Safe and Affordable Drinking Water for Sources Impaired by Harmful Algal Blooms: Clear Lake, California

By

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Abstract

Freshwater cyanobacterial harmful algal blooms (FCHABs) are an increasing threat to drinking water worldwide. Climate change and environmental degradation exacerbate naturally eutrophic water bodies and widen the geographic area where FCHABs are likely to occur. The health effects of toxin-producing cyanobacteria are well-known, but their concentrations are unregulated in drinking water. So monitoring efforts are voluntary, which limits the data available for comprehensive analyses and hinders water utilities' ability to prepare for and manage FCHABs events. FCHABs can cause human health, economic, and ecological damages, however, their socioeconomic impacts have not been quantified for vulnerable communities that are exposed seasonally to toxin-producing FCHABs in drinking water sources. This multidisciplinary study sheds light on four issues: (1) the risk of FCHAB development related to climate change; (2) the efficacy of current treatment solutions for public water supply; (3) drinking water affordability, especially for vulnerable communities; and (4) the lack of regulation and funding mechanisms for FCHABs. Five analyses were performed to evaluate the impacts of FCHAB management on drinking water sources. First, a risk analysis was developed to predict microcystin concentrations based on cumulative winter inflow. Second, the efficacy of surface water treatment plants in Lake County was evaluated to assess if public water systems (PWSs) adequately remove microcystin concentrations from finished drinking water supplies. Third, a water rate analysis for the surface water systems in Lake County assesses if there is a relationship between FCHABs and water rates. Fourth, water treatment chemical costs for four water systems in Lake County were calculated over a period of five years to assess if a relationship exists between water treatment cost and FCHAB events. Finally, a regulatory analysis assesses if the current regulatory proceedings lack an adequate funding mechanism for increases in the cost of water treatment due to FCHABs. The results of this study indicate that (1) FCHABs will continue to worsen with climate change; (2) surface water systems in Lake County adequately remove microcystins from finished drinking water; (3) FCHABs create a disproportionate financial burden on vulnerable communities; (4) there is a positive relationship between the cost of water treatment and FCHABs; and (5) current funding mechanisms are inadequate for the increased cost of water treatment from FCHABs. The discussion explores an avenue for policy intervention to assist public water systems treating for FCHABs.

1.0 Introduction

The term harmful algal bloom (HAB) collectively refers to a proliferation of algal biomass in fresh, brackish, or marine waters that have negative ecological, public health, or economic consequences. Freshwater HABs (FHABs) are dominated by toxin or non-toxin producing algal species such as cyanobacteria (blue-green algae), phytoplankton, and benthic algae (Ohio EPA, 2019). Toxin-producing FHABs are dominated by a subset of prokaryotic cyanobacterial species. Non-toxin producing blooms are classified as HABs for their ability to impact drinking water treatment processes, local recreational economies, and limnological food web dynamics. Toxin-producing FHABs have similar economic and environmental consequences but also release potent neuro-, hepato-, and dermatoxins that cause acute and chronic health effects in humans and are deadly to domestic animals and livestock (Cheung et. al., 2013). Because of their toxicity and widespread impact on waters throughout the world, freshwater cyanobacterial HABs (FCHABs) are the primary focus of this analysis. Toxin-producing FCHABs are a significant concern for drinking water treatment facilities, local communities, and local, state, national, and international governments due to their public health, economic, and ecological risks.

FCHABs occur a variety of habitats, including small ponds, slow moving streams, embankments, drinking water reservoirs, canals, estuaries, and large lakes. All continents, except Antarctica, have reported FCHAB events. Hundell et. al. [2008] compiled the documented FCHAB incidents which totaled in 107 incidents in North America, 137 in Europe, 55 in South America, and 90 in Australia with a growing number of reports in Africa and Asia. In the United States, all 50 states have a department dedicated to HAB management and response (State HAB Resources, USEPA). Florida and Ohio have the most frequent and numerous HAB events, but all

50 states are impacted by blooms. Florida’s high temperatures and slow moving water bodies such as swamps and bogs have significant FCHABs events. The Great Lakes, especially Lake Erie, develop FCHABs that impact recreation and drinking water supplies in Ohio. FCHABs in California have been reported widely in the Klamath River Basin, Clear Lake, the Salton Sea, the Eel River and Lake Isabella. The United States spends $2.2 - 4.6 billion annually toward HAB research, response, and monitoring (Hudnell, 2009).

Historically, FCHABs developed in naturally eutrophic, highly productive water bodies such as tropical and subtropical lakes and slow moving water bodies subject to high temperatures. In recent decades, more frequent and larger FCHAB events are developing across the world due to climate change and environmental degradation. Urbanization, habitat modification, improper septic tank maintenance, inadequate stormwater controls, and agricultural practices all contribute to nutrient loading in water bodies. Nutrient loading, especially from phosphorus and nitrogen, provide essential nutrients for the development of FCHABs. Climate change exacerbates FCHAB development in naturally eutrophic water bodies and widens the geographic area where they are likely to occur. Increasing temperatures and the accumulation of carbon dioxide in the atmosphere provides the blooms with ample conditions for photosynthesis (Ohio EPA, 2019). Water bodies that did not historically undergo eutrophication are reporting FCHABs events and naturally eutrophic water bodies see longer and more severe FCHAB events than in the past (Cheung et al., 2013).

As FCHABs appear in more water bodies worldwide, surface water suppliers are tasked with mitigating the health and palatability concerns from FCHABs. FCHABs and their toxins are not regulated by the United States Environmental Protection Agency (USEPA), so no national monitoring or treatment standards currently exist for water suppliers to employ. However, the health and palatability concerns from the presence of FCHABs motivate most affected water systems to take protective measures to protect the health and safety of their communities. Treating FCHABs may require retrofitting existing infrastructure, adding new infrastructure, obtaining higher water treatment operator certifications, and increased operations and maintenance (O&M) costs. When economically distressed communities (EDCs), disadvantaged communities (DACs) or severely disadvantaged communities (SDACs) (collectively referred to as vulnerable communities [VCs]) are struck by FCHABs, rate payers will likely be disproportionately impacted. VCs often consist of small, decentralized water systems with a small rate base and limited financial resources, which limits their ability to distribute the sizable unit costs of small-scale systems. Thus, there is a need to study the impacts of FCHABs in drinking water sources with an emphasis on VCs.

This study is a multidisciplinary analysis of safe and affordable drinking water that considers the risk of FCHAB occurrence as well as the water quality, social, economic and regulatory aspects related to FCHABs management in drinking water sources. This study seeks to sheds light on the risk of FCHAB development related to climate change, the efficacy of current treatment solutions, drinking water affordability, and the lack of regulation and funding mechanisms for FCHABs. Clear Lake, California is used as a case study because (1) it has the lowest median household income in California, (2) it seasonally develops toxin-producing FCHABs, and (3) has VCs impacted by rising water rates from FCHAB treatment. The research questions that prompted this study are:

1. How do microcystin[1] concentrations change with different cumulative winter inflow?
2. Do current treatment technologies adequately remove microcystins to below 1µg/L from drinking water supplies?
3. Do FCHABs affect drinking water affordability?
4. Do the current regulatory proceedings provide adequate funding to compensate for the cost of treating FCHABs?

The main hypothesizes are:

- Microcystin concentrations are partially driven by total cumulative winter inflows from October to May of each preceding water year, with higher concentrations corresponding to low winter inflows.
- The current treatment technologies used in the Clear Lake watershed adequately remove microcystins to below 1µg/L from finished drinking water supplies.
- FCHABs create a disproportionate financial burden on rate payers in VCs because of higher water treatment costs for FCHABs.
- The increased cost of water treatment caused by FCHABs exceeds current funding mechanisms.

Five analyses were done to answer these questions. For the first question, a risk analysis approach predicted microcystins concentrations based on cumulative winter inflow. The results from this analysis include a decision tree for water managers within Lake County to evaluate the probability of microcystin concentrations and help water managers prepare for the upcoming

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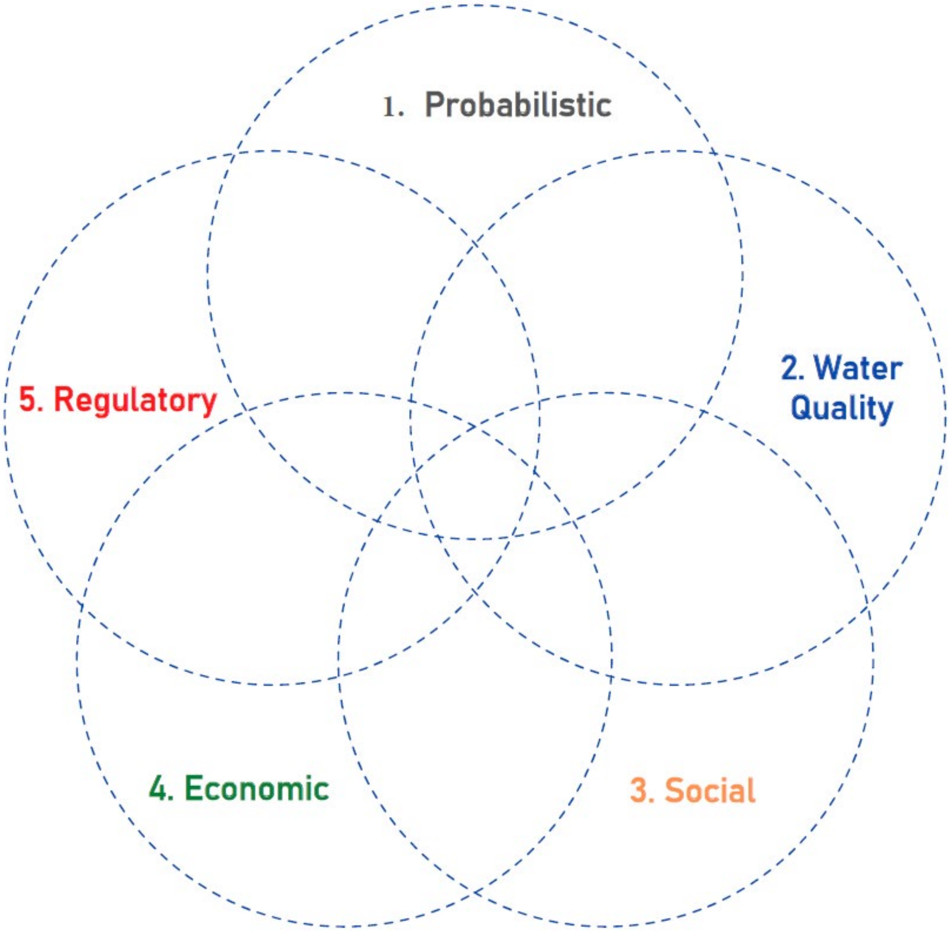
[1] A well-documented and studied cyanotoxin known to be present in Clear Lake.

FCHAB events. For the second research question, the efficacy of surface water treatment plants was estimated in Lake County for removing microcystins to assess if they adequately reduce microcystin concentrations to below the World Health Organization (WHO) guideline of 1µg/L. For the third question, a water rate analysis was done for public water systems in Lake County. The results were compared to results for similar public water systems that do not treat for FCHABs in California to assess if residents in areas affected by FCHABs pay a higher proportion of their gross monthly income toward water bills. Then the chemical costs for four water systems in Clear Lake were calculated over five years to assess if there is a relationship between water treatment cost and FCHAB events. For the fourth question, a regulatory analysis was done to if the current regulatory proceedings for FCHABs lack a funding mechanism to compensate for increases in the cost of water treatment. Figure 1 outlines the five components. This approach shows insights on risks and vulnerabilities for public water systems treating FCHABs, the performance of surface water treatment systems, drinking water affordability in VCs, the ongoing chemical costs required for surface water systems that seasonally treat FCHABs, and opportune areas for policy intervention.



Objectives

1. Develop risk analysis to predict microcystins concentrations based on cumulative winter inflow
2. Calculate percent microcystins removal to determine the efficacy of surface water treatment plants in Lake County
3. Conduct a water rate analysis to determine the relationship between FCHABs and affordable drinking water
4. Determine the O&M cost of water treatment and its relationship to FCHAB occurrence
5. Determine if the current regulatory proceedings lack a funding mechanism to compensate for increases in the cost of FCHAB water treatment

Figure 1: Study objectives

2.0 Literature Review

2.1 History and Significant FCHAB Events

The occurrence and severity of public health, economic, and ecological impacts of FCHABs is well-documented [Hudnell et al. 2008]. The earliest reports of HAB development are from aboriginal Australians in 1850, followed by reports in Europe as early as 1890 from widespread livestock deaths after grazing in a waterbody with visible surface scums. Of many reports from Australia, one case in the 1970's grabbed significant media attention. Australia's Palm Island drinking water reservoir in Queensland developed high concentrations of cyanobacteria not fully removed by water treatment. As a result, high cyanotoxin concentrations in finished drinking water resulted in hospitalization of 150 children for hepatoenteritis and kidney failure. In Brazil, the Itaparica Dam developed FCHABs that resulted in widespread gastroenteritis. In southern China, epidemiological studies confirmed that water supplies taken from surface waters and shallow wells impacted by FCHABs contributed to high liver and colon cancer rates in local communities (Hudnell et. al., 2008).

FCHAB incidents in the United States often have significant public health risks. For example, in 2013 two drinking water utilities in the Carroll Township, Ohio issued "do not drink" orders in response to microcystin concentrations exceeding state guidelines. The Township detected several microcystin results above the state guideline of 1.0 µg/L in finished drinking water supplies. The advisory was in place for 48 hours before the system could reduce microcystin levels below 1.0 µg/L. In 2014, the City of Toledo detected results above the state guideline and issued a "do not drink" order for approximately 55 hours (He et al., 2016; Ohio EPA, 2017).

2.2 FCHABs in California

Many water bodies in California seasonally develop FCHABs, but not all affect drinking water sources. For example, New Melones Lake in Calaveras County, Lake San Antonio in Monterey County, and Lake Isabella in Kern County all develop FCHABs but serve as flood control and recreational lakes that do not supply drinking water (USBR, 2021). The Salton Sea in Riverside County develops FCHABs but its salinity precludes its use for drinking water. FCHABs also are common in the Klamath River Basin, but the affected segment of the river is wild and scenic and is not used for drinking water (SDWIS, 2021). The Metropolitan Water District of Southern California owns and operates seven reservoirs, three of which seasonally develop non-toxin producing FHABs. Non-toxin producing FHABs present palatability concerns such as taste, odor, and color, in finished drinking water supplies, but do not present a public health concern.

The South Fork of the Eel River in Northern California undergoes seasonal toxin-producing FCHABs primarily as *Anabaena* blooms. Four drinking water systems draw water from the South Fork of the Eel River, including Weott Community Services District (CSD) (PWS CA1200553), Garberville CSD (PWS CA1210008), Redway CSD (PWS CA1210011), and Dell Oro Water Company - Benbow system (PWS CA1200671). The water systems have infiltration galleries that currently avoid FCHABs, but they are concerned that decreasing flow rates from climate change and nutrient loading from illegal marijuana grows in Humboldt County will continue to exacerbate eutrophication in the South Fork. Increasing abundance of eutrophication in the South Fork could cause toxicity issues in treatment facilities in the near future, but they are currently unaffected (Cox, 2021).

2.3 Toxin-Producing Cyanobacteria in Clear Lake

Clear Lake, however, is a multi-use natural lake that serves as a drinking water reservoir with frequent toxin-producing FCHABs. To date, it is the only drinking water reservoir in California with toxin-producing FCHABs (California Water Quality Monitoring Council, 2021). Three species of toxin-producing cyanobacteria are abundant in Clear Lake: *Aphanizomenon, Anabaena,* and *Microcystis*. These species of cyanobacteria are not toxic during growth and development. Rather, they contain toxins that exist intracellularly either in cell walls or within cytoplasm. Intracellular toxins may be released by natural excretion or via cell lysis. Toxin concentrations become harmful for human, animal, and ecosystem health during cellular decomposition of blooms, which historically occur in mid-to-late summer. Four classes of toxins are released by *Aphanizomenon, Anabaena,* and *Microcystis.* They include*:* microcystins, cylindrospermopsin, anatoxins, and saxitoxins. During growth and development, the majority of anatoxins and saxitoxins exist intracellularly (>95%), roughly 70% of microcystins remains intracellular, and 50% of cylindrospermopsin remains intracellular (Westrick, 2010; Schmidt et al., 2002).

During cell lysis, *Aphanizomenon* releases saxitoxins, anatoxins, and cylindrospermopsin. *Anabaena* releases microcystins, saxitoxins, and anatoxins, and *Microcystis* releases microcystins. Figure 2 visually presents the toxins released by *Aphanizomenon, Anabaena,* and *Microcystis.* The short-term health effects of these toxins are relatively well documented, but some long-term health effects remain under investigation. The health effects of toxins released by *Aphanizomenon, Anabaena, and Microcystis* are summarized in Table 1. Of the toxins explored in this paper, microcystins are the most well-studied due to its widespread occurrence throughout the United States (Cheung, 2013). There are currently no monitoring results in Lake

County for cylindrospermopsin, anatoxins or saxitoxins, therefore, the analyses here emphasizes concentration of microcystins as a proxy for cyanotoxins.

