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Cyanobacteria Harmful Algal Bloom Monitoring Strategy for the Sacramento-San Joaquin Delta

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Glossary

Having standardized terminology for HABs monitoring will improve consistency, collaboration, and ease of data sharing amongst the Delta science community. The following terms and their definitions are what we are using in this document, and we hope that these definitions can be standardized across monitoring efforts.

CCHAB Network	California Cyanobacteria and Harmful Algal Bloom Network
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CHAB[1]	Cyanobacteria harmful algal bloom
DWR	Department of Water Resources
FAIR	Findability, Accessibility, Interoperability, Reuse
FHAB	Freshwater and estuarine harmful algal bloom
HAB[1]	Harmful algal bloom
IEP	Interagency Ecology Program
Delta ISB	Delta Independent Science Board
MERHAB	Monitoring and Event Response for Harmful Algal Blooms
NOAA	National Oceanic and Atmospheric Agency
NPDES	National Pollutant Discharge Elimination System
QAPrP	Quality assurance program plan
SFEI	San Francisco Estuary Institute
SOP	Standard operating procedure
SPATT	Solid phase adsorption toxin tracking
SWAMP	Surface Water Ambient Monitoring Program
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey

[1] Throughout this document, "HAB" will be used as an umbrella term for all HABs when speaking in general, and "CHAB" will be used when we are specifically describing a cyanobacterial HAB.

Executive Summary

In winter 2021, the Central Valley Regional Water Quality Control Board and California Department of Fish and Wildlife approached the Delta Science Program (DSP) to discuss the development of a strategy to address harmful algal blooms (HABs) in the Sacramento-San Joaquin Delta (Delta). Although HABs have been a major nuisance in the Delta for decades, and many special studies have been conducted to demonstrate their noxiousness to the ecosystem and for public health, no formal monitoring program specifically for HABs exists in the Delta.

The DSP hosted a public workshop on HABs in November 2022 that brought together interested parties from federal, state, and local governments, Tribal governments, community-based organizations, academia, nonprofits, nongovernmental organizations, and general members of the public. This workshop was developed to facilitate discussions for developing a HAB monitoring strategy to fit the needs of the many varied interests on HABs in the Delta. The workshop included presentations and panels by experts working in HABs as well as breakout sessions and surveys to hear from all attendees. This was all captured in the HABs Workshop Summary[1].

After the workshop, the authors of this document worked to create a strategy that would address the expressed needs of workshop attendees to establish a pathway for developing a monitoring program to address HABs in the Delta. This included refining the scope of such a program to focus on cyanobacterial HABs (CHABs), the species that are most problematic in Delta waterways. Throughout the development of this document the authors worked with various technical experts, Tribes, environmental justice experts, and policymakers to establish a strategy that is detailed enough to kickstart specific actions but lenient enough for individual parties to continue to share their needs throughout the implementation of the document. This strategy recognizes that there is no dedicated funding to specifically monitor for CHABs in the Delta, however there are many established monitoring programs that collect water quality data that might support data collection for CHABs. This provides monitoring practitioners and policymakers with an opportunity to capitalize on this nexus to collect data work on collaborative approaches to sharing data and to mitigate CHABs in the Delta.

[1]https://www.researchgate.net/publication/368841409_Delta_Harmful_Algal_Blooms_Monitoring_Workshop_Summary_-_November_2022

The goals and objectives and recommendations from this document can be implemented through a “phased” or adaptive approach (Figure 1). Because of the nature of CHABs as an issue with multiple vested interests, this phased approach should be conducted with the community to prioritize investment and management questions throughout the implementation of this document. As recommended by the Delta ISB (2022), this adaptive approach to monitoring allows “a more rigorous system for establishing purpose, setting expectations, and conducting review of monitoring programs, as well as fostering communication at all levels”.

This document seeks to bring together community desires, synergistic efforts, and to build from the work conducted by many dedicated individuals throughout the system that led to this strategy being possible. This work specifically builds from material published by Dr. Peggy Lehman, Department of Water Resources, the California Water Boards’ Framework and Strategy for Freshwater Harmful Algal Bloom Monitoring (Southern California Coastal Water Research Project and State Water Resources Control Board 2021), the Delta Regional Monitoring Program’s long-term planning for nutrients, Central Valley Regional Water Quality Board’s Delta Nutrient Research Plan, and the Delta Independent Science Board’s Water Quality Science in the Sacramento-San Joaquin Delta (2018) and Review of the Monitoring Enterprise in the Sacramento-San Joaquin Delta (2022).

Figure 1. Description of the phased, or adaptive, approach to monitoring for HABs described through the goals, objectives, and recommendations of this strategy. Map is from the San Francisco Estuary Institute.

1 Introduction

1.1 Purpose

Following years of drought and decreased freshwater flows, an increase in the frequency and intensity of cyanobacterial harmful algal blooms (CHABs) is one of many threats to habitat quality in the Sacramento-San Joaquin Delta (Delta). The purpose of this document is to provide a forum for agencies, non-governmental groups, Tribes, and other parties that have a vested interest in mitigating adverse impacts from CHABs to work together toward the common goal of creating a collaborative and cohesive CHAB monitoring strategy for the Delta. While a number of state and federal agencies have legal responsibilities for water management and water quality in the Delta, there exists a “collaboration gap” among agencies for CHAB monitoring and inclusion of Delta communities and interested parties. This document seeks to provide a framework for 1) agreeing on management questions and monitoring goals and objectives that would help shape a common CHAB monitoring strategy, and 2) actionable steps with respect to developing a comprehensive CHAB monitoring program specific to the Delta, interested parties, and the agencies charged with protecting ecosystems and species, and 3) developing a strategy for using monitoring information to inform collaborative management and mitigation decisions. The overall goal of the framework described in this document is to promote shared responsibilities and standardized data collection and reporting protocols in a manner that will benefit CHAB monitoring to inform and improve water quality management decisions. This document provides an overview of current CHAB dynamics, a summary of current CHAB monitoring efforts, identifies potential collaboration and knowledge gaps, and provides goals and recommendations/action steps. This information can be used for organizing discussions around a common CHAB monitoring strategy, for improving our understanding of CHABs and their mitigation in the Delta.

1.2 Background on the Delta

The Delta is a 900 square mile region that is formed by the confluence of the Sacramento and San Joaquin rivers in northern California. This region is intersected by a large network of sloughs and channels that is connected to the northern part of San Francisco Bay via the confluence of the two rivers. The entire system is referred to as the San Francisco Estuary. (Nichols et al. 1986, Jassby and Cloern 2000, Whipple et al. 2012) (Figure 2). Freshwater from the Delta watershed provides drinking water to an estimated 23 million people and water resources for agricultural commodities. The Delta also serves as a critical habitat for fish, birds, other and wildlife. Because of the competing demands for the Delta's resources, the California legislature passed the Delta Protection Act (Section 12220 of the Water Code) in 1959 and established a legal boundary of the Delta (). Because this legal boundary is used by many of the agencies charged with protecting Delta resources it will also be used for the purposes of this framework.

Estuaries can be challenging to monitor for HABs due to the complexities of physical, chemical, and biological interactions along the continuum of freshwater to saltwater habitats. In addition to natural complexity, numerous jurisdictional boundaries and varying opinions on the goals and priorities for monitoring confers further challenges to monitoring in estuaries (Kudela et al. 2023). This framework will focus on freshwater cyanobacterial HABs, or CHABs, which are dominant in the Delta. To date, monitoring and assessments of CHABs in the Delta have relied on special studies, intermittent monitoring, and leveraging parts of established water quality programs (Lehman et al. 2005, 2013, 2020). Due to the short-lived nature of these studies, it has been challenging to uncover trends of CHABs over time in the Delta.

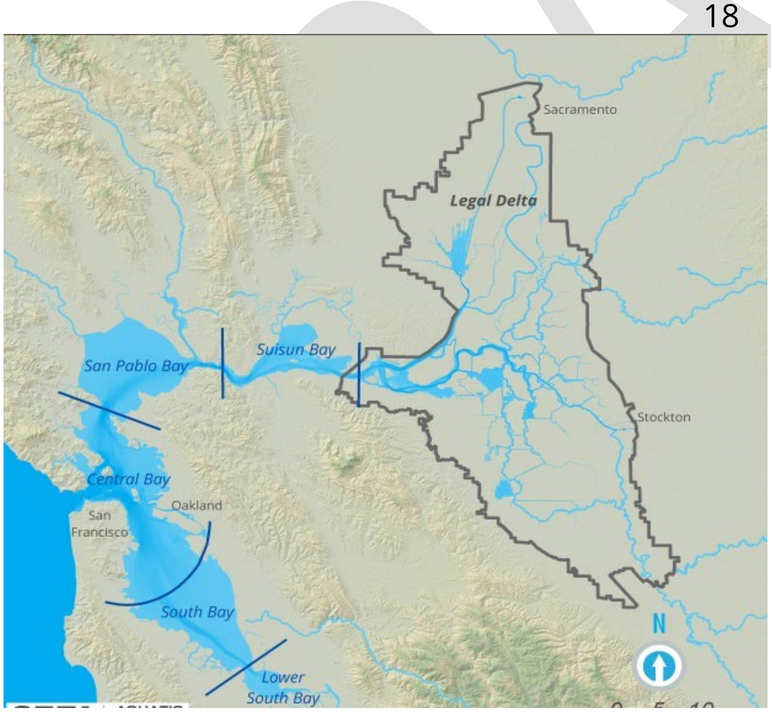


Figure 2. Map of the San Francisco Estuary. The brown line shows the area of the San Francisco Estuary that has been designated as the legal Sacramento-San Joaquin Delta (Delta).

1.3 November 2022 HABs Workshop

In November 2022, the Delta Stewardship Council – Delta Science Program hosted a 2-day public, hybrid workshop on HABs monitoring. This workshop supports the Delta Science Program's Science Action Agenda Action 2B: "Develop a framework for monitoring, modeling, and information dissemination in support of operational forecasting and near real-time visualization of the extent, toxicity, and health impacts of HABs", and Action 5C:

"Determine how environmental drivers (e.g., nutrients, temperatures, water residence time) interact to cause HABs in the Delta, identify impacts on human and ecosystem health and well-being, and test possible mitigation strategies".

Day 1 of the workshop focused on "Creating a Coordinated Partner Monitoring Strategy" and Day 2 on "Data Sharing and Integration" topics spanning from strategic methods to approach partner monitoring to communication and data sharing methods. This workshop was an opportunity to hear from the Delta science community on preferred approaches to a HABs monitoring program in the Delta. Major themes included information sharing, equitable and timely access to data, and building community partnerships. The authors of this document have tried to incorporate those values here to the best of their ability. More information on the HABs Monitoring Workshop is available in the Workshop Summary[7] (Delta Science Program 2023).

1.4 Multi-Organization Coordinated Monitoring

As described above, the Delta is a complex system both environmentally as well as jurisdictionally due to the many organizations charged with protecting the Delta's resources. These organizations have different missions, legal authorities, responsibilities, and interests. To capture the different needs of the various agencies, dischargers, Tribes, and partner organizations, the Delta CHAB Monitoring Strategy will need to be developed and implemented in a collaborative and coordinated manner. To this end, the CHAB Strategy has leaned on several publications that provide recommendations for a holistic integrative HAB monitoring approach (Paerl et al., 2018, Smith et al., 2021, Howard et al., 2022), though some of these recommendations are outside the scope of the development of this CHAB Strategy (see section 1.5 Strategy Scope).

Given the large number of partner organizations, one factor that is particularly relevant for the Delta is that CHAB monitoring needs to be coordinated across organizational boundaries and jurisdictions (Howard et al., 2022). An initial list of potential partner organizations with vested interests in Delta resources are as follows:

Government Agencies:

[7]https://www.researchgate.net/publication/368841409_Delta_Harmful_Algal_Blooms_Monitoring_Workshop_Summary_-_November_2022

Delta Plan Interagency Implementation Committee Member Agencies[8] are core to the intended implementation of this document. Agencies that might be most relevant to this work are:

- California Department of Fish and Wildlife
- California Department of Public Health
- California Department of Water Resources
- California State Water Resources Control Board
- Central Valley Regional Water Quality Control Board
- San Francisco Regional Water Quality Control Board
- Delta Stewardship Council
- United States Bureau of Reclamation
- United States Army Corps of Engineers
- United States Geological Survey
- United States Environmental Protection Agency
- Local environmental health and park departments
- Drinking water agencies
- Municipalities

Non-governmental Organizations:

Some organizations have been involved throughout this project and are listed here as examples and recommendations, but this is not intended to be an exclusive list.

- Restore the Delta
- San Francisco Baykeeper
- San Francisco Estuary Institute
- Little Manila Rising

Tribes:

Some tribes have been involved throughout this project and are listed here as examples and recommendations, but this is not intended to be an exclusive list

- Shingle Springs Band of Miwok Indians
- Buena Vista Rancheria
- California Indian Environmental Alliance

Universities:

[8] https://deltacouncil.ca.gov/dpiic/members

Many academic groups have studied the role and impact of CHABs in the Delta and may have an interest in continued engagement for special studies and sharing information.

1.5 Strategy Scope

1.5.1 Items Covered

This framework is focused on developing a strategy to achieve consistent data collection and collaboration to monitor Delta CHABs and inform water quality management decisions in a 3–5-year horizon. This Delta CHABs Monitoring Strategy builds off the recommendations and framework provided by the California Water Board's Framework and Strategy for Freshwater Harmful Algal Bloom Monitoring which states that "*monitoring data can be broadly grouped into two categories that have similar decision support needs: 1) public health protection and response and 2) FHAB water quality management decision support*" (Smith et al. 2021). Although the data collected from this strategy may support public health protection, the **focus of the strategy is to collect and use data to support water quality management decisions**. This strategy is scoped to cover cyanobacterial harmful algal blooms in the legal Delta. With this scope in mind, we hope that this document will provide a starting point for approaching the development of monitoring plan(s) for the Delta in a stepwise manner. The Delta CHABs monitoring strategy can eventually be expanded to cover additional focus areas (e.g., public health protection) through separate efforts.

1.5.2 Items Not Covered

Although HABs in general have impacted various parts of the greater San Francisco Estuary, this strategy document proposes **limiting the scope to cyanobacterial HABs (CHABs) and the Delta**. This allows HABs monitoring practitioners, researchers, and decision makers to focus on a very complex problem in a stepwise manner.

As such, this strategy will not cover:

- Non-cyanobacterial freshwater harmful algal blooms and marine HABs;
- Geographic area outside the legal Delta boundary (Figure 1);
- Public health protection and response such as:
    - informing the development of thresholds of cyanotoxins on drinking water or human food sources like fish;

- public health epidemiology as a result of acute or chronic CHAB exposure.

Although not covered, the abovementioned topics are important and this strategy may provide some structure or data that could inform them. For additional sources on these topics see reviews by Patiño et al. (2023), Kudela et al. (2023), and Anderson et al. (2021).

2 Existing Knowledge of Delta CHAB Dynamics

Like many freshwater systems worldwide, the Delta has been experiencing more frequent and severe CHAB events (Lehman et al. 2017). Delta CHAB events are typically dominated by the potentially toxin-producing genus *Microcystis* which was first reported in 1920 (Allen et al. 1920) but was not observed in colonial form until 1999 (Lehman et al. 2005). Since 1999, *Microcystis* blooms have been occurring in the Delta with increasing frequency and severity (Lehman et al. 2017, Lehman et al. 2022). Other common cyanobacteria which have also been observed with increasing frequency in some portions of the Delta include genera such as *Aphanizomenon*, *Planktothrix, Dolichospermum*, *Pseudanabaena* and *Planktolyngbia* (Lehman et al. 2008, Spier et al. 2013, Lehman et al. 2017, Lehman et al. 2022, Perry et al. 2023).

Because a number of natural resource agencies are responsible for protecting the Delta's resources, there are several monitoring programs already in place that collect water quality data at fixed stations throughout the Delta. These data are freely available to the larger research community, and as a result, much of the published literature on CHABs are from special studies that have leveraged data collected as part of these established water quality programs. However, methods employed, or types of data collected, in these programs may not be perfectly suited for CHAB monitoring. For example, methods employed for water column sampling may not specifically target CHAB species, or sampling locations may be outside of the areas where CHABs are most severe, to mention a few. To identify monitoring gaps, needs, and future monitoring priorities it is beneficial to have an overview of the water quality data collected to date that is particularly relevant for CHAB monitoring. The following sections synthesize known data on phytoplankton biomass levels in the Delta (section 2.1.1 and 2.1.2), Delta-specific CHAB community composition (section 2.1.3), cyanotoxin detections (section 2.2), and the environmental drivers (section 2.3) related to emergence and growth of cyanobacteria in the Delta. Data sources for these sections include the repositories established by agencies such as the Department of Water Resources (DWR) and the California Department of Fish and Wildlife (CDFW).[9]

2.1 Phytoplankton

2.1.1 Biomass measurements

Phytoplankton biomass is typically measured as the concentration of the light harvesting pigment chlorophyll-a (chl-a). Chl-a is common to all phytoplankton, including eukaryotic phytoplankton such as diatoms and prokaryotic phytoplankton such as cyanobacteria. Chl-a is considered a standard water quality measurement and is routinely collected throughout the San Francisco Estuary and the Delta (e.g. Jassby et al. 2002, Cloern and Jassby 2012, Sutula et al. 2017). It is also routinely used throughout most of the world to gauge whether a system is supporting unsustainably high densities of phytoplankton that can lead to water quality impacts including low dissolved oxygen concentrations (e.g. Nixon et al. 1995, Hagy et al. 2004, Kemp et al. 2005, Rabalais et al. 2014).

Specifically, mean summertime chl-a concentrations are often used to classify the trophic status of estuaries as eutrophic, mesotrophic, or oligotrophic and for establishing criteria that are protective of beneficial uses (Bricker et al. 2003, Carstensen et al. 2011, Harding et al. 2014, Sutula et al. 2017). Recent data for the past 5 years collected by DWR through their Environmental Monitoring Program (EMP) and North Central Regional Office (NCRO) program demonstrates that mean summertime chl-a concentrations typically vary between 1.5-4.0 µg/L at most locations in the central Delta (Figure 3).

In the south Delta, where the channels are less influenced by tidal exchange and have longer residence times, concentrations are typically greater and more variable than in other parts of the Delta (Figure 3). Mean summertime south Delta chl-a concentrations range from 2.5-8.0 µg/L, but in years with algal blooms can reach up to 40 µg/L (Perry et al. 2023).

Compared with other estuaries world-wide with similar levels of nutrient loading, mean summertime chl-a concentrations in the Delta are considered low. In a global comparison of chl-a concentrations in 12 estuaries, Jassby et al. (2002) found that

[9] Data included in this draft version of the Delta CHABs Monitoring Strategy is not yet fully complete. The authors intend to include additional South Delta data for the final release.

the Delta ranked fourth from the bottom with a Delta-wide, mean summertime chl-a concentration of 5.2 ± 0.7 ug/L (Jassby et al. 2002).

Low, mean concentrations of chl-a are reflected in relatively low thresholds for chl-a concentrations that constitute “bloom” conditions for the San Francisco Estuary. For example, using occurrences of total phytoplankton biomass exceeding the 99th percentile of a seasonal mean described by a periodic spline function, Carstens et al. (2015) characterized a bloom threshold for the San Francisco Estuary of approximately 300 µg carbon per liter (C/L), equivalent to 12 µg chl-a/L (i.e. using a C:chl-a ratio of 25). This is close to a threshold of 13 µg chl-a/L characterized by Sutula et al. (2017) for the San Francisco Estuary using a different statistical approach.

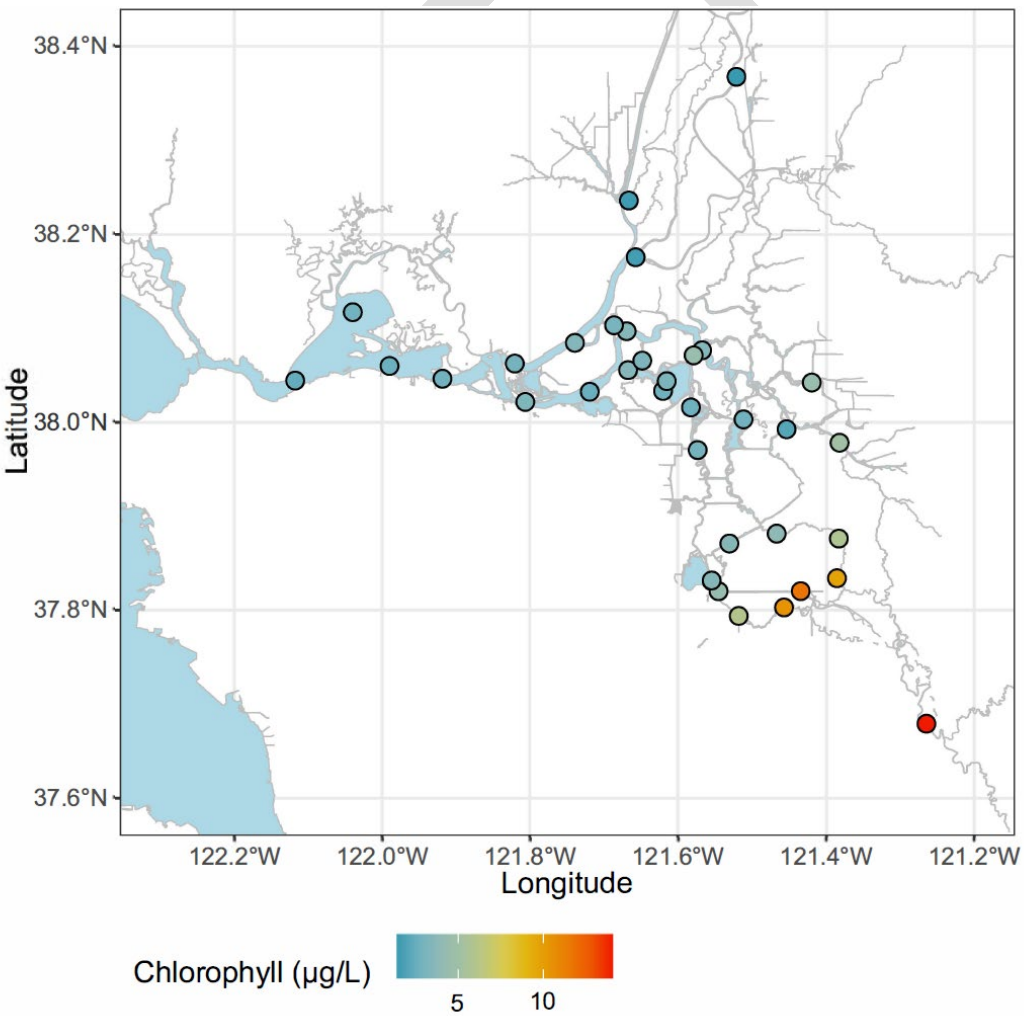


Figure 3. Chl-a concentrations averaged across the summer season (June-September) and recent time period (years 2017-2022) for individual stations in the Delta. Chl-a data from EMP and NCRO programs.

