WATER QUALITY SCIENCE IN THE SACRAMENTO – SAN JOAQUIN DELTA

Chemical Contaminants and Nutrients

A review by the
Delta Independent Science Board
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A word cloud of the most frequent 40 words in this review. Created using Wordle.

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List of Acronyms

ACWA	Association of California Water Agencies
Bay RMP	San Francisco Bay Regional Monitoring Program
CCHAB Network	California Cyanobacteria and Harmful Algal Bloom Network
CDEC	California Data Exchange Center
CDPR	California Department of Pesticide Regulation
CECs	Chemicals of emerging concern
CWA	Clean Water Act
CWQMC	California Water Quality Monitoring Council
CWS	Community water system
cyanoHABs	Nuisance blooms of cyanobacteria
DBPs	Disinfection by-products
DDTs	Dichlorodiphenyltrichloroethane and its degradation products
Delta ISB	Delta Independent Science Board
Delta RMP	Delta Regional Monitoring Program
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DPIIC	Delta Plan Interagency Implementation Committee
DWP	State Water Resources Control Board's Drinking Water Program
DWR	California Department of Water Resources
HABs	Harmful algal blooms
IEP	Interagency Ecological Program
NGO	Nongovernmental organization
NRC	National Research Council
NTNC water systems	Non-transient non-community water systems
Nutrient STAG	Nutrient Stakeholder & Technical Advisory Group
NWIS	National Water Information System
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
POD	Pelagic organism decline
POTWs	Publicly Owned Treatment Works
PPCPs	Pharmaceuticals and personal care products
PWS	Public water system
Regional San	Sacramento Regional County Sanitation District
SDWA	Safe Drinking Water Act
SFEI	San Francisco Estuary Institute
SFEWS	San Francisco Estuary and Watershed Science
SOP	Standard operating procedure
SPoT Monitoring Program	Stream Pollution Trends Monitoring Program
SRWTP	Sacramento Regional Wastewater Treatment Plant
SWAMP	Surface Water Ambient Monitoring Program
SWRCB	State Water Resources Control Board
TMDL	Total maximum daily load
TN	Total nitrogen
TNC Water Systems	Transient, non-community water systems
TP	Total phosphorus
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

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I. Overview

This review focuses on contaminants and nutrients in the Sacramento-San Joaquin Delta (the Delta), and on how findings about them have been sometimes used and sometimes neglected in decisions related to ecosystem health in the Delta. The review considers water quality measurements made both in support of basic research and as part of routine monitoring studies in the Delta. However, the topic of monitoring per se is not comprehensively covered in this review because the Delta ISB is in the initial stages of reviewing the extensive monitoring enterprise in the Delta. This review of water quality is based on responses to a questionnaire sent to government agencies and science programs, interviews with water quality specialists and users of water quality data, relevant scientific publications, presentations observed in workshops and conferences, and public comments received on draft versions of the review. While we sought input from a broad range of stakeholders, we do not assume that we received a complete range of perceptions about this important issue. Additionally, water quality research and monitoring efforts are constantly evolving in the Delta, and several new programs and improvements were made as this review was being researched and prepared. This review should be considered to be part of an ongoing process by the Delta ISB.

The main findings of this review, elaborated below, include:

1. It is not clear whether water quality data being collected are sufficient to optimally support management decisions and policies, nor is it clear how water quality data are currently being used in management decisions. This seems particularly true for ecosystem management decisions. We recommend continued and expanded use of water quality data in support of management decisions and policies.
2. Adaptive management, as outlined by the Delta Plan and the Delta ISB in previous documents, is rarely built into water quality programs. We recommend that more aspects of Delta water quality be managed adaptively.
3. Water quality too rarely enters into discussions about water supply and reliability. Water conveyance and storage can influence Delta water quality by affecting where, when, how, and how much freshwater is diverted.
4. Although several entities in the Delta fund research and monitoring activities aimed at protecting water quality in the Delta, these resources tend to support specific compliance needs. Responsibility for protecting in-Delta water quality should be broadly assigned, and more resources are needed to support coordinated and integrated water quality monitoring and science efforts.

GENERAL FINDINGS AND RECOMMENDATIONS:

1. **Finding:** There is little that is simple, and much that can be misconstrued, in the description and interpretation of water quality in the Delta. Because Delta water quality has different meanings, requirements and legal obligations among different users, discussions of water quality often do not start from a shared understanding. Water quality is also influenced by materials from the atmosphere and the surrounding landscape, as well as by physical, chemical, and biological processes in the waters themselves.

   Recommendation: A more comprehensive view of the multiple elements that comprise water quality in the Delta is needed among stakeholders. Improved development and use of numerical and conceptual models of water quality in the Delta could help the community move towards this goal.

2. **Finding:** Although the Delta is one of the most studied estuarine systems in the world, there is still much uncertainty about the effects of nutrients and some contaminants on the Delta ecosystem, especially those of emerging concern.

   Recommendation: Additional research is needed to support better management of chemical contaminants and nutrients. The management of chemicals of emerging concern (CECs) and harmful algal blooms (HABs) requires greater vigilance and coordination between agencies to protect both ecosystem health and drinking water safety.

3. **Finding:** There is sufficient science to show that some chemical contaminants, including certain pesticides, mercury, and selenium, are having deleterious effects on the health of organisms in the Delta. In addition, agricultural pesticides and nitrates in groundwater may contribute to unsafe drinking water for some Delta residents.

   Recommendation: There is a need to further assess the effects of chemical contaminants on the Delta ecosystem through holistic studies that combine toxicity testing and chemical analyses with fish and food-web monitoring. The quality of groundwater used for drinking water also requires more attention, especially for individual wells that are not tested routinely.

4. **Finding:** Little attention has been paid to interactions among chemical contaminants, as well as interactions between contaminants and other stressors. This is of particular concern for the wide range of pesticides discharged into the Delta, legacy loadings of mercury, and natural inputs of selenium.

   Recommendation: Interactions between chemical contaminants and other stressors require more attention. Improved understanding of the interactive effects of multiple chemicals on the ecosystem is also needed.

5. **Finding:** Studies that emphasize broad questions about interactions among nutrients, food webs, and ecosystem processes would more effectively serve management needs, compared to narrower research on nutrient forms and their ratios.

   Recommendation: Increased research is needed on the effects of nutrients on the Delta's food web and on the growth of aquatic weeds. The large-scale application of herbicides to control aquatic weeds likely affects primary productivity and also returns nutrients from decaying plants to the water, potentially affecting water quality; such unintended impacts require more consideration.

6. **Finding:** There is no comprehensive contaminants monitoring and assessment program. The nascent Delta Regional Monitoring Program (Delta RMP) is a positive step, but its temporal and spatial coverage is not sufficient to satisfy the need for information.

   Recommendation: The Delta RMP needs to expand the contaminants it monitors, and increase the temporal and spatial coverage of its measurements. Moreover, how contaminants affect ecosystem processes needs more attention from monitoring programs.

7. **Finding:** Collaboration among agencies conducting monitoring in the Delta is neither systemic nor well organized.

Recommendation: Improved collaboration among agencies could lead to better linkages between water quality monitoring done for regulatory compliance and monitoring being done for special studies and in research programs. Likewise, there is a need for more co-location of water quality and biological monitoring sites.

8. **Finding:** Water quality monitoring is often not done at frequencies commensurate with the variability of the contaminants. This is especially true at locations where flow is measured systematically. These measurements are needed to provide information about loadings and improve understanding of the role of key events in the delivery of contaminants to the Delta.