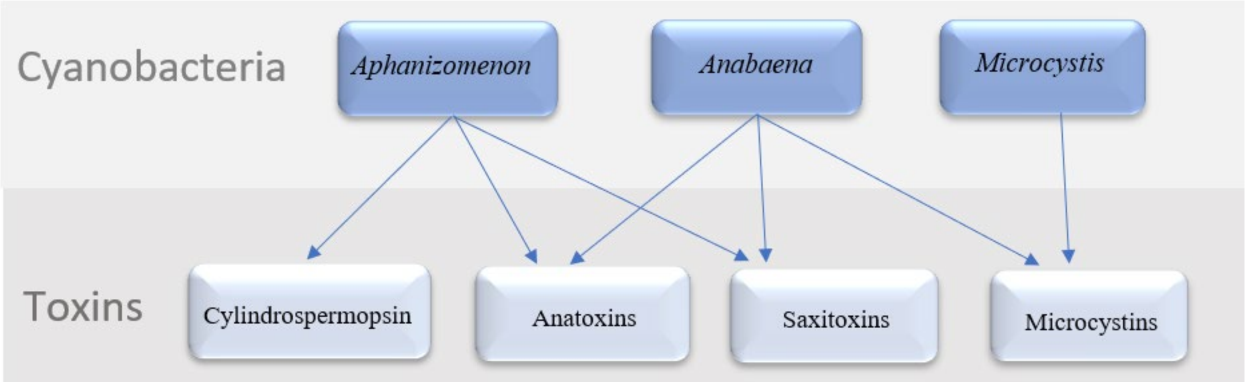


Figure 2: Cyanobacterial Cells and Associated Toxins

Table 1: Short and Long-Term Health Effects of Toxins Released by *Aphanizomenon, Anabaena* and *Microcystis* (modified from Cheung et al, [2013])

Cyanotoxin	Toxin Released	Short-Term Health Effects	Long-Term Health Effects
Aphanizomenon	Saxitoxins	Burning, tingling, numbness, incoherent speech, drowsiness, respiratory paralysis leading to death	Unknown
Aphanizomenon & Anabaena	Anatoxins	Burning, tingling, numbness, incoherent speech, drowsiness, respiratory paralysis leading to death	Cardiac arrhythmia leading to death
Aphanizomenon & Anabaena	Cylindrospermopsin	Gastrointestinal, liver inflammation and hemorrhage, pneumonia, dermatitis	Malaise, anorexia, liver failure leading to death
Anabaena & Microcystis	Microcystins	Heavy breathing, vomiting, weakness, diarrhea, gastrointestinal liver inflammation, and hemorrhage and liver failure leading to death, pneumonia, dermatitis	Tumor promoter, liver failure leading to death

2.4 Regulatory Status of Cyanotoxins

Despite the relatively well-known health effects of FCHABs and their presence in drinking water reservoirs throughout the world, there are no national primary drinking water regulations in the United States for cyanotoxins in drinking water. A Maximum Contaminant

Level (MCL) is a regulatory tool, authorized by the Safe Drinking Water Act (SDWA), used to protect public health and safety by limiting the concentration of contaminants in drinking water supplies. MCLs are enforceable standards set by the state or the federal government that define the maximum allowable concentration of a specific contaminant in drinking water. To date, the United States Environmental Protection Agency (USEPA) has established 90 MCLs (USEPA NPDWR, 2020). The State of California is subject to the rules and regulations set by the USEPA, but states have authority to adopt more stringent or additional MCLs. An example of a California MCL that is stricter than the federal MCL is Benzene. The federal MCL for Benzene is 5µg/L whereas the California MCL is 1µg/L. California has adopted eleven MCLs that are not regulated under the USEPA. Examples include perchlorate, 1,2,3-Tricholorpropane (123-TCP), and Methyl-tert-butyl ether (MTBE) (USEPA NPDWR, 2020). Despite the lack of regulatory controls for cyanotoxins in finished drinking water supplies, utilities across the nation have been proactive in finding treatment solutions for FCHABs.

Utilities rely on the available literature, guidance documents, and toxicological studies to guide their treatment decisions. The USEPA published a health advisory for microcystins and cylindrospermopsin in 2015; there are currently no health advisories for saxitoxins or anatoxins. Health advisories are informational documents that provide unenforceable health thresholds based on peer-reviewed epidemiology and toxicological laboratory data. Also included is information about the best available technologies to remove cyanobacterial cells and their toxins. The 10-day health advisory for microcystins and cylindrospermopsin are 0.3µg/L and 0.7µg/L for children under six years of age and 1.6µg/L and 3.0µg/L for persons over the age of six, respectively. A widely used guideline for microcystins is the World Health Organization guideline of 1µg/L adopted in 2003. Since then, seventeen non-US countries have adopted the guideline (USEPA Health Advisories for Cyanotoxins, 2020). FCHAB preparation and management documents are widely available through the USEPA, the American Water Works Association, the World Health Organization, Universities, and local governments.

2.5 FCHAB treatment

The treatment of FCHABs is inherently challenging. It requires extensive monitoring equipment, skilled water treatment operators, and an understanding of lake limnology. In addition, mechanisms to remove or inactivate one species of cyanobacteria or class of toxin may not remove other species or classes. So operators must be well-versed in the types of cells and toxins to be treated. There are two stages to treating algal blooms in source water, each stage containing various configurations of treatment units and processes. The first stage is to physically remove intact algal cells from raw water through conventional water treatment. The second stage is to chemically inactivate the toxins. Throughout the treatment process, treatment mechanisms must be robust enough to remove intact cells and their toxins, but also must be gentle enough to avoid cell lysis. Cell lysis is an unintended consequence of water treatment processes whereby the treatment process physically breaks the cell, releasing intracellular toxins. Water treatment processes are optimized when cell lysis is minimized, so special care must be taken to avoid cell lysis during the treatment process (Westrick, 2010; Cheung et al., 2013; Schmidt et al., 2002).

Conventional treatment includes four unit processes: coagulation, flocculation, sedimentation, and filtration. Dissolved air floatation (DAF) treatment units may be used as a substitute for conventional sedimentation processes to improve cyanobacterial cell removal. Conventional filtration units typically contain anthracite, green sand, mixed media, sand or gravel and are successful at removing most remaining solids before the final oxidation stage. However, some utilities use micro-, ultra-, nanofiltration, or reverse osmosis to remove both the remaining suspended solids and extracellular toxins before the final oxidation stage. Treatments such as granulated activated carbon (GAC) units or powdered activated carbon (PAC) may be added during or after conventional treatment to mitigate taste and odor (T&O) and partially remove extracellular toxins (Kerri, 2008; Cheung et al., 2013). Table 2 lists conventional treatment processes and some of their modifications. Table 3 outlines coagulant effectiveness for three species of cyanobacteria (*Aphanizomenon*, *Anabaena*, and *Microcystis*).

Table 2: Conventional Treatment Plant Configuration Options

Unit Process	Types	Options
Coagulation	Traditional Enhanced	Optional pretreatment: soda ash, muriatic acid Primary coagulants: aluminum sulfate, ferrous sulfate, polyaluminum chloride, ferric sulfate, polyferric sulfide, ferric chloride, cationic polymers Optional coagulant aids: bentonite clay, calcium carbonate, sodium silicate, anionic, nonionic polymers
Flocculation	Horizontal mixing Vertical mixing	Optional flocculant aids: aluminum sulfate, nonionic polymers, iron salts
Sedimentation	N/A	Rectangular Basin Upflow Clarifier/ Solid Contact Unit Dissolved Air Flotation (DAF)
Filtration	Direct Conventional	Filtration units: Slow sand, rapid sand, pressure filters Media types: dual sand, anthracite, green sand, mixed media
Auxiliary process: Membrane filtration	Microfiltration (MF) Nanofiltration (NF) Ultrafiltration (UF) Reverse Osmosis (RO)	Membranes of varying sizes
Auxiliary process: Activated Carbon	Granulated (GAC) Powdered (PAC)	Wood, coal, seashells, coconut, bones

Table 3: Coagulant Effectiveness

Cyanobacterium	Coagulant			
	Polyaluminum chloride	Polyferric sulfate	Aluminum sulfate	Ferric sulfate
Anabaena	Effective	Moderately Effective	Moderately Effective	Moderately Effective
Aphanizominon	Not effective	Not effective	Not effective	Not effective
Microcystis	Effective	Moderately Effective	Moderately Effective	Moderately Effective

The second stage of treatment is chemical oxidation and inactivation of microbiological contaminants, pathogens, and extracellular toxins (Westrick, 2010). The success of chemical inactivation depends largely on the characteristics of the toxin being treated including its hydrophobicity, molecular size, and functional groups susceptible to oxidation (Westrick, 2010). Oxidation chemicals are always added at the end of surface water treatment per the Surface Water Treatment Rule (SWTR), but many treatment configurations apply oxidizers both at the head and after the treatment works. Many treatment plants also use advanced oxidation techniques like ultraviolet light (UV) and ozone (O_3) to inactivate extracellular toxins. The combination of physical treatment and chemical oxidation removes intact cyanobacterial cells and extracellular toxins in drinking water (USEPA Health Advisory, 2015; Westrick, 2010; He et. al., 2016; Cheung et. al., 2013). Physical and chemical removal processes vary in effectiveness depending on the specific toxin. Water treatment operators must be familiar with the characteristics of the toxin they are treating before selecting a treatment technique (Westrick, 2010; USEPA Health Advisory, 2015). Table 4, adopted from Cheung et al [2013], outlines oxidant effectiveness for the four cyanotoxins (microcystins, cylindrospermopsin, anatoxins, and saxitoxins).

Table 4: Oxidant Effectiveness for Various Cyanotoxins (adopted from Cheung, et. al. [2013])

Oxidant	Toxin			
	Anatoxin-a	Cylindrospermopsin	Microcystin	Saxitoxin
Chlorine	Not Effective	Effective (pH 7-9)	Effective	Somewhat Effective
Chloramine	Not Effective	Not Effective	Not Effective within normal operating parameters	Inadequate information
Chlorine Dioxide	Not Effective within normal operating parameters	Not Effective	Not Effective within normal operating parameters	Inadequate information
Potassium Permanganate	Effective	Not Effective	Effective	Not Effective
Ozone	Effective	Effective	Effective	Not Effective
UV/Advanced Oxidation	Effective	Effective	Not Effective	Inadequate information

Intact cyanobacterial cells and their extracellular toxins clog filters, increase chemical demand, produce taste and odor (T&O) problems, and promote formation of disinfection byproducts (DBPs). When chlorine reacts with organic matter, carcinogenic DBPs are formed, a byproduct of chlorine disinfection. During FCHAB events, raw water turbidity increases, which requires more frequent backwash cycles to unclog filters. Increased turbidity from organic matter may cause earthy or musty T&O problems in finished drinking water. In addition, FCHABs deplete dissolved oxygen in the lake, creating anoxic conditions. Anoxic conditions catalyze internal phosphorus loading via the release of sediment bound phosphorus and ammonia, which further fuels development of FCHABs. When naturally-occurring ammonia is introduced into the treatment process, it reacts with sodium hypochlorite (the most commonly used oxidant for disinfection) and develops mono-, di-, and trichloramines. Some utilities intentionally create chloramines for disinfection because they mitigate the development of DBPs, but chloramines are ineffective at inactivating cyanotoxins and so should be avoided for treating FCHABs. To avoid the development of chloramines, chlorine dosages must be increased significantly to overcome the reaction with ammonia. As more ammonia is introduced from anoxic conditions associated with FCHABs, more chlorine must be added to overcome the reaction. Once an adequate chlorine residual is established, operators must avoid the development of DBPs. Anoxic conditions also oxidize iron, manganese, and hydrogen sulfide that contribute to objectionable T&O in finished drinking water supplies (Lorenzen and Mitchell, 1975).

2.6 The Effect of pH on FCHAB treatment

In non-eutrophic lakes, the growth of algae does not impact pH because there is not enough algal biomass to significantly alter water chemistry. However, highly productive eutrophic lakes have excessive algal growth, which can significantly raise the pH. During a bloom event, the algae photosynthesize during the daylight hours, extracting carbon dioxide from the water column. Under normal conditions, the pH increases during the daylight hours and decreases at night. These fluctuations are driven by the rapid uptake of carbon dioxide in the water column during the day when photosynthesis peaks and the subsequent decrease in carbon dioxide uptake during the night. See equation 1 for the chemical reaction between carbon dioxide and water. As carbon dioxide (CO_2) is added to the water (H_2O), the water dissociates into bicarbonate (HCO_3^-) and hydrogen atoms (H^+) which causes the pH to decrease. As carbon dioxide is removed from water, as in the case when FCHABs are present, the reaction does not dissociate into bicarbonate and hydrogen ions but rather stays as carbonic acid (H_2CO_3), causing the pH to increase (Tucker & D’Abramo, 2008).

$$[1] \quad CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

The presence of FCHABs increases the pH of raw water, which decreases coagulant effectiveness. Even small increases in pH (two or three tenths) in raw water can indicate the presence of an FCHAB. Large increases in pH (9 or higher) often indicate a severe bloom (Ohio EPA, 2019). High raw water pH requires high coagulant dosages to complete the reaction. Darin McCosker, former Water Treatment Plant Supervisor at the California Water Service – Lucerne stated, "[C]oagulant dosages in the winter range from 15-20mg/L, whereas coagulant dosages in the summer months are around 50-60mg/L to compensate for the increased organic loading and pH changes from HABs". One treatment alternative is to install an acid feed system that introduces sulfuric or muriatic acid to lower the pH of water entering the plant to within the acceptable ranges for coagulant effectiveness (Wendele, 2021). Table 5 outlines recommendations for conventional treatment unit processes for water utilities that treat FCHABs.

Table 5: Recommendations for Physical Treatment Unit Processes for Removal of Cyanobacterial Cells

Unit Process	Method	Recommendation	Justification
Coagulation	Enhanced Coagulation	Recommended	Enhanced coagulation agglomerates more NOM and intact cyanobacterial cells, increasing treatment efficacy. Aphanizomenon is the most resistant to coagulation.
Sedimentation	Rectangular Sedimentation Basin	Recommended	Recommended for conventional treatment due to their ability to accommodate for vast changes in water quality.
	Upflow clarifiers/ solid contact units	Not Recommended	Not recommended for treating FCHABs due to its inability to compensate for vast changes in water quality.
	Dissolved Air Flotation (DAF)	Recommended	DAF is recommended as a replacement for sedimentation basins or used as an auxiliary treatment process during algal blooms
Filtration	Direct Filtration	Not Recommended	Direct filtration should not be used in waters with high turbidity.
	Conventional filtration (rapid sand or slow sand)	Recommended	Recommended for use in conjunction with conventional treatment
	Membrane Filtration (micro-, ultra-, nanofiltration, reverse osmosis)	Recommended	Recommended to replace conventional particle filtration, if possible.
	Granulated Activated Carbon (GAC)	Recommended	Recommended for use after conventional treatment to mitigate T&O and facilitate partial removal of extracellular toxins
	Powdered Activated Carbon (PAC)	Recommended	Recommended for use during sedimentation for partial removal of extracellular toxins if GAC cannot be used.
Sources: Zamyadi et. al., 2013; Wendele, 2020; He et al., 2016; Schmidt et al., 2002; Kerri, 2008; Westrick, 2010; Water World, 2013; USEPA Health Advisory, 2015; Rizzo, 2020; Cheung et al., 2013; Continental Carbon Group, 2020; Albuquerque et al., 2008			

3.0 Case Study: Clear Lake

3.1 Overview

Clear Lake is a naturally eutrophic lake in Lake County, California, roughly 70 miles north of San Francisco (Horne, 1975). It is a multi-purpose recreational lake that also serves as a drinking water reservoir for roughly 38,000 people who live along its shore and an agricultural water supply for downstream Yolo County (SDWIS, 2020). Clear Lake has a high sedimentation rate, a long residence time, is affected by wind patterns and is in a climate that favors the growth of toxin-producing FCHABs. Clear Lake is a large, shallow, warm polymictic[2] lake in a Mediterranean climate that consists of three interconnected but fundamentally distinct basins: The Upper Arm, the Lower Arm, and the Oaks Arm. The basins are connected by a mile long strait called the Narrows (see Figure 3) (Horne, 1975). The lake is 18 miles long, covers 43,790 acres, has roughly 100 miles of shoreline, and has an average depth of 26 feet (Highlands Mutual Water Company, 2016). It is one of the oldest lakes in North America, dating back 2.5 million years. The lake was formed by volcanic activity from the neighboring volcano, Mount Konocti. The lake's current shape is due to Mount Konocti's most recent eruption that took place nearly 0.5 million years ago (History of Lake County, 2019).

Figure 3: Aerial View of the three connected basins in Clear Lake

3.2 FCHABs in Clear Lake

The water quality in Clear Lake is atypical for California because it is naturally eutrophic with FCHABs common in the summer (Cyanotoxins Management Plan, Highlands Mutual

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[2] A lake that is too shallow to maintain regular thermal stratification. Clear Lake undergoes periods of intermittent thermal stratification but is relatively well mixed throughout the year.

Water Company, 2016). It is dominated by three species of toxin-producing cyanobacteria: *Aphanizomenon*, *Microcystis*, and *Anabaena* (Horne, 1975). *Aphanizomenon* dominates in the winter and spring. *Anabaena* dominates in the fall but also may coexist with *Microcystis*. These blooms are abundant in the Oaks and Lower Arm and are mostly absent in the Upper Arm. Small amounts of *Microcystis* are present in the Lower and Oaks Arm starting in August but are absent in the Upper Arm until October. During bloom season, they form thick mats of noxious blue-green algae (formerly known as Cyanophyceae) that cover vast areas of the lake. When blooms decay, they have potential to release potent target organ toxins (microcystins, cylindrospermopsin, anatoxins and saxitoxins) and give off a putrid smell similar to untreated sewage (Cheung et. al., 2013; McCosker, 2020). Historical data shows the Lower and Oaks Arms of Clear Lake have more severe FCHABs than the Upper Arm (Horne, 1975; Kennedy, 2020).

Although Clear Lake is naturally eutrophic, the frequency and duration of FCHABs in the lake have increased from urbanization, the destruction of natural wetlands, high nutrient runoff from agricultural practices, and a lack of sediment controls. FCHABs hamper Lake County’s recreational economy, present health risks for humans and animals, and create significant drinking water treatment challenges. As climate change and environmental degradation continue to harm water supplies, it is likely that more drinking water reservoirs in California will develop toxin producing FCHABs. Therefore, it is important to address the impacts of FCHAB for drinking water supplies with an emphasis on vulnerable communities (VCs).

3.2 Surface Water Purveyors & Economic Classifications

Seventeen drinking water systems draw raw water from Clear Lake (see Figure 4) (SDWIS, 2020). In response to FCHABs, surface water purveyors in Lake County have implemented robust drinking water treatment systems. Technologies like onsite ozone generation, advanced oxidation via ultraviolet light (UV), granulated (and powdered) activated carbon, pH adjustment, microfiltration, and dissolved air flotation are often needed to supplement conventional water treatment processes (Little, 2019). Table 6 outlines current drinking water treatments in Clear Lake's surface water supply systems. The treatment processes needed to treat FCHABs increase costs for capital improvements and for the operation and maintenance. The increased cost of treating FCHABs disproportionally affects Lake County partly because it is the poorest county in California with all communities classified as economically distressed, disadvantaged, or severely disadvantaged (hereinafter referred to as vulnerable communities [VCs]) (Stebbins, 2019). Figure 5 is a map of economic classifications in Lake County.

