From:	Hartman, Rosemary@DWR <Rosemary.Hartman@water.ca.gov>
Sent:	Wednesday, May 11, 2022 12:32 PM
To:	Frazier, Scott@Waterboards; Foresman, Erin@Waterboards; Riddle, Diane@Waterboards; Ekdahl, Erik@Waterboards; Leahy, Tina@Waterboards; Heinrich, Dana@Waterboards; Holland, Matthew@Waterboards
Cc:	Hinojosa, Tracy@DWR; Reeves, Ryan@DWR; Dave Mooney; Grimaldo, Lenny@DWR; Manzo, Mario@USBR.GOV; Israel, JA; Arend, Kristi@USBR; Van Nieuwenhuyse, Erwin E; Jones, Kristopher@DWR; White, Molly@DWR; Halston, Armin A; Yarbrough, John@DWR; McQuirk, Jacob@DWR; Hunt, Thaddeus@Waterboards; Louie, Stephen@Waterboards
Subject:	RE: TUCO HABs/Weeds study plan
Attachments:	HAB-Weed_Report_studyplan 2022-05-10 draft.pdf; DWR responses to Water Board Comments on CHABs Study Plan 050322.docx; appendicies.zip

EXTERNAL:

Dear Mr. Ekdahl,

Attached is the draft study plan for assessing the impact of the TUCO on Harmful Algal Blooms and Aquatic Weeds in response to Condition 8 of the April 4, 2022 Temporary Urgency Change Order. Cyanotoxin sampling will begin per appendix A later this week. We have also attached responses to the comments on the draft cyanotoxin sampling plan provided by your staff. This supersedes the draft submitted on April 20th. If you have any suggested changes to the plan, please let us know as soon as possible. Any questions or comments can be addressed to me, Rosemary.Hartman@water.ca.gov

Rosemary Hartman, PhD (she/her)
Environmental Program Manager
Department of Water Resources
916-882-2926

The effect of the Temporary Urgency Change Petition and Emergency Drought Barrier on Harmful Algal Blooms and Aquatic Weeds

2022 Draft Study Plan

Date: 5/10/2022

Primary Investigators:

Kristin Arend, and Erwin Van Nieuwenhuyse, US Bureau of Reclamation

Rosemary Hartman, California Department of Water Resources

INTRODUCTION

Condition 8 of the April 2022 Temporary Urgency Change Order for the Central Valley Project and State Water Project requires a special study of harmful algal blooms (HABs) in the Sacramento–San Joaquin Delta (Delta), particularly HABs caused by cyanobacteria (i.e., cyanoHABs), and the spread of submerged aquatic vegetation (SAV) also referred to as "aquatic weeds". This study will include a synthesis of existing data as well as several new studies of cyanotoxins, satellite imagery, phytoplankton pigment fluorescence, and hyperspectral imagery.

Specifically, the TUCO says:

> In coordination with the State Water Board, Central Valley Water Board, IEP, Delta Science Program (DSP), the fisheries agencies, and USEPA, DWR and Reclamation shall continue and build upon the special study on the prevalence and extent of harmful algal blooms (HABs) and expansion of invasive aquatic weeds in the Delta as required by the 2021 TUCP, 2021 Emergency Drought Salinity Barrier (EDSB) Certification, and the 2022 Order on Reconsideration of the 2021 TUCP. The special study shall identify the effects of this TUCP Order, any future TUCP Orders, and any associated actions including drought barriers on the prevalence and extent of HABs and expansion of invasive weeds in the Delta. The study shall include the measurements of cyanotoxin concentrations in areas where this TUCP Order may modify hydrodynamics to Delta waterways. The cyanotoxin samples shall be collected consistent with the requirements of any approved extension of the EDSB certification, including, at a minimum, the types of cyanotoxins analyzed, locations, frequency, triggers for additional monitoring, and methods. The draft study plan shall be submitted by April 20, 2022, to the coordinating entities identified in the condition for review and comment. The final study plan incorporating the coordinating entities' comments are due to the State Water Board by May 10, 2022. Cyanotoxin monitoring shall be initiated in May 2022.
>
> The report shall summarize impacts to sub-regions of the Delta consistent with the localized nature of HABs and aquatic weeds and analyze potential for (or presence of) disproportionate impacts to vulnerable communities with respect to drinking water quality, contact and non-contact recreation, impacts to tribal cultural resources, and impacts to aesthetics including odors and the visual character of Delta waterways where HABs and aquatic weeds are

prevalent or where this TUCP Order may modify hydrodynamics to Delta waterways. This work shall be coordinated with IEP and DSP, and any broader watershed evaluation of HABs and aquatic weeds.

An interim draft Report shall be submitted to the State Water Board by December 15, 2022, summarizing the results available at that time. A summary of the interim draft report shall be presented at a public Board meeting in January 2023, or as designated by the Deputy Director of the Division of Water Rights. A completed, draft Report shall be submitted to the State Water Board by April 1, 2023, released for public comment, and presented at a public Board meeting as determined in coordination with the Deputy Director of the Division of Water Rights. In coordination with the State Water Board, Central Valley Water Board, IEP, DSP, CDFW, and USEPA, DWR and Reclamation shall review and consider comments from the State Water Board, other agencies, and the public and modify the final report as appropriate based on these comments. A complete, final report shall be submitted to the State Water Board 30 days after receipt of public and State Water Board staff comments unless the Deputy Director for the Division of Water Rights grants and extension.

This study plan outlines the approach that DWR and Reclamation will take in producing the report required by Condition 8. The study will include both collection of additional cyanotoxin samples and synthesis of existing data collection to create a comprehensive picture of cyanoHABs across the Delta.

Summary of actions

This study plan will focus on the impacts of the 2022 April-June TUCP and the West False River Emergency Drought Barrier (EDB or "Barrier"). The TUCP included four changes to Water Rights decision 1641, namely:

(1) Reduces the Delta outflow requirement as measured by the Net Delta Outflow Index (NDOI) from a minimum of 7,100 cubic-feet per second (cfs) on a 3-day running average to 4,000 cfs on a 14-day running average.[4]
(2) Moves the Western Delta agricultural salinity compliance point on the Sacramento River at Emmaton 2.5 to 3 miles upstream to Threemile Slough.
(3) Limits the maximum export rate to 1,500 cfs whenever unmodified D-1641 requirements are not being met.
(4) Reduces the minimum monthly average flow requirement on the San Joaquin River at Airport Way Bridge, Vernalis from 710-1140 cfs (April 1-14 and May 16-June 30) and 3,110-3,540 cfs (April 15 – May 15) to a minimum monthly average of 710 cfs.[5]

The 2021 EDB is a temporary physical rock fill barrier in West False River, near Franks Tract, that reduces the intrusion of high-salinity water into the Central and South Delta. During drought conditions, water stored in upstream reservoirs may be insufficient to repel salinity moving upstream from San Francisco Bay. Without the protection of the drought salinity barrier, saltwater intrusions could render Delta water unusable for agricultural needs, reduce habitat value for aquatic species, and affect roughly 25 million Californians who rely on the export of this water for personal use. The 2021 EDB was installed in June of 2021 and left in place thought the remainder of the year. A notch in the top of the barrier was cut in January of 2022 to allow for fish passage during the winter, then re-filled in April of 2022 to restore its effectiveness as a salinity barrier.

Goals and Research Questions

This study has the following goals and associated research questions:

1. Describe the impact of the 2022 April-June TUCP and Barrier on Harmful Algal Blooms.
    a. Where and when did cyanoHABs occur in 2022?
    b. What were the toxicities associated with cyanoHABs in 2022?
    c. Were cyanoHABs in 2022 better or worse than similar dry years, either for the Delta as a whole or regionally, based on areas hydrologically impacted by the TUCP/Barrier?
    d. What were the major drivers associated with bloom formation?
2. Describe the impact of the April-June TUCP and Barrier on aquatic vegetation.
    a. What was the distribution of weeds in 2022?
    b. How did coverage and community composition of weeds 2022 compare to similar dry years, for the Delta as a whole and regionally, based on areas hydrologically impacted by the TUCP/Barrier?
    c. What were the major drivers associated with weed distribution and coverage?

3. Describe the impact of the change in HABs and weeds caused by the April-June TUCP/Barrier on human uses of the Delta, in particular impacts to vulnerable communities.

    a. What is the impact of HABs and weeds on vulnerable communities?

    b. Where were increases in HABs or weeds thought to be caused by the TUCP/Barrier?

    c. Were areas impacted by the TUCP/Barrier disproportionately represented by vulnerable communities?

Regional analysis

The impacts of the April-June TUCP and Barrier will not be uniform across the area of the Delta, therefore, we have divided many of our analyses into regions based on the projected changes to flow caused by the TUCP and Barrier (Figure 1).

- In the upper Sacramento River, reduced inflows will cause increased residence time, though we expect minimal changes to maximum and minimum velocities, which are primarily controlled by tides.

- In the Cache/Liberty region residence time is controlled mainly through tidal dispersion,

- In the Lower Sacramento, the Barrier will cause salinity to increase and reduced inflows will cause increased residence time, though we expect minimal changes to maximum and minimum velocities.

- In the Lower San Joaquin, the barrier will cause salinity to increase. There will be local increases to flows and current speed on the San Andreas Reach.

- In Franks Tract, the Barrier will cause a significant increase in residence time, particularly on the western side of the tract. Maximum current speed and tidal flows will decrease through False River and increase through Fisherman’s Cut and Old River.

- South of Franks Tract, the Barrier will cause salinity to decrease and residence time to increase in Old River, with a smaller effect in Middle River. Residence time in this area is controlled mainly by Exports, so low, health-and-safety export levels will result in longer residence time than during wetter years.

- Reductions to San Joaquin Flow will increased residence time in the South Delta and Lower San Joaquin.

- Suisun Marsh and Suisun Bay will have slight increases in salinity, but this is not expected to influence HABs or Weeds in these regions, so data from these regions are not shown in this report.