   Recommendation: An understanding of spatial and temporal variability in contaminant delivery and the role of key events (e.g., first flush, floods, and tides) will contribute to better understanding and management of contaminants.

9. **Finding:** The California Water Quality Monitoring Council (CWQMC) can be critically important in making monitoring data available.

   Recommendation: The CWQMC needs sufficient resources and authority to be more effective. Several agencies can assist in the effort to make monitoring data available.

10. **Finding:** Data management efforts do not match the complexity and growing magnitude of water quality monitoring, assessment, and management issues and needs in the Delta.

    Recommendation: Data management efforts should be improved, especially regarding quality assurance and quality control. There have been positive developments in data sharing, but more is needed. Increased development and use of data visualization tools and support for data sharing resources could improve this important component of water quality management in the Delta.

II. Introduction: Overview of the Delta ISB Review Process

A. Motivation and scope

The mandate of the Delta Independent Science Board (Delta ISB) includes reviews of science activities in support of adaptive management in the Delta. This review considers the scientific basis for assessing water quality in the Delta, and how water quality information is being used in management decisions in the Delta, especially in support of adaptive management. This review focused on:

- Water quality data and information needs by the entities responsible for the management of Delta water quality.
- Assessing the water quality parameters that are currently being monitored, and what additional parameters may be necessary.
- Assessing the temporal and spatial resolution of water quality data collection needed to understand timing, magnitude, and trends of changes in water quality.
- Evaluating the current state and utility of water quality monitoring.
- Reviewing connections between habitat quality and water quality for species of interest.
- Examining how water quality data are being used in management decisions, including the technical basis of the data being generated, the utility of the different types of data, and whether the data are sufficient to support management decisions and policies.

Motivation

A healthy Delta ecosystem requires water of good quality. However, the definition of what is "good" water quality may vary at different locations in the Delta and be dependent on how water is being used (e.g., for drinking water, agriculture, or ecosystem needs). Likewise, regulations and management decisions differ when different water quality issues are considered. There is a perception, especially among Delta residents, that water quality is impaired in the Delta. Several specific water quality parameters are 303(d)-listed in the Delta and improvements are needed to address these problems. Ongoing attention to water quality concerns should continue, especially efforts directed at improving ecosystem health. Proposed changes in water conveyance and changes in hydrology, coupled with climate change, are likely to affect water quality (e.g., Sinha et al. 2017), providing further impetus and relevance for continued review of this topic.

Water quality is a complex subject and is closely linked to the coequal goals of providing a more reliable water supply for California and protecting and restoring the Delta ecosystem. Many agencies and groups monitor water quality, water flows, and ecological conditions in the Delta. However, even though science is increasingly telling us that 'sublethal' exposures to contaminants can profoundly affect fitness, and consequently survival and reproduction of many species (e.g., Fong et al. 2016; Baldwin et al. 2009), there is no comprehensive program that monitors and assesses contaminants in the Delta. In addition, much of the monitoring and assessment of contaminants is neither comprehensive nor coordinated.

Scope

We focused on three areas: chemical contaminants (including mercury, methylmercury, selenium, and pesticides, as well as other chemical contaminants such as pharmaceuticals, personal care products, and CECs), nutrients, and drinking water constituents of concern. Concurrent with our review, the Delta Science Program convened an expert panel to specifically review the Delta RMP's proposed monitoring design (Raimondi et al. 2016; Noon et al. 2017). This process was tracked as part of our broader review.

Water quality is defined in a variety of ways depending on the stakeholder group (e.g., for drinking water, agricultural use, or ecosystem health). The Clean Water Act (CWA) established the basic structure for regulating pollutant discharges into the waters of the United States and gave the United States Environmental Protection Agency (USEPA) the authority to implement pollution control programs such as setting wastewater standards for industry.[1] The Safe Drinking Water Act (SDWA) is the federal law that protects public drinking water supplies throughout the nation. Under the SDWA, the USEPA sets standards for drinking water quality and, with its partners, implements various technical and financial programs to ensure drinking water safety.[2] Our review focused primarily on the effects of chemical contaminants on ecosystem health in the Delta, but incorporated human health and well-being by also considering drinking water.

To understand water quality and ecological processes, it is important to look at many components concurrently, including: disinfection by-products (DBPs), dissolved organic carbon (DOC), pH, total suspended sediment/turbidity and light penetration, and biological components such as chlorophyll, cyanobacteria and cyanotoxins, and phytoplankton taxonomy and size. We evaluate how this information is integrated into existing monitoring programs.

This review did not consider salinity, temperature, or dissolved oxygen (DO). Although the importance of these attributes as a component of overall water quality is clear, several recent reviews have addressed salinity issues (Fleenor et al. 2008; Chen et al. 2010; Medellin-Azuara et al. 2014), and the scientific basis for both DO and temperature is strong already, while other aspects of water quality have not received as much attention. These aspects will be addressed in a future review by the Delta ISB.

B. The review process

Our analysis of the state of water quality science in the Delta is based on information gathered from: (1) a literature review of recent publications on the topic of water quality, (2) responses to a questionnaire distributed to several agencies (Appendix A), (3) in-person interviews with individuals involved in different aspects of water quality (Appendix C), and (4) comments received on a draft released for public comment. During the review process, members of the Delta ISB also attended meetings of the Pelagic Organism Decline (POD) Contaminants Work Team, the Delta RMP, and the CWQMC. In addition, members of the Delta ISB attended the Delta Nutrients Forms and Ratios Public Workshop, a University of California-Davis symposium on multiple stressors in the San Francisco Estuary, a workshop on CECs, and relevant talks and sessions at the 2016 Bay-Delta Science Conference. Relevant papers from the 2016 State of Bay-Delta Science were also consulted.

A questionnaire developed by the Delta ISB was distributed to agencies/programs engaged in water quality work in the Delta. Responses to this questionnaire provided many useful insights about the state of knowledge, ongoing activities by Delta agencies/programs, and concerns. Twenty-three entities responded to the questionnaire, representing a range of state and federal agencies involved in water quality science in the Delta. The respondents represented agencies that acquire water quality data as well as users of water quality data acquired by other agencies. The respondents included entities that use water quality data for

[1] https://www.epa.gov/laws-regulations/summary-clean-water-act
[2] https://www.epa.gov/sdwa

regulatory and compliance purposes (e.g., biological opinions), as well as those that oversee water quality monitoring programs (e.g., USGS, DWR), and others driven by research questions. Respondents were not asked to represent the views of their respective entities. Responses to the questionnaire were diverse, and we appreciate the willingness of many people to provide a wide range of perspectives about the nature of ongoing water quality science in the Delta as well as future needs. This feedback also revealed some of the challenges associated with current efforts to monitor water quality in the Delta. Some of the raw materials for this report include the responses, comments, and insights provided by the individuals and groups we consulted. Italicized comments below are taken verbatim from questionnaire responses or from interviews. These are intended to reflect the respondents' understanding of water quality issues and the Delta ISB neither endorses, accepts, or discounts these comments. However, because they provide a snapshot of the opinions of personnel involved in water quality assessments in the Delta, we believe these views are useful to highlight. A fuller listing of written comments received, along with a graphical representation of the distribution of responses to the questions, is presented in Appendix A, and a list of respondent entities is presented in Appendix B.

