Delta Nutrients
Drinking Water Issues
FINAL White Paper

Prepared for:

Delta Nutrient Science and Research Program

Stakeholder and Technical Advisory Group

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Acknowledgements

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Executive Summary

The Sacramento–San Joaquin River Delta (Delta) is a key component of California's water resource system and serves as an important source of drinking water to over 25 million Californians. However, issues associated with invasive macrophyte and cyanobacteria growth have been increasing over the last decade adding significant concern associated with infrastructure clogging, taste and odor issues, and rising cyanotoxin concentrations. Both macrophyte and cyanobacteria growth are affected by concentrations of the nutrients nitrogen and phosphorus which are required for their growth. However, the connection between nutrients and invasive macrophytes and harmful cyanobacteria is complex and remains an active area of study. This document provides a synthesis of the current state of knowledge regarding nutrient-related drinking water issues in the Delta and downstream conveyance and storage facilities, and presents a set of recommendations to address data gaps in monitoring, research, and modeling in order to support policy decisions on nutrient management.

The Central Valley Regional Water Quality Control Board (Central Valley Water Board) and stakeholders have invested significant resources into understanding the science behind these issues in order to make sound, science-based nutrient management policy decisions in the future. They have recently completed the following White Papers which served as a foundation for the research summarized in this document:

- *Cyanobacteria White Paper and Knowledge Gap Document*
- *Macrophyte White Paper and Knowledge Gap Document*
- *Modeling White Paper*

All of these documents can be found on the Central Valley Water Board website under the Science Work Groups section:
www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_nutrient_research_plan/science_work_groups/index.shtml.

A *Role of Nutrients in Shifts in Phytoplankton Abundance and Species Composition in the Sacramento-San Joaquin Delta White Paper* (a.k.a. Forms and Ratios White Paper) was recently released that discusses the role of nutrient forms and ratios in the Delta. However, due to its recent submittal, its contents were not summarized in this document. We encourage interested readers who want to know more about these particular issues to read the other associated White Papers.

This document provides a synthesis of the current state of the knowledge regarding nutrients in the Delta, highlights the unique nutrient-related drinking water quality issues faced by the Delta and water supply providers, explores factors which influence macrophyte and cyanobacteria growth, presents management options to deal with these issues, and identifies data gaps which require additional research and monitoring. The main nutrient-related drinking water issues identified include:

- Taste and odor issues due to cyanobacteria growth,
- Cyanotoxin release by harmful cyanobacteria blooms, and

- Filter and/or pump clogging by macrophytes and algae.

Section 6.0 of this document synthesizes the information presented in previous sections and outlines a set of recommendations for additional monitoring, research, and modeling priorities. Highlights of these recommendations include the following:

1. **Cyanobacteria – Cyanotoxins:** Expand system-wide monitoring in the Delta and downstream facilities in order to identify the location, timing, and duration of cyanotoxin-producing cyanobacteria blooms and the threat that cyanotoxins pose. Determine via field and laboratory studies if ancillary biological (e.g., chlorophyll a), chemical (e.g., nutrients), or physical (e.g., temperature, irradiance, flow) measurements co-vary with blooms such that they could be used to predict, limit initiation, and/or manage duration of cyanobacterial blooms.

2. **Cyanobacteria – Taste and Odors:** Expand system-wide monitoring in downstream facilities in order to identify the location, timing, and duration of taste and odor cyanobacteria events. Measure a suite of environmental parameters including geosmin and MIB (the compounds responsible for taste and odor events), nutrients, and perform microbial surveys in order to expand knowledge of possible drivers of taste and odor events. Determine via field (including *in situ* or mesocosm studies) and laboratory studies if ancillary biological (e.g., specific benthic or planktonic species), chemical (e.g., nutrients), or physical (e.g., temperature, irradiance, flow) measurements co-vary or contribute to taste and odor initiation and attenuation.

3. **Macrophytes:** Expand system-wide monitoring in the Delta and downstream facilities in order to determine the abundance and extent of invasive macrophyte blooms (including new invasive species) as well as any co-occurring environmental parameters that might contribute to their growth, and to determine where macrophyte blooms are impacting operations of water supply facilities. Perform field and laboratory studies to determine macrophyte growth rate as a function of nutrient concentrations, including nutrient uptake rates, and possible methods for *in situ* assessment of nutrient limitation. Conduct *in situ* studies to test the effect nutrient limitation may have on the enhancement of mechanical and chemical macrophyte control.

4. **Modeling Scenarios:** Utilize models to characterize and test management actions over a range of conditions, provide insight into the significance of nutrients on the ecosystem, and communicate information to stakeholders, regulators, and resource managers to arrive at consensus and understanding of the system.

5. **Management Considerations:** Once monitoring and modeling efforts have matured, these efforts should be used to address the question of whether nutrient reductions alone or in some combination with other management practices will be effective to significantly reduce taste and odor, cyanotoxin issues, and filter/pump clogging problems in the Delta and downstream facilities.

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1.0 Introduction, Purpose, and Organization of the Review

1.1 BACKGROUND AND CONTEXT

The Sacramento–San Joaquin River Delta (Delta) is a network of natural and engineered channels and agricultural lowlands located in Northern California, formed by the confluence of the Sacramento and San Joaquin Rivers (see **Figure 1**). The Delta is a component of the San Francisco Estuary system and is influenced by the tides, to varying degrees, throughout its domain. The Delta is a key component of the State's water resource system; water exported from the Delta serves more than 25 million people and 4.5 million acres of irrigated farmlands in the Bay Area, the San Joaquin Valley, and Southern California (Delta Stewardship Council 2013). On average, approximately 6.1 million acre feet (MAF) of water are exported from the Delta during wet years and about 4.1 MAF during dry years (Delta Stewardship Council 2013). The California State Water Project (SWP) and the Federal Central Valley Project (CVP) convey water from the South Delta to the San Francisco Bay Area, San Joaquin Valley, Central Coast, and Southern California. Additionally, the Delta is vital for the state's economy and environment as a home to thousands of residents as well as an important agricultural area and a critical habitat for fish, birds, and wildlife.

The Delta is widely recognized as being in a state of "crisis" due to the competing anthropogenic demands for its resources (Delta Plan 2013). The Delta's water resources are needed for ecosystem health, agriculture, fisheries, and municipal supplies. The consequences of these competing demands include habitat degradation, fragmentation and loss, highly modified flow regimes and water losses and water quality impairments, and non-native species invasions. The discharge of pollutants to the Delta and tributary waters from urban, agricultural, and nonpoint sources also poses potential threats to the many beneficial uses designated for the Delta.

In 2009, the California legislature passed the Delta Reform Act creating the Delta Stewardship Council (Council). The mission of the Council is to implement the coequal goals of the Reform Act and provide a more reliable water supply for California while protecting, restoring, and enhancing the Delta ecosystem. The Council wrote and adopted a Delta Plan in 2013 to implement these coequal goals which included a water quality recommendation to consider development of nutrient objectives for the Delta (WQ R8. Completion of Regulatory Processes, Research, and Monitoring for Water Quality Improvement). Nutrients are among the pollutants discharged to the Delta from municipal, industrial, agricultural, and other nonpoint sources. This recommendation addresses the excess nutrients in the Delta that are a primary concern because they, along with other factors, stimulate macrophyte growth and algal blooms which can disrupt water treatment processes, cause taste and odor problems, and contribute to cyanotoxin production (Delta Stewardship Council 2013). As nutrients are one of the pollutant groups believed to potentially cause impairments to Delta water quality, the State Water Resources Control Board and the San Francisco Bay and Central Valley Regional Water Quality Control Boards have been charged with developing and implementing a research plan to determine the need for either numeric or narrative nutrient water quality objectives for the Delta and Suisun Marsh.

In response to the recommendation in the Delta Plan, the Central Valley Regional Water Quality Control Board (Central Valley Water Board) has embarked on a Delta Nutrient Research Program to address the need for nutrient water quality objectives. In order to provide appropriate background regarding the current understanding and knowledge gaps associated with specific nutrient-related areas of interest, and to inform the need for future research in the Delta, workgroups were formed with local expert leadership to develop white papers and recommendations for future research needs on the following topics:

- Cyanobacteria
- Macrophytes
- Nutrient Forms and Ratios
- Drinking Water Concerns
- Modeling Science

1.2 GOAL AND ORGANIZATION OF DRINKING WATER ISSUES LITERATURE REVIEW

This document provides a synthesis of literature on the potential adverse impacts of ambient nutrient levels in the Delta on drinking water sources in the Delta and the SWP. As a means to gain insight into the nutrient-related issues encountered in out-of-Delta conveyance structures, reservoirs, and water treatment facilities, a workshop[1] on tastes and odors, cyanobacteria, macrophytes, and other factors was held to inform the Drinking Water Workgroup on these issues. The workshop presenters included current and former employees of the Metropolitan Water District who specialize in understanding and attempting to limit algae and macrophyte blooms that impact drinking water in the SWP and downstream reservoirs. This document identifies data gaps within the current body of knowledge, and suggests studies that would provide information to bridge those gaps. The literature review has three major objectives:

1. Provide a basic review of drinking water issues present in the Delta potentially associated with current nutrient levels;

2. Provide a discussion of associated impacts to California's drinking water resources, both within the Delta and in downstream conveyance and storage facilities; and

3. Identify data gaps and research needs to understand whether control of nutrient concentrations in the Delta would reduce existing drinking water concerns.

This review, and the recommended next steps, will contribute to the Delta Nutrients Science and Research Plan which will identify scientific research needed to determine whether and how to proceed with the development of nutrient water quality objectives for the Delta. The document is organized as follows:

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[1] Workshop to Identify Research Proposals – Tastes and Odors, Cyanobacteria, Macrophytes, and Other Factors. Workshop held on February 24, 2017, at the offices of Larry Walker Associates, Davis, CA.

Section 1: Introduction, Purpose, and Organization of the Review

Section 2: Nutrient-Related Drinking Water Issues

Section 3: Factors Influencing Nutrient-Related Drinking Water Issues

Section 4: Management of Identified Issues

Section 5: Data Gaps

Section 6: Recommendations for Research and Modeling Priorities

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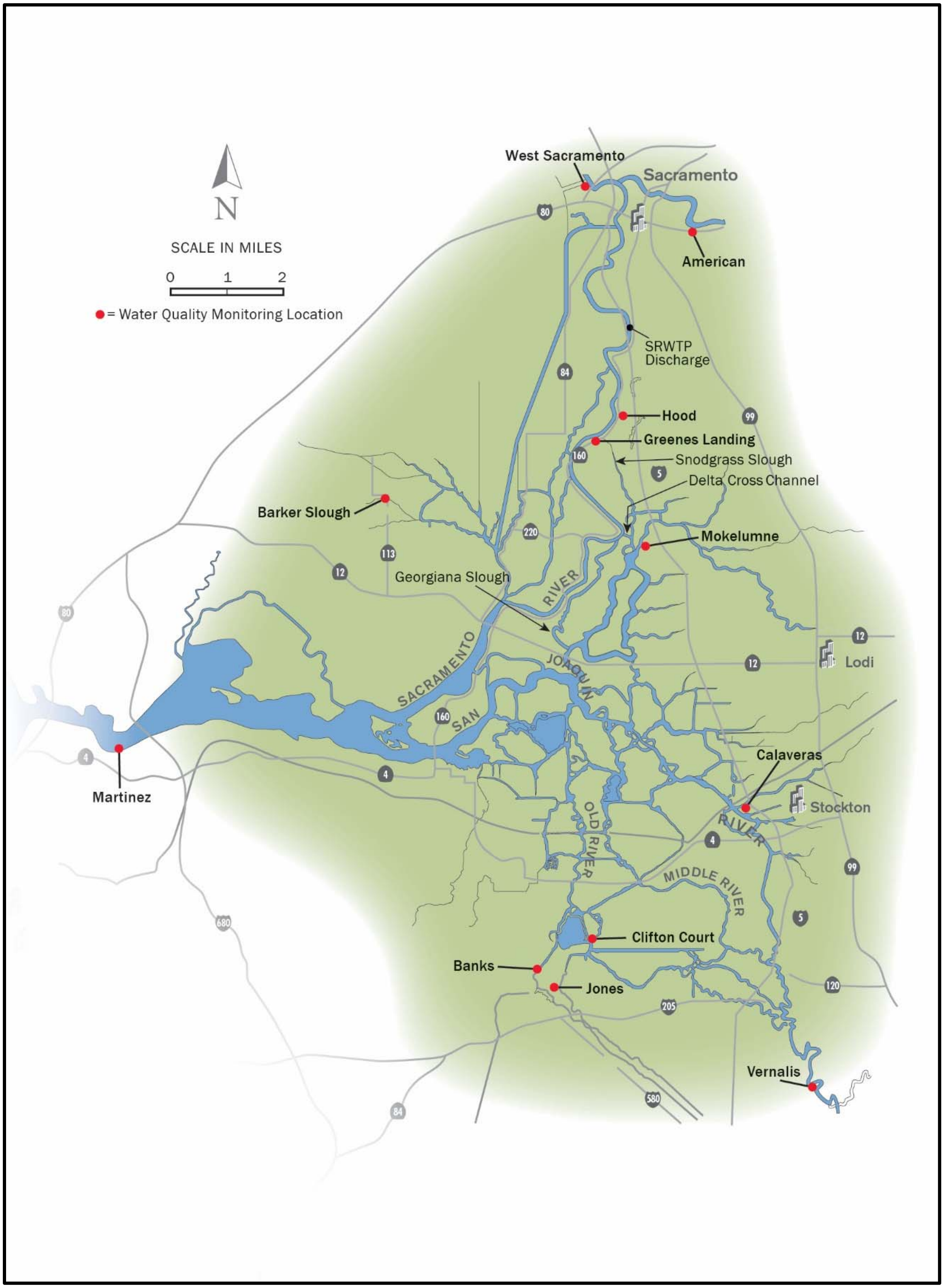


Figure 1. The Sacramento-San Joaquin Delta and SWP Monitoring Locations

2.0 Nutrient-Related Drinking Water Issues

2.1 DELTA NUTRIENTS BACKGROUND

2.1.1 Delta Hydrology

The two major sources of freshwater inflow to the Delta are the Sacramento and San Joaquin Rivers (**see Figure 1)**. Additional flows come from the eastside tributaries: the Mokelumne, Calaveras, and Cosumnes Rivers. The Sacramento River provides approximately 75 to 85 percent of the freshwater flow to the Delta and the San Joaquin River provides about 10 to 15 percent of the flow. During extremely wet years, Sacramento River flows can exceed 100,000 cubic feet per second (cfs) at Freeport. The flows in the San Joaquin River at Vernalis are substantially lower than flows in the Sacramento River. Peak San Joaquin River flows can exceed 50,000 cfs, but flows are normally much lower. Flows on the Sacramento and San Joaquin rivers are highly managed. Central Valley Project (CVP) and SWP reservoirs on the rivers and their tributaries attenuate the highly variable natural flows, capturing high volume flows during short winter and spring periods and releasing water throughout the year.

Water from the Sacramento River flows into the central Delta via Georgiana Slough and the Delta Cross Channel, which connects the Sacramento River to the Mokelumne River via Snodgrass Slough (see **Figure 1**). The Delta Cross Channel (DCC) is operated by the U.S. Bureau of Reclamation (Reclamation). The DCC operations are regulated to meet multiple needs, including fish migration, Delta water quality, flood protection, and flow in the Sacramento River. The DCC is generally closed between January and mid-June, open between mid-June and October, and closed in November and December. Flows of Sacramento River water through the DCC improve central Delta water quality by increasing the flow of higher quality (lower salinity, lower organic carbon) Sacramento River water into the central and southern Delta. The relative impact of the DCC operations on water quality at the south Delta pumping plants is governed by water project operations, tidal action, and flows on the San Joaquin River.

2.1.2 The State Water Project

The SWP extends from the mountains of Plumas County in the Feather River watershed to Lake Perris in Riverside County. **Figure 2** shows the major features of the SWP. Water from the north Delta is pumped into the North Bay Aqueduct (NBA) at the Barker Slough Pumping Plant. Barker Slough is a tidally influenced dead-end slough which is tributary to Lindsey Slough. Lindsey Slough is tributary to the Sacramento River. The pumping plant draws water from both the upstream Barker Slough watershed and from the Sacramento River, via Lindsey Slough. The NBA serves as a municipal water supply source for a number of municipalities in Solano and Napa counties.

In the southern Delta, water enters SWP facilities at Clifton Court Forebay (Clifton Court), and flows across the forebay about 3 miles to the H.O. Banks Delta Pumping Plant (Banks), from which the water flows southward in the Governor Edmund G. Brown California Aqueduct (California Aqueduct). Water is diverted into the South Bay Aqueduct (SBA) at Bethany Reservoir, 1.2 miles

Figure 2. The State Water Project

downstream from Banks. From Bethany Reservoir, water flows in the California Aqueduct about 59 miles to O'Neill Forebay. The forebay is the start of the San Luis Joint-Use Facilities, which serve both SWP and federal CVP customers. CVP water is pumped into O'Neill Forebay from the Delta-Mendota Canal (DMC). The DMC conveys water from the C.W. "Bill" Jones Pumping Plant (Jones) to, and beyond, O'Neill Forebay. San Luis Reservoir is connected to O'Neill Forebay through an intake channel located on the southwest side of the forebay. An intake on the west side of the reservoir provides drinking water supplies to Santa Clara Valley Water District.

Water released from San Luis Reservoir co-mingles in O'Neill Forebay with water delivered to the forebay by the California Aqueduct and the DMC, and exits the forebay at O'Neill Forebay Outlet, located on the southeast side of the forebay. O'Neill Forebay Outlet is the beginning of the San Luis Canal reach of the California Aqueduct. The San Luis Canal extends about 100 miles to Check 21, near Kettleman City. The San Luis Canal reach of the aqueduct serves mostly agricultural CVP customers and conveys SWP waters to points south. The junction with the Coastal Branch of the aqueduct is located 185 miles downstream of Banks and about 12 miles south of Check 21. The Coastal Branch provides drinking water supplies to central California coastal communities through the Central Coast Water Authority and the San Luis Obispo County Flood Control and Water Conservation District. From the junction with the Coastal Branch, water continues southward in the California Aqueduct, providing water to both agricultural and drinking water customers in the service area of Kern County Water Agency.

Edmonston Pumping Plant is at the northern foot of the Tehachapi Mountains. This facility lifts SWP water about 2000 feet by multi-stage pumps through tunnels to Check 41, located on the south side of the Tehachapi Mountains. About a mile downstream, the California Aqueduct divides into the West and East Branches. The West Branch flows 14 miles to Pyramid Lake, then another 17 miles to Castaic Lake, the drinking water supply intake of the Metropolitan Water District of Southern California (MWDSC) and Castaic Lake Water Agency. Pyramid Lake has a capacity of 171,200 acre-feet and Castaic Lake has a capacity of 323,700 acre-feet.

From the bifurcation of the East and West Branches, water flows in the East Branch to high desert communities in the Antelope Valley served by the Antelope Valley East Kern Water Agency and the Palmdale Water District. Drinking water supplies are delivered to MWDSC and San Bernardino Valley Municipal Water District from two Devil Canyon afterbays downstream of Silverwood Lake, where water is transported via the Santa Ana Pipeline to Lake Perris, which is the terminus of the East Branch. MWDSC routinely takes a small amount of water from Lake Perris.

A detailed description of the State Water Project is provided in **Appendix A**.

2.1.3 Contra Costa Water District

The Contra Costa Water District (CCWD) is a CVP contractor that diverts water supplies from locations in the western and southern Delta. **Figure 3** shows the locations of the CCWD water supply intakes in the Delta. CCWD diverts water under its CVP water rights at the Rock Slough Intake near Oakley, the Older River Intake near Discovery Bay, and the Middle River Intake on Victoria Canal. Depending on the intake and where water is needed in the CCWD service area, the water is diverted to into the Contra Costa Canal and conveyed to treatment plants and reservoirs located throughout eastern and central Contra Costa County or to Los Vaqueros Reservoir. Los Vaqueros Reservoir stored water is primarily used for blending in the Contra Costa Canal for improved water quality. CCWD also has its own Mallard Slough Intake in Bay Point, although diversions at this intake are unreliable due to high salinity at this point of diversion.

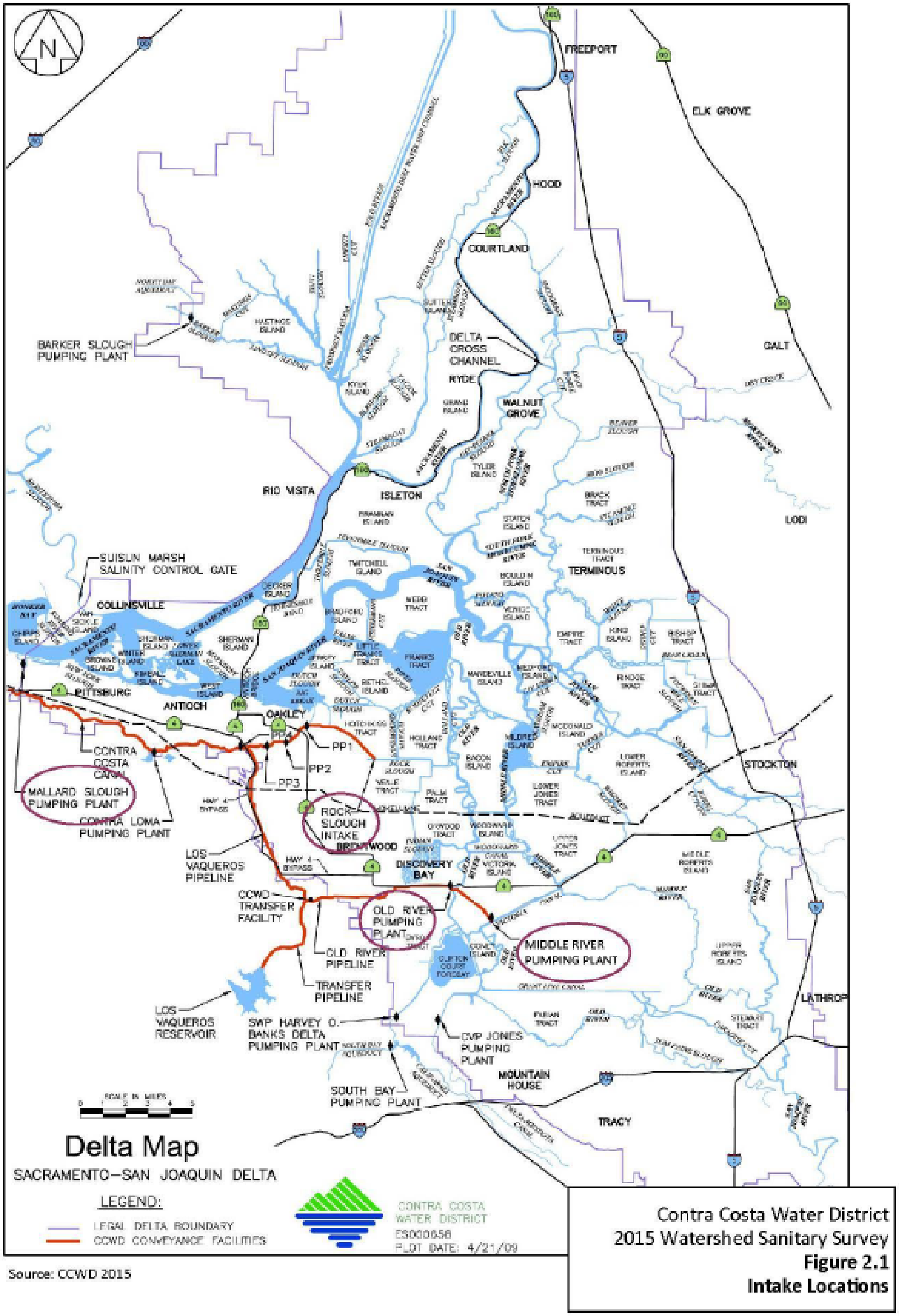
2.1.4 Nutrient Concentrations in the Delta and SWP

Nutrient data presented in this report were drawn from the Department of Water Resources (DWR) Municipal Water Quality Investigation (MWQI) Program and from the Division of Operations and Maintenance (O&M) water quality monitoring program. These data were used to provide a general background on nutrient concentrations measured in the Delta and SWP.

Figure 4 presents the total nitrogen (total N) data and **Figure 5** presents the total phosphorus (total P) data for the tributaries to the Sacramento-San Joaquin Delta (Delta), Clifton Court, and Banks for the period 2004 – 2010. Total N and total P concentrations are low at the American River and the Sacramento River at West Sacramento (West Sacramento) sites. There is an observable increase in both nutrients at the Sacramento River at Hood (Hood); however, the Hood concentrations of both nitrogen and phosphorus are much lower than those found in the San Joaquin River at Vernalis (Vernalis). **Appendix A** includes figures which show the seasonal and spatial variability in nutrient concentrations at Hood, Vernalis, Barker Slough, and Banks.

Nutrient concentrations increase considerably in the Sacramento River between West Sacramento and Hood, despite the inflow of the high quality American River, due to the discharge from the Sacramento Regional Wastewater Treatment Plant as well as inputs from agricultural, industrial, and urban runoff sources. The median concentrations of total N (0.67 mg/L) and total P (0.08 mg/L) at Hood are statistically significantly higher than the median concentrations of total N (0.29 mg/L) and total P (0.05 mg/L) at West Sacramento. Total N and total P concentrations in the San Joaquin River are considerably higher and more variable than concentrations in the Sacramento River. The median total N concentration at Vernalis of 2 mg/L is the highest in the SWP system. The median total P of 0.16 mg/L calculated for Vernalis is twice the level found at Hood.

Nutrient concentrations in the NBA are higher than in the Sacramento River. The median total N concentration is 0.8 mg/L and the median total P concentration is 0.18 mg/L. The Sacramento River is the primary source of water to Barker Slough, so it is evident that the local watershed supplies some nitrogen and a substantial amount of phosphorus to the NBA. There is extensive cattle grazing and farming throughout the watershed, and there is a golf course in the upper part of the watershed; all potential sources of nutrients.



Source: CCWD 2015

Figure 3. Contra Costa Water District Delta Water Intakes

Although the Sacramento River is the primary source of water diverted through Banks into the SWP system, the San Joaquin River is also a major source of water to Banks; the San Joaquin River's percent contribution varies with hydrology and water project operations. The total N concentration at Banks (median of 0.88 mg/L) is about 30 percent higher than the median concentration of 0.67 mg/L at Hood (Mann-Whitney, p=0.0002) and the data are more variable. The median total P concentration of 0.10 mg/L at Banks is slightly higher than the 0.08 mg/l median concentration calculated at Hood (Mann-Whitney, p=0.0046), with both data sets showing the same variability. As discussed previously, the median total N concentration at Vernalis is more than triple the median concentration at Hood, whereas the median total P concentration is about double. This may partially explain why the total N concentrations at Banks increase more than the total P concentrations; however, there are also in-Delta sources of nutrients including agricultural discharges, wastewater treatment plants, and urban runoff. Another complicating factor is that nutrients are not conservative constituents.

Data have been collected at a number of locations along the California Aqueduct from 2004 to 2010 (See **Appendix A**). Nutrient concentrations change very little as water flows from the Delta through the SBA and the California Aqueduct. A slight increase in total N is observed moving downstream in the Aqueduct from Check 21 to Check 41 due to non-project inflows from four major sources (Semitropic Water Storage District, Kern Water Bank Authority, Cross Valley Canal inflows, and Arvin Edison Canal inflows (Archibald Consulting et al., 2012)). Median total N concentrations are about 1.0 mg/L and median total P concentrations are about 0.1 mg/L throughout the system, with the exception of the Castaic Outlet and Perris Outlet. The median concentrations of total N and total P are substantially lower at the Castaic Outlet. Algal uptake and subsequent settling of particulate matter may be responsible for the lower nutrient concentrations in the terminal reservoirs.