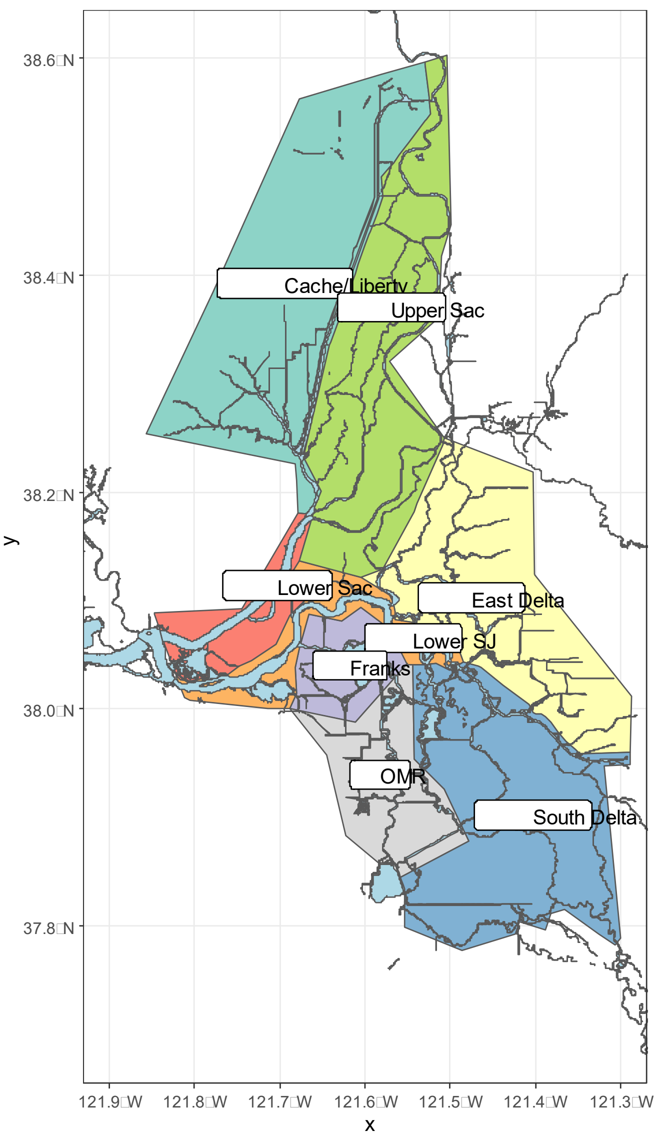

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Figure 1. Regions used for analysis

HARMFUL ALGAL BLOOMS

Background

HABs in the Delta

Blooms of the toxin-producing cyanobacteria *Microcystis aeruginosa* have been observed in the Delta by researchers working at DWR and other agencies since the late 1990s. These blooms were first documented visually appearing as little lettuce-like flakes in the water (Lehman and Waller 2003). Studies of these blooms have demonstrated that these blooms contain multiple microcystin toxins. In sufficiently high concentrations, these act as liver toxins (Lehman et al. 2005), and the presence of low concentrations in the Delta is cause for concern. Investigations after 2005 have found that the blooms frequently are composed of a mix of *Aphanizomenon* sp., *Microcystis* sp., *Dolichospermum* (formerly *Anabaena)* sp., *Planktothrix* sp. and *Pseudoanabaena* sp. (Lehman et al. 2010; Mioni et al. 2012), however research to date has focused primarily on *Microcystis*.

Overall, the Central and South Delta have the highest surface concentrations of *Microcystis* and *Aphanizomenon* (Berg and Sutula 2015; Lehman et al. 2013; Lehman et al. 2008; Lehman et al. 2018; Mioni et al. 2012). Starting in 2012, very high abundances of *Microcystis* colonies were observed in the South-East Delta region in the Turning Basin of the Stockton Shipping Channel, in Discovery Bay, and at Rough and Ready Island (Lehman et al. 2018; Spier et al. 2013). *Microcystis* abundance is typically much lower in Suisun Bay west of Antioch and north of Collinsville on the Sacramento River (Lehman et al. 2013; Lehman et al. 2005; Lehman et al. 2008; Lehman et al. 2018; Mioni et al. 2012).

Drivers

A worldwide increase in the incidence of cyanoHABs has prompted a great deal of research into the conditions that favor the growth of these species (Carmichael 2008; Chorus and Welker 2021; Hudnell 2008; Hudnell 2010; O’Neil et al. 2012; Paerl and Paul 2012). Environmental conditions favoring cyanoHAB formation typically include calm and stratified water, warm water temperatures, high light, and an ample supply of nutrients (Berg and Sutula 2015; Huber et al. 2012; Lehman et al. 2013; Lehman et al. 2018; Paerl et al. 2011). The most successful strategies for mitigating cyanoHABs have focused on these environmental factors, including increasing the flow of water, promoting mixing of the water column, and reducing the supply of nutrients (Paerl et al. 2011).

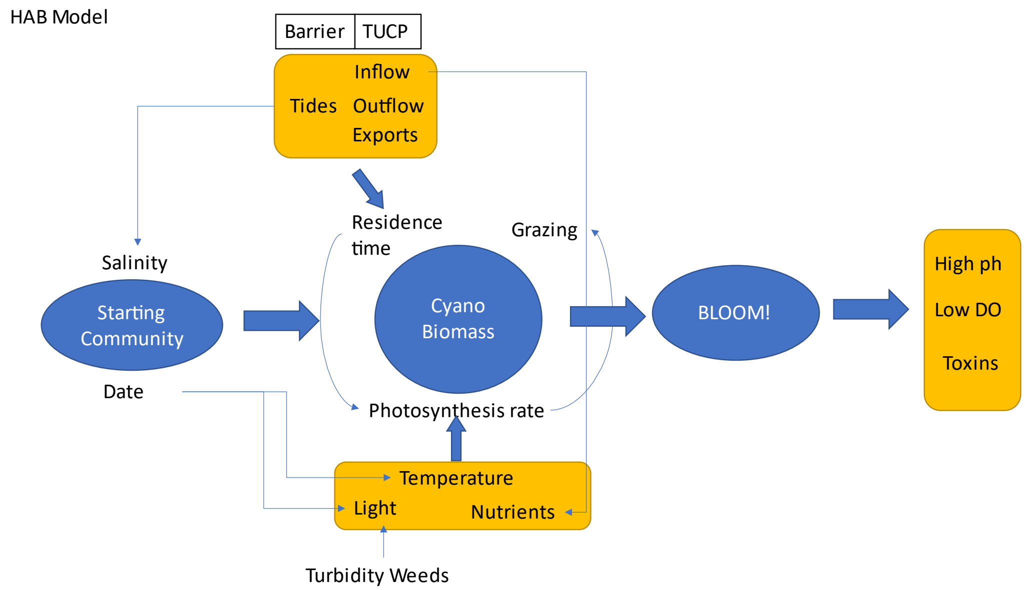


Figure 2. Conceptual model of the influence of hydrology and other factors on harmful algal blooms.

We have developed a conceptual model for how environmental factors impact cyanobacterial blooms (Figure 2). Cyanobacterial blooms are controlled by limitations on their photosynthetic rate or by external factors that remove them from the system. Limitations to their photosynthetic rate include nutrient supply, water temperature, and light availability (Lehman et al. 2013; Lehman et al. 2018). Nutrients in the system are controlled by both non-point sources – runoff from agriculture – and point sources – chiefly wastewater treatment plants within the Delta (Senn et al. 2020). Some cyanobacteria can also fix nitrogen gas dissolved in the water, though *Microcystis* (the dominant toxigenic cyanobacteria in the Delta) cannot. Nutrient concentrations peak in the winter and spring when high flows increase loading of nutrients from the watershed and decrease during the summer when there is less runoff and when primary productivity and nutrient uptake by phytoplankton are at their peaks. In the Delta, summertime chlorophyll concentrations are typically relatively low (2.5-3.5 μg/L), and nutrients are generally not considered limiting to phytoplankton growth and biomass accumulation (Jassby 2008). However, sporadically large phytoplankton blooms occur that completely deplete the available nitrogen supply.

Water temperatures in the Delta have increased over the period of record (Bashevkin et al. 2022), with substantial increases starting in 1999 (Brooks et al. 2011). Water temperatures in the Delta are driven mainly by air temperatures (Vroom et al. 2017), and periods of low inflow also tend to be warmer (Bashevkin and Mahardja 2022). Temperatures vary spatially within the Delta with warmer temperatures in the South Delta and cooler temperatures along the Sacramento River and in Suisun Bay (Bashevkin et al. 2022).

Light availability changes with solar irradiance and turbidity. While cloud cover and smoke may block sunlight temporarily, summer light availability is controlled mainly by turbidity. Turbidity in the Delta is driven by sediment concentration of the incoming water, water velocity and wind. The largest sediment inputs in the Delta occur during winter storms, so summer conditions will have clearer water, and sediment inputs in the Delta have been decreasing over the past 50 years, causing a trend toward increased water clarity (Schoellhamer 2011). As water slows, suspended particles sink and cause the water to clear further. During the summer, water velocity is controlled by tidal action, so (as for residence time) water velocity on the local scale is most impacted by physical characteristics of the Delta, particularly the presence of submerged vegetation. Vegetation causes the water to slow, and the trend toward increasing water clarity in the Delta has been linked to the increase in aquatic vegetation over the past twenty years (Hestir et al. 2016). Wind increases sediment re-suspension and turbidity in extended areas of shallow open water, such as Suisun Bay, but is less of a factor in narrow channels or areas with dense vegetation (Bever et al. 2018).

External factors controlling blooms include flow, residence time, and grazing rates. Residence time in the Delta is controlled by the combined interaction of tidal action, inflows, diversions, and physical characteristics of the Delta. On the large scale, inflows will dominate the inter-annual and intra-annual differences in residence time, with major floods greatly reducing residence time during the winter and spring months. Decreased flow typically occurs during July–September, which coincides with the occurrence of *Microcystis* blooms

(Lehman et al. 2013, 2018, 2020; Spier et al. 2013). At the local scale, particularly at low flow values, tidal action will dominate both residence time and velocity, with greater differences seen on the spring-neap tidal cycle. At low outflow values, changes to the physical characteristics of the Delta, such as installation of barriers, operation of gates, or growth of submerged vegetation will have a greater impact on residence time than changes to outflow since physical changes will alter tidal dynamics.

Most cyanobacteria are not preferred food for planktivorous grazers, though some zooplankton and clams will consume *Microcystis* and other cyanobacteria (Kimmerer et al. 2018; Liu et al. 2009; Silva et al. 2020). Therefore, top-down control of cyanoHABs appears to be rare in the Delta, and blooms are more frequently dissipated through depletion of nutrients and increases in flow.

When nutrients, turbidity, temperature and residence time are all at the right level, a phytoplankton bloom will occur (Glibert et al. 2014). However, the type of bloom will depend on the starting community, nutrients available, and time of year. Early in the season, spring blooms are more often dominated by diatoms and other "beneficial" phytoplankton. Later in the year, when temperatures are warmer, cyanobacteria are more likely to dominate (Lehman et al. 2013). The ratio of nitrogen to phosphorus, and the form of nitrogen present (ammonium versus nitrate) will also favor some taxa over others (Dahm et al. 2016; Wan et al. 2019).