C. Current and future threats to water quality

Factors that affect the Delta and its water quality have been identified in a series of reports and publications (e.g., Lund et al. 2007; Mount et al. 2006; Healey et al. 2008; David et al. 2015), as well as recent papers published in *San Francisco Estuary and Watershed Science* (SFEWS). These reports and articles include discussions of population growth and increased urbanization; wastewater inputs; agriculture and associated use of fertilizers, herbicides, and pesticides; water sources and management practices; HABs; landscape alteration; sea-level rise; and regional climate change. These factors are important to managing water quality in the Delta because availability of high quality water affects the management of endangered species, food webs, the fate of irrigation drainage, wastewater management, treatment of drinking water, and numerous other activities in the Delta and throughout California. In addition to these documents, we used information from presentations that we attended at regional scientific meetings and workshops.

California's complex water management system, as well as the supplies and demands on this system, influence the quantity and quality of water in the Delta (Lund 2016). Moreover, proposed plans to build diversion tunnels that would use different points of diversion than presently used (e.g., California WaterFix) and the construction of new storage and conveyance infrastructure (e.g., surface reservoir projects) could change the amount of water withdrawn and the quality of water in the Delta. These proposed changes in infrastructure and water management could have adverse effects on the Delta ecosystem (e.g., on fish species, as described in Delta ISB 2015).

Likewise, there could be unexpected and unintended consequences from the above-mentioned actions that affect water quality in the Delta in the future. Changes to diversion points and the potential for larger amounts of water to be withdrawn could affect Delta water quality and alter water residence times, which would further affect water quality. These issues should be considered more carefully in discussions about, and planning for, potential projects (Schoellhamer et al. 2016).

The anticipated effects of climate change on hydrology and water reliability have broad implications for every aspect of water and environmental management and are essential to consider in the development of any plan for water quality in the future. Projections indicate reduced water storage from loss of snowpack, earlier runoff, larger floods, and more extreme events (Cayan et al. 2008; Cloern et al. 2011). Climate change, including sea level rise, is expected to lead to more frequent and extended periods of drought as well as more frequent and intense floods and changes in salinity (Lund 2016 and references therein). These events will influence water quality both by altering the delivery of contaminants and pathogens, and by changing the residence time of water quality constituents. Storms and floods have been shown to increase runoff of sediment, organic matter, nutrients and contaminants from land to adjacent water bodies, and increase eutrophication (Sinha et al. 2017). Drought leads to less dilution of contaminant point sources in receiving waters and lengthens water residence time, which may reduce water quality in regions with poor circulation. Drought periods also affect groundwater and water quality in wells used for drinking water. The recent prolonged drought highlighted the interconnectedness of drought with these issues and implications for water quality.

III. Current State of Science Regarding Water Quality in the Delta

A. Chemical contaminants and nutrients are among multiple stressors impacting the Delta

Numerous panels, boards, and agencies have clearly stated that multiple stressors are impacting the Delta, and that a management focus on any one stressor, or limited group of stressors, is not appropriate (Delta ISB 2011; Mount et al. 2012; NRC 2012). Instead, strategies are needed to ameliorate each of those stressors that are considered to be significant. Significant stressors in the Delta are acknowledged to include alterations in hydrologic flow, water diversions, non-indigenous species, chemical contaminants, and nutrients. Here we provide brief descriptions of chemical contaminants and nutrients, and in part B (below) we describe them, and the status of Delta science concerning them, in more detail.

1. Chemical contaminants

For this review, we generally considered chemical contaminants to comprise those substances that are substantially derived from human activities. Major sources of chemical contaminants to the Delta include treated industrial and urban wastewater, agricultural and urban runoff, and atmospheric deposition. Major classes of contaminants are: polycyclic aromatic hydrocarbons (PAHs) that are largely derived from fossil fuels or various combustion processes; organohalogen compounds such as polychlorinated biphenyls (PCBs) and legacy pesticides such as DDTs; mercury and methylmercury; selenium; and current use pesticides for both agriculture and domestic use. In the Delta, some pesticides are applied directly to surface waters to control non-native aquatic weeds.

There is a growing list of chemical contaminants that are classified as CECs. Society has only recently become aware of the potential for these chemicals to cause environmental harm, whether because of previously unknown toxicity, increasing manufacture and releases, or both. CECs in the Delta include recently registered pesticides, flame retardants, pharmaceuticals and personal care products (PPCPs), and microplastics (either specifically manufactured microplastics, or microplastics formed by the physical breakdown of larger pieces of plastics). The discussion of chemical contaminants is perpetually clouded by the plethora of substances that are included or not included by different authors, and the multiple routes by which these substances are transported into and through the environment.

2. Nutrients

For the purposes of this report, nutrients refer to the dissolved inorganic forms of nitrogen (nitrate and ammonium), total nitrogen (TN), which includes dissolved and particulate nitrogen, and phosphorus (orthophosphate and total phosphorus [TP]) that are major factors regulating the growth of algae and other aquatic plants. The largest loads of these nutrients to the Delta derive from the Sacramento and San Joaquin rivers, with agricultural and municipal discharge providing the main sources (Kratzer et al. 2011). Agricultural sources are composed of irrigation return flows that transport fertilizer and soil-derived nutrients and discharge from dairies and feedlots. Municipal discharge of treated wastewater from Publicly Owned Treatment Works (POTWs) is also a significant source of nutrients to the Delta. In combination with upstream and in-Delta sources, POTWs account for about 25% of the TN and 20% of the TP loads to the Delta (Dahm et al. 2016). Most ammonia delivered to the Delta is from the Sacramento Regional Wastewater Treatment Plant (SRWTP), which contributes about 90% of the annual load of total ammonia to the Sacramento River at Freeport in the north Delta (Jassby 2008; Dahm et al. 2016). Nutrients (notably, nitrate) are also introduced to groundwater from agricultural drainage and may contribute to unsafe drinking water for some Delta residents using private wells. Nitrate accumulations in groundwater and soil in the Central Valley arise from historic and ongoing discharges from legal and accepted agriculture, municipal, and industrial activities (Central Valley Water Board, n.d.). Nitrate concentrations are impacting drinking water quality, and in some communities, water supply wells do not meet safe drinking water standards.

B. Status of Delta science on several major water quality issues

In the sections below, we *briefly* summarize the known threats for different water quality constituents to humans and wildlife, current science efforts addressing the threats, relevant comments from interviews and responses to a questionnaire, and the Delta ISB's assessment of the adequacy of the science.

1. Drinking Water

Contaminated water is estimated to result in more than half a million deaths per year worldwide. Nationally, recent attention has been drawn to contaminants in the drinking water of Toledo, Ohio, and Flint, Michigan. In California, as in most of the United States, however, contaminant effects of concern in drinking water differ from contaminant effects on the ecosystem, although contaminants can affect the ability to meet standards, treatment requirements, aesthetic qualities of drinking water, goals of water management programs, and drinking water provision costs (Fong et al. 2016). In California, public water systems are regulated and monitored by the Division of Drinking Water of the State Water Resources Control Board (SWRCB), commonly referred to as the Drinking Water Program (DWP). The DWP regulates approximately 7,500 public water systems (PWS) in California (SWRCB 2015). PWSs are divided into three principle classifications: community water systems (CWS); non-transient non-community (NTNC) water systems; and transient, non-community (TNC) water systems. These PWSs do not include private wells supplied by groundwater, which are common in parts of the Delta and are sometimes impacted by high levels of bacteria, nitrates, and agricultural pesticides.