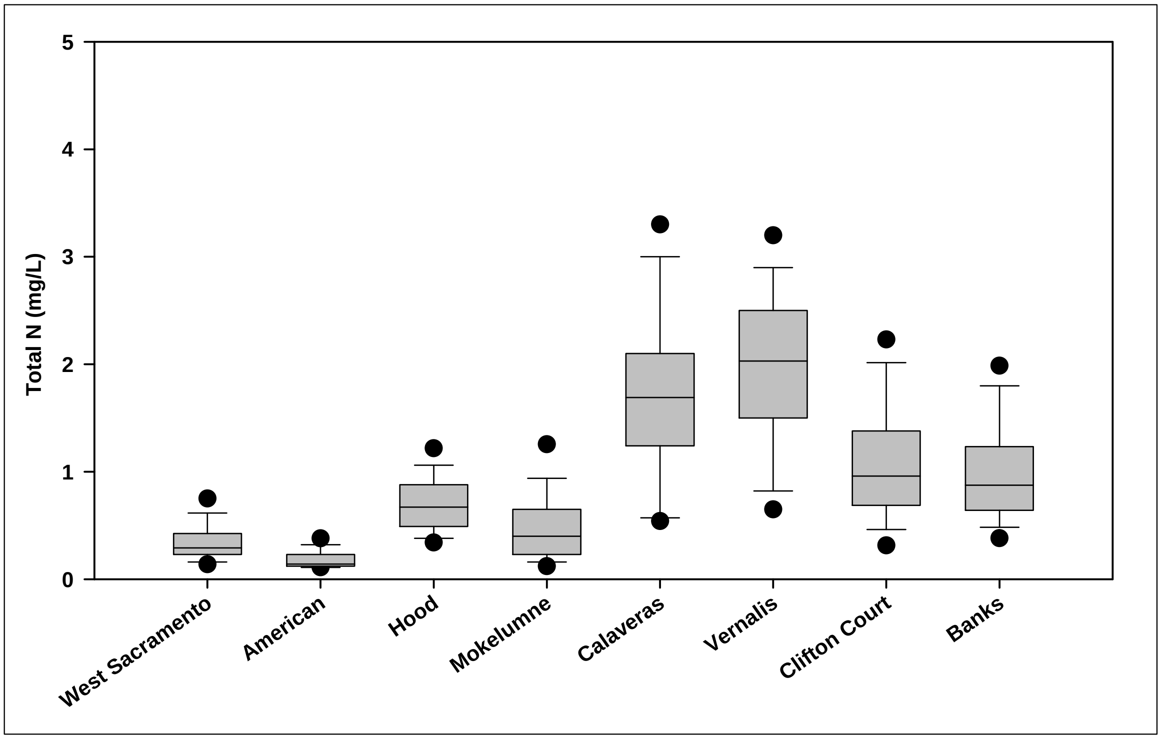


Figure 4. Total N Concentrations in the SWP Watershed: 2004 – 2010

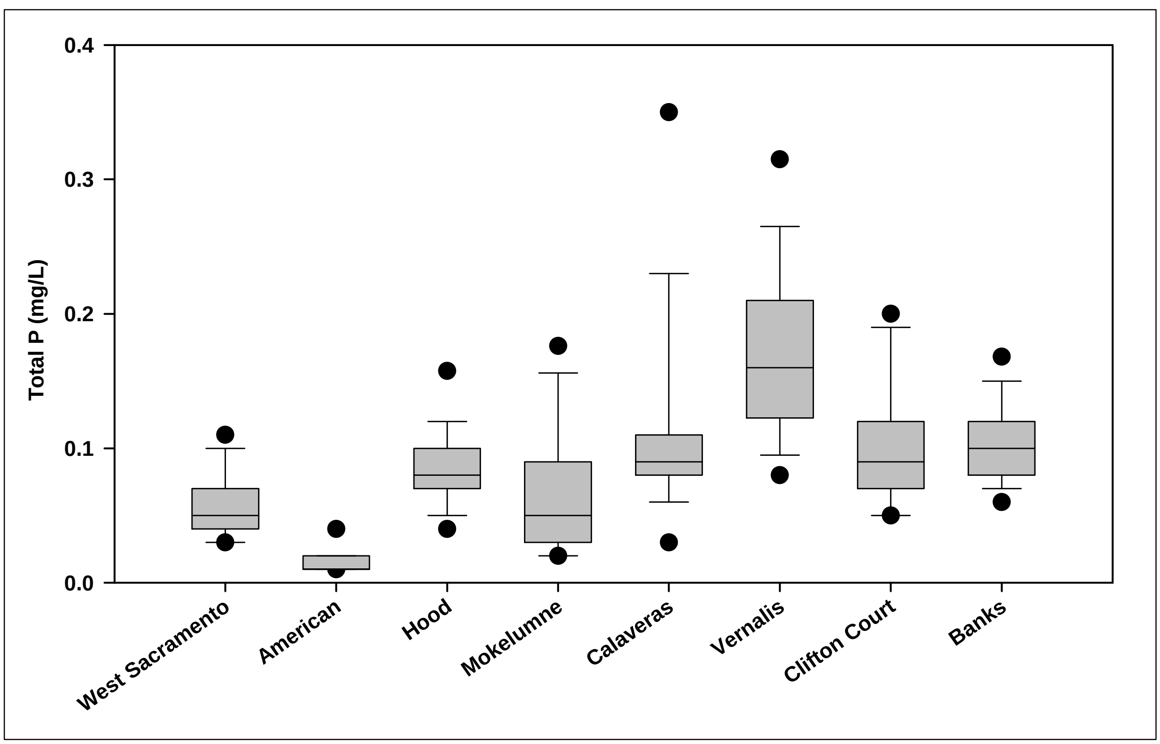


Figure 5. Total P Concentrations in the SWP Watershed: 2004 – 2010

CCWD implements a water quality monitoring program that includes monitoring for nutrients at CCWD intake facilities and reservoirs. At the Old River Intake the average Total Kjeldahl nitrogen concentration was 0.1 mg/L (range of non-detect (ND) to 0.8 mg/L), and the average total phosphorous concentration was 0.07 mg/L (range of ND to 0.18 mg/L) (see **Figure 6**). At the Middle River Intake the average Total Kjeldahl nitrogen concentration was 0.2 mg/L (range of ND to 2.2 mg/L), and the average total phosphorous concentration was 0.1 mg/L (range of ND to 1.0 mg/L) (see **Figure 7**).

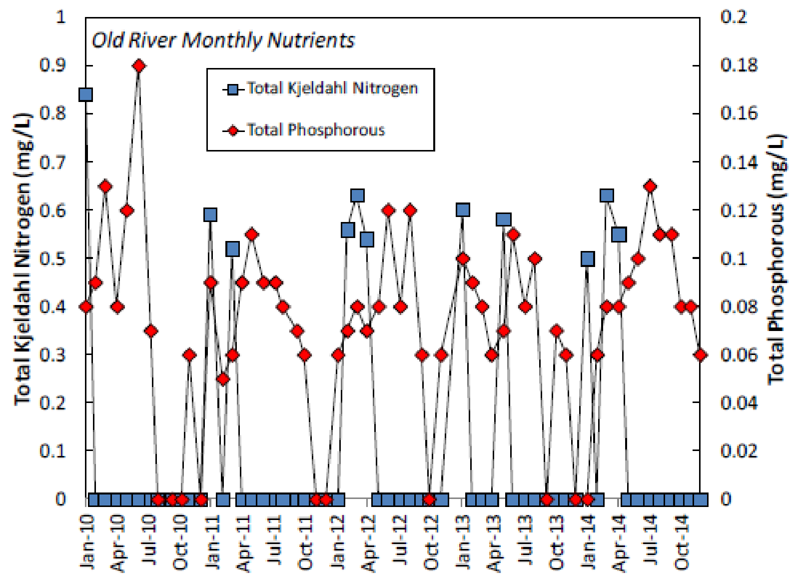


Figure 6. Total Kjeldahl Nitrogen and Total Phosphorus at Old River Intake: 2010 – 2014

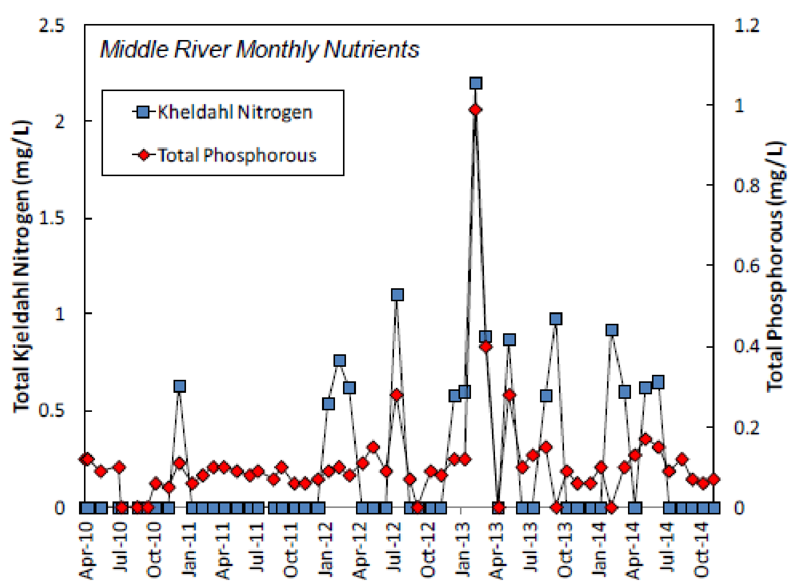


Figure 7. Total Kjeldahl Nitrogen and Total Phosphorus at Middle River Intake: 2010 – 2014

2.2 PROBLEMS ASSOCIATED WITH HIGH NUTRIENT LEVELS AND OTHER ENVIRONMENTAL FACTORS

Drinking water agencies that take water from the Delta via the SWP and CVP face challenges due to cyanobacteria harmful algal blooms (cyanoHABs) and macrophyte growth that occur in SWP and CVP conveyances and storage facilities (see **Figure 2**), as discussed further in **Section 3.0**. While there are many factors which can stimulate algae and macrophyte growth, nutrients, temperature, light, residence time (particularly in reservoirs), and water clarity are considered major drivers.

Traditionally, it has been assumed that high nutrient concentrations were responsible for causing periodic low dissolved oxygen levels in the Stockton Deep Water Ship Channel and several dead end sloughs on the southern and eastern side of the Delta due to the stimulation of algal growth, followed by senescence and breakdown by bacteria (Lee and Jones-Lee 2006). In contrast, it was also assumed that high nutrient levels did not encourage primary productivity in some regions of the Delta with high turbidity and low light (Alpine and Cloern 1992, Tetra Tech 2006). However, recent hypotheses described in the Draft Nutrient Strategy for the Delta (CVRWQCB 2013) postulate that high nutrient levels may shift algal species composition, decrease dissolved oxygen concentrations, cause taste and odor issues, and increase productivity of blue-green algae (i.e., cyanobacteria) and non-native macrophytes (i.e., water hyacinth (*Eichhornia crassipes*) and Brazilian waterweed (*Egeria densa*)). The recommendations for monitoring, research, and modeling provided in **Section 6.0** of this document are advanced to support the testing of these various hypotheses to determine if nutrients are of issue in the Delta and downstream conveyance and storage facilities as they relate to algal and macrophyte growth and community composition.

Elevated concentrations of nitrate (>10 mg/L) can also be toxic to humans and are associated with methemoglobinemia, also known as "blue-baby" syndrome, which occurs as nitrates in the body are converted to nitrite, which react with hemoglobin in red blood cells to form methemoglobin, which affects the ability of blood to carry oxygen around the body (Knobeloch et al. 2000). However, ambient nitrate levels in the Delta have not been observed to approach the primary MCL of 10 mg/l. Therefore, the major Drinking Water issues facing the Delta where nutrients may be a factor contributing to a problem relate to the recent changes in cyanobacteria and macrophyte prevalence and community composition. The following section briefly discusses the drinking water challenges as a result of cyanobacteria and macrophyte growth in the Delta and downstream systems, including taste and odor issues, cyanotoxin production, increased dissolved organic carbon, diurnal pH swings, and filter and pump clogging.

2.3 ALGAE AND MACROPHYTE PROBLEMS IN DRINKING WATER SUPPLIES

2.3.1 Nuisance Algae and Harmful Cyanobacteria Blooms

A Cyanobacteria Workgroup, convened by the Delta Nutrient Science and Research Program, reviewed literature for the purpose of determining which present and future factors are most likely associated with cyanobacteria harmful algal bloom (cyanoHABs) prevalence in the Delta and concluded, based on culture studies, that there is no significant or consistent change in growth rates of cyanobacteria with change in nitrogen source or nitrogen to phosphorus ratios when nutrient concentrations are not limiting (Tilman et al. 1982, Tett et al. 1985, Reynolds 1999, Saker and Neilan 2001, Roelke et al. 2003, Sunda and Hardison2007). Based on investigations carried out in the Delta, nutrient ratios have not been observed to vary from pre-bloom to bloom, indicating that nutrients are not limiting throughout the entirety of the summer season (Lehman et al. 2008, Mioni et al. 2012). The Cyanobacteria Workgroup suggested that while cyanoHABs observed in the Delta likely were not due to changes in nutrient concentrations or their ratios, the duration and magnitude of cyanoHABs are influenced by the available nutrient supply and therefore, a reduction in nutrients could reduce the duration and intensity of such blooms (Berg and Sutula 2015). Furthermore, although nutrients were not found to limit growth rates, the form of nitrogen (i.e., ammonia, ammonium, nitrate, nitrite) and nitrogen to phosphorus ratios have been postulated to have an effect on food web dynamics and composition (Dugdale et al. 2007, Glibert et al. 2011).

Taste and Odors

Certain cyanobacteria and actinomycete bacteria produce chemical compounds that are not removed in conventional water treatment processes and are capable of causing unpleasant tastes and odors (T&O) in drinking water. T&O incidents occur throughout the SWP in the treated water and are commonly associated with geosmin and 2-methylisoborneol (MIB) that are produced by benthic and planktonic cyanobacteria. Geosmin and MIB are non-toxic organic compounds that impart an earthy, muddy, musty-type odor/taste in water that many find unacceptable. The ability of individuals to detect these chemicals varies, but the general population can detect either compound at a concentration of about 10 ng/L (nanograms per liter, or parts per trillion), and sensitive individuals can detect even lower concentrations. As a result, some water agencies have installed advanced treatment processes, such as ozonation and powdered activated carbon, to reduce the levels of these T&O compounds in treated drinking water.

Strain specificity makes it difficult to determine *a priori* that occurrence of a particular taxon in the plankton (or benthos) of a drinking water source will lead to T&O events. Typically, the strains responsible for T&O issues are not the most dominant members of the community and therefore, often go misdiagnosed (See **Section A.3** in **Appendix A**). For example, in Castaic Lake, a terminal reservoir of the SWP in southern California, a T&O event in 1993 was blamed on a strain of *Pseudanabaena* in the plankton (Izaguirre and Taylor 1998). However, *Pseudanabaena* is common in southern California waters, and most strains isolated over a 23-year period have not caused T&O problems. According to Izaguirre and Taylor (1998), because MIB production is a rare phenomenon in this genus, it is difficult to predict T&O events involving the organism, or those involving other taxa such as *Synechococcus* (Izaquirre et al. 1984), *Hyella*, and *Oscillatoria limosa* (Izaguirre and Taylor 1995). There is a large literature describing efforts to isolate and identify strains of algae, cyanobacteria, and other T&O compound producing organisms.

Benthic cyanobacteria are responsible for most of the T&O events reported in the literature in terminal reservoirs receiving water from the SWP. Almost all of the T&O events in Diamond Valley Lake are associated with films of benthic cyanobacteria (*Oscillatoria* or *Phormidium* spp.), which grow on the sides of the reservoir and on the dam. The benthic colonies in Diamond Lake form on sediments 3-17 m deep (Izaguirre and Taylor 2007), usually in late summer. This indicates that they are frequently positioned near the thermocline, where they would have greater access to diffusive fluxes of nutrients released at the sediment/water interface during summer stratification. MIB producing strains of *Oscillatoria* that have been isolated from other southern California reservoirs (Lake Mathews, Las Virgenes Reservoir, Lake Bard, Lake Skinner, and Silverwood Lake) are also benthic forms (Izaguirre and Taylor 2007). The range of depths and thus, total surface area available to these colonies will vary positively with water clarity.

Samples have been collected from untreated water in SWP facilities by the Department of Water Resources (DWR) and analyzed for the T&O producing compounds, MIB and geosmin, since 2000 when the technology to readily analyze for these compounds became available. **Figure 8** through **Figure 14** show concentrations of MIB and geosmin at various locations along the California Aqueduct, Banks Pumping Plant, and lake outlets with peak concentrations typically occurring in the summer months. Benthic cyanobacteria are the primary sources of T&O compounds in the Delta and in Clifton Court Forebay (DWR 2013). The high levels of MIB and geosmin are transported to the South Bay Aqueduct (SBA) and down the California Aqueduct. MIB and geosmin are also generated by benthic cyanobacteria in the California Aqueduct, the Coastal Branch and the East Branch of the California Aqueduct (DWR 2013). MIB and geosmin are both frequently present at high concentrations in the East Branch of the aqueduct. The maximum concentrations recorded were 240 ng/L of MIB in May 2003 and 396 ng/L of geosmin in July 2012 (Archibald Consulting et al., 2012). Planktonic cyanobacteria are responsible for T&O problems in Silverwood Lake, Lake Perris, Pyramid Lake, and Castaic Lake in Southern California (DWR 2013) where concentrations reached as high as 1μg/L in some locations (See **Figure 11** through **Figure 14**). DWR uses a variety of aquatic pesticides in the SWP aqueducts and reservoirs to control these cyanobacteria, as does the Metropolitan Water District of Southern California in its reservoirs that store SWP supplies.

