory*

Cyanobacteria bloom recreational advisories are typically lifted when two consecutive sample events, taking place at least ten days apart, indicate total PTOX taxa densities and toxin concentrations are below advisory thresholds (EPA 2015). Concentrations of all four toxins (hepatotoxin and neurotoxins) below advisory thresholds and PTOX cell densities are recommended to lift advisories.

*Public Notification and Outreach for recreational swimming advisories*

The Algal Bloom Map located on the www.SwimHealthyVa.com site is updated during the HAB season (May – October) to indicate advisory status of investigated freshwater and marine events. @VDHBeach, the Twitter page for the Virginia Coastal Beach and Notification Program, may be used to notify the public in the tidewater area of Virginia in the event of blooms impacting any of the approximately 50 public beach sites.

VDH has developed a HAB toolkit containing resources necessary to support waterbody managers that speaks to the public health risks and best practices of avoiding blooms in waterways. This includes electronic informative flyers, signage, social media posts, imagery, videos, press release templates, and power point slides. VDH will share all media alerts, printed materials, and other public information messages with involved agencies and will collaborate on message development in the event of a HAB related event. Sample results of HAB investigations will be displayed on the Algal Bloom map updated routinely on the HAB Task Force website.

*Tracking bloom events, animal, and human incidents of exposure*

VDH: DSSWH tracks and reports HAB related animal and human health events and incidents through the Centers for Disease Control and Prevention's One Health Harmful Algal Bloom System (OHHABS). This national database allows for the information on both human and animal illnesses and environmental data related to HABs to be shared with health departments across the country, both in real time as well as providing historical data.

*The frequency and duration of recreational swimming advisories*

As the frequency of reported algal blooms has increased, so has the number of cyanobacteria recreational advisories issued. The prior VDH recreational swimming advisory guidance (2012) targeted a single cyanotoxin – microcystin; and was similar to guidance used in other states in the early and mid-2000s. However, due to emergency bloom events nationally which brought more attention to the difficulties in detecting the multiple cyanotoxins which may be present during blooms based on the cyanobacteria taxa present in addition to the ephemeral nature of cyanotoxin release and difficulty in detection, the hybrid approach for advisory guidance was implemented in Virginia. As a result of the hybrid approach, the majority of advisories issued in Virginia have been issued due to cyanobacteria cell densities, as opposed to toxin concentration.

The figures below map the location and frequency of HAB advisories issued within Virginia from 2016-2020 by county or city. The greatest number of advisories have occurred within the 9,600 acre Lake Anna (Spotsylvania and Louisa counties), which has had blooms annually beginning in 2018.

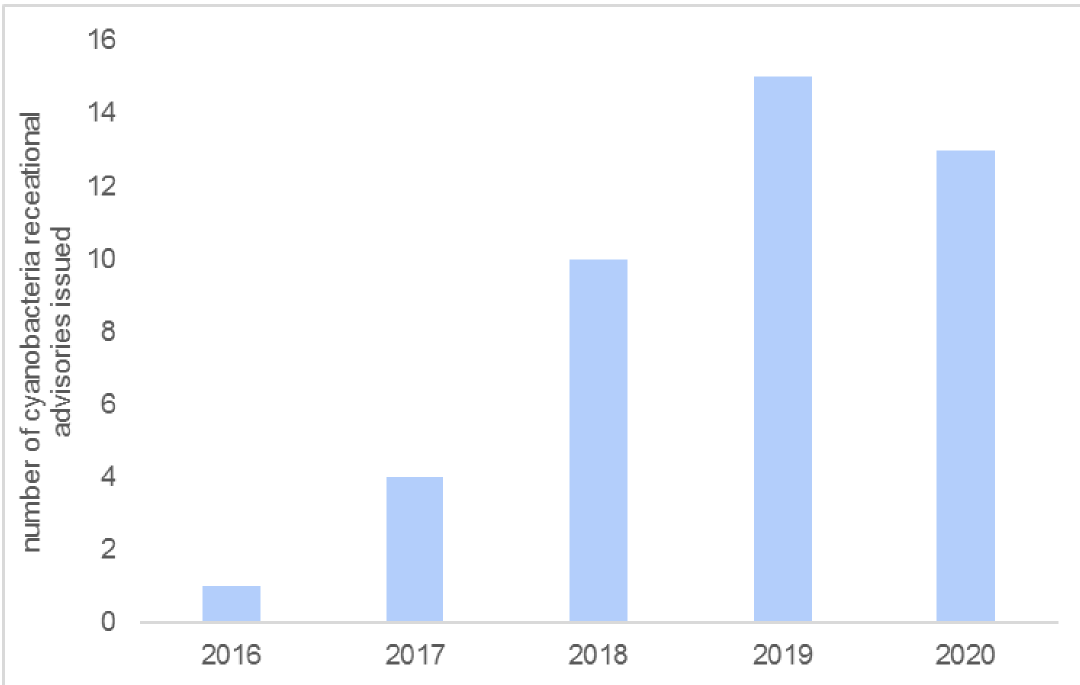


***Figure 13. HAB recreational advisories issued in Virginia (2016 - 2020)***

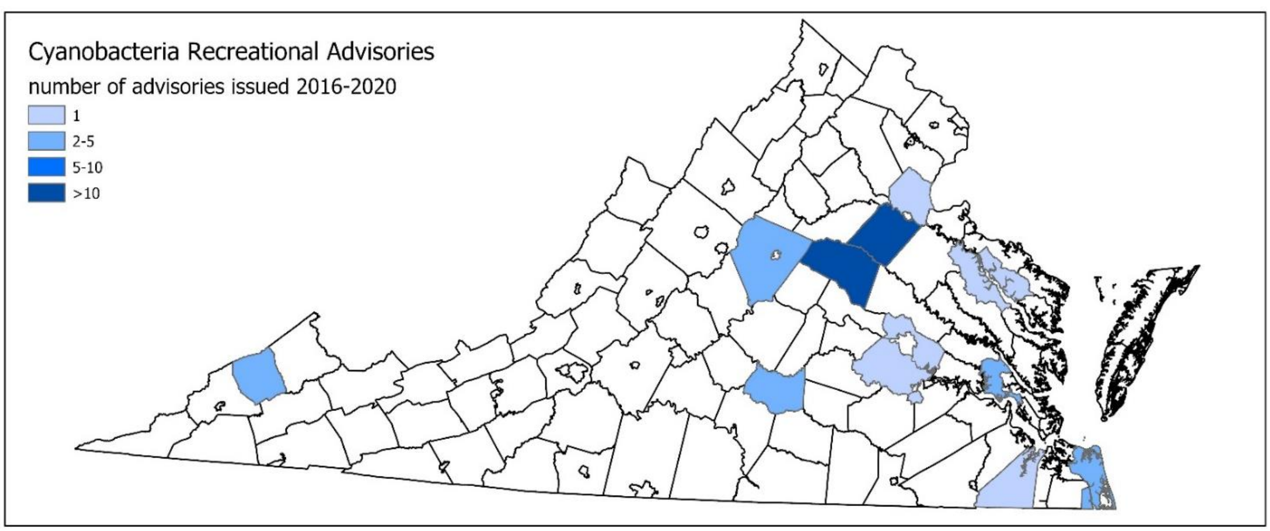


***Figure 14. Map depicting the locations of HAB recreational advisories in Virginia (2016 - 2020)***

Due to the large size of Lake Anna, the spatial variability of HABs in general and observations on this Lake in particular, VDH and DEQ determined that the HAB response both in sample collection as well as advisory management would be best handled on a segment by segment basis. This ensured that advisories could be issued and maintained where needed to protect public health based on the most recent lab results, and lifted where samples indicated that cyanobacteria were below criteria of concern. Segmentation provided the additional level of spatial relevance to waterbody users for the extent of a given advisory. The map below (Figure 15) shows the location of the eight Lake Anna segments where advisories were managed (color for illustration, not indicative of frequency or severity), along with the established stations (yellow dots) where follow up samples were collected to inform advisories.