In addition to chl-a, phytoplankton contain accessory pigments that are useful as taxonomic markers because some are unique within broader taxonomic phytoplankton groups (Mackey et al. 1996, Jeffrey et al. 2011, Kramer and Siegel 2019). These pigments occur in specific ratios with chl-a in the cell (e.g. Mackey et al. 1996) and can be measured chemically (Hooker and Van Heukelem 2011) or via fluorescence (Bertone et al. 2018). For example, cyanobacteria contain a unique light harvesting system called the phycobilisome composed of three different pigment-protein complexes, including allophycocyanin, phycocyanin, and phycoerythrin that function cooperatively with chlorophyll to increase the efficiency of light harvesting for photosynthesis (Ting et al. 2002, Berg et al. 2011). Phycocyanin fluorescence (f-PC) is increasingly used to quantify cyanobacteria *in situ* and is a rapid, non-invasive technique for quantifying CHAB occurrences (Bertone et al. 2018). In the Delta, recent f-PC measurements have demonstrated relative differences in cyanobacterial biomass in specific regions such as Franks Tract and Mildred Island (Hartman et al. 2022).

Monitoring Considerations

Measurement of phycocyanin concentrations can be used as a surrogate for freshwater cyanobacteria biomass specifically, just as chl-a is used as a surrogate for total phytoplankton biomass. However, it can be challenging to compare f-PC with chl-a fluorescence because cellular PC:chl-a ratios in cyanobacteria are influenced by factors such as cell volume, cyanobacterial colony morphology and geometry, nutritional state, and growth phase (Kong et al. 2014, Bertone et al. 2019, Choo et al. 2019, Ma et al. 2022, Rousso et al. 2022), and therefore can be highly variable (Foy 1993). This makes it difficult to convert PC to cyanobacterial biomass estimates, and to differentiate the proportion of the total phytoplankton community biomass that is comprised of cyanobacteria (Ma et al. 2022, Rousso et al. 2022). Nevertheless, phycocyanin readings can give a general indication of cyanobacterial presence and relative changes in cyanobacterial biomass.

2.1.2 Remote Sensing

Remote sensing is another tool that can be used to estimate phytoplankton biomass. This method measures color reflected off the surface of the water via satellite and converts the color reading to pigment concentrations via algorithms. The advantage of using satellite remote sensing is the synoptic view over which data can be acquired. For example, the National Aeronautics Space Agency (NASA) and European Space Agency (ESA) ocean color images are used by the National

Oceanic and Atmospheric Administration (NOAA) to forecast HABs (https://coastalscience.noaa.gov/about/).

In California, an ocean color visualization tool was developed as a partnership between NOAA, the California Surface Water Ambient Monitoring Program (SWAMP), and the San Francisco Estuary Institute (SFEI). SFEI stores and collates data that is acquired from ESA's satellite Sentinel-3 and post processed by NOAA with Ocean Land Color Imager (OLCI) to produce a cyanobacterial index that estimate cyanobacterial concentrations (Wynne et al. 2020). The web-based tool to visualize the data, with a spatial resolution of 300 by 300 meters, is hosted by SFEI. A beta version of the OLCI to determine chl-a data was released July 2023.

Monitoring Considerations

In the Delta, the cyanobacterial index is a good resource for visualizing cyanobacterial blooms over larger areas given the resolution of 300 by 300 meters but is currently not available for smaller waterways which comprise much of the Delta. However, this index is useful for providing early warnings of CHABs in the western portions of the Sacramento and San Joaquin Rivers, Franks Tract, Mildred Island, Clifton Court Forebay, and Liberty Island. Although this dataset goes back to 2016, Delta satellite data has never been evaluated for status and trends of algal blooms. Efforts are underway to obtain imaging from satellite Sentinel-2 which would provide finer resolution and provide more useful information for Delta waterways.

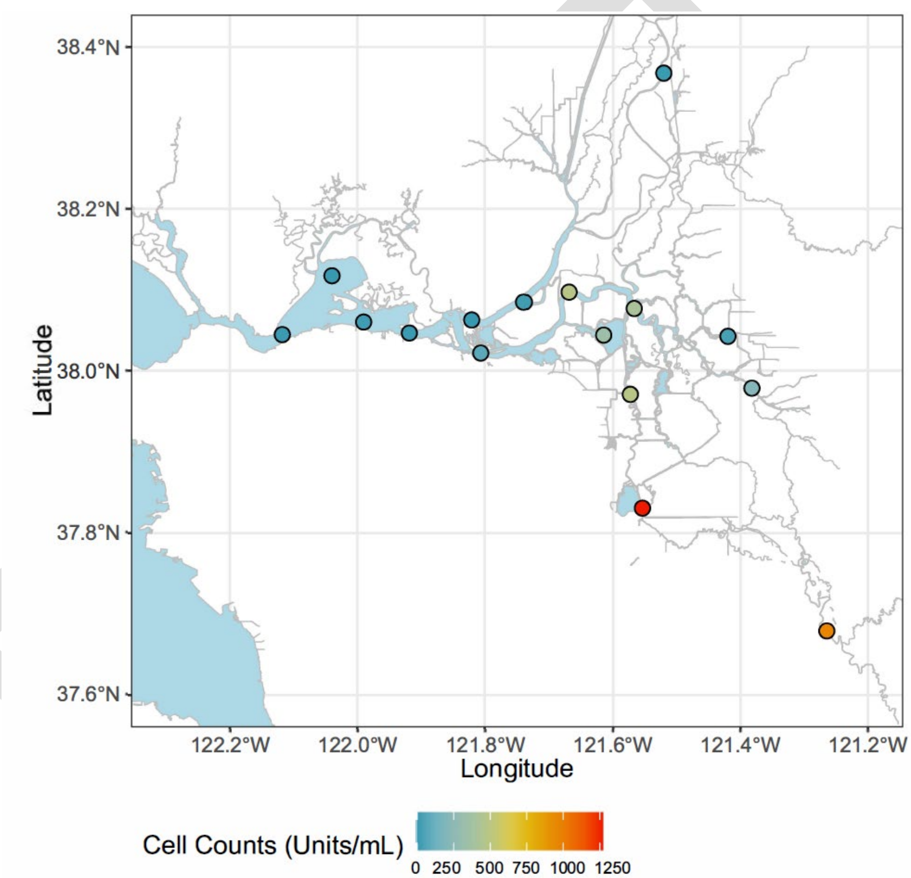
2.1.3 Phytoplankton identification

Microscopy remains the most commonly used method for phytoplankton identification and enumeration. Recently, a variety of additional techniques, including molecular methods, are available for characterizing phytoplankton and cyanobacterial community composition (Janse et al. 2003, Otten et al. 2017). Microscopy has been the most commonly employed method for analyzing cyanobacterial community composition in Delta water samples and has been used to identify 16 different cyanobacterial genera to date (Spier et al. 2013, Lehman 2022, Richardson et al. 2023, Hartman et al. 2022). In addition to enumeration of cell abundances, microscopy has been used to determine cyanobacterial biomass by measuring the volumes of individual cells or colonies.

As mentioned above, Delta CHAB events are typically dominated by blooms of *Microcystis* (Lehman et al. 2017, Lehman et al. 2022) and microscopic enumeration of *Microcystis* colony units has been incorporated into routine monitoring at certain stations throughout the Delta.

Recent data collected by the EMP shows that the abundances of *Microcystis* colonies tend to be the greatest in Clifton Court in the south Delta and in the San Joaquin River near Vernalis (Figure 4). Colony abundances decrease from the middle of the San Joaquin River towards the confluence; the lower Sacramento River has abundances an order of magnitude, or more, lower. In the Sacramento River proper, and in Suisun Bay, *Microcystis* colonies are typically not detected (Figure 4).

Figure 4. Abundance of *Microcystis* units (Units/ml) analyzed microscopically averaged across the summer season



(June–September) and recent time period (years 2017–2022) for individual stations in the Delta. *Microcystis* colony abundance data from EMP program courtesy of Tiffany Brown and DWR.

A growing number of studies in the Delta are using molecular methods to monitor cyanobacteria. The most widespread technique to identify the presence of specific cyanobacteria genera is to amplify the gene encoding the small subunit (16S) of ribosomal RNA using quantitative polymerase chain reaction (qPCR) (i.e., 16S rRNA amplification). Portions of the 16S rRNA gene sequence are highly conserved among all bacteria, including cyanobacteria, and this method can generally be used to enumerate total cyanobacteria or a specific genus of cyanobacteria (Janse et al. 2003). To evaluate species of cyanobacteria present in the community that are potentially toxigenic (i.e., produce cyanotoxins), qPCR of 16S rRNA sequences can be combined with qPCR of DNA sequences encoding toxin production genes. For example, a commonly used gene to detect potential microcystin toxin production is the microcystin synthase B (*mcyB*) gene. Quantitative amplification of a region of the *mcyB* gene combined with amplification of 16S rRNA can give insight into toxigenic *Microcystis* strain composition (Otten et al. 2017). RNA-based qPCR is useful for determining the relative abundances of single cells and small colonies that are too small to enumerate quantitatively by microscopy.

RNA-based qPCR has been used to measure total cyanobacteria and the percent abundance of the most common Delta cyanobacteria genera such as *Microcystis*, *Aphanizomenon*, and *Dolichospermum* (Lehman et al. 2017). RNA-based qPCR have confirmed that the abundance of cyanobacteria is likely dominated by genera that are less than 10 μm (Lehman et al. 2017). For example, small single-celled cyanobacteria such as *Synechococcus* are often present in background populations (Lehman et al. 2017, Kimmerer et al. 2018). These unicellular cyanobacteria are difficult to observe and generally not considered nuisance populations, thus they are commonly discounted in surveys of cyanobacterial populations. However, some of the unicellular cyanobacteria genera such as *Synechococcus* can also produce cyanotoxins (e.g., Vareli et al 2012, Kopfmann et al., 2016) and contribute to the pigment signal used to measure cyanobacteria.

Monitoring Considerations

Microscopic examinations indicate that Microcystis dominates in terms of the biomass of cyanobacteria. In contrast, RNA-based qPCR methods show that singled-celled cyanobacteria actually dominate the Delta cyanobacteria community. Although microscopy is useful for determining the most problematic cyanobacteria biomass, RNA methods are important for determining the picocyanobacterial community. Thus, the cyanobacteria communities generated by each method currently are complementary, not identical (MacKiegen et al. 2022). As such, monitoring efforts should consider a combined-method strategy to fully understand the cyanobacteria community in the Delta. It is also important to recognize that microscopy results may vary based on the laboratory conducting the analysis whereas RNA based methods are more comparable across laboratories. As such, microscopy results may not be useful for evaluating statuses and trends if utilizing data sets generated in different laboratories.

2.1.4 Visual Identification

Unique to the Delta is the development and implementation of a visual index for ranking of relative *Microcystis* colony densities. Albeit qualitative, this is the most comprehensive CHAB dataset across the Delta. Called the *Microcystis* visual index (MVI), data for this index has been collected monthly at discrete stations since approximately 2007 by DWR and CDFW. MVI data are also collected opportunistically by other researchers and agencies. These programs rely on the same visual ranking scale that takes advantage of the relative ease of identification of *Microcystis* colonies floating on the surface of the water and gives a general idea of when and where blooms of *Microcystis* occur in the Delta. This method is performed by ranking the density of colonies in the water or in a bucket according to a scale from 1-5 where 1 is absent and 5 is relatively high as depicted in Figure 5.

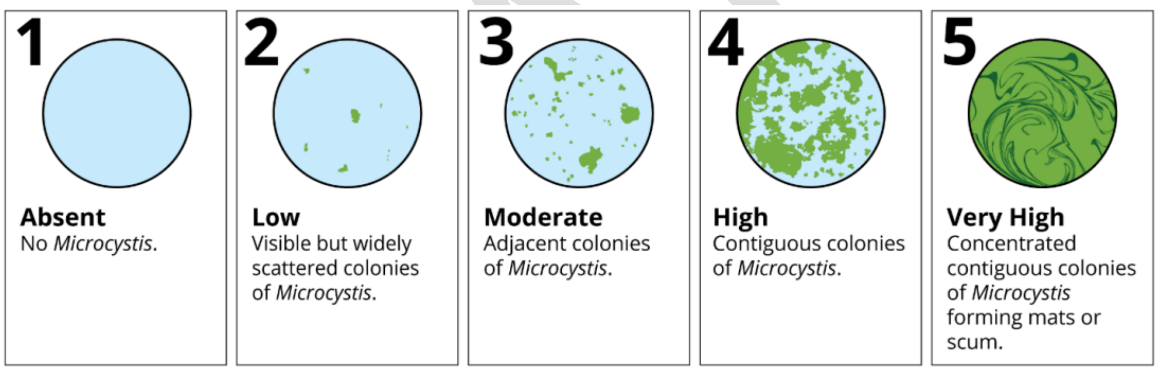


Figure 5. Microcystis visual index (Flynn et al. 2022)

For the past five years, the greatest frequencies of MVI Levels 4 and 5 have occurred close to Clifton Court in the south Delta, at Mildred Island, and the Middle and upper San Joaquin River (Figure 6A). These observations are consistent with the greatest mean summertime *Microcystis* colony abundances presented in Figure 4. While combined Level 4+5 frequencies (i.e., relatively high colony abundance for the Delta) typically occur at only select stations in the Delta, combined Level 3+4+5 MVI frequencies occur much more commonly throughout the Delta, including at stations surrounding Mildred Island, most of the San Joaquin River, Old River south of Franks Tract, and in Franks Tract (Figure 6B).

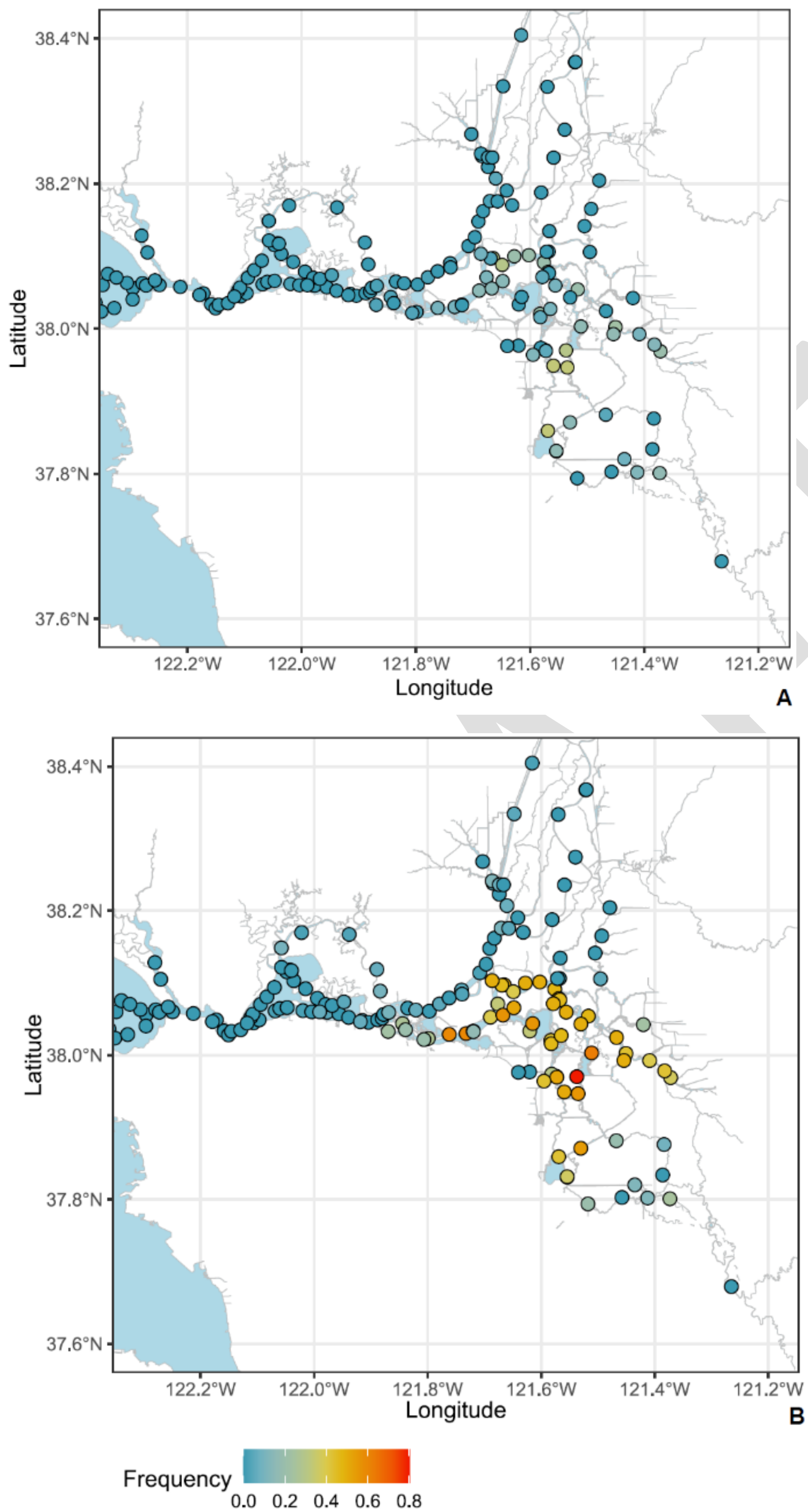


Figure 6. Map of (A) Frequency of occurrence of Microcystis Visual Index (MVI) levels 4+5 (Frequency=$Count_{level}/Count_{sumlevels}$) and (B) frequency of occurrence of MVI levels 3+4+5, for the summer season (June–September) and recent time period (years 2017–2022) for individual stations in the Delta. Data available at: (https://portal.edirepository.org/nis/mapbrowse?packageid=edi.731.7).

In an analysis of the rank distribution of Level 1 frequencies (i.e. *Microcystis* absent from the water) by region, only the 25th percentile rank included regions with Level 4 and 5 occurrences. These regions recorded Level 4 observations annually starting in 2012, and Level 5 observations close to annually starting in 2016, suggesting that the occurrences of Level 4+5 observations are on the rise in specific regions within the Delta (ESA 2022).

Monitoring Considerations

It is important to note that the assignment of Levels in this index are subject to individual observer bias. As such, improvements to standardize the visualization step with this method can be recommended (perhaps by use of bucket combined with digital photograph). Other recommendations may include a step-by-step written protocol (see Flynn et al. 2022), and the establishment of a training program to ensure more consistent and reliable scoring among agencies and staff.

2.2 Cyanotoxins

Concomitant with CHAB events, cyanotoxin detections have been growing in frequency and severity. Due to the high costs associated with toxin analyses, cyanotoxin monitoring has generally been associated with special studies or by opportunistic bloom response sampling. Further complicating toxin monitoring efforts, cyanotoxins are ephemeral and episodic. To date, microcystins have been the most monitored and detected cyanotoxin group throughout the Delta (Lehman et al. 2021, Kudela et al. 2023), with concentrations attributed to *Microcystis* (Otten et al. 2017). Thus, microcystins are discussed separately below from the other cyanotoxins that have been monitored less frequently, only detected occasionally, and detected at low concentrations.

For a synthesis of marine and brackish HAB toxins in San Francisco Estuary see Kudela et al. (2023).

2.2.1 Microcystins

Hepatotoxic microcystins, produced by a number of genera including, *Microcystis*, are recognized as the most common global cyanotoxin (Harke et al. 2016, Preece et al. 2017). Indeed, microcystins are the most frequently detected cyanotoxin in the Delta. The highest microcystin concentrations have been measured in edge water habitats and hydrologically isolated dead-end sloughs (CCHAB Network 2022, https://mywaterquality.ca.gov/monitoring_council/cyanohab_network/, Robertson-Bryan, Inc. 2023). This is exemplified in the dead-end Stockton Waterfront, an area known for dense CHABs. At this location in 2020, microcystins measured 1,239 μg/L in a scum sample and 61.1 μg/L in the surrounding water in 2020 (CCHAB Network 2022, https://mywaterquality.ca.gov/monitoring_council/cyanohab_network/). In contrast, open water areas of the Delta where dispersed flakes of *Microcystis* dominate (instead of small dense colonies), toxin concentrations are typically below the CCHAB Network's Danger trigger (i.e., 20 μg/L) and generally below the California Warning trigger of 6 μg/L (Lehman et al. 2017, Robertson-Bryan, Inc. 2023, *Personal Communication, Brianne Sakata, April 2023*). Concentrations are also frequently below the California Caution trigger of 0.8 μg/L (Lehman et al. 2017, Lehman et al. 2022). However, this is a limited dataset and cannot be extrapolated to all open water areas of the Delta.

In addition to being detected in water samples, microcystins have also been found in sediments, zooplankton, fish, and shellfish within the Delta (Lehman et al. 2010, Bolotaolo et al. 2020, *Personal Communication, Tim Otten, January 15, 2024*). For example, tissue lesions consistent with liver toxins were documented in Inland Silversides (*Menidia beryllina*) and in juvenile Striped Bass (*Morone saxatilis*) caught during *Microcystis* blooms (Lehman et al. 2010).

Monitoring Considerations

Microcystins are generally most concentrated in edge water habitats such as dead-end sloughs and marinas where dense colonies are more likely to occur. Yet, toxin monitoring in these areas is reactionary and thus, there is no consistent or long-term toxin data for these locations. Routine microcystin monitoring has been implemented in a few open water areas of the Delta (e.g., Clifton Court Forebay, Banks Pumping Plant). However, a majority of the Delta has no routine microcystin monitoring.

2.2.2 Other Cyanotoxins

Low concentrations of anatoxin-a, saxitoxin, lyngbyatoxin, cylindrospermopsin, and anabaenopeptins have been detected occasionally where short-term studies funded analysis of additional toxins besides microcystins (Lehman et al. 2005, 2010, 2021, Mioni et al. 2011). Because toxin monitoring has primarily focused on measuring microcystin, it is unknown if other toxins are newer to the system or if the toxins have been missed due to a lack of monitoring. Notably, a recent two-year study on cyanotoxins found no saxitoxin in Asian clam samples at locations across the Delta (*Personal Communication, Tim Otten, January 15, 2024*).

These other toxins are commonly found at lower concentrations and have generally been detected via solid phase adsorption toxin tracking (SPATT) samplers that have recently become incorporated into some discrete monitoring stations and in boat-based mapping surveys. Occasionally anatoxin-a has been detected in whole water grab samples (*Personal Communication, Keith Bouma-Gregson, February 2024*). SPATT samplers are exposed to water for longer durations and more sensitive than water grab samples at lower concentrations. However, at high and ephemeral concentrations of toxins a SPATT sampler may reflect this bias and not be representative of average concentrations, but rather represent an integrated toxin concentration over the time of their deployment. As a result, grab and SPATT sampling methods are not comparable to one another, but are complimentary (e.g., Kudela 2011, Berg and Sutula 2015, Howard et al. 2017, Peacock et al. 2018).