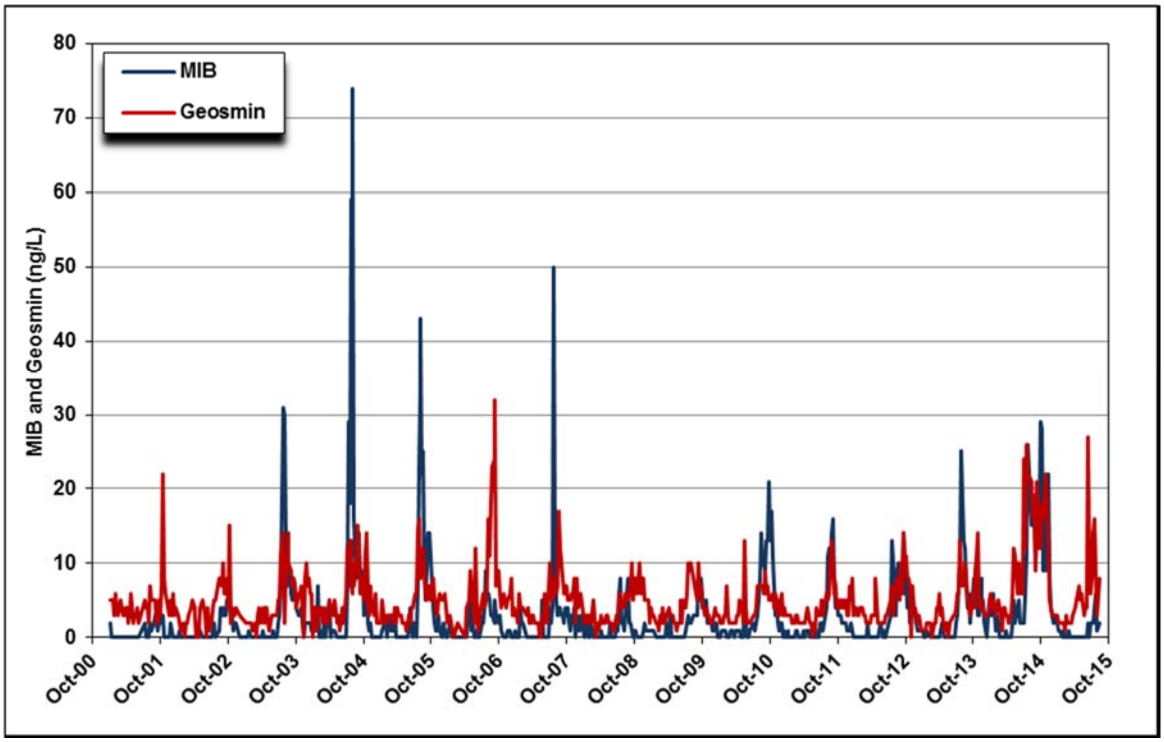


Figure 8. MIB and Geosmin Concentrations at Banks Pumping Plant

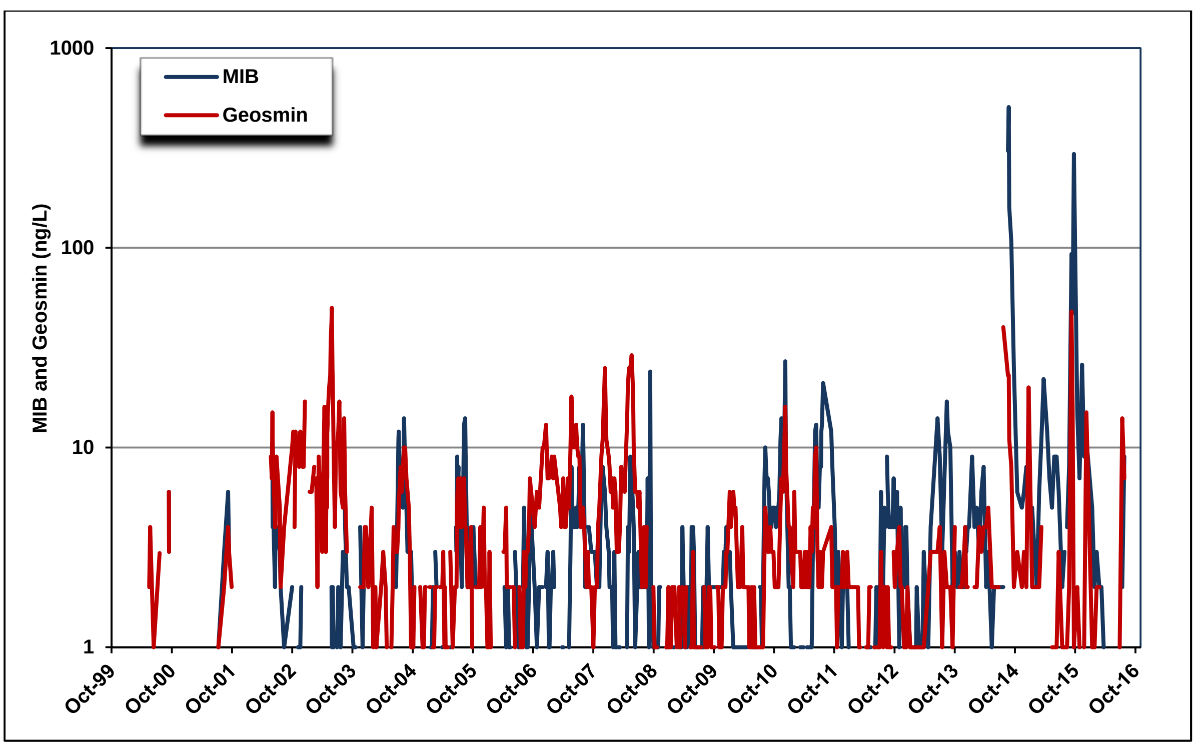


Figure 9. MIB and Geosmin Concentrations at Check 41 on the California Aqueduct

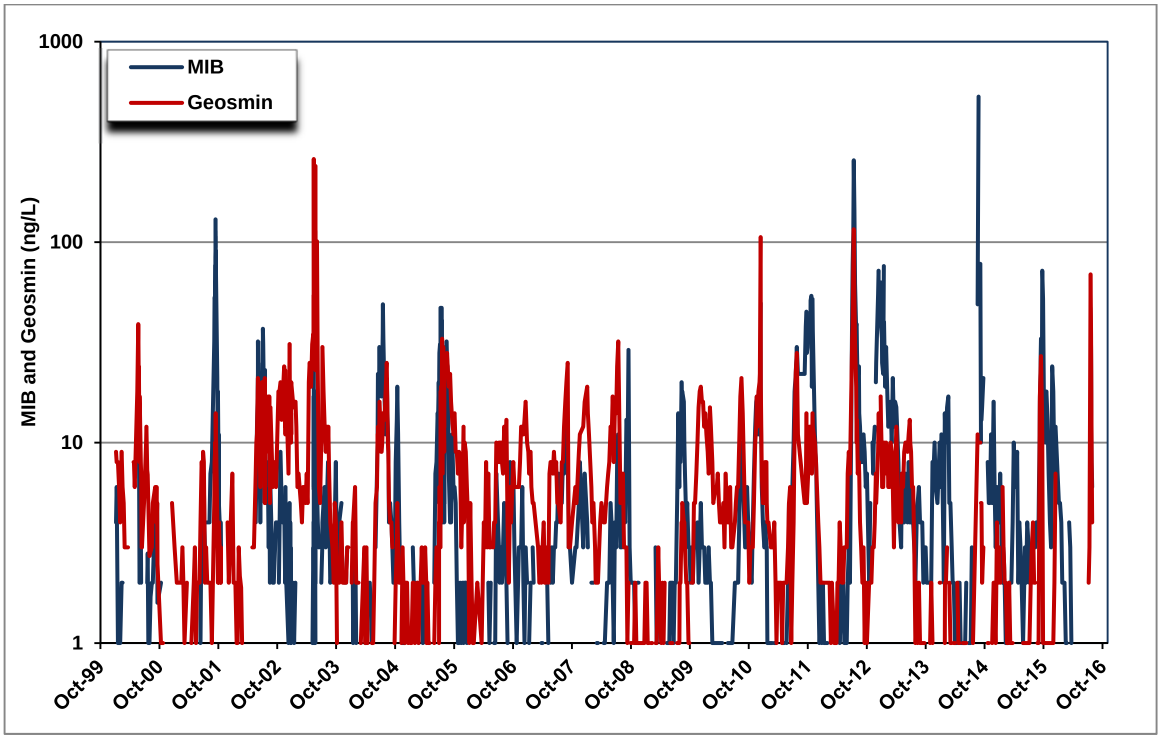


Figure 10. MIB and Geosmin Concentrations at Check 66 on the California Aqueduct

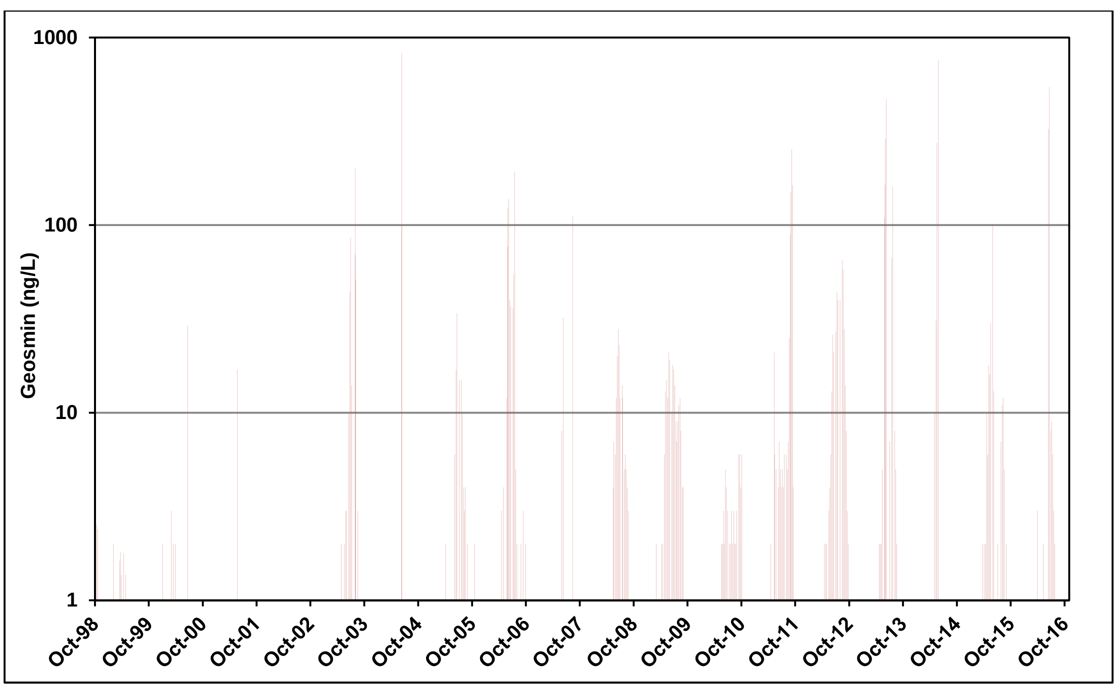


Figure 11. Geosmin Concentrations at Castaic Lake Outlet

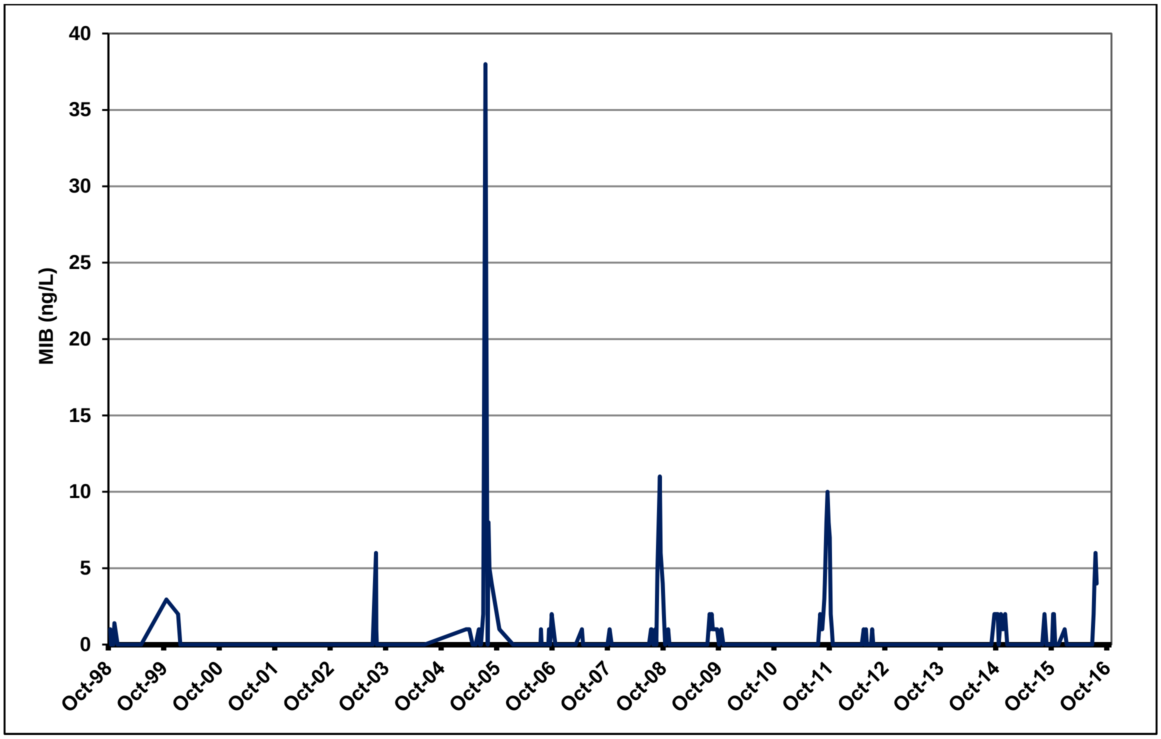


Figure 12. MIB Concentrations at Castaic Lake Outlet

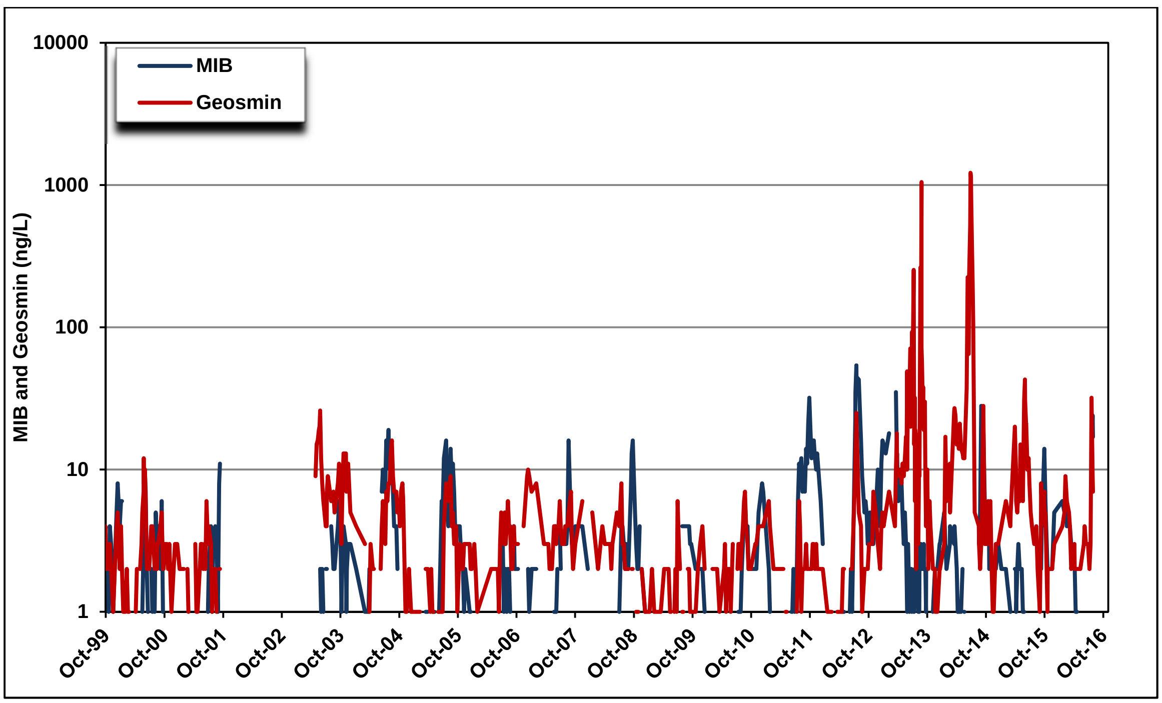


Figure 13. MIB and Geosmin Concentrations at Lake Silverwood Outlet

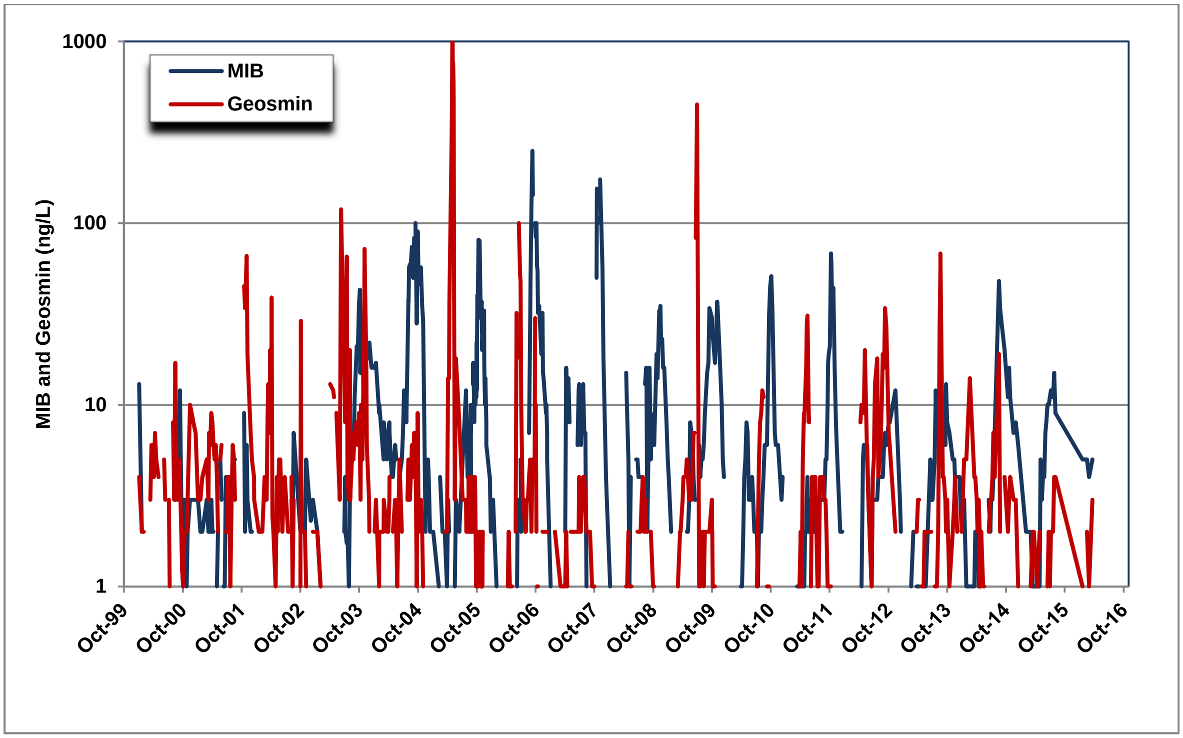


Figure 14. MIB and Geosmin Concentrations at Lake Perris Outlet

Areas of the SWP and the organisms targeted by the DWR Aquatic Weed and Algal Bloom Control Programs are shown in **Table 1**.

Table 1. State Water Project Facilities and Target Organisms Addressed by the California Department of Water Resources Aquatic Weed and Algal Bloom Control Programs (DWR 2013).

State Water Project Facilities	Macrophytes	Algae
South Bay Aqueduct	Unspecific	T&O-producing cyanobacteria, *Melosira varians*, *Cladophora* sp.
Clifton Court Forebay	*Egeria densa* *Potamogeton pectinalus* *Myriophyllum spicatum* *Ceratophyllum demersum* *Potamogeton nodosus* *Potamogeton crispus*	T&O-producing cyanobacteria
Patterson Reservoir	Unspecific	*Microcystis* spp. *Cladophora* sp.
Dyer Reservoir	Unspecific	T&O-producing cyanobacteria, *Aphanizomenon flos-aquae* *Anabaena* sp.

State Water Project Facilities	Macrophytes	Algae
O'Neill Forebay	*Potamogeton* sp. *Potamogeton pectinalus* L. *Stuckenia striata*	Unspecific
Coastal Branch Aqueduct	*Zannichellia palustris L.* *Potamogeton pectinalus*	T&O-producing cyanobacteria, *Cladophora* sp.
East Branch Aqueduct	Unspecific	T&O-producing attached cyanobacteria: *Phormidium* sp. *Oscillatoria* sp.
Pyramid Lake	*Ceratophyllum demersum* *Myriophyllum spicatum* *Stuckenia striata*	T&O-producing cyanobacteria, *Microcystis* sp., *Gloeotrichia* sp., *Anabaena* sp.
Castaic Lake	Unspecific	T&O-producing attached and planktonic cyanobacteria, diatoms
Silverwood Lake	Unspecific	*Anabaena lemmermannii*
Lake Perris	Unspecific	T&O-producing cyanobacteria, *Synechococcus* sp. *Pseudanabaena* sp. *Anabaena* sp.
Quail Lake	Unspecific	T&O-producing cyanobacteria, *Microcystis* sp., *Gloeotrichia* sp., *Anabaena* sp.

CCWD also monitors for taste and odor compounds in their facilities including the Contra Costa Canal and reservoirs. Monitoring during 2010 – 2014 in the Contra Costa Canal near the community of Clyde, which is a location in the canal after all water sources have blended, found geosmin levels that ranged from ND to 80 ng/L, with an average of 5 ng/L. MIB concentrations ranged from ND to 81 ng/L, with an average of 8.4 ng/L (see **Figure 15**). CCWD's Mallard Reservoir also experiences periodic algal blooms and elevated levels of geosmin and MIB. Monitoring in Mallard Reservoir during 2010 – 2014 found concentrations of geosmin ranging from ND to 2,200 ng/L, with an average of 43 ng/L (see **Figure 16**). MIB concentrations at Mallard Reservoir ranged from ND to 29 ng/L, with an average of 2.5 ng/L (see **Figure 17**).

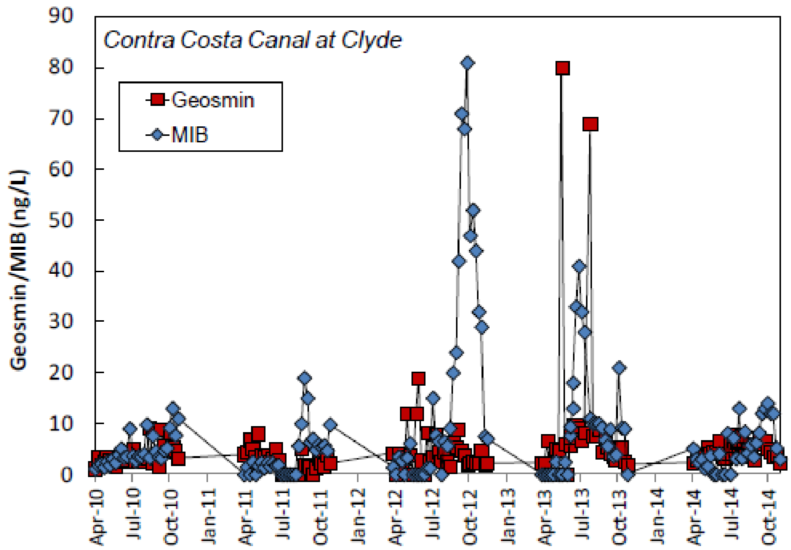


Figure 15. Geosmin and MIB in Contra Costa Canal at Clyde: 2010 – 2014

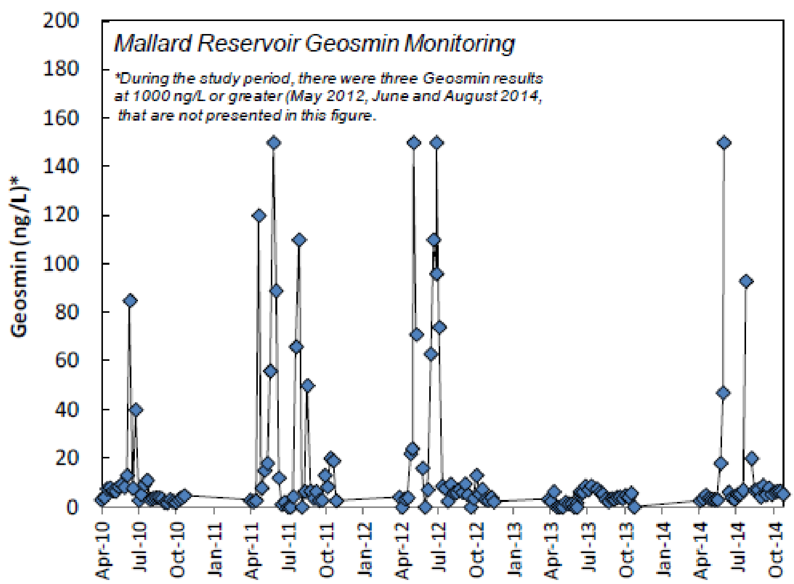


Figure 16. Geosmin in Mallard Reservoir: 2010 – 2014

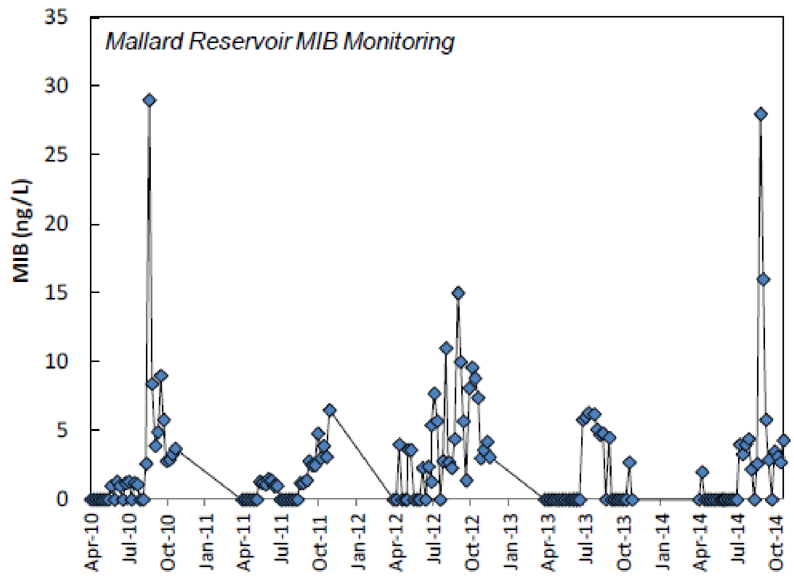


Figure 17. MIB in Mallard Reservoir: 2010 – 2014

Filter clogging

Algae and macrophytes can cause clogging, pumping failure, and treatment issues during water treatment due to high concentrations of total suspended solids (TSS) and an overabundance of plant tissue. Filter clogging algae occur throughout the SWP, but they are particularly troublesome in the SBA. The high concentrations of nutrients, combined with shallow canal depth, abundant sunlight, and warm water temperatures during the spring, summer, and fall months leads to excessive algal growth in the SBA. This creates a number of treatment challenges for the SBA Contractors and others. A benthic diatom, *Melosira varians*, and a benthic filamentous green alga, *Cladophora sp.*, are the primary algae that lead to filter clogging and reduced filter run times at SBA water treatment plants. DWR has set algal abundance thresholds (algal fluorescence > 200 units and algal biomass > 5,000 mg/m^3) for the SBA that when exceeded lead to the application of algaecides (DWR 2013).

The primary mechanism for controlling algal growth in the SBA is by application of copper sulfate, as this treatment has proven to be an effective algal control measure. Copper sulfate is applied every two to four weeks from March until October or November, depending upon water temperatures and algal conditions. Other control measures, such as light limitation, are in their early stages of development and therefore, have not been employed as a routine method to limit algal growth. As shown in **Figure 18**, algal biomass has exceeded 5,000 mg/m^3 almost every summer since data collection began in 2011, even with frequent application of copper sulfate.

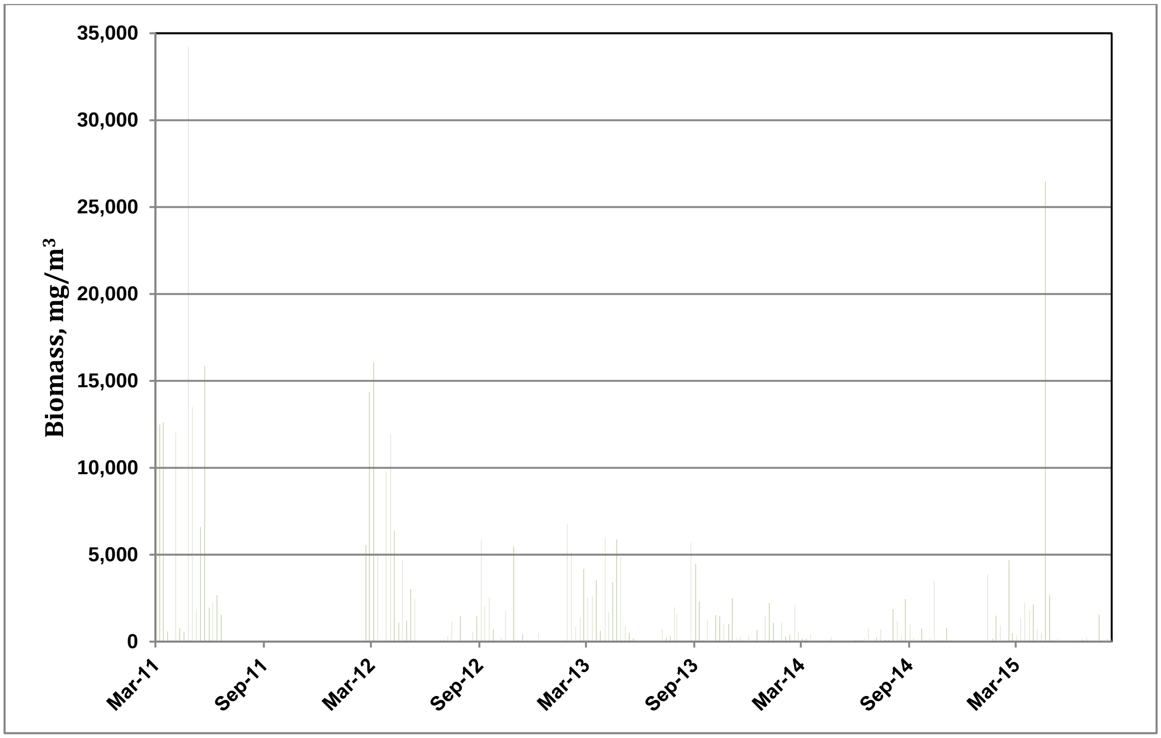


Figure 18. Algal Biomass in the South Bay Aqueduct at Del Valle Check 7

Cyanobacteria (Microcystis) and associated toxin-producing algae

Microcystis aeruginosa was first detected in the Delta in the eastern Stockton Deep Water Ship Channel in September 1999. It has bloomed every year during the late summer and early fall throughout the central and southern Delta since its initial detection. *Microcystis spp*. has been found in Clifton Court Forebay; Banks Pumping Plant; Dyer Reservoir, Patterson Reservoir, and Del Valle Check 7 on the SBA; and the Gianelli intake in San Luis Reservoir during the last three years. *Microcystis* produces microcystin, a potent hepatoxin (liver toxin). Other algal species, such as *Anabaena*, *Aphanizomenon,* and *Planktothrix* that produce algal toxins (US EPA 2012 and 2015a) have also been found at a number of locations in the SWP. Similar to the cyanobacteria which produce T&O compounds, toxin producing cyanobacteria are not always the most dominant member of the natural community and can sometimes represent a very small proportion of the biomass, but still produce a significant concentration of toxins (e.g., see **Appendix A**).

There are currently no state or federal drinking water standards for microcystins; however, the World Health Organization released a provisional guideline of 1.0 μg/L for microcystin-LR in drinking water in 1998. The United States Environmental Protection Agency (US EPA) added cyanobacteria and cyanotoxins to the Candidate Contaminant List[2] (CCL) in 1998, 2005, and 2009. Cyanotoxins are also on the draft CCL4 (2015). US EPA published 10-day drinking water health

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[2] The Contaminant Candidate List is a list of drinking water contaminants that are known or anticipated to occur in public water systems and are not currently subject to EPA drinking water regulations.

advisories for microcystins and cylindrospermopsin in June 2015 (US EPA 2015b). Health advisories describe non-regulatory concentrations of drinking water contaminants at or below which adverse health effects are not anticipated to occur over specific exposure durations (e.g., 10-days). **Table 2** presents the US EPA health advisories.

Table 2. US EPA Algal Toxin 10-Day Drinking Water Heath Advisories (applicable to tap water)

Age Group	Microcystins (µg/L)	Cylindrospermopsin (µg/L)
Children, Six Years and Younger	0.3	0.7
Older Children and Adults	1.6	3.0

DWR initiated microcystin monitoring in SWP facilities prior to treatment in 2006. Between 2006 and 2012, dissolved microcystin was detected in a few samples at levels ranging from <1.0 to 1.7 µg/L. In 2013, DWR changed laboratories and measurement methodology. The new method measures total microcystins (dissolved and particulate), including the microcystin contained in algal cells. This resulted in more frequent and higher concentration detected at more locations. Microcystin has been detected in Barker Slough at the North Bay Aqueduct intake, Clifton Court Forebay, Banks Pumping Plant, Dyer Reservoir on the SBA, the Gianelli and Pacheco intakes in San Luis Reservoir, the O'Neill Forebay Outlet (Check 13) on the California Aqueduct; and in Pyramid Lake, Castaic Lake, and Silverwood Lake in Southern California (see **Figure 19** through **Figure 30**).

Table 3 presents *Microcystis* biomass and microcystin data for Clifton Court Forebay, the forebay for the Banks Pumping Plant in the South Delta, during the period July 2013 to August 2015. This table presents data for the dates that either *Microcystis* biomass or microcystin was detected. Notably, both are not always detected on the same date. The US EPA 10-day Drinking Water Health Advisory for microcystin for young children was exceeded nine times in ambient samples and the adult level was exceeded twice in the Clifton Court Forebay ambient samples (see **Table 3**).

With reference to **Figure 19** through **Figure 29**, the highest microcystin concentrations were found in the SWP reservoirs. Concentrations in samples collected at several locations and depths in Pyramid Lake ranged from 0.23 to 81.5 µg/L in the summer of 2015. Silverwood Lake had concentrations ranging from 0.30 to 40 µg/L in the summer of 2013. San Luis Reservoir had concentrations ranging from 0.30 to 9.8 µg/L at the Gianelli intake, and 0.80 to 6.5 µg/L at the Pacheco intake in 2013. Many of these ambient samples exceeded the US EPA Health Advisories (applicable to tap water) for both children and adults.

DWR started sampling for cylindrospermopsin in 2012. Samples are collected only when algae known to produce this toxin are present. Cylindrospermopsin has only been detected in Lake Perris in Southern California where the concentrations ranged from 0.10 to 0.19 µg/L in 2015 (see **Figure 30**). These concentrations are below the US EPA Health Advisories for the toxin presented in **Table 2**.

Table 3. *Microcystis* Biomass and Microcystin Concentrations in Clifton Court Forebay.

Date	*Microcystis* Biomass, mg/m³	Percent of Total Biomass	Microcystin, µg/L[(1)]
07/22/13	7.9	42.5	
08/05/13	0.8	4.9	
09/16/13			**0.30**
11/12/13	86.5	91.9	
11/18/13	115.0	98.7	
06/23/14			0.19
07/07/14	112.50	28.45	**2.98**
07/22/14			**1.11**
08/04/14			**0.46**
08/18/14	200.9	85.4	**0.64**
09/02/14	23.0	9.4	**2.17**
09/15/14			**1.30**
09/22/14	257.5	49.4	
09/29/14			**0.41**
10/13/14			0.22
11/17/14	8.1	10.0	
07/06/15			**0.37**
08/10/15			0.17

[1] Bolded values exceed US EPA Algal Toxin 10-Day Drinking Water Heath Advisories of 0.3 µg/L for children 6 years and younger.