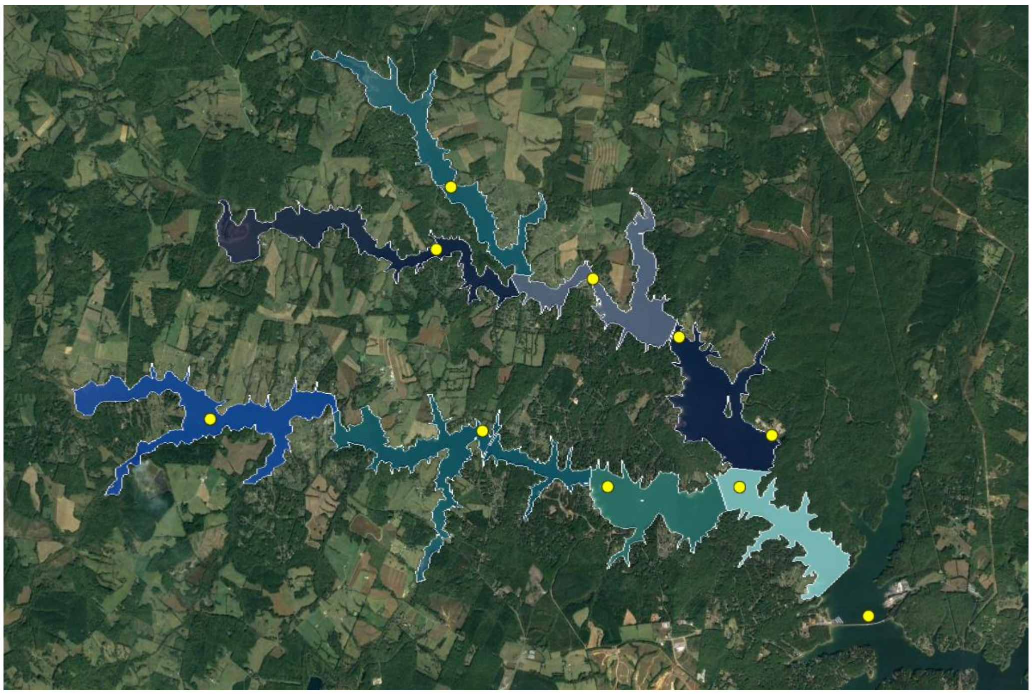

***Figure 15. Locations of eight Lake Anna segments where advisories are managed.***

## Marine and Freshwater HAB Response Funding Gaps

VDH and DEQ do not currently have the funding necessary to adequately support the existing marine HAB monitoring and response program which conducts surveillance year round to protect the public and the shellfish resource on the coast of Virginia. The marine HAB program was initially funded by the General Assembly in 2012, when CDC grant funding was eliminated by the agency for *Pfiesteria* response. The expanded funding necessary to protect public health is necessary in part due to the need to increase the number of sites open to shellfish harvesting areas, the need to support surveillance year-round, and the need to provide for biotoxin assays on shellfish product in order to reopen a growing area following a HAB closure event (NSSP 2019). These efforts and their associated costs are compounded by the need to sample and test for a growing number of co-occurring biotoxins and HAB species in the Chesapeake Bay and Virginia's coastal waters (Onofrio et al. 2021).

While the funding provided by the General Assembly in 2012 was originally intended to support marine HAB surveillance, VDH and DEQ have been required to respond to increasing reports of freshwater blooms in tidal-fresh estuaries as well as inland rivers, lakes, and ponds; all considered recreational waters of the state. Using level funding provided by the General Assembly since 2012, VDH together with DEQ and its contracted universities (VIMS and ODU) have provided these time-sensitive public-health based response efforts in order to ensure the safety of both shellfish consumers and recreational water users. The needs which VDH, DEQ, VIMS, and ODU now have are such that either funding must be increased or a reduction in current services will be necessary. A recent analyses by VDH identified a gap of approximately $510,000 in funding necessary to provide the level of support needed to adequately monitor the growing marine biotoxin concerns and manage freshwater cyanobacteria responses across Virginia. This included support for additional staff, analytical equipment, MOU funding, and laboratory supplies. Similarly, DEQ identified the need for additional staff and lab support in its recent analysis in response to Executive Order 6.

# Factors that Lead to Harmful Algae Blooms

The circumstances that lead to the development and persistence of algal blooms are complex and are not well understood. There are likely a number of environmental factors that contribute to the proliferation of algal blooms, including available nutrients, sunlight, temperature, water chemistry (e.g., pH, conductivity, salinity, carbon availability), and hydrology (e.g., stream flow, turbulence, reservoir dynamics). While many factors can contribute or combine to create conditions leading to algal blooms, there is not a single factor that can be identified at this time that will result in a HAB event.

The sections below include information on each of the factors that may contribute to HAB proliferation. When available, information from DEQ's recent 20-year water quality trend analysis in Virginia's waters is referenced. The trend analysis was completed for data collected from 1997 through 2016 and was published in the 2018 Water Quality Assessment Integrated Report (IR) (DEQ 2018). The next trends report will be published in the 2024 IR. It should be noted that the goal of trend analysis is to detect changes in concentrations or values of key water quality parameters and not to determine whether the measured values are particularly high or low. For example, an increasing trend in total nitrogen may indicate degrading water quality, but even after such an increase, total nitrogen may remain relatively low and the overall water quality relatively good.

The design of DEQ monitoring programs to assess overall water quality conditions and determine long-term trends is generally not at a fine enough scale to capture the specific causal factors contributing to HAB development or persistence. In order to better understand the specific causal factors contributing to individual HAB events, in depth sampling at higher frequencies and for a larger suite of parameters would be required.

Given the scope and complexity of HAB occurrences in Virginia, the timeline associated with this report is not sufficient to determine exact causal factors contributing to the HAB events outlined in the previous section. The additional monitoring needed to determine causal factors on a site-specific basis is entirely outside of the agencies' current budgets and available staffing resources.

## Nutrients

Nutrients are necessary for the survival and growth of aquatic plants, which are the base of the food chain for all other aquatic organisms. Plants and algae need a number of nutrients, such as nitrogen and phosphorus, for growth and reproduction. The lack of nitrogen and phosphorus limit plant growth in most aquatic system.

Nutrient levels in an aquatic system vary depending upon temperature, rainfall, runoff, biological activity, and the flushing of the aquatic system. Nutrient levels are generally higher in the spring and early summer and impact the aquatic system in several ways. Nutrients promote and support the growth of algae and Cyanobacteria. High nutrient levels can accelerate eutrophication (i.e., nutrient enrichment) of waterways and result in abundant growths of algal blooms. The main nutrients contributing to eutrophication are phosphorus and nitrogen.

Nutrient concentrations in aquatic systems are influenced by both natural and human sources. Natural sources of nitrogen and phosphorus include decomposition of organic matter, nitrogen fixation of atmospheric nitrogen by certain bacteria and algae, and geologic formations rich in nitrogen or phosphorus. Human sources include discharges from wastewater treatment plants, stormwater runoff, livestock wastes, use of fertilizers in lawn care and agriculture, groundwater seepage from failing septic systems, planting of nitrogen fixing plants (such as clover or beans) in agricultural fields, and atmospheric deposition (including acid rain) from the burning of fossil fuels.

Internal origins of nutrients come from the lake or reservoir sediments. Phosphate attaches to sediments. When dissolved oxygen concentration is low in the water, sediments release phosphate into the water column. This phenomenon encourages the growth of algae (CEES, 2021).

### *Total Nitrogen trends in Virginia's waters*

Nitrogen is an essential element to all life forms including aquatic plants and algae. Although some nitrogen is required to support plant and animal life in healthy lakes, streams and estuaries, an excess of nitrogen is an indication of nutrient enrichment, an undesirable water quality characteristic. Nutrient enrichment often accelerates algae and plant growth (a process called eutrophication). The algae, in particular, may decompose rapidly, consuming more dissolved oxygen than can be replaced in the water and suffocating aquatic life. In addition, algal blooms may produce toxins, which harm aquatic life and endanger human health.

A decrease in concentration of total nitrogen over time is considered an improvement in the watershed. Improving water quality nitrogen trends were detected at 159 DEQ trend monitoring stations (Table 3 and Figure 16) with most of the improvements occurring in the Chesapeake, James, Chowan, Potomac and Rappahannock basins (Table 4). Degrading water quality for nitrogen occurred at 20 DEQ trend stations in 8 of the 10 major river basins. The most occur in the Roanoke River basin, which drains to the Albemarle Sound.

| Stations | # of Samples | % Improving | % Degrading | % No Trend |
|---|---|---|---|---|
| 409 | 55,644 | 39 | 5 | 56 |

***Table 3. Percentage of stations statewide exhibiting no statistically significant trend, improving (decreasing) total nitrogen and degrading (increasing) total nitrogen.***