The Delta is an important source of drinking water for about 25 million people in the San Francisco Bay Area, Central Valley, and southern California. Priority drinking water quality issues described by Luoma et al. (2008) in Delta water supplies included salinity, bromides, and natural organic matter, and even today these remain important issues for Delta drinking water supplies. New drinking water regulations, adopted or proposed by the USEPA and the DWP, drive additional monitoring and science needs. Contaminants receiving attention in the Delta include pathogens, cyanotoxins, CECs, and DBPs and their precursors. For example, organic carbon can react with drinking water treatment disinfectants to form carcinogenic byproducts, which are regulated to be at low levels to protect public health (NRC 1980). Bromide, a component of salinity, also contributes to the formation of carcinogenic DBPs during the water treatment process. Levels of these constituents in Delta water may vary in response to hydrology, environmental conditions, and water project operations (Kraus et al. 2008).

As one respondent noted, there is a need to,

> "*develop tools and briefings to make clear that water quality is important and that the attitude of many big diverters that wet water is preferable to clean water (because…less clean water can be treated later) is harming the Delta. After all, the multi-barrier approach to drinking water quality requires that source water quality be protected. The excessive diversions in the Delta and upstream have meant that the water diverted and exported and later used for drinking water purposes and farm irrigation is no longer of desirable quality. Education is the first big step. After that the big diverters may be more comfortable and caring about water quality in the Delta*."

And, in terms of future needs,

> "*For drinking water purposes, existing monitoring captures most of what is needed. Additional monitoring and better availability of toxic algal bloom data would be helpful but it is unclear at this time whether the recent programs will be sufficient to not only identify locations of blooms but provide enough data to predict blooms in advance*." However, another respondent noted that multiple reviews focus "*on chemical constituents*…" but not including microbes is a problem because *"they rarely get included anywhere/by anyone, even though they are enormously important ecologically and for public health*."

Currently, DBPs in the Delta water supply are effectively managed using existing treatment standards and facilities. However, sea level rise and/or western-island levee failures could make treatment of Delta water for urban use more difficult and expensive. Bromide from seawater, combined with DOC, is a particularly problematic precursor of DBPs. Likewise, drinking water contamination in wells is an issue of ongoing and future concern.

2. Nutrients

The traditional view of nutrients in the Delta is that concentrations of nutrients are high and nutrient limitation is uncommon. Factors other than nutrients, such as filter feeding by non-native clams and light limitation, are thought to regulate the rates of primary production (Jassby et al. 2002; Dahm et al. 2016). However, in recent years, nutrient concentrations, the form these nutrients take, and ecosystem responses have become important topics for monitoring and research in the Delta (Dahm et al. 2016). This interest in nutrients has arisen from changes in water clarity, increasing frequency of HABs (including cyanoHABs), the spread of aquatic water weeds, and alterations to the food web of the Delta.

The effects of nutrients on primary producers within the Delta depend on the light regime (water clarity) and grazing pressure, which influence rates of primary production at different times and places in the Delta. The issue is critical for ecosystem management because of the importance of phytoplankton carbon biomass in supplying much of the organic matter to the estuarine pelagic food web (Sobczak et al. 2005). Nutrient distributions also likely influence HABs and non-native aquatic weeds.

Overall, primary producer responses to nutrients have been relatively under-studied in the Delta. Examples of gaps in knowledge include the effects of irradiance on nitrogen assimilation, the process of nutrient uptake in wetlands, which is important because of plans for large-scale restoration of wetlands, and the rates of phytoplankton uptake of phosphorus in the Delta (Dahm et al. 2016). Phytoplankton-nutrient processes in the Delta are largely unexplored due, at least in part, to the view that light-limited conditions buffer the Delta from the common negative effects of high nutrient loads and concentrations (e.g., "blooms" and ensuing eutrophication observed in systems such as Chesapeake Bay). In recent years, there has been a surge in attention to inorganic nutrients as a control on phytoplankton primary production within the San Francisco Estuary and Delta. Such work has responded to the debate surrounding the Ammonium Hypothesis.

The Ammonium Hypothesis (also called, the Ammonium Paradox) links low production in the Delta to high concentrations of ammonium (Dugdale et al. 2007; Parker et al. 2012). The underlying assumptions to this hypothesis include that: (1) higher ammonium concentrations inhibit nitrate uptake; (2) nitrogen uptake is lower when phytoplankton use ammonium instead of nitrate; and (3) phytoplankton primary production is lower when phytoplankton use ammonium rather than nitrate (Dahm et al. 2016). Each of these hypotheses has received scrutiny, and efforts to understand the Ammonium Hypothesis resulted in a workshop hosted by the Nutrient Stakeholder & Technical Advisory Group (Nutrient STAG) and a resulting white paper (Ward and Paerl 2017).

The workshop findings, as summarized in the white paper (Ward and Paerl 2017), suggest that the Ammonium Hypothesis contributed to an "over-emphasis on only one part of a larger complex of drivers in the Delta that result in observed nutrient and phytoplankton patterns." The white paper highlights that "a narrow focus on two different forms of nitrogen will not yield scientific findings that will result in effective, future management practices" and that a "broader understanding of critical Delta features that drive nutrient distribution, concentrations, forms and biological transformations is now needed to interpret results of previous experiments and forge a management path." As a result, their panel recommended that future research should include "thoughtfully designed field studies in broadened, ecosystem-scale, prioritized theme areas as a better way to more thoroughly illuminate phytoplankton-nutrient interactions in the complex Delta landscape and, ultimately, make progress on Delta nutrient management strategies."

Several of the questionnaire respondents noted the need for a better understanding of nutrients in the Delta including nutrient measurements over a larger range of spatial and temporal scales and greater consideration of nutrients in management decisions influencing threatened or endangered species. The white paper from the Nutrient STAG workshop and comments from respondents to the Delta ISB's questionnaire support the need for more holistic approaches when considering nutrient effects on the Delta ecosystem. Questionnaire respondents also identified a need for more high frequency data, especially at locations where flow and water quality parameters are measured concurrently. The Delta RMP and the Delta Stewardship Council are currently funding studies of high-frequency nitrogen data. This type of information will improve understanding of key processes and allow study of events such as floods, droughts and the upcoming conversion of the SRWTP (see back cover of this report). Planning and technical guidance for interpreting high-frequency nutrient data and integrating these data with other data sets is needed. As mentioned above, sensor technology is advancing, and improvements in sensor technology may make it feasible to establish a long-term, high-frequency base monitoring network to address questions of management concern and evaluate specific wetland restoration actions.

3. Pesticides

Pesticides are substances that are purposefully applied in order to control undesirable organisms. The term 'pesticide' commonly encompasses herbicides, insecticides, fungicides, and rodenticides, although there are also other types of pesticides. Over 13,000 pesticide formulations are registered for use in the California, which contain over 1,000 active ingredients, and more than 60% of those formulations are applied in the Central Valley (California Department of Pesticide Regulation[3] [CDPR], as reported by Fong et al. 2016). Herbicides are the most commonly applied pesticides, generally making up around 80% of the pesticides applied worldwide.

Numerous studies have determined the effects of some commonly used pesticides on fish and invertebrates resident in the Delta, often showing harmful effects across a wide range of biological systems (reviewed in Fong et al. 2016). Depending on the pesticide, systems affected include immune function, growth, reproduction, skeleto-muscular function, tissue structure, development, and behavior. These effects can occur at pesticide concentrations similar to levels measured in ambient waters of the Delta (Connon et al. 2009). While many of these effects are commonly termed 'sublethal effects,' studies in other systems have shown that these types of effects can scale up to impact fish populations (Baldwin et al. 2009). Recent analyses by Fong et al. (2016) showed "significant correlations between pyrethroid use and declining abundance of POD fish species" in the Delta. While correlation does not demonstrate causation, the strength of the correlation is intriguing, and indicates that additional investigation of this relationship is needed.