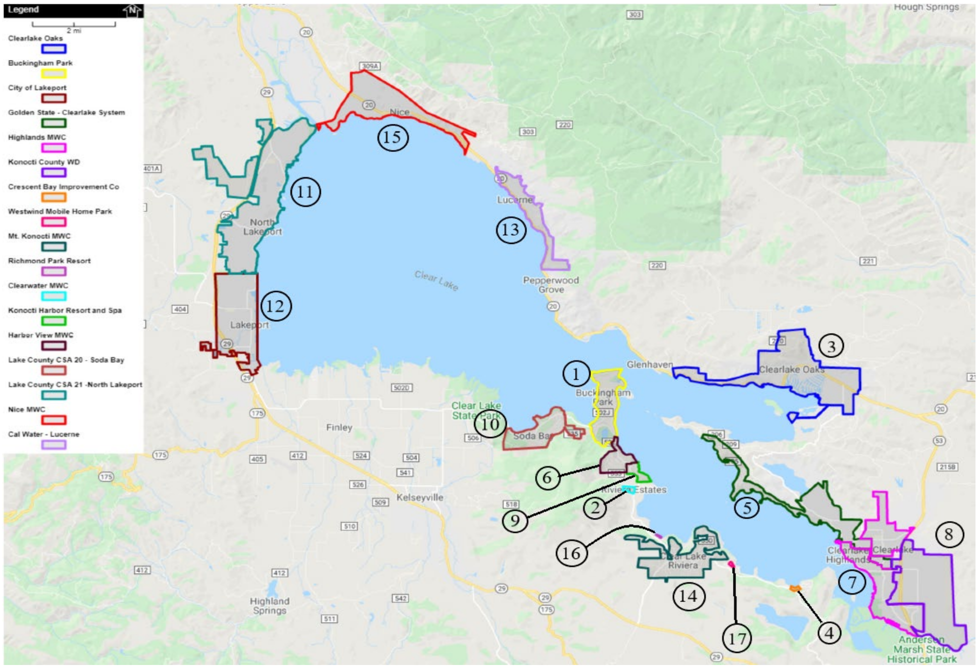


Figure 4: Surface Water Purveyors System Boundaries in Lake County

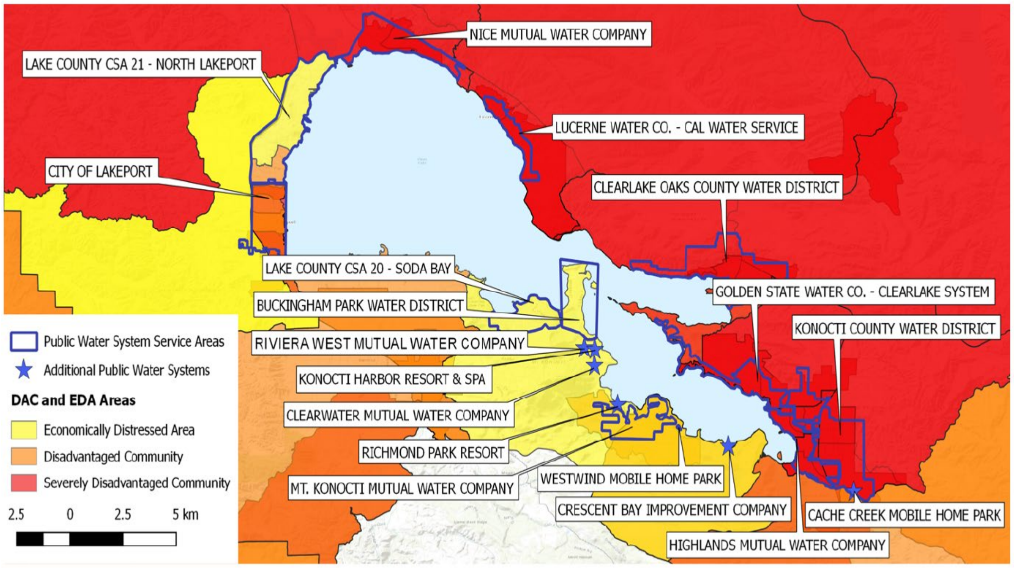


Figure 5: Economic Classifications of Communities in Lake County - used with permission from Corona Environmental Engineering

Table 6: Clear Lake Surface Water System Treatment Techniques

No.	System Name	Stage 1: Physical Treatment										Stage 2: Chemical Oxidation			Additional processes	
		Coagulation	Flocculation	Sedimentation	SC	DAF	Filtration	MF	DE	PAC	GAC	Pre- oxidation	AO	Disinfection	pH Adjustment	CC
1	Buckingham Park WD		X	X			X				X	X		X		
2	Clearwater MWC	X	X	X			X				X	X		X		
3	Clearlake Oaks County WD	X	X	X			X				X	X		X		X
4	Crescent Bay IC	X					X		X					X		
5	Golden State Water (Clear Lake)	X	X	X			X				X	X		X		X
6	Harbor View MWC	X	X			X	X				X	X		X	X	
7	Highlands MWC	X	X	X			X			X	X	X		X		X
8	Konocti County WD	X	X	X			X				X	X	X	X	X	X
9	Konocti Harbor Resort & Spa	X	X		X		X				X	X		X		
10	CSA 20 (Soda Bay)	X	X		X		X				X			X		
11	CSA 21 (N. Lakeport)	X	X		X		X				X	X		X		
12	City of Lakeport	X	X		X		X				X	X		X		
13	CA Water Service Co. (Lucerne)	X	X	X				X				X	X	X		X
14	Mt. Konocti MWC	X	X	X			X				X	X		X		X
15	Nice MWC	X	X	X			X				X	X		X		
16	Richmond Park Resort	X	X	X			X				X	X		X		
17	Westwind MHP	X	X	X	X		X					X		X		

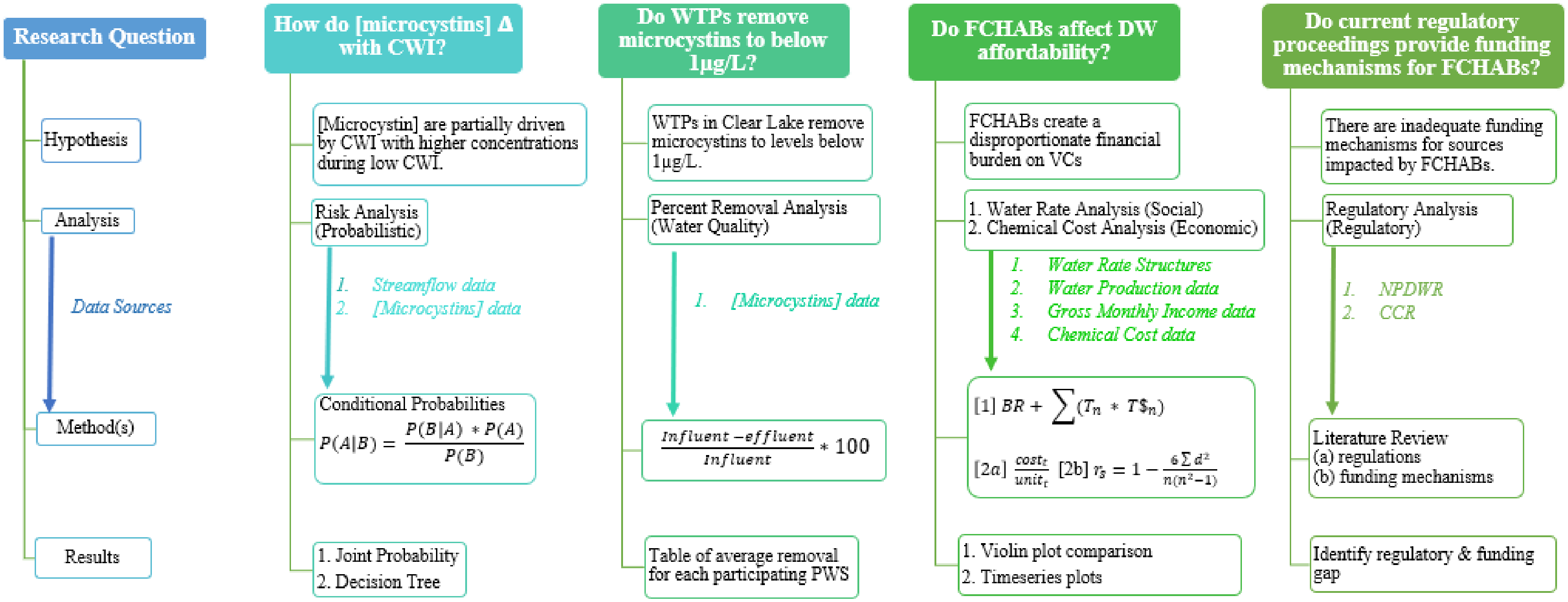
SC = Solids contactor, DAF = Dissolved Air Flotation, MF = Microfiltration, DE = Diatomaceous Earth, PAC = Powdered Activated Carbon, GAC = Granulated Activated Carbon, AO = Advanced Oxidation, CC = Corrosion Control, WD = Water District, MWC = Mutual Water Company, CSA = County Service Area, IC = Improvement Company, MHP = Mobile Home Park

Adding more processes to conventional water treatment, increases water treatment costs (Office of Operator Certification, 2020). Typical surface water treatment plants in California have a T2 classification, meaning that the operator must be certified as a T2 water treatment operator before operating the plant. In Clear Lake, most treatment plants are T3 and T4, indicating more chemical and physical processes to treat the source water and more highly skilled (T3 and T4) licensed operators can run these treatment plants. T3 and T4 operators are more difficult to find due to a general lack of T3 and T4 treatment plants nationwide and the rigorous testing of the California State Water Resources Control Board (SWRCB); operators with higher treatment licenses also require higher salaries. The limited financial resources in Lake County result in a high water treatment operator turnover rate.

Further exacerbating the impact of FCHABs in Clear Lake, the water utilities all manage their facilities separately, meaning that there are seventeen drinking water treatment facilities operating on the lake instead of one or two large water treatment facilities serving the entire region. The rate base of each small water system limits the system's ability to spread the cost of water treatment amongst economies of scale. Large water systems have a large rate base, which allows them to make significant infrastructure improvements on the order of a couple of cents per customer whereas smaller systems requiring the same infrastructure improvements are faced with a much steeper rate increase. The cost of robust treatment systems required for Clear Lake source waters is distributed across a small rate base, which is further exacerbated by the number of treatment plants in service, resulting in high water rates for the local communities.

4.0 Methods

Five distinct analyses are proposed to examine drinking water safety and affordability here. First, a risk analysis was developed to predict the concentration of microcystins based on cumulative winter inflows. Second, percent removal of microcystins was calculated using existing data from treatment facilities to determine if the surface water purveyors adequately remove microcystins concentrations from finished drinking water. Third, a water rate analysis was conducted to determine if disadvantaged communities treating FCHABs pay a disproportionate amount of their monthly income towards water bills. Fourth, an economic analysis was conducted to determine if the cost per unit of water changes in response to FCHABs. Fifth, a regulatory analysis was utilized to identify gaps in regulatory proceedings and funding as they relate to the management of FCHABs. See figure 6 for a diagram outlining the methods of the analyses herein.



Symbols:
[ ] = concentration
Δ = change
µg/L = micrograms per liter

Acronyms:
CWI = cumulative winter inflows
WTP - water treatment plant
FCHAB – freshwater cyanobacterial harmful algal bloom
O&M = operations & maintenance

Acronyms:
PWS – public water system
VC – vulnerable community
NPDWR – National Primary Drinking Water Regulations
CCR – California Code of Regulations

Figure 6: Diagram of Methods

4.1 Risk Analysis

Analytical microcystin concentration data from Kennedy Environmental consulting firm and inflow data from the California Data Exchange Center (CDEC) was used in this analysis. Tributaries used in this analysis include Kelsey Creek, Scott Creek, and Middle Creek. There are other significant tributaries into Clear Lake, but they lack streamflow gauges and are not reported in CDEC. Table 7 shows the station IDs. Bayes theorem (equation 2) was applied to the data to develop a risk analysis of microcystin concentrations from FCHAB events. It is expected that years with lower cumulative winter inflows (CWIs) will have higher microcystin concentrations with higher overall results in the Lower and Oaks Arm.

Table 7: California Data Exchange Center (CDEC) station codes

Station Code	Description	Data Type	Interval	Units
MCU	Middle Creek near Upper Lake	Inflow	15 mins	CFS
KCK	Kelsey Creek Below Kelseyville	Inflow	15 mins	CFS
SCS	Scott's Creek near Lakeport	Inflow	15 mins	CFS

$$[2] \quad P(A|B) = \frac{P(B|A) * P(A)}{P(B)}$$

Where A,B = events, P(A|B) = probability of A given B is true, P(B|A) = probability of B given A is true, P(A) = the independent probability of A, and P(B) = the independent probability of B.

Inflow data from the California Data Exchange Center (CDEC) was used to calculate cumulative winter inflows (October-May) from 2016 - 2020. A monthly streamflow time series was estimated in thousand acre feet (TAF). Monthly streamflow volume was summed for the months of October-December from the previous year and January-May from the year to be predicted. Table 8 shows the element wise calculation of each year. After calculating cumulative inflows, the years were grouped into categories ranging from 0-30 TAF, 31-75 TAF, and 76-120 TAF. The three inflow categories were selected based on the distribution of CWIs during the study period.

Table 8: Cumulative Winter Inflow Calculations

Year	Cumulative Winter Inflow
2016	$\sum(Oct - Dec\ 2015[TAF]) + \sum(Jan - May\ 2016[TAF])$
2017	$\sum(Oct - Dec\ 2016[TAF]) + \sum(Jan - May\ 2017[TAF])$
2018	$\sum(Oct - Dec\ 2017[TAF]) + \sum(Jan - May\ 2018[TAF])$
2019	$\sum(Oct - Dec\ 2018[TAF]) + \sum(Jan - May\ 2019[TAF])$
2020	$\sum(Oct - Dec\ 2019[TAF]) + \sum(Jan - May\ 2020[TAF])$

The available raw water microcystin concentration data was separated into two datasets. The first dataset contained raw water microcystin concentrations for water systems in the Upper Arm with a total of 84 sampling events. The second dataset consisted of raw water microcystin concentrations from the Lower and the Oaks Arm with a total of 190 sampling events. The concentrations were separated into four categories: 0-0.3µg/L, 0.31-0.7µg/L, 0.71-1.0µg/L, and >1.0µg/L. Concentration categories were selected based on the distribution of results during the time series. Results >1.0µg/L put healthy adults at risk of adverse health effects, therefore, this category was chosen to reflect hazardous toxin conditions. Conditional and joint probabilities of microcystin concentrations were calculated for each inflow category using equations 3 and 4, respectively.

$$[3]\ Conditional\ Probability\ = \frac{v\ [microcystin]\ |\ category}{\#\ of\ events\ in\ inflow\ category}$$

$$[4]\ Joint\ Probability\ = \frac{v\ [microcystin]\ category\ in\ inflow\ category}{total\ \#\ of\ events}$$

4.2 Microcystin Percent Removal Analysis

The data used in this analysis was collected by Kennedy Environmental consulting firm in conjunction with surface water suppliers in Lake County between June 2016 and December 2020 for a total of 247 paired sample events. Using these data, the average percent microcystin removal (equation 5) was calculated for each participating drinking water treatment plant that draws water from Clear Lake. The voluntary monitoring program consists of paired sample events; one sample from the intake that represents the raw (or influent) water quality, and another from the finished water after conventional treatment. Average percent removal for each treatment plant is based on the percent removal for each sample pair (influent and effluent) averaged over the number of samples collected for each system. The results from this calculation are used to assess if surface water systems in Lake County adequately remove microcystins concentrations to the World Health Organization (WHO) recommended guideline of 1µg/L. It is expected that the current treatment technologies adequately remove microcystins from finished drinking water supplies.

$$[5]\quad Percent\ Removal\ = \frac{influent\ -\ effluent}{effluent} * 100$$

4.3 Water Rate Analysis

For this analysis, the average percentage of gross monthly income (GMI) spent on water was used as a proxy for affordability of water. The California Department of Public Health guideline of 1.5% GMI was used as the recommended threshold for affordable water expenditures (“Water Rates: Water Affordability,” 2013). To illustrate the disproportionate financial burden of treating FCHABs in vulnerable communities (VCs), the average percentage of GMI devoted to water bills was calculated (using equation 6 and 7) for each surface water system that draws raw water from Clear Lake using actual cost and production data from 2018 annual reports. For comparison, the same analysis was repeated for 10 groundwater systems and 10 surface water systems that do not treat FCHABs. The results of this analysis show if VCs are disproportionately impacted by the costs of treating for FCHABs. It is expected that ratepayers in the Clear Lake watershed pay a significantly higher proportion of their monthly income towards water bills than the recommended guidelines of 1.5%. The comparison to other samples of similar water systems that do not treat FCHABs will likely show a disparity in the proportion of GMI devoted toward water bills for systems treating FCHABs.

$$[6] \quad Bill = base\ rate + (resource\ use * cost\ per\ unit\ of\ resource)$$

$$[7] \qquad \%\ of\ GMI = \frac{Average\ Monthly\ Bill}{GMI} * 100\%$$

To isolate the effect of FCHABs on water rates, each water system selected for comparison has a similar demographic and size characteristics as those in Clear Lake. The MHIs in Clear Lake range from \$28,888-\$44,813 with an average across all regions of \$41,556. The MHIs for the comparison ground and surface water systems range from \$26,368-\$53,703 with an average of \$41,443. Connection counts range from 25 - 2,500 for all three subsets of water systems. Therefore, economics of scale and economic classifications are comparable and the difference in average contributions is directly related to the cost of water treatment.

4.4 Chemical Cost Analysis

To assess if FCHABs significantly increase the cost of water treatment, proprietary cost data from four surface water systems in the Clear Lake watershed were used to calculate monthly water treatment chemical cost per unit of water over a five year period (2016-2020). The water systems evaluated in this analysis are the Golden State Water Company (Clear Lake System, Highlands Mutual Water Company, County Service Area 20), Soda Bay, and County Service Area 21(North Lakeport). The cost of chemicals was calculated by multiplying the pounds or gallons of chemicals used in a given month by the unit cost of the chemical (equation 8). To eliminate the influence that water demand has on the chemical cost, the total monthly chemical cost was divided by the finished water monthly production in thousand gallons (kgal) using equation 9. The monthly per unit cost of water treatment chemicals was plotted against finished water production, pH, and dosage to show the relationship between the cost per unit of water and FCHAB events that occur in the late summer.

$$[8] \quad Cost = (unit\ of\ chemical\ used) * (cost\ per\ unit)$$

$$[9] \quad \frac{cost}{unit} = \frac{cost\ (\$)_t}{monthly\ production\ (kgal)_t}$$

4.5 Regulatory Analysis

The regulatory analysis employed a literature review to identify gaps in regulatory proceedings and funding opportunities related to management of FCHABs. First, a review of the Safe Drinking Water Act’s (SDWA) National Primary Drinking Water Regulations (NPDWR) identified where the cyanotoxins relevant to this study (microcystins, cylindrospermopsin, anatoxins, and saxitoxins) are in the regulatory process and when Maximum Contaminant Levels (MCLs) are likely to be adopted. Second, non-enforceable regulatory guidelines and scholarly recommendations published throughout the world were compiled for the contaminants outlined in this study. Third, funding mechanisms in the United States and in California were identified that can be used to alleviate the disproportionate financial burden to drinking water systems in disadvantaged communities. Finally, the funding mechanisms currently in place were evaluated to assess if they address the needs of VCs treating for FCHABs.

4.6 Data Sources

Table 9 describes the data sources used for each analysis.