Drought Barrier and TUCP

Given that increased residence time, temperature, and water clarity increase the risk of the occurrence of blooms of *Microcystis* and other cyanoHABs, the drought is expected to result in an increase in both the duration and the severity of blooms of *Microcystis* and other potentially toxic cyanobacteria. Droughts tend to be hotter, with higher water clarity, and lower outflow (Hartman et al 2022). Important concerns are whether the TUCP will increase the effect of the drought on cyanoHABs, and whether the drought barrier in West False River will promote cyanoHABs in the Central Delta by restricting flows and increasing residence times.

The TUCP may increase residence time in the South and Central Delta broadly, by decreasing exports, decreasing San Joaquin River inflow, and decreasing outflow, but is not likely to influence local-scale velocities (which are mostly driven by tidal forces at low outflows). In contrast, the barrier will significantly change tidal dynamics in the vicinity of Franks Tract and therefore change local velocities and increase residence time within the Tract.

The analysis will be divided into three parts:

1. A description of where and when harmful algae were detected in 2022, across all regions of the Delta, along with the toxin levels observed during blooms, water quality conditions, and hydrologic conditions.

2. A comparison of harmful cyanobacteria levels in the Central Delta and South Delta in 2022 versus 2014-2021 using visual assessments and phytoplankton community composition as enumerated in grab samples.

3. A model of drivers of cyanobacteria observations versus several environmental correlates, with predictions for how changes resulting from the TUCP may have impacted the probability and severity of cyanoHABs.

Methods

Visual Assessments

Most monitoring surveys that collect data on water quality and fisheries in the Delta also collect visual observations of *Microcystis* and other visually detectable algal blooms. Because *Microcystis* colonies are relatively easy to identify visually in the field, this visual ranking gives a general idea of when and where the most common harmful cyanobacteria in the Delta occurs. However, this method does not detect other cyanobacteria taxa that may be present and is subject to observer bias. This method also provides no information on the toxicity of the bloom, since *Microcystis* may or may not carry toxin producing genes and those with toxin-producing genes may not be actively producing the toxin.

A surface water sample is brought on board in a bucket and *Microcystis* is ranked on a scale of 1–5, 1 meaning “absent” and 5 meaning “very high” (**Figure 3**). Although this method is imprecise, it is generally reliable on the for detecting Microcystis and giving a rough estimate of magnitude.

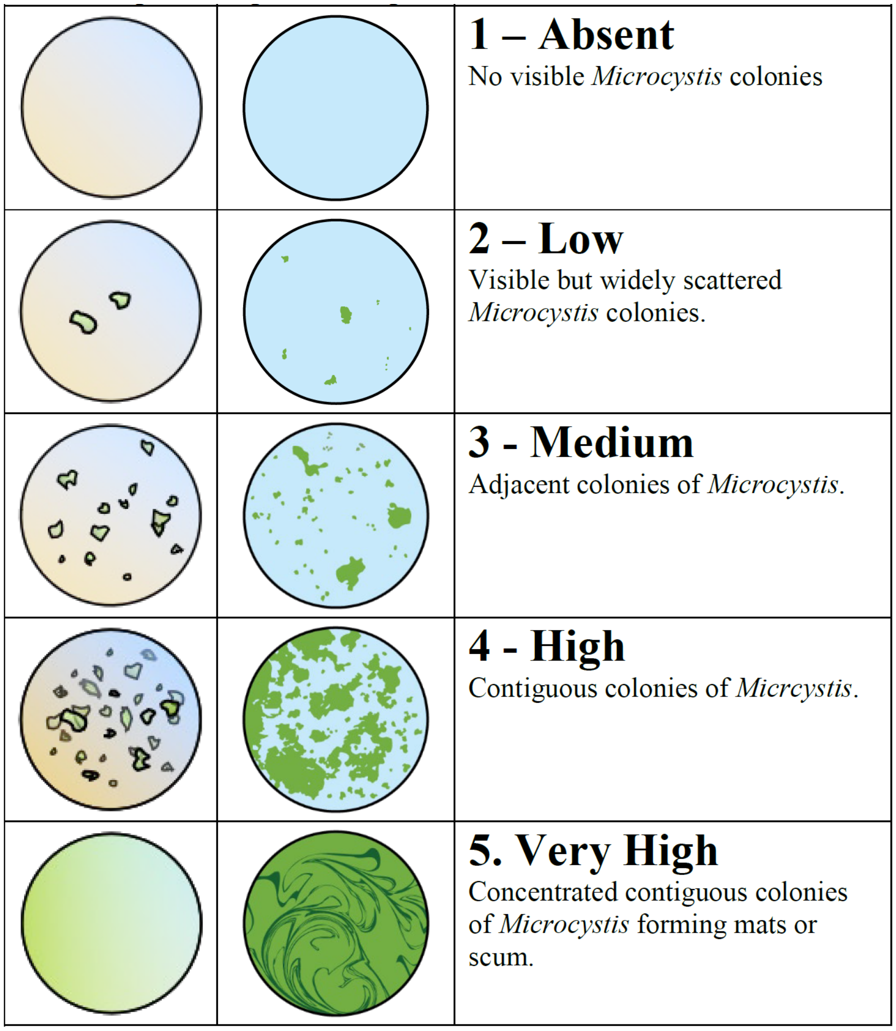


Figure 3
Scale for visual *Microcystis* index used by monitoring programs in the Delta.

Visual assessment data will be collated from five surveys, with additional surveys added if more become available. These data were subset to only include observations during the summer and fall, June-October, since this is the time frame when cyanoHABs usually occur. Total observations varied by region of the Delta and year, but ranged from 452-1246 data points per summer:

- The Environmental Monitoring Program (EMP) is conducted jointly by DWR, the California Department of Fish and Wildlife (CDFW), and Reclamation and collects water quality, phytoplankton, zooplankton, and benthic invertebrate data throughout the Delta, Suisun Bay, and San Pablo Bay. The EMP has recorded *Microcystis* observations at each of its discrete stations using the scale shown in Figure 3 since fall 2015. EMP also collects data on phytoplankton community composition via microscopic enumeration of grab samples, allowing an evaluation of which species are contributing to phytoplankton blooms. These data are collected at 24 fixed stations and up to four floating stations each month throughout the year (IEP 2020). These data are published annually on the Environmental Data Initiative repository, and advanced copies of the data will be requested from the PI's if necessary.

- The CDFW Summer Townet Survey samples fixed locations from eastern San Pablo Bay to Rio Vista on the Sacramento River, and to Stockton on the San Joaquin River and a single station in the lower Napa River. The survey runs twice per month during June, July, and August and samples at 40 stations. The survey primarily monitors young-of-the-year fishes, but also measures zooplankton and environmental variables including water temperature (°C), water clarity (Secchi Depth and nephelometric turbidity units [NTU]), and specific conductance (microSiemens per centimeter [μS/cm]). Visual observations of *Microcystis* have been collected since 2007. Data are available via the CDFW website, and advanced copies of the data will be requested from the PI's if necessary.

- The CDFW Fall Midwater Trawl survey samples at fixed locations from eastern San Pablo Bay to the Cache Slough complex and Sacramento Deep Water Ship Channel, on the Sacramento River, and to Stockton on the San Joaquin River. This survey runs once per month during September, October, and November at 122 stations. The survey primarily monitors young-of-the-year fishes, but also measures zooplankton and environmental variables including water temperature (°C), water clarity (Secchi Depth and NTU), and specific conductance (μS/cm). Visual observations of *Microcystis* have been collected since 2007. Data are available via the CDFW website, and advanced copies of the data will be requested from the PI's if necessary.

- DWR's North Central Region Office conducts water quality and cyanoHAB sampling at stations throughout the South Delta. These samples include chlorophyll, nutrients, bromide, and organic carbon. When collecting water samples, the study also measures environmental variables including water temperature (°C), water clarity (Secchi Depth and NTU), specific conductance (μS/cm), and visual *Microcystis* index. Data are available from DWR's Water Data Library platform.

- Reclamation's Directed Outflow Project samples at randomly selected stations throughout Suisun Bay, Suisun Marsh, and the

Delta in coordination with the U.S. Fish and Wildlife Service Enhanced Delta Smelt Monitoring Program. This program primarily collects zooplankton and water quality samples, as well as environmental variables including water temperature (°C), water clarity (Secchi Depth and NTU), specific conductance (µS/cm), and visual *Microcystis* index.

- USGS California Water Science Center began collecting visual *Microcystis* observations during their water quality cruises in the fall of 2020. These cruises conduct both continuous, high-speed water quality mapping as well as discrete grab samples for nutrients. Provisional Data will be obtained from the PI. DWR has contracted with USGS for additional water quality cruises in support of monitoring the Emergency Drought Barrier and the potential for installing additional drought barriers in future years (Appendix C).

The visual *Microcystis* scale goes from 1 (absent) to 5 (very high). However, because the scale is somewhat subjective and varies between observers, these data will be categorized for this analysis using a three-point scale. Values of 1 were recoded as "absent," values of 2 or 3 as "low," and values of 4 or 5 as "high." First, the difference between incidence of cyanoHABs across the entire Delta will be assessed, to determine any Delta-wide impacts of the TUCP. Then, the data will be broken up into subregions to see whether any subregion has a disproportionately large change in HABs. Regions where HABs were particularly high will receive additional analysis.

An ordered logistic regression (the 'polr' function from the MASS package in R (Ripley et al. 2021)) will be used to test for differences between regions and between years. This regression will be followed by a pairwise post-hoc test using the function 'emmeans' in the emmeans package (Lenth et al. 2021) to evaluate whether drought years had an increased probability of cyanoHAB presence or increased probability of high cyanoHAB presence compared to wet years, and whether there are significant differences between years with a drought barrier (2015, 2021, 2022) and drought years without a barrier (2014, 2016, 2020).

Community Composition

The EMP also provides data on phytoplankton community composition via microscopy from subsurface grab samples, allowing a determination of which species are contributing to phytoplankton blooms. These data are collected at 24 fixed stations and two stations that track the location of the salinity field each month throughout the year. Phytoplankton samples are collected with a submersible pump from a water depth of 1 meter below the water surface. Samples are stored in 50-milliliter (mL) glass bottles with 2 mL of Lugol's solution to act as a stain and preservative. Samples are analyzed by BSA Environmental Services, Inc. (Beachwood, Ohio). Phytoplankton are identified to the lowest taxonomic level possible using the Utermöhl method and American Public Health Association standard methods (APHA 2017; Utermöhl 1958). Additional data on community composition of harmful algae were collected at Banks Pumping plant and Clifton Court Forebay, associated with cyanotoxin sampling. We will subset these data to show only cyanoHABs species, defined as species in the genera *Anabaeopsis, Aphanizomenon, Cylindrospermopsis, Dolichospermum*, and *Microcystis*. While *Microcystis* is occasionally collected by these grab samples at one meter depth, it is better assessed by surface tows. We include these data to provide an idea of which taxa were present in the community, but should not be taken as a quantitative assessment of *Microcystis* abundance.

