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NONPOINT SOURCE 319(H) PROGRAM CYANOBACTERIA AND HARMFUL ALGAL BLOOMS EVALUATION PROJECT
HARMFUL ALGAL BLOOM PRIMER

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PURPOSE OF THE HAB PRIMER

Toxin-producing cyanobacterial harmful algal blooms (HABs) have increased globally in geographic range, frequency, duration, and severity in recent years (Carmichael 2008, Hudnell and Dortch 2008, Paerl and Huisman 2009, O'Neil et al., 2012, Paerl and Paul 2012, Paerl and Otten 2013, Quiblier et al., 2013, Hudon et al., 2014, Wood et al., 2014).

These increases have been attributed to a wide variety of factors such as increased nutrient pollution, increased temperature, salinity, water residence time, water column stratification and climate change (Paerl 1988, Paerl and Fulton 2006, Carmichael 2008, Paerl and Huisman 2009, Paerl et al., 2011, O'Neil et al., 2012, Paerl and Paul 2012, Paerl and Otten 2013). Many of these factors are ultimately intertwined, but generally increased nutrient loads, water residence time, and climate change are considered the most significant factors contributing to the global increase in HABs (Heisler et al., 2008, Paerl and Huisman 2009, O'Neil et al., 2012, Paerl and Otten, 2013, Paerl et al., 2018).

Due to associated adverse health effects and the growing recognition that toxin-producing cyanobacterial blooms can severely impact water quality (Chapman 2015, Brooks et al., 2017), the U.S. Environmental Protection Agency recently established health advisory thresholds for drinking water and human health recreational ambient water quality criteria and swimming advisories for cyanotoxins.

In California, HABs have been a recurring and escalating issue throughout the state. Between March and December of 2016, Central Valley Water Board staff investigated and responded to 21 reports of suspected cyanobacteria harmful algal blooms (HABs). In 2017, the number of suspected reports was 30. In 2018, staff received 116 reports of suspected blooms with 66 of those resulting in confirmed blooms. These HAB events occurred in the Sacramento-San Joaquin Delta, and in rivers, lakes and reservoirs throughout the entire Central Valley Region. HAB events impact drinking water supplies, popular recreation areas, wildlife and aquatic life, and the local economies and home values of Central Valley communities. The increasing number of reported HAB events each year highlight the need to develop a coordinated, multi-year, multi-program monitoring approach within California. This type of monitoring program would allow the Central Valley Water Board to better understand where blooms are occurring, what causes them and to identify potential mitigation strategies to manage them.

Because of the increasing reports of HABs occurring within the Central Valley, the Central Valley Water Board's Executive Management Group recognized the need to start assessing where HABs were occurring and the factors contributing to their development. Under the Nonpoint Source 319(h) Program, an initial cyanobacteria and harmful algal bloom evaluation project was approved. One of the tasks of the project was to develop a primer on cyanobacteria. The primer is not intended to be an exhaustive review of the HAB literature but more of a short overview on cyanobacteria, the environmental and physical factors that contribute to their growth, and the current mitigation and control measures that could be used to manage them.

Information from this evaluation project could then be used to initiate the Central Valley Water Board's longer-term goals of implementing actions to address HABs in our regional waterbodies. These actions could include identifying data gaps in our knowledge, prioritizing specific waterbodies for additional studies, and working with watershed stakeholders to develop and conduct a monitoring program, among others.

INTRODUCTION AND BACKGROUND

Cyanobacteria are a group of microorganisms that exist in all aquatic environments. Under the right environmental conditions, they can rapidly multiply (i.e., "bloom") to high densities. This bloom can overtake a waterbody and outcompete the other aquatic community members for resources. Blooms can discolor the water, cause noxious taste and odor issues, and form unsightly surface scums (Figure 1). In some cases, these cyanobacteria blooms can produce harmful toxins. These types of events are referred to as harmful algal blooms (HABs). HABs have become an increasing problem worldwide. Water quality issues related to HABs have been identified in all 50 states and HAB events appear to be increasing in frequency, duration and intensity (GAO, 2016; WHOI, 2016).