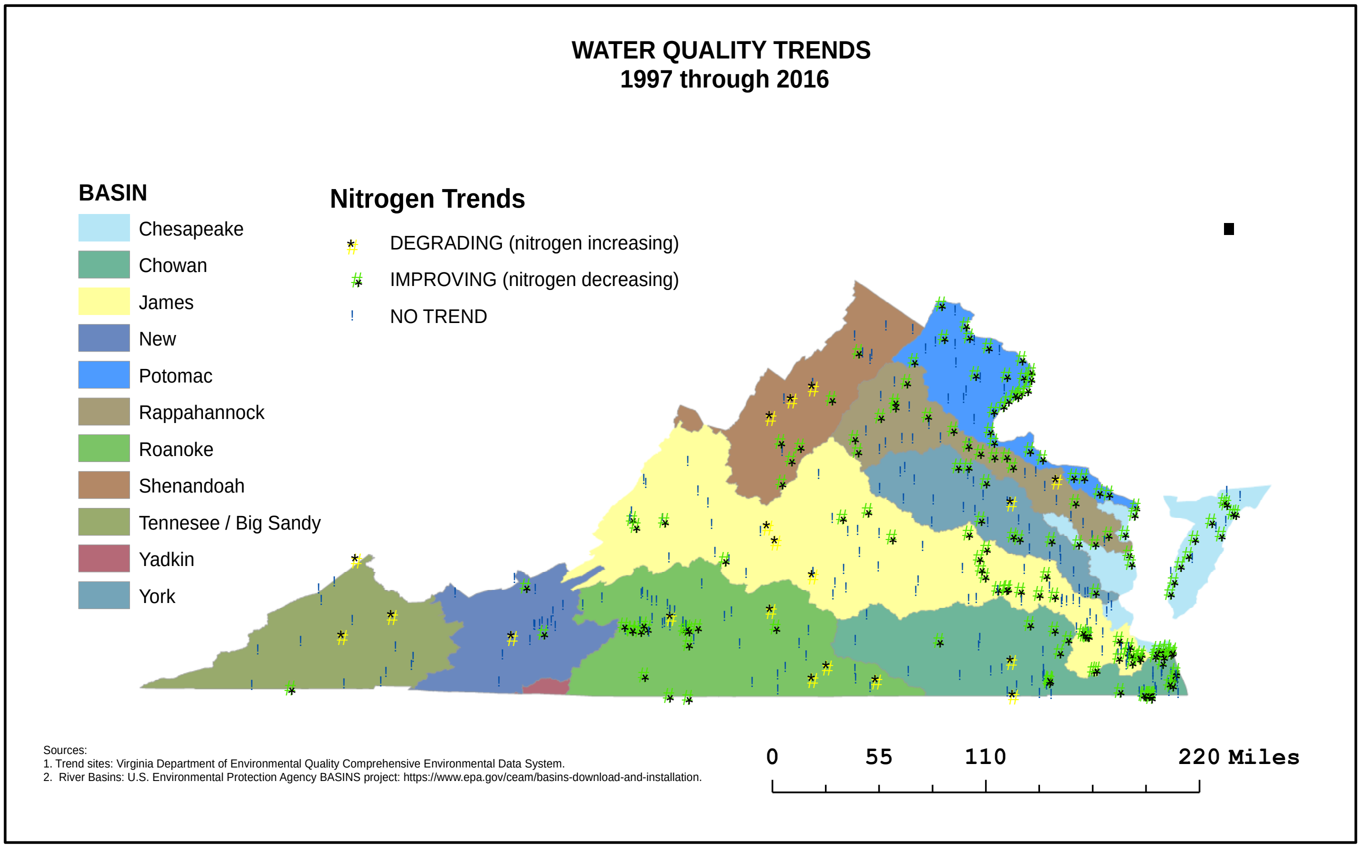


***Figure 16. Statewide trends in Total Nitrogen***

| Basin | Improving | Degrading | No Trend |
|---|---|---|---|
| Chesapeake* | 26 | 0 | 8 |
| Chowan | 20 | 2 | 33 |
| James | 34 | 3 | 57 |
| New | 2 | 1 | 15 |
| Potomac | 28 | 0 | 15 |
| Rappahannock | 17 | 1 | 19 |
| Roanoke | 16 | 6 | 35 |
| Shenandoah | 6 | 3 | 9 |
| Tennessee / Big Sandy | 2 | 3 | 14 |
| York | 8 | 1 | 25 |

* Chesapeake refers to water bodies that mostly drain directly into Chesapeake Bay. Seven stations drain directly or indirectly into the Atlantic Ocean.

***Table 4. Total Nitrogen: basinwide summary. Numbers indicate number of monitoring stations where improving (decreased nitrogen) or degrading (increased nitrogen) were detected.***

### *Total Phosphorus trends in Virginia's waters*

Phosphorus like nitrogen is essential to all life. Phosphorus enrichment may also lead to eutrophication, dissolved oxygen depletion, and proliferation of algae that may adversely affect human health. Phosphorus generally enters waterways as phosphate ($PO_4$), which may be in the form of orthophosphate ($PO_4$ molecules alone), organic phosphate, ($PO_4$ attached to organic chemicals such as proteins or carbohydrates), or condensed inorganic phosphate ($PO_4$ attached to inorganic chemicals). Sources of phosphorus to Virginia waterways are similar to nitrogen, except that little phosphorus input occurs from the atmosphere.

Phosphorus concentrations remained low during the time period of this study. Of the 365 stations analyzed, no trends were detected at 311 DEQ trend monitoring stations (85 percent), improving conditions (decreasing phosphorus concentrations) were detected at 39 trend stations (11 percent), and degrading conditions were detected at 15 trend stations (Table 5 and Figure 17).

Of the 15 trend stations where degrading conditions were detected, 12 occurred in a cluster in the Chowan River Basin, and 6 of these occurred along an approximately 5-mile stretch of the Northwest River (near Chesapeake, Virginia (Table 6)). The two stations with degrading trends not located in the Chowan River Basin were a station on the South Anna River in Louisa County (Piedmont region in central Virginia) and a station on an unnamed tributary of Pitts Creek in Accomack County.

| Stations | # of Samples | % Improving | % Degrading | % No Trend |
|---|---|---|---|---|
| 365 | 56,476 | 11 | 4 | 85 |

***Table 5. Percentage of stations statewide exhibiting no significant trend (p> 0.10), improving (decreasing) total phosphorus and degrading (increasing) total phosphorus.***

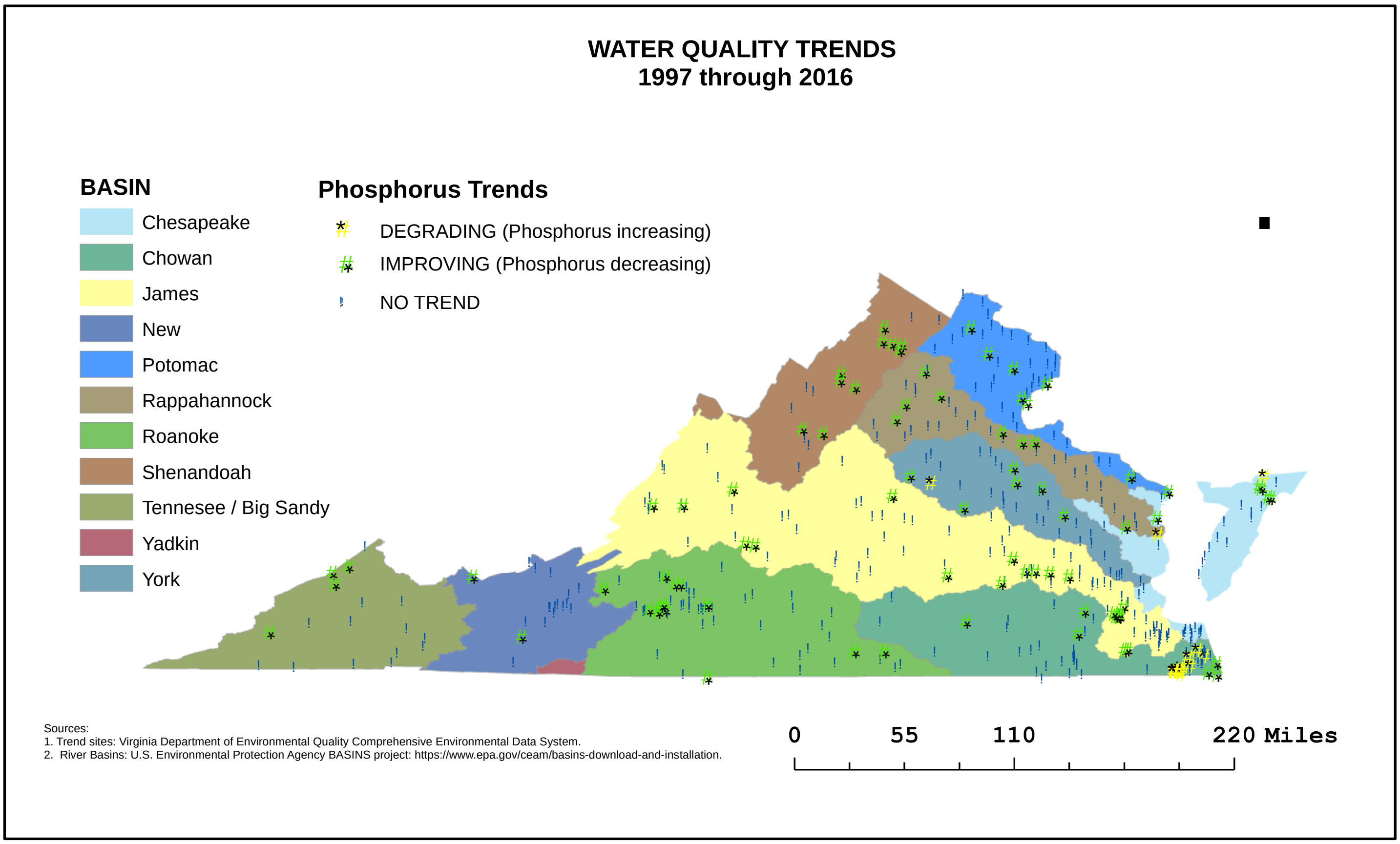


***Figure 17. Statewide trends in Total Phosphorus***

| Basin | Improving | Degrading | No Trend |
|---|---|---|---|
| Chesapeake* | 4 | 1 | 28 |
| Chowan | 0 | 12 | 37 |
| James | 14 | 0 | 74 |
| New | 1 | 0 | 16 |
| Potomac | 1 | 0 | 35 |
| Rappahannock | 1 | 1 | 28 |
| Roanoke | 8 | 0 | 44 |
| Shenandoah | 8 | 0 | 8 |
| Tennessee / Big Sandy | 0 | 0 | 14 |
| York | 2 | 1 | 27 |

* Chesapeake refers to water bodies that mostly drain directly into Chesapeake Bay. Seven stations drain directly or indirectly into the Atlantic Ocean.

***Table 6. Total Phosphorous: basinwide summary. Numbers indicate number of DEQ trend monitoring stations where improving (decreased phosphorous) or degrading (increased phosphorous) were detected.***

## Temperature

The rates of biological and chemical processes depend on temperature. Temperature affects the oxygen content of the water (i.e., oxygen levels become lower as temperature increases); the rate of photosynthesis by aquatic plants; the metabolic rates of aquatic organisms; and the sensitivity of organisms to toxic wastes, parasites, and diseases.

Early cyanobacteria algal blooms usually begin to develop during the spring when water temperature is higher and there is increased light. This growth is sustained during the warmer months of the year. Water temperatures above 25°C are optimal for the growth of Cyanobacteria. At these temperatures, HABs have a competitive advantage over other types of algae whose optimal growth temperature is lower (12-15°C). In temperate regions, such as Virginia, HABs generally do not persist through the winter months due to low water temperatures (CEES, 2021).