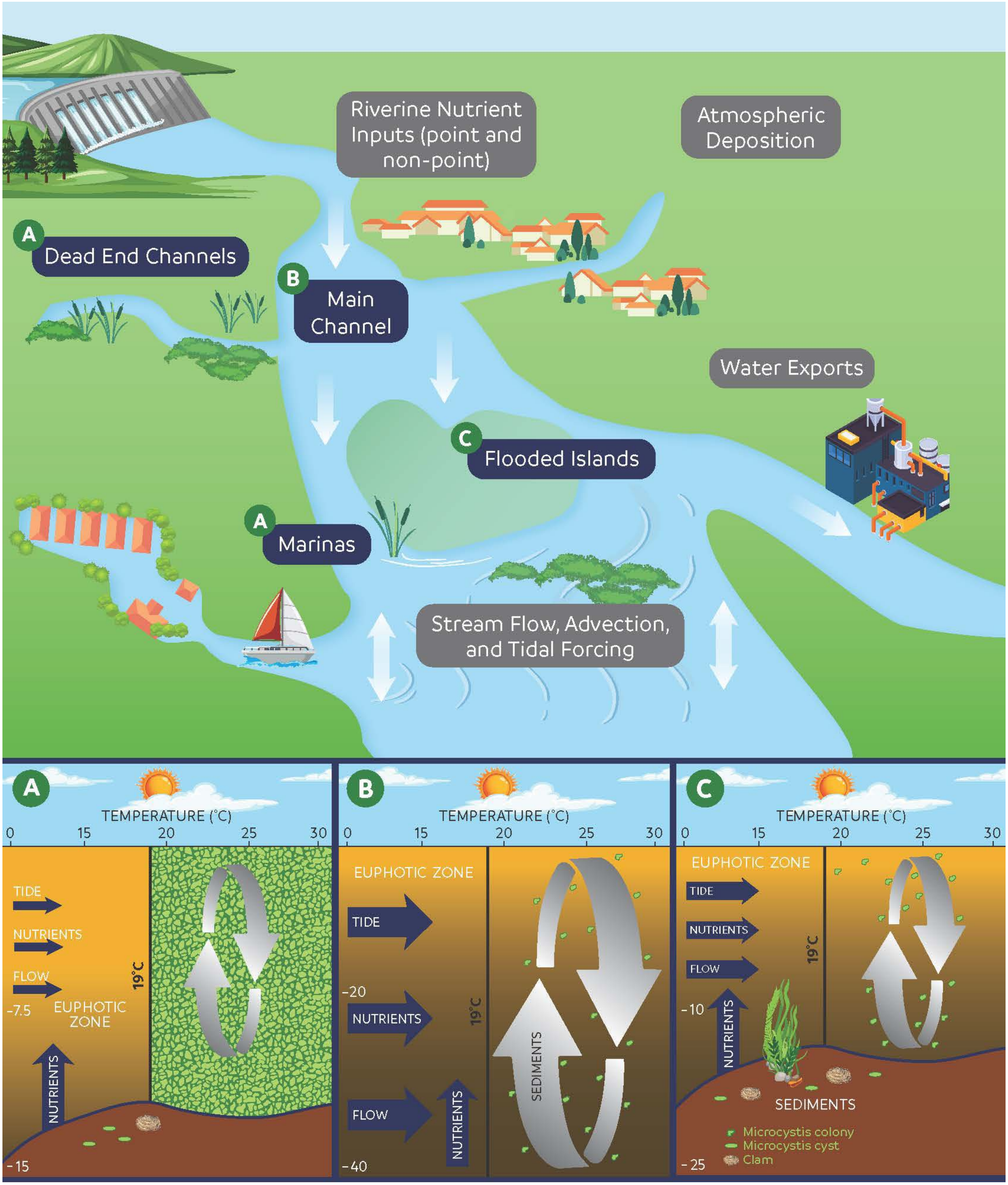
Notably, water grab samples collected as part of the routine cyanotoxin monitoring program at Clifton Court Forebay and Banks Pumping Plant have not detected any cylindrospermopsin, or anatoxin-a between 2014 to 2022 (*Personal Communication, Brianne Sakata, April 2023*).

Monitoring Considerations

A lack of cyanotoxin monitoring has made it difficult to determine where and when these other cyanotoxins may be present. SPATT samplers are an important tool that can be used to complement grab samples and to improve our understanding of toxin dynamics within a system.

2.3 Drivers of Delta CHABs

Knowing when and where CHABs will form is very difficult. Part of the process of getting closer to being able to predict their occurrences includes understanding how environmental drivers impact the frequency, magnitude, and intensity of their occurrences, as well as their toxicity. . While the word “driver” suggests a positive impact in terms of growth, there are also negative drivers which limit the growth of different CHAB species. Negative drivers may include processes such as sediment resuspension, which decreases light availability, water flow rate, which shortens residence time and time to grow in a region, and salinity, which may limit the distribution of a CHAB event to the freshwater and low salinity reaches of the San Francisco Estuary. These negative drivers work in tandem with positive drivers such as nutrients, temperature, and water column light availability to control cyanobacterial growth rates and ultimately CHAB occurrences. Below we discuss some of the drivers that have been suggested to play a role in CHAB occurrences in the Delta (e.g. Lehman et al. 2013, Berg and Sutula 2015, Lehman et al. 2017).



Riverine Nutrient Inputs (point and non-point)
Atmospheric Deposition
A
Dead End Channels
B
Main Channel
Water Exports
C
Flooded Islands
A
Marinas
Stream Flow, Advection, and Tidal Forcing
A
TEMPERATURE (°C)
0
15
20
25
30
TIDE
NUTRIENTS
FLOW
19°C
-7.5
EUPHOTIC ZONE
NUTRIENTS
-15
B
TEMPERATURE (°C)
0
15
20
25
30
EUPHOTIC ZONE
TIDE
-20
NUTRIENTS
19°C
SEDIMENTS
FLOW
NUTRIENTS
-40
C
TEMPERATURE (°C)
0
15
20
25
30
EUPHOTIC ZONE
TIDE
NUTRIENTS
19°C
FLOW
-10
NUTRIENTS
SEDIMENTS
Microcystis colony
Microcystis cyst
Clam
-25

1

Figure 7. Conceptual model for CHAB drivers in the Delta.

Top panel: Different physical environments provided by Delta waterways that influence CHAB development, including (A) dead end channels and marinas, (B) main channels, and (C) flooded islands with submerged aquatic vegetation (SAV) and wildlife. Processes that interact with these different types of physical environments include input of point and non-point nutrient sources, stream flow and tidal forcing, water exports, and atmospheric deposition.

Bottom panels: Representations of water column characteristics of
(A) *Dead-end channels and marinas* with weaker stream flow, weaker vertical mixing, lower degree of sediment resuspension, clearer water column, and longer residence times leading to less dilution of CHAB species and potentially higher primary productivity compared with the main channel. Less dilution can also result in a stronger coupling with the sediments aiding exchange of materials including nutrients. In this environment, *Microcystis* colony size may decrease, and colonies may become denser and more evenly distributed throughout the water column.
(B) *Main channels* with strong stream flow, lateral advection, tidal forcing, continuous vertical mixing (i.e. no change in temperature with depth), and a high degree of sediment resuspension. In this environment, CHAB species such as *Microcystis* are mixed from the top to the bottom of the water column, and spend limited time in the euphotic zone as the ratio of euphotic zone depth (Z_e) to total mixed water depth (Z_m), i.e. Z_e:Z_m may be 0.5 or less. Both limited time in the euphotic zone and vigorous physical mixing may produce lower growth rates and a colony morphology similar to small pieces of lettuce that are evenly distributed throughout the water column. In addition to vertical mixing, colony densities may also be limited by relatively short residence times and dilution.
(C) *Flooded islands* influenced by stream flow, lateral advection, and tidal forcings but with decreased depth and a Z_e:Z_m ratio of 0.5 or greater which potentially result in greater CHAB species productivity, but also greater contact and exchange with sediments containing filter-feeding grazers such as clams and SAVs competing for nutrients and resources. Both dead-end channels and flooded islands may be representative of *Microcystis* hot-spots in the Delta that may contain cysts in the sediments that allow blooms to re-establish from year to year.

2.3.1 Stream Flow and Residence Time

Blooms of cyanobacteria are sensitive to stream flow and water residence time both directly, by the rate that cells are flushed out of a region, and indirectly though changes in vertical mixing and turbidity following variations in stream flow (Paerl 2008). Over a Delta-wide scale, residence time (i.e. the time it takes to exchange the volume of water within a certain region) is primarily controlled by inflow. Inflow is driven by the combined streamflow in the Sacramento and San Joaquin Rivers, with the Sacramento River comprising approximately 83% of the total from these two sources (Arthur et al. 1996, Cloern and Jassby 2012). Outflow from the Delta constitutes the difference between inflow and water diversions to the state and federal pumping projects (i.e. exports) and typically varies around 70% of inflow on an annual basis (Monismith et al. 2002, Kimmerer 2004, Cloern and Jassby 2012). Inflow to the Delta varies substantially with precipitation and drought, with wet years greatly reducing residence time during the winter and spring months (Jassby et al. 1995, Kimmerer 2004). A useful index of the interannual variability in inflow is represented by “X2” which is the distance from the Golden Gate Bridge up the axis of the San Francisco Estuary to where the tidally averaged near-bottom salinity is 2 parts per thousand (Jassby et al. 1995). This distance typically ranges from 70 to 80 km, being closer to the higher end of the range in a drought year and the lower end of the range in wet years (Cloern and Jassby 2012). Decreased inflow to the Delta typically occurs during the July–September period, which coincides with peak water temperatures (Lehman et al. 2022). On a Delta-wide annual scale, inflow is inversely related to phytoplankton biomass accumulation (Jassby 2008).

Over smaller, regional scales, residence time is controlled by the combined interaction of tides, diversions, and physical characteristics of the channels (Gross et al. 2019). At this scale, differences in residence time can be evident on the spring-neap tidal cycle (Kimmerer 2004). During periods of low Delta inflow and outflow, flow modifications including salinity barriers and operation of gates such as the Delta Cross Channel may influence residence time in localized regions (Kimmerer et al. 2019).

Compared with the main channels that intersect the Delta, there are a number of locations such as dead-end channels and sloughs, marinas, and edge water habitats that have lower tidal or riverine velocity and lower water exchange with surrounding areas (Downing et al. 2016, Lenoch et al. 2021). Whereas relatively high-velocity flows serve to maintain low residence times and high flushing rates, preventing accumulation of phytoplankton biomass in the main channels (Jassby et al. 2002, Jassby 2008), increases in chl-a concentrations is evident in dead-end channels and sloughs as exchange with connecting main channels decreases during the summer period (Schemel et al. 2004). This occurs in deeper dead-end channels as well as shallower dead-end floodplains, underscoring the importance of residence time in the accumulation of phytoplankton, including CHAB, biomass (Lehman et al. 2008, Downing et al. 2016, Loken et al. 2022, Preece et al. 2024). Referred to as “hotspots”, a number of these hydrologically isolated dead-end sloughs have the potential for acting as CHAB incubators that seed surrounding waterways with CHAB cells (Spier et al. 2013, Preece et al. 2024). Potential influences in flow dynamics on CHAB biomass accumulations are represented in Figure 7 moving from a relatively fast-flowing channel (Panel B) to a dead-end slough (Panel A).

2.3.2 Sediment Resuspension and Water Column Light Availability

The main impact of sediment resuspension on CHABs is by limiting availability of light needed for photosynthesis and for growth (Visser et al. 20105). This is because resuspended sediments rapidly attenuate light with depth and restrict photosynthesis to the top layer of the water column (i.e. the euphotic zone). As a result, productivity decreases the more time phytoplankton spend below the euphotic zone, and growth rates tend to vary inversely with mixed layer depth (Cloern 1987, Alpine & Cloern 1988, Lucas and Cloern 2002, Mussen et al. 2023). For CHAB species such as *Microcystis* that have low photosynthetic efficiencies (e.g. Wu et al. 2009) and require exposure to continuous light in order to reach maximal growth rates (Mitrovic et al. 2003), mixing out of the euphotic zone and being exposed to fluctuating light restricts their growth (Mitrovic et al. 2003, Visser et al. 2015).

A persistent feature of the San Francisco Estuary, including the Delta, is the intense mixing of the water column due to tidal oscillations (Cloern 1991, Kimmerer 2004). High-energy tidal forcing combined with riverine sediment transport (i.e. McDonald and Chang 1997, Schoellhamer et al. 2012) leads to high suspended sediment concentrations and turbidity (Cloern 1987, May et al. 2003. Thus, mixing and sediment resuspension may be important negative drivers for CHAB occurrences in the Delta. Although not specifically investigated for the Delta, it is hypothesized that succession of various CHAB species could be connected with irradiance requirements. For example, *Microcystis* may be replaced by others such as *Aphanizomenon* as water flow and mixing increases (Lehman et al. 2022). Under even stronger mixing regimes, CHAB species may be replaced by eukaryotic green algae (Ibelings et al. 1994, Huisman et al. 1999). Summertime algal blooms in the Delta are mostly comprised of either green algae or filamentous or colonial cyanobacteria (Lehman et al. 2017), suggesting these two groups may occupy different niches based on, among other factors, water column mixing intensity.

2.3.3 Salinity

Most freshwater cyanobacteria cannot survive for extended periods of time in saline waters and therefore salinity can act as barrier to, and negative driver of, blooms (e.g. Sellner et al. 1988) However, some genera have a relatively high salt tolerance (Patiño et al. 2023). *Microcystis* has one of the highest salinity thresholds of all freshwater cyanobacteria. Literature reports generally agree that *Microcystis* has a salt tolerance of around ≤10 ppt (Preece et al. 2017). However, the adaptability and/or acclimation of some *Microcystis* strains to higher salinities allows cells to persist in more saline environments. This is exemplified in a study by Miller et al. (2010) that showed survival in seawater (average salinity of 35 ppt) for up to 48 hours. Salinity throughout most of the Delta is well below the 10 ppt salt tolerance threshold for *Microcystis* (Figure 8). Although *Microcystis* has been documented at salinities up to 18 ppt in the San Francisco Estuary just downstream of the Delta, it is likely to be stressed and not actively multiplying under these conditions (Lehman et al. 2005). Fewer studies have addressed the salt tolerances of other cyanobacteria species. Based on available literature it appears that the salinity tolerance of *Dolichospermum* and *Anabaenopsis* is similar to that of *Microcystis* (Moisander et al. 2002, Kemp and John 2006, Tolar 2014).

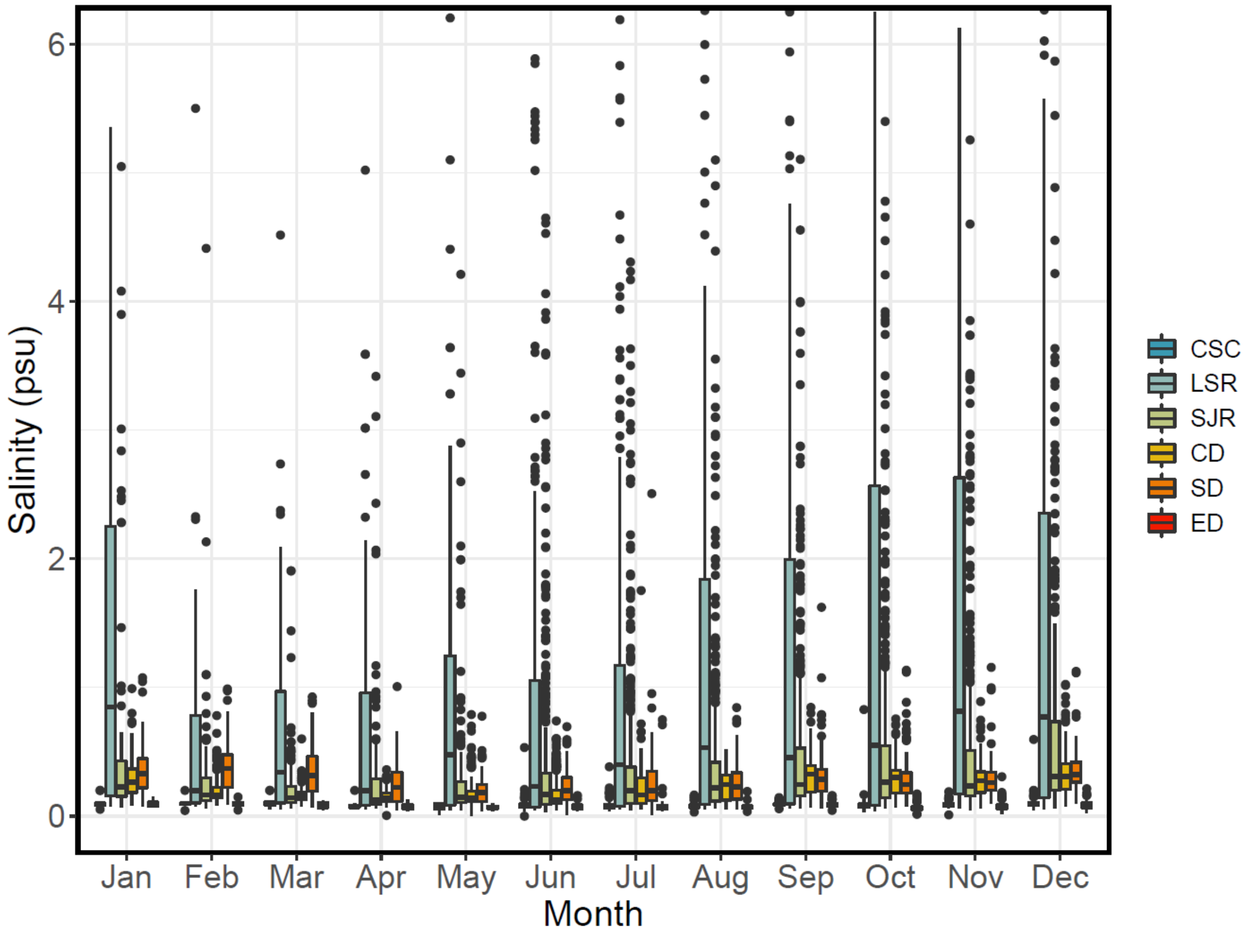


Figure 8. Boxplots of salinity by month and by region for the period 2008-2022. CD=Central Delta; CSC=Cache Slough Complex; ED=East Delta; LSR=Lower Sacramento River; SD=South Delta; SJR=San Joaquin River. Data from the Fall Midwater Trawl Survey (FMWT), Summer Townet Survey (STN), DWR-EMP, and DWR-NCRO monitoring programs available at: (https://portal.edirepository.org/nis/mapbrowse?packageid=edi.731.7).

Although *Microcystis* can survive at the salinities described above, *Microcystis* growth is constrained in more saline environments. Salinity impacts *Microcystis* physiology and growth through osmotic and ionic stresses that cause the inner membrane structure to contract. This disturbs the cellular osmotic balance, transport processes, and solubility of intracellular CO_2 and O_2 thereby slowing growth (Hageman 2011). Nevertheless, *Microcystis* cells have been shown to grow in a range of salinities (Otsuka et al. 1999, Tonk et al. 2007, Zhang et al. 2013, Qiu et al. 2022). Optimal salinities for *Microcystis* growth vary based on the system, strain, and or different physiological statuses of individual colonies (Bormans et al. 2023). Wang et al. (2022) reports optimal *Microcystis* growth occurred at a salinity of 0 ppt in the coastal Yuniao River, China and as salinity increased closer to the coast the relative abundance of *Microcystis* decreased. In contrast, a laboratory study found *M. aeruginosa* growth was higher at 4 and 7 ppt than in the control of 1 ppt (Qiu et al. 2022). The authors suggest these higher salinities promoted *M. aeruginosa* growth during the early stage of culture, in part because it facilitated photosynthesis. The same study found that a salinity of 10 ppt inhibited *M. aeruginosa* growth and caused irreversible damage to the organism.

As *M. aeruginosa* is transported through estuarine systems from freshwater to more saline environments it can cause cells to undergo a salt shock. This immediately decreases photosynthetic activity resulting in decreased growth (Georges de Aulnois et al. 2020). However, when cells are gradually exposed to increasing salinities, cells are able to acclimate or adapt and continue growing even if the cells originated in a lower salinity environment (Melero-Jimenez et al. 2019).

Salinities of 5 ppt are associated with higher microcystin production due to the upregulation of microcystin production genes (Qiu et al. 2022). Thus, *Microcystis* with higher salt tolerance have more intracellular toxins than those in lower salinity environments (Li et al. 2024). Increased salinity also results in higher osmotic pressures that cause *Microcystis* cells to lyse and release toxins into the surrounding waters (Preece et al. 2017). Salinities in most of the Delta remain below 6 ppt (Figure 8), so issues with increased toxin production and cell lysis would be of greater concern in waters downstream of the Delta.

2.3.4 Temperature

Temperature is recognized as one of the strongest positive drivers of CHAB events around the world (Pearl and Huisman 2008, Carey et al. 2012). One reason is that cyanobacteria achieve higher growth rates at warmer temperatures compared with other phytoplankton groups (Berg and Sutula 2015). For example, You et al. (2018) found optimal growth rate for *Microcystis* in the laboratory occurs at 27.5°C. In a survey of eight cyanobacteria the growth optima of two *M. aeruginosa* strains were 30–32.5°C and that of *Aphanizomenon gracile* was 32.5°C. Lower growth temperature optima were observed in *Cynlindrospermopsis raciborskii* and

Planktothrix agardhii, both 27.5°C, while *Dolichospermum* had an optimum of 25°C (Lurling *et al.* 2013). In another survey of six *Microcystis* strains, their temperature growth optima varied from 31–37° C (Bui et al. 2018). *Microcystis* also stands out with regard to being able to quickly accelerate its growth rate with increases in temperature (Carey et al. 2012). While the acceleration of growth rate with every 10°C increase in temperature (Q10) commonly varies from 1–4 for cyanobacteria in general it varies from 4–9 for *Microcystis*, the fastest acceleration recorded for any phytoplankton (prokaryotic or eukaryotic) species (Reynolds 2006).