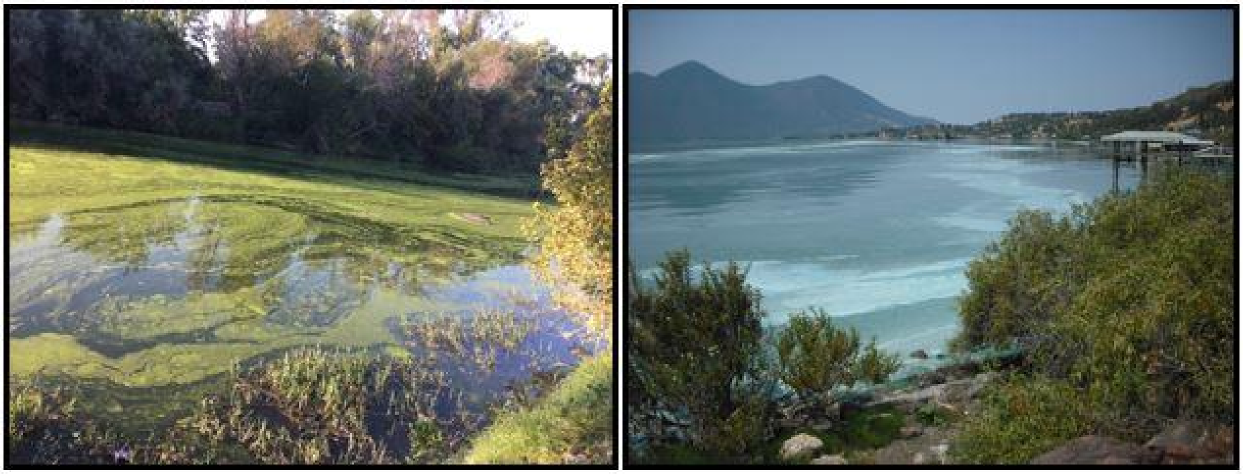

Figure 1. HAB events in Cache Creek and Clear Lake; Photos by Water Board staff

HABs create significant water quality issues that affect multiple beneficial uses such as recreation, aquatic life, and drinking water. These water quality issues include reduced visual aesthetics, reduced dissolved oxygen concentrations in the water column that affect aquatic life, taste and odor issues in drinking water, and production of potent toxins that can harm animals and human health (Anderson-Abbs et al., 2016). Economic damages related to HABs due to the loss of recreational revenue, decreased property values, recovery costs on threatened and endangered species, and increased drinking-water treatment costs amount to approximately $2.2 billion dollars annually in the U.S. (Dodds et al. 2009). Nationwide, HABs that also produce toxins have been implicated in human and animal illness and death in at least 43 states (USEPA, 2016). Expenditures among federal agencies working on HAB-related activities has steadily increased from 2013-2015. During that time, twelve federal agencies reported spending $101 million dollars to fund various research, monitoring, and other activities related to HABs (GAO, 2016).

The State of California, like other states across the U.S., has observed increasing numbers of waterbodies affected by HABs. In California, HABs have been found in all waterbody types such as streams and rivers, coastal estuaries and bays, natural lakes and reservoirs, artificial lakes and bays, ponds and municipal stormwater detention basins. Between 2016-2018, the number of HABs reported across California approximately doubled from 91 in 2016 to 190 in 2018. Reports of human and animal illnesses are also being reported in California associated with HABs. Illness cases were not consistently tracked in 2016/2017, but in 2018, 44 reports of human health and animal illnesses were reported across 17 counties.

WHAT ARE CYANOBACTERIA

Cyanobacteria are very simple organisms in terms of their cell structure. They belong to a group of organisms called prokaryotes that do not possess a true cell nucleus or other membrane-bound organelles such as mitochondria or chloroplasts. Cyanobacteria are small unicellular organisms that are natural members of the marine and freshwater aquatic community. Often called blue-green algae, cyanobacteria are bacteria. The name *‘cyano’* refers to the color of the phycocyanin pigment in the bacteria, which is blue. Originally, these organisms were mistaken as algae because they obtain their energy through photosynthesis just like algae, but they are the only major group of oxygenic photosynthetic bacteria able to produce oxygen (Allen M.M., 1985).

Cyanobacteria are one of the most successful groups of microorganisms on earth, and freshwater and marine environments are the prominent habitats for them.

Cyanobacteria can occur in a range of shapes, forms and sizes (Figure 2). They can occur as single cells, colonies, or as straight, coiled, twisted or branched filaments floating free in the water column (planktonic form), or form films or mats on the surfaces of rocks and sediment (benthic form). Filaments and single cells can aggregate into larger colonies, which can then be visible to the naked eye. Cell shape and cell size play a special role in the classification of cyanobacteria.

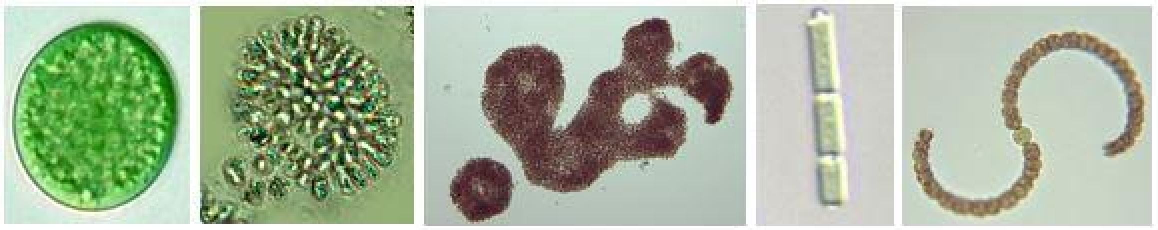

Figure 2. Different shapes and forms of free-floating planktonic cyanobacteria (single cell, elliptical colony, amorphous colony, straight filament, coiled filament)

Planktonic blooms, which are found within the water column, can discolor the water and form surface scums and mats that appear in multiple colors such as white, green, yellow, red and blue. Benthic cyanobacteria form mats on the bottom substrate (e.g. mud, sand, cobbles), or can be attached to rocks and submerged vegetation along the shoreline. Benthic blooms do not discolor the water. Figure 3 shows how the appearance of the two differs.

Figure 3. Surface blooms discolor the water; benthic cyanobacteria mats cover the substrate

Some of the more common genera of planktonic cyanobacteria in California include *Microcystis, Dolichospermum, Aphanizomenon, Planktothrix, Oscillatoria, Lyngbya, Nostoc, and Cylindrospermopsis.* Common genera of benthic cyanobacteria include *Anabaena, Phormidium, Nostoc and Cylindrospermum*.

IMPACTS FROM HARMFUL ALGAL BLOOMS

Cyanobacteria are naturally occurring members of the aquatic community and play a functional role in the ecology of the waterbody. However, they become a problem when they multiply very rapidly causing blooms that outcompete other aquatic community members for light and nutrients. These blooms can take over parts of a waterbody, or the entire waterbody, and they change the way in which the ecosystem functions. These blooms can be unsightly and aesthetically displeasing when they discolor the water and form a scum over the surface creating an “ick” factor and can cause an unpleasant odor when the cells begin to decay. For drinking water systems, some cyanobacteria can produce natural chemicals inside their cells such as geosmin (trans-1, 10-dimethyl-trans-9-decalol) and MIB (2-methylisoborneol). These chemicals can, under low concentrations, impart an unpleasant earthy and musty taste and odor to the water.

Aside from the aesthetic issue, when these blooms impair the normal function of an aquatic ecosystem or have the potential to harm human health, they become known as harmful algal blooms (HABs). This “harmful” effect can include reducing light penetration into the water column affecting the growth of other photosynthesizing community members (e.g., phytoplankton and submersed vegetation), outcompeting other phytoplankton community members for available nutrients thus shifting the community composition, reducing dissolved oxygen levels in the water resulting in fish kills, or producing harmful cyanotoxins. These cyanotoxins are responsible for illnesses in humans and illness and death of wild and domestic animals (Carmichael, 2001).