Table 9: Data Sources

Analysis	Data	Sources & Citations
Risk	Streamflow data	California Data Exchange Center (CDEC) (link) Station codes: MCU, KCK, SCS Date range: 1/1/2016-12/31/2020
	Microcystin concentrations	Kennedy Environmental*
Percent Removal		Kennedy Environmental*
Water Rate	Water Rate Structures	Annual reports* and water system websites: Golden State Water Company (Ahart, 2018)*Crescent Bay IC (Benson, 2018)*, Harbor View MWC (Fossa, 2018)*, Highlands MWC (Birdsey, 2018)*, Clearwater MWC (Reust, 2018)*, Buckingham Park WD (Wonderwheel, 2018)*, Clearlake Oaks WD (Larson, 2018)*, Konocti CWD (Parks, 2018)*, California Water Service - Lucerne (Moalem, 2018)*, CSA 20 - Soda Bay (Evans, 2018)*, CSA 21 - N. Lakeport (Evans 2018)*, Nice MWC (Fultz, 2018)*, City of Lakeport (Harris, 2018)*, Mt. Konocti MWC (Farr, 2018)*,Westwind MHP (Shields, 2018)*, Richmond Park Resort (Fultz, 2018)*, City of Rio Dell (link), City of Yreka (link), City of Shasta Lake (link), City of Brawley (link), City of Montague (link), Mountain Gate CSD (link), City of Calexico (link), City of El Centro (link), Weaverville CSD (link), Lake County CSA 2 - Spring Valley (link), Lake Shasta CSD (link), City of Alturas (link), City of Orland (link), California Pines CSD (link), Kelseyville CSD (link), City of McFarland (link), City of Crescent City (link), Smith River CSD (link), City of Kerman (link), City of Livingston (link), Upper Lake CSD (link)
Water Rate	Water Production	Annual reports* and California State Water Resources Control Board Water Conservation & Production Reports: Golden State Water Company (Ahart, 2018)*Crescent Bay IC (Benson,

		2018)*, Harbor View MWC (Fossa, 2018)*, Highlands MWC (Birdsey, 2018)*, Clearwater MWC (Reust, 2018)*, Buckingham Park WD (Wonderwheel, 2018)*, Clearlake Oaks WD (Larson, 2018)*, Konocti CWD (Parks, 2018)*, California Water Service - Lucerne (Moalem, 2018)*, CSA 20 - Soda Bay (Evans, 2018)*, CSA 21 - N. Lakeport (Evans 2018)*, Nice MWC (Fultz, 2018)*, City of Lakeport (Harris, 2018)*, Mt. Konocti MWC (Farr, 2018)*,Westwind MHP (Shields, 2018)*, Richmond Park Resort (Fultz, 2018)*, Water Conservation Portal (link)
Water Rate	Median Household Income	Data USA (link)
Chemical Cost	Chemical Costs	Water system invoices*
	Water Production	Operational records*
Regulatory	National regulations	National Primary Drinking Water Regulations (link)
	California regulations	California Code of Regulations (link)

* Proprietary data

5.0 Results

5.1 Risk Analysis

Two risk analyses were developed to estimate the relationship between microcystin concentrations and cumulative winter inflows (CWIs) - one for the Upper Arm and one for the Lower and Oaks Arm. The analyses were separated because historical data and feedback from water system managers show that the Lower and Oaks arm has more severe FCHAB events than the Upper Arm. A risk analysis for the entire lake would be inadequate because the probabilities of high microcystin concentrations would be overestimated for the Upper Arm and the probabilities of low microcystin concentrations would be overestimated in the Lower and Oaks Arm. Separating the risk analysis into two segments of the lake is the best way to predict microcystin concentrations in Clear Lake.

Figures 7 and 8 show the joint probabilities and a decision tree, respectively, as guidance for water managers for each inflow and microcystin concentration category. Figure 7 graphically represents each inflow category as it relates to the probabilities for microcystin concentrations. Assuming that all possible events are represented in the data collected, for all three categories of CWIs (0-30 TAF, 31-75 TAF, 76-120 TAF), there is a high probability that microcystin concentrations will be low (between 0-0.3µg/L) and all inflows above 30 TAF have a 0% probability for results above 0.71µg/L. CWIs between 0-30 TAF have an increased probability for high microcystin concentrations. The available data shows a 0% probability that microcystin concentrations will be between 0.31-0.7µg/L for inflows below 31 TAF, but the probabilities for higher microcystin concentrations increases in this CWI category. This indicates that most of the results in the Upper Arm of Clear Lake are below 0.31µg/L, however, as CWIs decrease, the probability for higher microcystin concentrations increases. High CWIs in the Upper Arm is almost always indicate low microcystin concentrations.

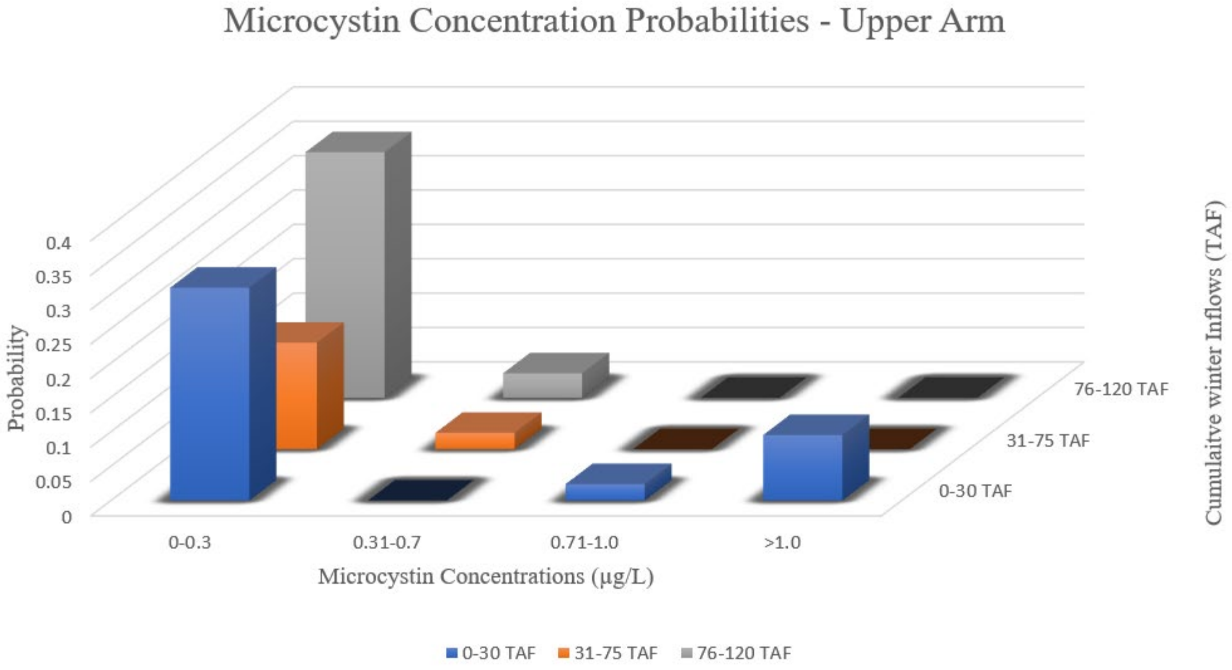


Figure 7: Microcystin concentration probabilities shown on 3D graph (Upper Arm)

Figure 8 is a contingent probability tree to estimate the probability of microcystin concentrations. This contingent probability tree will be most useful in May or June because the water system manager will have access to the CWI data in CDEC. The contingent probability tree starts with the categories of CWIs (0-30TAF, 31-75 TAF, 76-120 TAF). Once the manager determines which category of inflow the year falls into, they can evaluate the probability of microcystin concentrations for that year. The joint probability is included to show the overall probability of a microcystin concentration amongst all three categories of inflows.

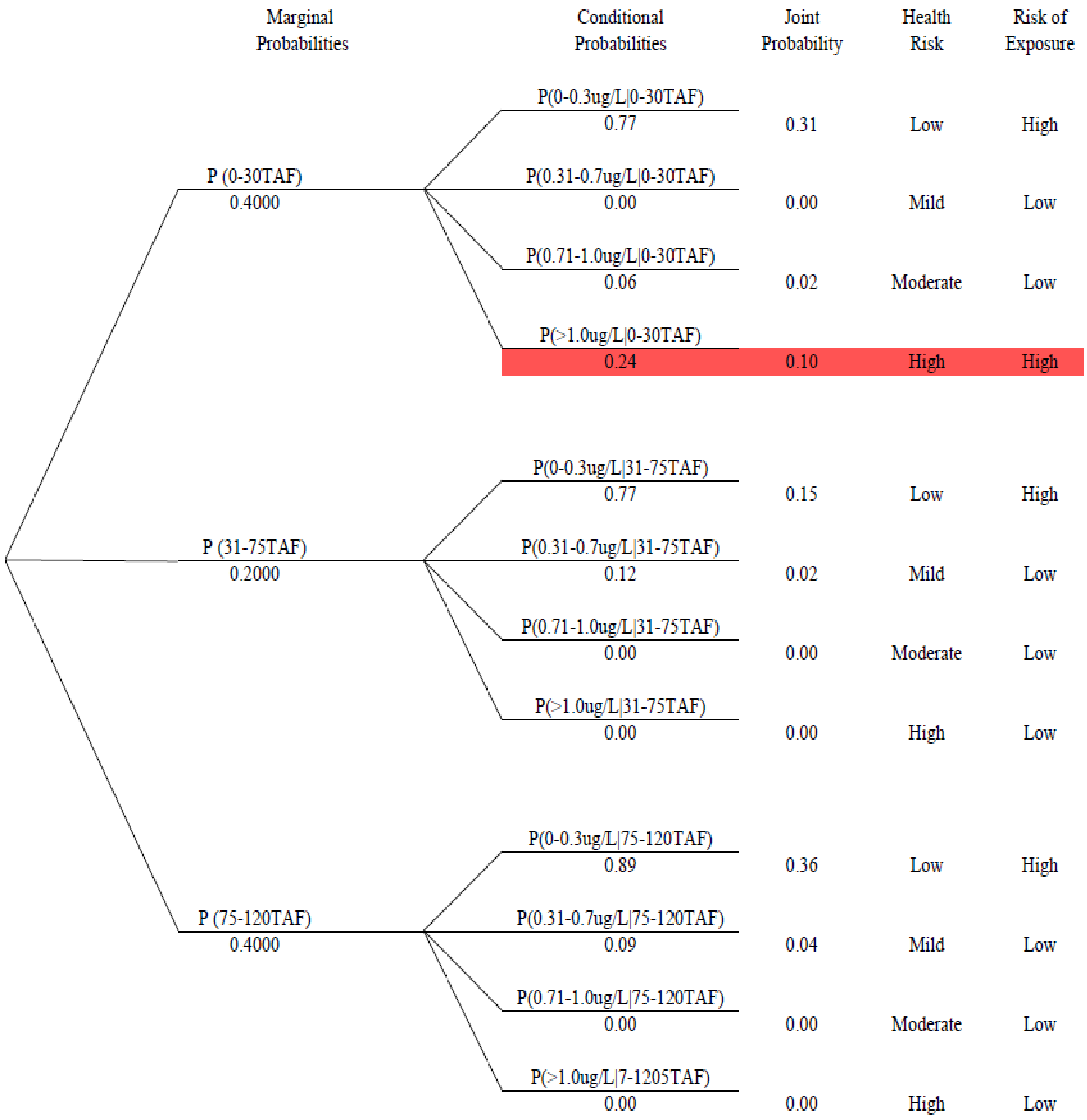


Figure 8: Contingent probability tree for water system managers in the Upper Arm

The results for the Clear Lake Lower and Oaks Arm risk analysis are summarized in Figures 9-10. Figure 9 is a graphical representation of each inflow category as they relate to the probabilities for microcystin concentrations. CWIs above 30 TAF (31-75 TAF and 76-120 TAF) have a high probability that microcystin concentrations will be low (0-0.3µg/L). These inflow categories have a sharp decline in probability for higher microcystin concentrations. CWIs between 0-30 TAF had a 29% probability that the microcystin concentration would be low (0-0.3µg/L), a 14% probability that microcystin concentrations will be between 0.3-0.7µg/L, a 16% probability that microcystin concentrations will be between 0.71-1.0µg/L, and a 54% probability that microcystin concentrations will be >1.0µg/L. These results are consistent with the understanding that the Lower and Oaks Arms undergo more severe FCHABs than the Upper Arm. The Lower and Oaks Arm of Clear Lake have a greater probability of high microcystin concentrations when CWIs are low than shown in the Upper Arm. However, both probability analyses show that microcystin concentrations are at least partially driven by low CWIs. Figure 10 shows the contingent probability tree that water managers in the Lower and Oaks arm can use to predict microcystin concentrations based on CWI.

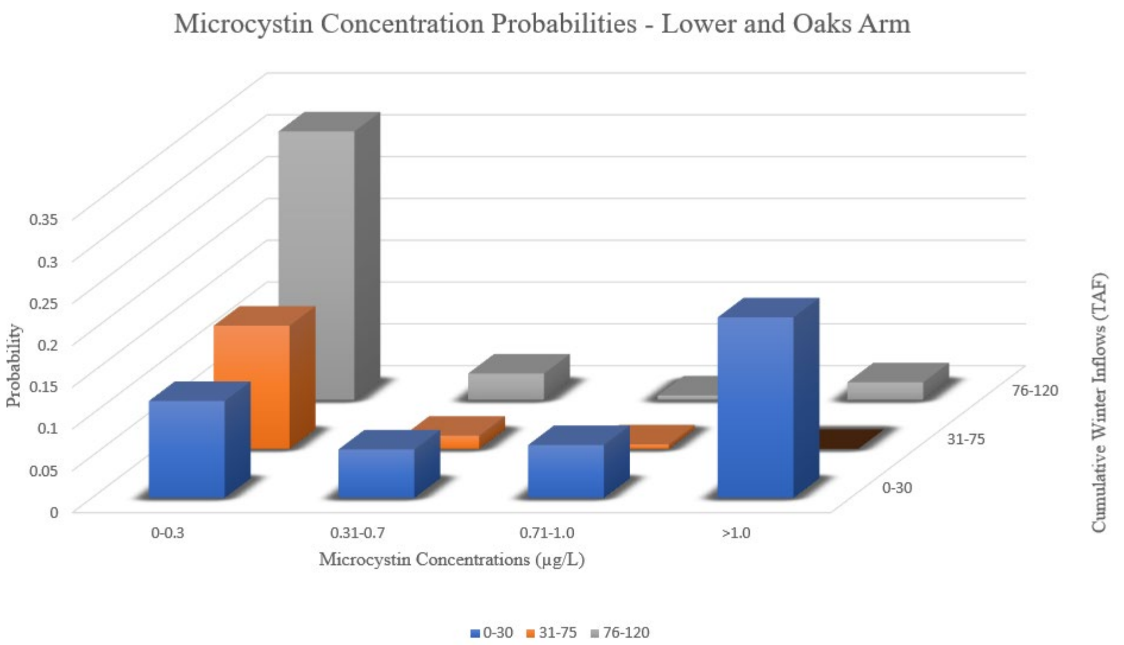


Figure 9: Microcystin concentration probabilities shown on 3D graph (Lower & Oaks Arm)

Figure 10: Contingent probability tree for water system managers in the Lower and Oaks Arm

5.2 Microcystin Removal Analysis

Of the seventeen water surface water utilities that draw from Clear Lake, thirteen participate, to varying extents, in the voluntary drinking water microcystins monitoring program administered through Kennedy Environmental. The Crescent Bay Improvement Company, Golden State Water – Clearlake System, Harbor View Mutual Water Company, and Konocti County Resort and Spa have not participated in the voluntary monitoring program. California Water Service – Lucerne, the City of Lakeport, Nice Mutual Water Company, Richmond Park Resort, and the Westwind Mobile Home Park has a limited data set due to varying rates of participation throughout the monitoring period. Table 10 shows participation in the voluntary monitoring program. The percent removal calculations for utilities with more sample events are likely to represent true values whereas utilities with less than 10 sample events may not fully capture the true percent removal capacity of their treatment facilities. More data are needed to validate the values for utilities with smaller sample sizes. Percent removal calculations were completed for 247 paired sample events taken between 2016-2020.

Table 10: Water System Participation in Voluntary Monitoring Program

PWSID	PWS	No of Sampling Events
CA1710001	Clearlake Oaks County WD	36
CA1710011	Buckingham Park WD	35
CA1710003	Highlands MWC	32
CA1710022	Lake County CSA 20 - Soda Bay	32
CA1710006	Konocti County WD	31
CA1710021	Lake County CSA 21 - North Lakeport	31
CA1700546	Clearwater MWC	21
CA1710014	Mt Konocti MWC	17
CA1710008	Nice Water Company	6
CA1710004	City of Lakeport	3
CA1700603	Richmond Park Resort	1
CA1700584	Westwind Mobile Home Park	1
CA1710005	California Water Service - Lucerne	1
CA1700519	Crescent Bay Improvement Company	0
CA1710002	Golden State Water – Clearlake System	0
CA1700568	Harbor View Mutual Water Company	0
Total		247

Results of the microcystins percent removal calculations are shown in Table 11. There is a significant data constraint for the water systems collecting less than 10 samples. For this reason, participating water systems with less than 10 sample events are presented here to show that limited data is available for these systems. Of the systems with 10 or more sample events, the highest rate of removal was found in Clearlake Oaks County Water District with an average percent removal of 85.2%. The lowest percent removal was in the Lake County Service Area (CSA) 20 – Soda Bay with an average percent removal of 71.1%. Average percent removal among the entire sample set is 78.5% while the average percent removal amongst the systems with 10 or more sample sets is 80.6%. The highest detection (31.3 µg/L) was found in the Oaks Arm of Clear Lake at the Clearlake Oaks County Water District's intake on October 30, 2020. All finished water samples in this analysis were below the WHO recommended guideline for microcystins of 1 µg/L. So based on the available data, the treatment mechanisms currently employed adequately remove microcystins to levels that are not known to cause acute or chronic health effects. However, more sample points are needed for the systems with less than 10 sample events. No conclusions can be drawn for systems not participating in the voluntary monitoring.

Table 11: Microcystins Percent Removal Calculations in Lake County

PWSID	PWS	No of Events	[Microcystin] raw, µg/L	[Microcystin] Finished, µg/L	Average % removal
CA1710001	Clearlake Oaks County WD	36	ND[3] - 31.3	ND - 0.2	85.2
CA1710011	Buckingham Park WD	35	ND - 11.3	ND - 0.2	83.9
CA1710003	Highlands MWC	32	ND - 29.3	ND - 0.2	80.6
CA1710022	Lake County CSA 20 - Soda Bay	32	ND - 3.5	ND - 0.2	71.1
CA1710006	Konocti County WD	31	ND - 25	ND - 0.2	81.2
CA1710021	Lake County CSA 21 - North Lakeport	31	ND - 4.1	ND - 0.2	78.8
CA1700546	Clearwater MWC	21	ND - 5	ND - 0.7	83.2
CA1710014	Mt Konocti MWC	17	ND - 11	ND - 0.1	80.8
CA1710008	*Nice Water Company*	*6*	*0.1 - 2.3*	*ND - 0.5*	*87.9*
CA1710004	*City of Lakeport*	*3*	*ND - 0.2*	*ND*	*100.0*
CA1700603	*Richmond Park Resort*	*1*	*0.5*	*0.1*	*84.5*
CA1700584	*Westwind Mobile Home Park*	*1*	*0.3*	*0.1*	*63.5*
CA1710005	*California Water Service - Lucerne*	*1*	*0.4*	*0.2*	*40.0*

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[3] Non-Detect. The concentration of contaminant, if present, is lower than the laboratory's method detection limit (MDL).