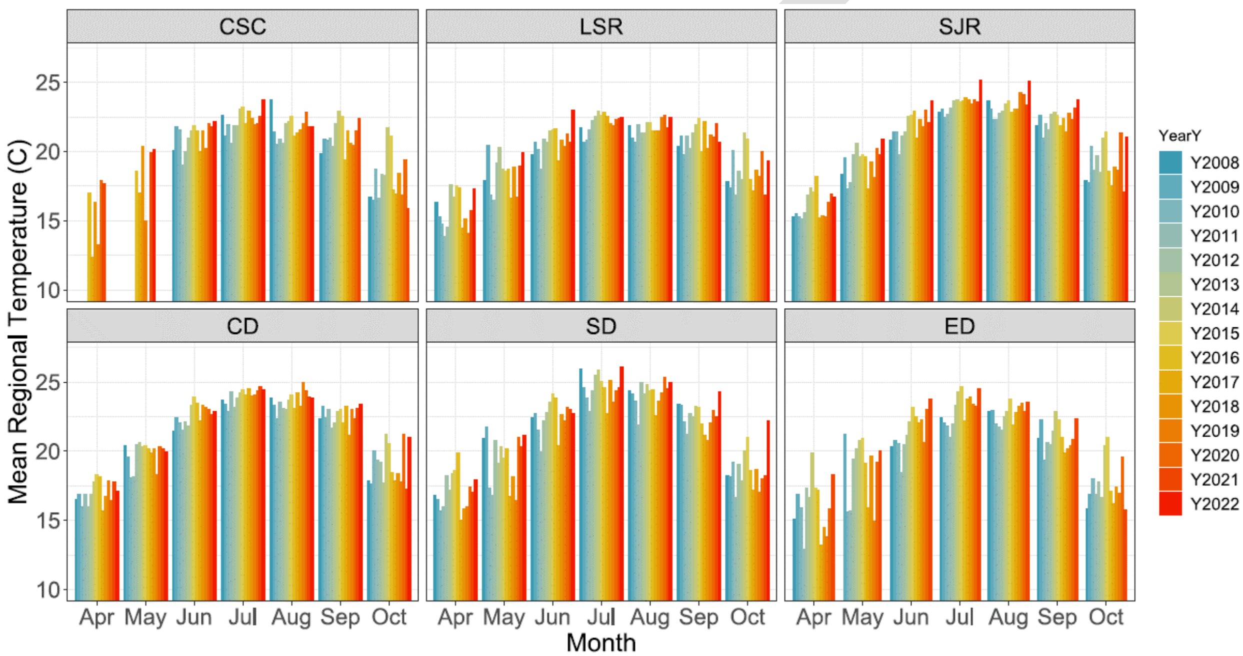


Figure 9. Monthly surface water temperatures averaged from daily surface water temperatures by year and by region for the period 2008-2022. Data from the Fall Midwater Trawl Survey (FMWT), Summer Townet Survey (STN), DWR-EMP, and DWR-NCRO monitoring programs available at: (https://portal.edirepository.org/nis/mapbrowse?packageid=edi.731.7). CD=Central Delta; CSC=Cache Slough Complex; ED=East Delta; LSR=Lower Sacramento River; SD=South Delta; SJR=San Joaquin River.

Surface water temperatures recorded in the Delta during the summer season are usually not as high as the growth optima of the various CHAB species mentioned above. However, water temperatures commonly exceed 23°C in Delta waterways during July–September, the period of peak CHAB abundance (Lehman et al. 2013). Notably, long-term temperature data is almost entirely restricted to main channels. In contrast with the main channels where high flushing rates may limit surface water temperatures, dead-end sloughs and marinas are more susceptible to higher absolute temperatures as well as increases over time. In these locations, surface water temperatures from July–September may range from 25–28°C or warmer (Preece et al. 2024) and could provide ideal conditions for CHAB species to outcompete other phytoplankton groups that have lower growth temperature optima (Berg and Sutula 2015 and references therein). Although these locations appear to have warmer temperatures, limited monitoring of dead-end sloughs and marinas had made it difficult to evaluate temperature changes and trends.

Throughout the Delta, mean monthly surface water temperatures peak in July but the absolute July temperature varies substantially by region (Figure 9). The regions with the lowest July temperatures are in the northern portion and include the Cache Slough Complex region and the lower Sacramento River region (Figure 9). The highest recorded mean July surface water temperatures are in the south delta region where they have varied from 25.9°C–26.1°C, followed by the San Joaquin River varying from 22.8°C–25.1°C, and the central Delta varying from 23.7°C–24.4°C, over the last 15 years (Figure 9).

Perhaps the most interesting month in terms of temperature changes over time in the Delta appears to be June. While at the beginning of the record presented in Figure 9 average June surface water temperatures varied around 19–20°C, the temperature hypothesized to promote the emergence of *Microcystis* from the sediments into the water column (Lehman et al. 2017), there has been a significant and linear increase in the June temperatures over time in several regions. The steepest change has been in the east Delta with an increase of 0.24°C per year, followed by the San Joaquin River at 0.15°C per year, and the central Delta at 0.10°C per year. Smaller increases have also occurred in the other regions of the Delta but are not significant (Table 1) In the south Delta temperatures are high relative to the other regions and do not appear to be increasing in the summer months like in the other regions (Figure 9). For example, in the south Delta June surface water temperatures have not increased significantly, varying between 22.4–22.7°C over the 2008–2022 time period (Figure 9, Table 1).

Table 1. Regressions of mean June surface water temperatures (°C) as a function of year (2008-2022; n=15) in six separate regions of the Delta. CD=Central Delta; CSC=Cache Slough Complex; ED=East Delta; LSR=Lower Sacramento River; SD=South Delta; SJR=San Joaquin River. Significant slopes in bold.

Region	Slope (Temp~Year)	Probability Slope	R^2
CD	**0.10**	**0.024**	**0.34**
CSC	0.09	0.132	0.17
ED	**0.24**	**0.005**	**0.50**

LSR	0.11	0.062	0.24
SD	0.06	0.372	0.06
SJR	**0.15**	**0.006**	**0.46**

Mean surface water temperatures have also increased for the months of May and October, extending the potential bloom season for *Microcystis* (e.g. Lehman et al. 2017), in a number of Delta locations (Figure 9). Previous studies suggest that *Microcystis* can persist in surface waters for eight months or longer as long as temperatures are warmer than 15°C (Lehman et al. 2017, Robertson-Bryan Inc., 2023).

2.3.5 Nutrients

Concentrations of nutrients can influence the composition, magnitude, and duration of CHAB events and is an important positive driver (e.g., Paerl 2008, Lehman et al. 2017, Wang and Zang 2020, Phlips et al. 2023). Dissolved inorganic nitrogen and inorganic phosphorus concentrations are relatively high across all regions in the Delta year-round (Figure 10). The two principal sources of these nutrients are point-source discharges from publicly owned treatment works (POTWs) and agricultural discharges in the form of irrigation return flows and other non-point discharges associated with agriculture (Kratzer et al. 2011, Saleh and Domalgaski 2015, Dahm et al. 2016). The two primary vehicles for loading of nutrients into the Delta are the Sacramento River, a principal source of nutrients from POTWs, and the San Joaquin River, a principal source of nutrients from agricultural return flows. During summer when inflows and dilutions are at a minimum, the San Joaquin River and the Sacramento River each contribute about half of the total nitrogen load to the Delta, despite the San Joquin River contributing less than 20% of the water flow volume (Kratzer et al. 2011, Novick et al. 2015).

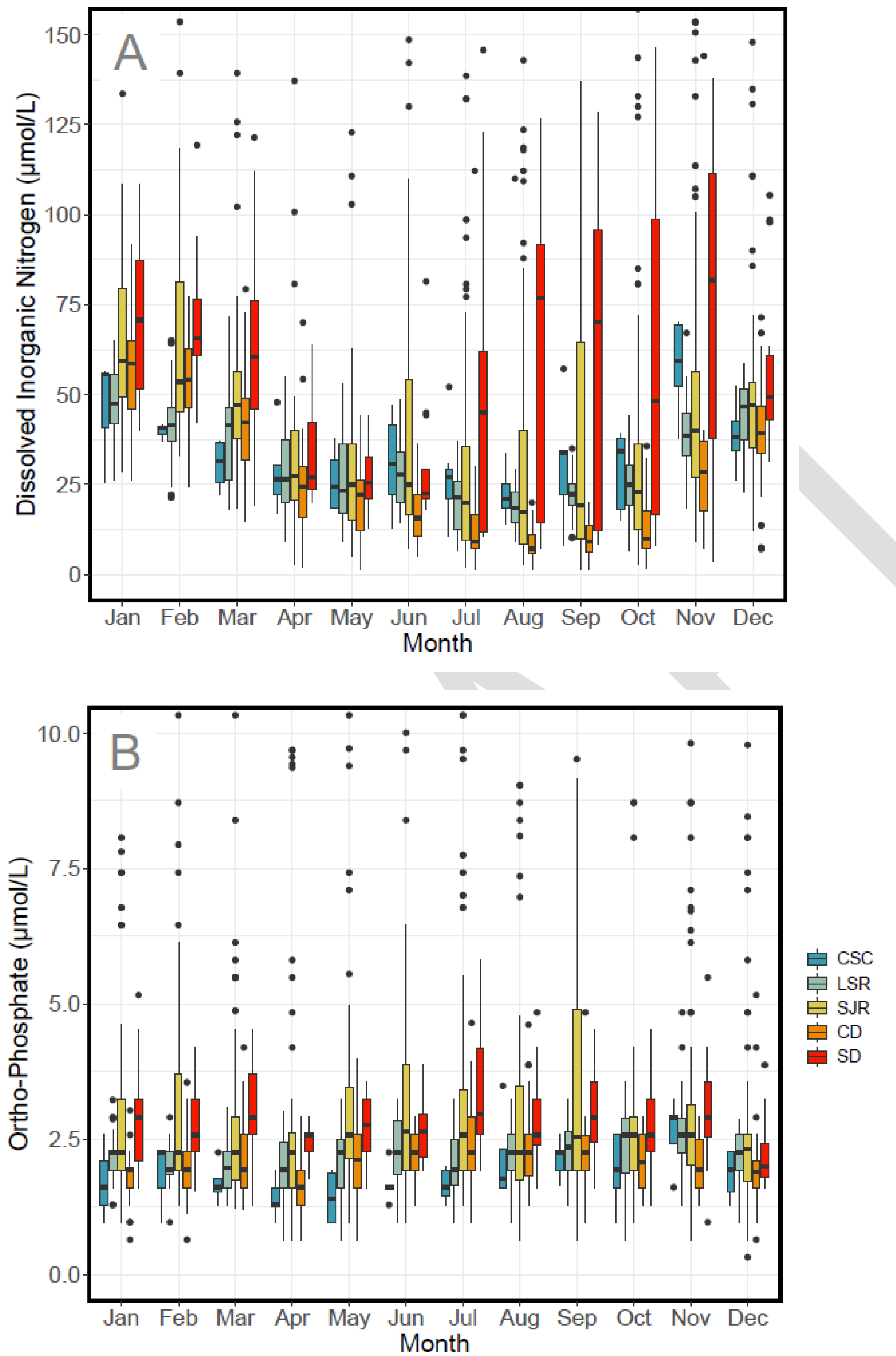


Figure 10. Boxplots of A) DIN (sum of nitrate, nitrite, and ammonium concentrations) and B) ortho-Phosphate, by month and by region for the period 2009-2022. Boxes show median concentration and 25th/75th percentiles; whiskers extend to 1.5x the interquartile range; outliers are shown as black dots. Data from IEP and NCRO programs available at (URL). CD=Central Delta; CSC=Cache Slough Complex; ED=East Delta; LSR=Lower Sacramento River; SD=South Delta; SJR=San Joaquin River. Data from DWR-EMP and DWR-NCRO monitoring programs available at: (https://portal.edirepository.org/nis/mapbrowse?packageid=edi.731.7).

Given optimal temperatures and irradiances for growth, the upper bound on phytoplankton biomass will be set by the concentration of nutrients available in the water. Referred to as the yield of chlorophyll, the magnitude of phytoplankton biomass that can be produced per unit nutrient consumed has been investigated for freshwater systems based on phosphorus (Dillon and Rigler 1975, Schindler et al. 1978) and for estuarine and coastal systems based on nitrogen (Gowen et al. 1992, Edwards et al. 2003). It is a useful parameter for predicting the size of a harmful algal bloom and for predicting eutrophication (Tett et al. 2003). This parameter has shown remarkable consistency within pelagic mixed phytoplankton communities (i.e. including eukaryotic and prokaryotic phytoplankton groups) across the freshwater to marine continuum (Tett et al. 2003). The reason for this consistency can be summed up as phytoplankton containing certain amounts of chlorophyll consume the same amount of nitrogen regardless of location. For example, the yield of chlorophyll from nitrogen (µg chl-a produced per µmol nitrogen utilized) in the lower Sacramento River was recently measured by Mussen et al. (2023) as 1.3 which is similar to the yield of 1.1 which has been measured in Scottish coastal water (Gowen et al. 1992).

While the yield of chlorophyll can be measured and calculated for any system, it cannot be used to predict the degree of eutrophication based on nutrient concentrations unless a complete depletion of nutrients occurs in the system. As such, the yield of chlorophyll may not be a useful parameter for predicting the degree of eutrophication that can be expected in Delta waterways where nutrients are not depleted even during months of peak phytoplankton productivity (Jassby et al. 2002).

Because nitrogen and phosphorus are not depleted, nutrients are often referred to as being in “excess” of phytoplankton growth requirements in the Delta (Jassby et al. 2002). Both the term “excess” and the term “limiting” with respect to nutrient concentrations are ambiguous. But they can be refined for a given system by comparing the potential yield of chlorophyll to the measured concentration of chlorophyll. If we define “limitation” as a concentration of nutrients that does not allow for a full doubling of existing phytoplankton biomass, and “excess” as a concentration of nutrients that allows two or more doublings of phytoplankton biomass then we can describe all the different regions of the Delta using a chlorophyll yield of 1.1 (e.g. Gowen et al. 1992). Focusing on the summer season, concentrations of dissolved inorganic nitrogen (DIN), i.e. the summed concentrations of nitrate, nitrite, and ammonium, typically varies from 8–20 µmol/L in the central Delta to 27–63 μmol/L in the south Delta (Figure 10A). Compared with measured chl-a concentrations of 2–4 μg/L in the central Delta and 6–26 μg/L in the south Delta (Figure 3), phytoplankton biomass could double two or more times. Therefore, we can describe DIN as being in excess of phytoplankton demand in all regions of the Delta.

One reason for phytoplankton biomass being low relative to the available nutrient pool has been discussed above and is related to light limitation of phytoplankton growth due to water column mixing and sediment resuspension (section 2.3.1). This is a physiological limitation. Other limitations at the population level may include factors such as grazing (e.g. Lopez et al. 2006) that act in concert with physiological limitations to potentially restrict the density of a bloom as well as the geographical distribution of CHABs in the Delta.

A question that comes to mind given the excess of nutrients available in Delta waterways is what would happen if conditions, whether it be temperature, mixing, sediment resuspension, or grazing, changed and phytoplankton were able to deplete the available pool of nutrients? In other words, how bad could eutrophication (and potentially CHAB events) become in the main channels if given the chance? Again, using the same chlorophyll yield relationship we can add the residual water column DIN concentration to the measured chl-a (because the chl-a represents DIN that has already been converted into phytoplankton biomass) to give the potential chl-a concentration that could be present in the water if nutrients were completely drawn down (Figure 11). This exercise demonstrates that the Delta phytoplankton community has “room to grow”, particularly in the San Joaquin River and in the south Delta (Figure 11). Moving into a warmer and hydrologically uncertain future, this large and unused nutrient pool may present an increasing risk for CHAB events. For an excellent review of the link between nutrients and CHAB dynamics, see Ibelings et al. (2021).

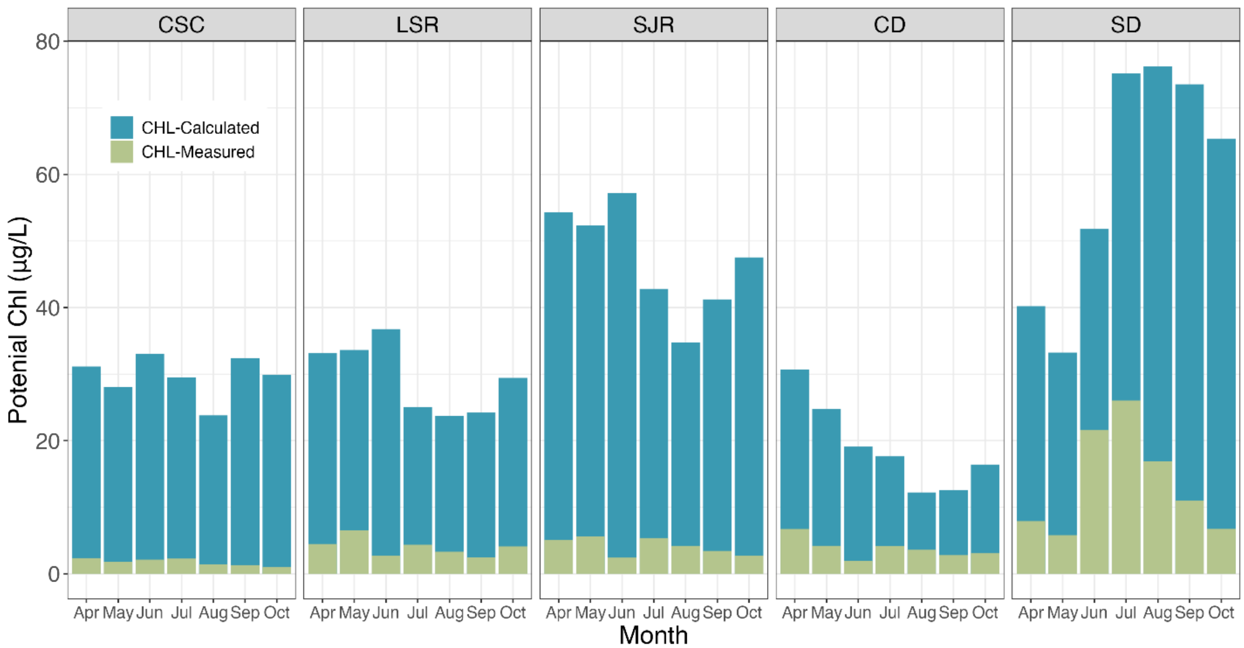


Figure 11. Potential chl-a averaged by month and by region for the period 2008-2022. Potential chl-a estimated as the sum of measured chl-a (CHL-measured) and chl-a calculated (CHL-calculated) based on the yield of chlorophyll from DIN (µg chl:µmol DIN; Gowen et al. 1992). Data from the DWR-IEP and DWR-NCRO programs, available at (https://portal.edirepository.org/nis/mapbrowse?packageid=edi.731.7). CD=Central Delta; CSC=Cache Slough Complex; ED=East Delta; LSR=Lower Sacramento River; SD=South Delta; SJR=San Joaquin River.

2.3.5 Cyanobacteria Seedstock

Cyanobacteria cells in the water column are subject to a range of fates, including physical export, death or dormancy. Dormant cells enter a vegetative state and sink out of the water column and into to the sediment. Overwintering vegetative *Microcystis* colonies remain photosynthetically active and reenter the water column through active resuspension when environmental factors provide favorable growth conditions or through passive wind-induce resuspension (Verspagen et al. 2005). Once established in a system, this overwintering strategy allows *Microcystis* cells to form recurring, seasonal blooms (Cai et al. 2021).

With no obvious upstream sources for *Microcystis* to enter into the Delta, the most likely source of summer blooms within the system is that they originate primarily from overwintering *Microcystis* seedstocks that recruit to the water column when conditions are favorable.

A recent study found that the hotspot location of the Stockton Waterfront and Discovery Bay had significantly higher seedstock ($p<0.05$) in April than the six other study sites including main channel sites and the flooded islands (*Preece et al., in review*). However, other locations also retained *Microcystis* seedstock in the spring suggesting that multiple locations in the Delta may seed summertime *Microcystis* blooms. Further work is necessary to fully elucidate the importance of cyanobacteria seedstock as a positive driver of CHABs in the Delta.

3 Overview of Current CHAB Monitoring Efforts

Although a coordinated program with dedicated funding for monitoring CHABs in the Delta does not exist, there are long-term ambient water quality monitoring programs in place that generate a remarkable coverage of ancillary data that can potentially be used to support CHABs monitoring. In addition, efforts have developed over time to monitor a few CHAB-specific parameters, but to date most information regarding CHABs in the Delta has been obtained through short-term special studies. The fragmented nature of these studies and current monitoring efforts highlight the need for the development of a strategy to achieve a coordinated and collaborative approach to CHAB monitoring.

Section 3.1 below describes the long-term continuous and discrete monitoring that is in place for water quality in the Delta that can be used to indicate the development or presence of CHABs. Maps in this section show the spatial coverage of monitoring by various partners. More information regarding the monitoring efforts of partners can be found in the Delta HABs Monitoring information sheet.

A recommendation of this strategy is to compile these a list of current and past special studies (Recommendation 4.5).

3.1 Long-term Continuous and Discrete Monitoring

Table 2 shows the ongoing monitoring programs for the Delta that collect continuous and/or discrete data that can be used to indicate the development or presence of a CHABs. The spatial scope describes the general areas in which the monitoring program oversees. Individual monitoring sites may have been added, removed, or moved by programs over time. Monitoring frequency may also have changed over time. The phytoplankton time span column notes when each program monitored phytoplankton. The water quality time span notes when the first relevant constituents to CHAB monitoring may have been added to these monitoring programs midway through the time spans. Thus, in most cases, the full dataset these organizations offer is not available for these full time spans. Agencies who manage water quality monitoring stations include the DWR, CDFW, USBR, and USGS.

Locations and water quality constituent data of the maps were consolidated from the California Data Exchange Center (CDEC), the Environmental Data Initiative (EDI) Delta Water Quality Integrated Dataset Package (Bashevkin, Perry, and Stumpner, 2022), and through personal communication with individual monitoring programs. Some stations may have been excluded from the map if they were not listed in CDEC or were no longer in service. CDFW stations were not included if data were only collected in either summer or fall, rather than in both seasons. Each monitoring program samples at an annual level but may occur at different periods throughout the year. DWR (Perry et al. 2023) and USGS have the longest time frame since the 1970's, and 1990's, respectively though methodological changes prohibit using their full extents. Differences in methods and monitoring locations within and between monitoring programs mean that some data are not comparable. This issue essentially shortens any one dataset and greatly limits the use of the existing data for any data intensive project such as forecasting CHABs formations and outbreaks. Note the lack of a cyanotoxin map. No long term continually funded program collects routine cyanotoxin data at set stations in the Delta.

Table 2. Temporal and spatial information about the monitoring programs included in Figures 6-10.