Human health risk from exposure to cyanobacteria and cyanotoxins during recreational water activities arises through three routes: (1) direct contact of exposed parts of the body; (2) accidental swallowing and ingestion of water; and (3) uptake of water by inhalation. When a HAB is occurring, it is critical to understand what the potential public health risk is based on the cyanobacteria and cyanotoxins present.

HABs can have negative impacts on aquatic life, recreation, drinking water facilities, and the economies of local communities as shown below.

Environment & Aquatic Life Impacts

- Increase in low dissolved oxygen conditions (hypoxia and anoxia)
- Increase in nutrient releases from sediment
- Increase in organic matter loading
- Increase in water soluble toxins
- Increase in fish kills and wildlife mortality events
- Decrease in overall species composition and community structure
- Decrease in light penetration

Recreational & Drinking Water Impacts

- Closure of fishing and shellfish areas
- Decrease in tourism
- Loss of waterbody aesthetics (visual and odor)
- Loss of recreational activities (boating, swimming, skiing)
- Increase in reported human illnesses and pet illnesses
- Increase in reported pet deaths
- Increased operations for drinking water treatment plants
- Taste and odor issues in drinking water

Economic Impacts

- Loss to commercial fishing and restaurant industries
- Loss to tourism industry
- Decrease revenue to recreational managers
- Decrease revenue to local economy
- Decrease in property values
- Increased costs for drinking water treatment
- Increased costs for health care treatment

PRINCIPLE DRIVERS OF CYANOBACTERIA BLOOMS

Cyanobacteria blooms can occur naturally, but most are caused by excess nutrient loading from municipal, industrial and agricultural sources into local watersheds. Other factors that can influence the growth of HABs include hydromodification of natural systems as well as the physical, chemical, biological, and environmental factors of each waterbody.

Berg and Sutula 2015 completed a global literature review on the factors that influence the growth of cyanobacteria and they identified five principal drivers that are important determinants of blooms.

- Water temperatures above 19°C
- Nutrient enrichment (nitrogen and phosphorus) in non-limiting amounts
- Long residence times and a stable, stratified water column
- High irradiance and water clarity
- Salinity tolerance

WATER TEMPERATURE

Water temperature is an important environmental factor that controls phytoplankton growth (Paerl and Huisman 2008, Berg and Sutula 2015). Phytoplankton (e.g., chlorophytes, dinoflagellates, diatoms, and cyanobacteria) have specific growth rates based on optimum growth temperatures. Cyanobacteria have slower growth rates compared to other phytoplankton. They grow slower at colder water temperatures but as the temperature increases their growth increases. For cyanobacteria from temperate latitudes, the optimum temperature for peak growth occurs between 25°C and 35°C. Other phytoplankton such as diatoms have their peak growth between 10°C and 20°C. Thus, cyanobacteria can outgrow diatoms and dominate a waterbody when water temperatures are >25°C (Paerl 2014). As water temperatures continue to increase globally above 20°C due to climate change, the difference in these optimum growth temperatures for the different species of phytoplankton will become increasingly important in determining the overall aquatic phytoplankton community composition in Central Valley waterbodies.

NUTRIENT ENRICHMENT

Nutrient over-enrichment by urban, agricultural, and industrial activities has contributed to the growth of HABs in our waterbodies. Nutrients such as nitrogen and phosphorus are key environmental drivers that influence the proportion of cyanobacteria in the phytoplankton community, the cyanobacterial biovolume, cyanotoxin production, and the impact that cyanobacteria may have on ecosystem function and water quality (Paerl et al. 2011). Cyanobacteria production and cyanotoxin concentrations are dependent on nutrient levels (Wang et al. 2002); however, nutrient uptake rates and the utilization of organic and inorganic nutrient forms of nitrogen and phosphorus vary considerably by cyanobacteria species.

Cyanobacteria use the various forms of nitrogen for growth. These forms include ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), urea, amino acids, and cyanate. Several cyanobacteria species can also fix dinitrogen gas (N_2) from the atmosphere. They use specialized cells called heterocytes when other nitrogen sources are not available (Berg and Sutula, 2015). This process is only induced under nitrogen starvation and in the absence of other nitrogen sources since fixing atmospheric nitrogen is a very energy expensive process (Herrero et al., 2004).

In addition to nutrient forms and concentrations, the ratio of nitrogen to phosphorus (N:P) and organic matter availability can also play a role in determining HAB composition and cyanotoxin production (Paerl and Huisman 2008; Paerl & Otten 2013b).

STRATIFICATION, WATER COLUMN STABILITY AND RESIDENCE TIME

Cyanobacteria blooms generally occur in warm, calm, stratified waters with high residence times. Stratification occurs when water masses with different physical and chemical properties (e.g., salinity, density, and temperature) form layers that act as barriers to water mixing. Since cyanobacteria are not strong competitors for light in well-mixed systems, they rely on their ability to regulate their buoyancy up and down in the water column to access light during the day and nutrients at night. Stable water conditions allow the cyanobacteria to maintain their position in the surface water layers during the day where they are tolerant of high irradiance levels. As their cell densities increase, they can shade out and outcompete other phytoplankton community members (e.g., diatoms), which cannot regulate their buoyancy. Stratification also contributes to warmer water. Warm water temperatures promote increased growth in cyanobacteria.

Residence time is another factor that can help promote cyanobacteria blooms. Residence time is the average length of time that a volume of water persists in a waterbody before being moved out. This length of time is determined by the flushing rate of the waterbody. Residence time affects the loss rates of cyanobacteria. Under high residence times (low flushing), loss rates are low. Under low residence times (high flushing), loss rates are high. Residence time is inter-related to stratification. When residence time is high, stratification conditions can develop and persist. Studies by Elliot 2010 and Romo et al. 2013, suggest that cyanobacteria abundance, cell size, and toxin concentration are positively related to increased residence time. Thus, the longer amount of time that water resides in a waterbody, the more time that allows for the cyanobacteria cells to grow and multiply.