### *Surface Water Temperature trends in Virginia's waters*

Most DEQ trend stations (82 percent) showed no trend in water temperature (Table 7 and Figure 18). Surface water temperature in degrees Celsius, °C, increased at 63 trend stations. Many of these increases were clustered at reservoir sites around Smith Mountain Lake in the Roanoke basin, estuary sites on the mainstem of the York and Rappahannock rivers and streams and estuaries in the Chowan basin (Table 8).

| Stations | # of Samples | % Improving | % Degrading | % No Trend |
|---|---|---|---|---|
| 410 | 64,189 | 2 | 15 | 82 |

***Table 7. Percentage of stations statewide exhibiting no statistically significant trend, improving (decreasing temperature) and degrading (increasing temperature).***

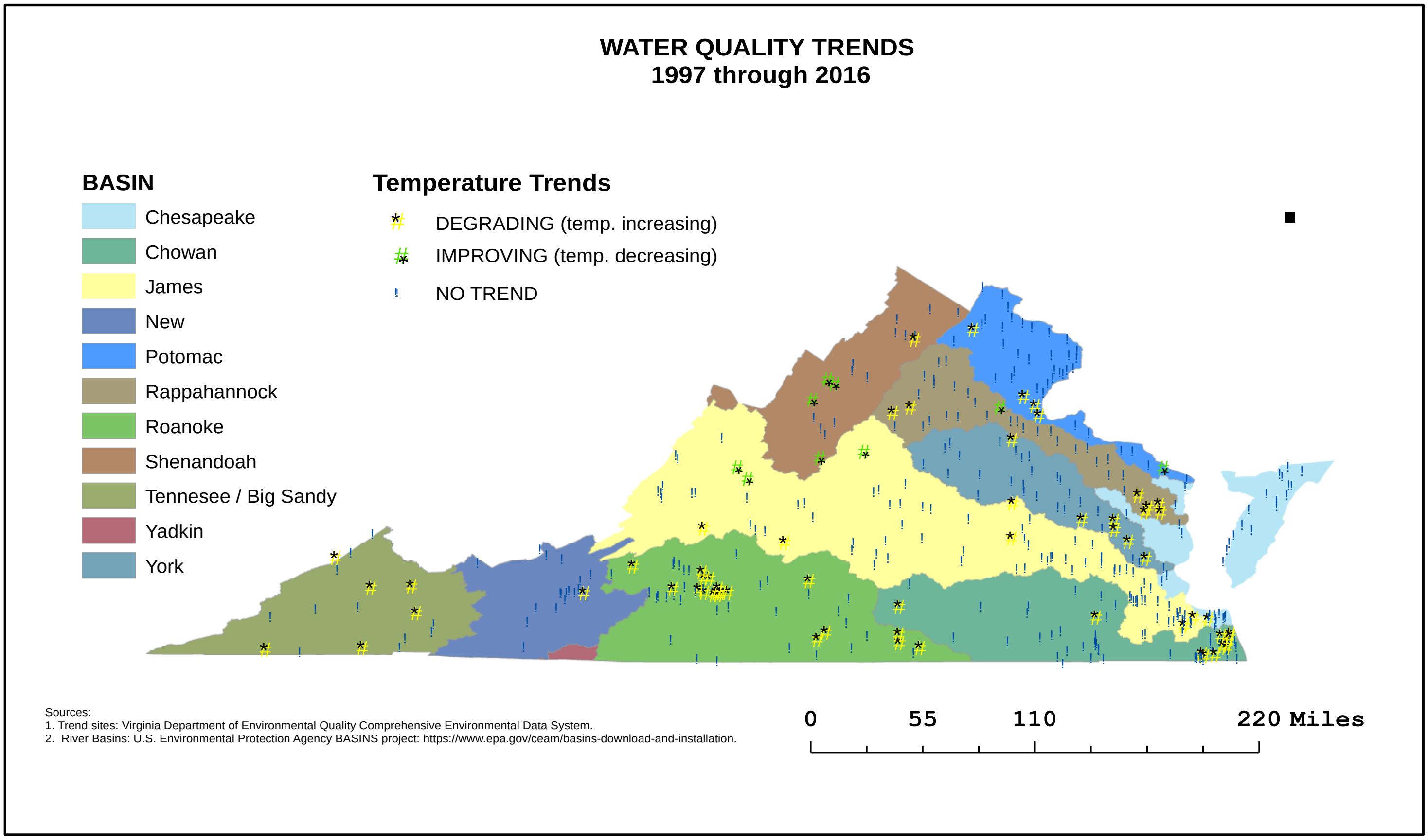


***Figure 18. Statewide trends in Surface Water Temperature***

| Basin | Improving | Degrading | No Trend |
|---|---|---|---|
| Chesapeake* | 0 | 1 | 33 |
| Chowan | 0 | 11 | 44 |
| James | 3 | 6 | 86 |
| New | 0 | 1 | 17 |
| Potomac | 1 | 4 | 38 |
| Rappahannock | 1 | 7 | 29 |
| Roanoke | 0 | 20 | 37 |
| Shenandoah | 4 | 1 | 13 |
| Tennessee / Big Sandy | 0 | 6 | 13 |
| York | 0 | 6 | 28 |

* Chesapeake refers to water bodies that mostly drain directly into Chesapeake Bay. Seven stations drain directly or indirectly into the Atlantic Ocean.

***Table 8. Surface water temperature: basinwide summary. Numbers indicate number of DEQ trend monitoring stations where improving (decreased temperature) or degrading (increased temperature) were detected.***

## Light

Sunlight is an essential component needed for all algae growth, but variation in light intensities can impact or support HABs growth. HABs experience optimal growth when sporadically exposed to high light intensities. Algal growth may be reduced when they are instead exposed to long periods of high light intensity. Even under low light conditions, harmful algae have higher growth rates than any other group of algae, which gives them a competitive advantage over other algal species (Chen et al, 2009).

## Low Velocity, Stable Conditions

Most algae have optimal growth under stable water conditions with low flows, low velocity, and minimal turbulence.

Events that contribute to decreased flows of water in river systems (e.g., droughts, surface water withdrawals, the regulation of rivers via dams) can lead to stable water conditions. In such cases, water moves more slowly or becomes ponded, which can encourage the growth of algae.

Thermal stratification occurs in lakes and reservoirs that experience stable conditions. During the summer months, thermal stratification (i.e., where the top layer of warmer water sits above the lower layer of colder water) can keep dissolved oxygen from reaching deeper waters. Thermal stratification may contribute to HAB development in two ways. First, when the two layers stop mixing, the upper layer becomes more stagnant, which may contribute to the development of summer blooms of harmful algae in lakes and reservoirs. Second, bottom waters that are depleted of oxygen may release nutrients from sediment into the water column. This pulse of nutrients into the water column can further encourage algae growth in the upper, warmer layer (CEES, 2021).

## Turbidity

Turbidity is the cloudiness of water determined by measuring how the material suspended in water affects the water's clarity (i.e., how well light passes through the water column). Turbidity does not measure the amount of materials suspended in the water (such as organic matter, algae, and plankton); but it does measure the amount of light scattered by these particles. Turbid water appears murky or cloudy.

High turbidity occurs when a lot of water is running through the system, such as high discharge after a rain event. Low turbidity occurs when there is only a small amount of suspended matter present in the water column. Low turbidity can be due to slow moving or stagnant water that allows suspended particles to settle out of the water column. When turbidity is low, more light can penetrate through the water column. This creates optimal conditions for algal growth. In return, growing algae create a turbid environment (CEES, 2021).

### *Water Clarity, Turbidity trends in Virginia's waters*

Overall water clarity, as measured by turbidity, improved between 1997 and 2016. Of the 408 DEQ trend stations analyzed 168 (41 percent) showed significant improvement. Most improvements occurred in the Chesapeake Bay and the Albemarle Sound basins although improving conditions outnumbered degrading conditions in all of the major river basins. In 6 of 10 Virginia river basins (Albemarle Sound and the New, Potomac, Rappahannock, Shenandoah and Tennessee river basins) no degrading trends in turbidity were detected (Table 9).

| Stations | # of Samples | % Improving | % Degrading | % No Trend |
|---|---|---|---|---|
| 401 | 49,504 | 41 | 2 | 57 |

***Table 9. Percentage of stations statewide exhibiting no statistically significant trend, improving water clarity (decreasing turbidity) and degrading water clarity (increasing turbidity).***