Pesticides occur in the Delta as mixtures, and in combination with other stressors such as higher temperatures, lower DO, and pathogens. Mixtures of pesticides can often have more than additive (e.g., synergistic) effects (Laetz et al. 2009, 2015). Consequently, the frequent occurrence of multiple pesticides in Delta water samples (Orlando et al. 2013) is of concern. Immunosuppressive effects of pesticides reduce an organism's ability to resist pathogens, and it has been shown that increased temperatures can increase the toxicity of pesticides to juvenile coho salmon (Laetz et al. 2014).

Thus, while there is sufficient science to show that pesticides have potential to harm the health of individual organisms in the Delta and may also reduce populations of several fish species, additional research could provide a better mechanistic understanding of these effects. For example, major science gaps exist regarding monitoring of pesticides in the waters and sediments in the Delta and determining to what extent pesticides are affecting Delta species. Several questionnaire responses called for greater effects-based assessment of chemical contaminants in the Delta, especially for pesticides. For example, one response was *"We need to examine potential water and sediment toxicity with a diverse suite of test species."* Another was *"Toxicity testing and the other biological tools available that assess the health of organisms or biological effects of exposure are highly underused."* Toxicity testing of ambient water and sediment samples is one focus of the recently developed Delta RMP. However, the Delta RMP acknowledges that

[3] http://www.cdpr.ca.gov/

their current level of effort, in terms of both spatial and temporal coverage, is not adequate. As one respondent said in response to our questionnaire "*there does not appear to be sufficient information for regulatory agencies to prioritize aquatic ecosystem health over anthropogenic interests.*" Developing such information on toxicity and other effects is a formidable task. A recent study by Biales et al. (2015) attempted to provide such information, using a wide array of endpoints and detailed chemical analyses of water, at four sites in the Delta. While effects were seen, these authors also concluded that:

> *"No clear linkages of specific analyte exposure to biological response were observed, nor were linkages across biological levels of organization. This failure may have resulted from limitations of the scope of molecular endpoints used, inconsistent timing of exposure, or discordance of analytical chemistry through grab sampling and longer term, integrative exposure. Together, results indicate a complicated view of the watershed."*

In addition to better monitoring of pesticides and toxicity testing of ambient environmental samples, there is likely a need to reduce pesticide loadings in the Delta, by reducing applications and further developing methods to minimize transport of pesticides to surface waters. The Delta is a highly productive agricultural area, and pesticides will continue to be used. One recent report pointed to the effectiveness of vegetated agricultural drainage ditches in reducing the transport of organophosphate and pyrethroid pesticides from fields in the Delta (Moore et al. 2011).

4. Mercury and Selenium

Contaminants that biomagnify in the environment by increasing the concentration of a substance in the tissues of organisms at successively higher levels in a food chain pose major risks to aquatic species at higher trophic levels in the Bay-Delta, including fish, birds, and mammals. Two contaminants that bioaccumulate, selenium and mercury, were identified by Luoma et al. (2008, 2015) as pressing problems of water quality, both in the Delta and in other parts of the San Francisco Estuary. As a result, we focus on these contaminants in this section.

Mercury

Mercury is poisonous to the nervous systems of humans and other animals. The harmful effects of mercury exposure depend on the form of mercury (e.g., methylmercury, elemental [metallic] mercury), the concentration, the length of exposure, the overall health of the organism, and a variety of other factors (Bernhoft 2012). For humans, exposure to methylmercury most commonly occurs when people eat fish and shellfish that have high levels of methylmercury in their tissues. For animals, mercury tends to be an increasing problem as it concentrates (i.e., "bioaccumulates") up the food chain, especially in birds and fish (Bernhoft 2012).

Mercury in the highly toxic form of methylmercury can pose major risks to aquatic and terrestrial species at higher trophic levels, including fish, birds, and mammals. Methylmercury exposure is a significant concern for special-status bird species in the Bay-Delta, including the federally endangered Ridgway's Rail (*Rallus obsoletus*), the California Least Tern (*Sternula antillarum browni*), and Forster's Tern (*Sterna fosteri*), which perhaps is the species at greatest risk (Ackerman et al. 2014). Wood et al. (2010) note that the management plans for mercury in both the Bay and the Delta should include a concentration target for prey fish to protect piscivorous birds. Average concentrations of methylmercury in species of concern are also commonly in the range that affects biochemical processes, damages cells and tissue, and reduces reproduction in fish, particularly in peripheral areas of the Delta (Sandheinrich and Wiener 2011).

As one respondent noted,

> "*Until about a decade ago, fish were thought to be insensitive to mercury toxicity; however, research has found that they are as sensitive, if not more sensitive, as humans. A recent study has implicated mercury toxicity to Delta fish species. In addition, many studies have shown mercury toxicity to piscivorous birds in the Bay-Delta*."

The management strategy for mercury adopted in 2003 (Wiener et al. 2003) launched a comprehensive mercury research program in the Bay-Delta. However, continued funding for this research program was lost with the dissolution of CALFED. The Delta methylmercury total maximum daily load (TMDL) was adopted by the Central Valley Regional Water Quality Control Board on 22 April 2010. It was approved by the SWRCB and the California Office of Administrative Law. Final approval by the USEPA was received on 20 October 2011. The TMDL was adopted as a Basin Plan Amendment and includes a control program to reduce methylmercury and inorganic mercury in the Delta.