5.3 Water Rate Analysis

To determine the average water bill for each surface water utility in Lake County, the author gathered data for water rates, connection count[4], and annual production data[5]. First, the average monthly water use was calculated by dividing annual production data by the connection count and divided by twelve (see equation 10) [6]. To find the average water bill, the rate structures were applied to the average monthly water use. Using the rate structure rules for each water district, equation 11 was used to calculate the average water bills for each district.

$$[10]\ Average\ monthly\ water\ use\ =\frac{annual\ production\ (gal)}{Connection\ count}*\frac{1\ year}{12\ months}$$

$$[11]\quad Average\ Water\ Bill\ =\ BR\ +\ (T1*T1\$)\ +\ (T2*T2\$)\ +\ (T3*T3\$)$$

where, BR = Base Rate, T1 = Volume used in Tier 1, T2 = Volume used in Tier 2, T3 = Volume used in Tier 3, T1$ = price of Tier 1, T2$ = price of Tier 2, T3$ = price of Tier 3.

For example, Buckingham Park Water District charges a base rate of $55.19. If customers use 0 gallons of water during the month, their water bill will be $55.19. Included in the base rate price are service fees, employee salaries, operating costs, capital improvement and reserve funds. If the customer uses water during the billing month, the following rules apply: (1) between 0-10 hundred cubic feet (HCF), the customer is charged $2.41 per HCF; (2) between 11-15 HCF, the customer is charged $4.64 for every HCF over 10 HCF; (3) water use that exceeds 15 HCF is charged $6.39 per additional HCF (Wonderwheel, 2018). Buckingham Park Water District has a 2018 average water use of 10.35 HCF (7,743 gal), therefore, the customer's average water bill is $55.19 + (10HCF * $2.41) + (0.35HCF *$4.64) + (0HCF * $6.39)= $97.92.

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[4] Connection count is the number of drinking water services in the water system or the point of entry for potable water unto the unit. Each single-family residential unit has one meter, which serves as the connection count. Multi-family residential meters may have one meter/complex.

[5] The total volume of treated water provided to customers in a given calendar year, expressed in gallons.

[6] We did not account for variability in water use with seasonality because our goal was to find the overall average water bill amount.

Average water bill data were compared to regional median household income (MHI) data. The median annual household income was divided by 12 to find the average gross monthly income (GMI). The average water bill was divided by the monthly GMI and multiplied by 100% to find the overall percentage of gross income dedicated to paying water bills (see equation 12). For example, Buckingham Park's median household income is $32,463. The average monthly GMI is $32,463/12 = $2,705. To find the average percentage of gross monthly income devoted to water bills in Buckingham Park, $97.92 was divided by $2,705 and multiplied by 100%, which equals 3.62%.

$$[12] \qquad \%\, of\ monthly\ GMI\ = \frac{Average\ Monthly\ Water\ Bill}{monthly\ GMI} * 100\%$$

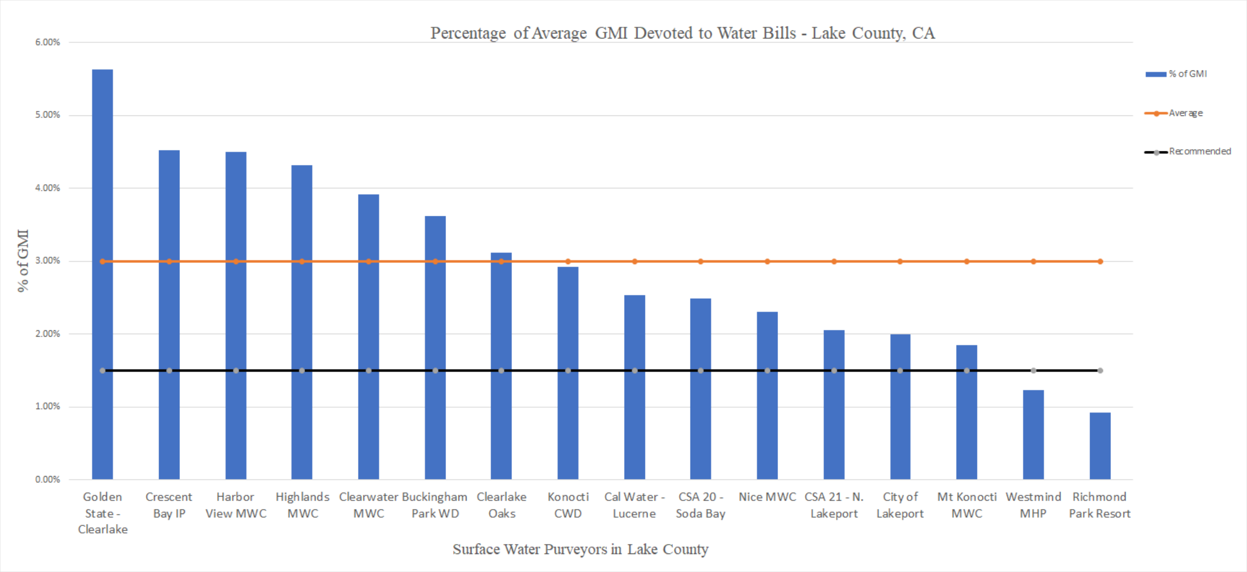
Surface water utilities in Lake County contribute an average of 3.0% of their gross monthly income (GMI) to water bills, which is double the recommended level of 1.5%. The highest percentage of income devoted to utility bills is in Golden State Water's Clearlake System (5.6%). The lowest percentage is in Richmond Park Resort (0.9%), however, the data for Richmond Park Resort is an outlier. Richmond Park Resort consists of a waterfront restaurant and 30 RV hook-ups. All utilities exceed the recommended percentage (1.5%) issued by the California Department of Public Health for water affordability except Richmond Park Resort and the Westwind Mobile Home Park ("Water Rates: Water Affordability," 2013). The average for surface water purveyors in Lake County is double (1.5% higher than) the recommended level.

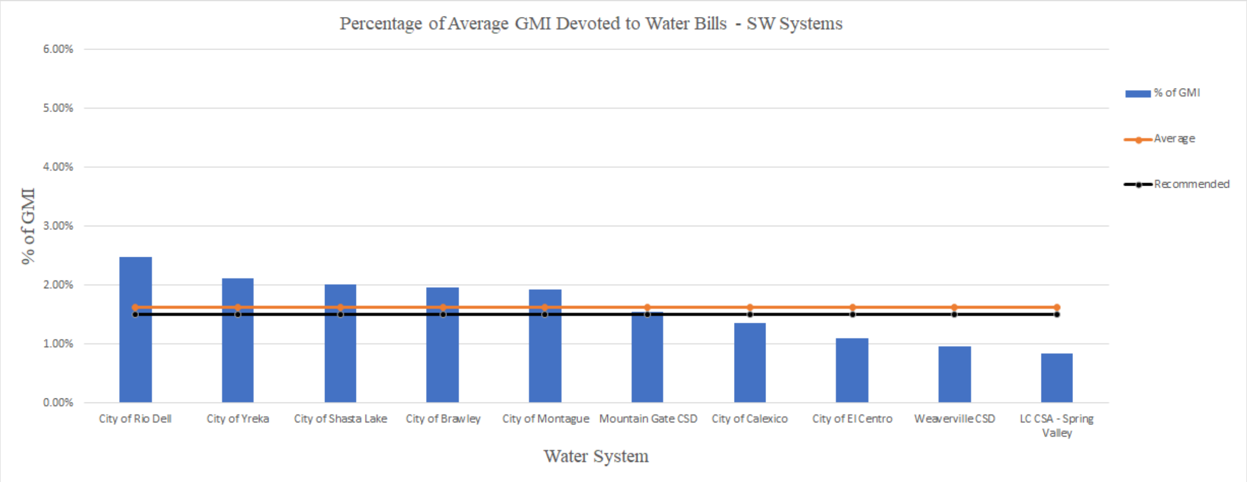
The subset of surface water systems chosen for comparison include: (1) the City of Rio Dell; (2) the City of Yreka; (3) the City of Shasta Lake; (4) the City of Brawley; (5) the City of Montague; (6) Mountain Gate Community Services District; (7) the City of Calexico; (8) the City of El Centro; (9) Weaverville Community Services District; and (10) Lake County Service

Area - Spring Valley. None of the selected surface water systems draw raw water from sources that are impacted by FCHABs. The surface water systems selected for comparison contributed an average of 1.63% of their gross monthly income to water bills, which is 0.13% above the recommended level. The highest percentage is the City of Rio Dell (2.5%) and the lowest percentage is in the Lake County Service Area - Spring Valley (0.8%). The Lake County Service Area - Spring Valley draws water from Wolf Creek, which is not tributary to Clear Lake.

The subset of groundwater systems chosen for comparison include: (1) Lake Shasta Community Services District; (2) Alturas; (3) Orland; (4) California Pines Community Services District; (5) Kelseyville County Water District; (6) City of McFarland; (7) Crescent City; (8) Smith River Community Services District; (9) Kerman; (10) Livingston; and (11) Upper Lake County Water District. The groundwater systems selected contributed an average of 1.5% of their gross monthly income to water bills, which equal to the recommended level. The highest percentage is the Lake Shasta Community Services District (2.4%) and the lowest percentage is in the Upper Lane County Water District (1.0%).

Figure 11 shows the percentage of GMI devoted to water bills in Lake County, comparable surface water systems that do not treat FCHABs, and comparable groundwater systems. Figure 12 shows the same results presented on a violin plot. It shows the distribution of results in each set and their relation to the recommended GMI contribution. surface water systems in Lake County range from 0.9%-5.6% with both clusters above the recommended GMI contribution. Comparable surface water systems range from 0.8%-2.5% with one cluster below the recommended GMI contribution and a larger cluster slightly above the recommended GMI contribution. Comparable groundwater systems ranged from 1.0%-2.4% with the largest cluster below the recommended GMI contribution.





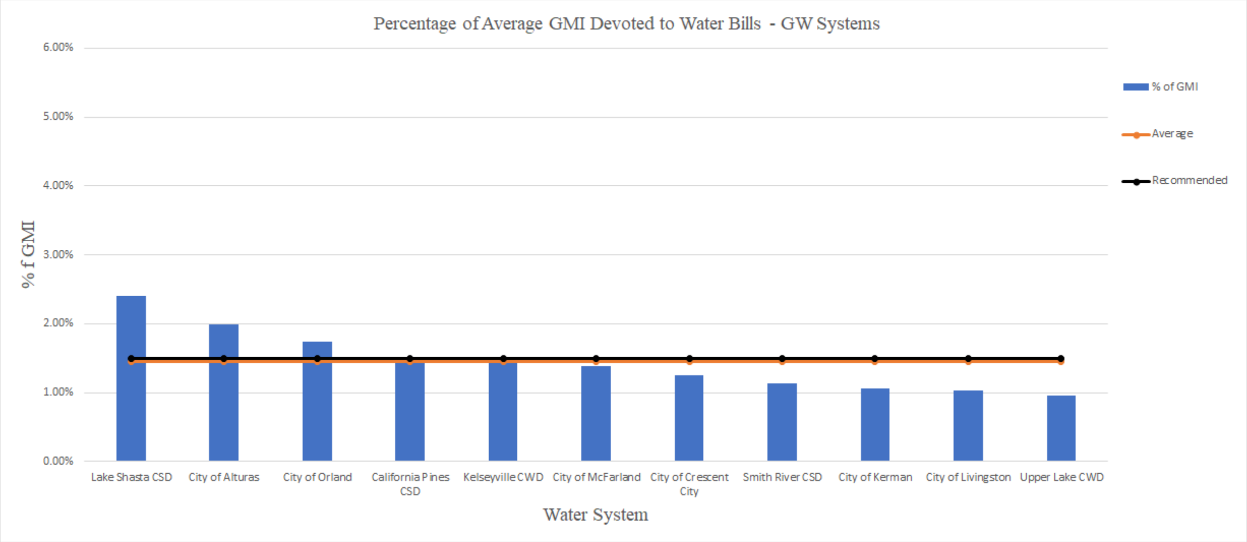
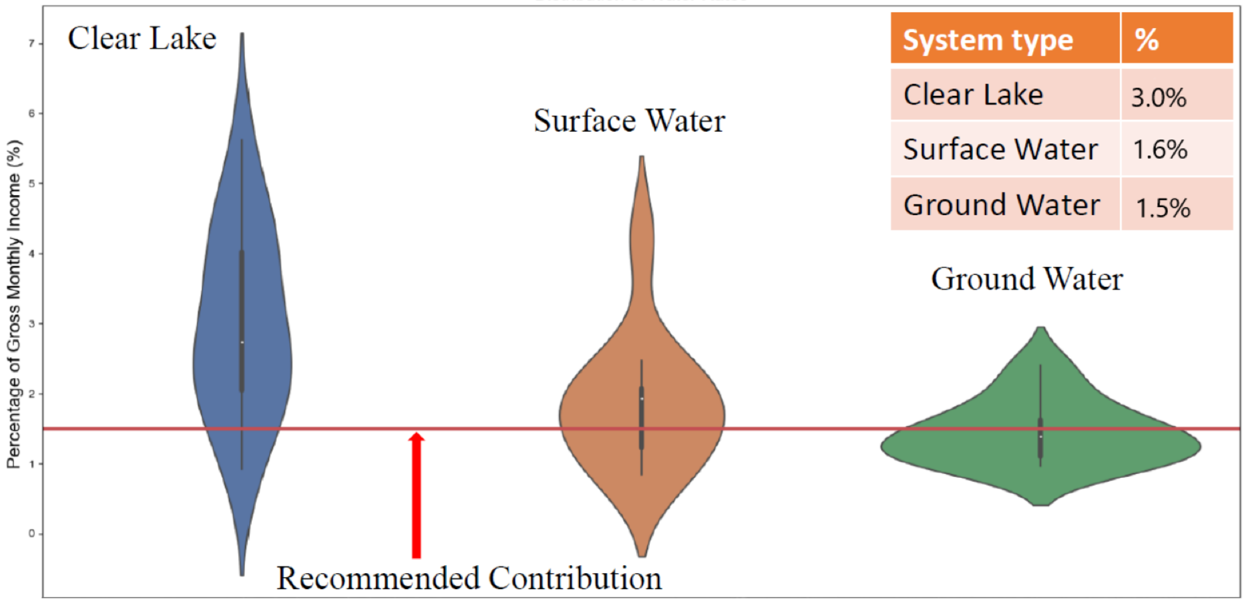


Figure 11: Percentage of Average GMI Devoted to Water Bills



System type	%
Clear Lake	3.0%
Surface Water	1.6%
Ground Water	1.5%

Figure 12: Percentage of household GMI distributed among three sets of water systems

Sources for Figure 11 and 12: Shields, 2018; Moalem, 2018; Benson, 2018; Wonderwheel, 2018; Harris, 2018; Larson 2018; Reust, 2018; Bensen, 2018; Rinde, 2018; Fossa, 2018; Birdsey, 2018; Parks, 2018; Evans 2018; Ahart, 2018; Farr, 2018; Fultz, 2018; Fultz, 2018; Craig, 2018; Water Conservation and Production Reports, 2016; Del Norte Local Agency Formation Commission, 2018; City of Alturas, 2015; California Pines CSD, 2020; Spring Valley, 2020; City of Calexico, 2018; City of Brawley, 2015; City of El Centro, 2020; Mountain Gate CSD, 2019; City of Shasta Lake, 2019; City of Yreka, 2008; City of Montague, 2017; Weaverville CSD, 2020; Shasta CSD, 2021; City of Orland, 2021; Kelseyville CWD, 2003; City of McFarland, 2021; City of Crescent City, 2021; City of Kerman, 2021; City of Livingston, 2018; Upper Lake CWD, 2021; City of Rio Dell, 2021

5.4 Chemical Cost Analysis

Table 12 lists the surface water systems evaluated in this analysis, their water treatment chemicals, intended use, and price per unit. Daily chemical dosages were converted to pounds with equation 13. Sodium hypochlorite is priced per gallon instead of per pound. Sodium hypochlorite has a specific gravity of 1.21, therefore, the pounds of sodium hypochlorite used was divided by the weight of a gallon of water (8.34lbs) multiplied by the specific gravity of sodium hypochlorite to obtain the value in gallons (see equation 14). Once each individual chemical cost was determined, they were added together to get a total chemical cost for the month. Water demand increases in the summer, therefore, the total cost to treat water also increases in the summer by virtue of demand. To eliminate the influence that water demand has on chemical costs of water treatment, the total monthly chemical cost was divided by the finished water production in that month. Production was reported in thousand gallons (kgal), so the resulting value is the monthly chemical cost per thousand gallons (see equation 15).

$$[13]\ lbs\ of\ chemical\ used\ =\ MG\ *\ 8.34\frac{lbs}{gal} * dosage\ (mg/L)\ *\ \%\ strength$$

where MG = million gallons produced (daily), 8.34 = the weight of a gallon of water, dosage monitored daily in milligrams per liter, % strength = chemical solution strength expressed in decimal form

$$[14]\ Gallons\ =\ \frac{lbs}{8.34lbs\ *\ specific\ gravity}$$

$$[15]\quad \frac{monthly\ chemical\ cost}{kgal} = \frac{\sum_{t=1}^{N}\ (chem\ 1)_t * (\$\ chem\ 1) + \ldots + (chem\ x)_t * (\$\ chem\ x)_t}{Production\ (kgal)}$$

Table 12: Chemicals Used, Purpose, and Cost per Unit

PWS	Parameter	Purpose	Chemical cost
Golden State Water Company - Clear Lake System	Aluminum chlorohydrate (primary coagulant)	Coagulation, flocculation, sedimentation	$0.42/lb
	Coagulant aid	Coagulation, flocculation, sedimentation	$1.22/lb
	Filter Aid	Aid in particle removal during filtration	$1.22/lb
	Potassium permanganate	Oxidation of organics	$2.80/lb
	Sodium hypochlorite	Disinfectant	$1.49/gal
	Zinc orthophosphate	Corrosion inhibitor	$1.18/lb
Highlands Mutual Water Company	Aluminum chlorohydrate (primary coagulant)	Coagulation, flocculation, sedimentation	$0.42/lb
	Potassium permanganate	Oxidation of organics	$2.80/lb
	Sodium Hypochlorite	Disinfectant	$1.49/gal
	Zinc orthophosphate	Corrosion inhibitor	$1.18/lb
CSA 20 - Soda Bay	Aluminum chlorohydrate (primary coagulant)	Coagulation, flocculation, sedimentation	$0.74/lb
	Coagulant aid	Coagulation, flocculation, sedimentation	$1.22/lb
	Sodium hypochlorite	Disinfectant	$1.49/gal
CSA 21 - North Lakeport	Aluminum chlorohydrate (primary coagulant)	Coagulation, flocculation, sedimentation	$0.74/lb
	Coagulant aid	Coagulation, flocculation, sedimentation	$1.22/lb
	Filter Aid	Aid in particle removal during filtration	$1.22/lb
	Potassium aluminum sulfate (alum)	Promotes coagulation	$1.80/gal
	Sodium Hypochlorite	Disinfectant	$1.49/gal

All water systems evaluated had significant increases in the cost per unit of water produced during months with seasonal FCHABs. Figures 13-16 show the relationship between the cost per thousand gallons (kgal) and production data over five years for the four water systems evaluated in this analysis. The production data shows seasonality because demand for water increases in the summer months and decreases during the winter months. The Golden State

Water Company - Clear Lake System had a winter cost of production between \$0.05-\$0.12 per kgal and a summer month cost of production between \$0.17-\$0.23 per kgal, which is an increase of up to four times between the winter and summer months. The Highlands Mutual Water Company had a winter cost of production between \$0.08-\$0.11 and a summer month cost of production between \$0.15-\$0.25, which is also an increase of up to four times between the winter and summer months. Highlands Mutual Water Company has a relatively constant cost per unit of water produced in 2019. Pam Sentelle, Water Treatment Operator at Highlands Mutual Water Company, expressed that treatment controls sat dormant in 2019 due to staff turnover. All other peaks and valleys align with seasonality.