Agency	Dataset	Spatial Scope	Monitoring Frequency	Parameters	Phytoplankton Time Span	Water Quality Time Span
DWR	Environmental Monitoring Program	San Pablo Bay, Suisun Bay, Suisun Marsh, Montezuma Slough, Sacramento River, San Joaquin River, Old and Middle Rivers	At least monthly	Phytoplankton ID, MCVI, Chl-a, Nutrients, Temperature, Turbidity, Conductivity, pH, Dissolved Oxygen	1975-present	1975 - present
DWR	Yolo Bypass Fish Monitoring Program	Yolo Bypass, Cache Slough Complex, Sacramento River	Variable, roughly monthly, typically December/January through June	Phytoplankton ID, Chl-a, Temperature, Turbidity, Conductivity, pH, Dissolved Oxygen	1998-present	1998 - present
DWR	Water Quality Evaluation Section	South Delta, Central Delta, North Delta	Monthly	Phytoplankton ID, Chl-a, Temperature, Turbidity, Conductivity, pH, Dissolved Oxygen	2019- present (FlowCam)	1999-present
CDFW	Fish Restoration Program Effectiveness Monitoring Team	Cache Slough Complex, Lower Sacramento River, Confluence, Suisun Bay, Suisun Marsh	Spring, summer, and fall	Phytoplankton ID, MCVI, Chl-a, Nutrients, Temperature, Turbidity, Conductivity, pH, Dissolved Oxygen	2015-present	2016-present
USGS	California Water Science Center Biogeochemistry Group	Delta wide during mapping surveys (30 sites), currently ~12 fixed stations but amount of sampling depends on funded projects.	Monthly, spring, summer, fall	Phytoplankton ID, MCVI, Chl-a, Nutrients, Temperature, Turbidity, Conductivity, pH, Dissolved Oxygen , Algal Toxins	2018-present	1971- present

Agency	Dataset	Spatial Scope	Monitoring Frequency	Parameters	Phytoplankton Time Span	Water Quality Time Span
USGS	SFB Research and Monitoring Program	San Francisco Bay, San Pablo Bay, Suisun Bay, and Lower Sacramento River	Every 2 weeks, monthly, year-round	Phytoplankton ID, Chl-a, Nutrients, Temperature, Turbidity, Conductivity, pH, Dissolved Oxygen	1992-present	1969- present
SWB/SFEI	HAB Satellite Analysis Tool	Statewide lakes and major water bodies including Cache Slough, Franks Tract and lower Sacramento and San Joaquin Rivers.	Composite 1- or 10-day pixel max.	Cyanobacterial index; Chl-a (beta)	2016-present, (Cyanobacterial index); 2023-present (Chl-a)	N/A

The series of maps below show where existing monitoring stations collect long term data related to CHABs by the monitoring programs in Table 2. Data collected at these locations can potentially be leveraged toward a collaborative monitoring strategy and help in implementing other aspects of this strategy including providing information on the status, trends, and drivers of CHABs.

The map in Figure 12 shows the extent of the HAB Satellite Analysis Tool, as described in section 2.1.2 Remote Sensing. This tool estimates cyanobacterial abundance and chlorophyll over time in large waterbodies. It does not cover benthic blooms because measurements are based on surface reflectance. The other maps, Figure 13-Figure 16, spatially summarize long term water quality monitoring programs with consistent funding, as defined by their agencies. The continuous stations (Figure 13) collect water quality data and chlorophyll concentrations. The nutrient monitoring stations (Figure 14) represented a mix of stations with continuous monitoring by sensors and stations where discrete grab samples were collected and analyzed in a laboratory. The *Microcystis* index score (Flynn et al., 2022) measurements were collected discretely (Figure 15), thus, monitoring at these locations occurred at different frequencies and different periods of the year including summer and fall or year-round. Routine phytoplankton monitoring stations, which monitor for the abundance of phytoplankton taxa, including cyanobacteria, and biovolume are obtained at each sampling location (Figure 16). The locations of the phytoplankton stations were obtained from USGS's Data Integration Portal Phytoplankton dashboard and verified with each individual monitoring program. Additional maps with monitoring data are in Appendix A.

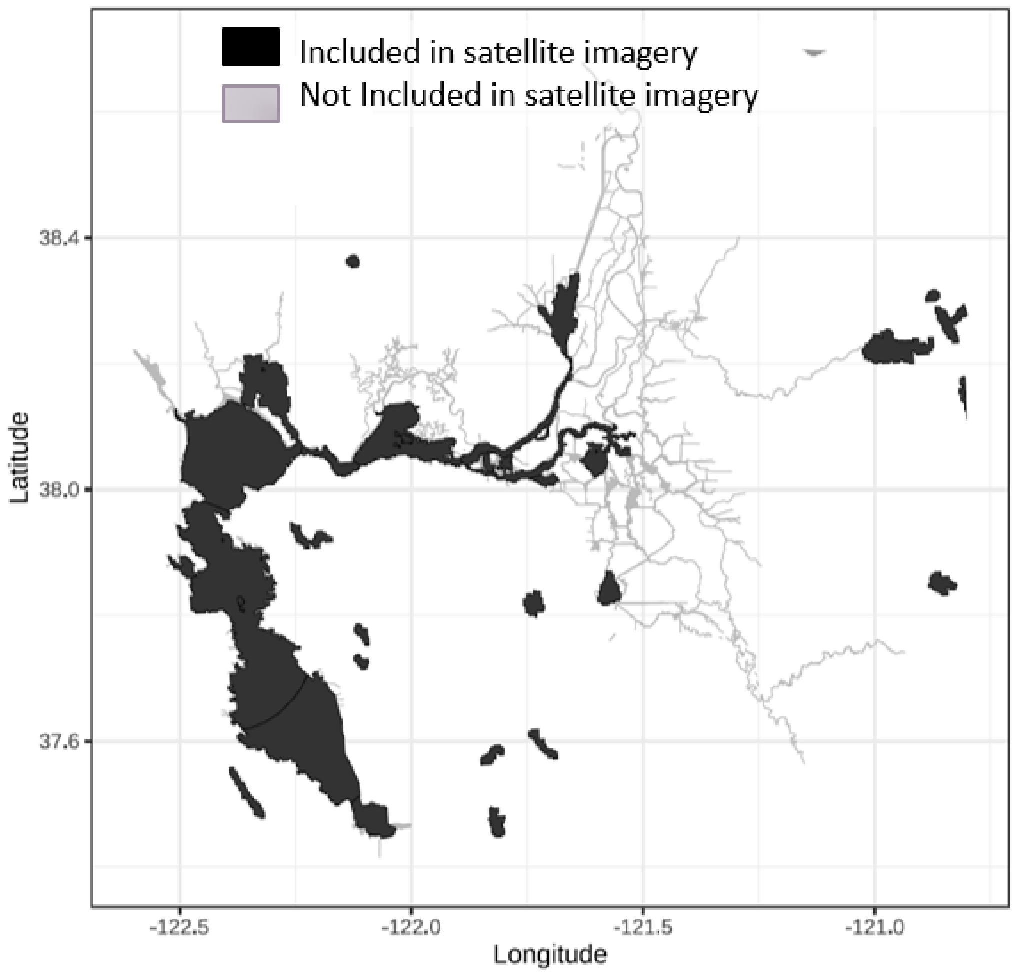


Figure 12. Map of sites that are covered by the SWB Harmful Algae Satellite Analysis Tool hosted by the San Francisco Estuary Institute. The area covered by the tool is filled in black. The tool routinely acquires satellite-imagery products with data sourced from geospatial satellite imagery from Sentinel-3's Ocean Land and data post-processed by NOAA.

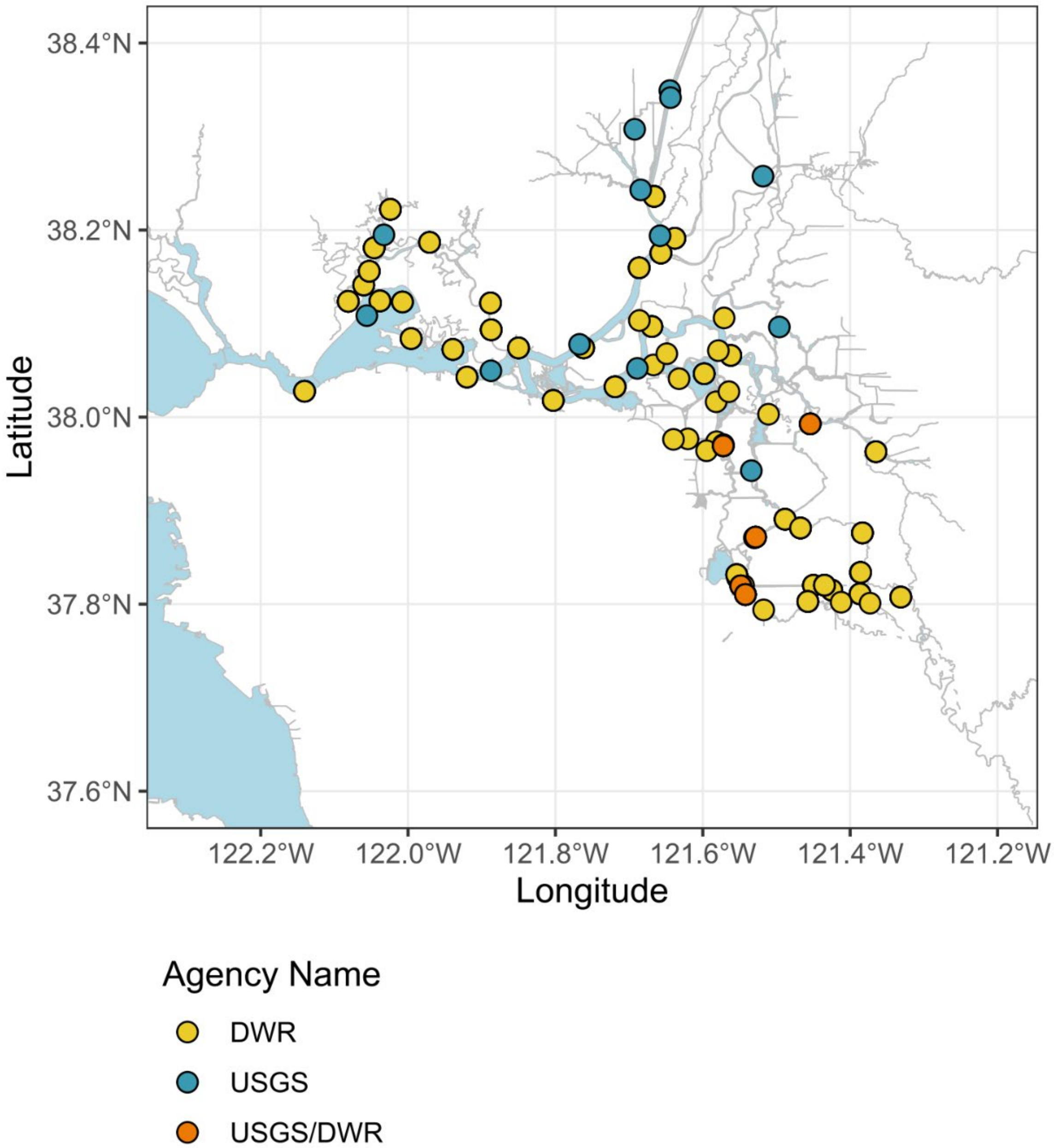


Figure 13. Map of continuous water quality stations that measure pH, dissolved oxygen, electrical conductivity, temperature, and chlorophyll.

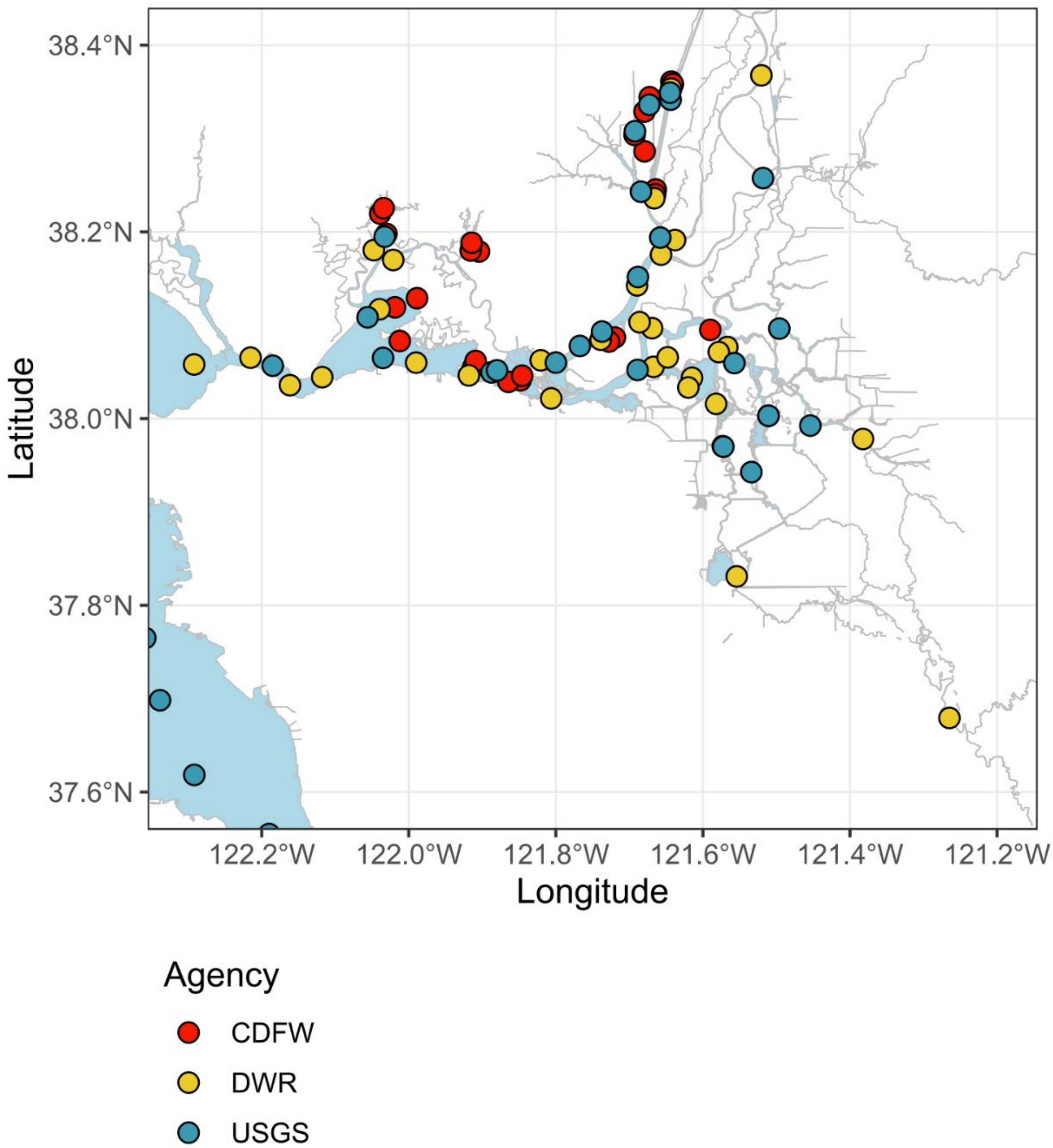


Figure 14. Map of stations that measure dissolved ammonia, dissolved nitrate/nitrite, dissolved organic nitrogen, and/or total Kjeldahl nitrogen. Total phosphorus and/or dissolved orthophosphate measurements are collected at the CDFW, DWR, DWR/USBR, and a subset of the USGS stations. See Appendix A for map showing information on phosphorus.

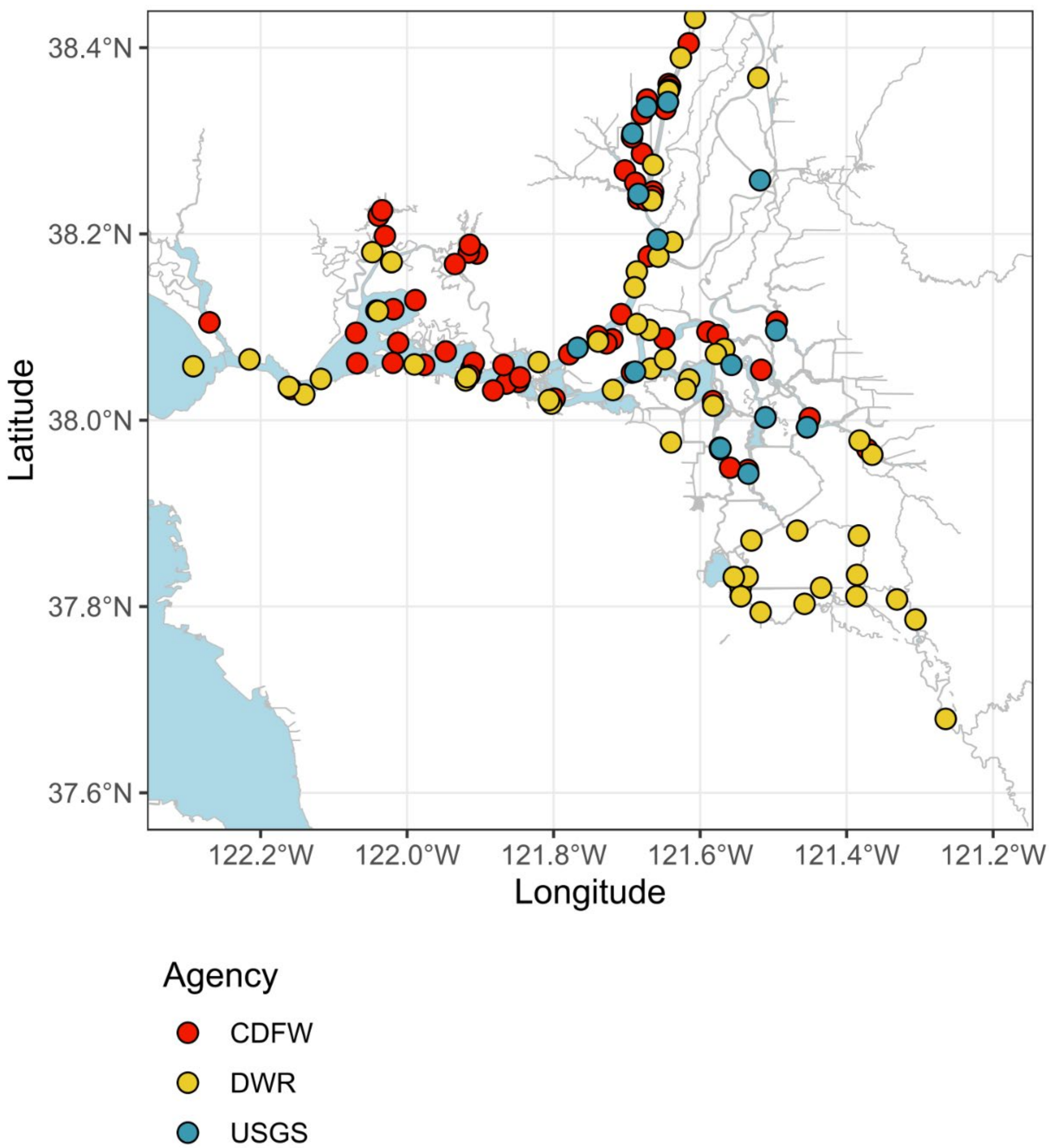


Figure 15. Map of Microcystis Visual Index Scale measurement locations.

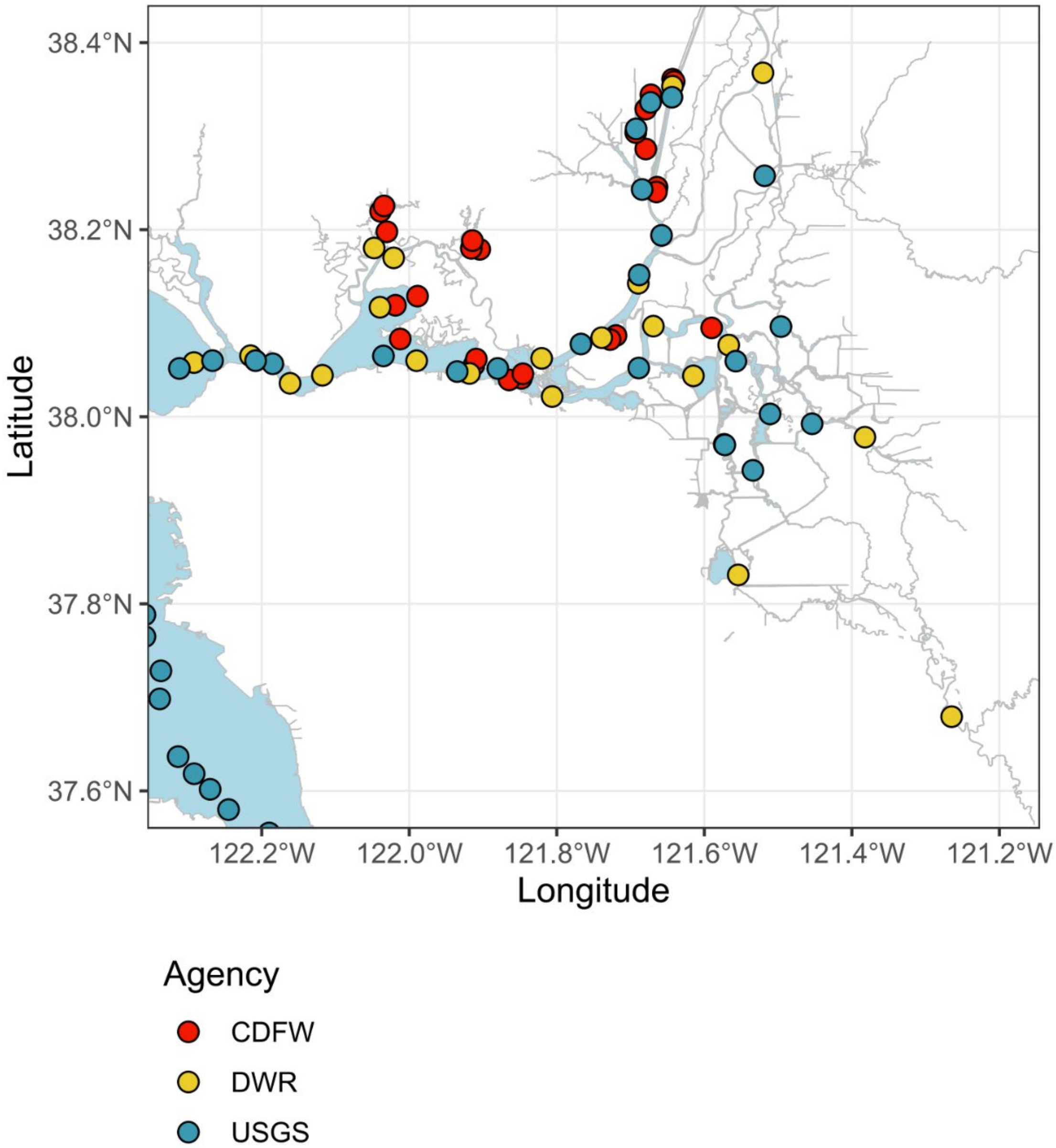


Figure 16. Map of phytoplankton measurement locations at which samples were collected for taxonomic analysis and biovolume measurement. Depth of sample collection varied by program.

3.2 On-going Parallel Efforts

3.2.1 SWB's FHAB Framework and Strategy

The SWB FHAB program began in 2014 and in 2019 the Governor signed AB834 to establish a formal statewide program. In 2021, the FHAB program, in partnership with Southern California Coastal Watershed Project, released a "Framework and Strategy for Freshwater Harmful Algal Bloom Monitoring" that provided the background for development of this strategy.

The FHAB Framework and Strategy project is referenced throughout the recommendations in Section 5 below as goals, objectives, and recommendations build off the information contained in that document.