Nutrients and discrete chlorophyll

Nutrient data (ammonium, nitrate + nitrite, and ortho-phosphate) will be collected from three sources:

1. The EMP, which collects discrete water quality grab samples at all stations where samples for phytoplankton community composition are collected. Water is collected using a flow-through system whereby it is pumped into the ship-board laboratory from a fixed intake located one meter below the water's surface or from a Van Dorn water sampler or via a submersible pump (IEP 2020). Analyses are performed for dissolved ammonia, dissolved nitrate + nitrite, total kjeldahl nitrogen, total phosphorus, and dissolved orthophosphate by CDWR's Bryte Laboratory using EPA methods or Department-approved modifications of these methods (IEP 2020).

2. DWR's North Central Region Office (NCRO) collects discrete nutrient and chlorophyll-a data at six locations in the Central Delta surrounding Franks Tract. Chlorophyll-a samples were collected routinely from 2014-2021, while nutrient samples were only collected in 2014-2016 and 2021. Water is collected from a Van Dorn water sampler at a depth of one meter (DWR 2022). Samples were analyzed by DWR's Bryte Laboratory using EPA methods or Department-approved modifications of these methods (IEP 2020).

3. USGS has two programs that routinely collect discrete nutrient and chlorophyll-a data in the Delta: the California Water Science Center (CAWSC) and the San Francisco Bay Water Quality Survey (SFBS). CAWSC collects samples at numerous locations throughout the Delta, while the SFBS collects most of their samples downstream of the Delta with a few locations extending into the Delta. The SFBS has been collecting discrete water quality samples from 1969 to present, while the CAWSC began collecting samples more recently.

Data from 2022 will be plotted across the Delta separated by region to show trends across the summer. Data will then be subset to include stations in the Lower Sacramento, Lower San Joaquin, and South Delta (where cyanoHABs are most frequent) and summarized by month and year. We will run a generalized linear mixed model on each constituent using the formula Concentration ~ Year + Season + Error(Month) + Error(Station) to see whether nutrients or chlorophyll in 2022 were different from previous years using the lme4 package. We will perform a tukey post-hoc test on all pairwise comparisons and visualized significant differences between years using the estimated marginal means for the 'emmeans' package.

Nutrients are frequently identified as a driver for cyanoHABs, but nutrients are seldom limiting for phytoplankton production in the Delta. It is instructive to compare actual measured chlorophyll concentrations with potential chlorophyll concentrations that could be expected if all the available nitrogen in the water (i.e. the residual nitrogen) were converted to chlorophyll biomass to assess the phytoplankton biomass accumulation (i.e. bloom development) potential of a particular region. To perform this comparison, residual nitrogen concentration will be converted to chlorophyll using the ratio 1 µmol N: 1 µg chlorophyll a (Gowen 1992, Cloern and Jassby 2012). Residual nitrogen will be calculated by summing all the dissolved inorganic nitrogen species (nitrate + nitrite + ammonium) in units of molar mass N. Potential chlorophyll will be compared with measured chlorophyll for each region of the Delta for the summers of 2014-2020, and for the summers of 2021 and 2022.

Cyanotoxin Data

Cyanotoxin data will be assembled from multiple sources. These studies all use either ELISA or LCMS to analyze toxin concentrations. There is generally very high agreement between these two methods, though ELISA may produce higher concentrations ((Preece et al. 2021)Table 3). Across most of the national HAB research community, data from either method are compared to thresholds and there is no conversion factor applied, nor is one method disregarded.

- The State Water Board's freshwater HAB program collects samples for cyanotoxins when large blooms are reported (https://www.waterboards.ca.gov/water_issues/programs/swamp/freshwater_cyanobacteria.html). Samples are lysed and analyzed for total microcystins/nodularins using the enzyme-linked immunosorbent assay (ELISA) method, and using qPCR to detect the number of microcystin-producing cells present. Analyses are conducted by Bend Genetics, LLC, Sacramento, CA. The Water Board's HAB program also provides a platform for storage and display of other HAB occurrences collected by other programs. We will work with Karen Atkinson and other data managers to access all relevant cyanotoxin and cyanobacteria data collected over the time period of the TUCP.

- DWR collects cyanotoxin samples at Clifton Court Forebay and the Harvey O. Banks Pumping Plant (Banks Pumping Plant) to ensure that the water exported from the Delta is safe for use. Samples are collected every two weeks in April–October and analyzed by GreenWater Laboratories (Palatka, Florida), using a tiered approach. Samples are first assessed via microscopy to identify whether potentially toxic algae or cyanobacteria are present. If potentially toxic algae are detected, cells are lysed and samples are then tested for probable toxins using either ELISA or liquid chromatography–mass spectrometry (LC-MS), as appropriate (Foss and Aubel 2015).

- Through a special study conducted collaboratively by USGS and DWR with funding from the Delta Regional Monitoring Program, samples are collected at several stations throughout the Delta: Jersey Point (JPT), Decker (DEC), Middle River (MDM), Liberty Island (LIB), Rough and Ready Island (P8, DWR-EMP), and Vernalis (C10; DWR-EMP). For these efforts, cyanotoxins are being measured in whole water discrete samples as well as using Solid Phase Adsorption Toxin Tracking (SPATT) samplers every two to four weeks. All (100 percent) of these cyanotoxin samples will be analyzed using LC-MS, and—upon review of LC-MS data—a subset (approximately 20 percent) will be selected for analysis using ELISA. All analyses will be conducted by Lumigen Instrument Center, Wayne State University, Detroit, MI.

Preliminary data from water quality samples will be requested from the PIs.

- Under a Proposition 1 Grant, principal investigators (PIs) David Senn (SFEI), Janis Cooke (CVRWQCB), Ellen Preece (Robertson-Bryan, Inc), and Timothy Otten (Bend Genetics), are conducting a study of bioaccumulation of cyanotoxins in invertebrates at ten stations throughout the Delta. The study, "Identifying cyanobacterial harmful algal bloom toxins in Delta invertebrates: implications for native species and human health", includes analysis of Asian clams (*Corbicula fluminea*), crayfish, and whole water samples. Samples are collected monthly in the winter and every two weeks during the summer and analyzed for microcystins by Bend Genetics using ELISA. Preliminary data from water quality samples will be requested from the PIs.

- East Bay Regional Parks conducts sampling at Big Break Regional Shoreline where they visually inspect the water for signs of cyanobacteria twice per month. If signs of cyanobacteria are detected, they conduct microscopy and toxin analysis using Abraxis CAAS ELISA. Preliminary data from water quality samples will be requested from the PIs.

- DWR is also conducting additional cyanotoxin sampling in the vicinity of the Emergency Drought Barrier and South Delta Temporary Ag Barriers to assess the impacts of the Barriers and TUCP on cyanotoxins. All toxin analyses will be conducted by GreenWater. See attached study plans (Appendix A and B) for more information.

- Restore the Delta, a local community group, is currently working with the Central Valley Regional Water Board to implement a new citizen science program to monitor cyanotoxins near Stockton and other areas of high recreational use. They will be posting testing results to their website starting in May of 2022, and any additional data will be obtained from their science coordinator, Spencer Fern (spencer@restorethedelta.org).

None of the cyanotoxin data presented here are part of a comprehensive monitoring program. The USGS/DWR SPATT study and the Prop 1 Senn/Preece/Cooke/Otten studies were designed as special studies to better understand toxin dynamics rather than to establish a baseline. The Regional Board data is designed as a response to severe blooms, not a comprehensive monitoring program. The DWR Banks/CCF monitoring is designed specifically to assess water quality for water export, so is not necessarily applicable to the rest of the Delta. While there may be some variation between testing laboratories and field collection procedures, all methods are considered comparable and can be used for health advisories. Combining these data sets does provide a relatively wide spatial and temporal scope of cyanotoxin monitoring, though it may miss small-scale or short-lived toxin events, particularly in smaller, backwater sloughs in the Delta.

FluoroProbe Data

The EMP and USGS both employ vessels equipped with high-resolution sensors that collect data continuously on both water quality and phytoplankton community composition while underway. During these surveys, the EMP monitors water quality using a YSI EXO2 water quality sonde (Xylem, Inc.) to measure pH, turbidity, specific conductance, chlorophyll a (with the Total Algae™ sensor), dissolved oxygen (DO), and water temperature. Both surveys monitor the phytoplankton community's composition using a FluoroProbe instrument (bbe moldaenke GmbH, Schwentinental, Germany) that differentiates cyanobacteria, diatoms, green algae, and chlorophytes based on the wavelength of the fluorescence given off by each taxonomic group's characteristic photopigments.

DWR has contracted with USGS to provide additional mapping cruises in the vicinity of Franks Tract and the North Delta (see task order attached, Appendix C)

FluoroProbe data collected by both the EMP and USGS are processed following the methodology described in the Methods PDF of the USGS data release at www.doi.org/10.5066/P9FQEUAL (Bergamaschi et al. 2020). Briefly, data are spatially aligned to equally spaced polygons spaced at approximately 150 meters. Interpolated values are calculated in ArcGIS using the Spline with Barriers tool (Terzopoulos and Witkin 1988) and used to create a continuous map of values (e.g., the concentration of chlorophyll a from blue-green algae) across the mapped domain.

Satellite Data

Satellite data, available from the San Francisco Estuary Institute's HAB Satellite Analysis Tool (SFEI 2021), can provide estimates of CyanoHAB abundance with broader spatial scale and higher temporal resolution than grab samples and visual observations. Satellite imagery is collected by the Copernicus Sentinel-3 mission and provides images of the Delta every 1-2 days. The HAB Satellite Analysis Tool provides estimates of CyanoHAB abundance in the upper 1 meter of the water column by measuring the absorption of light by chlorophyll and phycocyanin, an accessory pigment in photosynthesis specific to cyanobacteria. Estimates of CyanoHAB abundance are reported in an exponential, satellite-specific, unitless metric called the Cyanobacteria Index (CI) for pixels with dimensions of 300 meters by 300 meters, each approximately an area of 22 acres. The Cyanobacteria Index is derived from post-processing methods established by the National Oceanic and Atmospheric Administration's National Ocean Service (Wynne et al. 2018). Because of the limitations of the satellite-based sensor in distinguishing subtle differences in absorption from cyanobacteria at levels that are very low (CI of 6.310×10^{-05} is near natural background levels of cyanobacteria) or very high (CI of 6.327×10^{-02} in extremely dense scums), minimum and maximum detectable levels have a smaller range than are possible using traditional water grab samples. Because the smallest pixel available is 22 acres, only larger areas of open water, such as Franks Tract, can be analyzed. Smaller sloughs are not large enough for accurate classification. Further information on these methods are detailed on the National Ocean Service website: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-monitoring-system/more-information/

Satellite mosaics of rasterized CI data across the Central Delta for June–October in 2020-2022 will be downloaded from the San Francisco Estuary Institute's HAB Satellite Analysis Tool (SFEI 2021). Raster pixels for four open water regions in the Delta (Franks Tract, Clifton Court Forebay, Liberty Island, and Mildred Island) will be extracted from each file using the 'exact_extract' function in the 'exactextractr' R package version 0.7.1 (Baston 2021). The four open water regions were defined using polygons from CDFW expanded by 200 meters around their perimeters to account for the large raster pixels. Pixels will be categorized into four CI categories (Low, Moderate, High, and Very High) based on WHO recreational guidance level thresholds (WHO 2021).