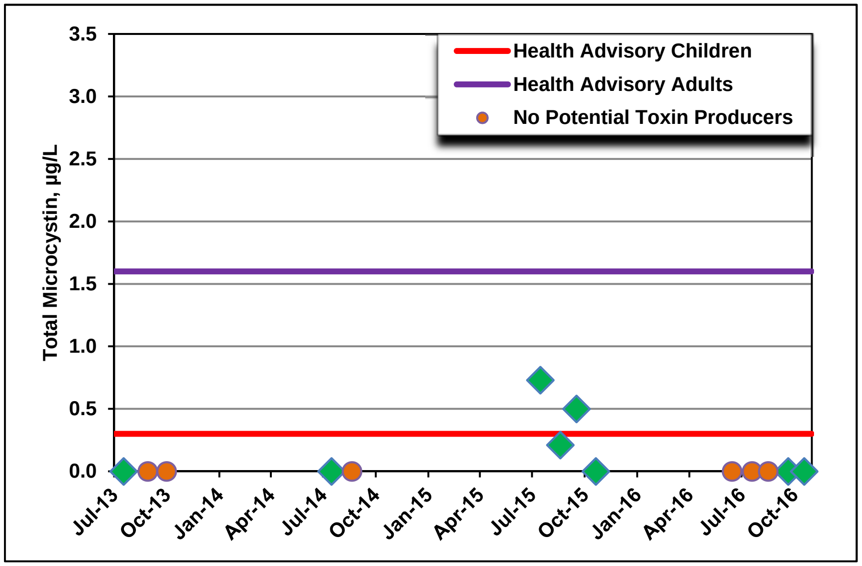

Figure 19. Total Microcystin in Barker Slough

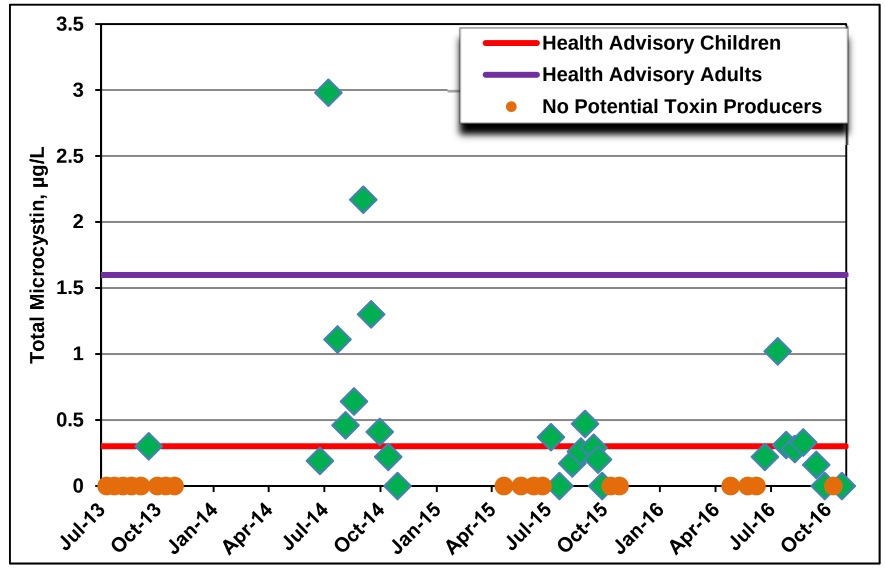

Figure 20. Total Microcystin in Clifton Court Forebay

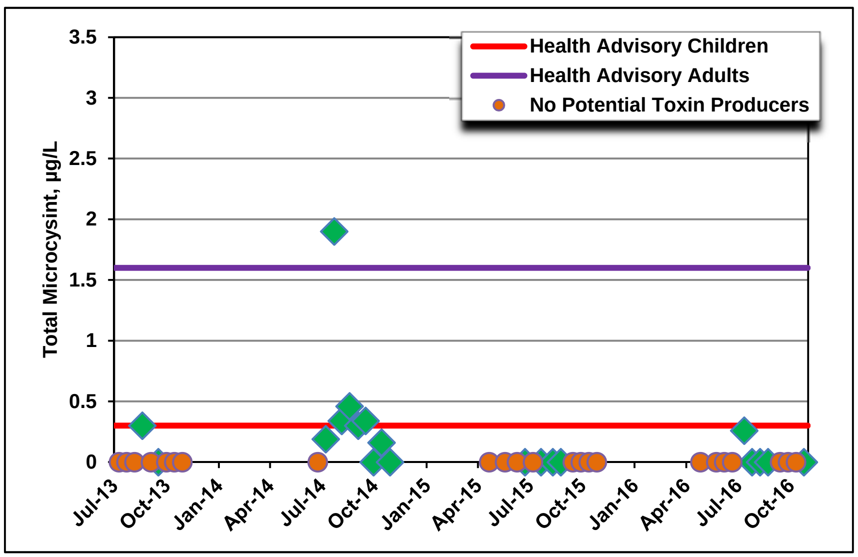

Figure 21. Total Microcystin in Banks Pumping Plant

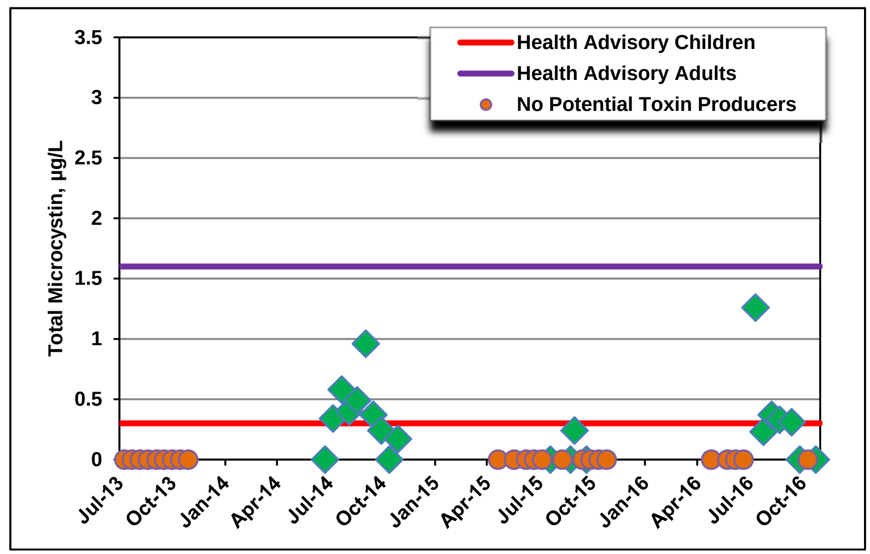

Figure 22. Total Microcystin in Dyer Reservoir

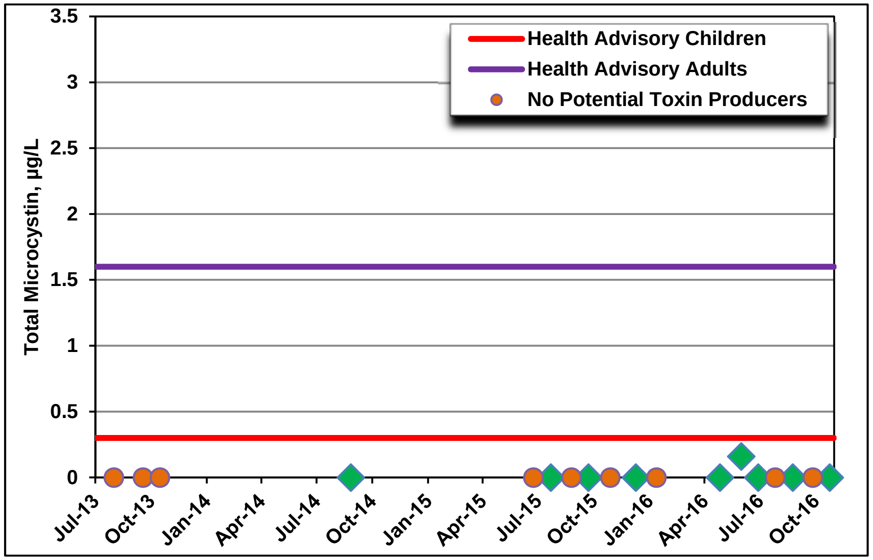

Figure 23. Total Microcystin in Lake Del Valle Check

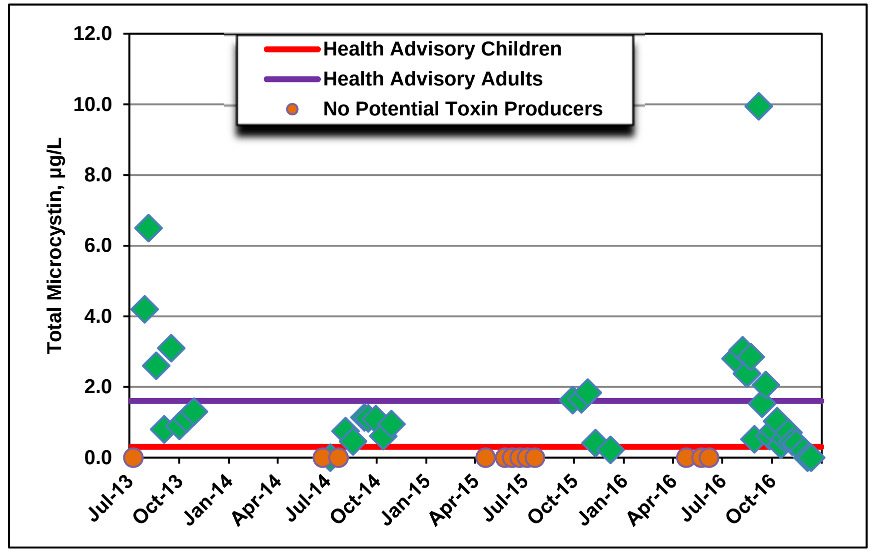

Figure 24. Total Microcystin in San Luis Reservoir at Pacheco intake

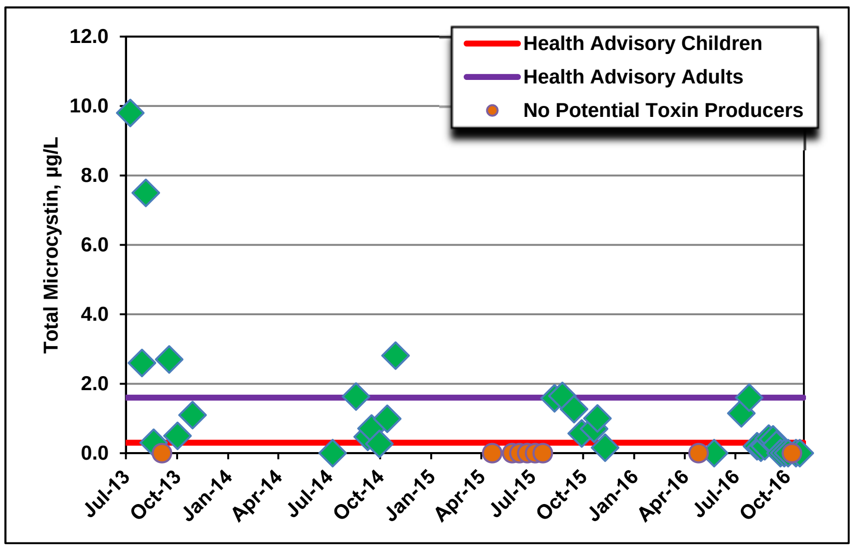

Figure 25. Total Microcystin in San Luis Reservoir at Gianelli Intake

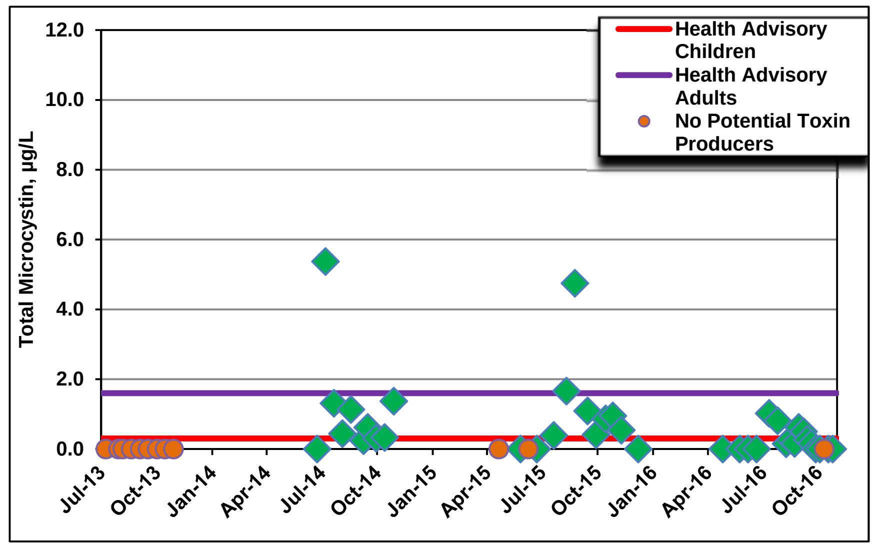

Figure 26. Total Microcystin in O’Neill Forebay Outlet

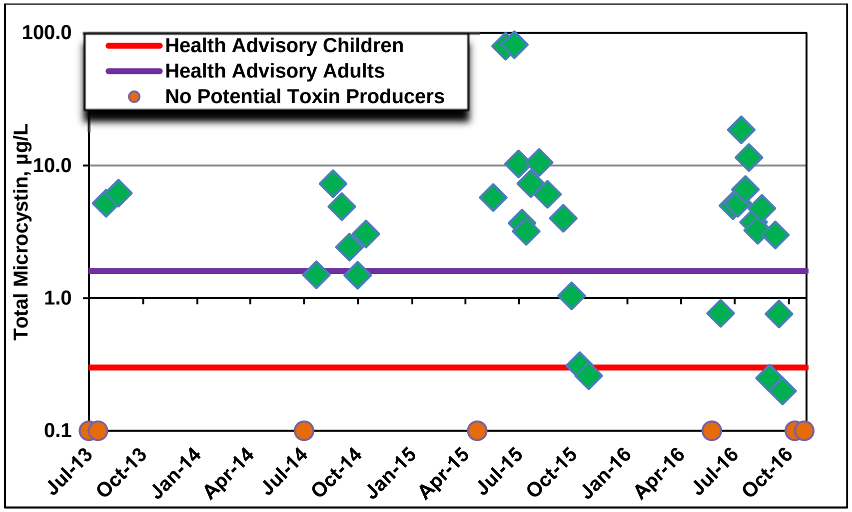

Figure 27. Total Microcystin in Pyramid Lake

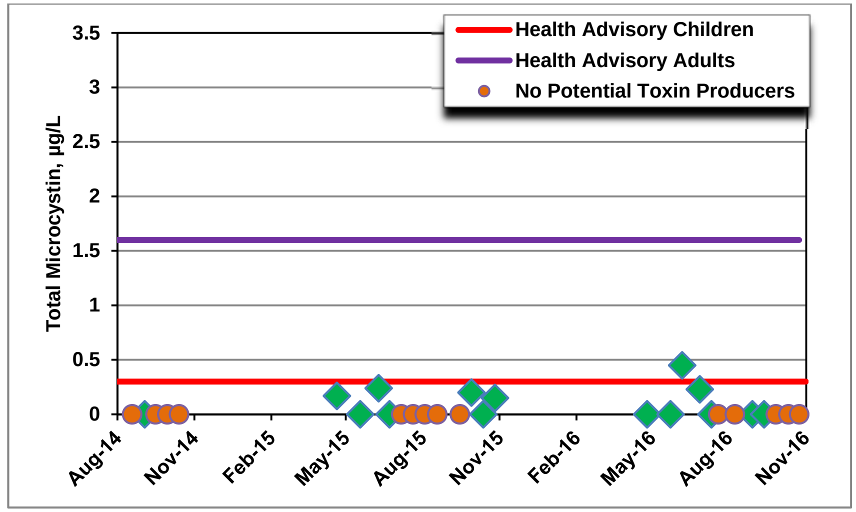

Figure 28. Total Microcystin in Castaic Lake

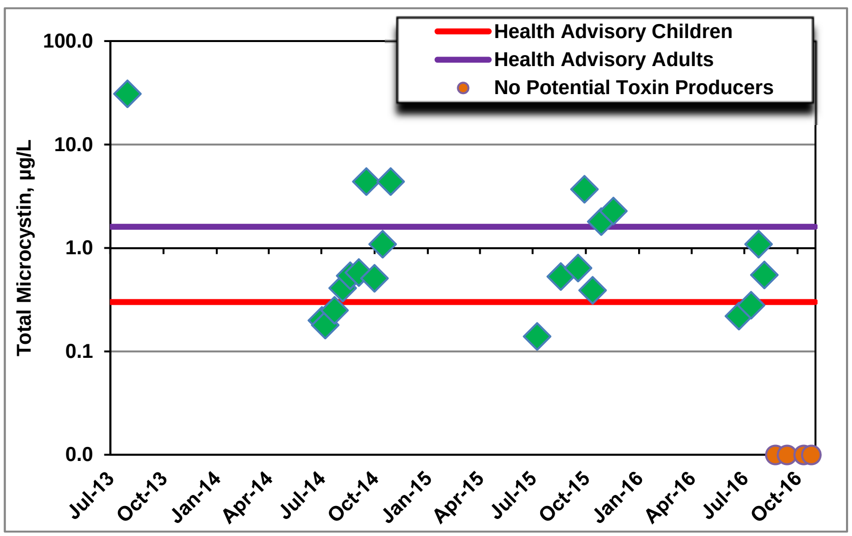

Figure 29. Total Microcystin in Lake Silverwood

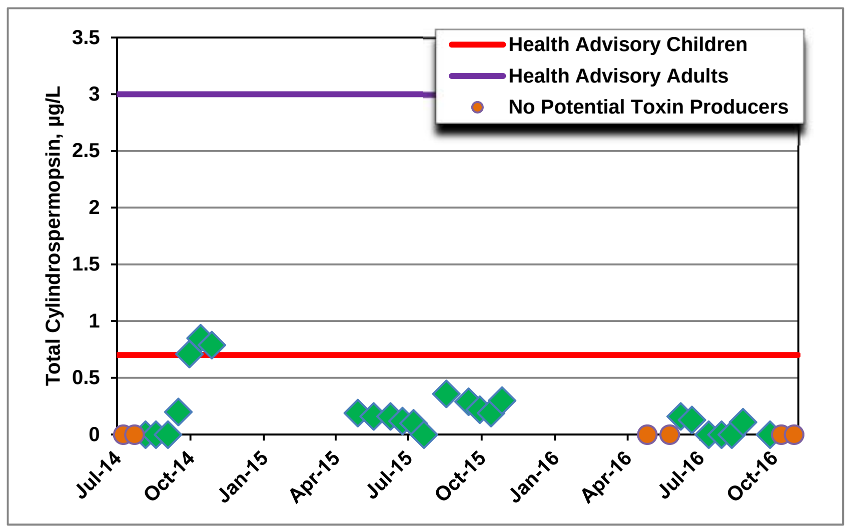

Figure 30. Total Cylindrospermopsin in Perris Lake

Dissolved Organic Carbon Production

Ambient nutrient levels in the Delta can cause an increase in total and dissolved organic carbon concentrations as a result of increased primary productivity. Increased productivity causes the release of organic compounds into the dissolved organic carbon pool, as does the death and decomposition of aquatic plants and algae. Dissolved organic carbon is a drinking water concern primarily due to the formation of carcinogenic byproducts that are formed during disinfection at a water treatment facility (Tetra Tech 2006). Chlorine, which is added to disinfect drinking water, reacts with dissolved organic carbon to form compounds such as trihalomethanes and haloacetic acids (generally referred to a disinfection byproducts or DBPs) which are both known carcinogens (Fleck et al., 2004). The amount of organic carbon that must be removed by a water treatment plant is based on the concentrations of total organic carbon (TOC) and alkalinity in the source water, as prescribed in the US EPA Comprehensive Disinfectants and Disinfection Byproduct Rules (Stage 1 and Stage 2 (D/DBP Rule)) – see **Table 4**. Algal production in the SWP facilities results in higher concentrations of total organic carbon in the system. Currently, copper sulfate addition is the only control measure used to manage algal growth. The relative contribution from the Delta and from primary production in the SWP system is not known.

Table 4. US EPA D/DBP Rule Requirements for TOC Removal.

Subpart H systems[1] that use conventional filtration treatment are required to remove specific percentages of organic materials, measured as total organic carbon (TOC) that may react with disinfectants to form DBPs. Removal must be achieved through a treatment technique (enhanced coagulation or enhanced softening) unless a system meets alternative criteria. Systems practicing softening must meet TOC removal requirements for source water alkalinity greater than 120 mg/L as $CaCO_3$.

Source Water TOC (mg/L)	Source Water Alkalinity, mg/L as $CaCO_3$		
	0-60	>60 to 120	>120
> 2.0 to 4.0	35.0%	25.0%	15.0%
> 4.0 to 8.0	45.0%	35.0%	25.0%
> 8.0	50.0%	40.0%	30.0%

1. Subpart H systems are public water systems using surface water or ground water under direct influence of surface water as a source that are subject to the requirements of Subpart H of 40 CFR Part 141 (40 CFR 141.3).

For additional information see: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100C8XW.txt

The direct control of TOC and DOC levels in the Delta was considered in detail as part of an extensive stakeholder collaborative known as the Central Valley Drinking Water Policy work group in the period from 2002 through 2012. That effort culminated in findings that ambient TOC and DOC levels were not expected to increase at drinking water intakes in the near future and that additional water treatment would not be required to address existing TOC and DOC levels under the current Safe Drinking Water Act regulatory requirements (Central Valley Drinking Water Policy Workgroup 2012).

Diurnal Swings in pH

Wide swings in pH periodically occur in the SBA, as shown **Figure 31**. Excursions of pH above the upper limit of the US EPA Secondary Maximum Contaminant Level (MCL) of 8.5 standard units (s.u.) for the parameter were observed during May, June, September, November, and December 2016. Increases in pH in the SBA are most likely a result of photosynthetic removal of carbon dioxide (CO_2) from the water column along the length of the open canal, primarily by algae. These pH excursions are problematic for the SBA Contractors because the pH of the treatment plant influent must be adjusted to be within a pH range of 6.5 – 8.5 standard units (s.u.) for the drinking water treatment process to meet US EPA secondary standards[3] for pH and the Sacramento-San Joaquin Basin Plan[4] objectives and to effectively disinfect the water. In 2016, pH data collected in the SBA exceeded a pH of 8.5 on two (2) separate occasions. Tracking rapid pH changes and adjusting acid feed makes it difficult to meet water treatment regulations and increases treatment costs. Treatment costs increase because acid is added to lower the pH of the raw water going into the plant and then must be subsequently offset by the addition of a base to raise the pH of the finished water leaving the plant to meet the requirements of the Lead and Copper Rule.

Solids Production

Water agencies must use additional quantities of chemicals, such as ferric chloride, alum, and polymers in the water treatment process to remove algae from the source water. This produces greater quantities of solids in addition to the overabundance of plant tissue that must be disposed of to avoid clogging and pumping failure, resulting in higher solids disposal costs.

2.3.2 Macrophytes

The Macrophyte Workgroup came to no conclusion regarding the effect of nutrients in the Delta on triggering or increasing non-native macrophyte expansion across the Delta in recent years. The expansion of invasive macrophytes in the Delta observed when comparing the results of two mapping events in 2008 and 2014 cannot be linked to a change in ambient nutrient concentrations, as an evaluation of nutrients in the Delta from 2004 – 2014 found no obvious trends in ammonium, nitrate, phosphate, total N, or total P concentrations across multiple Delta monitoring locations (LWA 2015). To this end, the Macrophyte Workgroup concluded that the expansion of invasive macrophytes in recent years cannot be linked to changes in water column nutrient concentrations across the Delta during the same period and suggested that other factors besides nutrients might be contributing to the extensive plant growth (Boyer and Sutula 2015).

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[3] https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals

[4] http://www.waterboards.ca.gov/centralvalley/water_issues/basin_plans/2016july_1994_sacsjr_bpas.pdf

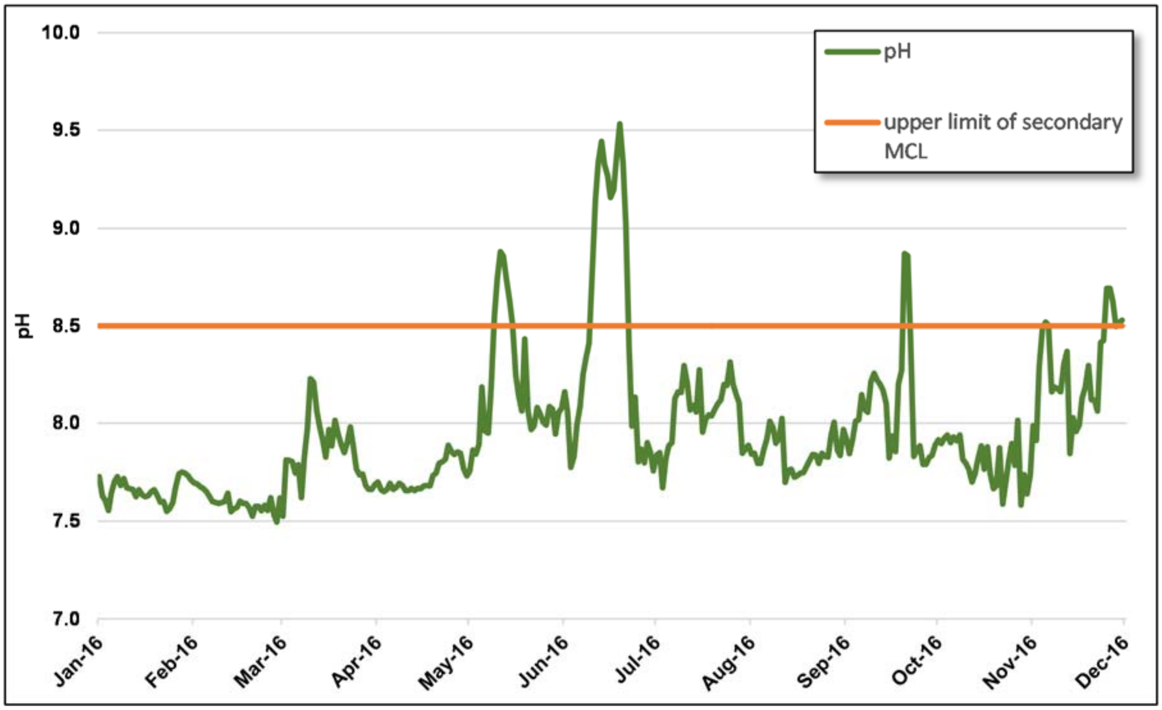

Figure 31. pH levels in South Bay Aqueduct during 2016

Obstruction of Conveyance and Pumping Facilities

Excessive growth of macrophytes and algae create water conveyance problems at a number of locations in the SWP. Macrophyte accumulation can be so severe at Banks that pumping is restricted or halted. During certain periods, up to 20 cubic yards of macrophytes are removed each day from the trash racks at Banks. Macrophytes also create major operational problems in O'Neill Forebay, the California Aqueduct, and the Coastal Branch. Macrophytes are also present in the littoral zone of the four Southern California SWP reservoirs. DWR expends a significant amount of time and money controlling macrophytes in the SWP. Copper products are used in many locations, although they have not been used since 2006 in Clifton Court due to potential impacts on threatened and endangered species. Mechanical harvesting is used in Clifton Court Forebay and O'Neill Forebay and some sections of the aqueduct are scraped by dragging a large chain along the aqueduct lining.

3.0 Factors Influencing Nutrient-Related Drinking Water Issues

The following section provides information pertaining to the factors that may influence the cyanobacteria and macrophyte prevalence problems within the SWP identified in **Section 2.0**. The information presented below was taken from the white papers produced by the Cyanobacteria and Macrophyte Workgroups.

3.1 LIGHT/SOLAR IRRADIANCE

All photosynthetic organisms possess a characteristic photosynthesis-irradiance relationship where the rate of photosynthesis increases with increased irradiance up to some point where the light-harvesting complex of the photosystem becomes overwhelmed and photo-inhibition (i.e., a decline in photosynthetic rate) occurs. Cyanobacteria have carotenoid pigments in their photosystems that protect them against photo-inhibition at a given irradiance, as compared to a photosynthetic organism lacking such protective pigments (Huisman et al. 1999, Reynolds 2006).