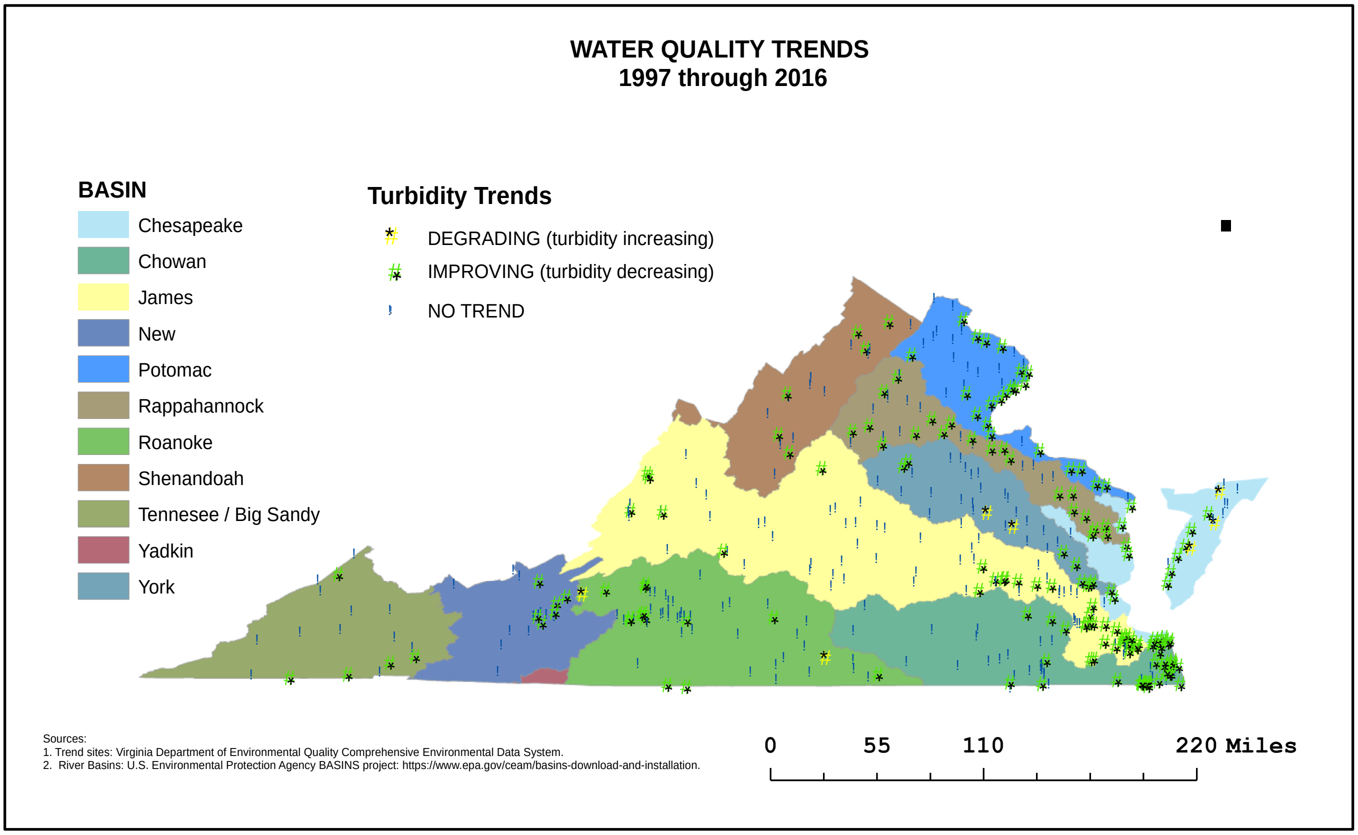


***Figure 19. Statewide trends in water clarity as measured by Turbidity***

| Basin | Improving | Degrading | No Trend |
|---|---|---|---|
| Chesapeake* | 21 | 3 | 10 |
| Chowan | 27 | 0 | 28 |
| James | 37 | 0 | 55 |
| New | 6 | 0 | 12 |
| Potomac | 22 | 0 | 20 |
| Rappahannock | 22 | 0 | 15 |
| Roanoke | 13 | 2 | 39 |
| Shenandoah | 6 | 0 | 12 |
| Tennessee / Big Sandy | 5 | 0 | 12 |
| York | 9 | 2 | 23 |

* Chesapeake refers to water bodies that mostly drain directly into Chesapeake Bay. Seven stations drain directly or indirectly into the Atlantic Ocean.

***Table 10. Water clarity as measured by turbidity: basinwide summary. Numbers indicate number of monitoring stations where improving (decreased turbidity) or degrading (increased turbidity) were detected.***

## Utilizing DEQ's Existing Monitoring Network and Resources to Understand HAB Occurrences

DEQ's monitoring network relies on data collected monthly or bimonthly from rivers, lakes, and estuaries to provide the public with a big picture view of water quality status for parameters such as bacteria, nutrients, dissolved oxygen, pH, temperature, and specific conductance. The design of DEQ monitoring programs to assess overall water quality conditions and trends is generally not at a fine enough scale to capture the specific causal factors contributing to HAB development or persistence. In order to better understand the specific causal factors contributing to individual HAB events, in depth sampling at higher frequencies and for a larger suite of parameters would be required.

Given the scope and complexity of HAB occurrence in Virginia, the timeline associated with this report is not sufficient to determine exact causal factors contributing to the HAB events outlined in the previous section. While DEQ does have a large amount of general water quality monitoring data, a full analysis of the existing data to determine what is particularly relevant to understanding the noted HAB formation and occurrence at a specific location, as well as identifying additional water quality parameters that may be needed to better understand and characterize specific HAB events, is beyond the scope of this report. A minimum of two full years of data collection is necessary to complete a site-specific study as intended. Data analysis and report generation would take an additional year.

The current monitoring conducted by DEQ on Lake Anna and in response to other potential HAB events serves to support decisions on health advisories related to harmful algal blooms by VDH and to support assessment of waters of the Commonwealth as required by state and federal law. The additional monitoring needed to determine causal factors for the Lake Anna blooms is entirely outside of the agencies' current budgets and available staffing resources. The total cost for field sampling and laboratory analysis, if required of DEQ and VDH, would depend on the specific study design. It is estimated that intensive monitoring and contractual and staffing associated with source characterization for a single large HAB event on Lake Anna may approach $400,000.

# Plans and Strategies for Appropriate Mitigation Efforts

## Pollution Reduction and Prevention

These strategies are focused on human activities associated with land use practices and pollution to water bodies. Pollution reduction and prevention is a major focus of DEQ, given the potential causative factors of HABs listed above in the previous section, the considerable effort and funding already spent in this area, and benefits to overall water quality.

### *Watershed and Non-Point Source Pollution Management Plans*

Water quality pollution is addressed through programs administered by DEQ, and include point source and non-point source pollution programs. Point source discharges of nutrients are addressed through permit programs, such as the Virginia Pollutant Discharge Elimination System program. Virginia has a Non-Point Source Pollution Management Plan[2], as required by the federal Clean Water Act, which identifies and outlines the Commonwealth's plan and approach to addressing non-point source pollution. This includes the work of multiple agencies to reduce run-off and identify measures, goals, and programs to reduce non-point source pollution with a specific emphasis on nutrient runoff reduction.

Within DEQ's watersheds programs, once a waterbody has been identified as being impaired based upon water quality standards, the next step is establishment of a Total Maximum Daily Load (TMDL). A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can accept and still meet the state's Water Quality Standards. Virginia currently develops TMDLs using a "watershed approach" when possible. The watershed approach to TMDL development allows watersheds with similar characteristics to be combined under a single TMDL equation, resulting in cost and time efficiencies. To date, over 975 TMDLs have been developed to address water quality impairments. Consistent with water quality impairment identification, the vast majority of these TMDLs are focused on bacteria impairments and no current TMDLs for HABs exist. However, TMDLs for aquatic life use impairments due to poor benthic communities have been developed which have identified nutrients as the driver for the impairments.

TMDL development requires extensive monitoring to understand the nature and characteristics of the factors causing the impairment. While Virginia has developed TMDLs for nutrients, it has not yet developed a TMDL to address eutrophication which can lead to HAB events. The prior section of this report discussed the complexities of water quality monitoring to understand the causal factors leading to HABs; the TMDL process, which includes development of water quality models to understand and predict the effect of pollutant controls, would also be very complex and resource intensive. Additionally, the ability to undertake a TMDL development requires resources, funding, and stakeholder engagement, and can be a prolonged process due to the data, analysis, complexity, and the steps involved.

Once a TMDL has been developed through an active stakeholder process, a TMDL report is prepared and distributed for public comment and then submitted to EPA for approval. Following this process, a TMDL implementation plan (IP) or watershed-based plan (WBP) is developed to describe actions (i.e., best management practices) to implement the allocations contained in the TMDL. A single plan may address multiple impairments and may address multiple TMDLs, portions of TMDLs, or impairments not

---

[2] Virginia's Non Point Source Management Plan 2019 Update. https://www.deq.virginia.gov/home/showpublisheddocument/4334/637462334964400000.

addressed by a TMDL. As of June 30, 2018, Virginia has completed 90 IPs that address 476 impairments. Though not specific to HABs, the establishment of TMDLs and resulting IPs reduce nonpoint source pollution overall in a watershed, thus reducing increased nutrient pollution and a factor contributing to HABs.

Additionally, through federal funding DEQ provides funds to stakeholders to implement projects identified in IPs to address non-point source pollution. This funding, in addition to other state funding, has collectively provided over $152,000,000 in implementation funding from 2001 through 2018. This includes primarily funding agricultural and residential septic best management practices aimed to reduce non-point source pollution in a watershed as identified through the IP.

In addition to these local TMDLs, the Chesapeake Bay TMDL and Watershed Implementation Plan (WIP) and Milestones have identified significant and specific mitigation strategies to address nutrient and sediment pollution in Virginia's portion of the Chesapeake Bay watershed. Substantial funding has been made available for accelerated implementation of Best Management Practices and additional improvements at wastewater treatments across the various river basins in the Chesapeake Bay watershed to reduce nutrient inputs into state waters over the next several years. As part of this effort, Virginia also adopted revised chlorophyll criteria for portions of the James River in 2019. The revised criteria are set to prevent eutrophication and to reduce harmful algae.

The 2022 Water Quality Assessment will consider any HAB advisories in determining whether a waterbody supports its designated uses or should be identified as impaired. As specific water quality impairments for HABs are identified in the future, TMDLs and IPs will be developed to address these impairments. TMDL development is accomplished through a prioritization process which identifies TMDLs for a specific watershed to be considered for development over a given a cycle. As new impairments are identified, these TMDL priorities can be shifted as well through the Water Quality Assessment Integrated Report update process which occurs every two years. As specific HABs TMDLs are developed, IPs will similarly be developed to identify specific projects and activities in a watershed to reduce HAB formation.

### *Community based water quality improvement projects*

There are numerous community (i.e. non-agency) groups and projects focused on enhancing water quality. These projects include wetlands restoration, living shorelines, oyster reef projects, and other green infrastructure that works to reduce runoff, build natural habitat, and improve water quality which should work towards reducing eutrophication and HABs.