Continuous Water Quality Data

DWR and USGS maintain a network of water quality sondes that collect data continuously (i.e., every 15 minutes) across the Delta. These sondes collect data on water temperature, specific conductance, flow, dissolved oxygen, chlorophyll fluorescence, turbidity, and pH (though not all stations contain all sensors). To assess how HABs impact water quality parameters, we will plot the daily mean of data collected at stations where harmful algal blooms occurred versus day of the year for the past eight years (2015-2022).

To see how extended periods of high temperatures may drive harmful algal blooms, we will calculate the number of degree-days over 19 degrees C by averaging the daily maximum and minimum water temperature at seven stations in the South Delta. This was converted to degree-days using the formula:

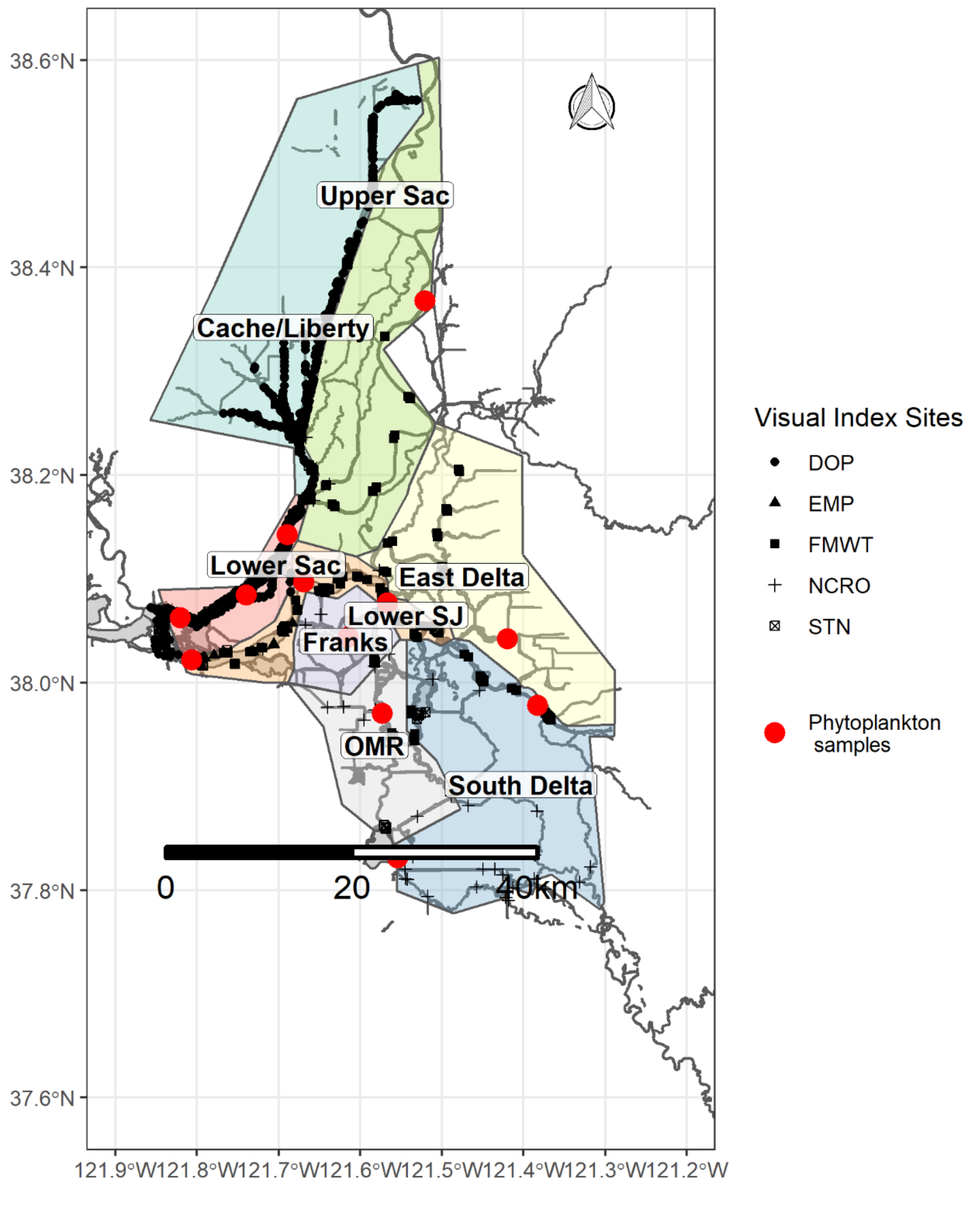
Degree Days = (Daily Max Temp – Daily Min Temp)/2 – 19

We will conduct the degree-day analysis using both water temperature and air temperature, to see whether air temperature patterns were similar to water temperature patterns.

Table 1. Stations used for continuous water quality and air temperature analyses.

StationCode	Station Name	Latitude	Longitude	Sensors
FAL	False River near Oakley	38.05547	-121.667	Chlorophyll, DO, Specific Conductance, Water Temperature, Turbidity
HOL	Holland Cut Near Bethel Island	38.01582	-121.582	DO, Specific Conductance, Water Temperature, Turbidity
HLT	Middle River near Holt	38.00308	-121.511	Chlorophyll, Specific Conductance, Water Temperature, Turbidity
ORQ	Old River at Quimbly	38.02712	-121.565	Specific Conductance, Temperature, Turbidity
OSJ	Old River at Franks Tract near Terminous	38.07125	-121.578	Chlorophyll, DO, Specific Conductance, Water Temperature, Turbidity
FRK	Franks Tract Mid Tract	38.04642	-121.598	Chlorophyll, DO, Specific Conductance, Water Temperature, Turbidity, pH
MDM	Middle River at Middle River	37.9430	-121.534	Chlorophyll, Flow, Specific Conductance, Water Temperature, Turbidity
SJR	San Joaquin R Mccune Station	37.6789	-121.265	Air Temperature
HBP	Harvey O Banks Pumping Plant	37.8019	-121.6203	Air Temperature

MSD	San Joaquin River at Mossdale	37.7860	-121.3060	Air Temperature



NOTE: Analysis to assess the impact of the 2021 Emergency Drought Barrier will focus on the Lower Sacramento, Lower San Joaquin, and Southern Delta. Analysis to assess the impact of the TUCP will encompass the entire area.

Figure 4

Stations for long-term monitoring programs contributing *Microcystis* visual observations (black), and phytoplankton grab samples (red) in 2021. Additional sampling by USGS will be integrated in the 2022 report

Hydrodynamic Modeling and Flow

To assess changes in residence time and temperature, three-dimensional simulations will be carried out using the Bay-Delta SCHISM three-dimensional circulation model (Ateljevich et al. 2014), which is an application of the Semi-implicit Cross-scale Hydroscience Integrated System Model (Zhang et al. 2016). Mean water age is used as a surrogate for residence time, evaluated using the Constituent oriented Age and Residence Time theory or CART (Deleersnijder et al. 2001) and the formulation described by Delhez et al. (2014). This method uses pairs of supplementary tracer transport equations to evolve the mean age of water at each point in the domain; the method naturally incorporates multiple pathways of travel and dispersion and is an economical tool for evaluating spatial patterns. “Age” in this case is defined as the time of last contact with the San Joaquin River. Quantitative results within Franks Tract are sensitive to assumptions concerning the vegetation field. Vegetation will be included using the method of Zhang et al. (2020), which was originally tested in Franks Tract using spatial patterns of vegetation inferred from hyperspectral imagery from 2015 (Ustin et al. 2016).

Data limitations

The datasets assembled as part of this monitoring effort will broadly document cyanobacteria and other potentially harmful algal blooms in the Delta during 2021 and 2022 by virtue of the wide range of different data sets. However, each of these data sets has certain limitations.

Uses and limitations of each data set are as follows:

- Visual index data provides a spatial and temporal scope, and a good indicator of Microcystis presence, but cannot provide a quantitative measure of Microcystis concentration and is not appropriate for other CyanoHAB taxa.

- Chlorophyll fluorescence data collected with a sonde provides continuous data on chlorophyll concentrations, but cannot distinguish between cyanobacteria and other phytoplankton. It also does not accurately quantify chlorophyll in surface films or cyanobacteria that forms colonies or clumps.

- Chlorophyll-a data collected with grab samples and analyzed in a laboratory is more accurate than sonde data but may also miss surface-oriented cyanobacteria and cannot distinguish between cyanobacteria and other phytoplankton. Grab samples may also miss the peak of the bloom.

- Grab samples collected and analyzed with microscopy provide the best taxonomic resolution. However, samples collected by EMP are collected at 1-meter depth, so may miss surface-oriented cyanobacteria, such as *Microcystis*. While these samples identify taxa that are present, they do not indicate whether the taxa present are made of strains capable of producing toxins, nor whether they were producing toxins at the time of collection.

- Chlorophyll and phycocyanin data collected during high-speed mapping cruises using the Fluoroprobe provide data on a broad spatial scale and can distinguish between cyanobacteria and other algae, but are limited in temporal scope. The Fluoroprobe also cannot distinguish between types of cyanobacteria (not all cyanobacteria are harmful).

- Satellite data provides broad spatial scope, however it cannot quantify low concentrations of cyanobacteria, nor can it distinguish between types of cyanobacteria (not all cyanobacteria are harmful). This data also cannot quantify cyanobacteria in small channels.

- The incident data reported to the State Board's Cyano-HAB portal relies on agencies and members of the public submitting reports, which may not be consistent over space and time. Many of these reports are based on visual observations rather than cyanotoxin data. However, these reports provide better coverage of marinas, boat ramps, and other places where the public regularly comes in contact with the water than other areas.

- Toxin data provides the most accurate assessment of potential harm caused by an algal bloom. However, unless sampling occurs on a daily basis, it may not characterize the toxicity over the entire time period. Furthermore, the ecological and human health impacts of some cyanobacterial metabolites (such as anabaenopeptins) are still unknown.