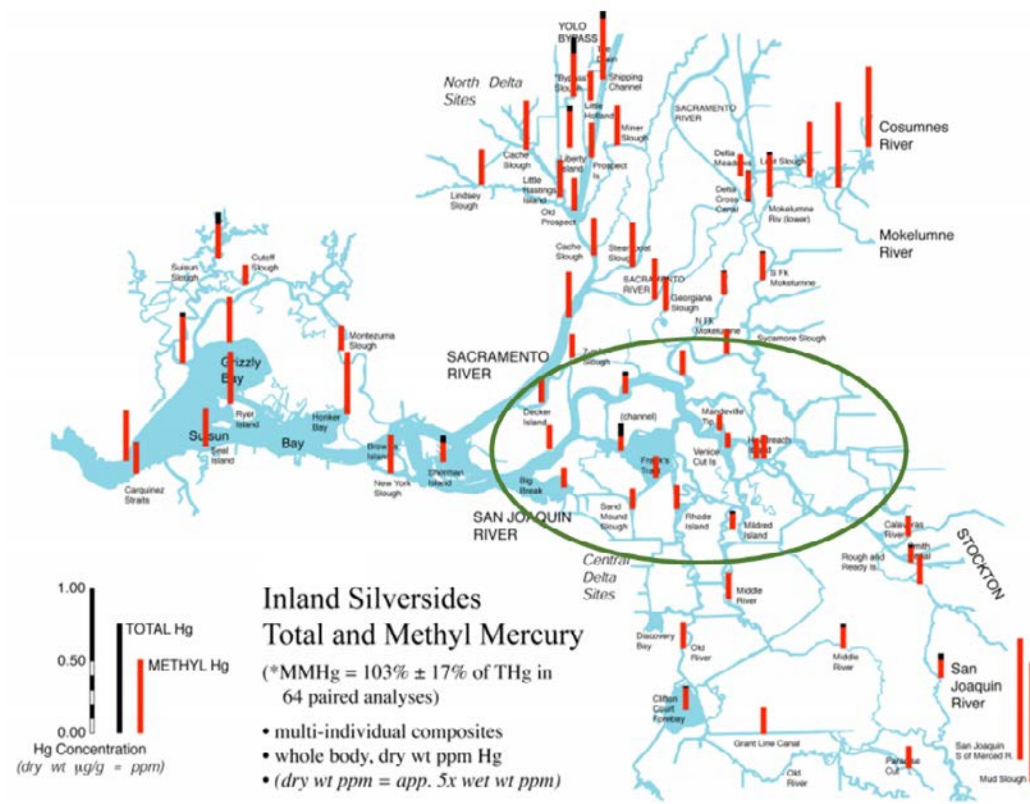

Figure 1. Total and methylmercury concentrations in inland silversides (*Menidia beryllina*) from 1998 to 2000 that illustrates what is colloquially referred to as "The Delta Doughnut," where higher concentrations of mercury occur along the periphery of the Delta, and lower concentrations are found in the center. Figure taken from Slotton et al. (2002) and used with permission. The green circle indicates the area of lower concentrations, as shown in Windham-Myers et al. (2016).

Subsequent research appears to be mostly piecemeal and scattered. However, a recent synthesis (Fleck 2016) presents a scientific foundation to build a unifying framework for mercury research in the Bay-Delta, and to generate knowledge that will help address the primary threat from mercury in the region, which is human dietary exposure to mercury through consumption of fish. The objective of this approach is to understand the link between mercury sources and the regulatory end-point of fish tissue mercury concentrations.

Mercury concentrations vary spatially in the Delta. High concentrations of methylmercury occur along Delta's periphery, while low concentrations (up to three-times lower) are found in the central Delta. This is colloquially referred to as "The Delta Doughnut" (Figure 1). Several reasons have been proposed to explain this spatial pattern: the periphery is closer to legacy mining-related mercury sources; there is more mercury methylation in seasonal wetlands at the periphery; there is more degradation and settling of tributary-sourced methylmercury in open waters of the central Delta; and/or there is more tidal dispersion and rapid flushing in the central Delta. Windham-Myers et al. (2016) incorporated various factors related to these hypotheses into the CASCaDE hydrodynamic model to determine whether the model can reflect concentrations in the central Delta compared to the peripheral Delta, which could indicate which processes may work together to influence the "doughnut" phenomenon. An update on this effort was presented by Stewart et al. (2018).

Krabbenhoft et al. (2016) summarized the state of knowledge about mercury in the Delta into three categories:

1) *Issues that are generally well understood, which include*: spatial trends in total mercury and methylmercury in water and sediment; methylmercury production in various ecosystems; macroscopic mass balance (mercury and methylmercury); toxicological effects on birds; a growing understanding of how to reduce impacts of legacy mercury sources; and innovative land and water impact reduction strategies including coagulation, wetland modification, and rice production.

2) *Issues that are regarded as well understood but in actuality may require more information and research, which include*: iron and sulfate reduction are key microbial processes driving methylation; the relative importance of different mercury sources to methylmercury production, such as particulate-bound mercury being less important than dissolved mercury. Moreover, the relationship between mine-related mercury and exposure risk is improving. In San Francisco Bay, for example, legacy mining effects are more important than mercury from atmospheric deposition. However, this relationship breaks down with distance from mines in the Delta watershed. This has important implications for determining the effects of mine clean-up activities downstream.

3) *Issues that are best described as having gaps in knowledge:* summarized in the next two paragraphs.

Much of the current information on mercury in the Bay-Delta is not directly comparable for several reasons: no common database exists for mercury studies and monitoring; monitoring and some of the methods used are not standardized; and data are not available at the level needed to make robust inferences. Windham-Myers et al.

(2016) used available information to develop a set of conceptual models that can be used to assess what types of processes and associated risks are most important in a particular habitat or system. The presumption is that these models can be used by managers to assess potential actions to control mercury bioaccumulation. One suggested application is to integrate the conceptual models with different control measures. However, Fleck (2016) showed that incorporation of transport effects into conceptual models resulted in only slightly higher concentrations in the central Delta and slightly lower concentrations in the periphery than what is found in the field, indicating that additional mechanisms are involved in mercury loss in the central Delta and mercury generation in the periphery. Other modeling efforts have been used for developing TMDLs, such as Cooke's (2016) use of data collected prior to 2008 to develop a mass balance box model for mercury and methylmercury. Additionally, more recent data should be used to update the mass balances to adaptively manage the Central Valley Regional Water Quality Control Board's Delta Mercury Control Program.

Gaps in knowledge about mercury in the Delta have been highlighted by Krabbenhoft et al. (2016) and include: What are the temporal trends of mercury and methylmercury in biota and water? What is the importance of hydrodynamics? Where and what are the main sources of mercury and methylmercury? What is the importance of water chemistry and other factors? How important are atmospheric sources of mercury? Are there links between environmental and human health from mercury? We generally agree that these are important gaps in the knowledge of mercury threats in the Delta. Krabbenhoft et al. (2016) also noted that no common database exists for mercury studies and monitoring, and also recommended the collection of both filtered and non-filtered mercury samples to improve mass balance calculations and to better understand mercury sources.

The potential for mercury to affect human health in the Delta is not well understood. Shilling et al. (2010), based on data collected between 2005 and 2008, reported that Delta subsistence anglers and their families, including young children and pregnant women, especially of some ethnic groups, are likely bioaccumulating substantially more mercury than is safe. As noted in the Delta ISB's *Review of Research on the Delta as an Evolving Place* (2017), little research is being conducted on human activities in the Delta, and critical follow up research has not been conducted.

Selenium

Selenium is an essential trace element and micronutrient that is of fundamental importance to animal health. However, in higher quantities selenium can cause a range of effects, including mortality, impaired reproduction, and embryo or larval deformities (Stewart et al. 2004; USEPA 2016). In aquatic environments, selenium exhibits a complex mode of toxicity. Selenium effects are further complicated by exposure pathways and bioaccumulation (Cutter and Cutter 2004). Dietary uptake of particulate selenium is the most important exposure pathway for aquatic organisms, especially predators, and some types of food webs bioaccumulate selenium more efficiently than others (Hamilton 2004; Stewart et al. 2004).

Selenium inputs to the Delta and San Francisco Bay come from natural (Nichols et al. 1986) and human (Luoma and Presser 2004) sources. Marine sedimentary rocks of the California Coast Ranges contribute selenium to soil, surface water, and groundwater in the western San Joaquin Valley. Because irrigation moves selenium into subsurface drains and canals, it eventually flows into the Delta and San Francisco Bay. Although discharges from oil refineries have declined in recent years, they continue to be an additional source of selenium.