IRRADIANCE AND WATER CLARITY

Cyanobacteria have poor light absorption efficiency, which makes them very poor competitors for light when living in well-mixed environments (Huisman et al. 1999). However, they have evolved to tolerate high light irradiance levels without experiencing photoinhibition. Aided by the ability to regulate their buoyancy in the water column, cyanobacteria can grow very well when close to the surface of the water. For other members of the phytoplankton community, these high light irradiance levels would be inhibitory to their growth and survival. Being able to control their position in the water column and grow at the surface allows cyanobacteria to avoid light limitation if the water column has a high amount of suspended sediment matter. In contrast, other phytoplankton community members that cannot control their buoyancy and tolerate high light levels at the surface can become shaded out and then outcompeted in growth by the cyanobacteria (Berg and Sutula 2015).

SALINITY REGIME

Most of the toxin forming cyanobacteria species are freshwater species. However, laboratory investigations have shown that many of these species are tolerant to wide salinity ranges. For example, *Microcystis aeruginosa* can tolerate salinities up to 35 parts per thousand with no change in their growth rate (Tonk et al. 2007, Preece et al., 2015). This data suggests that, under the right growth conditions, these species could bloom in brackish and estuarine waters. Within the past 10 years, coastal monitoring programs around the world have documented the spread of these species into mesohaline (5-35 parts per thousand) reaches of coastal environments.

CLIMATE CHANGE

In California, forecasts for climate change include rising air temperatures, less snowpack, earlier snowpack melt, more precipitation in the form of rain rather than snow, longer periods of drought, and a decreasing volume of available water.

Climate change has been identified as a contributing factor to both freshwater and marine HABs because it alters key environmental conditions that promote the growth and persistence of HABs. For freshwater HABs in California, these altered climate conditions include:

- Increases in water temperatures (due to increased air temperatures, drought and other global oceanographic processes)
- Changes in salinity (due to reduced freshwater flows)
- Increases in atmospheric carbon dioxide concentrations (due to increasing greenhouse gas emissions)
- Changes in precipitation patterns (i.e., drought, floods, and less snowpack)
- Reduced freshwater flows that increase stratification and stable conditions

Variability in precipitation patterns and amounts will magnify HABs. In California, droughts are becoming more frequent and severe and extending geographically across the state. Climate forecasts are predicting increases in their occurrence and duration. Excessive rainfall and runoff followed by a prolonged period of drought increase residence times, which can increase water temperatures and nutrient salts. These types of extreme events tend to increase the hydrologic variability. This pattern will most likely increase HAB events, especially if they are accompanied with increasing temperatures since cyanobacteria exhibit maximum growth rates at higher temperatures (Paerl et al., 2016).

Droughts, rising sea levels, and increased irrigation and municipal potable water demands will lead to increased salinization of freshwater and estuarine systems. Some cyanobacteria such as the nitrogen-fixers of *Anabaenopsis, Dolichospermum, Nodularia*, and some species of *Lyngbya* and *Oscillatoria* as well as the non-nitrogen fixing cyanobacteria *Microcystis, Oscillatoria, Phormidium, Synechococcus* and *Chrococcus* are salt tolerant. Thus, climate conditions that increase nutrient levels and salinization in freshwater systems will promote the proliferation of these types of cyanobacteria (Paerl et al., 2016).

MANAGEMENT AND MITIGATION OF HABS

One of the biggest challenges in dealing with HABs is understanding what management actions or mitigation strategies can be taken to reduce the frequency and severity of HABs and to prevent them from reoccurring. Waterbody management can be complex, and which mitigation measure you select needs to be based on site-specific factors of your waterbody and your intended goals (i.e., reduce the severity of blooms, shut down an existing bloom, or preventing a bloom from occurring). It is critical to understand all the drivers of HABs, and for nutrients, it is important to understand the sources and dynamics within the waterbody prior to selecting any mitigation measures.

The waterbody assessment needs to factor in all the competing uses of the waterbody and a basic understanding of the characteristics unique to the waterbody such as watershed morphometry, land use, hydrodynamics and other factors before determining the final management goal and which potential management strategies are acceptable and can be afforded by the waterbody manager(s) and interested stakeholders. In addition, selection of mitigation measures should be based on at least one year or more of monitoring data.

APPROACHES FOR HAB MANAGEMENT

Waterbody management is a collection of approaches that have different management goals. Some approaches can be used as preventive measures (i.e., tools to prevent HABs from occurring) while others are used for short-term treatments to shut down an existing bloom or long-term treatments designed to subside an existing HAB and prevent it from reoccurring.

One management approach does not fit all waterbodies, and each management approach must be carefully considered based on the management goal(s), and the specific physical, chemical and biological characteristics of the waterbody. These approaches can essentially alter the characteristics of the waterbody.

U.S. EPA recommends a larger systems approach, which combines direct waterbody management treatment with larger overall watershed management efforts. Before choosing an approach, it is important to establish what are the beneficial uses of the waterbody, and understand if there are any competing uses, and if possible, conduct studies to assess the root cause of the problem. Then, based on the results of the assessment, stakeholders should work together to choose the most appropriate management approach.