AQUATIC WEEDS

Background

Ecology and Impacts

Aquatic vegetation provides important structure and function for aquatic organisms and waterfowl and greatly influences nutrient cycling, water quality, and the stability of sediments (Caraco and Cole 2002; Miranda et al. 2000). Diversity of fish and invertebrate species tends to be greater in native aquatic plant beds, and water quality conditions are generally more favorable for native fish and invertebrates (Boyer et al. 2013; Kuehne et al. 2016; Toft et al. 2003). Alternatively, non-native aquatic plants can have dramatic spatial and temporal effects on DO, temperature, and pH (Caraco and Cole 2002; Frodge et al. 1990) and can affect fish and macroinvertebrates (Brown 2003; Nobriga et al. 2005; Schultz and Dibble 2012).

Aquatic vegetation is commonly discussed in terms of their growth forms: submerged aquatic vegetation (SAV), emergent aquatic vegetation (EAV), and (3) floating aquatic vegetation (FAV) (Boyer and Sutula 2015). SAV grows predominantly below the water's surface and may or may not be rooted in the sediment. Examples of SAV found in the Delta include Brazilian waterweed (*Egeria densa*), coontail (*Ceratophyllum demersum*), and Canadian waterweed (*Elodea canadensis*). EAV is rooted in shallow water, with the majority of its growth occurring above the water's surface. Examples include cattail (*Typha* spp.), tules (*Schoenoplectus spp*.), and common reed (*Phragmites australis*). FAV floats on the water's surface and is not rooted in the sediment. An example of FAV in the Delta is water hyacinth (*Eichhornia crassipes*), though creeping emergents such as water primrose (*Ludwiggia spp*.) and alligatorweed (*Alternanthera philoxeroides*) are also frequently categorized as "FAV".

Weeds in the Delta

Coverage by FAV and SAV in the Delta has increased over the past 20 years (Ta et al. 2017), with particularly high increases seen during the last drought (Kimmerer et al. 2019). From 2008 to 2019, aquatic vegetation increased in coverage by 2.4 times (7,100 acres to 17,300 acres), occupying nearly one-third of the area of Delta waterways (Ta et al. 2017; Ustin et al. 2020). This expansion of SAV has caused a suite of problems for use of the Delta, including clogging of water infrastructure, navigation hazards, and difficulty conducting scientific surveys (Caudill et al. 2021; Khanna et al. 2019). There have also been major changes to ecosystem functions, including increased water clarity (Hestir et al. 2016), changes to nutrient cycling (Boyer and Sutula 2015), reduction in sediment supply for tidal marshes (Drexler et al. 2020), increased invasive fish habitat (Conrad et al. 2016), changes to primary production (Cloern et al. 2016), and changes to invertebrate community composition (Young et al. 2018) .

Impacts of submerged vegetation in the Delta have become severe enough that management has intervened to mitigate the impacts on human use of the waterways. The Aquatic Invasive Plant Control Program of the California Department of Parks and Recreation, Division of Boating and Waterways (DBW) is chiefly responsible for aquatic vegetation control in the Delta and employs primarily chemical control tools. DBW is permitted to treat up to 15,000 acres per year of aquatic vegetation, but typically treats only about 40 percent of that limit (DBW 2020).

Drivers

Factors contributing the biomass of aquatic vegetation include parameters that impact growth and photosynthetic rate, parameters that impact establishment, and top-town effects of grazers and herbicides, which we have organized into a conceptual model (Figure 5). Photosynthetic rate is controlled by, light, sediment nutrient availability, and water temperature (Barko and Smart 1981; Chambers et al. 1991; Riis et al. 2012). In general, photosynthesis rates are largely driven by light levels; they increase from sunrise, peak at midday, then slowly decline in a fairly predictable manner. Light levels are also highest during mid-summer and decline during the fall. However, light available to an individual plant will vary with water depth, and water clarity. The maximum depth of plant growth is typically driven by the maximum depth to which light penetrates the water column to support photosynthesis and can vary greatly between species (Chambers and Kalff 1987). Increased water clarity allows for greater light penetration for photosynthesis to occur. In many cases, this can cause a feedback loop whereby the presence of SAV lowers water velocity and increases sediment deposition which increases water clarity and promotes further growth (Hestir et al. 2016; Petticrew and Kalff 1992). Increased water clarity in the Delta has been implicated in the increased spread of Brazilian waterweed (Durand et al. 2016), and the increase in Brazilian waterweed has been implicated in increasing water clarity and the reduction in sediment transport to tidal wetlands (Drexler et al. 2020; Hestir et al. 2016).

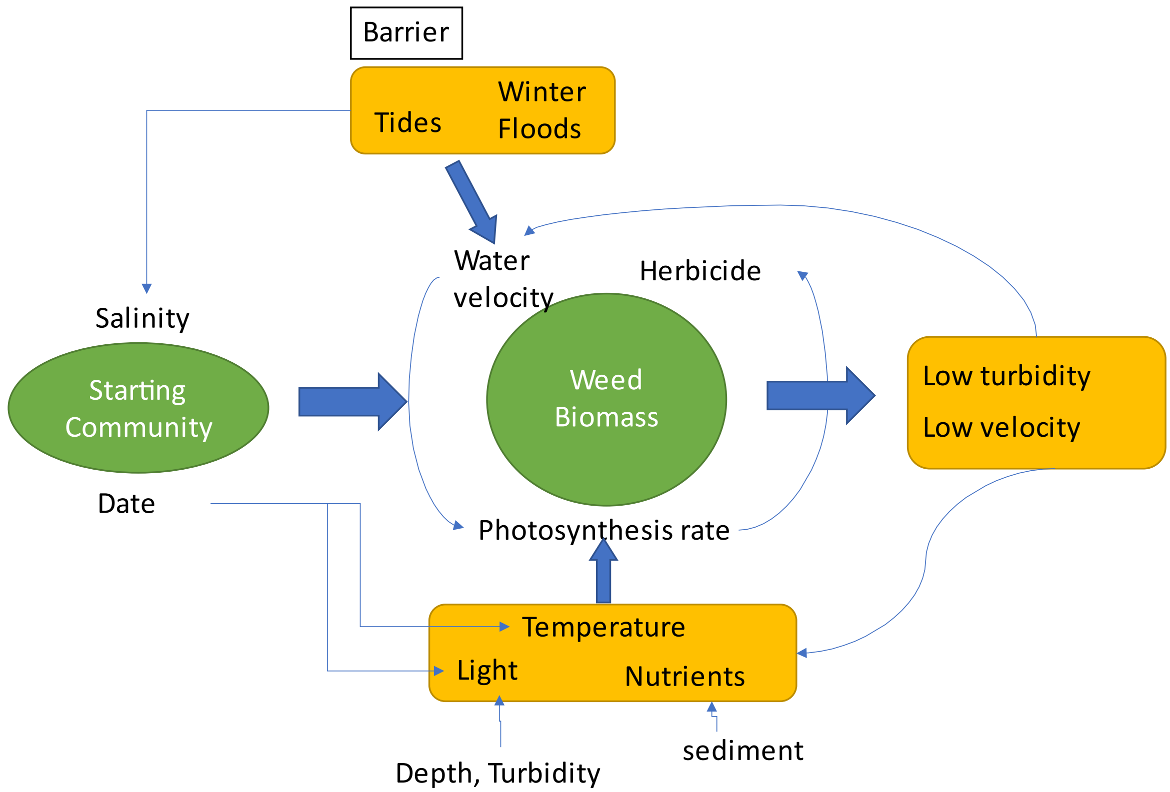


Figure 5. Conceptual model of aquatic weed biomass in the Delta.

Higher temperatures, in general, increase photosynthetic rate and therefore vegetation growth rate. The combination of high water temperatures with high light availability in the summer means that this is when most plants experience their highest growth, with peak biomass occurring in the fall. However, temperature tolerances will vary by species, and extremely high temperatures will lead to reduced growth or senescence.

Nutrients are also key for driving photosynthetic rate, and, unlike cyanoHABs, vegetation may acquire nutrients from the water or the sediment. Rooted SAV and EAV obtain the majority of their nutrients from the sediment, particularly nitrogen and phosphorus (Barko et al. 1991), but many submerged plants can also acquire nutrients directly from the water column. During plant decomposition, this interface provides a mechanism for nutrient recycling between the sediment and the overlying water column. Factors that can affect rates of decomposition, and hence nutrient cycling, include the diversity of the plant community (Banks and Frost 2017) and water temperature (Carvalho et al. 2005). True FAV that is not rooted in the sediment must acquire all their nutrients form the water column. Increases in nutrients, such as those seen during 2013–2014, may facilitate the expansion of aquatic vegetation, although this effect is less conclusive (Boyer and Sutula 2015; Dahm et al. 2016).

Both SAV and EAV establish more readily in slower-moving water, so low-flow conditions that occur during droughts have been linked to increases in coverage of invasive vegetation. During the winter, high velocities that occur during floods may prevent vegetation from establishing or flush established vegetation out of the system. Also, water temperatures are cooler, turbidity is higher, and water is deeper, limiting vegetation regrowth immediately after floods. During the summer, velocity patterns are dominated by tides, so changes to outflow play a smaller role in control of SAV. However, changes to the physical structure of the Delta, such as installation of barriers and growth of vegetation itself, will have a large role in impacting local velocity patterns. For example, changes to flow patterns caused by the 2015 emergency drought barrier were implicated in the expansion of submerged vegetation in Franks Tract (Kimmerer et al. 2019).

Top-down control of vegetation occurs as grazing by invertebrates and treatment with herbicides. A variety of herbivorous insects occur on FAV and SAV (Marineau et al. 2019; Young et al. 2018), and several biocontrol agents have been released in the Delta to help control invasive vegetation (Caudill et al. 2021; Reddy et al. 2019). However, none of these herbivores appears to be limiting growth of vegetation in the Delta.

Human control efforts have had mixed success. For control of FAV, DBW most commonly uses glyphosate but also uses some imazamox and 2,4-D. For SAV control, fluridone is by far the most commonly applied herbicide in the Delta. However, recent studies have shown the use of fluridone on SAV in tidal environments such as the Delta to be generally ineffective (Khanna et al. in review; Rasmussen et al. in press). Therefore, this treatment program may increase the loading of herbicides into the system without significantly affecting weed abundance. Treatment of FAV with herbicides is thought to be somewhat more effective, although there are noticeable changes in water quality post-treatment (Portilla and Lawler 2020; Tobias et al. 2019).