Scientific research on the effects of selenium on wildlife in the Delta and the Central Valley was greatly expanded when abnormalities were found in fish and various waterfowl, and attributed to high selenium concentrations more than three decades ago (Stewart et al. 2004). In the 1990s, selenium concentrations in biota in the North San Francisco Bay were at levels considered to exceed thresholds harmful to fish and wildlife (Luoma and Presser 2004). Because water with high concentrations of selenium flows through the Delta, recent studies in the San Francisco Bay that examined effects of selenium on biota may be relevant to current selenium issues in the Delta. For example, high selenium concentrations were reported in white sturgeon (*Acipenser transmontanus*) tissues (Linares-Casenave et al. 2015) in the San Francisco and Delta. Laboratory studies showed kidney lesions, reduced growth, and deformities in Sacramento splittail (*Pogonichthys macrolepidotus*) that were fed a selenium-enriched diet (Deng et al. 2007). Populations of both species are exposed to high levels of selenium through their diet, notably from the overbite clam *Potamocorbula amurensis* (Feyrer et al. 2003; Stewart et al. 2013). Moreover, as part of the development of a TMDL for the North San Francisco Bay (Baginska 2015), extensive research has been done, and revised criteria for the North San Francisco Bay were prepared, supported by an ecosystem-scale selenium model, a model of transport, fate, and uptake into the food web, and additional monitoring and review (Chen et al. 2012; Presser and Luoma 2013). Long-term trend monitoring by several agencies also continues (SFEI 2013; Stewart et al. 2013).

Monitoring programs for selenium have been conducted in San Francisco Bay for over 25 years by a variety of government agencies (e.g., USGS) and more recently, as part of the Regional Monitoring Program for Water Quality in San Francisco Bay[4] (Bay RMP). As part of the USGS monitoring program, selenium concentrations have been examined in water, sediment, fish, bivalves, and bird eggs. In the mid-1990s, regulations reduced input of selenite and selenate forms of selenium from oil refineries in the North San Francisco Bay. A major effort associated with the San Joaquin-Grasslands Bypass Project[5] set targets for load reduction that the Central Valley Regional Water Quality Control Board required. The approach used during this project has been successful in that selenium loads from that region have been significantly reduced.

Tetra Tech, an environmental consulting firm, is examining historical selenium data in the San Francisco Bay, and some organizations are interested in proposing research projects to increase these efforts.

Since 2014, measurements of selenium in sturgeon muscle tissue have been made to

[4] http://www.sfei.org/rmp
[5] https://www.usbr.gov/mp/grassland/

determine an appropriate TMDL for San Francisco Bay. Closer to the Delta, some monitoring has been done in rivers entering Suisun Bay. The Bay RMP is doing several studies on tissues of white sturgeon, a species that moves from the San Francisco Bay to the Delta. Selenium concentrations in tissues are collected through the annual "Sturgeon Derby" and muscle plug extractions in Suisun Bay. A TMDL has been developed for the North San Francisco Bay using concentrations in white sturgeon as the indicator (Jay Davis, SFEI, pers. comm.). Research on the effects of selenium on newly hatched larvae of sturgeon and their relationship to morphological deformities suggests that levels in some areas of the Delta approach those shown to cause deformities. USGS monitoring studies and research on *Potamocorbula* and splittail in the North San Francisco Bay and in the Delta suggest that selenium may be causing developmental abnormalities in splittail. The Central Valley Regional Water Quality Control Board has expressed interest in the selenium issue but selenium has not yet emerged as a top priority for them. The Delta RMP is focused on several topics such as mercury, nutrients, and pesticides, and although selenium may not be a high priority now, it is likely that more research and monitoring will be needed in the future. The San Francisco Bay Regional Water Quality Control Board has requested that the Bay RMP design a monitoring program to examine the relationship between selenium and changes in hydrology. A goal of this monitoring would be to determine whether there is a link between changes in selenium concentrations in North San Francisco Bay from water passing through the Delta. The Bay RMP does not extend to the Delta but considers inputs from the Delta. The effects that the proposed California WaterFix project and other upstream projects have on selenium dynamics are also of interest and related to Delta water quality interests. Although Johns et al. (1988) found no correlation between selenium and mercury concentrations in the Delta, we are unaware if any research on whether the ameliorating effect of selenium on mercury contamination has been examined in the Delta. However, these interactions are of general interest and are broadly studied in the wider research community (e.g., Yang et al. 2008; Ralston and Raymond 2010).

Based on the interviews we conducted, obtaining more information on direct effects of selenium on fish seems worthwhile. For example, developing an index of selenium exposure from tissue is useful but selenium may be more harmful to fish embryos and larvae. Selenium exposure in eggs may be an important topic for further research. Concentrations of selenium in sturgeon appear to already be in a harmful range. Many questions are not resolved, and more monitoring of selenium and the testing of cause-effect relationships on biota in the Delta are needed in the Delta and San Francisco Bay, especially given the movement of fish across these connected habitats.

One scientist that we interviewed noted that selenium may be an increasing problem in the Delta. It is clearly a problem in the North San Francisco Bay, which receives water from the Delta. Likewise, the Bay RMP indicates that selenium may become more of a problem in the future and more baseline information is needed (Tetra Tech 2017). As Fong et al. (2016) noted, a more precise understanding of the concentrations that cause harm would be valuable information. This would be a worthwhile effort that would require additional research, and the available monitoring data would be valuable in designing appropriate studies. There was only one specific comment that mentioned selenium in the questionnaire responses, which was "*Potentially harmful chemicals* *are known to occur in the Delta, including selenium, but detection does not necessarily mean they are having an effect.*"

5. Chemicals of Emerging Concern (CECs)

There is growing concern about whether ecosystem and human health can be protected from harm that might derive from new classes of chemicals being released into the environment. Chemicals such as PPCPs, newer industrial chemicals, and some current use pesticides, are often referred to as CECs. In some cases, CECs might be chemicals that have been in use for many years, but that are only being detected now because of improvements in analytical methods. Diamond et al. (2011) defined CECs as, *"chemicals that are known or suspected to be released to aquatic environments but are not commonly regulated or monitored, and whose potential risk to ecological health are relatively unknown."* Generally, there are no standardized analytical methods or substantial toxicological data for CECs, which limits our ability to determine what risks, if any, are posed by their presence. Concerns about CECs in the Delta were nicely summed up by one respondent to our questionnaire, who said "*Chemicals of emerging concern will require increased vigilance and modifications of water quality monitoring and analysis programs*."

Some studies have been done to determine the effects of CECs on aquatic organisms in the Delta (reviewed in Fong et al. 2016). Biological systems affected by PPCPs include immune function, osmoregulation, the nervous system, tissue structure, development, and behavior. While there is little evidence that single CECs are affecting organismal health at levels measured in the waters and sediments of the Delta, CECs are similar to pesticides in that they commonly occur as mixtures. For example, Biales et al. (2015) reported detections of up to 17 PPCPs in a single water sample taken from the Sacramento River in the spring of 2009. Moreover, while pesticides are generally applied in seasonal patterns, PPCPs have a more or less constant level of discharge, because they commonly derive from daily human activities.

Little is known about how mixtures of CECs, or CECs in combination with other Delta stressors, might affect the ecosystem. The immediate challenge is to devise the appropriate survey and monitoring strategies that can help determine the presence and potential risks that might be posed by these substances. Towards that end, other systems have developed strategies, including in Puget Sound (James et al. 2015), San Francisco Bay (Sutton and Sedlak 2015), and southern California (Mehinto 2017). The Southern California Coastal Water Research Project proposes using cell-based assays to screen for chemicals having a common mode of action, starting with chemicals that affect estrogen receptors (Mehinto 2017).

In May 2017, the Delta RMP helped convene a two-day workshop about CEC issues in the Delta to learn about strategies developed in other systems, and to begin devising a CEC strategy for California and the Delta. Key questions that were addressed during this workshop included: (1) What types of studies are most critical for the Delta? and (2) Are there opportunities to partner with other programs in California? This was a good initial step to take, but at the meeting it was recognized that resources for the Delta RMP are constrained and are already inadequate to meet the needs of the monitoring program they have recently started. In addition to the Delta RMP, current efforts to monitor CECs include the USGS CEC monitoring of streams and the SWRCB, which requires CEC monitoring of Recycled Waters. The Department of Toxic

Substances Control developed monitoring strategies for CECs in California aquatic ecosystems with key prioritization principles based on potential exposure to chemicals and significant or widespread adverse impacts to the environment.