The County Service Areas evaluated in this study had a less clear relationship between the unit cost of water treatment and production which is likely due to ozone treatment in these systems. Advanced oxidation technologies like ozone significantly increase the cost of electricity but does not involve a chemical addition. Its powerful oxidation decreases the amount of chemicals needed to attain water quality goals. Electricity use was not captured in this analysis, so including the costs for advanced oxidation processes in the County Service Areas would give a more accurate relationship between the cost of water treatment and production. The County Service Area 20 - Soda Bay had a winter cost of production between \$0.03-\$0.05 and a summer month cost of production between \$0.07-\$0.20. The County Service Area 21 - North Lakeport had a winter cost of production between \$0.02-\$0.08 and a summer month cost of production between \$0.11-\$0.20. Both County Service Areas have a general trend of increasing costs during the summer months, but ozone decreases the dependence on chemical additives, resulting in a less clear relationship.

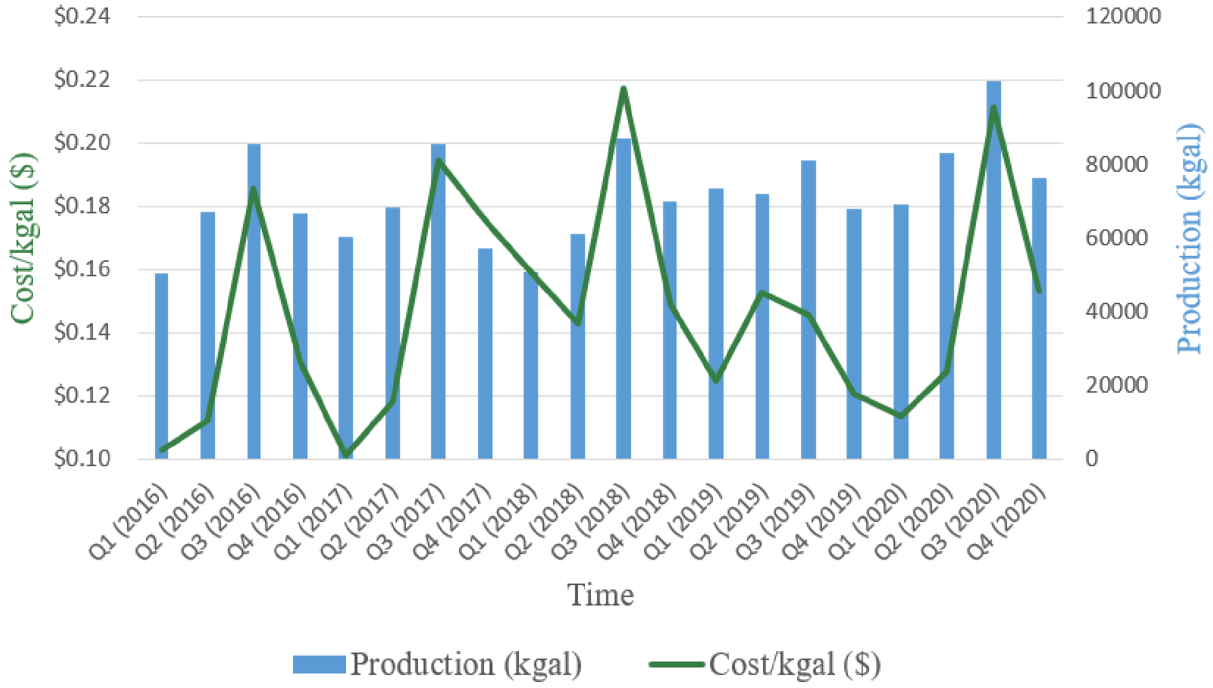


Figure 13: Chemical Cost per Thousand Gallons vs Production - Golden State Water Company (Clear Lake System)

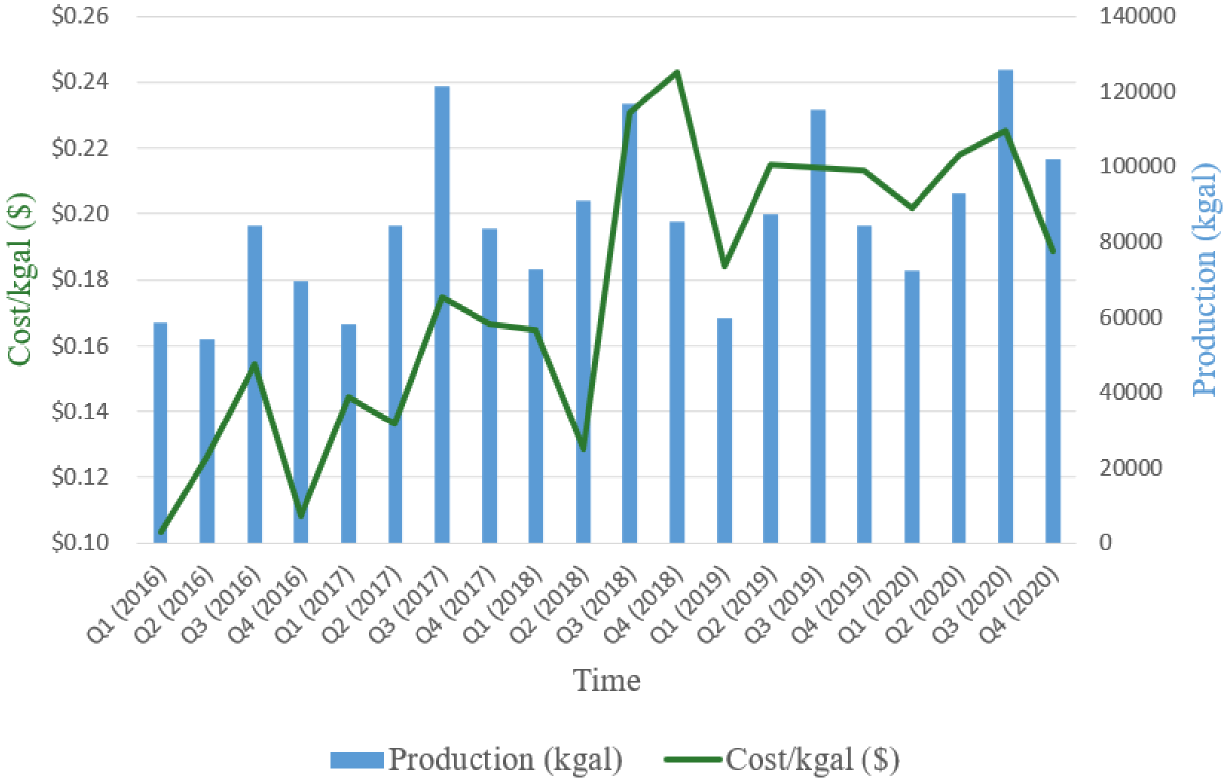


Figure 14: Chemical Cost per Thousand Gallons vs Production - Highlands Mutual Water Company

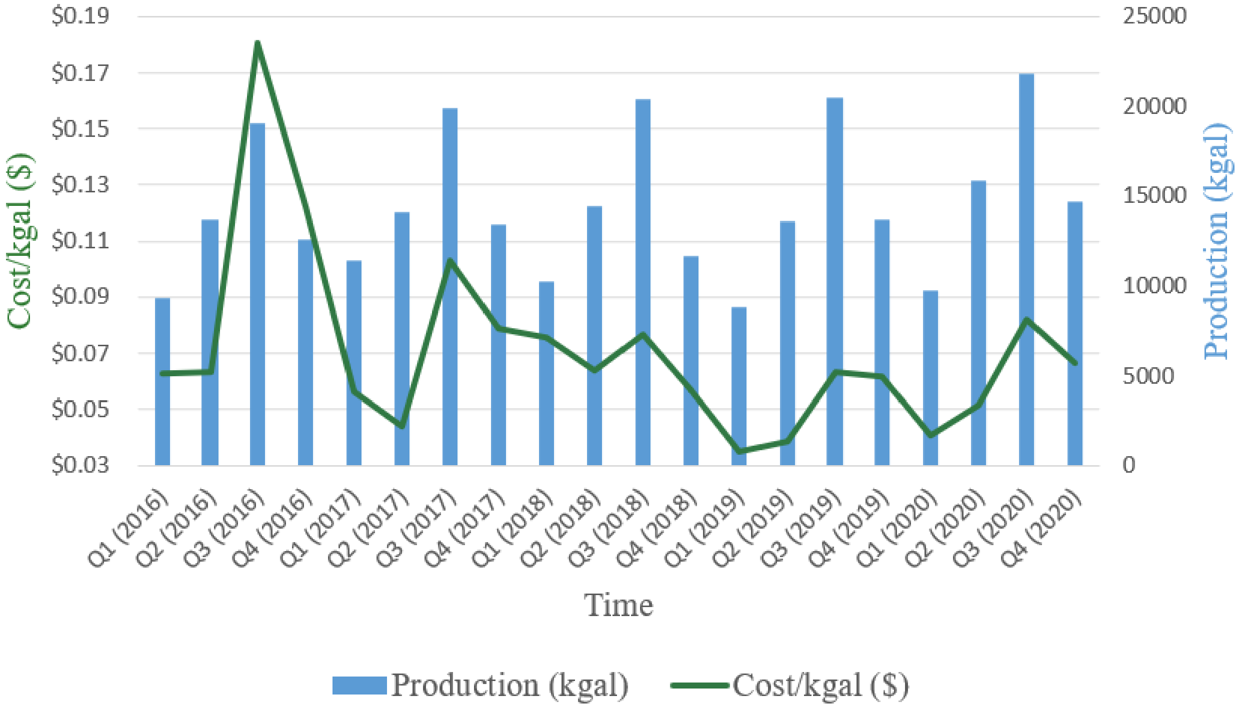


Figure 15: Chemical Cost per Thousand Gallons vs Production - County Service Area 20 (Soda Bay)

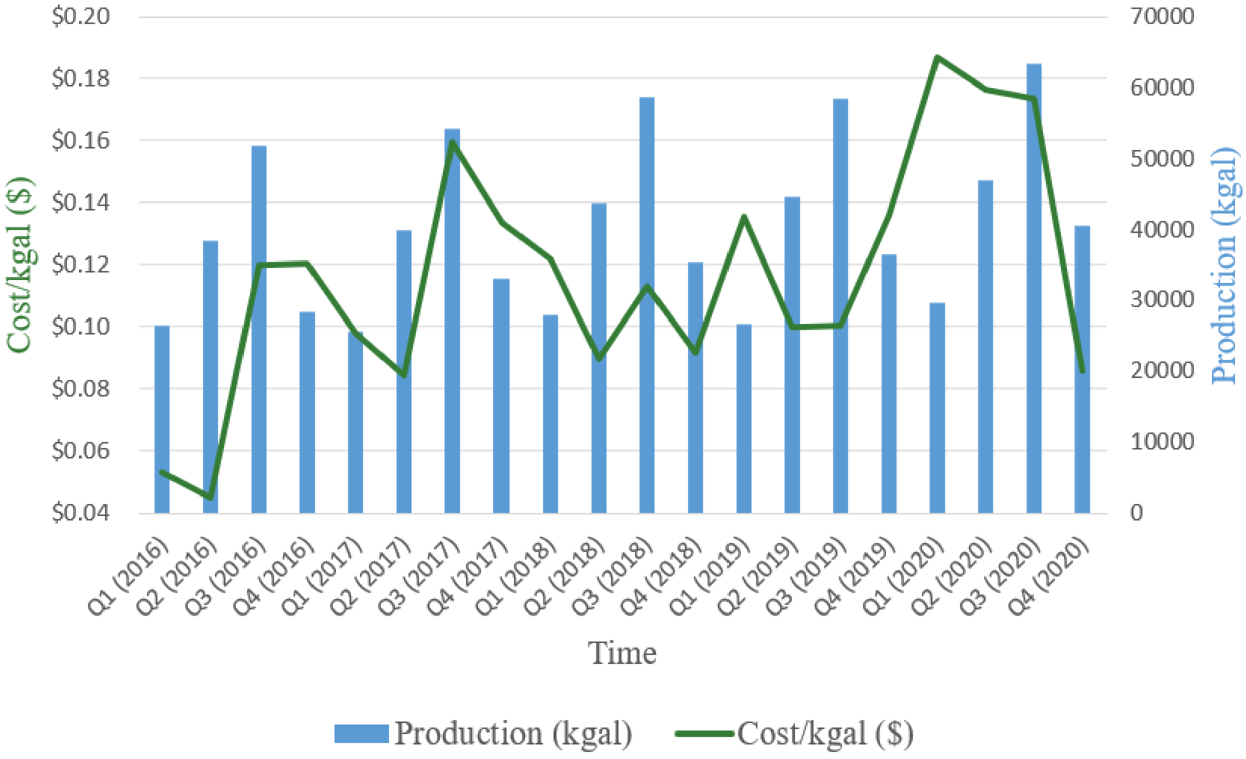


Figure 16: Chemical Cost per Thousand Gallons vs Production - County Service Area 21 (N. Lakeport)

Raw water pH was used to indicate excessive algal growth due to the significant increases in pH from FCHAB events. Many biological and chemical processes occur during FCHAB events; the ability to choose a single parameter as a proxy for FCHAB events is constrained by available data. The best parameters used to monitor FCHAB concentrations are toxin concentrations. Lake County's toxin data are sparse and cannot reliably show FCHABs on a daily timescale. In addition, the absence of microcystins does not indicate the absence of an FCHAB, only that the sample did not contain toxins. In the absence of comprehensive monitoring of toxins, chlorophyll-a measurements can be used as an indicator for algal biomass. However, due to inconsistent funding for sample analysis, the Lake County Department of Water Resources has little chlorophyll-a concentration data. To make a clear connection between the monthly cost of water treatment and chlorophyll-a concentrations, access to monthly chlorophyll-a concentrations must be available. The large data gaps may not account for significant changes in chlorophyll-a concentrations. Turbidity and pH were also evaluated as a proxy for FCHABs. Turbidity monitoring did not prove to be a reliable indicator because winter inflows result in turbidity peaks, but are not associated with bloom events. pH, which indicates water chemistry changes that accompany FCHAB events, proved to be the most reliable proxy for FCHAB events in this analysis.

To demonstrate that the cost of water treatment increases with increasing pH, the cost per unit of water produced was plotted against raw water pH for each water system (see Figures 17-20). There is a clear direct relationship between the cost per unit of water produced and raw water pH for all water systems evaluated in this analysis. As pH rises, as it does when FCHABs are present, the cost of water treatment increases. Increases in pH decreases the effectiveness of coagulation, therefore, the coagulant dose has to be increased significantly during the summer months to force the coagulation reaction to happen. Figures 21-24 show the relationship between coagulant dose and production. The coagulant dose increases significantly during the summer to overcome changes in raw water pH for all water systems evaluated in this analysis. The hypothesis for this analysis was that the cost per unit of water produced increases in response to FCHAB events. The results confirm this hypothesis.

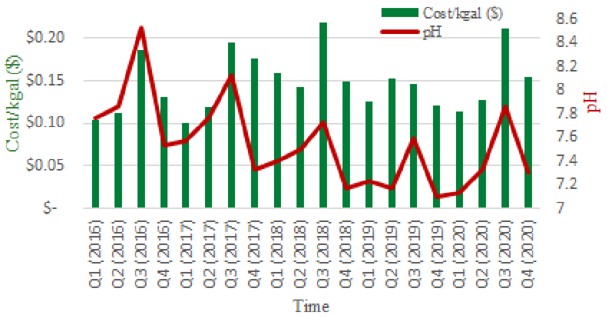


Figure 17: Chemical Cost/kgal vs pH: Golden State Water Company (Clear Lake)

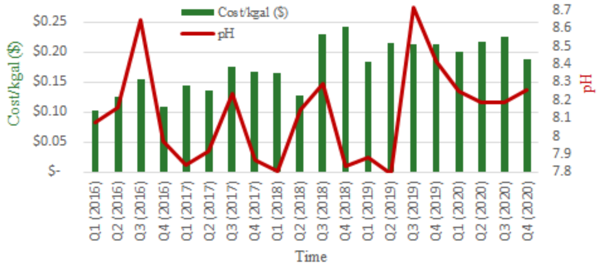


Figure 18: Chemical Cost/kgal vs pH: Highlands MWC

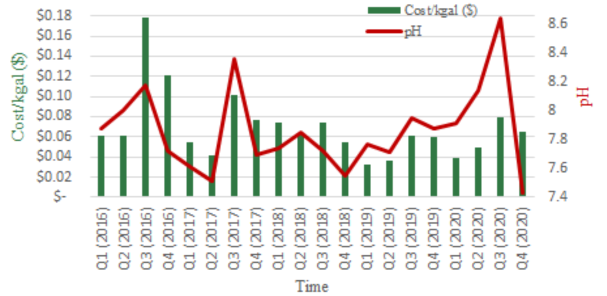


Figure 19: Chemical Cost/kgal vs pH: Soda Bay

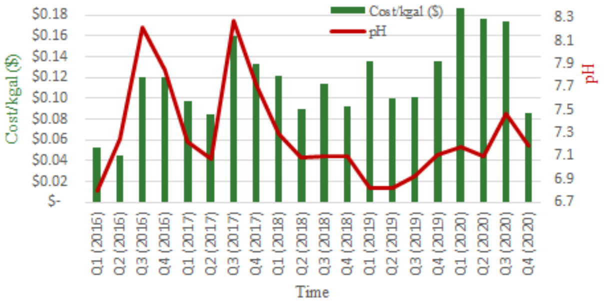


Figure 20: Chemical Cost/kgal vs pH: N. Lakeport

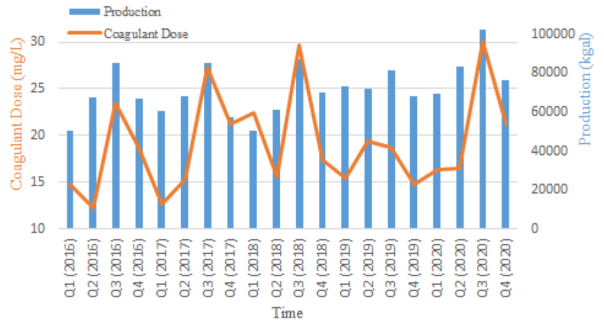


Figure 21: Coagulant Dose vs Production: Golden State Water Company (Clear Lake)