Microcystis growth is poor at low and mixed light, but grows very efficiently at high irradiances; especially, those species of *Microcystis* that produce toxins (Huisman et al. 2004, Reynolds 2006, Carey et al. 2012). *Microcystis* also shows positive buoyance, which allows it to grow near the water surface in poorly mixed conditions. Phytoplankton that show less buoyancy can become shaded out by surface growths of *Microcystis* under low mixed conditions (Carey et al. 2012). Other species of cyanobacteria, including *Cylindrospermopsis raciborskii* and *Planktothrix* sp. are good competitors at low light levels and grow well within the water column under low irradiances. *C. raciborskii* also grows well at high irradiances, making it well-suited to produce harmful cyanobacterial blooms (cyanoHABs) under a variety of environmental conditions.

Light conditions in the Delta are generally adequate for floating macrophytes, such as *E. crassipes* (water hyacinth). Attenuation of photosynthetically active radiation (PAR, wavelengths of 400 – 700 nm) in the water column by suspended particles, including phytoplankton, can limit photosynthesis of some submersed macrophytes. Studies of *E. densa* (Brazilian waterweed) growth under different light conditions show the submersed macrophyte to have varying responses to changes in irradiance, with one study showing the macrophyte to have lower biomass under low light levels as compared to higher levels (Borgnis and Boyer, unpublished data), and another study showing an increase in biomass at low light levels due to an extension of the plant's canopy upward through the water column (Rodrigues and Thomaz 2010). The buoyancy of *E. crassipes* allows it to shade out any photosynthetic organism growing within the water column and thus, potentially affects its ability to compete with other species under a modified light regime. With regard to submersed macrophytes, a species that can effectively outgrow its competitor under ambient light conditions in the Delta has the ability to shade out its competitors and/or utilize more of the available resources to the detriment of competing species.

3.2 WATER CLARITY

The Delta has historically been viewed by researchers as light limited due to high turbidity, and this condition has been used to explain, in part, the overall low productivity of the estuary in the presence of nutrient concentrations thought sufficient to cause eutrophication (Cole and Cloern 1984, 1987). Light limitation is likely to be most severe in turbid waters of the estuary which are affected by wind- and tide-driven vertical mixing and re-suspension of inorganic sediment, and is particularly high in shallow areas and areas subject to strong winds (Kimmerer et al. 2012). In localized areas where light limitation isn't limiting primary productivity, secondary factors, such as nutrient availability, temperature, salinity, and photoperiod, can support algal blooms (Cole and Cloern 1984). Delta waters have showed increased clarity over the past 50 years. Wright and Schoellhamer (2004) found that suspended sediments from the Sacramento River to the Delta have decreased by about half during the period 1957 to 2001, while Jassby (2008) showed a 2 to 6% decrease per year in suspended particulate matter between 1975 and 2005.

As discussed above, increased irradiance can impart a competitive advantage to those species that have protective pigments to limit or avoid photo-inhibition under conditions of high irradiance, those species with high photosynthetic rates under high irradiance, and those species that exhibit low photosynthetic efficiency at low light levels. An increase in water clarity would result in an increase in irradiance in the water column, which would benefit those species – particularly, cyanobacteria, such as *Microcystis* and *C. raciborskii* – that grow well under high light conditions. Researchers have observed an increase in the abundance of *Stuckenia pectinata* (sago pondweed), a native submersed macrophyte, in the Delta over the last 20 years and have posited increased water clarity and thus greater light availability may be partially responsible for its expansion (Wright and Schoellhamer 2004; Schoellhamer 2011; Hestir et al. 2013).

3.3 TEMPERATURE

Increases in temperature, up to some critical threshold, are expected to increase the establishment and growth rates of phytoplankton and floating and submersed macrophytes. Temperature is considered a key factor that controls the growth rate of cyanobacteria (Robarts and Zohary 1987, Butterwick et al. 2005, Watkinson et al. 2005, Reynolds 2006, Paerl and Huisman 2009). Cyanobacteria isolated from temperate latitudes (i.e., excluding polar regions) exhibit growth optima at temperatures between 25 and 35°C (Reynolds 2006, Lurling et al. 2013). Species responsible for cyanoHABs show growth optima within this range, with *Anabaena* spp. observed to have optimum growth at 25°C, *C. raciborskii* and *Planktothrix agardhii* at 27.5°C, and two *Microcystis aeruginosa* strains at 30-32.5°C (Lurling et al. 2013). Cyanobacteria typically show lower growth rates at colder temperatures and higher growth rates at warmer temperatures as compared to other phytoplankton taxa, such as diatoms and dinoflagellates (Boyd et al. 2013, Butterwick et al. 2005, Kudo et al. 2000, Lurling et al. 2013, Yamamoto and Nakahara 2005). As evidence of this, decreases in temperature that occur in the fall and winter are observed to coincide with non-active growth phases in phytoplankton. Differences in temperature growth optima among various phytoplankton taxa are hypothesized to have importance in influencing phytoplankton community composition as global climate change produces temperatures above 20°C with more regularity (Lehman et al. 2005, Paerl and Huisman 2008).

T&O events have also been found to be correlated with temperature in some systems. Regression approaches using a suite of environmental variables have shown air and/or water temperature to be a strong correlate with T&O compound concentrations in at least four reservoirs (Tung et al. 2008; Uwins et al. 2007; Yen et al. 2007).

With respect to macrophytes, increased growth tends to cause a reduction in flow surrounding a stand, which causes increases in local temperatures that further enhance growth up to some limiting temperature. Laboratory growth studies of *E. densa* showed increases in biomass at a water temperature of 22°C, reduced biomass production at 26°C, and great reductions in biomass at 30°C (Borgnis and Boyer, in press). Similar to phytoplankton, decreases in temperature that occur in the fall and winter are observed to coincide with senescence and dieback in macrophytes. Dieback of *E. crassipes* has been observed in the Delta during periods of frost and freezing temperatures (Foe, pers. comm.; Khanna, pers. comm.; as cited in Boyer and Sutula 2015).

3.4 RESIDENCE TIME/FLOW

Residence time is a measure of how long an object (e.g., fish, plant, pollutant, parcel of water) remains in a defined region. It is a good measure of the length of time an object stays in the estuary. Delta residence time is affected by inflows, seasonal changes in hydrology, diversions/exports, tides, physical structures of water channels (i.e., dead end slough vs. river channel), and the operation of structures such as gates and barriers. Flow velocity certainly has a large impact on residence times as higher flows produce shorter residence times and lower flows promote longer residence times. A long-term trends analysis (1990 – 2004) of Delta residence time performed by DWR's Delta Modeling Section[5] found no significant differences in residence time indexes for the Sacramento and San Joaquin rivers over the period analyzed. However, the study did find the following: Sacramento River residence time was higher during the drier water years of the early 1990s; San Joaquin River residence time was higher in late fall/early winter in the early 1990s; late summer and early fall periods showed the highest residence times; later winter exhibited the lowest residence times; and spring featured the greatest variability in residence times.

Longer residence times generally promote greater exposures of organisms to their physical and biogeochemical environments. Lower flows and longer residence time help to establish macrophyte beds that can eventually lower flows and alter local habitats themselves, which promote their own continued growth (Boyer and Sutula 2015). Lower flows, altered deposition of suspended sediments, and increased temperatures can lead to altered habitats that promote the growth of some organisms (e.g., macrophytes, phytoplankton, fish, zooplankton, etc.) over others. Cyanobacterial abundance, cell size, and toxin concentration are also positively correlated to increased residence time (Elliott 2010, Romo et al. 2013).

[5] Poster available at: http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/presentations/DeltaResidenceTimeResults_mmierzwa.pdf

3.5 SALINITY

Ambient salinity in the Delta is typically managed to provide freshwater for municipal, industrial, and agricultural beneficial uses (Moyle et al. 2010). Diminished freshwater flows into the Delta during the recent drought (2011 – 2015) have resulted in increased salinities (up to 5 ppt or more) reaching as far east as Sherman Island (Boyer and Sutula 2015). Sea level rise and changes in the timing and magnitude of snowmelt due to global climate change are hypothesized to increase Delta salinity by 1 to 3 ppt by 2090 (Knowles and Cayan 2002). Salinity measurements taken in the western Delta by the C&H Sugar Refining Company since the early 1900s have revealed that salinity intrusion in Suisun Bay now occurs four months earlier each year than historically; March as compared to July (Contra Costa Water District 2010).

Freshwater cyanobacteria capable of forming toxins show a range of tolerances for salinity. The least tolerant is *Cylindrospermopsis*, which shows decreased growth above 2.5 ppt. *Anabaenopsis* and *Nodularia* spp. can thrive at salinities from 5-20 ppt (Moisander et al. 2002). *Microcystis aeruginosa* can tolerate salinities up to 10 ppt without a change in growth rate as compared to that observed when the alga is grown in freshwater (Tonk et al. 2007). The white paper produced by the Cyanobacteria Workgroup concluded that salinity may not be a strong barrier that restricts the occurrence of cyanoHABs in the Delta (Berg, and Sutula 2015).

A study that investigated the salinity tolerance of *E. densa* found the growth of the macrophyte to be strongly limited by increases in salinity, with loss of biomass at a salinity of 5 ppt and mortality and decomposition at salinities of 10 and 15 ppt (Borgnis and Boyer, in press). The native pondweed *S. pectinata* is expected to have the greatest salinity tolerance among all macrophytes in the Delta based on greenhouse growth experiments that showed biomass accumulation with increased salinities up to 15 ppt as compared to controls (Borgnis and Boyer, in press). *E. crassipes* has been shown to undergo stress at salinities as low as 2.5 ppt (Haller et al. 1974) and experience mortality at salinities above 6 – 8 ppt (Muramoto et al. 1991; Olivares and Colonnello 2000).

3.6 NUTRIENT CONCENTRATIONS AND RATIOS

The San Francisco Estuary (SFE), which includes the Sacramento-San Joaquin Delta, Suisun Bay, San Pablo, Central and South Bays, is an example of an aquatic ecosystem possessing nitrogen and phosphorus concentrations sufficient to produce eutrophication, yet, overall, it features low phytoplankton production (Cloern 2001; Jassby et al. 2002). Its annual loading rates of both total N and total P are greater than those measured in Chesapeake Bay, but the San Francisco Estuary historically exhibited none of the phytoplankton blooms characteristic of the Chesapeake (Cloern 2001). In the SFE, it is well established that factors such as turbidity (acting to limit light penetration in the water column), freshwater flow, residence time, and benthic grazing by bivalves all decrease the sensitivity of the system to nutrient loading (Cloern 2001). Jassby et al. (2002) showed that increases or decreases in nutrient levels in the Delta have little effect on the ecosystem's primary productivity due to the physical factors that exert a stronger influence on phytoplankton production than ambient nutrient concentrations. In recent years, some researchers have hypothesized that the forms of N (ammonium versus nitrate) available for uptake in the system (Wilkerson et al. 2006) and the ratio of N to P in the system (Glibert 2010) are acting to control the primary productivity of the SFE to a greater degree than once thought. Those hypotheses are addressed in the Nutrient Forms and Ratios white paper produced in 2017 as part of the Delta Nutrient Science and Research Program.

3.7 DISSOLVED INORGANIC CARBON

The process of photosynthesis allows plants and other organisms to convert light energy into chemical energy through uptake and conversion of inorganic carbon dioxide and water to organic carbon compounds (sugars) and oxygen. Floating macrophytes can access adequate carbon dioxide from the atmosphere, but phytoplankton and submersed macrophytes must obtain their carbon source from the water column in the form of dissolved inorganic carbon (DIC). As photosynthesis by aquatic plants and algae preferentially removes CO_2 from the water column, carbonic acid (H_2CO_3) becomes more prevalent and pH concentrations increase. This leads to bicarbonate (HCO_3^-) becoming a more prominent form of DIC in the water column (Sand-Jensen 1989; Santamaría 2002). When photosynthesis removes CO_2 from the water column at a rate faster than atmospheric CO_2 and respiration contribute CO_2 to the water column, a higher pH condition is formed where bicarbonate becomes the primary form of DIC available to photosynthetic organisms. Macrophytes that can utilize bicarbonate efficiently, such as *E. densa* and *Ceratophyllum demersum* (coontail; a submersed, native perennial) (Cavalli et al. 2012), may have a competitive advantage over those species that do not grow as well with bicarbonate as a DIC source. In addition to potential competitive advantage for some organisms, the conversion of DIC to dissolved organic carbon (DOC) via photosynthesis may result in drinking water quality problems due to the formation of carcinogenic byproducts from the disinfection process as discussed earlier in **Section 2.0**.

4.0 Management of Identified Issues

4.1 MANAGEMENT OPTIONS

This section discusses possible management options to address several of the important issues discussed in the previous sections regarding impacts to Drinking Water sourced from the Delta.

4.1.1 Nutrient Load Management

Taste and Odors

Nutrient control measures have proven to be ineffective as management tools to control T&O events or the distribution and abundance of T&O-causing microbes in the few systems which have studied the issue, although it is unclear whether the results from other systems are applicable to the Delta and water supply systems that transport and store Delta water. Outbreaks of Chrysophytes (taxonomic group containing diatoms, yellow-green, and golden-brown algae), and their polyunsaturated fatty acid (PUFA) derivatives, show little apparent relationship to nutrients on a broad scale across 91 north temperate lakes in Canada (Watson et al. 1997; Watson et al. 2001a). Furthermore, in certain cases remedial nutrient reduction may actually increase episodes of Chrysophyte blooms (e.g., Juttner et al. 1986; Yano et al. 1988; Nicholls 1995). Where T&O episodes have been linked to planktonic cyanobacteria, the events are not well-explained by the nutrient status or planktonic productivity of the systems (e.g., Watson et al. 2008).

In some cases, remedial action plans for T&O problems were found to be unsuccessful because they attempt control of noxious metabolites through a reliance on water treatment and broad-scale nutrient–biomass models. Nutrient control approaches are undermined by several factors, including the fact that (1) different T&O-compound producing taxa show disparate patterns across nutrient and mixing regimes, (2) epibenthic and periphytic microbes are widespread culprits in the production of T&O compounds – and growth of attached microbes is more weakly linked to conditions in the water column than phytoplankton, (3) deep-layer cyanobacteria maxima, supplied by internally recycled nutrients in the hypolimnion of a stratified system, can be a source of T&O compounds, (4) nutrient reduction strategies have increased water transparency and littoral production in many systems, improving conditions for attached algae, and (5) other groups of MIB and geosmin-producing organisms are not algae, but actinomycete bacteria, myxobacteria, fungi, and others. Proactive management of taste and odor issues needs to consider the sources of the problem by identifying the environmental and biological agents and their potential controls, including ecologically sound watershed and source water remediation and management (Juttner & Watson 2007).

Although surface blooms are perceived as primary sources of water odor, twice as many known odor-causing cyanobacterial species are epibenthic, not planktonic (Jutter & Watson 2007). In addition, two cyanobacteria genera (*Hyella* and *Microcoleus*), which form biofilms on aquatic macrophytes, have been associated with T&O events. Attached cyanobacteria have been implicated as sources of MIB or geosmin in many studies of lakes, reservoirs, or rivers (Burlingame et al. 1986;

Sugiura et al. 1998; Watson & Ridal 2004; Baker et al. 2006). Consequently, decreases in phytoplanktonic biomass (such as might be the aim of nutrient reduction strategies) could have the unintended consequence of increasing the available substrate for the main culprits of T&O episodes in these reservoirs.

Cyanobacteria

The Cyanobacteria Workgroup concluded that the initiation of *Microcystis* blooms are probably not associated with changes in nutrient concentrations, the forms of the nutrients (e.g., ammonium) or the ratios of N to P in the Delta (Berg and Sutula 2015). Therefore, it is unlikely that nutrient control will have an effect on limiting bloom initiations of cyanoHABs, such as *Microcystis.* However, the Workgroup concluded that nutrient reduction might limit bloom duration, intensity, and possibly geographic extent. In order to achieve these changes nutrients would likely need to be managed to bring their concentrations down to a level that was limiting to cyanobacteria growth.

Macrophytes

The Macrophyte Workgroup determined that, due to the inconclusive connection between nutrient concentrations and macrophyte prevalence in the Delta, the effect that nutrient management will have on controlling invasive floating and submersed macrophytes is uncertain. Other management options identified by the Workgroup included mechanical, chemical, biological control, and integrated control methods, as well as barriers to protect sensitive areas. The group recommended additional studies to determine the best control mechanism (Boyer & Sutula 2015).

4.1.2 Harvesting (macrophytes)

The Macrophyte Workgroup found that mechanical removal is practiced in certain areas of the Delta, but may not always be effective and can exacerbate the problem if fragments of plants are created which serve as propagules which can seed new populations in distant locations of the Delta. Mechanical removal of *E. Densa* has occurred but caused distant populations to establish due to propagule formation (Anderson 2003; Spencer et al. 2006). Mechanical gathering of *E. Crassipes* has been effective in limited areas; however, the remaining shredded pieces of the plants either need to be removed which incurs a significant cost or, if left in place, will decompose thus re-mineralizing nutrients, lowering dissolved oxygen, and potentially seeding future populations through propagule generation (Greenfield et al. 2007).

A United States Department of Agriculture Agricultural Research Service (USDA-ARS) program investigated integrated control methods for both *E. densa* and *E. crassipes* and developed a mapping application to track development of problem populations in order to prioritize harvesting treatment locations. The tool is used to target nursery populations in the Delta that serve as sources for early season infestations (Brenda et al. 2015). Mechanical harvesting is also used in Clifton Court Forebay and O'Neill Forebay, and some sections of the aqueduct are scraped by dragging a large chain along the aqueduct lining.

4.1.3 Biological Control (macrophytes)

Biological control mechanisms can include introducing competitors or grazers to help control the population of invasive macrophytes. Certain species were introduced to the Delta in the early 1980s in an attempt to control *E. crassipes,* including the weevil, *Neochetina bruchi*, which became established, but did not result in any effective reduction of the *E. crassipes* population (Stewart et al. 1988). The Macrophyte Workgroup also detailed the ongoing introduction of the planthopper, *Megamelus scutellaris,* for *E. crassipes* control which is being managed by the USDA-ARS and the California Department of Food and Agriculture (CDFA) (Boyer and Sutula 2015). This organism has been shown to be effective in reducing the *E. crassipes* population in Florida.

4.1.4 Chemical Additions (e.g. copper sulfate, etc. for nuisance algal blooms, taste and odor episodes)

The primary mechanism for controlling algal growth in the Delta and various locations in the SWP is by application of copper sulfate or other copper products. In the SBA, copper sulfate has been applied every two to four weeks from March until October or November since 2011, depending upon water temperatures and algal conditions. The chemical application is effective in reducing total algal biomass to prevent filter clogging; however, even with the application biomass reaches concentrations high enough to affect filtering every summer (See **Section 2.2.1**). Copper products have not been used since 2006 in Clifton Court due to potential impacts on threatened and endangered species.

There are potential unintended negative consequences with using copper sulfate and other chemical additives to treat algal blooms. One study in a Minnesota Lake found short-term effects of dissolved oxygen depletion, rapid nutrient recycling, and release following death of a bloom, as well as occasional fish kills from oxygen depletions and copper toxicity. Long-term effects of nearly 60 years of treatment included copper accumulation in sediments, growth of copper-tolerant algal species, algal and fish population shifts, loss of macrophytes, and reductions in benthic macroinvertebrates (Hanson & Stefan, 1984).

5.0 Data Gaps

This section summarizes the knowledge gaps identified for the following topics:

- Nuisance Algal Blooms
    - Cyanobacteria
- Macrophytes

Literature reviews and data gap analyses have been performed to date by the Cyanobacteria and Macrophyte Workgroups. The results from that work have relevance to the concerns of drinking water purveyors regarding the impacts of cyanobacteria and macrophytes on their conveyance facilities and drinking water treatment plants. The literature reviews performed by the Cyanobacteria and Macrophyte Workgroups found a lack of information specific to the Delta, as well as what ecological factors in the Delta may be promoting primary productivity. To this end, each workgroup was only able to answer fully the first question posed to them:

- Provide a basic review of biological and ecological factors that influence the prevalence of cyanobacteria and the production of cyanotoxins (Cyanobacteria Workgroup).

- How does submersed and floating aquatic vegetation support or adversely affect the ecosystem services and related beneficial uses? (Macrophyte Workgroup).

Recommendations for the types of research and modeling that are needed to bridge existing data gaps are provided in **Section 6.0**.

5.1 PREVALENCE OF PROBLEMS IN THE DELTA AND DOWNSTREAM CONVEYANCE AND STORAGE FACILITIES

The prevalence of cyanoHABs in the Delta is not well documented, and prompted the Cyanobacteria Workgroup to recommend expanded surveillance monitoring to collect a comprehensive set of measurements that will assist a full evaluation of the risk to human health and aquatic life due to cyanotoxins, as well as to better understand the linkages of various factors or drivers (nutrients; temperature; high irradiance; flow as it relates to water clarity, residence time, and water column stratification; benthic grazing; and salinity) in promoting and maintaining cyanoHABs.

Similarly, the Macrophyte Workgroup found that knowledge regarding macrophyte growth and biomass trends in the Delta is lacking, and recommended expanded surveillance monitoring through remotely-sensed areal coverage and field-based measures to estimate biomass over time. Monitoring was also recommended to evaluate macrophyte species community composition over time. Similar to the data needs of those studying cyanobacteria, there is also a need to collect information regarding the effects of light, temperature, salinity, flow, substrate stability, chemical/mechanical control, and interspecies competition.

With respect to cyanoHABs in State and Federal conveyance and storage facilities, as discussed in **Section 2.0**, monitoring programs implemented by DWR and others have detected microcystin in

Barker Slough at the North Bay Aqueduct intake, Clifton Court Forebay, Banks Pumping Plant, Dyer Reservoir on the SBA, the Gianelli and Pacheco intakes in San Luis Reservoir, the O'Neill Forebay Outlet (Check 13) on the California Aqueduct; and in Pyramid Lake, Castaic Lake, Lake Perris, and Silverwood Lake in Southern California. The extent of monitoring performed by drinking water purveyors for cyanoHABs and various factors suspected of promoting blooms in their facilities is unknown, but expanded monitoring in the Delta and in conveyance and storage facilities would certainly help to expand the knowledge base to determine what management actions may be most helpful in controlling cyanoHABs and macrophytes.

5.2 SPATIAL AND SEASONAL OCCURRENCE OF PROBLEMS

Similar to the lack of knowledge regarding prevalence of cyanoHAB and macrophyte problems, both workgroups recommended expanded surveillance monitoring as a means to better characterize the spatial and seasonal occurrences of these problems. In general, cyanoHABs are warm season (summer and early fall) phenomena, both in the Delta and drinking water facilities. Due to the lack of comprehensive monitoring data in the Delta, a complete understanding of the spatial occurrence of cyanoHABs has yet to be developed.

Problems caused by *E. crassipes* and *E. densa* growth are most common in spring through fall when these macrophytes grow most rapidly. Both of these non-native macrophytes occur throughout the Delta, with their control by the California Department of Boating and Waterways linked to their impairment of navigable waters.

Again, the spatial and seasonal occurrence of cyanoHABs and macrophytes in drinking water facilities is unknown, but expanded monitoring in the Delta and in conveyance and storage facilities would certainly help to enhance the knowledge base that all stakeholders will rely upon to determine what management actions may be most helpful in controlling cyanoHAB and macrophyte growth.

5.3 EFFECTIVENESS OF ALTERNATIVE MANAGEMENT OPTIONS ON SPECIFIC PROBLEMS

Historically, control of macrophytes in the Delta and drinking water facilities has been accomplished through application of chemicals (primarily, copper sulfate) and mechanical harvesting. Control of algae in drinking water facilities has also been conducted through the application of copper sulfate. Alternative management options for the control of specific problems have not been attempted to any great degree, if at all. The control capabilities of various drivers as potential management options have yet to be evaluated. The research and modeling recommendations in the following section are intended to develop information regarding the factors necessary to identify potential management actions that can be taken to limit cyanoHABs and the spread and growth of macrophytes. It remains to be seen whether some or all management actions that could act to limit cyanoHABs and the spread and growth of macrophytes in the Delta could be used in drinking water facilities.

5.4 MONITORING DATA AND PROCESS COEFFICIENTS/PARAMETERS REQUIRED FOR ECOSYSTEM AND MANAGEMENT MODELS

The literature reviews conducted by the Cyanobacteria and Macrophyte Workgroups identified multiple areas where ambient monitoring data and process coefficients/parameters are lacking for the Delta, and will need to be developed through future monitoring and research efforts to best inform the ecosystem model(s) recommended for development. In addition to a suite of environmental parameters pinpointed for monitoring, cyanobacteria and macrophyte growth rates, macrophyte turnover rates, nutrient uptake, transformation and flux rates, water column mixing rates, and flushing rates (causing washout) were identified as being necessary to support ecosystem model development (Berg and Sutula 2015; Boyer and Sutula 2015).

6.0 Recommendations for Monitoring, Research and Modeling Priorities

6.1 PROBLEM DEFINITION

Multiple knowledge gaps exist in our understanding of the importance of nutrient processes and drivers thought to impact cyanobacteria, cyanotoxins, taste and odor problems, macrophytes, and other problems impacting drinking water uses in the Delta and in areas served by Delta water supplies. In order to develop the knowledge necessary to bridge the gaps in our understanding of these problems, additional monitoring, research and modeling is needed, both in the Delta and in downstream conveyance and storage facilities. Future research needs to be targeted to answer questions related to the importance of nutrients in combination with other hydrologic, physical, biological, and chemical factors in the control of the identified problems. The development of new information will provide a more complete understanding of the most appropriate management actions.

Both the Cyanobacteria and Macrophyte Workgroups proposed a number of major science recommendations given the data gaps that were identified. Both workgroups identified the need for additional monitoring in the Delta (Berg and Sutula 2015; Boyer and Sutula 2015). The Cyanobacteria Workgroup recommended the development of an ecosystem model of primary productivity to further inform hypotheses on factors controlling primary productivity and the future risk of cyanoHABs (Berg and Sutula 2015). The Macrophyte Workgroup recommended the development of a biogeochemical model of the Delta focused on nutrient and organic carbon fate and transport. The Macrophyte Workgroup also recommended a review of current and potential future control strategies for invasive macrophytes in the Delta that includes consideration of barriers to reduce the movement of vegetation into sensitive areas or those with heavy human use (Boyer and Sutula 2015). These major science recommendations should be supportive of developing initial information useful to addressing drinking water concerns for cyanobacteria and macrophytes.

6.2 ROLE OF NUTRIENTS IN COMBINATION WITH OTHER FACTORS

Cyanobacteria – Cyanotoxins

Much remains unknown with regard to the role nutrients play in influencing the magnitude and frequency of cyanobacteria blooms in the Delta and downstream conveyance and storage facilities. A shift in Delta phytoplankton community composition in recent years to include a larger percentage of cyanobacteria, both toxin-producing and non-toxin-producing strains, currently affects drinking water due to taste and odor problems and the presence of cyanotoxins. We currently lack information about whether an attainable reduction in nutrient concentrations in the Delta could reduce cyanobacteria blooms and associated cyanotoxin production within the Delta and downstream. Gaps in our understanding of the role nutrients play regarding cyanobacteria blooms in the Delta and downstream facilities are associated with our lack of understanding of the roles of other drivers, including: temperature; irradiance; flow as it relates to water clarity, residence time, and water column stratification; benthic grazing; and salinity.

Expanded system-wide surveillance monitoring in the Delta and downstream conveyance and storage facilities is recommended to develop greater spatial and temporal knowledge in the following areas:

- Identification of locations, extent, timing and duration where cyanobacteria blooms occur in the Delta and in downstream conveyance and storage facilities. Determination of the risk that cyanotoxin concentrations in the Delta and in south of Delta reservoirs and conveyance structures pose to drinking water due to physical proximity.