When growth conditions favor SAV in general, the community composition of an SAV patch will depend on salinity, starting community, transport of propagules, and light availability. Some invasive SAV species, such as Brazilian waterweed, are adapted to low-light conditions, which enables rapid elongation of shoots and subsequent canopy formation that further blocks light to other native SAV species. Different species of SAV also have varying temperature tolerances that factor into their life history patterns. For example, curlyleaf pondweed (*Potamogeton crispus*) commonly sprouts early in the growing season and can outcompete native SAV species that are not tolerant of lower water temperatures (Stuckey 1979). Species also vary in their salinity tolerances, with the native *Stukenia pectinata* having a higher salinity tolerance than the invasive *Egeria densa* (Borgnis and Boyer 2015). There are also species-specific sensitivities to different herbicides, leading to altered community composition in areas that receive herbicide treatment (Caudill et al. 2019).

Drought Barrier and TUCP

Drought conditions are predicted to cause an increase in invasive FAV and SAV due to the lack of winter floods. The April-June TUCP, which reduces spring outflow, is not expected to significantly impact vegetation establishment or growth because water velocities, and thus establishment of weeds, is dominated by tides during this time period.

While the TUCP is expected to have minimal impact on weeds, installation of the EDB is expected to cause a local increase in aquatic weeds in Franks Tract. With the Barrier in place, tidal velocities on the western side of the tract decrease while velocities in Fisherman’s Cut and the eastern side of the tract increase. In 2021, installation of the Barrier may have caused an increase in weeds in the western side of the tract and a decrease in weeds in the high flow region on the eastern side (Hartman et al. in prep). Similarly, in 2015, weeds spread across the middle of Franks Tract, and the area was not cleared when high flows returned (Kimmerer et al. 2019). This was attributed to the decrease in water velocity through the center of the tract. A similar response to the 2022 EDB is expected, although the high coverage by weeds within Franks Tract over the past several years will make detecting a response difficult.

Methods

Three sources of data will be used to evaluate whether the 2022 TUCP and the 2021-2022 EDB contributed to changes in the abundance and/or species composition of aquatic weeds. The first two data sets are from the Center for Spatial Technologies and Remote Sensing (CSTARS) at the University of California, Davis. These data sets consist of (1) hyperspectral imagery that classifies the types of aquatic vegetation growing across the Bay-Delta landscape and (2) the vegetation field surveys used to ground-truth this hyperspectral imagery. (3) The third data set, collected by SePRO Corporation (SePRO), consists of annual field surveys of SAV in Franks Tract and is used to assess the efficacy of herbicide treatments at this site.

Hyperspectral Imagery

Since 2004, hyperspectral airborne imagery has been collected by fixed-wing aircraft over the Delta in many years, although the time of year and spatial extent of these surveys has varied. Franks Tract has been included in all surveyed years (2004-2008, 2014–2021). DWR will contract for additional years of imagery in the summer of 2022 and 2023.

It is difficult to differentiate potential impacts of the Barrier and TUCP on the abundance and composition of aquatic vegetation from impacts simply caused by drought. However, it is useful to compare changes in Franks Tract to those at similar sites not influenced by the Barrier (Figure 6). Previous studies have used Big Break as a reference site for Franks Tract because it is near Franks Tract but not influenced by the barriers (Kimmerer et al. 2019). Clifton Court Forebay was also chosen because it shares some similarities to Franks Tract in size, bathymetry, and hydrology and is far from the influence of the 2021-2022 EDB. Imagery for this site is available for ten of the 13 years for which there is Franks Tract imagery: 2004-2008, 2014, 2015, and 2019–2021. Mildred Island was also considered as a candidate reference site but was ultimately rejected because this site is too turbid to produce accurate classification maps of SAV using hyperspectral imagery.

Another challenge to isolating impacts of the Barrier and TUCP on aquatic vegetation is the use of herbicides for vegetation management. Herbicide treatments have been conducted at Franks Tract and Clifton Court Forebay, and the timing, type, and amounts of chemicals used in these treatments have varied among sites and years.

Survey and analysis methods for the hyperspectral imagery have varied somewhat among years, but the approach generally proceeds as described here for the 2018 survey. During this survey, HyVista Corporation (Sydney, Australia) used the HyMap sensor (126 bands: 450–2,500 nanometers, bandwidth: 10–15 nanometers) to collect imagery at a resolution of 1.7 meters by 1.7 meters. A diverse suite of inputs was derived from these images to capture reflectance properties across different regions of the electromagnetic spectrum, which track biophysiological characteristics useful for distinguishing types of plants. These intermediate inputs were generated using IDL scripts (IDL 8.01, ITT Visual Information Solutions) in ENVI (ENVI 4.8, ITT Visual Information Solutions).

Concurrent with imagery collection, ground-truthing surveys will be conducted to determine species composition at points across the Delta region (e.g., 2018: 950 points; see the *Hyperspectral Imagery Ground-Truthing* section for details). Field data will be divided into training and validation subsets for image classification and independent validation of class maps. Training and validation polygons will be overlaid on the raster images with generated inputs, and corresponding pixels within the raster images will be extracted using the R statistical computing language (version 4.0.2, R Core Team 2021) and packages 'sp' (version 1.4.5) (Pebesma and Bivand 2021), 'rgdal' (version 0.5.5) (Bivand et al. 2021), and 'rgeos' (version 1.5.23).

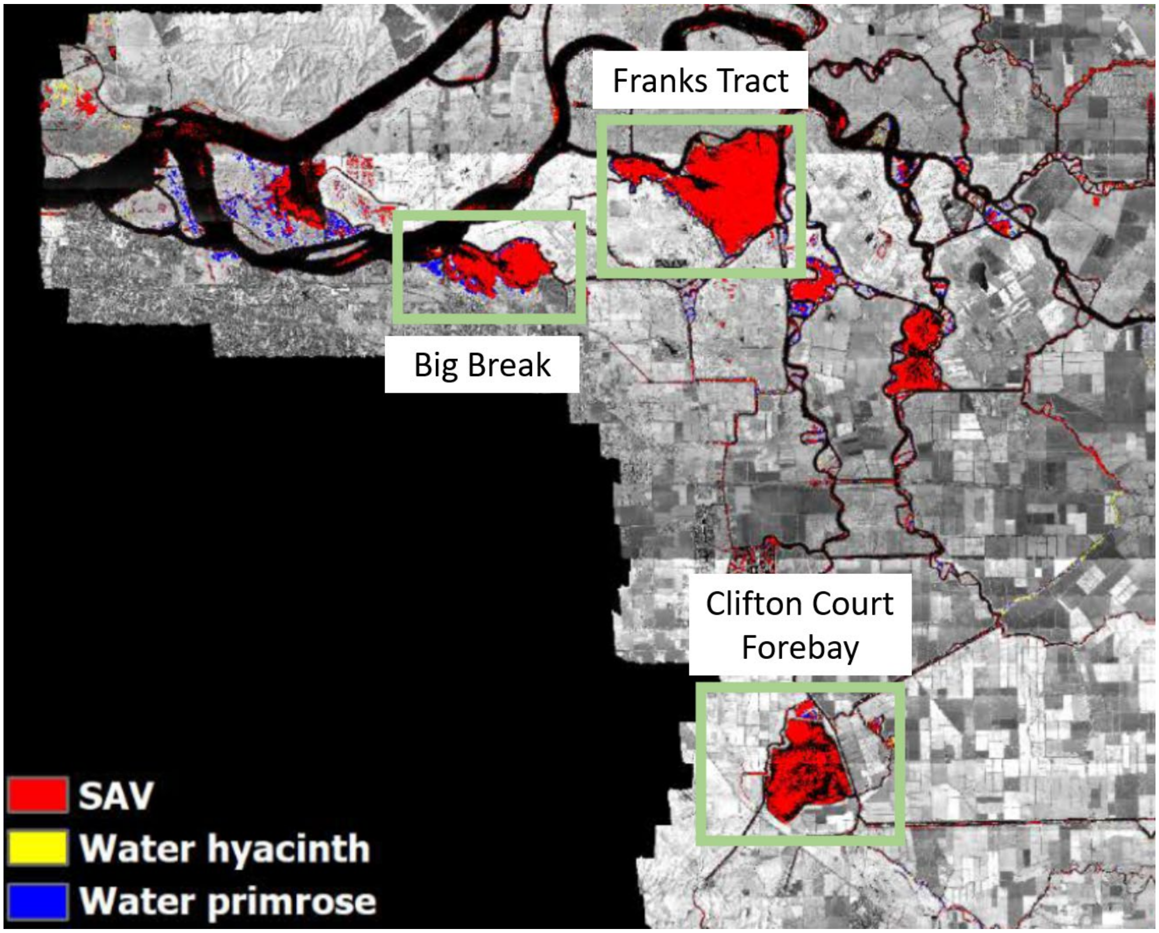


Figure 6
Map of the central and south regions of the Delta for 2019 showing the locations of Franks Tract and the two reference sites, Big Break and Clifton Court Forebay.

Training data will be fed into a Random Forests classifier (packages 'raster': version 3.4.5 (Hijmans 2021) and 'randomforest': version 4.6.14 (Breiman 2001). The best-fit class type (e.g., open water, SAV, water hyacinth, water primrose) for each pixel will be chosen based on consistency across tree predictions. The accuracy of the final maps will be assessed using confusion matrices and Kappa coefficients. The area of SAV will be calculated per site as the number of pixels classified as SAV multiplied by the area of a single pixel. These area calculations will be then used to make comparisons among sites and years. For additional details about the imagery analysis methodology, see Khanna et al. (2018).

Hyperspectral Imagery Ground-Truthing

Around the time that hyperspectral imagery is collected each year, the CSTARS staff collects ground-truthing field data on the community composition of aquatic vegetation across the Delta, including areas in and around Franks Tract. For SAV sampling, they collect data on the species present at the water's surface and the fraction of surface area covered, Secchi depth, depth of the plant below the water surface, species, and fractional cover using a standard rake sample for vegetation. At sites where FAV and EAV are present, they record the species present, the fraction of surface area covered, the state of the plant (in a flowering or vegetative state versus senescent), and the mat density (classified as sparse, medium, or thick).

SePRO Vegetation Survey

Since 2006, DBW has collaborated with SePRO Corporation to manage SAV in Franks Tract using the herbicide fluoridone (Caudill et al. 2019). SePRO monitors changes in SAV community composition using point-intercept surveys (Madsen and Wersal 2018) conducted on one date annually in the fall. Sampling points are chosen by generating a grid of evenly spaced points projected over the full area of Franks Tract (Figure 7). The number of sampling points varies among years but is usually 100 (range: 50–200 samples). Most surveys have been conducted in mid-October (range: October 1–October 13). To sample each point, SePRO uses a weighted, double-headed, 0.33-meter-wide rake attached to a rope, which is dragged for approximately 3 meters along the bottom and then pulled up to the boat for analysis. All SAV present on the rake is identified to species and species-specific abundances are estimated based on the percentage of the rake each covers. Abundances are recorded using ordinal scores (1 = 1–19 percent, 2 = 20–39 percent, 3 = 40–59 percent, 4 = 60–79 percent, 5 = 80–100 percent). Monitoring data for 2022 will be requested from SePRO as soon as possible after collection.