There are three main strategies used for effective management and mitigation to minimize HABs in lakes and reservoirs. These methods include:

- Biological Controls – Manipulation of lake ecology to favor cyanobacteria grazers (i.e., top-down approach) and increased competition for nutrients (i.e., bottom-up approach)
- Physical Controls - Manipulation of intake locations or depths, waterbody surface covers, aeration devices, and mechanical mixers
- Chemical Controls – Reduction in watershed nutrient and sediment loading and application of chemicals that bind or remove nutrients (e.g., lime, alum, clay particles) or chemicals that target cyanobacteria and other phytoplankton (i.e., algaecides such as copper sulfate and hydrogen peroxide)

The U.S. EPA’s Nutrient Policy and Data, Control and Treatment webpage, along with an article from Dick Osgood in the North American Lake Management Society LAKELINE newsletter (Vol. 35, No.1, Spring 2015) titled, “Do you want something that works?” identifies various strategies and approaches, including a brief description and listing of the benefits and limitations. To prevent HABs from occurring, management and mitigation tools need to focus on restricting the cyanobacteria’s growth requirements by:

- Restricting nutrient (N & P) availability
- Reducing light availability
- Reducing water temperature
- Increasing mixing and preventing quiescent, stagnant waters
- Applying chemical and physical algaecides
- Bio-manipulating the aquatic environment

CALIFORNIA’S RESPONSE TO HABS

In 2006, the state established the Statewide Blue-Green Algae Working Group (Working Group). The Working Group was composed of representatives from federal, state, and local agencies. In 2010, this Working Group developed a draft statewide guidance document titled “Cyanobacteria in California Recreational Water Bodies: Providing Voluntary Guidance about Harmful Algal Blooms, Their Monitoring, and Public Notification.” This voluntary guidance document provided background information on HABs and established recommended thresholds for voluntarily posting and de-posting of advisories for waterbodies affected by HABs (Anderson-Abbs et. al. 2016). In 2016, the guidance document was updated and included a new decision tree framework. This framework was developed to assist health departments and waterbody managers for making decisions on when to post health advisory warnings and provided recommendations for developing health advisory signs.

Between 2012 and 2016, the Working Group reorganized and became a workgroup under the California Water Quality Monitoring Council (WQMC). The WQMC is a collaboration between the California Environmental Protection and Natural Resource Agencies and is comprised of wide variety of water quality related interests. The working group renamed itself into the California Cyanobacteria and Harmful Algal Bloom (CCHAB) Network. The CCHAB Network is made up of a diverse group of stakeholders working with federal, state and local government agencies, tribal governments, academic researchers, private corporations, and non-profit communities.

The mission of the CCHAB Network is to develop and maintain a comprehensive and coordinated program to identify and address the causes and impacts of HABs in California. As part of that mission, the CCHAB Network identified four key goals – (1) develop and prioritize Water Board management questions, (2) collect, assess and synthesize data, (3) identify knowledge data gaps, and (4) develop communication tools and guidance documents to assist local agencies, waterbody managers and tribal partners for responding to HABs. Since its establishment, the CCHAB Network has developed guidance documents for responding to HABs that includes action levels for three cyanotoxins (microcystin, anatoxin-a, and cylindrospermopsin), held numerous training sessions on HAB identification and field sampling.

The Central Valley Water Board participates in the overall freshwater HAB Program by:

- Collecting information on HABs
- Sampling and analyzing HABs
- Providing information on blooms to local waterbody managers, health officers, and drinking water systems
- Conducting outreach and education to the general public
- Collaborating with academia and interested stakeholders to better understand the causes of HABs.

CONCLUSIONS

Across the globe, HABs within our freshwater and estuarine systems continue to be an increasing water quality and human health concern. In the U.S., all 50 states have waterbodies affected by HABs. Beneficial uses such as recreation, drinking water, aquatic life, and agriculture are all being impacted. The loss of these beneficial uses then directly impacts the economies of local communities.

The number of reports of human health illnesses and animal impacts (illnesses and deaths) continues to increase year after year. However, education and awareness of HABs by the general public is increasing and more states are developing guidance documents and resources for the general public, local public health agencies and waterbody managers.

There is a general understanding on the factors that contribute to these blooms – too many nutrients in a warm, stable water column promotes the optimum conditions for uncontrolled growth. Thus, reducing nutrient loading into our local waterways must be one of the actions considered when discussing control strategies. However, how all these bloom factors interact with other physical, chemical, and biological characteristics of each waterbody can be very different. So, there is no “one-size fits all” approach for managing blooms. The best way to address these impacts across the state is to develop a comprehensive, multi-year, multi-agency monitoring program that would allow for the collection of data to better understand where blooms are occurring, what physical, chemical and biological factors are driving the blooms and toxin production, and what management measures would be effective in reducing the frequency, severity and duration of the blooms, or prevention of blooms all together.

ATTACHMENT A – CYANOTOXINS

The following attachment provides a brief description of cyanotoxins and their most common groups based on chemical structure.

CYANOTOXINS

There are about 1,500 species of cyanobacteria. However, only about 46 species can produce potent cyanotoxins, which can have chronic, acute, and lethal biological effects (Carmichael, 2001; Chorus & Bartram, 1999). These cyanotoxins appear to be more harmful to terrestrial mammals than to aquatic life and have been shown to be toxic to vertebrates. The ecological role of cyanotoxins is unclear. Researchers think toxin production is more of a strategy utilized by cyanobacteria to inhibit the growth of their competitors (i.e., allelopathy), to deter predators from eating them (i.e., taste bad to prevent from getting eaten), and to bind metals that are needed for growth but are limiting in the environment (e.g., iron) or to bind metals that are toxic in high concentrations (e.g. copper). Researchers don’t yet understand all the factors that enhance toxicity. However, research into toxin production and function is increasing, which may provide a basis for predicting occurrence of toxicity in the future (Chorus & Bartram, 1999). Factors that influence the formation and toxicity of toxic cyanobacteria blooms include genetic factors (i.e., distinct toxin and non-toxin producing strains), growth factors (i.e., factors that lead to good growth also lead to optimum toxin production), and the ratio of toxin producers to non-toxin producers (Carmichael, 2001).

Cyanotoxins can exist both inside (intracellularly) and outside the cell (extracellularly). When the cellular membranes become more permeable or when the cyanobacteria cells lyse (i.e., die) they release toxin into the water column. Exposure to cyanotoxins can result from direct water contact, ingestion and inhalation during recreational water activities (e.g., wading, swimming, boating and water skiing), consumption in drinking water, and ingestion of cyanobacteria from benthic mats and in food supplements. Symptoms of exposure can range based on the type of toxin, the toxin concentration, route of exposure and duration. These symptoms can include allergic skin reactions, rashes, eye, nose, mouth or throat irritation including blistering of the mouth, headache, fever, gastrointestinal upset including abdominal pain, nausea, vomiting, diarrhea, atypical pneumonia, elevated liver enzymes, tingling, burning, numbness, seizures, and respiratory paralysis leading to death (observed in animals) (Carmichael, 2001).