Each year DEQ receives hundreds of water quality data points from citizen monitoring groups across the state. Many of these data are used by the agency in its Integrated Water Quality Assessment Report and are considered equivalent to agency-collected data. As established by the Virginia General Assembly in 1999, the agency provides funding each year for citizens to conduct water quality monitoring through a competitive grant process. In a typical fiscal year, the General Assembly allocates $88,000 for this monitoring. Further, in accordance with Virginia Code § 62.1-44.19:5.F, DEQ reviews nominations by citizens for monitoring and conducts monitoring in response to these nominations as staff availability and resources allow.

Interest in water quality and active monitoring by citizens can play a critical role in HAB management, not only through overall improvements to water quality as described above but also through direct actions associated with HAB events. For example, the efforts of the Lake Anna Civic Association (LACA) have provided hundreds of data points which inform DEQ's water assessments of Lake Anna as well as data and information that inform the management HAB-associated swimming advisories by VDH. The group leads, coordinates, and actively participates in numerous efforts associated with HAB management conducted by LACA members, state agencies, and university partners. See: https://www.deq.virginia.gov/water/water-quality/monitoring/citizen-monitoring for more information on DEQ activities associated with citizen monitoring and the Virginia Water Monitoring Council website (https://vwmc.vwrrc.vt.edu/) for more information on community based water quality improvement and monitoring in Virginia.

## HAB Treatments

HAB treatments are typically, *in situ,* that is, applied directly to a water body to prevent or mitigate HABs. The literature reviewed indicates that these strategies are most commonly employed in inland, fresh waters in the US and, therefore, on cyanobacteria blooms. The large size and greater wind and current effects in marine and estuarine waters presumably make these strategies infeasible in many cases. Some of the most common treatment strategies are reviewed here with supporting references. This is a rapidly expanding field of study and the range of treatment strategies is broad and increasing. Therefore, this review is not comprehensive of all strategies shown to be effective. In addition, an analysis of the relative cost of each strategy is beyond the scope of this review, as such an analysis requires extensive information on the systems and algae types to be treated. A recent report by the ITRC provides a broader overview of treatment strategies for Cyanobacteria than is presented here, including a broad comparison of the costs of the strategies reviewed (ITRC 2020). A review is also provided by Burford et al (2019). Common themes among these reviews and the sources below are that the effectiveness of each treatment strategy and its potential for unintended, deleterious ecological effects are highly system-specific, depending on both the environmental characteristics of the water body and the HAB species of concern. Further, all of the strategies reviewed exhibit some potential for unintended effects, though this potential remains largely unknown for many treatments. Finally, HAB treatments, unlike pollution prevention and reduction, are applied specifically to the water body of interest, must be repeated for lasting HAB mitigation and, therefore, typically do not result in broad, long-term improvements to water quality. This final commonality among treatment strategies has led many experts to the conclusion that pollution reduction and prevention, most notably nutrient management on the landscape, is essential for effective, lasting reductions in HAB occurrences (ITRC 2020, Burford et al 2019, Ibelings et al 2016).

### *Traditional chemical algaecides*

These compounds are most commonly used to treat cyanobacteria blooms in fresh water bodies, with some examples of application in marine systems (e.g. Ebenezer et al. 2014, Wang et al. 2012). Many common traditional chemical algaecides are copper-based (e.g. copper sulphate, copper II alkanolamine, copper citrate). Others include potassium permengenate, chlorine, lime and oxidizing agents. Traditional algaecides have been shown to be effective at reducing algal cell densities (e.g. Greenfield et al. 2014 and others as reviewed below), however, many do not immediately reduce water column toxin concentrations, and may cause initial increases as algal cells die, rupture, and release toxins (Greenfield et al. 2014, Liu et al. 2017). In addition, some chemical algaecides may persist in the environment longer than needed and may cause unintended toxic effects on aquatic life such as invertebrates, fish, vascular plants, and non-target algae (Chi et al 2016, Geer et al. 2016, Wagner et al. 2016, Kjær, and Elmegaard 1996). The effectiveness of chemical treatment strategies and the potential for unintended ecological effects depends on both the type of chemical treatment used and the treatment concentration. For example, Sinha et al. (2018) provided evidence that sodium carbonate peroxyhydrate (SCP; an oxidizing agent) not only kills toxic cyanobacteria, but also destroys toxins, and that the treatment does not persist in the environment. The authors showed that the treatment was effective and did not affect non-target organisms at moderate concentrations, but that high concentrations were toxic to zooplankton and non-toxic algae. In contrast, Liu et al. (2017) showed that SCP may stimulate the release of intercellular toxins from large cyanobacteria colonies. The effectiveness and potential for non-target effects of algaecides also depend on the specific environmental conditions of the water body (e.g. sediment chemistry; Willis and Bishop 2016, water temperature; Wagner et al. 2016). Evidence has been presented that in some cases, traditional chemical algaecides can be effective, with minimal unintended ecological effects (Sinha et al. 2018, Willis and Bishop 2016, Geer et al. 2016) although the authors of works reviewed for this report consistently expressed the need for further knowledge to fully understand the risks and nature of unintended effects.

### *Vascular Plants*

Virginia's Noxious Weeds Law, (Virginia Code § 3.2-800 *et seq*.) was reviewed by this working group to determine its applicability to HAB management, and whether it provided VDACS with regulatory authority over HAB events. The Noxious Weeds Law provides that a person cannot "move, transport, deliver, ship, or offer for shipment into or within the Commonwealth any noxious weed, or part thereof, without first obtaining a permit from the Commissioner." The Noxious Weeds Law further defines a noxious weed as any living plant or part thereof which is detrimental to crops, surface water, etc. HAB events generally occur due to proliferation of native algal species that exist within a given water body, limiting the potential for regulation focused on movement and transport as a mitigation strategy. As HABs are not classified as a plant, they subsequently do not meet the definition of a noxious weed. Therefore, VDACS has no authority to regulate HABs.

In addition, elimination of vascular plants, regardless of whether they are considered invasive or not, may increase the availability of water column nutrients, and, therefore stimulate algal blooms (Hodgson and Carter 1982; Hodgson and Linda 1984). Vascular aquatic plants may inhibit algal blooms by reducing available nutrients as well as by releasing inhibitory chemicals and providing habitat for zooplankton grazers (see brief review by Bakker and Hilt 2016). Management strategies aimed at reducing plant biomass (e.g. physical removal, herbicide application, stocking of herbivorous grass carp) may increase the potential for HAB events. In contrast, management strategies that promote vascular plant growth in and near water bodies have been shown to reduce nutrient inputs and to promote conditions that inhibit HAB growth (Onorevole et al. 2018, Bakker and Hilt 2016).

### *Biochemical treatments*

A number of recent studies have focused on the use of bacteria and bacteria-derived compounds to induce lysing (i.e. rupturing) of algal cells, which destroys blooms and thus inhibits further growth (Cai et al. 2011, Li et al. 2014, Li et al. 2016, Eckersley and Burger 2018). The objective these studies is to develop compounds that act specifically on algal cells, thus avoiding the widespread toxicity and resulting negative ecological consequences of traditional algaecides. These studies do not report evidence related to the potential of unintended effects however, therefore, their utility as a sustainable strategy remains unknown. It seems plausible that, similar to traditional chemical treatments, these compounds may promote short-term increases in algal toxins as the cells rupture and release their internal contents.

### *Physical manipulations*

A wide range of physical modifications to the water or bottom substrate have been employed, with some evidence that they are effective as HAB mitigation strategies. Common methods include hydrologic modification, mixing and aeration, and physical removal of algal cells from the sediment or water surface (ITRC 2020, Burford et al. 2019, EPA 2021). The applicability of these strategies, their effectiveness, and the potential for unintended effects are system-specific (see review by Bakker and Hilt 2016). For example, water level drawdown in lakes may inhibit HABs by promoting light penetration to the bottom in near-shore areas, favoring the growth of vascular plants over algae. However, in shallow lakes, drawdown may stimulate HAB growth by increasing water temperature. In impoundments, decreasing water residence time may inhibit HABs by preventing algal cells from accumulating, or may favor algal growth over vascular plants if the in-flowing water source is turbid or nutrient-rich (Bakker and Hilt 2016).

### *Barley straw*

Although the exact mechanism is unknown, there is some evidence that the breakdown of barley straw, when applied before bloom development, may inhibit the growth and proliferation of HABs (Sellner et al. 2014). Barley straw does not appear to kill active blooms, but can inhibit their occurrence, and, therefore, is recommended for application before blooms occur (Haberland and Mangiafico 2011, ITRC 2020).