- Measurement of environmental factors (e.g., nutrients, temperature, irradiance, turbidity, flow, and salinity) that co-occur with different stages of bloom development to gain an understanding of the presence and magnitude of the drivers that influence bloom initiation, bloom magnitude, and cyanotoxin production. Monitoring should include instantaneous, annual, and inter-annual measurements.

Field and laboratory studies are also recommended to provide insight to whether the drivers that influence cyanobacteria blooms can be managed, and what effect the control of these factors has on cyanobacteria bloom magnitude and duration. Studies are recommended in the following areas:

- Initiation of laboratory and field studies during blooms to determine whether modification of nutrient concentrations can reduce the magnitude and frequency of cyanobacteria blooms (and associated toxin levels) in the Delta and downstream facilities.

- Investigation of the effects that other key factors (e.g., temperature, turbidity, mixing rates, and flow (causing wash-out)) have on bloom formation and attenuation.

Cyanobacteria – Taste and Odors

The role of nutrient concentrations in influencing the occurrence, magnitude, and duration of taste and odor episodes in the Delta and in downstream conveyance facilities and reservoirs is not well understood. We currently lack information about the forms and concentrations of nutrients that influence the growth of the species of benthic and planktonic cyanobacteria that cause taste and odor problems. Finally, gaps exist in our understanding of the roles of other factors on the occurrence and duration of these episodes, including temperature; light levels; water clarity; water residence time; water stratification; and other factors that influence algal community composition and the production of compounds responsible for taste and odor problems.

Expanded surveillance monitoring, modeling, and analysis of available data in the Delta and in downstream conveyance and storage facilities is recommended, as follows:

- Performance of microbial surveys and/or species studies to expand our knowledge of the prevalence of problematic benthic and planktonic cyanobacteria species, the drivers that promote their growth, and what their potential contribution to taste and odor episodes might be. Assess impacts of benthic species as compared to the better studied planktonic cyanobacteria species.

- Synthesize available data to identify spatial and temporal occurrence of taste and odor problems in the water supply conveyance facilities downstream of the Delta. Determine if modifications to monitoring, such as focused monitoring during blooms, would enhance the quality of the data and understanding of bloom distributions in these facilities.

- Perform monitoring and modeling to understand the magnitude and importance of sources of nitrogen and phosphorus in the Delta, with consideration for Delta hydrodynamics, variable Delta flow conditions, nutrient transformations, tributary inputs, sediment flux, etc. as part of an assessment of the role of nutrients in taste and odor problem occurrence and control. This effort should include analysis of the DWR MWQI enhanced monitoring for N and P data that was collected to provide inputs to the DSM2 water quality model and analysis of historical MWQI monitoring of Delta Island discharges.

Field and laboratory studies are also recommended to provide insight into the possible management of taste and odor problems in the Delta and in downstream facilities. Studies are recommended in the following areas:

- Measurement of environmental factors (e.g., nutrients, temperature, irradiance, turbidity, flow, and salinity) that co-occur with different stages of taste and odor-producing cyanobacteria bloom development in downstream water supply facilities. Investigation of the effects that turbidity, mixing rates, and flow (causing wash-out) have on taste and odor episode initiation and attenuation.

- *In situ* studies in reservoirs and conveyance facilities to isolate the incremental impact of changes in nutrient water column concentrations on proliferation of planktonic and benthic cyanobacteria species responsible for taste and odor episodes. Determination of the effect that ambient nutrient concentration reductions will have on taste and odor occurrences downstream of Delta in reservoirs and conveyance structures. The use of “Limno corrals[6]” was suggested as one idea. Note that a limitation in the use of “limno corrals” is that they reduce turbulence and quickly change the light climate.

Macrophytes

Similarities exist between cyanobacteria and macrophyte blooms with regard to our lack of knowledge about the extent of the macrophyte problem in the Delta and downstream conveyance and storage facilities. Questions also exist regarding the degradation of water quality and impacts to beneficial uses, drivers that are most influential in promoting the growth of invasive and native

[6] A limno corral (or limnocorral, limno-corral) is an enclosure that extends from the water surface to the sediment, where it is anchored, that allows a defined volume of water to be physically separated from the surrounding waterbody.

macrophytes, and which of these drivers can be controlled through management actions. As with cyanobacteria, the role that nutrients (via forms, concentrations, and timing) play in stimulating macrophyte growth in the Delta and downstream – especially, as it influences the growth of invasive, non-native species, such *as E. crassipes* and *E. densa* – is not completely understood, nor is the impact that other factors (light, temperature, salinity, flow, substrate stability, chemical/mechanical control, and interspecies competition) have on the spread and growth of macrophytes in the Delta and downstream conveyance and storage facilities. Of greatest interest to drinking water managers is the ability to control the spread and growth of macrophytes in reservoirs and conveyance structures in areas where such growth clogs pumps and filters and impedes flows. Expanding surveillance monitoring in the Delta and downstream facilities is recommended to develop greater knowledge in the following areas:

- Determination of the extent of invasive aquatic plant blooms in the Delta and in downstream conveyance and storage facilities, as well as the detection of new invasions through implementation of a comprehensive multi-year monitoring program.

- Measurement of environmental factors and physical conditions (e.g., nutrients, temperature, light, turbidity, flow, and salinity) that co-occur with native and non-native macrophytes to gain an understanding of the presence and magnitude of factors that co-occur with and influence macrophyte growth in the Delta and in downstream facilities. Monitoring should include instantaneous, annual, and interannual measurements.

Field and laboratory studies are also recommended to provide insight into the management of drivers that influence macrophyte growth, and to what effect the control of these factors has on macrophyte growth. Studies are recommended in the following areas:

- Determination of field methods for rapidly assessing *in situ* nutrient limitation of macrophytes in the Delta and in downstream facilities. Conduct laboratory culture studies to evaluate growth rate as a function of ambient nutrient concentrations in water and sediment. Analyze tissue nutrient concentrations to determine the relationship between tissue growth, nutrient uptake rates, and nutrient concentrations. Confirm relationships in field trials.

- If nutrient reductions are shown to sufficiently limit macrophyte growth and such reductions can be achieved through the control of point sources, use of mesocosm studies to determine if mechanical and chemical control of macrophytes is enhanced by nutrient reductions.

6.3 MODELING TOOLS AND SCENARIOS

Development of Modeling Tools

The complex nature of the Delta ecosystem and the range of questions for which answers are sought regarding the factors that influence phytoplankton, cyanobacteria, and macrophyte growth require the ability to characterize multiple processes in the form of a model or models. The collection and analysis of empirical data alone will not provide the ability to test future Delta management scenarios. The Modeling Science Workgroup identified four reasons why models will provide valuable tools for managing water quality in the Delta (Trowbridge et al., 2015):

- The Delta is too complex to comprehensively understand without models. Empirical data collection cannot be achieved at the spatial and temporal scales necessary to fully characterize and test potential management actions.
- Models can provide insight into the ecological significance of nutrient changes from an ecosystem perspective.
- Models can efficiently allow stakeholders to develop and assess management scenarios to characterize the effect of nutrients over a range of conditions.
- Models can be effective for communicating important information to stakeholders, regulators, and resource managers, leading to a common understanding of complex systems.

Future modeling efforts must consider a suite of important processes that operate simultaneously in the Delta, including hydrodynamics, nutrient concentrations, other water quality conditions, primary productivity, benthic and pelagic grazing, sediment transport, and other cyanobacteria and macrophyte-related processes. A consideration of these factors and their interactions will also provide insight into how a change in a given driver or drivers could affect cyanobacteria and macrophyte blooms in the Delta. Through the use of modeling scenarios and sensitivity analysis, it will be possible to gain an understanding of how changes in nutrient concentrations and forms, as well as other drivers, may impact drinking water problems associated with cyanobacteria and macrophytes.

Modeling Scenarios

The development of modeling tools to answer nutrient management questions is planned to occur in two phases. The initial phase is anticipated to be completed by 2020 or 2021. This timeframe coincides with expected changes in the discharge of nutrients into the Lower Sacramento River from the Sacramento Regional Wastewater Treatment Plant (SRWTP), the discharge of nutrients from the Cities of Modesto and Turlock into the Lower San Joaquin River due to the redirection of their flows to the Delta Mendota Canal, and the discharge of nutrients from the City of Stockton wastewater treatment plant into the San Joaquin River due to the implementation of new nutrient removal processes (LWA 2017). Future modeling of the Delta ecosystem will need to consider a baseline condition with respect to nutrient inputs from the Lower Sacramento River, the Lower San Joaquin River, and the San Joaquin River that varies from current conditions. Modeling efforts will also need to consider a multitude of physical and biological changes expected to occur if the projects proposed as part of the Bay Delta Conservation Plan are implemented. Future expanded surveillance monitoring and research coming from implementation of the Delta Nutrient Research Plan will provide additional empirical data and a refined mechanistic understanding of Delta processes that will need to be incorporated into modeling tools.

Once information gathering, research, and model development efforts are sufficient to begin assessing changes in baseline conditions through specific management actions, it will be important that modeling scenarios appropriately consider future changes in climate, Delta hydrology, wetland restoration, and nutrient loading. It will be necessary to develop modeling scenarios that consider planned, possible, and outer boundary changes that can be produced through varying levels of nutrient load management and system management.

6.4 EFFECTIVENESS OF MANAGEMENT

As model development matures, and modeling scenarios are created that show projected outcomes of various management actions, it will be important to consider the following aspects of such management actions:

- Can reductions in nutrient loads alone, or in combination with other management efforts, limit the growth and proliferation of cyanobacteria and non-native macrophytes and, thereby, prevent or significantly reduce taste and odor, cyanotoxin and/or macrophyte problems in the Delta and in downstream storage and conveyance facilities?

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Appendix A

A.1 THE STATE WATER PROJECT

The SWP extends from the mountains of Plumas County in the Feather River watershed to Lake Perris in Riverside County. Water from the north Delta is pumped into the North Bay Aqueduct (NBA) at the Barker Slough Pumping Plant, as shown in **Figure A. 1**. Barker Slough is a tidally influenced dead-end slough which is tributary to Lindsey Slough. Lindsey Slough is tributary to the Sacramento River. The pumping plant draws water from both the upstream Barker Slough watershed and from the Sacramento River, via Lindsey Slough. Other local sloughs may also contribute water to the NBA. The NBA pipeline extends 21 miles from Barker Slough to Cordelia Forebay (Cordelia) and Pumping Plant, and then 7 miles to its terminus at two 5-million gallon terminal tanks. The NBA serves as a municipal water supply source for a number of municipalities in Solano and Napa counties. The Solano County Water Agency (SCWA) and the Napa County Flood Control and Water Conservation District (Napa County) are wholesale buyers of water from the SWP. SCWA delivers water to Travis Air Force Base and the cities of Benicia, Fairfield, Vacaville, and Vallejo. Napa County delivers water to the cities of Napa, and American Canyon.

In the southern Delta, water enters SWP facilities at Clifton Court Forebay (Clifton Court), and flows across the forebay about 3 miles to the H.O. Banks Delta Pumping Plant (Banks), from which the water flows southward in the Governor Edmund G. Brown California Aqueduct (California Aqueduct). Water is diverted into the South Bay Aqueduct (SBA) at Bethany Reservoir, 1.2 miles downstream from Banks. **Figure A. 2** is a map showing the locations of the SBA facilities. The SBA consists of about 11 miles of open aqueduct followed by about 34 miles of pipeline and tunnel serving East and South Bay communities through the Zone 7 Water Agency of the Alameda County Flood Control and Water Conservation District (Zone 7 Water Agency), Alameda County Water District (ACWD), and Santa Clara Valley Water District (SCVWD). Water from the SBA can be pumped into or released from Lake Del Valle at the Del Valle Pumping Plant. Lake Del Valle has a nominal capacity of 77,110 acre-feet, with 40,000 acre-feet for water supply. The terminus of the SBA is the Santa Clara Terminal Reservoir (Terminal Tank).

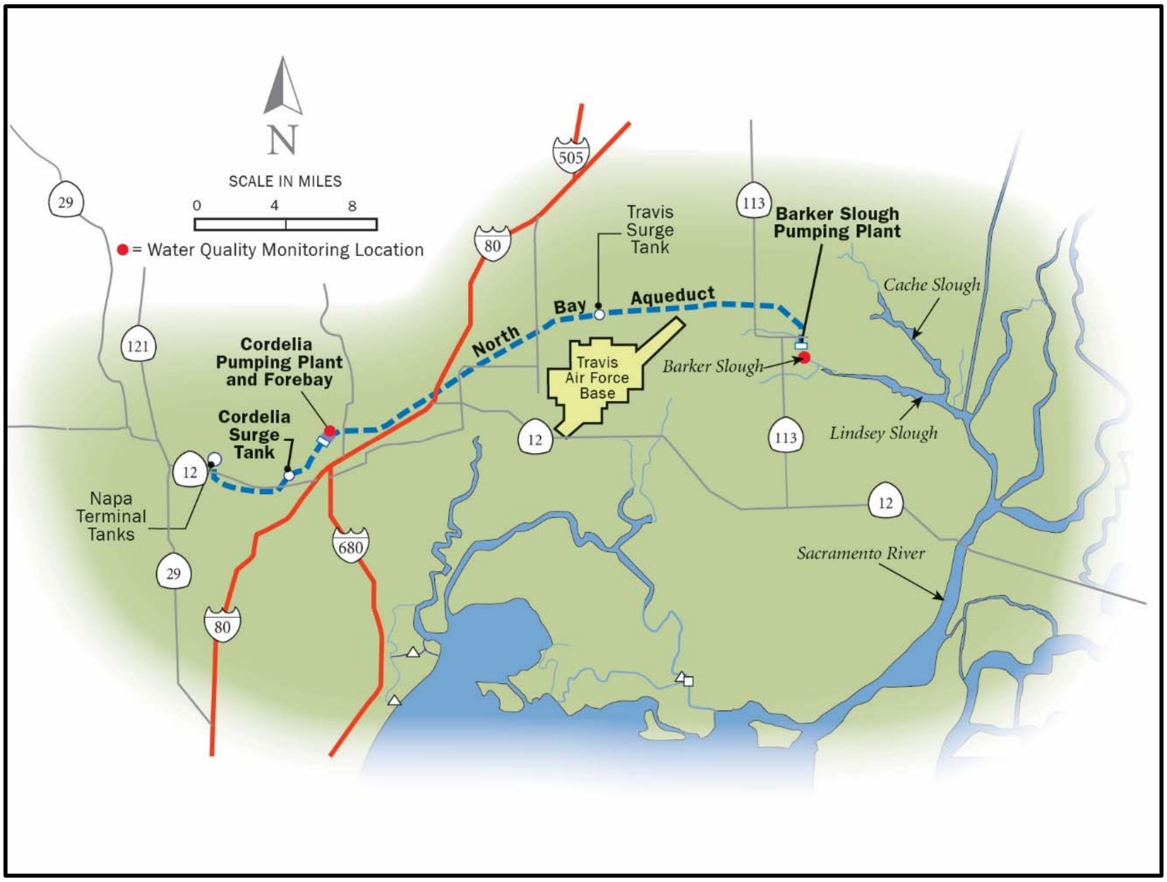

Figure A. 1. The North Bay Aqueduct

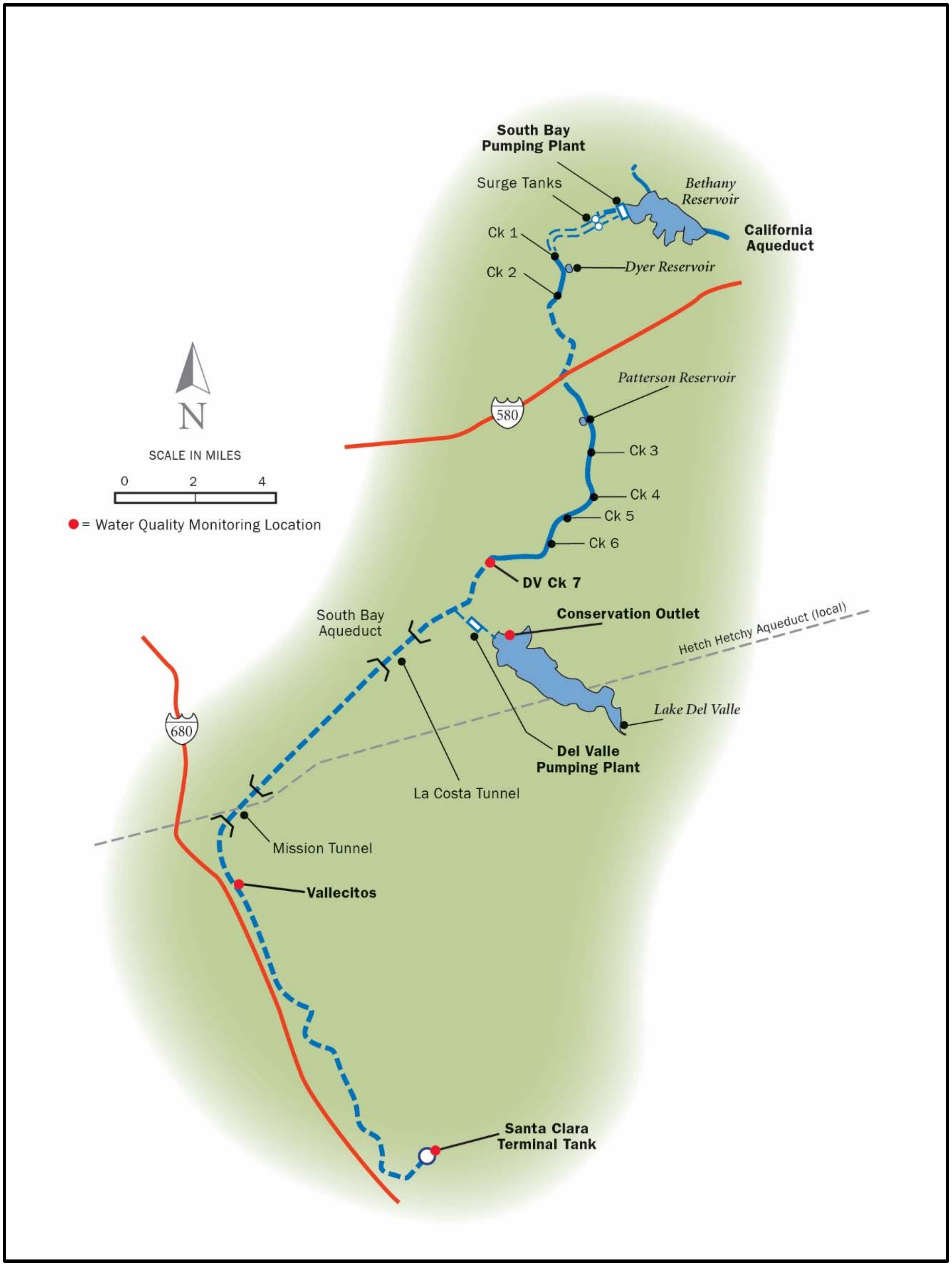

Figure A. 2. The South Bay Aqueduct

From Bethany Reservoir, water flows in the California Aqueduct about 59 miles to O'Neill Forebay, as shown in **Figure A. 3**. The forebay is the start of the San Luis Joint-Use Facilities, which serve both SWP and federal Central Valley Project (CVP) customers. CVP water is pumped into O'Neill Forebay from the Delta-Mendota Canal (DMC). The DMC conveys water from the C.W. "Bill" Jones Pumping Plant (Jones) to, and beyond, O'Neill Forebay. The O'Neill Pump-Generation Plant (O'Neill Intake), located on the northeast side of O'Neill Forebay, enables water to flow between the forebay and the DMC. San Luis Reservoir is connected to O'Neill Forebay through an intake channel located on the southwest side of the forebay. **Figure A. 4** is a location map that shows these features. Water in O'Neill Forebay can be pumped into San Luis Reservoir by the William R. Gianelli Pumping-Generating Plant (Gianelli) or released from the reservoir to the forebay to generate power. San Luis Reservoir, with a capacity of 2.03 million acre-feet, is jointly owned by the SWP and CVP, with 1.06 million acre-feet being the state's share. An intake on the west side of the reservoir provides drinking water supplies to SCVWD. Water enters SCVWD facilities at Pacheco Pumping Plant (Pacheco), from which it is pumped by tunnel and pipeline to water treatment and ground water recharge facilities in the Santa Clara Valley.

Water released from the reservoir co-mingles in O'Neill Forebay with water delivered to the forebay by the California Aqueduct and the DMC, and exits the forebay at O'Neill Forebay Outlet, located on the southeast side of the forebay. O'Neill Forebay Outlet is the inception of the San Luis Canal reach of the California Aqueduct, as shown in **Figure A. 5**. The San Luis Canal extends about 100 miles to Check 21, near Kettleman City. The San Luis Canal reach of the aqueduct serves mostly agricultural CVP customers and conveys SWP waters to points south. Unlike the remainder of the California Aqueduct, which was constructed by the state, the San Luis Canal reach was federally constructed and was designed to allow drainage from adjacent land to enter the aqueduct. Local streams that run eastward from the Coastal Range Mountains bisect the aqueduct at various points. During storms, water from some of these streams enters the aqueduct. This is generally not the case for the other reaches of the aqueduct.

The junction with the Coastal Branch of the aqueduct is located 185 miles downstream of Banks and about 12 miles south of Check 21. The Coastal Branch provides drinking water supplies to central California coastal communities through the Central Coast Water Authority (CCWA) and the San Luis Obispo County Flood Control and Water Conservation District. **Figure A. 6** is a map showing locations of these facilities. The Coastal Branch is 115 miles long; the first 15 miles are open aqueduct and the remainder is a pipeline.

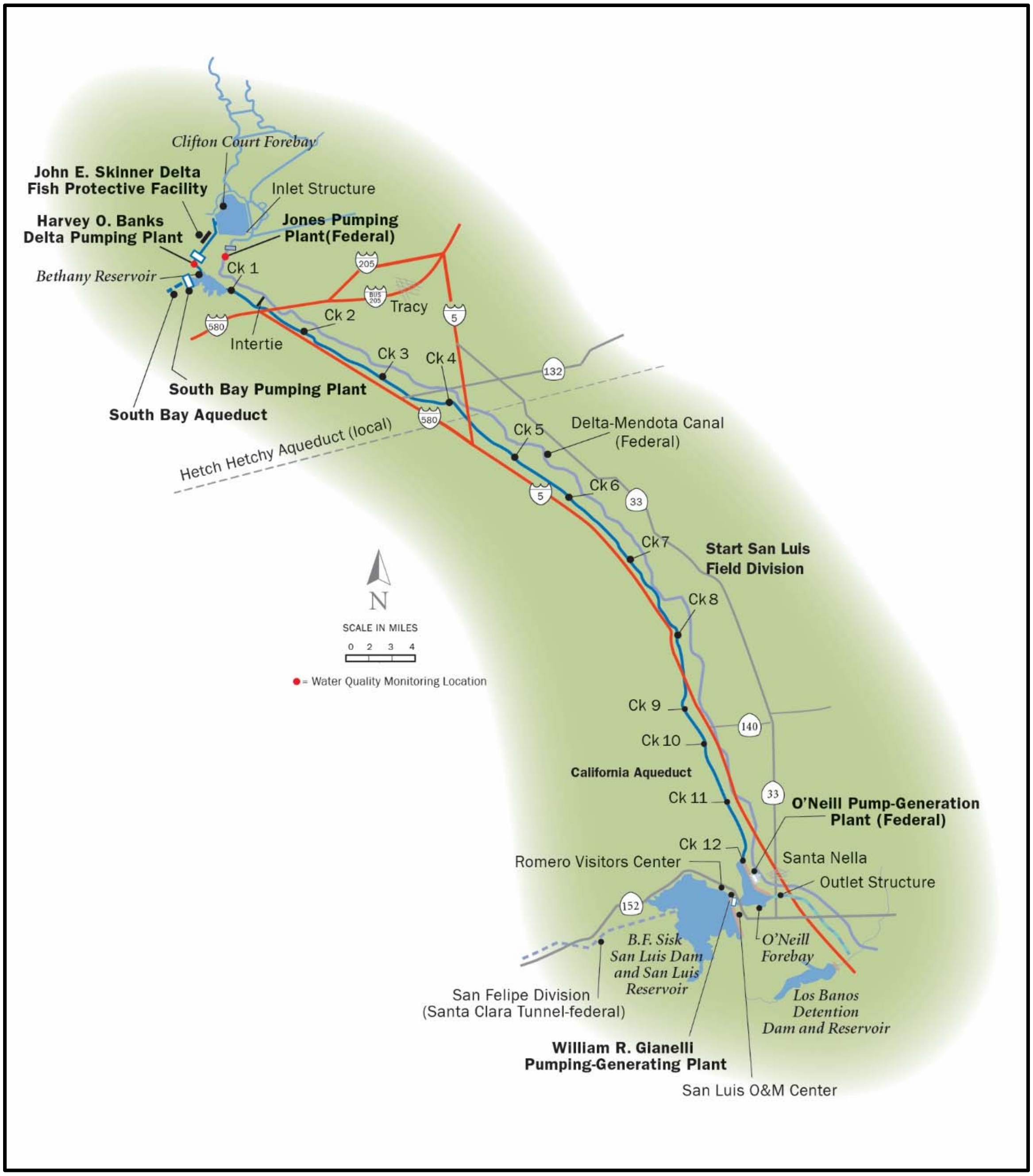

Figure A. 3. California Aqueduct between Banks Pumping Plant and San Luis Reservoir