Cyanotoxins fall into three broad groups based on chemical structure: Hepatotoxins (cyclic peptides), Neurotoxins (alkaloids) and Dermatoxins (lipopolysaccharides). The mechanisms of toxicity among the cyanotoxins are diverse. Hepatotoxins damage the liver. Neurotoxins affect the nervous system and disrupt the normal function of nerve cells. Dermatoxins damage the skin and/or mucous membranes and act as skin irritants, and other bioactive compounds inhibit protein synthesis. Below is a brief description of each group.

HEPATOTOXINS (CYCLIC PEPTIDES) – MICROCYSTINS AND NODULARINS

Microcystin is the most common detected freshwater cyanotoxin and is involved with the most widespread human and animal poisonings (Chorus & Bartram, 1999). *Microcystis* is the main cyanobacteria genus that produces microcystin. However, other cyanobacteria genera are also known to produce microcystin such as *Planktothrix, Oscillatoria, Nostoc, Dolichospermum, and Anabaenopsis*. Microcystin and nodularin are cyclic peptides with over 70 known structural variants. These toxins damage the liver and are known to be potent tumor promoters (Falconer et. al., 1996; Carmichael, 2001). The mechanism of toxicity is the inhibition of protein phosphatases, which can cause programmed cell death that leads to internal hemorrhaging of the liver. For the Central Valley, microcystin has been detected at numerous waterbodies with some locations reporting concentrations above the danger advisory level of 20 micrograms per liter (µg/L). Table 7 under the section on Central Valley Waterbodies provides more information on reported locations.

CYTOTOXIC HEPATOTOXINS (ALKALOIDS) – CYLINDROSPERMOPSIN

Cylindrospermopsin is an alkaloid hepatotoxin that mainly affects the liver, although it can induce pathological symptoms in the kidneys, spleen, thymus and heart. It is produced by several cyanobacteria genera such as *Cylindrospermopsis sp.,* and *Aphanizomenon sp.* and is known for causing problems in drinking water supplies in Australia and elsewhere in the world. Cylindrospermopsin-producing genera most commonly form toxic blooms in subtropical, tropical or arid zone water bodies. However, increasing occurrences of *Cylindrospermopsis raciborskii* have been reported in Europe and the USA. For the Central Valley region of California, only two locations have been reported with detections of low concentrations of cylindrospermopsin - Lake Berryessa (Napa County) and Stone Lakes National Wildlife Refuge (Sacramento County). However, cylindrospermopsin is not always tested for during each bloom event response so it is likely that this toxin is being under reported in blooms occurring across California.

NEUROTOXINS (ALKALOIDS) – ANATOXIN-A, ANATOXIN-A(S), SAXITOXIN AND NEOSAXITOXIN

Three families of neurotoxins are known: anatoxin-a/homoanatoxin-a, anatoxin-a(S), and saxitoxins. These alkaloid neurotoxins are diverse in their chemical structures and in their toxicity to mammals. Each has varying chemical stabilities and often undergo spontaneous transformations to by-products, which may have a higher or lower toxicity than the parent toxin. Some of the alkaloids are also more susceptible to breakdown under exposure to light. Anatoxin-a is the most common neurotoxin associated with animal poisonings. Anatoxin-a mimics the neurotransmitter acetylcholine and binds to the nictonic acetylcholine receptors but then cannot be degraded by the enzyme acetylcholinesterase. This activity leads to the overstimulation of the muscle cells eventually causing paralysis followed by asphyxiation (Carmichael, 1997). This toxin, otherwise known as Very Fast Death Factor, is very potent and can cause death within minutes to a few hours depending on the species exposed, the amount of toxin ingested and the amount of food present in the stomach. The clinical acute signs of anatoxin-a poisoning in pets can include difficulty in breathing, muscle tremors, convulsions, paralysis and death due to asphyxiation (Carmichael, 2001). Several dog deaths associated with exposure to anatoxin-a have occurred in California and the Central Valley.

Dermatotoxins (Alkaloids) – Aplysiatoxins and Lyngbyatoxin

Some benthic marine and freshwater cyanobacteria can produce toxins that cause severe dermatitis among swimmers and animals who come into contact with the filaments. Aplysiatoxins and debromoaplysiatoxin are potent tumor promoters and protein kinase C activators. Some of these toxins can also cause severe oral and gastrointestinal inflammation (Chorus & Bartram, 1999). A paper by Puschner et al. 2017 documented a case study of a dog who suffered from acute dermatitis and gastrointestinal upset after swimming in a freshwater lake in northern California where the cyanotoxin debromoaplysiatoxin was detected.

Endotoxins (Irritant Toxins) – Lipopolysaccharides

Lipopolysaccharides (LPS) are integral components of the cell walls of all cyanobacteria, which help the cell to maintain their size and shape. LPS compounds have been shown to produce irritant and allergic responses in human and animal tissues. LPS is a condensed product of a sugar (usually hexose) and a lipid (normally a fatty acid) that are generally found in the outer membrane of the cell wall where they form complexes with proteins and phospholipids. It is the fatty acid component of the LPS molecule that triggers an allergic response in the tissue of people and mammals when they come into contact with the compounds. LPS composition among the different genera of cyanobacteria is very diverse, and the stability of the LPS in surface waters is unknown. LPS may contribute to human health problems associated with exposure. However, LPS is poorly studied and more research is needed to evaluate the chemical structures and potential health risks (Chorus & Bartram, 1999).