3.2.2 SWB's Bay-Delta Water Quality Control Plan updates

The SWB is currently updating the Water Quality Control Plan for the San Francisco Bay and Sacramento-San Joaquin Delta (Bay-Delta Plan). The Staff Report acknowledges that CHABs are increasing in magnitude and frequency in the Bay-Delta system yet are not routinely monitored. The Staff Report states the SWB's intent to coordinate with the development of this Strategy as well as the broader community to ensure that the highest priority monitoring for CHABs is conducted. Additionally, the Staff Report iterates the SWB's interest in pursuing special studies and synthesis of HABs data in the Delta to fill knowledge gaps.

3.2.3 Delta Regional Monitoring Program

The Delta Regional Monitoring Program (RMP) is conducted by entities with discharges or project activities that will likely impact Delta water quality. The Delta RMP intends to track and document the effectiveness of beneficial use protection and restoration efforts through comprehensive monitoring of water quality constituents such as those that drive CHABs (i.e., nutrients). For FY-23-24, the Delta RMP is continuing long-term planning for nutrients and the Nutrient Technical Advisory Committee has been directed by the RMP Steering Committee to develop a multi-year study plan.

3.2.4 NOAA MERHAB

In September 2023 NOAA announced that it was awarding a grant, through its Monitoring and Event Response Research Program (MERHAB) to support the development of a HAB monitoring program for the San Francisco Estuary. The project, led by scientists at the SFEI, USGS, and DWR, will leverage on-going research and monitoring activities in the Bay and Delta to build a robust system-wide HAB monitoring program for the San Francisco Estuary. Key collaborators include UC Santa Cruz, Bend Genetics, the San Francisco Bay and Central Valley Regional Water Quality Control Board, San Francisco Bay Regional Water Quality Control Board, San Francisco Baykeeper, Cal Maritime Academy, Restore the Delta, and NOAA-NCCOS.

Major project components include:

1. Enhancing existing monitoring data sources with new technologies and tools, including: remote sensing, continuous water quality sensors, molecular DNA-based methods, and community science monitoring
2. Building an online HAB dashboard to provide managers with a decision-support-tool for HAB mitigation
3. Improved understanding of HAB transport dynamics through sampling of toxins/HAB cells using multiple methods such as water grab samples, passive samplers (Solid Phase Adsorption Toxin Tracking), shellfish, and molecular tools
4. Convening a Management Transition Advisory Group (MaTAG) composed of managers, regulators, and NGOs to generate information necessary for developing a coordinated HAB strategy

The MERHAB project is referenced throughout the recommendations in Section 5 below, as there are numerous opportunities to leverage the Delta CHAB strategy with components of the MERHAB project.

4 Knowledge Gaps and Collaboration Opportunities

As a result of the Fall 2022 workshop and a review of available Delta CHAB information (see above in Sections 2 and 3), a number of knowledge gaps – both data and collaboration related – were identified. Addressing these gaps will lay the foundation for the Delta science community to move beyond reactionary monitoring for CHABs to having tools to effectively gather data that can inform management and mitigation options for CHABs.

4.1 Data Gaps

1. The lack of routine CHAB monitoring data is a significant impediment to progress on mitigation and management for Delta CHABs.

2. Most monitoring to date has focused on main channels and excluded dead-end sloughs and backwaters, the areas of the Delta known for having the most severe CHAB problems. Data that has been collected in these dead-end areas have been disconnected from routine water quality monitoring programs. Thus, it is necessary to routinely monitor these areas in conjunction with interconnected Delta waterways to understand localized and broad scale CHAB dynamics and to inform the development of mitigation strategies..
3. Although the environmental factors that drive CHABs are understood in a general sense (e.g. warm temperatures, sufficient nutrients, etc.), many questions remain about the interaction between environmental factors, annual environmental variations, site specific processes, a changing climate, and how anthropogenic activities impact Delta CHABs.
4. There is not enough information on the importance of different CHAB drivers on a spatial or temporal scale, or funding available to implement realistic mitigation approaches or to develop a predictive CHAB model.

4.2 Collaboration Gaps and Opportunities

1. There is a collaboration gap amongst the state agencies that have legal responsibilities for water management and water quality.
2. There is no formal mechanism for collaboration with Delta communities and other interested parties.
3. The Delta science community would benefit from a standardized approach to monitoring and CHAB data analysis.
4. Data should be publicly available in format that is accessible and able to be readily integrated.
5. Training should be made available to ensure a consistent approach to sample collection and reporting.

5 Goals and Objectives and Recommendations

The overall goal of this document is to develop a collaborative and cohesive CHAB monitoring strategy for the Delta. Building upon the data and collaboration gaps, five primary goals were identified, and within each goal are two to four objectives that can help accomplish the goal (

Table 3. Goals and Objectives.). Detailed recommendations are provided to expand on the goals and objectives.

Table 3. Goals and Objectives.

Goal 1: Enhance Delta CHAB collaboration	• Objective 1-1 Organize collaborative approach to implement Delta CHAB Strategy • Objective 1-2 Promote coordination, collaboration, and communication among agency and community partners • Objective 1-3 Identify mechanisms to ensure sustainability of long-term Delta CHAB monitoring and collaboration.
Goal 2: Identify management questions, monitoring goals, and objectives	• Objective 2-1 Identify how monitoring results will be used by decision makers • Objective 2-2 Consider data and monitoring gaps needed to answer management priorities • Objective 2-3 Determine how to prioritize questions and goals
Goal 3: Develop a CHAB monitoring program	• Objective 3-1 Identify specific monitoring program(s) needed to achieve the management questions and goals • Objective 3-2 Identify priority monitoring parameters, locations, sampling period/frequency, and methods for the monitoring program(s) • Objective 3-3 Create implementation guidance for Delta CHAB monitoring • Objective 3-4 Synergize Delta CHAB monitoring with ongoing HAB efforts
Goal 4: Develop collaborative reporting protocols	• Objective 4-1 Validate and standardize current methods used for monitoring CHABs • Objective 4-2 Develop protocols for accurate and timely reporting
Goal 5: Utilize a data sharing platform	• Objective 5-1 Identify existing CHAB and HAB data repository platforms • Objective 5-2 Explore how to integrate Delta CHAB monitoring data with existing data repositories • Objective 5-3 Develop protocols to make CHAB data accessible and available to all

This Strategy is focused on informing water quality management decisions in a 3- to 5-year horizon, consistent with the FHAB Strategy's guidance of a "near-term" implementation. However, recommendations in this Strategy may also fall under long-term implementation of >5 years and are included for consideration as this Strategy is implemented. The focus of these recommendation are on water quality management decision support, but where possible we provide the nexus to public health.

There are multiple recommendations identified throughout different sections of this CHAB Strategy and some are conceptual while others are technical. There are some recommendations that have been previously implemented but have not included a collective agreement or 'buy-in' from all Delta interested parties. The development of the CHAB Strategy will provide the mechanism for this collective agreement to occur.

This section provides recommendations to address the overall goals and objectives of the Delta CHAB strategy. Table 6 summarizes the recommendations while the sections following provide details on each recommendation. Due to the costs associated with each recommendation, and other considerations, prioritization of the recommendations for funding will be necessary (*Recommendation 2.4 Provide approach(es) for prioritizing management questions and goals).*

Given general funding uncertainties and lack of an overall CHAB management framework for the Delta, an adaptive management approach is necessary to ensure implementation of this strategy is effective for all interested parties (Delta ISB 2022). Please see section 7 for details on the adaptive management approach.

5.1 Goal 1: Enhance Delta CHAB Collaboration

- **Objective 1-1 Organize collaborative approach to implement Delta CHAB strategy**
- **Objective 1-2 Promote coordination, collaboration, and communication among partners**
- **Objective 1-3 Identify mechanisms to ensure sustainability of long-term Delta CHAB monitoring and collaboration**

Recommendation 1.1 Identify co-chairs or mechanism for someone to lead coordination and implementation of Delta CHAB strategy

There is no funding associated with this strategy, thus to achieve this recommendation it is necessary to have one or more people volunteer to take this role. Several potential approaches for helping to achieve this recommendation include; 1) A rotation of key personnel – a representative from a different agency, two different agency representatives, etc. that rotates on a 2-3 year cycle, similar to the CCHAB Network co-chairs; 2) this work could be folded into an existing workgroup; or 3) an individual could be appointed as the full time lead and work with an interagency advisory panel to help direct the work.

This final option is most feasible if funding were secured to develop a funded position with a leadership role in representing all Delta CHAB partners and be a collective voice for all Delta-related CHAB issues. That person could implement this plan and develop any successor plans and policies for CHABs in the Delta and scale to HABs generally in the watershed and San Francisco Estuary. This position could potentially be developed by an agency or agencies or filled by a consultant.

Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy.

This recommendation is in place to develop the advisory committee to work closely with the lead(s) described in *Recommendation 1.1 Identify co-chairs or mechanism for someone to lead coordination and implementation of Delta CHAB strategy*. To ensure that this group is effective and able to effectively work together to develop final management goals and questions it is recommended that approximately 8 to 10 representatives serve on this group. One of the major roles of the advisory committee will be to work together to develop and finalize the management goals and questions (see Goal 2 and Recommendations below). In addition to developing and finalizing the management goals and questions the advisory committee should also plan to develop a prioritization structure to address the recommendations within this document (*Recommendation 2.4 Provide approach(es) for prioritizing management questions and goals*).

The first step in developing the advisory committee is to identify key personnel from government, citizenry, and stakeholder groups. This key group of key personnel should be willing and able to allocate sufficient time to work on developing the management goals and questions and to develop the monitoring strategy. The advisory committee should seek input from managers to ensure the strategy is able to address management needs. This can either be achieved by including managers on the advisory committee, or having manager representatives that have technical expertise participate. For the key personnel representatives may include those listed above in Section 1.4 Multi-Organization Coordinated Monitoring.

Although it will be critical to have the voices of many people heard in the advisory committee, *Recommendation 1.4 Strengthen and expand partner relationships* below focuses on how to include a wider group of people in the ongoing CHAB related work.

The advisory committee will coordinate with the MERHAB MaTAG to build consistency between efforts.

Recommendation 1.3 Identify existing barriers to collaboration/cooperation and identify methods for overcoming them

It is well recognized that there are many interested parties on the topic of CHABs in the Delta. This recommendation seeks to ensure that groups with a vested interest are allowed access to discussions on implementation of all components of this strategy. Special attention should be given to including those historically disenfranchised by government work such as Tribal nations and disadvantaged communities. The groups identified above in Section 1.4 Multi-Organization Coordinated Monitoring are those that have been identified as having significant interest in this work and can serve as a starting point for including the right individuals for this effort.

Goals of each represented group should be defined and opportunities to synergize efforts should be identified to promote the most mutually beneficial monitoring goals. Where goals are so dissimilar or valuable data collection or perspectives cannot be brought into this work, representatives for these groups should be brought together to discuss how to best work together and what could make partnerships more tenable. Depending on the severity of differences held, third party negotiation might be the most feasible to advance these conversations.

Methods recommended for identifying interested parties include:

- Workshop focused on identifying ways to develop partnerships specific to CHABs in the Delta. (*Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*)

- Maintaining all materials associated with implementation of the CHAB monitoring strategy in an accessible and public location. (*Recommendation 5.1 Develop a comprehensive list of all currently used data repository platforms, data resources, and other Delta CHAB related resources* and *Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard*)
- Upholding the FAIR principles for all data created as a result of implementation of this strategy. (*Recommendation 5.4 Incorporate open data principle*)

Recommendation 1.4 Strengthen and expand partner relationships

A number of relationships have been developed in the Delta CHAB community over the past decade. However, there continues to be a need to strengthen those existing relationships to ensure that everyone has a voice in how CHAB are monitored in the Delta. Existing relationships can be strengthened by reviewing current approaches and making adjustments based on community input.

There is also the need to expand the partner base by engaging with new members who have an interest in water quality issues. This expansion can include people directly/indirectly involved in monitoring, or other interested community members. These groups will be involved by receiving updates from the key personnel group and the co-chair of the overall strategy. These partners will also be invited to the annual meeting (*Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*) and asked for continued input as this strategy continues to be developed and refined.

A listserv could be developed for all Delta CHAB partners to ensure information related to this strategy, and Delta CHABs in general, reaches all interested parties.

Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs

As recommendations are implemented and lessons learned, consistent meeting of people engaged in Delta CHAB monitoring is necessary. This allows a cohesive approach to CHAB monitoring and community-based course correction to support adaptive management.

An annual meeting is an important event that can be used to keep the community informed about ongoing efforts related to CHABs. An annual meeting will require someone to lead the meeting each year. It will also likely require a funding source to pay for an event space. There are several approaches that can be used to identify a lead. First, a single agency could volunteer to lead the meeting each year.

Second, the co-chairs in *Recommendation 1.1 Identify co-chairs or mechanism for someone to lead coordination and implementation of Delta CHAB strategy* could ask for volunteers to lead the meeting. With either option it would be helpful to follow the approach taken to lead the Interagency Ecological Program (IEP) Annual Workshop. For the IEP Annual Workshop the leads rotate on a two year basis – having a 2nd person sit in to learn from the lead then leading the meeting the following year.

The first meeting can be used to orient people to the goals, objectives, and recommendations of this strategy (*Recommendation 2.5 Publish and share final management questions and goals with all interested parties*) and to hold the first training (*Recommendation 4.4 Develop training and intercalibration plan*). Subsequent meetings can also include trainings, provide a mechanism to implement the adaptive management strategy (see Section 6), and provide updates on monitoring and special studies (*Recommendation 4.5 Report on CHAB monitoring and special study findings*).

Recommendation 1.6 Identify funding to support implementation of the CHAB Monitoring Strategy

To ensure sustainability of Delta CHAB monitoring it will be necessary to secure funding, continue collaboration, and share data in a collaborative manner. Full implementation of this strategy will require funding from multiple sources. In addition to acquiring new funding, the funding may include in-kind contributions (e.g., staff time or direct funding), cost-sharing, regulatory actions, and/or grants. There has been interest expressed from various agencies that certain components of this strategy are priorities for them to fund. The advisory committee (*Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy*) can be used as vehicle to have funding related discussions and to identify different components of this strategy that can be implemented by various partners.

New legislative efforts may also be needed to address CHAB monitoring. For example, at the federal level, the Clean Water Act (CWA) establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. In 2014, the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act was signed into law. Under the CWA the SWB and Regional Water Boards (collectively, Water Boards) have regulatory responsibility for protecting the water quality and thus regulatory pathways that require and fund robust and regular monitoring. These pathways may include adding CHAB monitoring or payment for CHAB monitoring into existing permits. It is also possible that CHABs could be included in the SWB Water Right Decisions and Central Valley Regional Water Board's Basin Plan.

The California Legislature passed a bill that mandated the creation of the Freshwater and Estuarine Harmful Algal Bloom Program in 2019. Building off of this the California Legislature could allocate some funds annually to pay for some of the monitoring necessary to address CHAB issues in the state including in the Delta.

5.2 Goal 2: Identify management questions, monitoring goals, and objectives

- **Objective 2-1 Identify how monitoring results will be used by decision makers**
- **Objective 2-2 Consider data and monitoring gaps needed to answer management priorities**
- **Objective 2-3 Determine how to prioritize management questions and goals**

Recommendation 2.1 Consider the amount and type of monitoring information needed by managers to support decision making

Identifying management questions is necessary to inform the monitoring goals and objectives and to ensure that the monitoring plans are fit for their purpose (Howard et al., 2022). The amount and type of information needed to support decision making should be considered when developing management questions and goals. Since needs and interests will differ based on the specific needs and interests of each partner there will be a number of questions and goals. This will require a wide variety of monitoring information to be collected.

Below are some example management questions that highlight the nexus between the management questions and potential decisions that may be made based on each question. This set of example management questions can provide a working framework for the advisory committee (*Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy*) to use when finalizing the management questions for this strategy. Importantly, even after the management questions are finalized the adaptive management process should be used to continue to evaluate and refine these questions as more data is collected and collaboration is enhanced (Section 6).

Table 4. Example management questions and linkages to decision making

Category	Management question (large/regional spatial scale)	Example of decisions that are supported by the monitoring	Management question (small/localized monitoring scale)	Examples of decisions that are support by the monitoring
Status	What is the overall magnitude and spatial extent of CHABs within the Delta region?	• Prioritize waterbodies or hydrologically distinct areas; • 305(b) report; • Briefings for legislature and state agencies; • Inform status and trends report to the public	Are CHABs degrading water quality in this area of the Delta and what is the timing of when CHABs occur?	• 303(d) listing; total maximum daily load (TMDL) compliance; • Catchment conservation/ protection; • Public health advisory posting; • Inform changes to compliance monitoring
Trends	How are the magnitude, extent, and frequency changing over time?	• Prioritize waterbodies or hydrologically distinct areas; • 305(b) report;	Are CHABs in this area of the Delta getting better or worse over time?	• 303(d) listing; total maximum daily load (TMDL) compliance; • Catchment conservation/ protection;

		• Briefings for legislature and state agencies; Inform status and trends report to the public		• Public health advisory posting; Inform changes to compliance monitoring
Environmental Driver (Natural and Human causes)	What are the relative influences of flow and water residence time, nutrients, temperature, and other environmental factors in driving CHABs in hot spots and other areas of the Delta?	• Biostimulatory objectives and implementation policy • Environmental flow policy • State/regional nonpoint source control strategies • Irrigated lands program/Ag waiver requirements • NPDES permit requirements	What are the environmental drivers and controllable factors of CHABs in this area of the Delta?	• TMDL development and implementation through municipal stormwater (MS4), NPDES, and industrial permits; • Irrigated Lands Program/Ag Waiver Requirements, etc.; • Modification of water operations

CHAB Prediction	Which hydrologically distinct areas of the Delta are at risk of experiencing CHABs?	• Prioritization of funding for monitoring; • Inform development of management actions	What are the time periods that this area of the Delta most likely has a CHAB problem?	• Timing to go out to sample a waterbody for a bloom; • Prioritization of management actions, including monitoring requirement; • Modification of water operations
Mitigation and Prevention	What are the most effective mitigation and prevention measures for CHABs in the Delta over short- and long-term periods? What are short- and long-term management measures of HABs that would be applicable and effective in the Delta	• Briefings for Legislature and SWB; • Status and trends report to public on MyWaterQuality portal; • Inform funding mechanisms and prioritize funding; • Development and testing of CHAB mitigation measures	How effective are management actions in mitigating the CHAB problem in this area of the Delta?	• Adaptive management of watershed or waterbody-specific restoration actions (best management actions, floodplain restoration, water column mixing)

	to restore and maintain beneficial uses, and what steps would need to be taken prior to implementation?			
Management Activities	In what ways do different water management actions during drought affect the risk of CHABs?	• Prioritization of funding for restoration; • Prioritization of funding for monitoring of management actions • Inform water management actions • Inform Drought Contingency Plans	How do drought management actions affect CHABs in localized areas?	• Document, and to the extent possible, mitigate the impact of drought barrier(s), temporary barriers, operable gates, flow actions on CHABs
Environmental Impacts	What are the ecological impacts of CHAB's?	• Informing mechanisms to obtain funding;	Are the ecological impacts of CHABs most severe in hot spot locations?	• Prioritization of funding for monitoring of management actions

	What species are highest at risk to CHAB's?	• Prioritization of funding for monitoring;		

Recommendation 2.2 Consider regional, state, and national CHAB documents, strategies, and guidance when developing management goals and questions

There are a number of documents that address potential CHAB management goals and questions. These documents were considered in the development of the example management questions in *Recommendation 2.1 Consider the amount and type of monitoring information needed by managers to support decision making*. At a minimum the following documents should continue to be considered when finalizing the management goals and questions.

- SWBs' Framework and Strategy for Freshwater Harmful Algal Bloom Monitoring
- CCHAB Network's guidance to respond to CHABs
- SWAMP's California Freshwater Harmful Algal Bloom Field Guide and standard operating procedures (SOPs)
- Delta Regional Monitoring Program Nutrient Research Plan
- Interstate Technology Regulatory Council (ITRC) Strategies for Preventing and Managing Harmful Cyanobacterial Blooms
- ITRC Strategies for Preventing and Managing Benthic Harmful Cyanobacterial Blooms
- Delta Conservancy Compendium of Resources, Protocols, and Guidelines for Environmental Monitoring
- IEP Phytoplankton and water quality work group
- IEP Phytoplankton enumeration synthesis project
- Existing efforts have been captured in this document and will be included throughout implementation of this strategy.

Recommendation 2.3 When possible, coordinate Delta CHAB questions and goals with ongoing local and state efforts

Building off *Recommendation 2.2 Consider regional, state, and national CHAB documents, strategies, and guidance when developing management goals and questions*, it will be important to coordinate questions and goals with ongoing local and state efforts (e.g., see Section 0). There may be opportunities to leverage ongoing monitoring efforts and management questions and goals may build off ongoing work. Coordination with local and state efforts will also be useful for sharing ideas and information.

Recommendation 2.4 Provide approach(es) for prioritizing management questions and goals

A number of different management questions and goals are necessary to inform collaborative management and mitigation decisions. The advisory committee should identify a process for prioritizing the management questions and goals. This will allow different perspectives to be considered when choosing the prioritization structure. The prioritization structure and approach should also be discussed at the annual meeting (*Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*) to ensure open communication on the topic.

There are several approaches that could be considered by the advisory committee when developing the prioritization structure. One approach is to identify the monitoring needs that can be leveraged with existing monitoring programs or special studies that are currently in place (e.g., see Section 0). Another approach is to identify potential constraints such as inadequate resources, funding, time, or other factors that may impact the ability to meet a specific management question or goal. It may also be useful to designate certain questions/goals to agencies who are willing to provide resources to ensure sufficient monitoring is available to achieve the questions/goals.

This strategy was developed to inform water quality management decisions in a 3–5-year horizon, consistent with the FHAB Strategy's guidance of a "near-term" implementation. However, recommendations in this Strategy may also fall under long-term implementation of >5 years and are included for consideration as this Strategy is implemented. The advisory committee could choose to prioritize near-term recommendations as part of the prioritization structure.

Recommendation 2.5 Publish and share final management questions and goals with all interested parties

Once the management questions and goals have been finalized it will be important to share this information with all potential interested parties. The management questions and goals could be shared via the CCHAB Network webpage, through an email listserv (see *Recommendation 1.4 Strengthen and expand partner relationships*), or other means.

It will also be important to share the management questions and goals at the annual meetings (*Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*). The adaptive management process is an important part of this monitoring strategy. As additional information is learned about Delta CHABs and the science on the topic evolves it is likely that the management goals and objectives will be adjusted to adapt to this additional information. Thus, it will be important to keep the published version of the management questions and goals up to date.

5.3 Goal 3: Develop a Delta CHAB Monitoring Program

Objective 3-1 Identify specific monitoring program(s) needed to achieve the management questions and goals

- **Objective 3-2 Identify priority monitoring parameters, locations, sampling period/frequency, and methods for the monitoring program(s)**
- **Objective 3-3 Create implementation guidance for Delta CHAB monitoring**
- **Objective 3-4 Synergize Delta CHAB monitoring with ongoing HAB efforts**

Recommendation 3.1 Based on the goals and objectives developed in Goal 2 identify monitoring programs and special studies needed to achieve outcomes

A combination of a routine monitoring program(s) and special studies will be needed to achieve management goals. Routine CHAB monitoring is necessary to provide information on current conditions and data to understand status and trends. Design characteristics that should be considered in the development of the routine monitoring program(s) are described below in *Recommendation 3.2. Develop monitoring program(s) design characteristics*.