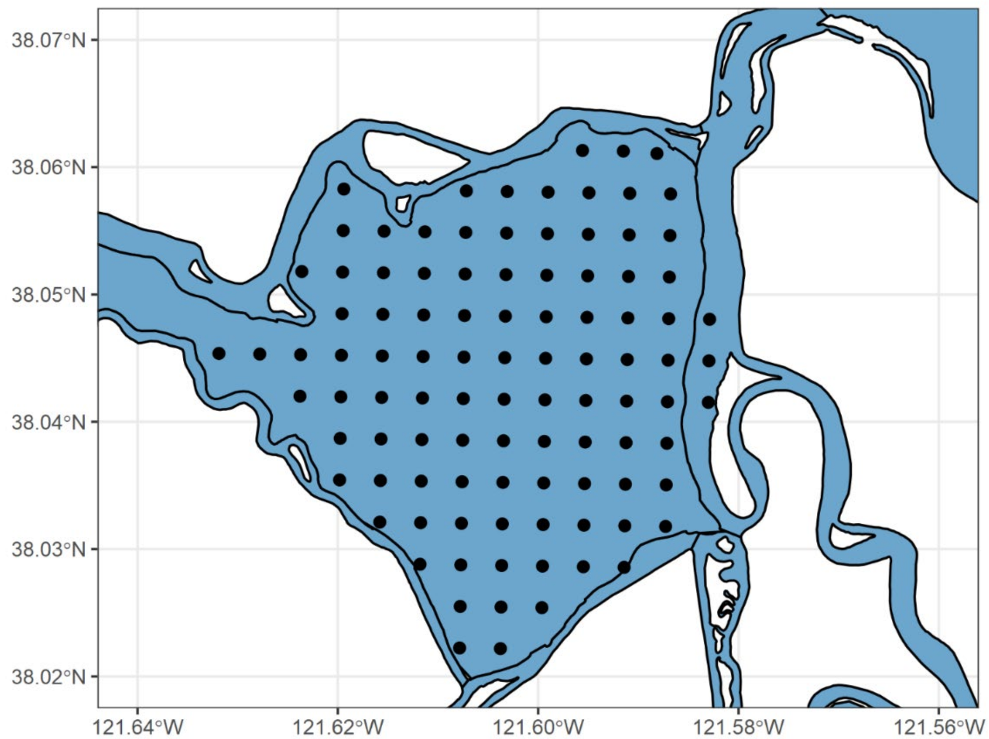


Figure 7
Sampling design for SePRO's annual long-term monitoring of submerged aquatic vegetation in Franks Tract, conducted in conjunction with herbicide treatments.

Environmental drivers and responses

Aquatic weed data will be compared with water quality, flow, and herbicide application data to determine drivers of variation in abundance and composition of aquatic weeds. Variables hypothesized to affect aquatic weeds include measures of flow, turbidity, salinity, temperature, and herbicide applications. Variables hypothesized to be affected by aquatic weeds will also be included in analyses, including dissolved oxygen and pH. Net Delta Outflow data will be obtained from DWR's CDEC station DTO. For water quality, monthly data will be obtained from DWR's EMP station D19 (Franks Tract) and DFW's Bay Study station 853 (San Joaquin River just W of Big Break). Discrete water quality stations were chosen over continuous stations for these two sites because the discrete stations covered most of the parameters of interest for all years of aquatic vegetation monitoring (hyperspectral imagery started in 2004) whereas most continuous station parameters did not. In addition, continuous sonde data will be obtained from DWR station FRK (Franks Tract). For flow and water quality, annual means based on the main growing season for aquatic weeds (March-October) will be used. Herbicide application data for Franks Tract and Clifton Court in 2022 will be obtained from DBW and DWR, respectively.

Data Analysis

For this report, total coverage by aquatic weeds in each region (Sacramento, San Joaquin, and Central) was calculated for 2014–2021, along with the change in coverage between years using hyperspectral imagery as described above. The change in community composition over time from DBW/SePro sample data was assessed via graphs of changes in the relative abundance of each species collected in rake samples.

Hyperspectral Imagery

Vegetation cover changes in Franks Tract and reference sites

To examine changes in coverage of SAV and FAV at the focal sites, the area of each type of vegetation is calculated from the annual classification maps (i.e, pixel size × number of pixels). FAV comprise the combined area of water hyacinth and water primrose, the two most dominant FAV taxa. SAV species cannot be differentiated from the imagery, so SAV is already a combined class. To calculate proportion of each site occupied by SAV and FAV, we will divide the area of each vegetation type by the DBW waterways area for each site. With these data, we will produce time series graphs showing cover for each vegetation type for each site. In addition, we will conduct Pearson correlations comparing Franks Tract with each of the reference sites for each of the two types of vegetation. If landscape scale environmental changes, such as droughts, are more important in driving patterns of vegetation cover through time, then Franks Tract and the reference sites should change in similar ways across years (i.e, they should be correlated). If drought barriers affect aquatic vegetation in Franks Tract, then changes in aquatic vegetation cover in Franks Tract may differ from that of the refences sites (i.e, points for drought barrier years stray from the correlation line).

Relationships with environmental drivers and responses

For Franks Tract and the reference site Big Break, we will conduct a series of Pearson correlations to determine which environmental drivers and responses (see 3.2.4 Environmental drivers) exhibit a statistically significant relationship with SAV and FAV coverage.

Vegetation cover changes in the broader Delta region

To examine landscape scale changes in aquatic vegetation cover, we will calculate the area for SAV and FAV using the same approach described above for individual sites. We will make these calculations for the largest composite region that includes all years of hyperspectral imagery. This region includes large areas of the North and Central Delta (~one-third of the legal Delta), where aquatic weeds are considered most problematic. The region for the Central Delta ranges from the northernmost extent of Twitchell Island to the southern extent of Rhode Island in the north-south orientation and from the western extent of Sherman Island to eastern extent of Fourteen-Mile Slough in the east-west orientation. The region for the North Delta ranges from the northernmost extent of Liberty Island to the southern extent of Prospect Island in the north-south orientation and the western extents of Lindsey Slough to the eastern extent of Prospect Island.

SePRO Vegetation Surveys

Vegetation composition changes in Franks Tract

To examine changes in SAV community composition in Franks Tract, we will plot times series of data for the ten most common species. We will calculate annual means and standard errors from the ordinal abundance scores.

Relationships with environmental drivers and responses

For Franks Tract and the reference site Big Break, we will conduct a series of Spearman correlations to determine which environmental drivers and responses (see 3.2.4 Environmental drivers) exhibited a statistically significant relationship with the SAV species abundances.

VULNERABLE COMMUNITIES

Background

The issue of Harmful Algal Blooms in the Delta impacts all people who live, recreate, and work in the Delta, as well as people who source drinking water from the Delta. However, cyanoHABs may disproportionately impact vulnerable communities – low-income communities and communities of color - more than others. This report is limited in its scope – it only assesses increases in harmful algal blooms caused by or exacerbated by the TUCP and Emergency Drought Barrier in 2022. The ongoing and increasing cyanoHABs crisis in the Delta is out of scope, but in writing the 2021 report it became clear that a larger, multi-agency effort to fully assess the drivers, impacts, and mitigation methods of cyanoHABs is needed.

HABS and SAV are an existing problem throughout the Delta. The focus of the environmental justice analysis will be to use the HABs study findings and additional research to answer the following questions:

1) Did implementing the April-June TUCP and/or Barrier change HABS and weeds in a way that would worsen existing conditions or expected conditions (drought) without the TUCP and/or Barrier?
2) Would effects be worse for vulnerable communities than the general population (i.e., disproportionate), and how?

Methods

In the 2021 HABs/Weeds report, we completed an initial analysis of the impact of HABs and weeds on vulnerable communities using primarily existing data, including surveys of people living, working, and recreating in the Delta, and census data. In the 2022 report, this will be updated with new information on impacts of the April-June 2022 TUCP and will include additional outreach and surveys.

To assess the impacts to vulnerable communities living in the area, the areas influenced most by the TUCP (the Lower Sacramento, Lower San

Joaquin, Franks Tract, and OMR) will be overlayed with census tracts showing population of minority and low-income populations.

To supplement existing data, DWR and Reclamation will reach out to local community organizations and Tribal organizations and hold listening sessions to hear how people have been impacted by HABs and Weeds.

COLLABORATION

This study plan could not be completed without close collaboration with multiple outside entities. The leaders of this project have already developed close relationships with leaders in cyanoHABs research in the Delta and elsewhere, including the Delta RMP, California CyanoHAB network, the USGS, the Interagency Ecological Program, and the Water Board's freshwater cyanoHABs program. In the report on the 2021 TUCO, we worked closely with Water Board staff to leverage their excellent cyanoHABs database to identify other stakeholders with information to share on HABs.

Activities for monitoring and assessing the impact of DWR and Reclamation's drought actions are being done in coordination with larger, multi-agency efforts to address Harmful Algal Blooms. DWR is participating in a workshop being planned by the Delta Science Program on HABs in the Delta. The workshop, planned for fall of 2022, will discuss the major issues in monitoring and managing HABs, with the goal of producing a framework for monitoring HABs in the Delta as a multi-agency effort.

DWR and Reclamation are also participating in the Interagency Ecological Program's Water Quality and Phytoplankton and Project Work Team (PWT), which will provide a forum for discussion of HABs and other phytoplankton topics. The goals of this team are to encourage sharing of data and methods to benefit development of formal synthesis and strategy documents, discuss changes to monitoring to inform management priorities, share new research on water quality and phytoplankton, and coordinate phytoplankton sampling. This study plan was shared with them at their April 29th, 2022, meeting and via email for comments from a wide audience.

DWR and Reclamation are also contributing to the IEP Delta Drought Synthesis project (See Appendix D). This project is made up of an inter-agency team taking an ecosystem-wide view of drought in the Delta to assess how water quality, phytoplankton, zooplankton, fish, and aquatic vegetation change during multi-year droughts. Regular updates on this study will be given at Drought Synthesis Team meetings.

DWR and Reclamation will share plans and drafts of these analyses with the IEP Phytoplankton PWT, IEP Estuarine Ecology PWT, CCHAB network, and any other groups that the State Board would recommend.

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APPENDICIES

Appendix A. TUCP and Emergency Drought Barrier Cyanotoxin Monitoring 2022 Work Plan

Appendix B. NCRO WQES Proposed HAB Monitoring Workplan 2022

Appendix C. Task order for additional HABs work by USGS

Appendix D. Drought synthesis study plan