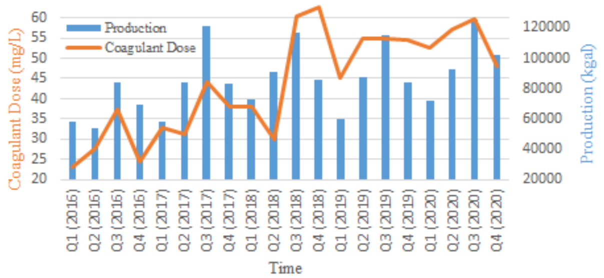


Figure 22: Coagulant Dose vs Production: Highlands MWC

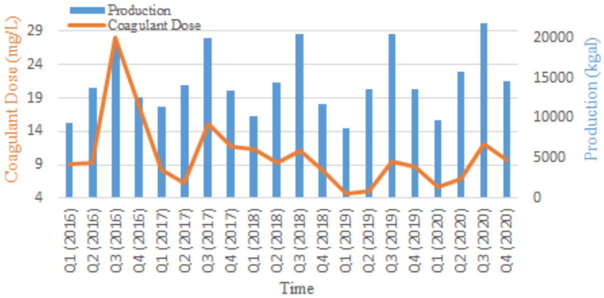


Figure 23: Coagulant Dose vs Production: Soda Bay

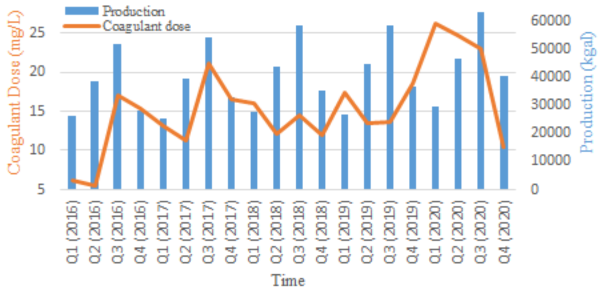


Figure 24: Coagulant Dose vs Production: N. Lakeport

5.5 Regulatory Analysis

Although cyanotoxins are not currently regulated under the Safe Drinking Water Act (SDWA), Maximum Contaminant Levels (MCLs) for several species of cyanotoxins will likely be adopted in the future. Every five years, the United States Environmental Protection Agency (USEPA) publishes a Contaminant Candidate List (CCL) that outlines potentially harmful contaminants that are likely to be present in drinking water supplies throughout the United States. Once the CCL is finalized, the USEPA requires water systems to monitor for a suite of unregulated contaminants under the Unregulated Contaminant Monitoring Rule (UCMR). The USEPA evaluates the results to determine how widespread unregulated contaminants are in drinking water supplies. If a contaminant is both harmful and widespread, the USEPA will determine if an MCL should be adopted. CCL 1 and CCL 2 included cyanotoxins generally, but they were not speciated. CCL 3, published in 2009, included three cyanotoxins: Anatoxin-a, Microcystin-LR, and Cylindrospermopsin. Preliminary determinations for CCL 4 were published in February 2020; they include: Anatoxin-a, Cylindrospermopsin, Microcystins, and Saxitoxins. If a contaminant on the CCL does not undergo the MCL rulemaking process, it will roll over into the next CCL, which is why Anatoxin-a, Microcystin-LR, and Cylindrospermopsin are listed in both CCL 3 and CCL 4 (USEPA CCL, 2020).

Contaminants may remain on the contaminant candidate list (CCL) for many years, possibly decades, before regulations are passed. In the interim, water treatment operators refer to the available literature to guide their treatment decisions. All four classes of toxins explored in this study have non-enforceable drinking water effluent guidelines set forth by governmental agencies and scholars for the purpose of supporting the regulatory rulemaking processes. Table 13 outlines the current non-enforceable guidelines set by governmental agencies and scholars.

Twenty countries, two states, and the World Health Organization have published microcystin (or microcystin-LR as a precursor to total microcystins) drinking water treatment effluent guidelines due to its potent toxicity and its relative distribution throughout the world. Four countries, two states, and Falconer et al. [2005] published guidelines for cylindrospermopsin concentrations in finished drinking water. Saxitoxins and anatoxins are the least studied classes of toxins. One country (Australia) published a saxitoxin guideline and Fawell et al. [1995] published a recommendation for anatoxins.

Table 13: Worldwide Guidelines for Cyanotoxins in Drinking Water

Authority or Scholar	Toxin	Guideline
United States	Microcystins	0.3µg/L for children under 6 years 1.6µg/L for people over 6 years
Ohio		1.0µg/L
World Health Organization (WHO), Oregon, Brazil, China, Czech Republic, Denmark, Finland, France, Germany, Italy, Japan, Korea, Netherlands, Norway, New Zealand, Poland, South Africa, Spain	Microcystin-LR	1.0µg/L
Australia		1.3µg/L
Canada		1.5µg/L
Minnesota		0.04µg/L
Oregon, Ohio, New Zealand, Australia, Falconer et al.,2005	Cylindrospermopsin	1µg/L
Brazil		15µg/L
United States		0.7µg/L for children under 6 years 3.0µg/L for people over 6 years
Fawell et al., 1995	Anatoxins	1µg/L
Australia	Saxitoxins	3µg/L

The disproportionate financial burden on small and disadvantaged water systems to comply with the regulations set forth in the SDWA fueled the development of the Drinking Water State Revolving Fund (DWSRF). The DWSRF was established by the 1996 amendments to the SDWA as a funding mechanism to help vulnerable water systems comply with the SDWA. Eligible water systems can apply for low interest loans, with grant options available for disadvantaged communities. In California, the DWSRF has evolved to include references from the 2012 Human Right to Water legislation (Assembly Bill 685) and the Safe and Affordable Funding for Equity and Resilience (SAFER) Drinking Water Program. The objective of the DWSRF is to provide financial assistance for the purpose of water system compliance with the national primary drinking water regulations (NPDWR). Eligible projects include planning and design loans, construction loans, purchasing and refinancing debt obligations, insurance of guarantee for local debt, and security reserve for leveraging.

Although the objective of the DWSRF program is to help facilitate compliance with the SDWA, funds from the program have been used to make capital improvements to water systems beyond the scope of the SDWA. For example, microcystin concentrations were found in the finished drinking water supply in Sandusky, Ohio. The City was granted \$2.1 million from the DWSRF program to upgrade their powdered activated carbon (PAC) feed system. After the project, finished drinking water was non-detect for microcystins. This improved water quality for 76,000 residents. The City of Anderson, North Carolina used \$13.5 million in DWSRF funds to install Ozone treatment with hydrogen peroxide addition to mitigate seasonal algal blooms that resulted in taste and odor complaints. The source water did not produce toxins, but funds were allocated because there is a reasonable certainty that toxins would be produced in the future with climate change and watershed degradation. This upgrade improved water quality for 200,000 residents. The DWSRF program can help water systems upgrade their existing infrastructure to treat FCHABs, however, the funds cannot be used to cover operation and maintenance (O&M) costs associated with FCHABs. In summary, funding through the DWSRF can include projects related to FCHABs, but funds can only be used to cover discrete capital improvements; O&M costs cannot be covered.

The United States Department of Agriculture Water and Environment Program (USDA WEP) offers a wide variety of funding mechanisms tailored towards rural development. The Water and Waste Disposal Loan and Grant Program offers funding for state and local government agencies, private nonprofit organizations, and federally recognized tribes for the development or improvement of water and wastewater systems. Eligible areas include rural areas or towns that have a population less than or equal to 10,000, tribal lands in rural areas, and Colonias. Unlike the DWSRF program, the overall objective of the USDA WEP program is to aid with rural development. Funds from the Water and Waste Disposal Loan and Grant Program provide low interest loans and grants to cover capital costs associated with drinking water sourcing, treatment, and distribution, as well as a suite of other projects associated with wastewater development. Funds also may cover planning costs, start up O&M costs, land acquisition, water rights, and legal fees. Funds from this program have been used to mitigate FCHABs. The USDA WEP program can cover start-up O&M costs but does not cover ongoing O&M costs. O&M costs rise significantly when treating FCHABs, which can be prohibitively expensive for small water systems in disadvantaged communities. In summary, the USDA WEP can fund FCHAB related projects; both discrete capital improvements and start-up O&M costs can be covered. However, ongoing O&M costs cannot be covered, which is a significant cost when treating FCHABs.

Despite California being the number 5 economy in the world, over a million Californians lack access to safe and affordable drinking water. The development of California’s water resources has been piecemeal with over 3,000 community water systems, 5,000 non-community water systems, and over 600,000 private wells (Dobbin and Fencl, 2019; Water Education Foundation, n.d). Of the community water systems, 76% of them are classified as small water systems. Small water systems are subject to the same requirements as large water systems, but often lack the resources to carry out compliance requirements. As a result, hundreds of water systems are routinely out of compliance with drinking water regulations.

As a response to trends of noncompliance in California, the Safe and Affordable Funding for Equity and Resilience (SAFER) program was established in 2019 to provide funding for systems that are out of compliance with the Safe Drinking Water Act (SDWA) with an emphasis on VCs. The funding mechanism is called the Safe and Affordable Drinking Water (SADW) fund. The SADW fund allocates $130 million annually. Project categories currently eligible for funding include consolidation efforts, short and long-term O&M costs, interim replacement water, administration support, managerial capacity, and infrastructure improvements, and more. To date, it is the only funding mechanism that considers the ongoing O&M costs of water treatment. SAFER is a huge triumph for California, but it does not address VCs treating FCHABs. Since cyanotoxins are not regulated under the SDWA, funding to cover O&M costs associated with FCHAB treatment cannot be attained through the SAFER program. The SADW fund is the most versatile funding mechanism available to purveyors in California; it can cover ongoing O&M costs, however, its eligibility is restricted to noncompliance with the SDWA. Therefore, purveyors treating contaminants of emerging concern (like cyanotoxins) are ineligible for funding under the SADW fund. Refer to Table 14 for a comparison of funding mechanisms available to drinking water purveyors.

Table 14: Funding Mechanism Comparison

Eligible Entities	SADW Fund	USDA WEP	DWSRF
CWS - publicly owned	X	X	X
Mutual water companies	X	X	X
Non-profit organizations	X	X	X
Native American Tribes	X	X	
CWS - investor owned	X		
Administrators	X		
GSA	X		
Domestic Wells	X		
State Small Water Systems	X		
NCWS - non-profit			X
Colonias		X	
Eligibility Requirements			
Rural areas (<=10,000 population)		X	
Must be in violation of SDWA	X		
Must have TMF capacity to comply with SDWA			X
Funding Priorities			
SDWA compliance	X		X
CWS at risk of non-compliance	X		X
DACs and SDACs	X		X
TMF development	X		
Rural development		X	
CEC		X	X
Types of Funding Projects			
Water treatment, storage, and distribution infrastructure (construction costs)	X	X	X
Planning and design of water treatment system upgrades		X	X
Legal fees		X	
Interest paid during construction		X	
TMF capacity	X		
Interim replacement water	X		
Administration support	X		
Consolidation efforts	X		
O&M costs (start-up)	X	X	
O&M costs (on-going)	X		

List of abbreviations

CWS	community water systems
GSA	groundwater sustainability agencies
NCWS	non-community water systems
SDWA	Safe Drinking Water Act
TMF	technical, financial, managerial
DAC	disadvantaged community
SDAC	severely disadvantaged community
CEC	contaminants of emerging concern
O&M	operations and maintenance

MCLs for cyanotoxins are likely to be adopted within the next decade. After MCLs are adopted for cyanotoxins, small water systems treating FCHABs may still be unable to attain funding through the SAFER program to cover ongoing O&M costs. A critical eligibility requirement for the SADW fund is that the system must be in violation of the NPDWR. FCHABs are widely known to create health risks in communities, so water systems have taken measures to ensure the health and safety of their communities in the absence of regulations. The diligence and perseverance of water systems in areas affected by FCHABs have resulted in proactive installation of robust treatment systems to treat FCHABs. The health and safety of the communities in areas impacted by FCHABs comes at a high cost for disadvantaged communities. Capital costs for infrastructure improvements can be funded by the DWSRF or the USDA WEP, however, the O&M costs from FCHAB treatment cannot be supplemented by the SAFER program. This funding gap leaves disadvantaged communities vulnerable to severe increases in water rates to cover the cost of water treatment. The O&M costs of treating FCHABs leaves some of the most vulnerable populations in California paying the highest water rates.

The available data supports that Clear Lake water systems are adequately treating cyanotoxins below the World Health Organization (WHO) recommended guideline. During the MCL development process, the USEPA works with the WHO to establish an MCL that is as close as technologically and economically feasible to the WHO recommended guideline, maximum contaminant level goal, or health advisory. The development of recommended guidelines only considers health effects, but the USEPA must establish an MCL that considers health effects, feasibility, and the best available technologies for contaminant removal. The MCL may be equal or above the recommended guideline, but it will not be less than the recommended guideline. Therefore, when the MCL is adopted, water systems that draw water from Clear Lake will likely be in compliance with the MCL.

Compliance with SDWA regulations precludes water systems from obtaining funding from the SADW fund. Their commitment to protecting their communities has resulted in high water rates relative to gross monthly income in Lake County, which alone should be enough to qualify them from funding through the SADW fund. However, this is not the case. Water systems would have to put the community at risk of ingesting cyanotoxins to receive aid from the SADW fund. Table 15 outlines the funding gap described in this study. The SADW fund does not apply to FCHAB related projects because they are not regulated contaminants. The DWSRF includes projects related to FCHABs but does not cover O&M costs. The USDA WEP includes projects related to FCHABs, but only covers start-up O&M costs.

The ongoing operations and maintenance costs of treating contaminants of emerging concern are ineligible for funding, which gives the public water system two choices: (1) disproportionately impact rate payers with high water rates or; (2) knowingly put the community as risk by not optimizing current treatment processes in hopes that funding will come when MCLs are adopted. Thus, there is a need to expand the scope of the SAFER program to include VCs (1) impacted by contaminants listed on the CCL and (2) whose water rates impose a disproportionate burden on the community. The federal equivalent action is to expand the scope of the USDA WEP program to include ongoing O&M costs and to expand the scope of the DWSRF program to include start-up and ongoing O&M costs.

Table 15: The Funding Gap

Funding Mechanism	Discrete Capital Improvement Costs	Continuous Operation & Maintenance Costs	FCHAB related projects
SADW Fund	Yes	Yes	**No**
DWSRF	Yes	**No**	Yes
USDA WEP	Yes	Partly (Start-up only)	Yes

6.0 Discussion

This study builds a case to expand funding eligibility under the Safe and Affordable Drinking Water (SADW) fund and offers federal equivalents to expand beyond the scope of current California regulations and support. Each analysis is distinct and employs different techniques to look at the problem from different angles. Each analysis is a building block to guide readers to a solution that is beneficial and achievable. The availability of funding to alleviate the disproportionate financial burden in vulnerable communities addresses current and prevents future environmental injustices. Clear Lake is currently the only drinking water reservoir in California that seasonally develops toxin-producing FCHABs. However, the impacts measured in this study are transferable on a national and international scale and will be applicable to a wider audience in California as more waterbodies become affected by FCHABs.

The effects of climate change are projected to exacerbate FCHABs with more irregular and extreme precipitation events resulting in runoff of fertilizers and nutrients that aid in the development of FCHABs. Previously unaffected waterbodies report FCHABs every year (Amador Water Agency, 2020; Redway Community Services District, 2021). Extreme precipitation events are likely to be followed by prolonged droughts which increase residence time, stagnation periods, and strengthens stratification which provides ample conditions for FCHABs. Toxin-producing FCHABs out-compete their non-toxin-producing counterparts at high temperatures, so toxin-producing FCHABs are expected to become more common in the future. Climate change will continue to exacerbate FCHAB events causing longer and more severe blooms in naturally eutrophic waterbodies and widens the geographic area where they are likely to occur (Chapra, et. al., 2017).

The way climate change effects cyanobacterial cell biomass and toxin production is complex [Aditee et. al. 2020]. However, the risk analysis herein demonstrates that microcystin concentrations are at least partially driven by cumulative winter inflows, which are likely to decrease with climate change. The risk analysis highlights the need for immediate financial assistance in VCs that treat FCHABs. Because FCHABs will worsen, proactive and immediate action is needed by the SAFER group. Waiting until FCHABs worsen may result in environmental injustices such as exposure to the toxins through drinking water or a disproportionate financial burden to pay for treatment.

The microcystin percent removal analysis shows that surface water systems in Lake County adequately remove microcystins from finished drinking water supplies. However, the increased load on treatment systems threaten the efficacy of water treatment. Water treatment operators in Lake County consistently hit ceilings with water treatment technologies that wear on the treatment system. In addition to maximizing infrastructure improvements to their facilities, many systems have made customized modifications to battle the bloom season. Examples of the modifications include rakes to remove floating cyanobacterial cells and customized sludge pumps to account for significant biomass accumulation during bloom events (Ahart, 2021).

The microcystin percent removal analysis reveals the dedication of water system managers and operators that consistently succeed in the increasingly difficult task of treating FCHABs. FCHABs will continue to worsen with climate change, which forces water purveyors to deal with increasingly complex source water quality. However, surface water systems in Lake County, despite being faced with seemingly insurmountable treatment challenges, adequately remove microcystins from finished drinking water supplies. FCHAB treatment requires more treatment chemicals, infrastructure, overtime hours, and monitoring equipment, all of which increase the overall treatment cost. As source water quality continues to decrease, the cost of treatment increases, which affects rate payers.

The water rate analysis results showed the water rates for surface water systems in Lake County impose a disproportionate burden on the local communities, which are all economically distressed, disadvantaged, or severely disadvantaged. Their average percentage of gross monthly income devoted to water bills is double the recommended level while comparable surface and groundwater systems are within 0.1% of the recommended level. The chemical cost analysis refines the water rate analysis to show why FCHABs increase the cost of water treatment. Specifically, the cost of primary coagulant drives the unit cost of water during FCHAB events. Due to the health risks associated with FCHABs, water purveyors took proactive measures to ensure the health and safety of their communities in the absence of state or federal directives. The cost to keep Lake County communities safe creates a disproportionate financial burden, raising significant environmental justice concerns.

Vulnerable communities are often silent in major political decisions and usually lack the resources, time, or money to commit to environmental justice issues in their communities. Many are likely unaware of environmental justice issues. Lake County has a long history of high turnover, sparce resources for staffing, and projects that could never launch due to the lack of funding. As a result, the County faces non-compliance orders and hefty fines for their inability to maintain compliance with environmental statutes. Compare Lake County with a more affluent community like Placer and El Dorado counties that surround Lake Tahoe. Lake Tahoe is one of the world's most regulated lakes. Stormwater, construction, and recreation are heavily regulated to support the community members, to preserve the lake as a place of biological significance, and to maintain a robust tourist economy. Lake County has a rich wine presence, and Clear Lake remains one of the best bass fishing lakes in the world, but environmental programs in Lake County are mostly absent or unenforced. The difference between the two communities reflects the ability of community members to pay. The two lakes are entirely different; Clear Lake is naturally eutrophic and will never resemble Lake Tahoe. However, the lack of functional environmental programs in Lake County is directly related to the community's inability to pay. Since Clear Lake also provides drinking water to the communities in Lake County, it remains a significant environmental justice concern.