Despite the need for routine monitoring of CHABs in the Delta, it is recognized that some questions would be better addressed through special studies. These special studies can be focused on addressing technical questions related to the factors that cause CHABs, evaluate different monitoring techniques, evaluate feasible mitigation options, and address specific management actions. Collectively, special studies can advance the development of routine monitoring program(s) components and be used in the adaptive management process. A list of potential special studies is provided below in *Recommendation 3.5 Implement special studies to address data gaps and technical questions*.

Recommendation 3.2. Develop monitoring program(s) design characteristics

A monitoring program or programs will need to be designed with the purpose of satisfying the management questions and goals. The monitoring program(s) should also have enough flexibility to adapt to unforeseen circumstances and take advantage of novel techniques and technologies (Delta Independent Science Board (ISB) 2022). During the design phase it will be critical to consider how the data that will be collected can be used to address the management questions, goals, and management decisions identified in Goal 2.

The ITRC Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCB-1) and State FHAB Strategy have identified considerations for developing a CHAB monitoring program and are a good resource to use during the design of Delta CHAB monitoring program(s). These considerations are incorporated into the following Recommendations to provide Delta-relevant guidance for the monitoring program(s).

Decisions on the locations, frequency of samples, and specific sample types should be based on monitoring goals and objectives since different combinations may be used (Howard et al., 2022). While designing the monitoring program(s) it will be important to consider the funding, time, and personnel available to complete the monitoring and to leverage these resources with other projects when possible. Sustainability of the monitoring program(s) is important, thus design strategies should be incorporated to increase the likelihood of maintaining the monitoring program(s) over the long-term.

The following sections identify specific characteristics that should be incorporated into the monitoring design.

Recommendation 3.2.1 Identify geographic areas for monitoring

Based on the management questions and goals, different geographic areas may be prioritized for monitoring. For example, as identified in Data Gap 4.1.1.-2 the majority of CHAB sampling to date has occurred in the main channels. As such, static peripheral areas that often experience the most severe CHABs have been chronically understudied. This data gap is addressed in the management question "What are the relative influences of flow and water residence time, nutrients, temperature, and other environmental factors in driving CHABs in hot spots and other areas of the Delta?" To address this management question, it would be important to include areas that have historically been under sampled but have annual CHABs.

Other criteria may include identifying areas with annual blooms, areas that are most utilized by disadvantaged communities, areas that are most commonly used by special status species, areas that are already part of other routine water quality monitoring, etc.

Recommendation 3.2.2 Identify spatial coverage, temporal coverage, and monitoring frequency

Monitoring during and in response to a CHAB event is a reactive approach that can make it difficult to understand the conditions that caused the bloom to form. Thus, monitoring criteria should consider sampling before, during, and after a bloom event which in the Delta may require sampling throughout much of the calendar year (ITRC 2024).

The time of sampling should also be considered as cyanobacteria are strongly responsive to sunlight. To understand status and trends of CHABs it is useful to complete sampling during the same time period of a day.

When considering spatial coverage it is important to recognize that cyanobacteria blooms are often patchy and not uniformly distributed. CHABs are often most dense along the shoreline relative to the open water. Thus, multiple grab samples or a composite sample should be considered in the spatial design. The spatial component of the monitoring design should also consider where in the water column to collect samples and if it is worthwhile to collect integrated samples.

Some other questions to address spatial coverage, temporal coverage, and monitoring frequency include:

- How many sampling points are needed to answer each question?
- Follow CCHAB Network guidance that recommends monitoring events occur a minimum of two times per month at select stations?
- Should temperature threshold (e.g. 19ºC) should be used to increase sampling events?

- How do other environmental factors (e.g. water year type) influence sampling needs?
- How do tidal cycles impact sampling and how this could influence sample comparisons?
- How do various management actions impact the spatial design?

Recommendation 3.2.3 Identify the metrics/parameters that should be collected for the monitoring program(s)

There are a wide range of metrics that can be included in a monitoring program. These include collecting discrete water quality samples for nutrient, chlorophyll, genetic, and/or toxin analysis, to time integrated samples such as solid phase adsorption toxin tracking bags (SPATT), to remote sensing, etc. Depending on the management question, collection of a different set of metrics may be needed to help answer the question. Regardless of the metrics that are utilized it will be important for there to be consistency between laboratory and analysis methods (e.g., ELISA vs LC-MS to measure toxins, phytoplankton enumeration, etc.).

Modern technologies also continue to evolve and there will likely be opportunities for machine learning/artificial intelligence methods to be integrated with more conventional sampling metrics to monitor cyanobacteria (e.g., Saleem et al. 2023). Although many of these newer technologies have limitations in their current state of development it is likely that there will be increasing opportunities to incorporate these technologies over the next few years. As such, the adaptive management process should be used to incorporate technologies into monitoring programs when it is appropriate.

Recommendation 3.2.4 Identify how data will be used

Design characteristics should include plans for how the data would be used, adequate data management (*Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard*), quality control (*Recommendation 4.3 Develop a programmatic Quality Assurance Program Plan (QAPrP) for Delta CHABs, Recommendation 4.4 Develop training and intercalibration plan*), and data analysis and synthesis (*Recommendation 4.1 Compare, review, and standardize sampling and laboratory methods, Recommendation 4.2 Ensure CHAB related SOPs are easily accessible*). Data collected in the monitoring program(s) should be readily available to the public (*Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard*, *Recommendation 5.4 Incorporate open data principle*) (Delta ISB 2022).

Recommendation 3.3 Based on recommendations described above, design monitoring program(s)

Develop a document(s) that provides a design for the monitoring program(s). This document(s) should include the design characteristics outlined in *Recommendation 3.2. Develop monitoring program(s) design characteristics*. It should also describe the resources that will be used to collect and analyze the samples. If there are multiple monitoring documents to address the different management questions and goals it will be important that documents are coordinated so that data can be compared across monitoring efforts if necessary.

Table 5. Example of management questions and associated design considerations and plan for use of monitoring data

Management Question	Geographic	Spatial, temporal, frequency	Metrics	Data	Additional Considerations
Which hydrologically distinct areas of the Delta are at risk of experiencing CHABs?	• Identify locations known for having CHABs • Identify locations that may be prone to CHABs based on hydrologic characteristics • Identify high use areas that may be prone to CHABs	• Identify sampling frequency to capture bloom development • Consider the number of samples needed to represent distinct areas	• Select relevant driver data for chosen site • Are genetic and toxin data needed? • how can remote sensing be used to monitor CHABs in these areas?	• Do methods and SOPs meet data management and quality control measures to be used for management decisions?	• e.g., Does public access or other use require modifications to the design? • How much data is needed to inform management decisions? • How can this work be leveraged with ongoing routine water quality monitoring?

Recommendation 3.4 Consider resources that are currently available or that may be available in the future

As described above in Section 0 there are a number of routine water quality monitoring programs in the Delta; however, none of these are CHAB focused. Adding focused CHAB monitoring to these existing programs may be a good option for leveraging resources to address CHAB management questions and goals. However, additional resources will be necessary to answer all the management questions and goals since many of the established water quality monitoring programs do not sample in the areas that experience the most severe CHAB.

The availability of various resources may impact the ability to implement certain recommendations in this document.

Recommendation 3.5 Implement special studies to address data gaps and technical questions

The following special studies represent some potential ideas to advance this recommendation but should not be treated as an exclusive list. The special studies listed below can be used by those who have the ability to pursue CHAB related research from independent funding sources as well as providing guidance for agencies and work groups that have funding to pursue special studies.

Management questions and goals identified in Goal 2, *Recommendation 2.4 Provide approach(es) for prioritizing management questions and goals* above can be used to prioritize special studies. However, in cases where independent researchers have funding to pursue special study projects studies may not follow the same priorities identified through this strategy. In this case, the plan for implementing special studies will be based on the researchers or partners that provide funding for the special study. *Recommendation 5.3 Develop and maintain list of all routine and special studies* is in place to encourage collaboration among those working on special studies.

The design of each special study will be specific to the type of study that is implemented and the resources available to complete each study.

Environmental Processes, CHAB development, CHAB decline

Special Study 3.5.1 Investigate role of different nutrient sources on CHAB bloom formation throughout the Delta

Nutrients have been identified as non-limiting for cyanobacteria growth throughout the Delta. However, there are numerous questions remaining about how nutrient manipulations may impact CHABs in various areas of the Delta. Some examples include:

- What is the site-specific role of external vs internal nutrient loading?
- What is the relationship between macrophytes, cyanobacteria, and nutrients?
- Do nutrient limitations that prevent cyanobacteria dominance in the literature apply to the Delta?
- If nutrients are reduced to limiting amounts would nitrogen fixing cyanobacteria become problematic?

Special Study 3.5.2 Investigate how changing atmospheric carbon levels may impact CHABs in the Delta

Rising atmospheric CO_2 concentrations associated with climate change are anticipated to stimulate cyanobacteria blooms, shift the genetic composition of cyanobacteria blooms, and potentially change growth responses of different phytoplankton species (Visser et al. 2016). Field- and laboratory-based studies should be developed to assess how rising CO_2 will impact CHABs in the Delta. This information will be an important component of a predictive model as well as helping managers understand how to plan for potential changes to CHAB ecology in the Delta.

Special Study 3.5.3 Investigate how localized flow conditions, site specific residence times, and tidal velocity influence CHAB formation

It is well accepted in the scientific community that flow, velocity, and residence time play an important role in the ability of cyanobacteria to grow, aggregate, and form blooms. There are some studies that suggest flow thresholds for disrupting CHABs in the literature (e.g., Mitrovic et al. 2011), but there is little to no work on this topic in the Delta. Similarly, studies have shown that long residence times increase the potential for CHABs, but it remains unknown how long residence time in number of hours or days is sufficient for CHABs to form. Studies should be developed to address impacts of flow, residence time, and tidal velocity on CHABs in different areas of the Delta (e.g., static peripheral areas, canals, edge water habitats, main channels, etc.) and how these factors relate to other environmental conditions that are conducive to CHABs.

Special Study 3.5.4 Investigate role of cyanobacteria seed stock in Delta CHABs

Growing evidence suggests that overwintering cyanobacteria inoculates summertime cyanobacteria blooms. Determining the role of seed stock in bloom formation will be important to identify potential areas to implement targeted mitigation practices.

Special Study 3.5.5 Study factors that cause bloom decline/collapse (viruses, decreasing light, nutrient depletion, salinity changes, etc.) and whether those factors can be manipulated

Little is known about what causes cyanobacteria blooms to decline or collapse in the Delta. Field- and laboratory-based studies could be implemented to understand the various factors that result in cyanobacteria cell lysis and collapse.

Monitoring Methods

Special Study 3.5.6 Coordinate with SWB to collect field data and other information needed to support remote sensing recommendations in the State FHAB Strategy (Smith et al. 2021).

There are many studies that could be developed to address this specific recommendation. Coordination with the State Water Board can be used to prioritize remote sensing needs. One idea is to explore the feasibility of generating drone imagery of hotspot locations as an early warning indicator, to track seasonal variation, and to better understand how CHABs are transported from peripheral areas into the main Delta. A second idea is to compare in-situ chlorophyll data with remotely sensed chlorophyll-a data.

Special Study 3.5.6 Improve use of visual index data

The visual index data is one of the largest and longest-term data sets of *Microcystis* available in the Delta. Visual index data may not be used to make regulatory decisions, but it is easy and inexpensive to collect the data and can be used to supplement routine monitoring and special studies. Currently, the visual index data is subjective based on the observer collecting the data and it remains unknown how well correlated it is with actual *Microcystis* presence. Several ideas for studies to improve use of visual index data are described below.

- First, collection of visual index should be standardized. To achieve this there should be annual visual index training or workshop in the spring prior to the start of the CHAB season (see *Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs* and *Recommendation 4.4 Develop training and intercalibration plan*). As part of this training there should be an explanation of what the visual index is supposed to represent. A standard operating procedure could be developed and shared at each training to ensure that people from different agencies and other groups are collecting the data in the same way.
- Second, measurements should be taken to compare *Microcystis* visual index data with cell abundances and chlorophyll concentrations, which could include comparing it to remote sensing data. This information can be used as a line of evidence in understanding the temporal and spatial extent of cyanobacteria. This data will be especially helpful if no other data is collected in certain areas of the Delta.
- Third, develop a revised visual index score procedure that incorporates visual indicators common to non-*Microcystis* species, step-by-step instructional document. This procedure should be incorporated into the visual index training once it has been developed.

Special Study 3.5.7 Evaluate the effectiveness of chlorophyll sensors to detect cyanobacteria

In-situ optical and fluorometric measurements have the potential to fill the gap that exists from relying only on laboratory-based extractions. However, it remains unknown how effective various chlorophyll sensors are at measuring chlorophyll from buoyant cyanobacteria. Studies should explore the relationship between chlorophyll fluorescence measurements and laboratory extracted chlorophyll. There is also evidence that different brands of sensors provide varying chlorophyll readings so it could be useful to continue exploring the differences between sensors. Eventually, it would also be useful to relate in-situ measurements to cyanobacterial cell density.

Special Study 3.5.8 Determine how well mixed Microcystis is throughout the water column and its contribution to total community chlorophyll-a

Different sampling groups collect phytoplankton samples at varying depths in the water column (typically at the surface or one meter below the surface). It would be useful to measure distribution of *Microcystis* vertically (at multiple depths in the water column) and correlate this with chlorophyll-a profiles.

Special Study 3.5.9 Determine if benthic cyanobacteria occur in the Delta and if so, contribute toxins to the water column.

Little work has been conducted to determine if benthic cyanobacteria are an issue in the Delta. A first step would be to investigate areas that have habitats conducive to the formation of benthic cyanobacteria.

Special Study 3.5.10 Determine concentrations at which cyanobacteria become a management concern

A CHAB "event" is largely determined by regulatory agencies concerned with food and human safety. These CHAB events are at times based on visual appearance of a waterbody and there is often not toxicity data associated with observed blooms. Studies could investigate the relationship between water column toxicity and cyanobacteria cell abundance to determine if there is any relationship in the Delta. This could be investigated for different species of cyanobacteria and at different times of the year when toxin producing strains may or may not be present.

Special Study 3.5.11 Explore use of artificial intelligence and machine learning for monitoring Delta CHABs

Artificial intelligence and machine-learning algorithms can be applied to cyanobacteria monitoring through cell imaging and predicting changes in water quality. For example, CHABs monitoring data, such as chlorophyll-a or phycocyanin, together with environmental data such as flow, temperature, and nutrients, can be used to train machine learning algorithms to hindcast and predict when cyanobacteria blooms may form. Special studies could work on integrating multiple algorithms and available datasets to apply machine learning models to the Delta. Information that comes out of these studies may inform the types of monitoring data that are needed to validate such technologies.

Special Study 3.5.12 Explore mechanistic approach to predict CHAB events

A mechanistic approach, specifically coupled hydrodynamic and biogeochemical models, can potentially be effective in modeling CHABs. Unlike the data-driven nature of machine learning methods, these predictive models establish causal connections between phytoplankton biomass and environmental drivers. While observational data aids in parameter tuning and model calibration, the mechanistic approach inherently requires less data and imposes fewer stringent requirements on data structures compared to machine learning techniques. These two approaches also complement each other; while the mechanistic method enriches machine learning by proving a more comprehensive training dataset, insights from machine learning can enhance the robustness of mechanistic linkages. Notably, mechanistic models have already been successfully employed to model non-HABs-related blooms in the Delta.

CHAB Toxicity

Special Study 3.5.13 Develop methods to identify and detect novel or emerging cyanotoxins

Current laboratory methods are focused on detecting the most common cyanotoxins (i.e., microcystin, anatoxin-a, cylindrospermopsin, and saxitoxin). Indeed, the majority of research has focused on microcystins, specifically the microcystin congener microcystin LR. Yet, new toxins and their congeners continue to be discovered and may have adverse impacts on the environment. Investigations of cyanobacteria peptides and other compounds will be useful for understanding the true impacts of CHABs across the Delta.

Special Study 3.5.14 Compare analytical methods for toxin detection in complex matrices

There is evidence in the literature that cyanotoxin detection may differ between ELISA and LC-MS methods, especially in complex matrices such as sediments and biota. There are a limited set of analytical standards available for LC-MS analysis and matrix interference with both methods. Since microcystin is the most common cyanotoxin observed in the Delta, and a stable toxin that is commonly observed in matrices other than water, it would be useful to conduct special laboratory studies on this toxin. Studies can focus on the comparison of ELISA and LC-MS to study microcystin concentrations in sediments and biota to work on developing standard methods that can be adopted by laboratories.

Special Study 3.5.15 How do changes in cell physiology (e.g., manipulated by nutrient limitation vs. sufficiency) impact toxin formation?

There is growing evidence in the literature that nitrogen and micronutrients disproportionally influence the toxicity of CHABs dominated by *Microcystis* (e.g. Wagner et al. 2019, Wagner et al. 2021). However, many questions remain about how nutrient availability affects toxin production and potential for presence of different microcystin congeners. Gradients of nitrogen and salinity have also been shown to have physiological costs and benefits in toxin-producing cyanobacteria. Investigations could further study how the combinations of high and low salinity with high and low nitrogen concentrations impact toxin production by *Microcystis* and *Aphanizomenon* (Osburn et al. 2023).

Special Study 3.5.16 Are there conditions that promote more toxic strains of cyanobacteria?

Do warmer temperatures, changes in salinity, decreases in turbidity, nutrient limitation, changes in atmospheric carbon, or other factors contribute to more toxic strains of cyanobacteria in the Delta? Studies could explore various combinations of these factors to better understand how environmental drivers impact potential for toxic strains to enter the water column.

Special Study 3.5.17 What are the impacts of cyanotoxins, mixtures of multiple cyanotoxins, and/or mixtures of cyanotoxins with other contaminants, on aquatic resources?

Limited information is available on how cyanotoxins impact the health of managed fish species such as Green and White Sturgeon. Since these species are benthic feeders and consume shellfish in the Delta, the fish may be exposed to cyanotoxins through their diets (*Tim Otten, Personal Conversation, February 2024*). Studies should investigate how cyanotoxins, and combination of cyanotoxins with other environmental contaminants, may impact aquatic resources including managed species in the Delta.

Mitigation

Special Study 3.5.18 Identify practicable Delta CHAB mitigation options

Many CHAB mitigation options are not practical for the hydrologically complex Delta. An assessment should be conducted of various CHAB mitigation options to determine which are feasible for the Delta. Once feasible mitigation options are identified the options can be refined for different habitat types (e.g., flowing channels, backwater areas, channel margins, etc.). Considering scale, it would also be useful to identify the potential costs of implementing applicable mitigation measures. Finally, a plan should be developed to outline the mitigation measures that require pilot studies to confirm applicability in the Delta.

Special Study 3.5.19 Conduct pilot studies in laboratory-based environments or localized areas of the Delta to evaluate potential mitigation techniques

Special studies could conduct small scale experiments to test different mitigation techniques. Mitigation techniques should be explored under a range of environmental conditions to understand the true feasibility of various techniques.

5.4 Goal 4: Define Collaborative Reporting Protocols

- **Objective 4-1 Validate and standardize current methods used for monitoring CHABs**
- **Objective 4-2 Develop protocols for accurate and timely reporting**

Recommendation 4.1 Compare, review, and standardize sampling and laboratory methods

Standardizing species identifications, extraction protocols, and laboratory analysis for cyanotoxins across the Delta is important for ensuring that monitoring data collected by different groups are consistent and comparable (Stauffer et al. 2020).

This is especially important for data collected as part of a regular monitoring activity (i.e., not for a special study).

Participating agencies and groups such as IEP have SOPs for various monitoring efforts that should be considered when defining SOPs for Delta CHAB monitoring. SWAMP protocols may also exist for many of the environmental factors that drive CHABs, however these are for immediate response and not for routing monitoring. These protocols include SOPs that should be utilized to develop a Delta CHAB monitoring SOP. Whenever possible, data collection methods should follow established norms in the Delta by existing surveys (mostly IEP).

Sampling and laboratory methods and SOPs should be consistent and documented. SOPs should be compared across monitoring groups for consistency and reviewed to determine where they can be optimized, including quality control (QC) requirements, to allow standardization across monitoring groups. Where significant discrepancies across SOPs exist, SOPs should be evaluated, and a community consensus should attempt to mitigate these differences.

Recommendation 4.1.1 Standardize terminology

In addition to standardizing methods and SOPs, major relevant terms for Delta CHABs need to be consistent. “Bloom” is an example of a term that needs a specific definition and metric to meaningfully agree on monitoring practices.

Recommendation 4.2 Ensure CHAB related SOPs are easily accessible

After SOPs are reviewed and standardized, they should be retained in a common location for use by all current and future monitoring practitioners. By maintaining this common location for materials there is no barrier to access for novel monitoring programs and materials are not lost as staff and programs turn over. Below, *Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard* describes one option for the common location to store these materials.

Recommendation 4.2.1 Create an inventory of SOPs

An inventory listing methods and SOPs for CHAB monitoring and analysis should be created in the same common location for ease of locating this information. In circumstances where an SOP or method is already published (e.g., IEP, SWAMP, USGS), the webpages for those documents should be linked to the inventory.

Recommendation 4.3 Develop a Programmatic Quality Assurance Program Plan (QAPrP) for Delta CHABs

A QAPrP, similar to the WaterBoards SWAMP QAPrP, should be developed to allow projects implemented by partners to "enroll" under it as long as they used the standardized procedures, approved lab methods and labs, etc. This allows project-specific flexibility while upholding a high standard of quality assurance. The QAPrP should include QA metrics and standardized procedures and training plan quality control protocols such as data quality requirements for participating groups. This QAPrP can be developed so that participating agencies can leverage the QAPrP for individual projects implemented under the overall programmatic QAPrP. Each

CHABs monitoring participant should also maintain a quality assurance project plan (QAPP) that adheres to the values outlined in the programmatic QAPrP

Recommendation 4.4 Develop training and intercalibration plan

The first step of the training and intercalibration plan will be identifying a person, group, or agency that can organize and lead this annual training. The advisory group in *Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy* could take the lead on this or a volunteer could agree to take on this recommendation. It would be useful to have a document prepared that describes the procedures for training and the intercalibration plan. This document could be used as the resource for the in-person training described below.

The training should be held annually for all personnel who may collect CHAB related field data. This training could be included in the annual meeting focused specifically on Delta CHABs that is identified in *Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*. Ideas for the annual training includes a review of standard operating procedures, equipment maintenance and calibration, decontamination protocols, health and safety protocols, and data quality assurance and quality control protocols and standards. The lead for the training should also consider equipment and sampling standardization that is missing. This training could be a good opportunity to discuss ideas for troubleshooting any issues and for identifying approaches that ensure better standardization in the future.