B-N-methylamino-L-alanine (BMAA)

Some cyanobacteria in marine, freshwater and terrestrial habitats can produce a neurotoxic amino acid called β-N-methylamino-L-alanine (BMAA). BMAA exposure in animals and humans can cause motor neuron dysfunction. Dietary studies of the Chamorro people of Guam have shown that BMAA also bio magnifies up the food chain and that chronic dietary exposure to BMAA can cause amyotrophic lateral sclerosis/parkinsonism-dementia complex (ALS/PDC). The mechanisms by which this occurs is not well understood but there is current ongoing research into the role of

BMAA as an environmental factor in neurodegenerative disease (Carmichael, 2001; Beta-Methylamino-L-alanine. 2017, August 30).

OTHER BIOACTIVE COMPOUNDS

Cyanobacteria are known to produce several bioactive compounds that are toxic to other cyanobacteria, bacteria, algae and zooplankton. Cyanobacteria are also known to produce antiviral, antitumor, antibiotic and antifungal bioactive compounds that are of medical interest. Some of these are promising candidates for anticancer drugs.

ATTACHMENT B – WATER QUALITY CRITERIA

The following attachment provides a brief overview on the recreational ambient water quality criteria for cyanotoxins and the U.S. EPA's 10-day health advisories for cyanotoxins in finished drinking water.

RECREATIONAL AMBIENT WATER QUALITY CRITERIA

Based on the variety of possible exposure routes and the need to differentiate between allergenic irritant symptoms caused by unknown cyanobacterial substances and the more severe health effects from high concentrations of known cyanotoxins, the World Health Organization (WHO) concluded that a single guideline value was not appropriate. In 2003, the WHO derived a series of guideline values for recreational exposure to cyanobacteria based on the incremental occurrence of cyanobacteria and the relative probability of acute health effects.

In 2010, in the absence of federal recreational criteria, the California Working Group drafted a voluntary guidance document titled, "*Cyanobacteria in California Recreational Water Bodies: Providing Voluntary Guidance about Harmful Algal Blooms, Their Monitoring, and Public Notification*". In 2016, the CCHAB Network updated and revised this guidance document to include a decision tree framework and narrative to guide local health departments and waterbody managers for deciding when to post and de-post health advisories. Included in the new guidance was the development of primary and secondary action triggers. These triggers are non-regulatory but could be used by managers for determining when to post signs at the appropriate advisory levels – Caution, Warning, and Danger. Primary action triggers were developed for three cyanotoxins based on their toxin concentrations, and secondary triggers were developed using site specific factors (Tables 1 and 2).

Table 1. Non-Regulatory Recreational Cyanotoxin Advisory Levels for California – Primary Triggers

Toxin Type Primary Triggers[a]	Caution	Warning	Danger
Total Microcystins[b]	0.8 µg/L	6 µg/L	20 µg/L
Anatoxin-a	Detection[c]	20 µg/L	90 µg/L
Cylindrospermopsin	1 µg/L	4 µg/L	17 µg/L

[a] The primary triggers are met when ANY toxin exceeds criteria.

[b] Microcystins refers to the sum of all measure microcystin variants.

[c] Must use an analytical method that detects ≤1µg/L Anatoxin-a.

Table 2. Non-Regulatory Recreational Cyanotoxin Advisory Levels for California - Secondary Triggers

Secondary Triggers	Caution
Cell Density *(toxin producers)*	4,000 cells/ml
Site Specific Indicators	Blooms, scums, mats

The presence of cyanotoxins above these recreational action levels is a concern for public health and animal welfare. These levels indicate that the waterbody should be monitored for the possibility of increasing toxin concentrations because concentrations can change quickly during a bloom event. Based on which action level was met determines the necessary follow-up actions and appropriate notification and signage.

In June 2019, the U.S. EPA published in the Federal Register their recommended recreational ambient water quality criteria or swimming advisories. This criteria document titled, "*Recommended Human Health Recreational Ambient Water Quality Criteria or Swimming Advisories for Microcystins and Cylindrospermopsin*" identifies the recommended concentrations for microcystins and cylindrospermopsin at which human health is protected while swimming or participating in other recreational activities in and on the water. This criterion can either be adopted by the state into their water quality standards and used for Clean Water Act purposes or be used as the basis for swimming advisories for public notification at recreational waters. The values developed for microcystin and cylindrospermopsin are similar but higher than the values developed in CCHAB's voluntary guidance document. Thus, the state will need to determine within the next few years which values to use once they move forward on developing standards for cyanotoxins in California recreational waters.

DRINKING WATER QUALITY HEALTH ADVISORIES

The U.S. EPA Safe Drinking Water Act (SDWA) protects public health by regulating the nation's public drinking water supply and its sources such as rivers, lakes, reservoirs, springs, and ground water wells. Currently, however, there are no state or federal regulatory criteria for cyanobacteria or their toxins in finished drinking water. The SDWA requires U.S. EPA to publish a list of unregulated contaminants that are known or expected to occur in public water systems that may pose a risk in drinking water. For unregulated contaminants such as cyanotoxins, the U.S. EPA publishes health advisories to help states and water systems assess local situations. Health advisories are not federally enforceable, federal regulatory limits. Instead, the health advisories describe non-regulatory concentrations of drinking water contaminants at which adverse health effects are anticipated to occur over a specific exposure duration. Health advisories serve as informal technical guidance to assist federal, state and local officials as well as managers of public or community water systems in protecting public health (EPA, 2015).

In 2015, the U.S. EPA published their national 10-day health advisories for the cyanotoxins microcystins and cylindrospermopsin (Table 3). These 10-day health advisories provide the cyanotoxin levels in drinking water that are less than or equal to levels of which adverse human health impacts are unlikely to occur over a 10-day period. Two distinct health advisories were developed for two population groups – (1) infants and children six years and under, and (2) children six years and older, and adults.

In addition to the health advisories, the U.S. EPA also developed Health Effect Support Documents that provide a comprehensive review of the published literature on the chemical and physical properties of the cyanotoxins, the toxin synthesis and environmental fate, occurrence and exposure information, and health effects. As companions to the health advisories, the U.S. EPA developed a support document (*Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water*) that provides recommendations for states and utilities on how to manage the risks from cyanotoxins in drinking water, including information and frameworks that water systems can consider in their cyanotoxin risk management efforts.