### *Phosphorus Binding Agents*

Several compounds have been used to bind phosphorus to the sediment, making it unavailable for uptake by algae. Common and effective binding agents include aluminum-based compounds (e.g. aluminum sulfate (alum; e.g. Dawah et al 2015) and Lanthanum modified clay (Phoslock ™; e.g. Robb et al 2003,) and newly developed compounds such as Lanthanum/Aluminum Hydroxide composites (Pan et al 2019) and aluminum-modified zeolite (Aqual-P™, Gibbs et al. 2011). These binding agents cause *in situ* reductions of phosphors and prevent the release of phosphorus from the sediment. Phoslock™ is gaining widespread popularity for HAB mitigation and has been shown to be effective though this effectiveness is system specific (Robb et al 2003). Laboratory toxicity data on Phoslock™ is relatively extensive (see reviews in Bishop et al. 2014 and Spears et al. 2013). Bishop et al 2014 found no evidence that Phoslock™ application degraded benthic macroinvertebrate or water quality in Laguna Niguel Lake, California, though further evidence of effects in the field is needed, as they are most probably system-specific. For example, Spears et al. showed that Lanthanum in the water column of lakes as a result of Phoslock™ application was strongly and negatively correlated with lake water alkalinity. Lakes with the low alkalinity exhibited Lanthanum concentrations from Phoslock™ application posed some toxicity risk to invertebrates, whereas Lanthanum was negligible in lakes with moderate or high alkalinity. Alum has been used for decades for phosphorus reduction, and had been shown to effective reduce algal growth (Dawah et al 2015, Nogaro et al. 2013), however, Nogoro et al. 2013 showed that treatment with alum increased surface water concentrations, of sulfate, ammonium, nitrate and aluminum, all of which may pose toxicity risks and inhibit ecosystem functioning. The magnitude of these effects varied among three treatment lakes. Binding agents, which adhere to the sediment and may persistent in the environment, may have also have longer term effects that are not readily detectable in traditional toxicity tests or surveys of lake biota and water quality. Clearwater et al. (2014) detected no toxicity effects of alum of Aqual-P on a variety aquatic animals, however, they did observe accumulation of aluminum in animal tissue, which may lead to proliferation of the contaminant in the aquatic food web. Gibbs et al. 2011 found that four phosphorus binding agents (Phoslock™, Aqual-P, alum and allophane) all caused reductions in nitrification and denitrification rates by microbes. These microbial processes are essential to healthy ecosystem functioning. This finding presents a potential, yet under investigated mechanisms by which binding agents may substantially hinder proper ecosystem functioning.

## References


Anderson, D.M., Fensin, E., Gobler, C.J., Hoeglund, A.E., Hubbard, K.A., Kulis, D.M., Landsberg, J.H., Lefebvre, K.A., Provoost, P., Richlen, M.L. and Smith, J.L., 2021. Marine harmful algal blooms (HABs) in the United States: history, current status and future trends. *Harmful Algae*, *102*, p.101975.

Anderson, D.M., Glibert, P.M. & Burkholder, J.M. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* 25**,** 704–726 (2002). https://www.epa.govt.nz/assets/FileAPI/proposal/NSP000002/Evidence/5f2f6ff071/Miller-D-0476-Article-harmful-algal-blooms-and-eutrophication.pdf.

Backer, L.C., Manassaram-Baptiste, D., LePrell, R. and Bolton, B., 2015. Cyanobacteria and algae blooms: review of health and environmental data from the harmful algal bloom-related illness surveillance system (HABISS) 2007–2011. *Toxins*, *7*(4), pp.1048-1064.

Bakker, E. S., and Hilt, S. 2016. Impact of water-level fluctuations on cyanobacterial blooms: options for management. Aquatic ecology, 50:485-498.

Bishop, W.M., McNabb, T., Cormican, I., Willis, B.E. and Hyde, S. 2014. Operational evaluation of Phoslock phosphorus locking technology in Laguna Niguel Lake, California. Water, Air, & Soil Pollution, 225:1-11.

Burford, M.A., Gobler, C.J., Hamilton, D.P., Visser, P.M., Lurling, M. and Codd, G.A. 2019. Solutions for managing cyanobacterial blooms:
A scientific summary for policy makers. IOC/UNESCO, Paris (IOC/INF-1382). http://hab.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=26293. Last accessed June 30, 2021.

Cai, W., Wang, H., Tian, Y., Chen, F. and Zheng, T., 2011. Influence of a bacteriophage on the population dynamics of toxic dinoflagellates by lysis of algicidal bacteria. Applied and environmental microbiology, 77:7837-7840.

Center for Earth and Environmental Science (CEES). Indiana University, Purdue University, Indianapolis. https://cees.iupui.edu/research/algal-toxicology/bloomfactors. Last accessed June 21, 2021.

Chen, Xuechu & Kong, Hai-Nan & He, Sheng-Bing & Wu, Deyi & Li, Chun-Jie & Huang, Xiao-Chen. (2009). Reducing harmful algae in raw water by light-shading. Process Biochemistry. 44. 357-360. 10.1016/j.procbio.2008.11.002.

Chi, C., Giri, S. S., Jun, J. W., Kim, H. J., Kim, S. G., Yun, S., & Park, S. C. 2016. Effect of the algaecide palmitoleic acid on the immune function of the bay scallop Argopecten irradians. Molecules: 21, 610.

Clearwater, S.J., Hickey, C.W. and Thompson, K.J., 2014. The effect of chronic exposure to phosphorus-inactivation agents on freshwater biota. *Hydrobiologia*, *728*:51-65.

D'Anglada, L.V., J.M. Donohue, J. Strong and B. Hawkins. 2015. Health effects support document for the cyanobacterial toxin anatoxin-a. United States Environmental Protection Agency. Document No. EPA 820R15104. Washington, DC, USA.

United States Environmental Protection Agency (EPA). 2009. Drinking water treatability database: Saxitoxin. https://iaspub.epa.gov/tdb/pages/contaminant/contaminantOverview.do?contaminantId=10320.

Davis, Timothy & Berry, Dianna & Boyer, Gregory & Gobler, Christopher. (2009). 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. 715-725. 10.1016/j.hal.2009.02.004.

Dawah, A., Soliman, A., Abomohra, A.E.F., Battah, M. and Anees, D. 2015. Influence of alum on cyanobacterial blooms and water quality of earthen fish ponds. *Environmental Science and Pollution Research*, 22:16502-16513.

Ebenezer, V., Lim, W. A., and Ki, J. S. 2014. Effects of the algicides CuSO 4 and NaOCl on various physiological parameters in the harmful dinoflagellate Cochlodinium polykrikoides. Journal of applied phycology, 26:2357-2365.

Eckersley, E. and Berger, B.W., 2018. An engineered polysaccharide lyase to combat harmful algal blooms. Biochemical Engineering Journal, 132:225-232.

EPA (Environmental Protection Agency) 2021. Control Measures for Cyanobacterial HABs in Surface Water. https://www.epa.gov/cyanohabs/control-measures-cyanobacterial-habs-surface-water. Last accessed June 30, 2021.

Foulon et al, "A global scan of how the issue of nutrient loading and harmful algal blooms is being addressed by governments, non-governmental organizations, and volunteers", Water Quality Research Journal, 2020. https://iwaponline.com/wqrj/article/55/1/1/69781/A-global-scan-of-how-the-issue-of-nutrient-loading.

Geer, T. D., Kinley, C. M., Iwinski, K. J., Calomeni, A. J. and Rodgers Jr, J. H. 2016. Comparative toxicity of sodium carbonate peroxyhydrate to freshwater organisms. Ecotoxicology and environmental safety, 132:202-211.

Gibbs, M.M., Hickey, C.W. and Özkundakci, D. 2011. Sustainability assessment and comparison of efficacy of four P-inactivation agents for managing internal phosphorus loads in lakes: sediment incubations. Hydrobiologia, 658:253-275.

Gobler, Christopher. (2019). Climate Change and Harmful Algal Blooms: Insights and perspective. Harmful Algae. 91. 101731. 10.1016/j.hal.2019.101731.

Greenfield, D. I., Duquette, A., Goodson, A., Keppler, C. J., Williams, S. H., Brock, L. M, Stackley, K.D., White,D., and Wilde, S. B. 2014. The effects of three chemical algaecides on cell numbers and toxin content of the cyanobacteria Microcystis aeruginosa and Anabaenopsis sp. *Environmental management*, 54:1110-1120.

Guiry, M.D., 2012. How many species of algae are there?. *Journal of phycology*, *48*(5), pp.1057-1063.

Hodgson, L. M., and Carter, C. C. 1982. Effect of hydrilla management by herbicides on a periphyton community. Journal of Aquatic Plant Management, 20:17-19.

Hodgson, L. M., and Linda, S. B. 1984. Response of periphyton and phytoplankton to chemical control of hydrilla in artificial pools. Journal of Aquatic Plant Management, 22:48-52.

Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M. and Visser, P.M., 2018. Cyanobacterial blooms. *Nature Reviews Microbiology*, *16*(8), pp.471-483.

Ibelings, B. W., Bormans, M., Fastner, J., and Visser, P. M. 2016. CYANOCOST special issue on cyanobacterial blooms: synopsis—a critical review of the management options for their prevention, control and mitigation. Aquatic ecology, 50:595-605.

ITRC (Interstate Technology & Regulatory Council). 2020. Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCB-1). Washington, D.C.: Interstate Technology & Regulatory Council, HCB Team. https://hcb-1.itrcweb.org/. Last accessed June 30, 2021.

Kjær, C., and Elmegaard, N. (1996). Effects of Copper Sulfate on Black Bindweed (Polygonum convolvulusL.). Ecotoxicology and environmental safety, 33:110-117.

Li, D., Zhang, H., Fu, L., An, X., Zhang, B., Li, Y., Chen, Z., Zheng, W., Yi, L. and Zheng, T., 2014. A novel algicide: evidence of the effect of a fatty acid compound from the marine bacterium, Vibrio sp. BS02 on the harmful dinoflagellate, Alexandrium tamarense. PLoS One, 9, e91201.

Li, Y., Lei, X., Zhu, H., Zhang, H., Guan, C., Chen, Z., Zheng, W., Fu, L. and Zheng, T., 2016. Chitinase producing bacteria with direct algicidal activity on marine diatoms. Scientific reports, 6:1-13.

Liu, M., Shi, X., Chen, C., Yu, L., and Sun, C. 2017. Responses of Microcystis colonies of different sizes to hydrogen peroxide stress. Toxins, 9, 306.

Mangiafico, S.S. and Haberland, M., 2011. Pond and Lake Management Part VI: Using Barley Straw to Control Algae. Rutgers NJAES Cooperative Extension. Fact Sheet FS1171.