Participating agency members may hold their own trainings, but it is essential that training is provided to all personnel. Ideally, all trainings should be recorded and documented.

Recommendation 4.5 Report on CHAB monitoring and special study findings

Present CHAB monitoring and special study findings at annual meetings (*Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*). Consider using speed talks and posters if there is not sufficient time available to present on all studies. Researchers should focus on an open science mindset and work to distribute findings to the best of their ability to all interested parties. When possible, researchers should publish research papers as open access to ensure accessibility to all interested parties.

5.5 Goal 5: Utilize a Data Sharing Platform

- **Objective 5-1 Identify existing CHAB and HAB data resources**
- **Objective 5-2 Explore how to integrate Delta CHAB data with existing data repositories**
- **Objective 5-3 Develop protocols to make CHAB data accessible and available to all**

Recommendation 5.1 Develop a comprehensive list of all currently used data repository platforms, data resources, and other Delta CHAB related resources

The advisory committee should develop a comprehensive list that can then be used in *Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard*. It is important to recognize that the list may evolve over time as new resources become available.

Examples of data resources that should be considered include:

- California Environmental Data Exchange Network (CEDEN)
- California Data Exchange Center (CDEC)
- Water Data library
- Electronic Data Exchange Portal (EDI)
- United States Geological Survey Data Integration Portal Phytoplankton dashboard

Examples of other resources that should be considered include:

- Documents listed in *Recommendation 2.2 Consider regional, state, and national HAB documents, strategies, and guidance when developing management goals and questions*
- Delta CHAB related journal publications

Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard

In fall of 2023 the San Francisco Estuary Institute, United States Geological Survey, Department of Water Resources, and project partners received funding for a five year project to address HABs across the San Francisco Estuary, as described in section 3.2.4 NOAA MERHAB. As part of this funding the team at San Francisco Estuary Institute is developing a data dashboard that will bring together various data types, including remotely sensed data, high-frequency data, and discrete data samples. The team has assembled data transformation libraries and special scripts to perform these integration tasks affordably and reliably. The data integration platform and data dashboard work hand-in-hand to ensure alignment among various partners, community members, Tribes, researchers, and decision makers. The MERHAB project team agrees that this data dashboard offers a promising platform to integrate historic and existing CHAB data from the Delta in line with the recommendations in this strategy..

The data dashboard is still in the early stages of development, but there are plans to develop crosswalks to make data more available and comparable across agencies. Crosswalks will allow databases to remain with their hosts.

Although the funding for the data dashboard is tied to the MERHAB project funding, it is a goal of the MERHAB team to secure long-term funding for the data dashboard. Leveraging the MERHAB data dashboard provides a unique opportunity to integrate all San Francisco Estuary HAB data and resources into a single platform.

Recommendation 5.3 Develop and maintain list of all routine and special studies

Many groups are working on various aspects of CHAB monitoring. This strategy is intended to increase coordination among these different entities. Nevertheless, due to discrete funding opportunities and the large number of people who are working on CHAB issues in the Delta it is often difficult to be aware of all of the different monitoring efforts and special studies that are occurring at any given time. Organizing a location within the data dashboard (*Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard*) where people can list a high level overview of their work and contact information would increase coordination efforts. This recommendation will rely on individuals to self-report. However, with the common goal of sharing the information identified here, individuals participating in the advisory committee and other associated groups will have access to all relevant CHABs information and can encourage individuals to self-report.

Recommendation 5.4 Incorporate open data principles

In line with the special study recommended in the FHAB Strategy "SS4: Develop partner program open data systems" it will be important to incorporate open data principals for all Delta CHAB data and findings. Incorporating open data principles means data should be freely accessible, usable, and shareable for any purpose.

Open data principals are outlined in AB 1755 Open Water Data Act, which directs all water data in the state to be accessible and available to the public (AB-1755 (ca.gov)), FAIR principles (https://www.go-fair.org/fair-principles/), and SWB's Open Data Resolution's Handbook (Data Tool Kit - Open Data Handbook | California State Water Resources Control Board). These resources should be utilized when considering how to best consolidate and share data.

The MERHAB data dashboard will utilize open data principles by providing data management and visualization infrastructure to communicate Delta CHAB findings. However, as noted in the FHAB Strategy some disadvantaged communities may have poor access to electronic information. Thus, those with data to share should consider multiple dissemination modes and not rely entirely on the data dashboard. The annual meeting (*Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs*) will be one tool that can be used to communicate findings beyond the data dashboard.

Table 6. Recommendations and Objectives that they address

Recommendation	Primary Objective(s)	Secondary Objective(s)
Recommendation 1.1 Identify co-chairs or mechanism for someone to lead coordination and implementation of Delta CHAB strategy	**1-1**	**1-2, 1-3**
Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy.	**1-1**	**1-2, 1-3, 2-1, 2-2, 2-3, 4-1, 4-2, 5-1, 5-2, 5-3**
Recommendation 1.3 Identify existing barriers to collaboration/cooperation and identify methods for overcoming them	**1-2**	**1-1, 1-3**
Recommendation 1.4 Strengthen and expand partner relationships	**1-2, 1-3**	**1-1, 2-1, 2-2, 2-3**
Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs	**1-2, 1-3**	**1-1, 2-1, 2-2. 2-3, 3-1, 3-2, 3-3, 3-4, 4-1, 4-2, 5-1, 5-2, 5-3**
Recommendation 1.6 Identify funding to support implementation of the CHAB Monitoring Strategy	**1-3**	**1-1. 1-2**
Recommendation 2.1 Consider the amount and type of monitoring information needed by managers to support decision making	**2-1**	**2-2, 2-3, 3-1, 3-2, 3-3, 3-4**
Recommendation 2.2 Consider regional, state, and national HAB documents, strategies, and guidance when developing management goals and questions	**2-3**	**2-1, 2-2, 3-1, 3-2, 3-3, 3-4**
Recommendation 2.3 When possible, coordinate Delta CHAB questions and goals with ongoing local and state efforts	**2-3**	**2-1, 2-2, 3-1, 3-2, 3-3, 3-4**
Recommendation 2.4 Provide approach(es) for prioritizing management questions and goals	**2-2**	**1-1, 1-2, 1-3, 2-1, 2-3, 3-1, 3-2, 3-3, 3-4**

Recommendation 2.5 Publish and share final management questions and goals with all interested parties	**2-2**	**1-1, 1-2, 1-3, 2-1, 2-3, 3-1, 3-2, 3-3, 3-4**
Recommendation 3.1 Based on the goals and objectives developed in Goal 2 identify monitoring programs and special studies needed to achieve outcomes	**3-1, 3-2, 3-3**	**2-1, 2-2, 2-3, 3-4**
Recommendation 3.2. Develop monitoring program(s) design characteristics	**3-2, 3-3**	**2-1, 2-2, 2-3, 3-1, 3-4**
Recommendation 3.3 Based on recommendations described above, design monitoring program(s)	**3-2, 3-3**	**2-1, 2-2, 2-3, 3-1, 3-4**
Recommendation 3.4 Consider resources that are currently available or that may be available in the future	**3-4**	**2-1, 2-2, 2-3, 3-1, 3-2, 3-3**
Recommendation 3.5 Implement special studies to address data gaps and technical questions	**3-3**	**2-1, 2-2, 2-3, 3-1, 3-2, 3-4**
Recommendation 4.1 Compare, review, and standardize sampling and laboratory methods	**4-1**	**4-2**
Recommendation 4.2 Ensure CHAB related SOPs are easily accessible	**4-1**	**3-1, 3-2, 3-3, 3-4, 4-2**
Recommendation 4.3 Develop a programmatic Quality Assurance Program Plan (QAPrP) for Delta CHABs	**4-1**	**3-1, 3-2, 3-3, 3-4, 4-2**
Recommendation 4.4 Develop training and intercalibration plan	**4-1**	**3-1, 3-2, 3-3, 3-4, 4-2**
Recommendation 4.5 Report on CHAB monitoring and special study findings	**4-2**	**3-1, 3-2, 3-3, 3-4, 4-1**
Recommendation 5.1 Develop a comprehensive list of all currently used data repository platforms, data resources, and other Delta CHAB related resources	**5-1**	**5-2, 5-3**
Recommendation 5.2 Coordinate with the NOAA MERHAB data dashboard	**5-2, 5-3**	**3-1, 3-2, 3-3, 3-4, 5-1**
Recommendation 5.3 Develop and maintain list of all routine and special studies	**5-2**	**5-1, 5-3**

Recommendation 5.4 Incorporate open data principle	**5-3**	**3-1, 3-2, 3-3, 3-4, 5-1, 5-2**

6 Adaptive Management

To create a monitoring plan that best meets management needs, an adaptive management approach should be incorporated (Delta ISB 2022). This document supports adaptive management through iterative implementation of the goals and objectives:

1. Monitoring is tied to management questions, goals and objectives (Goal 2)
2. The management questions are used to design the monitoring program (Goal 3)
3. Information resulting from monitoring efforts are communicated widely (Goals 4 and 5) to facilitate learning.

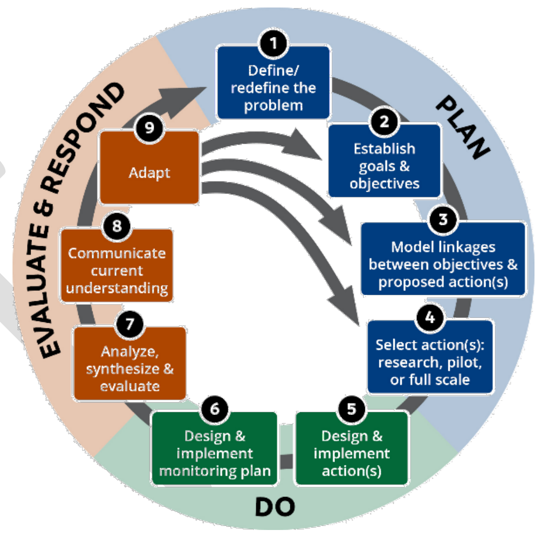


Figure 17. Adaptive Management Cycle

Recommendations 2.4 Provide approach(es) for prioritizing management questions and goals and *2.5 Publish and share final management questions and goals with all interested parties* detail more information about prioritization of management questions, which should be used to define criteria for achieving progress made toward addressing goals and objectives of the monitoring program.

Recommendation 1.5 Hold an annual meeting focused specifically on Delta CHABs calls for an annual meeting to discuss findings from monitoring and progress made on CHABs data collection which creates a natural opportunity to discuss progress made toward defined management objectives and evaluate the monitoring program plan to adapt before the next data collection season.

The structure proposed in this strategy can be iteratively applied to evaluate progress toward defined management goals and to inform adjustments to the strategy as needed. At a minimum this strategy should be revisited every 3 to 5 years. However, since there is no funding attached to this strategy the advisory committee will need to seek volunteers to spend time working through the adaptive monitoring process.

As part of the review process the following items should be considered:

1. Assess and report progress towards each of the goals and objectives.
2. Describe any changes in management objectives or needs
3. Describe any new technologies that could be leveraged in the strategy
4. Assess the extent to which the strategy is meeting current management objectives and information needs
5. Propose any necessary changes to the strategy to better meet current management objectives and information needs, while maintaining long-term data comparability

7 Implementation

Full implementation of the recommendations in this strategy will require considerable time and funding. As stated above, there is no funding associated with this strategy and implementation of the recommendations within this document. As such, it will be necessary for volunteers to implement recommendations in this document and for additional funding to be secured. As described in *Recommendation 1.6 Identify funding to support implementation of the CHAB Monitoring Strategy* there are a number of mechanisms through which funding could be secured to help implement this entire strategy.

Implementation of all the recommendations in this document would benefit from the development of implementation guidance with input from partners to develop a coordinated monitoring program. This could be through the advisory committee (*Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy.*) or through some other mechanism. Although implementation guidance will ensure that the recommendation in this document are undertaken through a coordinated approach there are a number of recommendations that can be implemented immediately if resources are available to undertake the efforts.

It will also be important to leverage ongoing related work to implement these recommendations. When possible, these leveraging opportunities have been identified throughout this document.

This strategy is focused on informing water quality management decisions in a 3- to 5-year horizon, consistent with the FHAB Strategy's guidance of a "near-term" implementation. However, recommendations in this Strategy may also fall under long-term implementation of >5 years and are included for consideration as this

Strategy is implemented. Recommendations that are identified as long-term priorities can be implemented once funds and resources become available.

7.1 Near-Term Implementation

The first steps in the near-term implementation of this strategy will be to implement *Recommendation 1.1 Identify co-chairs or mechanism for someone to lead coordination and implementation of Delta CHAB strategy* and *Recommendation 1.2 Form advisory committee to develop final goals, questions, and monitoring strategy.* Many of the recommendations that follow involve action by the co-chairs/mechanism to lead the strategy and the advisory committee. Once these recommendations have been achieved the next high priority task will be to implement Goal 2 – Identify management questions, monitoring goals, and objectives. This will be important to ensure that there is a coordinated approach to implementing this strategy.

Within Goal 2 is *Recommendation 2.4 Provide approach(es) for prioritizing management questions and goals* which can be used in deciding next steps in the implementation process.

It is important to recognize that this strategy and ongoing Delta CHAB efforts are fluid. Components of this strategy are being implemented while the document is being written. The adaptive management framework can be used to address this fluidity, but it is also important to recognize that some components will be implemented prior to the full adoption of the document. Part of the real-time process involves meetings where partners volunteer to take on components of this document. Ideally future meetings will be funneled through the advisory committee for a coordinated Delta CHAB approach.

7.2 Long-Term Implementation

The strategy should be revisited every 3 or 5 years via the adaptive management process. This should include new data, new technologies, and an assessment of the near-term implementation process. The process should also consider identifying long-term goals beyond those that are captured in the document.

Appendix A

Additional station maps.

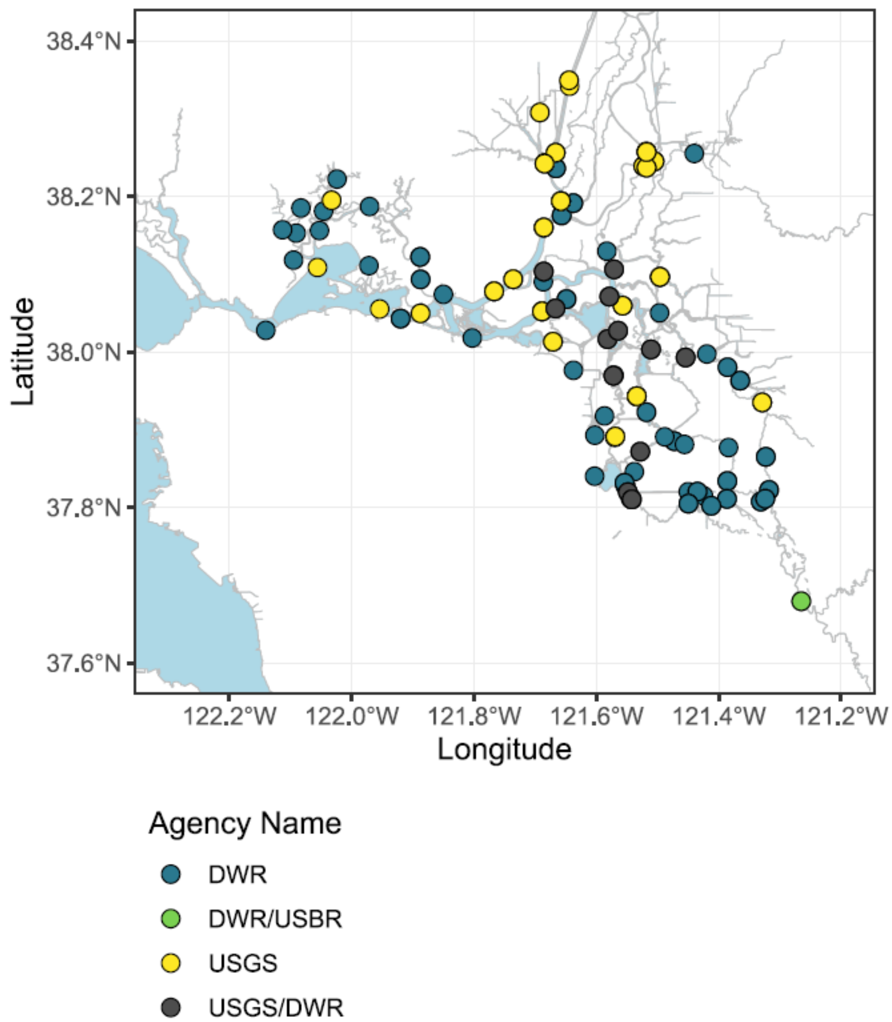


Figure 18. Map of continuous water flow stations that measure flow, velocity, and/or river stage.

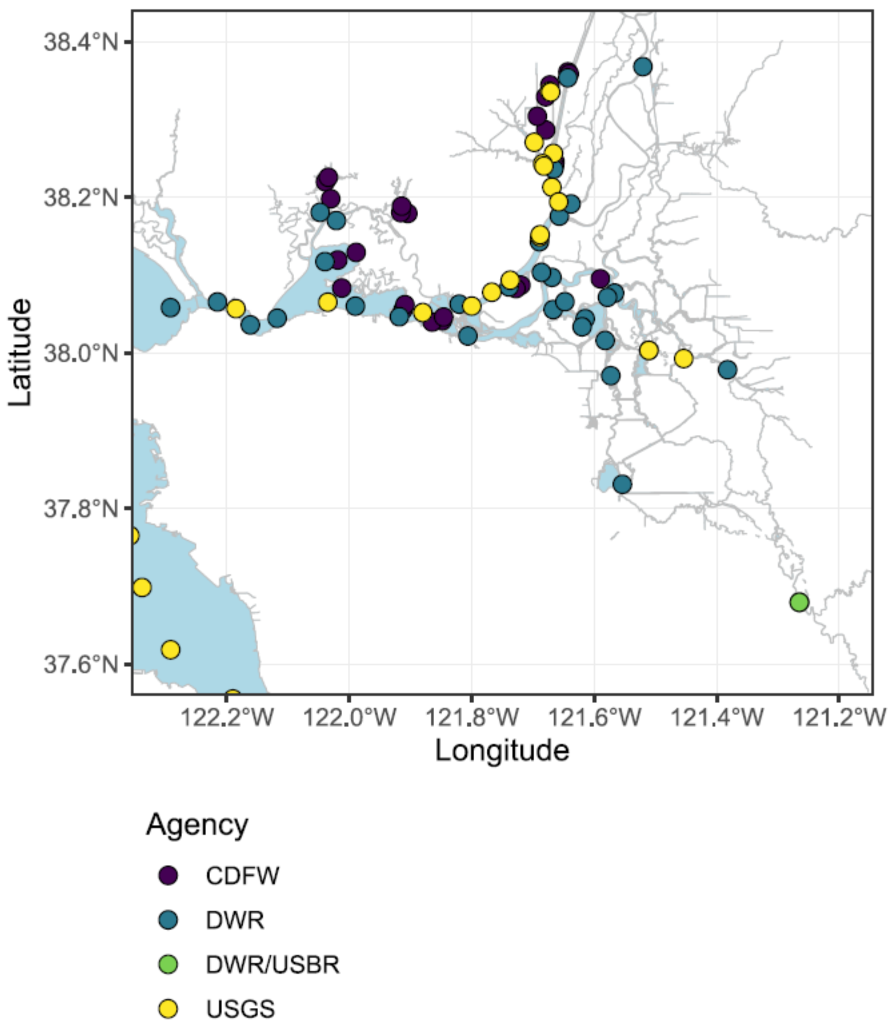


Figure 19. Map of total phosphorus and/or dissolved orthophosphate measurement locations.

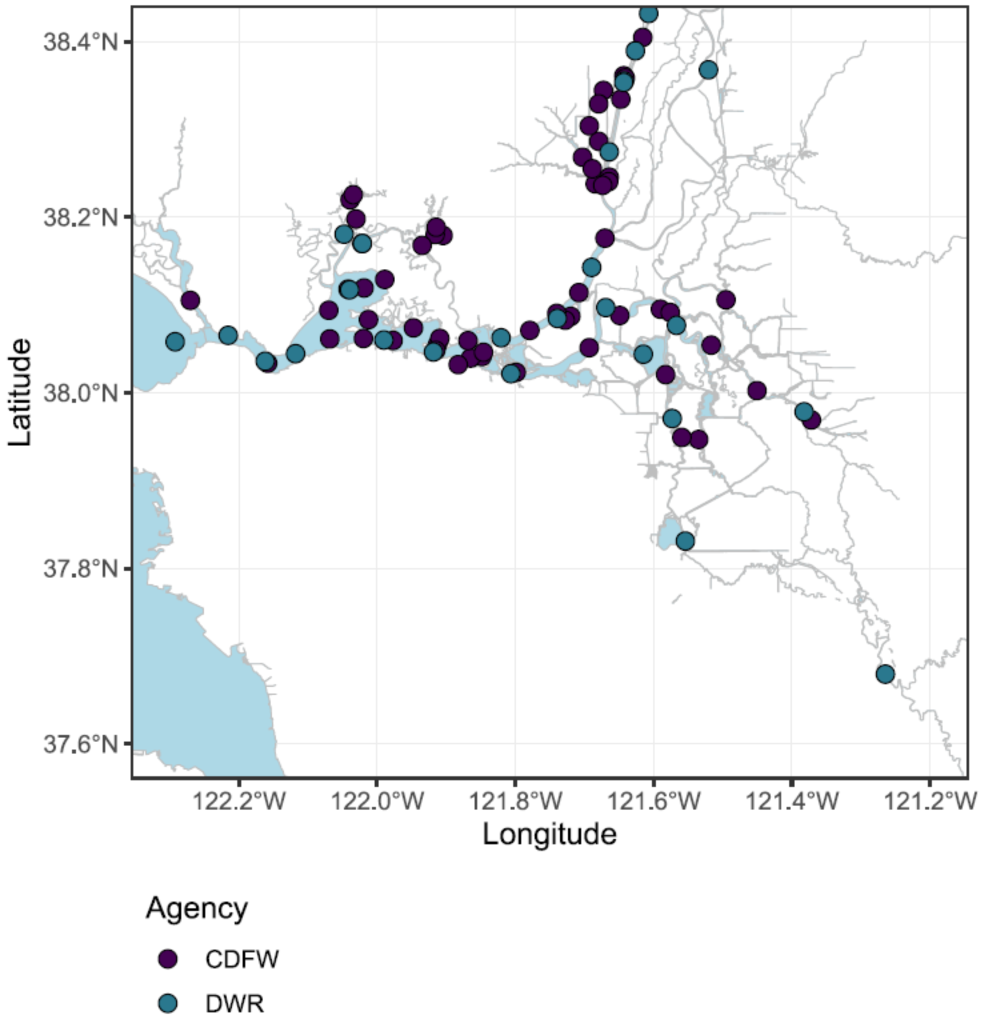


Figure 20. Map of Secchi depth measurement locations.

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