FCHABs will continue to worsen, Lake County surface water purveyors adequately remove microcystins, but it comes at a significant cost to rate payers. So, what can be done to alleviate the financial burden? The SAFER program's main objective is to provide safe and affordable drinking water to every community and every Californian. However, the SAFER does not include provisions for contaminants of emerging concern (CECs), nor does it consider the financial burden of compliance. The funding gap in the SADW fund prevents vulnerable communities from attaining funding for the ongoing O&M costs of treating FCHABs. Given the health impacts of FCHAB toxins and other CECs, it is necessary to include CECs listed on the contaminant candidate list in the eligibility requirements under the SADW fund.

It will likely take years, even decades, before MCLs are adopted, so it is the responsibility of the SAFER program to include CECs in the eligibility requirements if it is to fulfil its mission statement. Once MCLs are adopted, the systems proactively treating FCHABs will be overlooked, again ineligible for funding. The systems would have to knowingly put their communities at risk to attain funding through the SADW fund. Therefore, the only path forward is to include in the eligibility requirements contaminants listed on the contaminant candidate list and systems whose SDWA compliance imposes a disproportionate financial burden on ratepayers. On a federal level, the USDA Water and Environment Program (WEP) and the Drinking Water State Revolving Fund (DWSRF) may be expanded to include the same changes to eligibility.

7.0 Conclusions

The goal of the risk analysis was to determine if (and how) microcystin concentrations change in response to cumulative winter inflows (CWI). Both risk analyses showed that the driest CWI category had higher probabilities of greater microcystin concentrations. Prolonged droughts from climate change will likely increase toxin concentrations. The microcystin removal analysis showed that, despite increasingly degraded surface water quality from FCHABs, surface water treatment plants in Lake County adequately remove microcystins from finished drinking water supplies. The objective of the water rate analysis was to determine if FCHABs affect drinking water affordability in VCs. The average percentage of gross monthly income spent on water bills in Lake County is double the California Department of Public Health recommended level of 1.5% whereas results from the comparable system subsets are within 0.1% of the recommended contribution. These analysis results show that FCHABs affect drinking water affordability. The objective of the chemical cost analysis was to determine if the cost of water treatment changes in response to FCHAB events. The analyses showed a seasonal increase of up to four times in response to FCHABs. This analysis shows that the ongoing O&M costs associated with treating FCHABs imposes a disproportionate financial burden on VCs. The objective of the regulatory analysis was to determine if the current regulatory proceedings lack a funding mechanism to address the treatment costs associated with FCHAB management in VCs. The funding mechanisms in place to alleviate the disproportionate burden on disadvantaged communities has a gap in applicability that results in unaffordable water for VCs treating FCHABs.

It is recommended that the SAFER program's Safe and Affordable Drinking Water Fund eligibility requirements be expanded to (1) include financial assistance to systems treating contaminants listed on the Contaminant Candidate List and (2) provide financial assistance to water systems whose SDWA compliance results in a disproportionate financial burden on rate payers. Such changes to the eligibility requirements (1) align with the SAFER program mission statement to provide safe and affordable drinking water to every Californian in every community and (2) alleviate some current and prevent future environmental injustices in California. The federal equivalent would be to include the abovementioned eligibility criteria into the USDA WEP or the DWSRF program.

References

Aditee, Alexander F., et. al., Climate Change and Marine and Freshwater Toxins (2020). Web.

Albuquerque Júnior, E. C. de, Méndez, M. O. A., Coutinho, A. dos R., & Franco, T. T. (2008). Removal of cyanobacteria toxins from drinking water by adsorption on activated carbon fibers. Materials Research, 11(3), 371–380. https://doi.org/10.1590/S1516-14392008000300023

Benson, M. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Crescent Bay Improvement Project.

Birdsey, N. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Highlands Mutual Water Company.

California Pines Community Services District, "Notice of Public Hearing on Proposed Drinking Water, Wastewater, and Trash Service Rates for the California Pines Community Service District", January 22, 2020.

California State Water Resources Control Board, "California Regulations Related to Drinking Water", 10 April 2017, Retrieved May 2020, from https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/lawbook/dwregulations-2017-04-10.pdf

California State Water Resources Control Board. Water Conservation and Production Reports, 2016, retrieved 1 March 2021, from https://www.waterboards.ca.gov/water_issues/programs/conservation_portal/conservation_reporting.html

California Water Quality Monitoring Council: My Water Quality, “California Cyanobacteria and Harmful Algal Bloom (CCHAB) Network”, 2021, https://mywaterquality.ca.gov/monitoring_council/cyanohab_network/index.html

Chapra, Steven C, Brent Boehlert, Charles Fant, Victor J Bierman, Jim Henderson, David Mills, Diane M. L Mas, Lisa Rennels, Lesley Jantarasami, Jeremy Martinich, Kenneth M Strzepek, and Hans W Paerl. "Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwaters: A Screening-Level Assessment." Environmental Science & Technology 51.16 (2017): 8933-943. Web.

Chen, S., C. Lei, C. C. Carey, P. A. Gantzer, and J. C. Little (2017), A coupled three-dimensional hydrodynamic model for predicting hypolimnetic oxygenation and epilimnetic mixing in a shallow eutrophic reservoir, Water Resource. Res., 53, 470–484, doi:10.1002/ 2016WR019279

Cheung, M. Y., Liang, S., & Lee, J. (2013). Toxin-producing cyanobacteria in freshwater: A review of the problems, impact on drinking water safety, and efforts for protecting public health. Journal of Microbiology, 51(1), 1–10. https://doi.org/10.1007/s12275-013-2549-3

City of Alturas Municipal Water and Wastewater, “Municipal Utility Billing for the City of Alturas”. 2015.

City of Brawley, “Proposition 281 Notification, Notice to Property Owners of Public Hearing on Proposed Water and Sewer Rates”, 2015.

City of Calexico, “Proposed Water Rates”, 2018.

City of Crescent City, “Water and Sewer”, 2021, Retrieved 1 March 2021, https://www.crescentcity.org/departments/WaterandSewer

City of El Centro, “Exhibit A: Water Rates and Charges”, 2012.

City of Kerman, “Utility Billing/Rates”, 2021, Retrieved 1 March 2021, https://cityofkerman.net/utility-billingrates/

City of Livingston, “Water Rates”, 2018, Retrieved 1 March 2021, https://www.cityoflivingston.org/finance/page/water-rates

City of McFarland, “Billing Information”, 2021, Retrieved 1 March, 2021, https://www.mcfarlandcity.org/216/Billing-Information

City of Montague, “Water and Sewer Rate Increase”, 2017.

City of Orland, “Public Works Department”, 2021. Retrieved 1 March 2021, http://cityoforland.com/govt/dept/public_works/#:~:text=The%20water%20rate%2C%20every%20two,in%20excess%20of%2015%2C000%20gallons.

City of Rio Dell, “Water Rates”, 2021, Retrieved 1 March 2021, https://cityofriodell.ca.gov/water-rates

City of Shasta Lake, “Water Rates to Increase by 10% in March 2019”, 2019.

City of Yreka, “City of Yreka Utility Fees Schedule”, 2008.

Corona Environmental Consulting, “*Golden State Water Company: Clear Lake Watershed Sanitary Survey Update - Source Water Quality Improvement Grant Applications* (Rep.)”, 2017.

Cox, Cody, General Manager, Redway Community Services District. Personal Interview. April 14, 2021.

“Cyanotoxins Management Plan, Highlands Mutual Water Company”, Highlands Mutual Water

Company in Conjunction with the State of California and the United States Environmental Protection Agency., 2016.

Del Norte Local Agency Formation Commission. “Smith River Community Services District, Municipal Service review and Sphere of Influence Update”, September 24, 2018.

Dobbin, K., Fencl, A., “Who governs California’s drinking water systems?”, California Water Blog, 1 September 2019. https://californiawaterblog.com/2019/09/01/who-governs-californias-drinking-water-systems/

Evans, W. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Lake County County Service Area No. 21 - North Lakeport.

Evans, W. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Lake County County Service Area No. 20 - Soda Bay.

Falconer IR (2005) Cyanobacterial toxins of drinking water supplies: cylindrospermopsins and microcystins. CRC, Boca Raton

Farr, A. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Mt. Konocti Mutual Water Company.

Fawell JK, Mitchell RE, Hill RE, Everett DJ. (1999). The toxicity of cyanobacterial toxins in the mouse: II. Anatoxin-a. Hum. Exp. Toxicol 18(3): 168–173.

Fossa, J. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Harbor View Mutual Water Company.

Fossa, J. General Manager, Harbor View Mutual Water Company. Personal Interview. October, 2020.

Fultz, D. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Nice Mutual Water Company.

Fultz, D. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Richmond Park Resort.

Gregor, J., Maršálek, B., & Šípková, H. (2007). Detection and estimation of potentially toxic cyanobacteria in raw water at the drinking water treatment plant by in vivo fluorescence method. Water Research, 41(1), 228–234. https://doi.org/10.1016/j.watres.2006.08.011

Han, Y., Smithheart, J. W., Smyth, R. L., Aziz, T. N., & Obenour, D. R. (2020). Assessing vertical diffusion and cyanobacteria bloom potential in a shallow eutrophic reservoir. Lake and Reservoir Management, 36(2), 169–185. https://doi.org/10.1080/10402381.2019.1697402

Harris, P. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). City of Lakeport.

He, X., Liu, Y. L., Conklin, A., Westrick, J., Weavers, L. K., Dionysiou, D. D., Lenhart, J. J., Mouser, P. J., Szlag, D., & Walker, H. W. (2016). Toxic cyanobacteria and drinking water: Impacts, detection, and treatment. Harmful Algae, 54, 174–193. https://doi.org/10.1016/j.hal.2016.01.001

Horne, A. J., "The Ecology of Clear Lake Phytoplankton", 1975, Clear Lake Algal Research Unit. University of California, Davis Library.

"How Much Does a Wastewater Treatment System Cost? (Pricing, Factors, Etc.)", Samco Tech. 18 May 2016, Retrieved May 4, 2020, from https://www.samcotech.com/cost-wastewater-treatment-system/

Hudnell, K., Back, N., Lajtha, A., et al., *Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs.* DOI:10.1007/ 978-0-387-75865-7, Springer, 2008.

Hudnell, K., "The state of U.S. freshwater harmful algal blooms assessments, policy and legislation". DOI:10.1016/j.toxicon.2009.07.021, Elsevier, 2009.

Imteaz, M. A., & Asaeda, T. (2000). Artificial mixing of lake water by bubble plume and effects of bubbling operations on algal bloom. Water Research, 34(6), 1919–1929. https://doi.org/10.1016/S0043-1354(99)00341-3

Kelseyville County, Lake County Sanitation District. (2019). Retrieved May 4, 2020, from http://www.lakecountyca.gov/Assets/Departments/SpecialDistricts/Kelseyville+waste+water+2019+rate.pdf

Kelseyville County Waterworks District #3, "Ordinance No. 2652", 2003.

Kerri, Kenneth, D., Water Treatment Plan Operation, a Field Study Training Program, Volume 1, Sixth Edition, California State University, Sacramento, Office of Water Programs, 2008.

Lake County: Economic and Demographic Profile. (2018). Chico, CA: Center for Economic Development California State University, Chico. Retrieved May, 2020, from http://www.lakecountyca.gov/Assets/Departments/SpecialDistricts/Lake+County+Economic+and+Demographic+Profile.pdf

Larson, D. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for*

Year Ending December 31, 2018 [Section 116530 Health & Safety Code] (Rep.). Clearlake Oaks County Water District, CA.

Lehman, J. T. (2014). Understanding the role of induced mixing for management of nuisance algal blooms in an urbanized reservoir. Lake and Reservoir Management, 30(1), 63–71. https://doi.org/10.1080/10402381.2013.872739

Little, A. (2019). *Compilation of Water Quality collected at Intakes from Public Water Systems Around Clear Lake, CA*. California State Water Resources Control Board Division of Drinking Water.

Little, A. (2018). "Microcystin Barrier Index Score for Drinking Water Treatment Plants in Clear Lake, CA", California State Water Resources Control Board Division of Drinking Water Mendocino District.

Lorenzen, M. W., Mitchell, R., "An Evaluation of Artificial Destratification for Control of Algal Blooms", Journal (American Water Works Association), July 1975, Vol 67, No. 7 pp. 373-376, http://www.jstore/com/stable/41267959

McCosker, Darin., Former Chief Drinking Water Treatment Plant Supervisor, California Water Service, Lucerne., Personal Interview., October 5, 2020.

Michele, J., & Michele, V. (2002). The free jet as a means to improve water quality: Destratification and oxygen enrichment. Limnologica, 32(4), 329–337. https://doi.org/10.1016/S0075-9511(02)80024-X

Mioni, C., Kudela, R., Baxa, D., Sullivan, M., Hayashi, K., Smythe, T., & White, C. (2011). Harmful cyanobacteria blooms and their toxins in Clear Lake and the Sacramento-San Joaquin Delta (California). Delta (California), 10, 58–150.

Moalem, S. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). California Water Service - Lucerne.

Mountain Gate Community Services District, “Ordinance No 2019-01: An Ordinance of the Mountain Gate Community Services District Amending Water Consumption in Accordance with the 2019/2020 District Budget. 2019.

Ohio Environmental Protection Agency, Developing a Harmful Algal Bloom (HAB) Treatment Optimization Protocol Guidance for Public Water Systems, Division of Drinking and Ground Waters Version 2.1 January 2019

Operator Certification Program | California State Water Resources Control Board. (2020). Retrieved May, 2020, from https://www.waterboards.ca.gov/water_issues/programs/operator_certification/

Parks, T. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Konocti County Water District.

“Private Wells”, Water Education Foundation. n.d. Accessed 20 October 2020. https://www.watereducation.org/post/private-wells

Reust, M. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Clearwater Mutual Water Company.

Richerson, P. J., T. H. Suchanek, and S. J. 1994. *The causes and control of algal blooms in Clear Lake. Clean Lakes diagnostic/feasibility study for Clear Lake,* California. Division of Environmental Studies, University of California. Davis, California, USA.

Rinde, B. (2018). *Large Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Golden State Water Company - Clearlake System.

Rizzo, Christopher, Southern California Circuit Rider, California Rural Water Association, Personal Interview., December 10, 2020.

Safe Drinking Water Information System (SDWIS), California Public Water Supply System Search, Drinking Water Branch, Drinking Water Watch (2020) Version 20.12

Schmidt, W., Willmitzer, H., Bornmann, K., & Pietsch, J. (2002). Production of drinking water from raw water containing cyanobacteria?pilot plant studies for assessing the risk of microcystin breakthrough. Environmental Toxicology, 17(4), 375–385. https://doi.org/10.1002/tox.10067

Shasta Community Services District, "Rates & Policies", 2021, Retrieved 1 March 2021, https://shastacsd.org/rates-and-policies

Shen, X., Zhang, H., He, X. et al. Evaluating the treatment effectiveness of copper-based algaecides on toxic algae Microcystis aeruginosa using single cell-inductively coupled plasma-mass spectrometry. Chem 411, 5531–5543 (2019). https://doi.org/10.1007/s00216-019-01933-9

Shields, C. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Westwind Mobile Home Park.

Spring Valley County Service Area # 2, "Rate Key Ordinance No. 2945", 2011.

Stebbins, S., "Poorest counties in the US: A state-by-state look at where median household income is low", USA Today., January 25, 2019, https://www.usatoday.com/story/money/2019/01/25/poorest-counties-in-the-us-median-household-income/38870175/.

"The History of Lake County, California", California's Lake County, Lake County Marketing and Economic Development Program, 2019.

The Metropolitan Water District of Southern California, "Quality & Treatment", 2021, http://www.mwdh2o.com/AboutYourWater/Water-Quality

Tucker, C.S., D'Abramo, L.R., "Managing High pH in Freshwater Ponds", Southern Regional Aquaculture Center, SRAC Publication No. 4604, July 2008.

United States Bureau of Reclamation, "Projects and Facilities", 2021, https://www.usbr.gov/projects/facilities.php?type=Dam#C

United States Environmental Protection Agency, "Contaminant Candidate List 4 (CCL 4)", 2020, https://www.epa.gov/ccl/contaminant-candidate-list-4-ccl-4-0

United States Environmental Protection Agency, "EPA Drinking Water Health Advisories for Cyanotoxins", 2020, https://www.epa.gov/cyanohabs/epa-drinking-water-health-advisories-cyanotoxins

United States Environmental Protection Agency, "Drinking Water Requirements for States and Public Water Systems: Surface Water Treatment Rules", 2020, https://www.epa.gov/dwreginfo/surface-water-treatment-rules

United States Environmental Protection Agency, "National Primary Drinking Water Regulations", 2020, https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

United States Environmental Protection Agency, "State HABs Resources", 2021, https://www.epa.gov/cyanohabs/state-habs-resources

Upper Lake County Water District, “Rates and Policies”, Retrieved 1 March 2021, https://ulcwd.com/rates-and-policies

Water Rates: Water Affordability | Pacific Institute. (2013, January). Retrieved May 4, 2020, from https://pacinst.org/wp-content/uploads/2013/01/water-rates-affordability.pdf

Water & Environmental Programs | Rural Development. (2020). Retrieved May 4, 2020, from https://www.rd.usda.gov/programs-services/all-programs/water-environmental-programs

Weaverville Community Services District, “Ordinance #19-11C: New Water Rates”, 2020.

Wendele, John., Former Federal Programs Manager, California Rural Water Association, Personal Interview., December 15, 2020.

Wert, C., Rosario-Ortiz, L., Intracellular organic matter from cyanobacteria as a precursor for carbonaceous and nitrogenous disinfection byproducts. Environ Sci Technol. 2013 Jun 18;47(12):6332-40. doi: 10.1021/es400834k. 2013 Jun 4. Environ Sci Technol. 2013 Nov 5;47(21):12617. PMID: 23675656.

Westerhoff, P., Sommerfeld, M., Baker, L., “Guidance Manual for Reducing 2-Methylisoborneol (MIB) and Geosmin in the Metropolitan-Phoenix Area Water Supply, A Cooperative Research and Implementation Program by Arizona State University, City of Phoenix, Salt River Project, Central Arizona Project”, July 2002

Westrick, J. A., Szlag, D. C., Southwell, B. J., & Sinclair, J. (2010). A review of cyanobacteria and cyanotoxins removal/inactivation in drinking water treatment. Analytical and Bioanalytical Chemistry, 397(5), 1705–1714. https://doi.org/10.1007/s00216-010-3709-5

Winder, M., Reuter, J., Schladow, G., “Clear Lake Historical Data Analysis”, University of

California, Davis, 2010

Wonderwheel, A. (2018). *Small Water System 2018 Annual Report to the Drinking Water Program for Year Ending December 31, 2018 [Section 116530 Health & Safety Code]* (Rep.). Buckingham Park Water District.

Zamyadi, A., Dorner, S., Sauvé, S., Ellis, D., Bolduc, A., Bastien, C., & Prévost, M. (2013). Species-dependence of cyanobacteria removal efficiency by different drinking water treatment processes. Water Research, 47(8), 2689–2700. https://doi.org/10.1016/j.watres.2013.02.040