Marshall, H. G., Egerton, T., Stem, T., Hicks, J. & Kokocinski, M. 2004. Extended bloom concentration of the toxic dinoflagellate *Dinophysis acuminata* in Virginia estuaries during late winter through early spring 2002. In Steidinger, K. A.,Landsberg, J. H., Tomas, C. R. & Vargo, G. A. [Eds.] Harmful Algae 2002. Florida Fish and Wildlife Conservation Commission, Florida Institute of Oceanography, and Intergovernmental Oceanographic Commission of UNESCO, pp. 364–6.

Marshall, H.G. and Egerton, T.A., 2009, October. Increasing occurrence and development of potentially harmful algal blooms in Virginia tidal rivers. In *Conference Proceedings: Water Resources in Changing Climates. Virginia Tech Virginia Water Research Center, October, Richmond, VA* (pp. 89-101).

Marshall, H.G. and Egerton, T.A., 2012, October. Bloom and toxin producing algae in Virginia tidal rivers. In *2012 Oceans* (pp. 1-5). IEEE.

Marshall, H.G., Burchardt, L. and Lacouture, R., 2005. A review of phytoplankton composition within Chesapeake Bay and its tidal estuaries. *Journal of Plankton Research*, *27*(11), pp.1083-1102.

Miller, R.W. 2019. A couple took their 3 dogs to a pond. Then toxic algae killed the pets. USA Today. Aug 13, 2019. https://www.usatoday.com/story/news/nation/2019/08/13/blue-green-algae-kills-dogs-north-carolina-pond-owner-says/1995217001/.

Mizuta, D.D. and Wikfors, G.H., 2020. Can offshore HABs hinder the development of offshore mussel aquaculture in the northeast United States?. *Ocean & Coastal Management*, *183*, p.105022.

National Shellfish Sanitation Program, 2019. NSSP Guide for the Control of Molluscan Shellfish: 2019 Revision. https://www.fda.gov/media/143238/download.

Nogaro, G., Burgin, A.J., Schoepfer, V.A., Konkler, M.J., Bowman, K.L. and Hammerschmidt, C.R. 2013. Aluminum sulfate (alum) application interactions with coupled metal and nutrient cycling in a hypereutrophic lake ecosystem. Environmental pollution, 176:267-274.

O'neil, J.M., Davis, T.W., Burford, M.A. and Gobler, C.J., 2012. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. *Harmful algae*, *14*, pp.313-334.

Onofrio, M.D., Egerton, T.A., Reece, K.S., Pease, S.K., Sanderson, M.P., Jones III, W., Yeargan, E., Roach, A., DeMent, C., Wood, A. and Reay, W.G., 2021. Spatiotemporal distribution of phycotoxins and their co-occurrence within nearshore waters. *Harmful Algae*, *103*, p.101993.

Onorevole, K. M., Thompson, S. P., and Piehler, M. F. 2018. Living shorelines enhance nitrogen removal capacity over time. Ecological engineering, 120:238-248.

Pan, M., Lyu, T., Zhang, M., Zhang, H., Bi, L., Wang, L., Chen, J., Yao, C., Ali, J., Best, S. and Ray, N., 2020. Synergistic recapturing of external and internal phosphorus for in situ eutrophication mitigation. Water 12:2.

Ritzman, J., Brodbeck, A., Brostrom, S., McGrew, S., Dreyer, S., Klinger, T. and Moore, S.K., 2018. Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 US West Coast harmful algal bloom. *Harmful Algae*, *80*, pp.35-45.

Robb, M., Greenop, B., Goss, Z., Douglas, G. and Adeney, J. 2003. Application of Phoslock TM, an innovative phosphorus binding clay, to two Western Australian waterways: preliminary findings. In *The Interactions between Sediments and Water* (pp. 237-243). Springer, Dordrecht.

Schaefer, A.M., Yrastorza, L., Stockley, N., Harvey, K., Harris, N., Grady, R., Sullivan, J., McFarland, M. and Reif, J.S., 2020. Exposure to microcystin among coastal residents during a cyanobacteria bloom in Florida. *Harmful algae*, *92*, p.101769.

Sellner, K., Place, A., Williams, E., Gao, Y., VanDolah, E., Paolisso, M., Bowers, H. and Roche, S., 2014. Hydraulics and barley straw (Hordeum vulgare) as effective treatment options for a cyanotoxin-impacted lake *in* A. Lincoln MacKenzie [Ed]. *Marine and Freshwater Harmful Algae 2014.* Proceedings of the 16th International Conference on Harmful. Algae. Cawthron Institute, Nelson, New Zealand and the International Society for the Study of Harmful Algae (ISSHA).

Sinha, A. K., Eggleton, M. A., and Lochmann, R. T. 2018. An environmentally friendly approach for mitigating cyanobacterial bloom and their toxins in hypereutrophic ponds: Potentiality of a newly developed granular hydrogen peroxide-based compound. Science of The Total Environment, 637:524-537.

Spears, B.M., Lürling, M., Yasseri, S., Castro-Castellon, A.T., Gibbs, M., Meis, S., McDonald, C., McIntosh, J., Sleep, D. and Van Oosterhout, F. 2013. Lake responses following lanthanum-modified bentonite clay (Phoslock®) application: an analysis of water column lanthanum data from 16 case study lakes. Water Research, 47:5930-5942.

Steffen, M.M., Davis, T.W., McKay, R.M.L., Bullerjahn, G.S., Krausfeldt, L.E., Stough, J.M., Neitzey, M.L., Gilbert, N.E., Boyer, G.L., Johengen, T.H. and Gossiaux, D.C., 2017. Ecophysiological examination of the Lake Erie Microcystis bloom in 2014: linkages between biology and the water supply shutdown of Toledo, OH. *Environmental science & technology*, *51*(12), pp.6745-6755.

United States Environmental Protection Agency (EPA). 2015. Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water. https://www.epa.gov/ground-water-and-drinking-water/recommendations-public-water-systemsmanage-cyanotoxins-drinking.

US Environmental Protection Agency, 2019. Recommended Human Health Recreational Ambient Water Quality Criteria or Swimming Advisories for Microcystins and Cylindrospermopsin. https://www.epa.gov/sites/production/files/2019-05/documents/hh-rec-criteria-habs-document-2019.pdf.

U.S. Environmental Protection Agency, Climate Change and Harmful algae blooms. https://www.epa.gov/nutrientpollution/climate-change-and-harmful-algal-blooms. Last accessed June 21, 2021.

Vézie, C., Rapala, J., Vaitomaa, J. *et al.* Effect of Nitrogen and Phosphorus on Growth of Toxic and Nontoxic Microcystis Strains and on Intracellular Microcystin Concentrations. *Microb Ecol* 43**,** 443–454 (2002). https://doi.org/10.1007/s00248-001-0041-9.

Virginia Department of Environmental Quality. (2018). 2018 Water Quality Assessment Integrated Report. https://www.deq.virginia.gov/water/water-quality/assessments/integrated-report.

Virginia Department of Environmental Quality. https://www.deq.virginia.gov/water/water-quality/nonpoint-source-management. Last accessed June 21, 2021.

Virginia Department of Health, 2012. EPI-605: Virginia Recreational Water Guidance for Microcystin and Microcystis Blooms Provisional Guidance. https://townhall.virginia.gov/L/ViewGDoc.cfm?gdid=5479.

Virginia Department of Health, 2012. Virginia Recreational Water Guidance for Microcystin and Microcystis Blooms Provisional Guidance. https://townhall.virginia.gov/L/GetFile.cfm?File=C:\TownHall\docroot\GuidanceDocs\601\GDoc_VDH_5479_v1.pdf.

Virginia Department of Health, 2021. Guidance for Cyanobacteria Bloom Recreational Advisory Management.

https://www.vdh.virginia.gov/content/uploads/sites/178/2021/03/Guidance_for_Cyanobacteria_Recreational_Advisory_Mgt.pdf.

Virginia Harmful Algal Bloom Taskforce, 2018. Commonwealth of Virginia Harmful Algal Bloom Response Plan. https://www.vdh.virginia.gov/content/uploads/sites/12/2018/05/Virginia_HAB_ResponsePlan_Final_2018.pdf.

Virginia Seafood and Virginia Marine Products Board, 2020. FACTS ABOUT THE VIRGINIA SEAFOOD INDUSTRY 2018. http://www.virginiaseafood.org/2020/03/23/1762/.

Wagner, J. L., Townsend, A. K., Velzis, A. E., and Paul, E. A. 2017. Temperature and toxicity of the copper herbicide (NautiqueTM) to freshwater fish in field and laboratory trials. Cogent Environmental Science, 3, 1339386.

Wang, B., Yang, X., Lu, J., Zhou, Y., Su, J., Tian, Y and Zheng, T. 2012. A marine bacterium producing protein with algicidal activity against Alexandrium tamarense. Harmful Algae, 13:83-88.

Willis, B. E., & Bishop, W. M. 2016. Understanding fate and effects of copper pesticides in aquatic systems. Journal of Geoscience and Environment Protection, 4:37-42.

Wolny, J.L., Egerton, T.A., Handy, S.M., Stutts, W.L., Smith, J.L., Whereat, E.B., Bachvaroff, T.R., Henrichs, D.W., Campbell, L. and Deeds, J.R., 2020. Characterization of Dinophysis spp.(Dinophyceae, Dinophysiales) from the mid-Atlantic region of the United States1. *Journal of phycology*, *56*(2), pp.404-424.

World Health Organization, 2003. Algae and cyanobacteria in fresh water. *Guidelines for safe recreational water environments*, *1*, pp.136-158.