Table 3. U.S. EPA 10-day Health Advisories for Cyanotoxins in Finished Drinking Water

10-day Drinking Water Health Advisory	Microcystins	Cylindrospermopsin
Bottle-fed infants and pre-school children (under 6 years old)	0.3 µg/L	0.7 µg/L
School-age children (6 years and older) and adults	1.6 µg/L	3 µg/L

Note: U.S. EPA found the data was inadequate to develop a Health Advisory for Anatoxin-a

In California, the State Water Board's Division of Drinking Water regulates public drinking water systems. The Division of Drinking Water has no plans to develop any state drinking water standards for cyanotoxins. Instead they recommend that California water utilities refer to the U.S. EPA's health advisories and guidance materials in managing cyanotoxins in their water systems.

ATTACHMENT C – CENTRAL VALLEY WATERBODIES WITH HABS

Cyanobacteria blooms have been reported in a wide variety of Central Valley waterbodies such as the Sacramento-San Joaquin Delta, natural and man-made lakes, reservoirs, rivers and creeks. HABs have been confirmed in numerous waterbodies within the Central Valley region. Most of these waterbodies are reservoirs and lakes used for drinking water and contact recreation. An additional number of lakes are suspected of having blooms based on satellite images.

Cyanobacteria blooms in these waterbodies typically occurs from late spring through early fall, coinciding with warmer water temperatures and periods of lower flow. These blooms may be short lived or persist for several months. The blooms can also be localized or extend across the entire waterbody. For some warmer, low elevation lakes, the bloom can begin earlier and last over a longer time interval. Though rare, dog and cattle deaths have been documented during blooms in the Central Valley region. Causes of the blooms are still undetermined and have not been investigated. Lakes with blooms often have higher surface-water temperatures, more nutrient inputs and increased residence time with low flow, than other lakes in the region.

Most of the blooms in the Central Valley were reported in the past several years and may be in part associated with the drought that occurred from 2012 through 2016. Yet, new locations are being reported each year. However, some of these waterbodies may have previously had an issue with HABs but are only now being reported due to continued education and outreach with the public. Detailed information on historic bloom locations, bloom frequencies and duration in the Central Valley and throughout California is generally lacking.

A list of Central Valley waterbodies where HABs were reported and confirmed was developed in 2017 and is updated annually at the end of each HAB season. The list can be found on the Central Valley Water Board's Nonpoint Source webpage for Cyanobacteria and HABs in the Central Valley. Although HABs occurred within these waterbodies, not all of them had toxins detected. HABs in waterbodies can lead to reduced contact recreation and heightened public concern about safety of children, dogs, fish consumption and drinking water. Stress on cyanobacteria from wave action, grazing, elevated temperature, or water treatment can lead to production of toxins. Fish kills and deaths of livestock and pets have been reported at a small number of these waterbodies. Assessment of what is causing HABs at these waterbodies along with mitigation to prevent and reduce blooms is needed to protect beneficial uses. Until the frequency and severity of HABs can be reduced, monitoring is needed at these waterbodies to protect public health.

Water Board staff have also identified additional Central Valley waterbodies where HABs are suspected to have occurred but have not yet been confirmed. These suspected HABs were identified by images obtained from Google Earth and satellite or other sources. Water Board staff are conducting internet searches and speaking with waterbody managers and local public health departments to collect more information on these Central Valley waterbodies. Obtaining more information on waterbodies with suspected HABs will identify data gaps and prioritize waterbodies that warrant further study.

CYANOTOXINS IN CENTRAL VALLEY WATERBODIES

There are no federal or state regulations requiring routine monitoring of waterbodies for HABs and their associated toxins. Thus, monitoring data is lacking across the state. Some waterbodies with a history of HABs have established monitoring programs (e.g., Klamath River, East Bay Regional Parks and Clear Lake) but most have not. For those waterbodies without a monitoring program, limited monitoring only occurs after a bloom has been reported. Even then, not all blooms are tested for toxins. Toxin testing is expensive so to stretch limited funding, an efficient cost-effective approach has been implemented by SWAMP in the state’s response to HABs. This approach involves a step-wise progression of collecting information. The first step is to identify what kind of cyanobacteria are present (i.e., cell identification) and determine what potential toxins they can produce. A cyanobacteria and known toxins chart was produced by SWAMP. The chart is used to evaluate which potential toxin analyses to perform based on the genus of cyanobacteria present in the bloom. A second step of analysis may involve analyzing the genome of the organism to see if it possesses the genes for producing toxin. The technique for performing this is through quantitative real-time polymerase chain reaction (qPCR). However, if the waterbody is a drinking water reservoir and/or has a high amount of public use for contact recreation then toxin testing is generally conducted immediately because of the need to determine the potential health risk and provide necessary public notification.

There are at least 10 different classes of cyanotoxins. However, labs in California and across the U.S. routinely only test for about five of them. These five common classes of cyanotoxins include microcystins, nodularins, anatoxin-a, cylindrospermopsin and saxitoxin. Microcystins are the most common detected cyanotoxin across the world (Chorus & Bartram, 1999). In California, and specifically the Central Valley, microcystin and anatoxin-a are the most common detected toxins with fewer reports of cylindrospermopsin and saxitoxin. However, it is important to note that most agencies do not monitor over the entire course of a bloom nor do they routinely test for all pertinent cyanotoxins due to high analytical costs. The Harmful Algal Bloom Portal's HAB Incident Reports Map identifies waterbodies where toxin testing was performed in response to a HAB event and cyanotoxins were detected. Generally, agencies test only for microcystin since it is the most common and anatoxin-a when reports of animal death have occurred. Rarely do agencies test for cylindrospermopsin and saxitoxin. Thus, the distribution and concentration of all these cyanotoxins across the state and in the Central Valley are most likely under reported and not well understood.

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