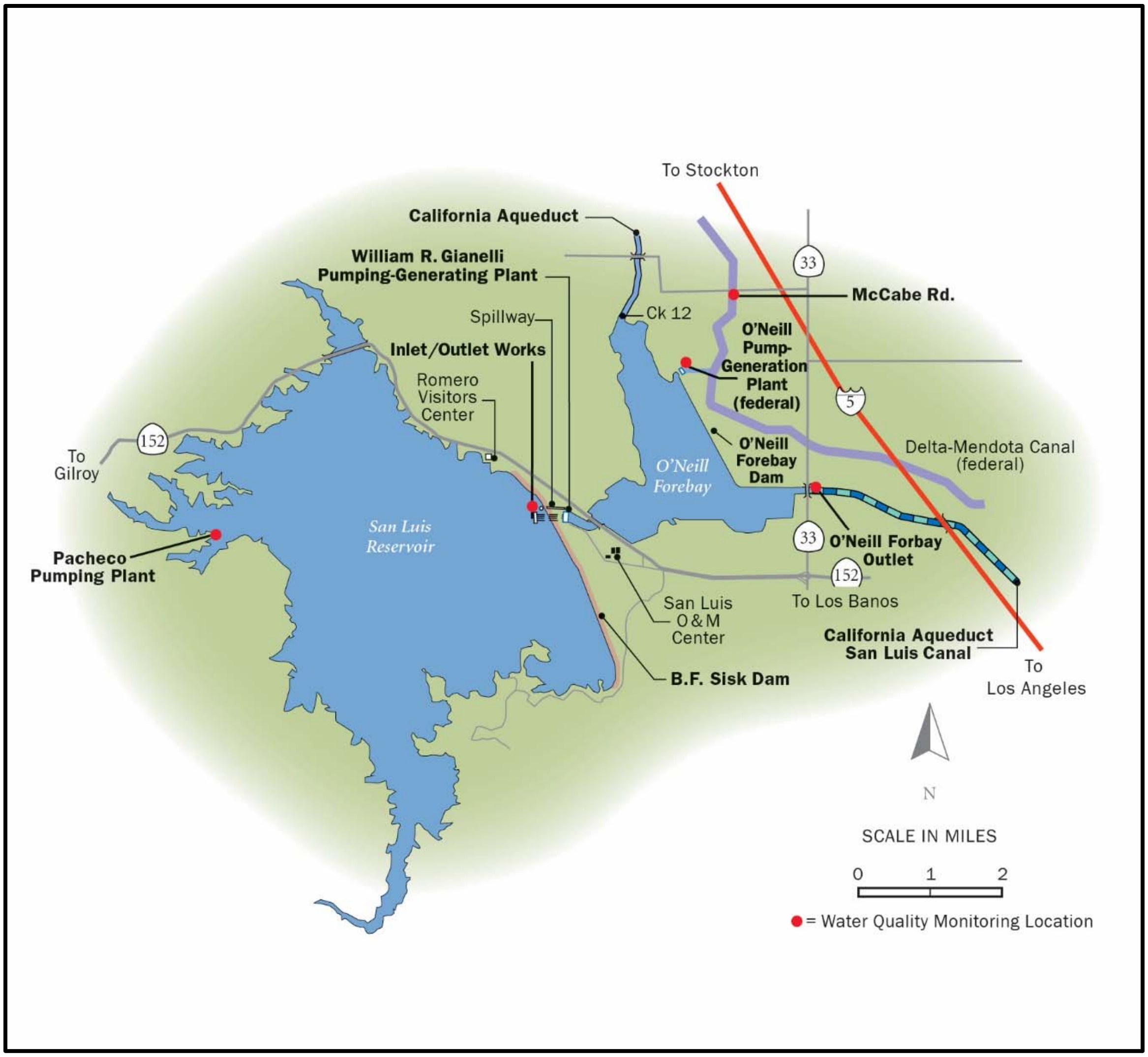

Figure A. 4. O'Neill Forebay and San Luis Reservoir

Figure A. 5. San Luis Canal Reach of the California Aqueduct

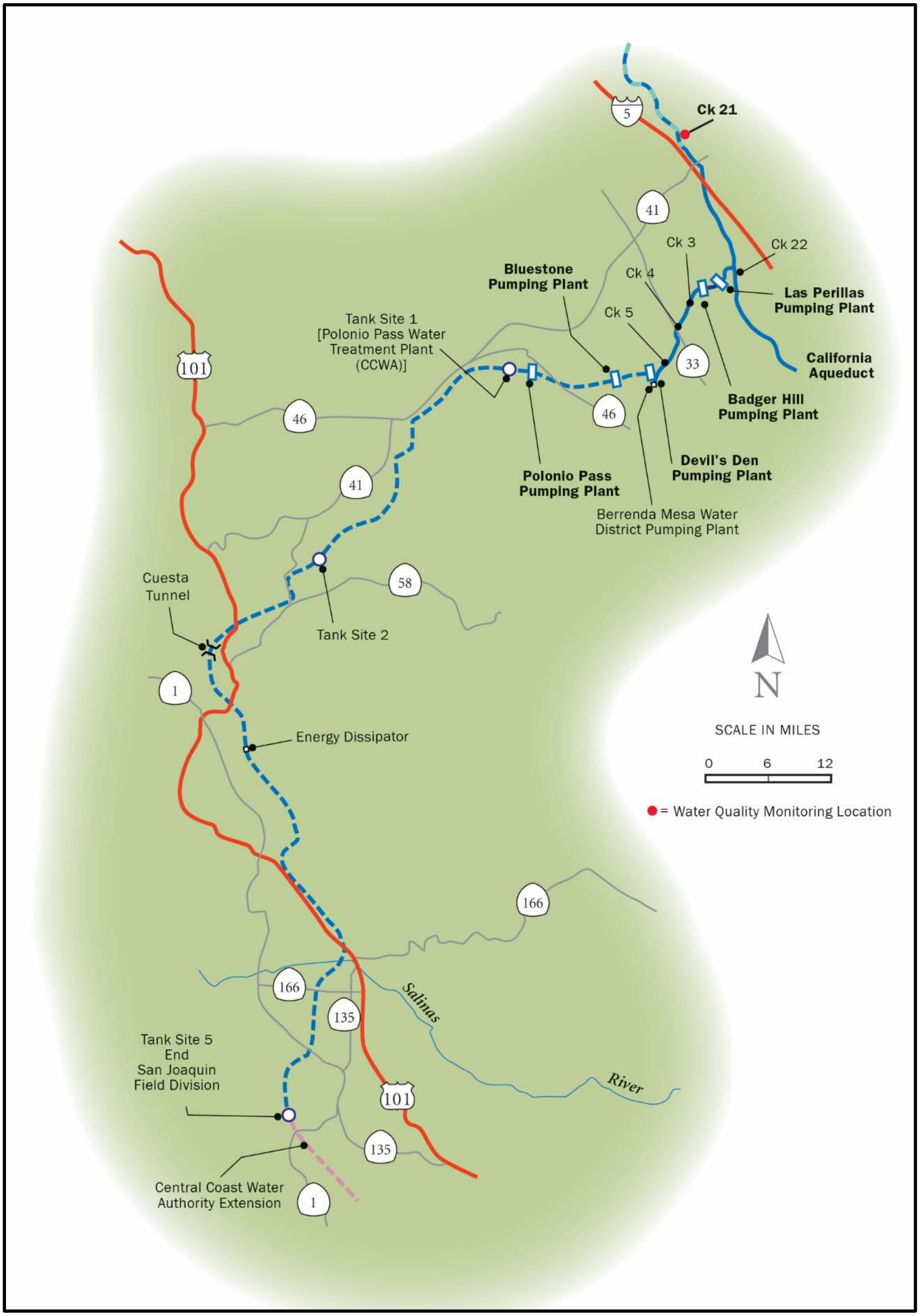

Figure A. 6 The Coastal Branch of the California Aqueduct

From the junction with the Coastal Branch, water continues southward in the California Aqueduct as shown in **Figure A. 7**, providing water to both agricultural and drinking water customers in the service area of Kern County Water Agency (KCWA). The Kern River Intertie is designed to permit Kern River water to enter the aqueduct during periods of high flow. Due to increasingly scarce California water supplies, the SWP is used to convey both surface water and groundwater acquired through transfers and exchanges among local agencies. Most of the non-Project water enters the aqueduct between Check 21 and Check 41.

Edmonston Pumping Plant is at the northern foot of the Tehachapi Mountains. This facility lifts SWP water about 2000 feet by multi-stage pumps through tunnels to Check 41, located on the south side of the Tehachapi Mountains. About a mile downstream, the California Aqueduct divides into the West and East Branches. The West Branch flows 14 miles to Pyramid Lake, then another 17 miles to the outlet of Castaic Lake, the drinking water supply intake of the Metropolitan Water District of Southern California (MWDSC) and Castaic Lake Water Agency (CLWA). Pyramid Lake has a capacity of 171,200 acre-feet and Castaic Lake has a capacity of 323,700 acre-feet. **Figure A. 8** is a map showing locations of West Branch features.

From the bifurcation of the East and West Branches, water flows in the East Branch to high desert communities in the Antelope Valley served by the Antelope Valley East Kern Water Agency (AVEK) and the Palmdale Water District (Palmdale). Figure A. 9 is a map showing East Branch features. As in the southern San Joaquin Valley, groundwater from the local area has occasionally been allowed into the aqueduct to alleviate drought emergencies. On the East Branch near Hesperia, surface water drainage from part of that city enters the aqueduct during storm events. The inlet to Silverwood Lake is located on the north side of the reservoir near Check 66. Silverwood Lake has a capacity of 74,970 acre-feet and serves as a drinking water supply for the Crestline-Lake Arrowhead Water District (CLAWA). Water is drawn from the south side of the reservoir and flows through the Devil Canyon Powerplant to the two Devil Canyon afterbays. Drinking water supplies are delivered to MWDSC and San Bernardino Valley Municipal Water District from this point, and water is also transported via the Santa Ana Pipeline to Lake Perris, which is the terminus of the East Branch. MWDSC routinely takes a small amount of water from Lake Perris.

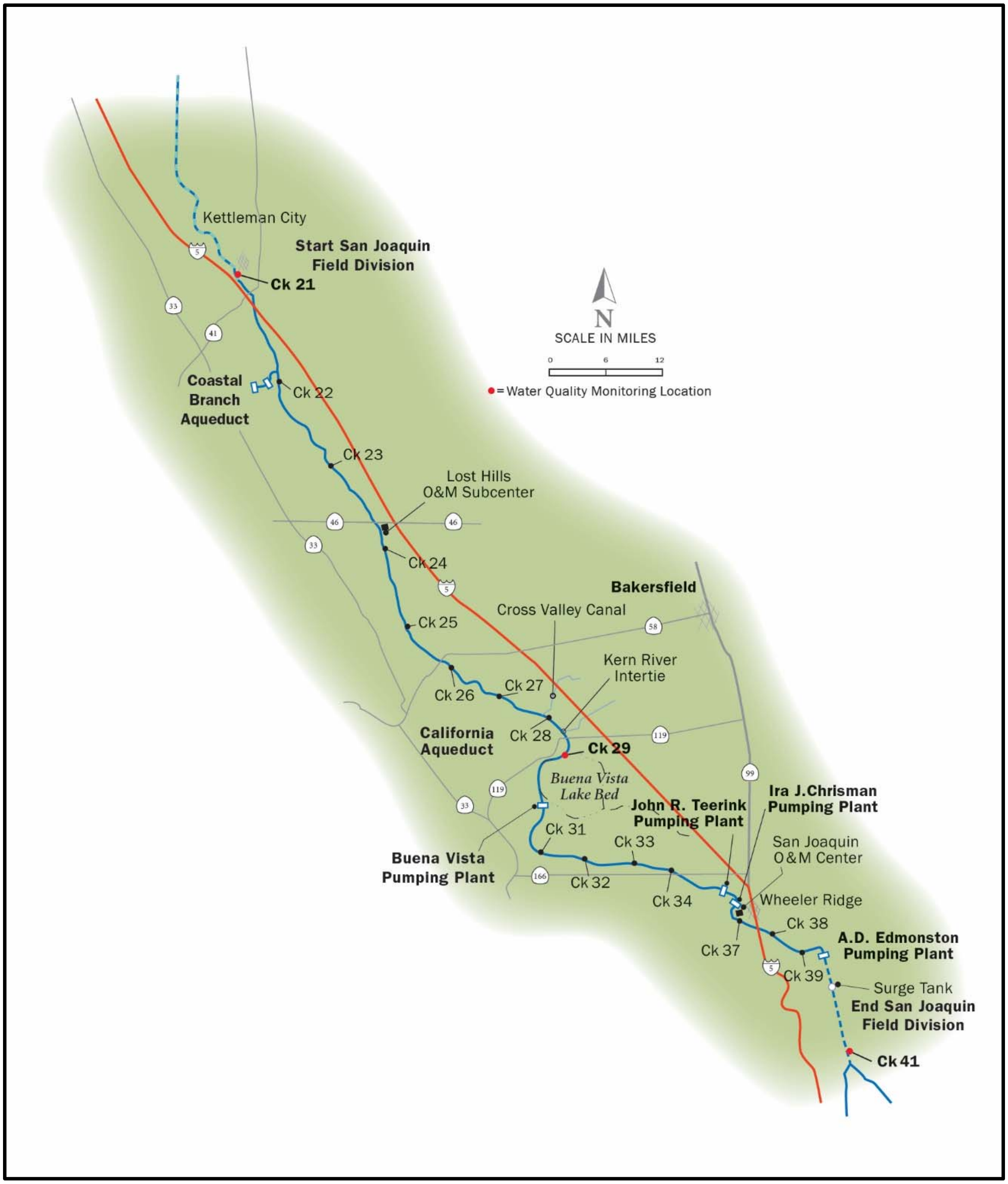

Figure A. 7 California Aqueduct between Check 21 and Check 41

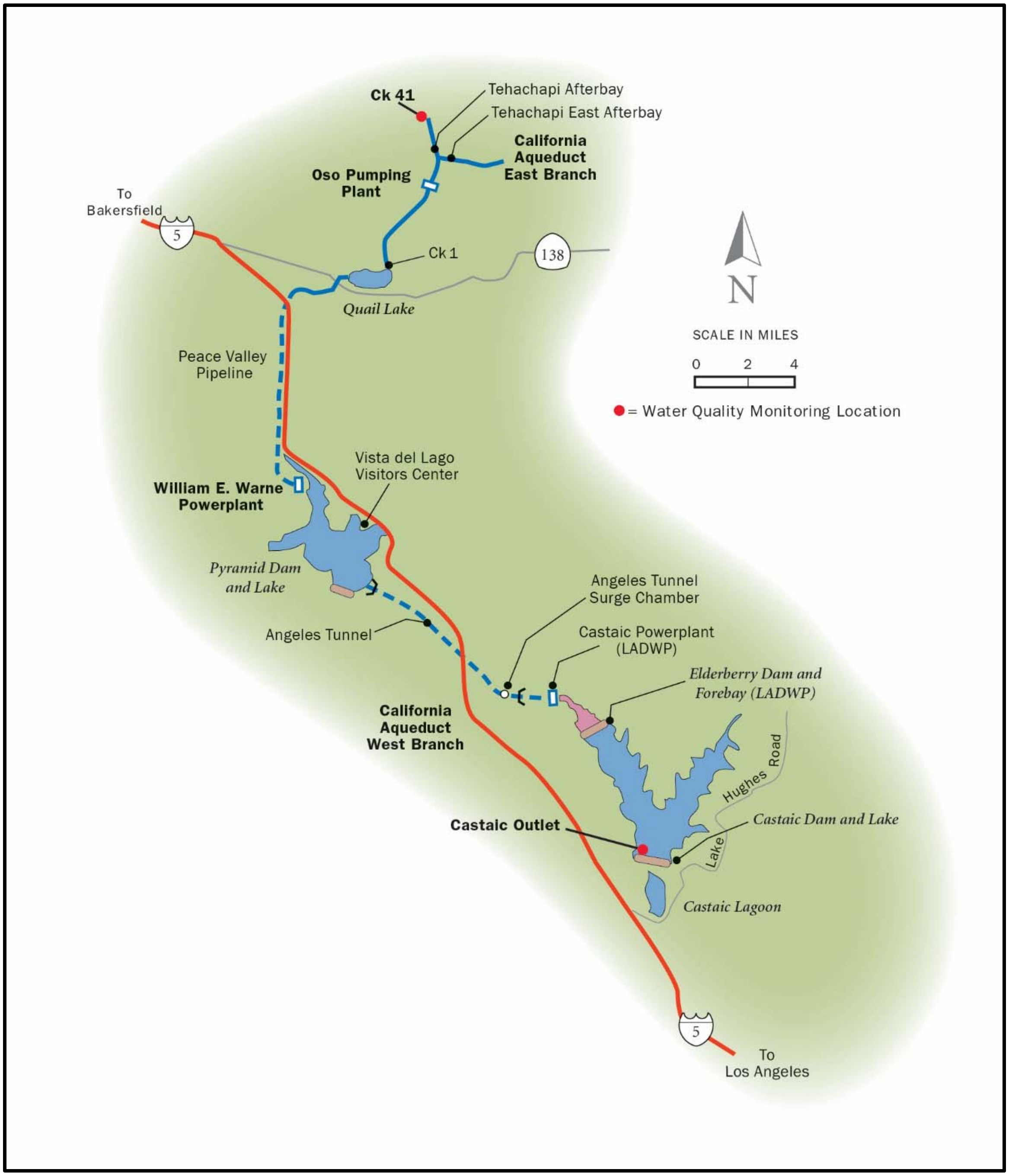

Figure A. 8 The West Branch of the California Aqueduct

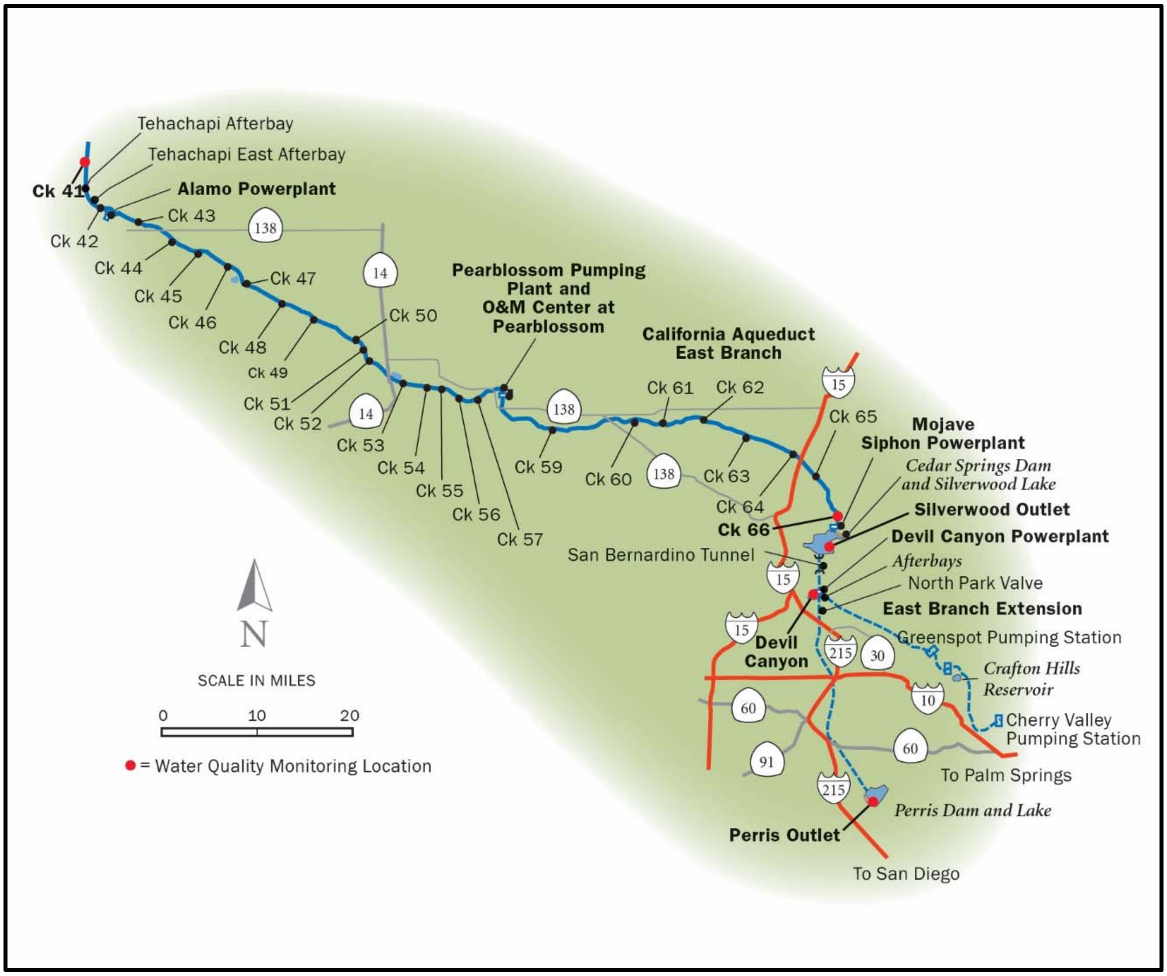

Figure A. 9 The East Branch of the California Aqueduct

A.2 NUTRIENT CONCENTRATIONS IN THE DELTA AND SWP

Nutrient concentrations show considerable seasonal and spatial variability. **Figures A.10 to A.17** show the variability in nutrient concentrations at Hood, Vernalis, Barker Slough, and Banks as well as the annual and interannual variability. **Figures A.18 and A.19** show data which has been collected at a number of locations along the California Aqueduct from 2004 to 2010.

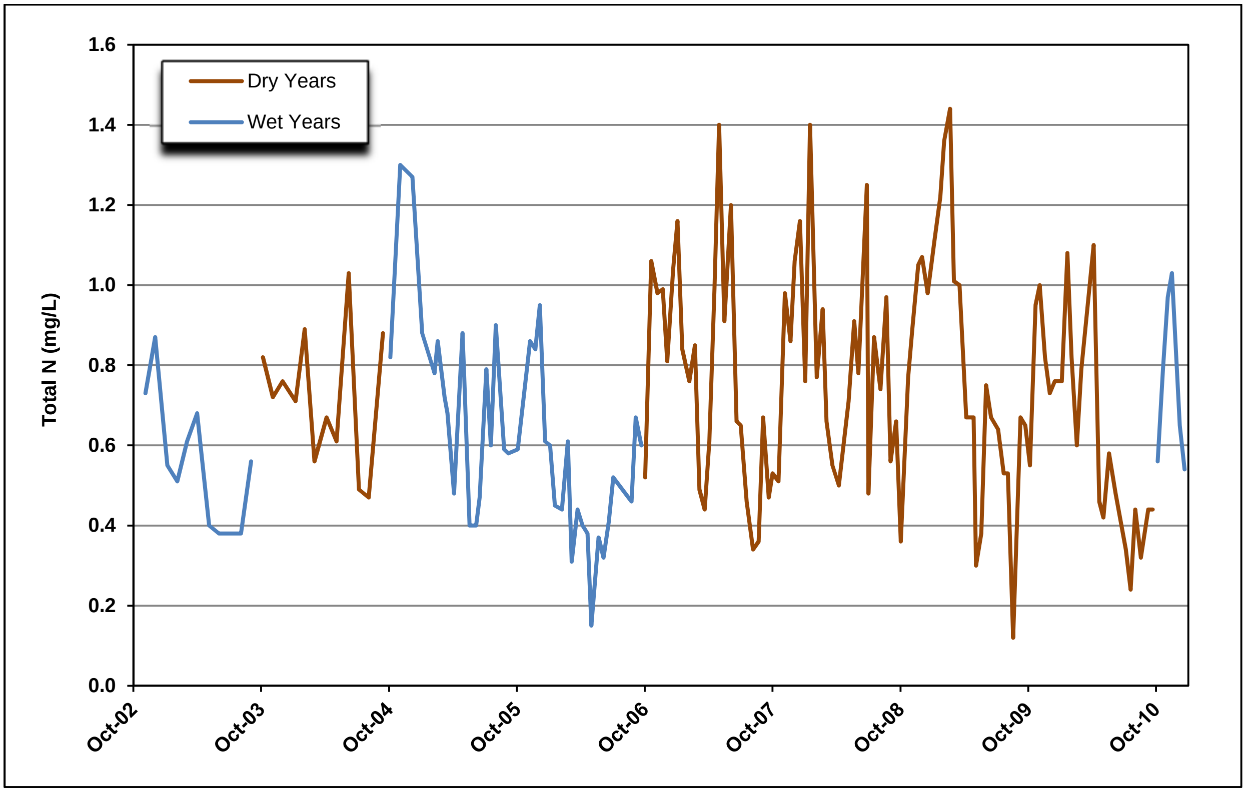

Figure A. 10. Total N Concentrations at Hood

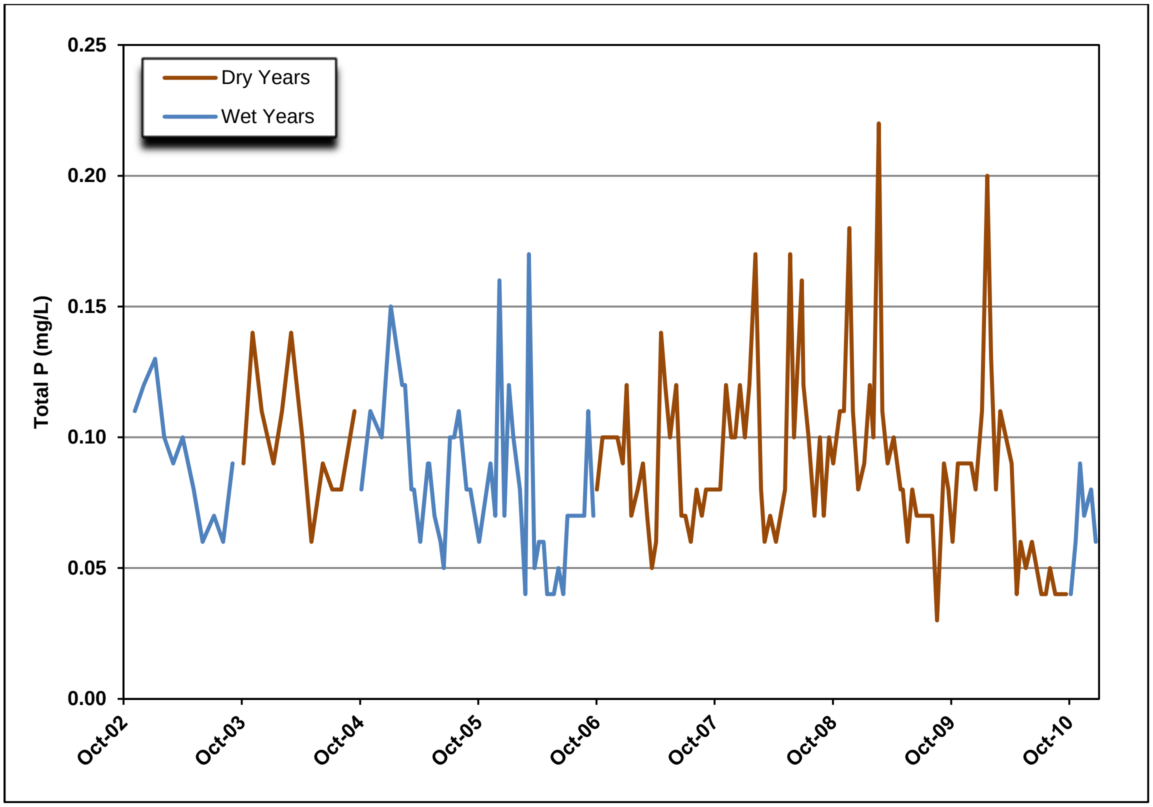

Figure A. 11. Total P Concentrations at Hood

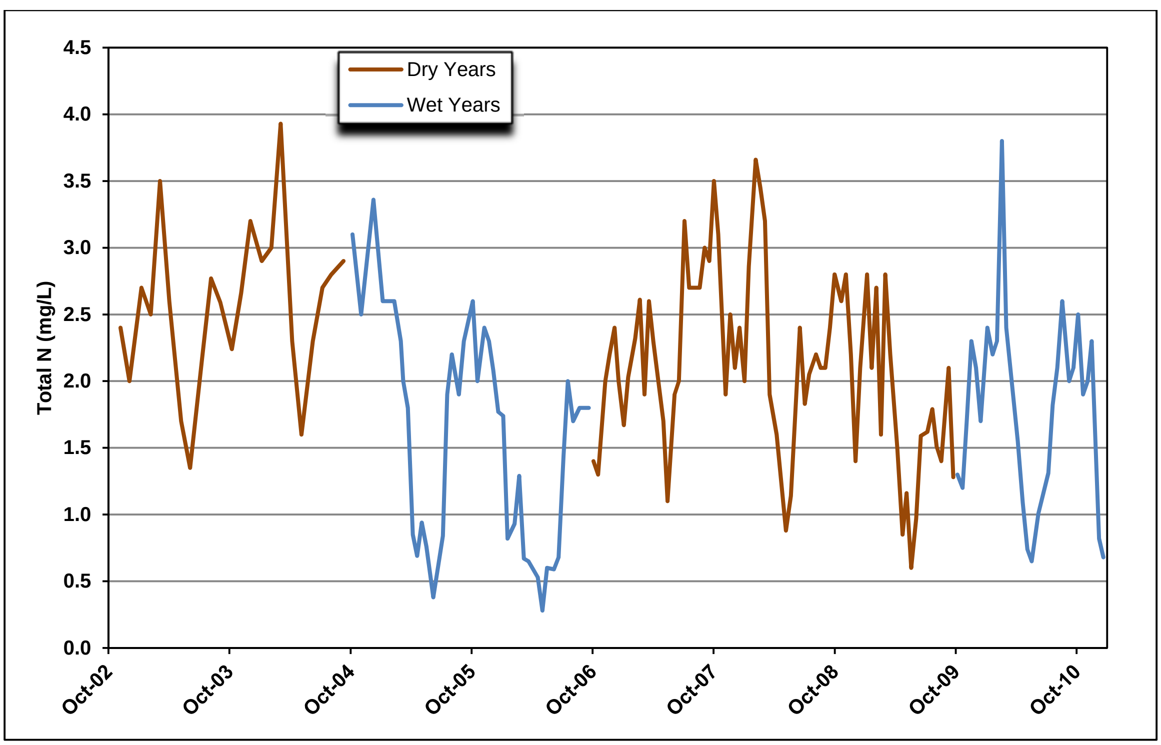

Figure A. 12 Total N Concentrations at Vernalis

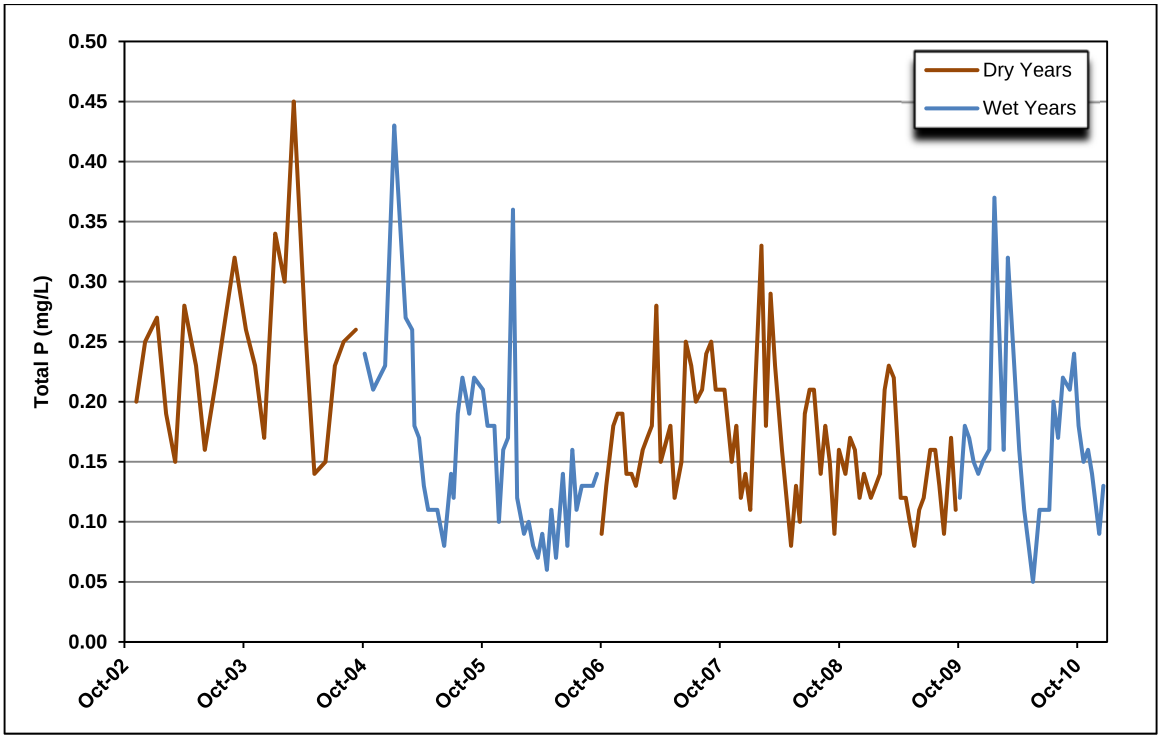

Figure A. 13. Total P Concentrations at Vernalis

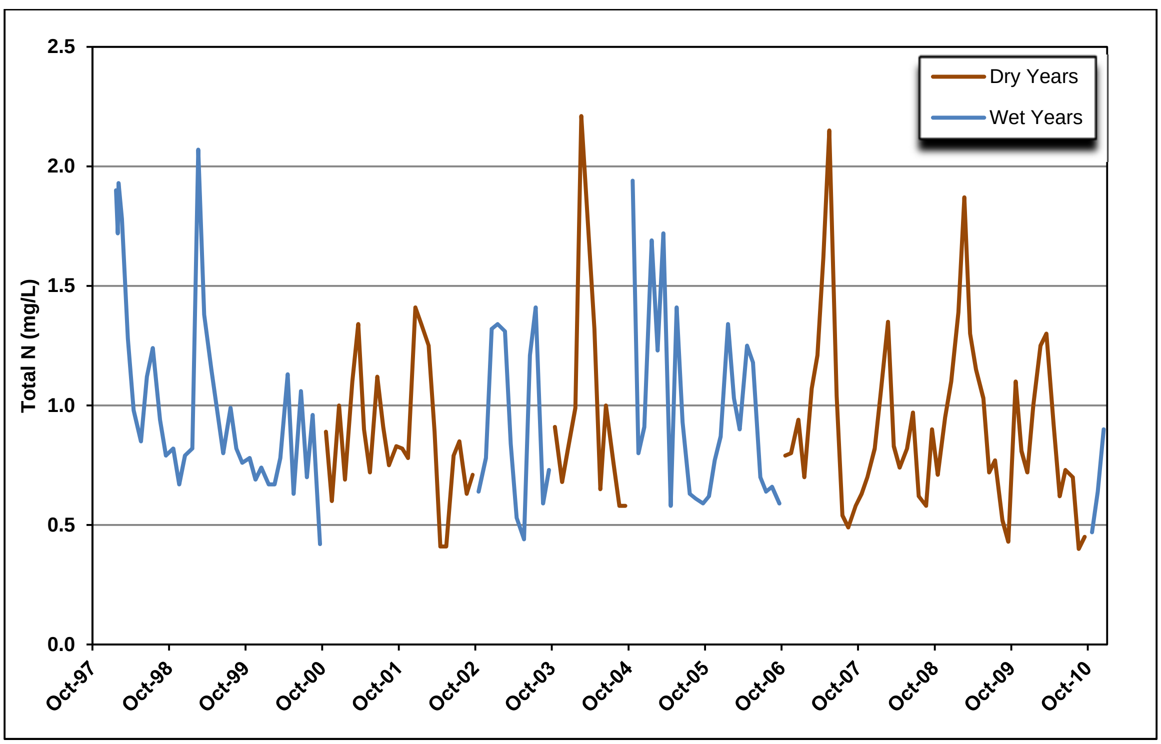

Figure A. 14 Total N Concentrations at Barker Slough

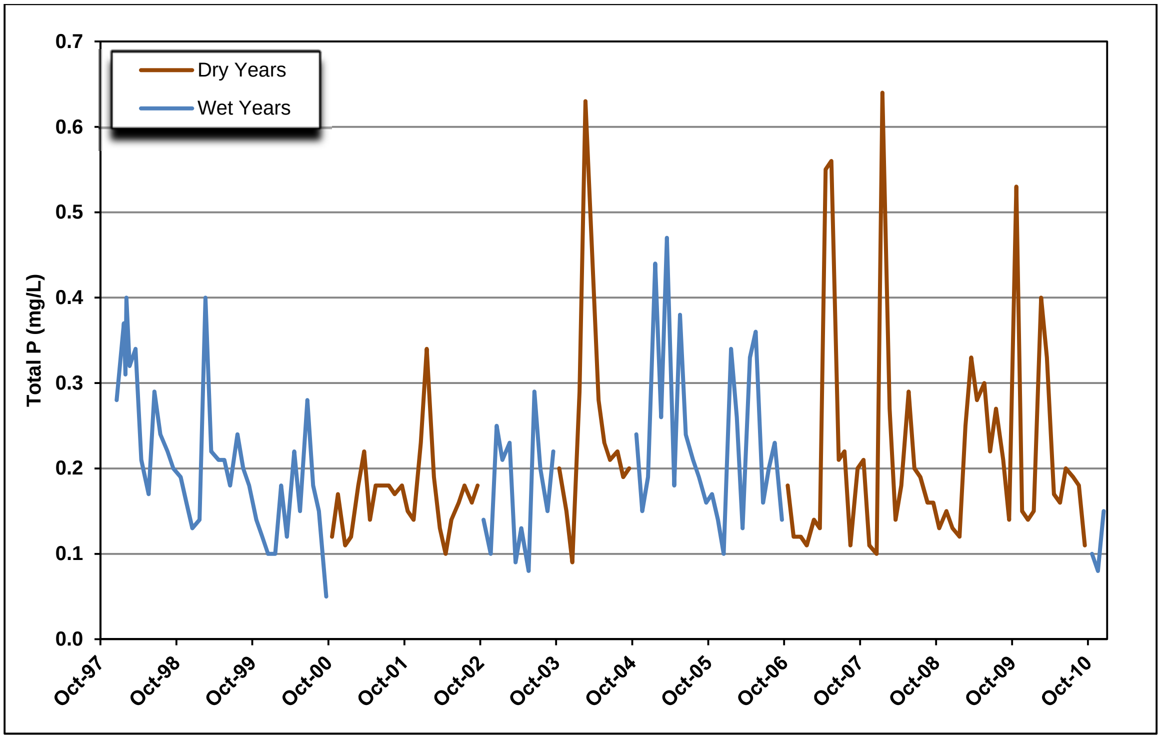

Figure A. 15. Total P Concentrations at Barker Slough

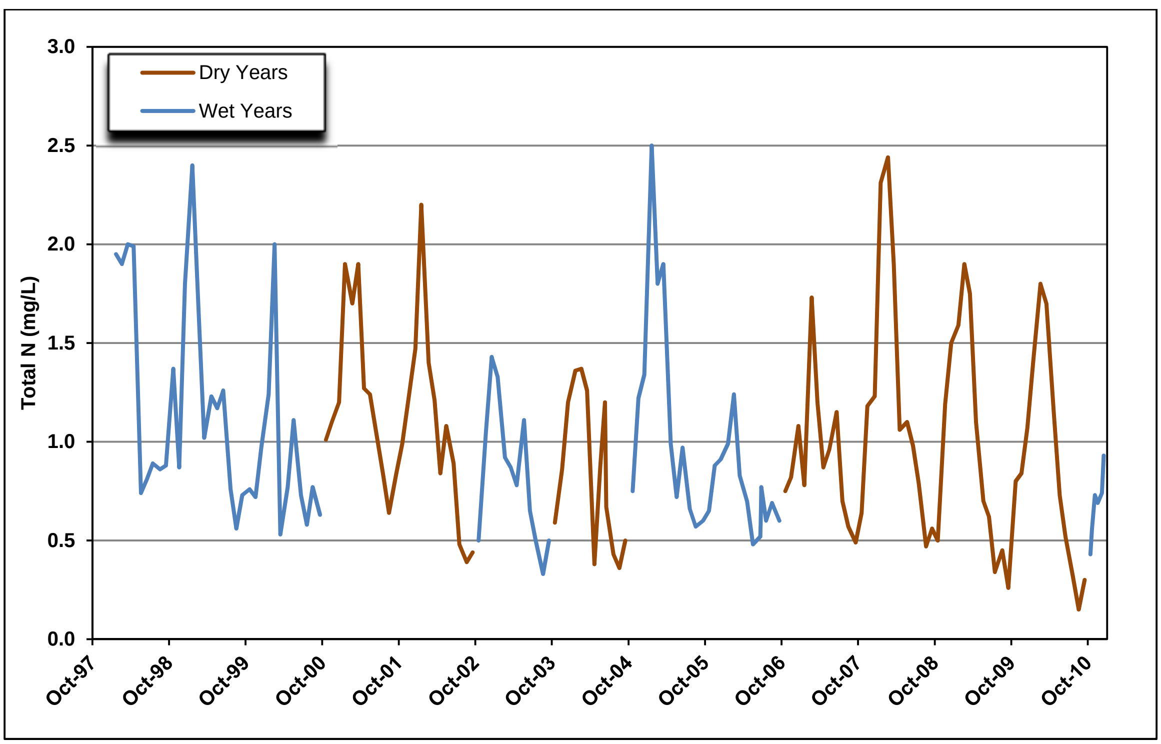

Figure A. 16Total N Concentrations at Banks

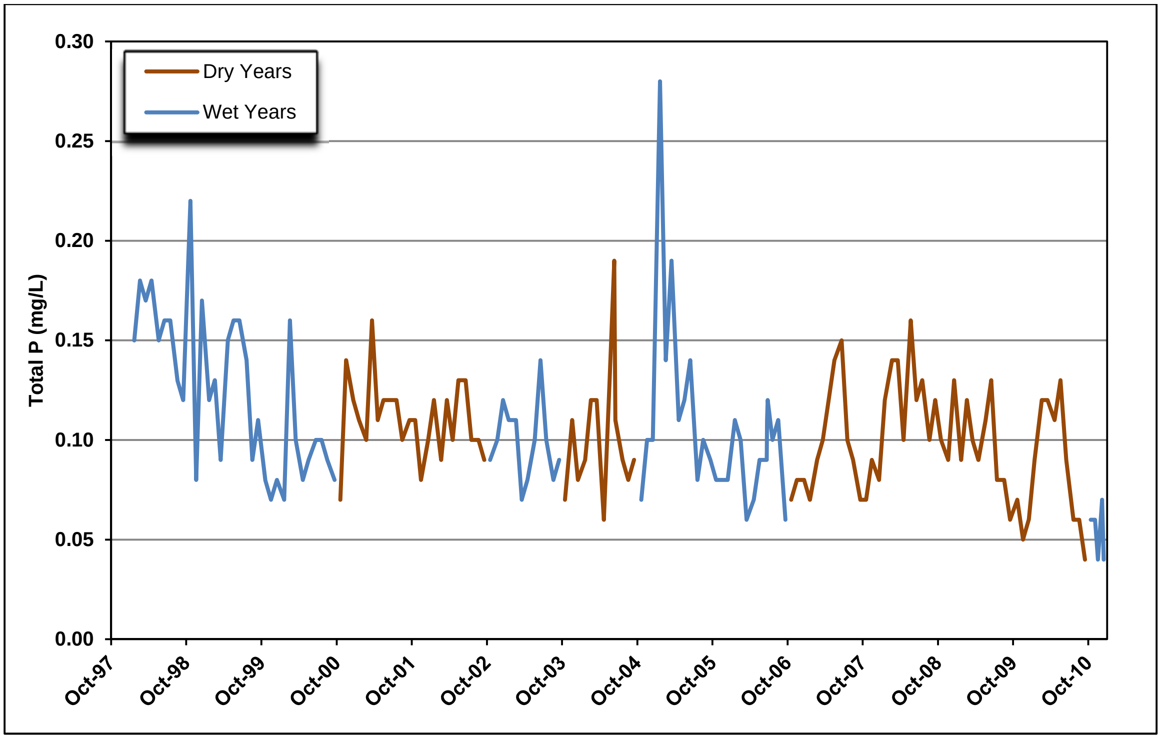

Figure A. 17. Total P Concentrations at Banks

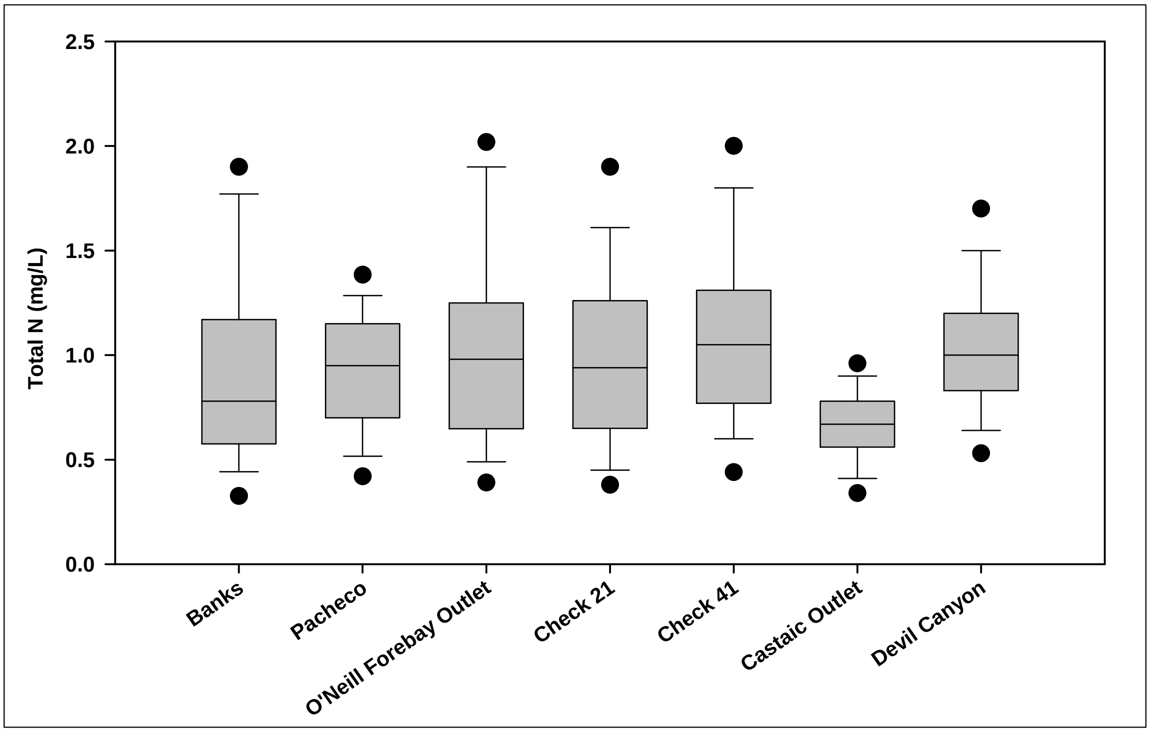

Figure A. 18 Total N Concentrations in the SWP (2004-2010)

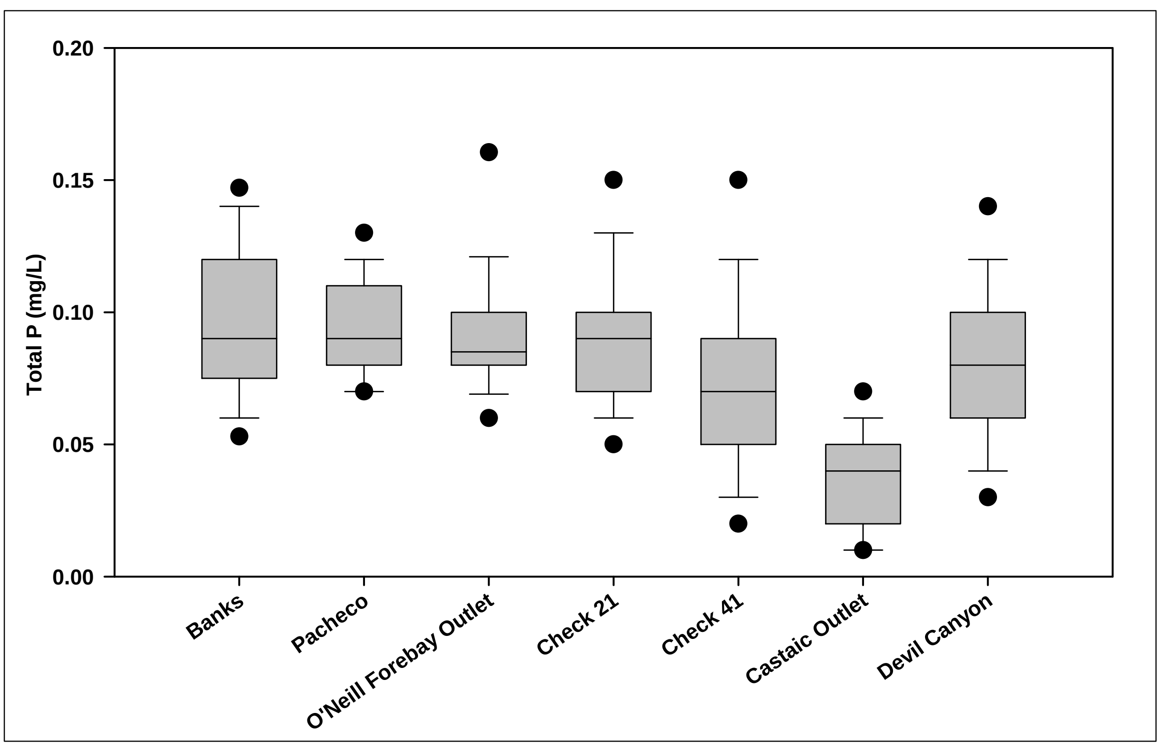

Figure A. 19 Total P Concentrations in the SWP (2004-2010)

A.3 CYANOBACTERIA TAXA MAKEUP

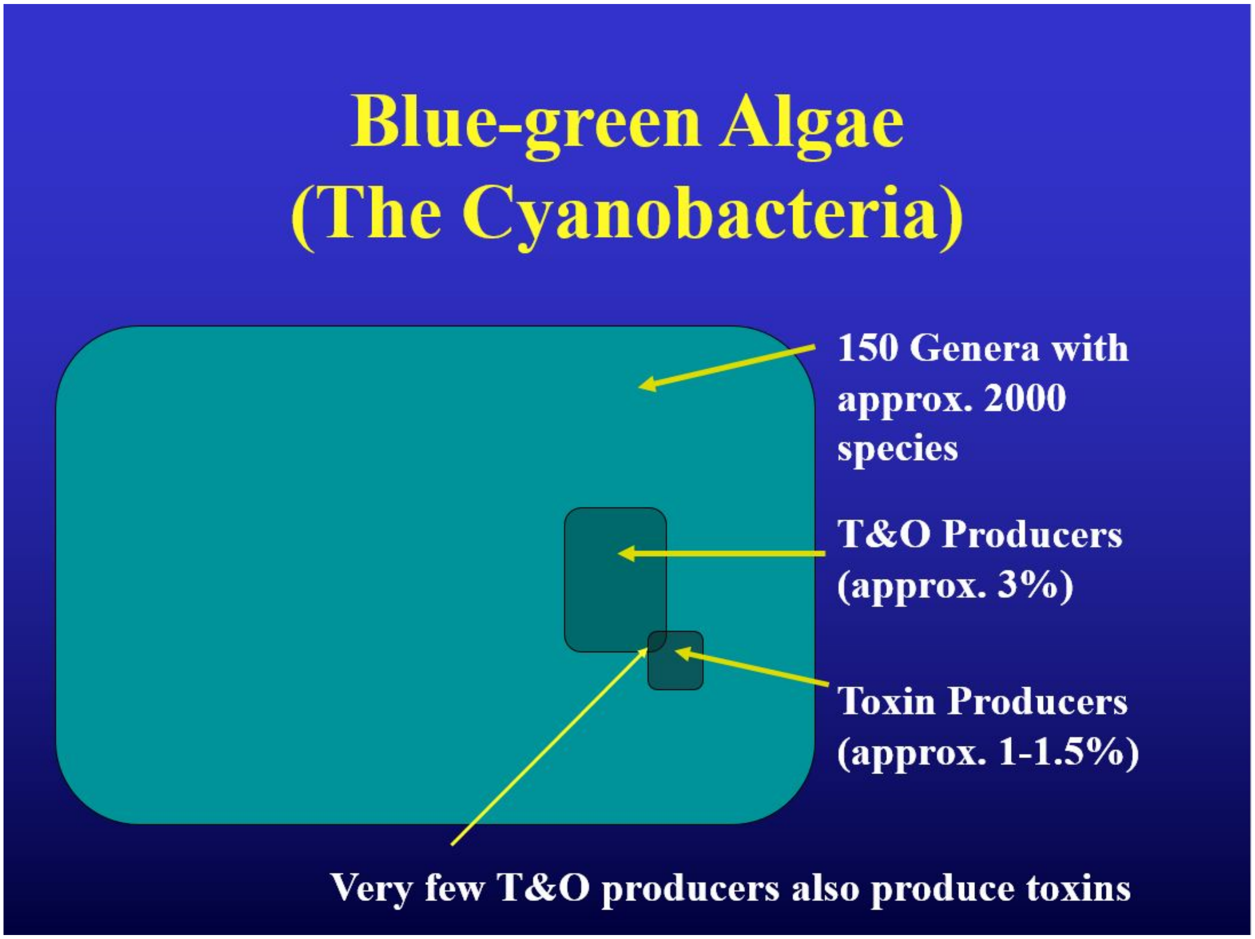

Figure A.20 Proportion of cyanobacteria genera which are responsible for producing taste and odor compounds and toxin compounds.

A.4 POTENTIAL ALGAL PRODUCTION OF SOURCE WATERS

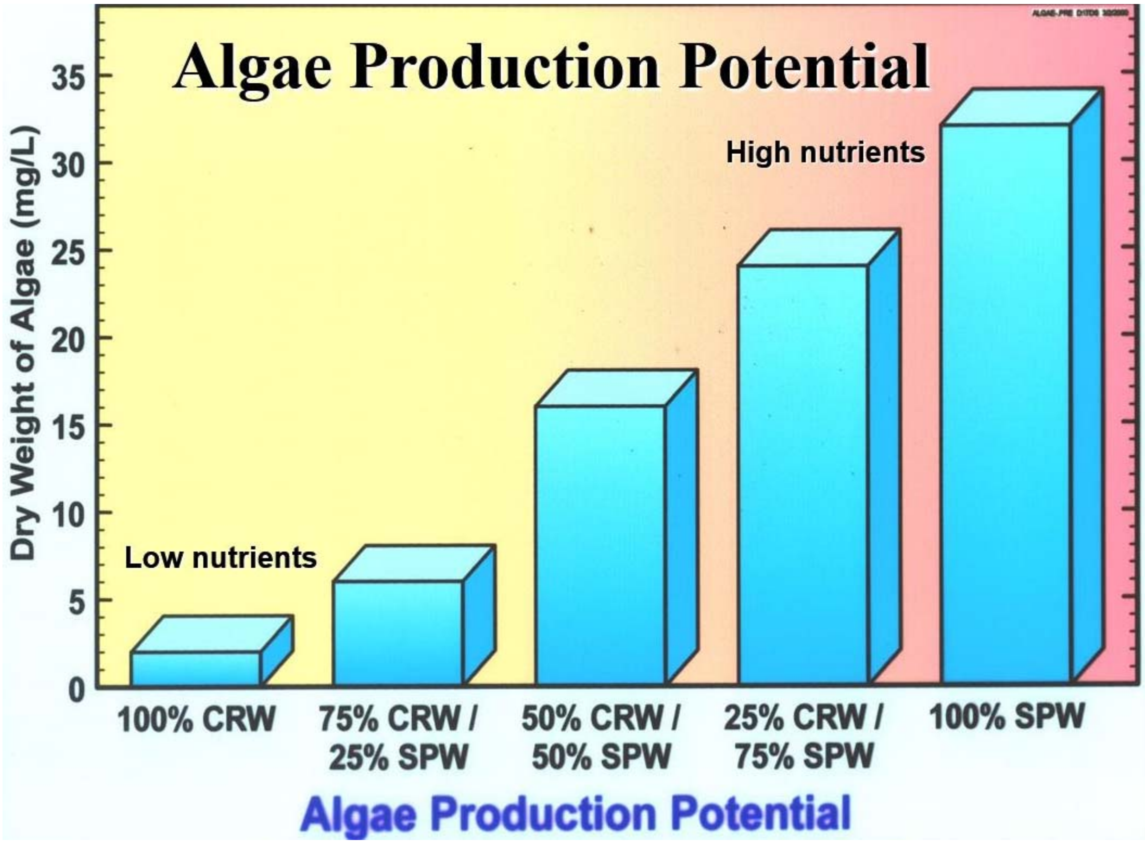

Figure A.21 Algae production potential in Colorado River Water (CRW) versus State Water Project (SPW) based on a standard assay test using a common diatom test species *Selenastrum* using varying proportions of the CRW and SPW waters.