As regional and state programs further evaluate the occurrence and impacts of CECs in the environment, coordination between entities will be important. Examples of ways these agencies can coordinate include the development of a consistent definition of CECs and use of conceptual models to target appropriate media and determine a systematic prioritization process to develop a target CEC list.

6. HABs and CyanoHABs

A prevalent concern of many questionnaire respondents was the presence of HABs/algal toxins, especially those that transfer to the food web or otherwise influence ecosystem health. Other comments on this topic included:

> "*Additional monitoring and better availability of toxic algal bloom data would be helpful - unclear at this time whether the recent programs will be sufficient to not only identify locations of blooms but provide enough data to predict blooms in advance;*" and "*CyanoHAB sources and environmental conditions leading to their blooms needs to be researched.*"

Monitoring for both public health concerns as well as aquatic ecosystem health are also seen as current shortcomings of responsible entities of the Delta. The most pervasive of these HABs for the Delta are cyanobacteria (cyanoHABs), which include *Microcystis, Anabaena,* and *Aphanizomenon*.

Microcystis was first reported in the Delta in 1999 (Lehman et al. 2005). This species produces cyanotoxins (i.e., microcystins) that accumulate in the food web (Lehman et al. 2010) and cause harm or death to wildlife, domesticated animals, and humans including through promotion of tumors and liver cancer (Zegura et al. 2003). *Microcystis* is the only consistently occurring harmful algal species in the Delta. It is deterred by temperatures below 19˚C and high turbidity (Lehman et al. 2013), thus populations of this species are frequently sharply reduced by the onset of fall conditions in the Delta. However, as warm water temperatures extend later in the season, this may extend the ability of *Microcystis* to remain actively growing in the water column for longer periods of the year.

Current efforts addressing the threats of HABs in California waterways have been spearheaded by the SWRCB's Surface Water Ambient Monitoring Program (SWAMP) and the CWQMC. The CWQMC's California Cyanobacteria and Harmful Algal Bloom (CCHAB) Network disseminates timely information regarding HAB reported locations[6] and hosts a decision framework for managers and the public to notify others about potential cyanoHAB concerns. The CCHAB Network advises the public to be cautious when recreational exposure reaches 0.8 µg/L microcystin (CWQMC 2016). Although this is stricter than the USEPA drinking water health advisory of 1.6 µg/L microcystin (USEPA 2017), Lehman et al. (2010) showed accumulations of microcystin and liver lesions in Delta sportfish where *Microcystis* were reported to comprise 100% of the surface phytoplankton, and dissolved microcystin concentrations (0.00005-0.01088 µg/L)

[6] http://www.mywaterquality.ca.gov/habs/

were 73x lower than the above trigger caution action levels. These findings support the continued need for focused studies to understand how cyanotoxins affect wildlife in the Delta and what these effects mean for overall ecosystem health and human health.

The Southern California Coastal Water Research Project developed a white paper on cyanoHABs (Berg and Sutula 2015), their relevance to Delta waterways, and determining gaps of knowledge in understanding HABs. Two major recommendations from Berg and Sutula (2015) are to develop and fund a 3- to 5-year monitoring and special study program to monitor cyanoHABs in the Delta and to assess the toxicological risk of cyanotoxins to people and wildlife. The monitoring program would develop an ecological model to better understand drivers and controls on primary production and phytoplankton assemblage in the Delta. These results would be useful in determining what triggers *Microcystis* bloom initiation and development, and what determines the size of the final bloom and thus the geographical extent of concern after the bloom dies off.

Although cyanoHABs, such as *Microcystis,* have been found in the Delta consistently since their initial detection in 1999, routine monitoring of at-risk locations for bloom development during peak trigger conditions should be carried out more comprehensively. These programs could be added to long-term monitoring efforts as resources become available. Anderson-Abbs et al. (2016) illustrate additional shortcomings, specifically that landscape risk assessment is missing completely from current efforts, while other monitoring and forecasting efforts such as waterbody monitoring and immediate or long-term bloom response are carried out in various levels of comprehensiveness by responsible agencies. Given that the known triggers of *Microcystis* blooms, which include warm, slow, and clear waters, are likely to become more prominent with climate change, it is important to address cyanoHAB formation and identify mitigation actions as a short-term management priority.

More structured and exhaustive monitoring for cyanoHABs and toxins is needed to more effectively forecast bloom inception and mitigate HAB events. SWAMP is completing guidance documents for decision making regarding cyanoHAB development as well as undertaking development of a publically available database for timely dissemination of legacy and current data regarding blooms, including satellite imagery of any bloom events (Anderson-Abbs et al. 2016). SWAMP has set aside resources for completing guidance documents and standard operating procedures for response to and management of cyanoHABs (Anderson-Abbs et al. 2016). However, the recommendations set forth cannot be fully implemented without additional resources. Continued support for landscape-scale risk assessment and endorsing crosstalk among monitoring groups is key to managing cyanoHABs as the Delta faces changing threats in a changing climate.

IV. Key Points from the Delta ISB Questionnaire

This section highlights some key points identified by questionnaire respondents. A more detailed presentation of responses is provided in Appendix A, while the list of respondents is given in Appendix B. Key points are in bold type and supporting quotes were copied verbatim from the questionnaire responses. These points represent the diversity of perspectives expressed in the responses to the questionnaire and should not be considered as endorsements by the Delta ISB.

Water quality is defined in a variety of ways depending on different stakeholder groups and agencies (e.g., for drinking water, agricultural use, or ecosystem health). Consequently, criteria and priorities regarding different water quality constituents vary, and become complex.

"We recognize that to understand water quality and ecological processes it is important to look at many constituents concurrently, including: DBPs, DOC, pH, total suspended sediment/turbidity, light penetration, and also biological components such as chlorophyll, blue-green algae and cyanotoxins, and phytoplankton taxonomy and size."

"Let's get serious about water quality. Up until this time, only "one agency" has been really serious about Delta water quality for urban uses. The other members of the California Urban Water Agencies have been more interested in wet water and protecting their ability to export water, or are not invested in Delta water quality because they divert their water upstream of the Delta. Some, through California WaterFix, are hoping to also divest themselves from worrying about (protecting) Delta water quality by taking their water very close to the Sacramento inflow point to the Delta. Those that discharge wastewater or agricultural drainage into the Delta are also not interested in improving Delta water quality, which is why ACWA (Association of California Water Agencies) seldom fully engages in protecting Delta water quality. Unless this is solved at a policy/political level, there will never be enough support on a financial, technical or legislative level regarding water quality in the Delta."

Multiple stressors related to water quality affect the Delta ecosystem and these must be examined more closely.

"The effects of multiple compounds and the effects of these compounds combined with other abiotic stressors (e.g., increased temperature, increased salinity, reduced habitat range) needs more attention along with the sublethal effects that can lead to decreased abundance or genetic diversity."

The interactions between contaminants and other stressors require more attention.

"More research is necessary to determine the impacts to individuals and the population from the interaction of contaminants and other stressors (e.g., altered temperature, predation, and mixtures)."

"Pesticides, particularly additive and synergistic adverse effects of multiple pesticides and degradates; nutrients; and CECs, some of which may have additive and synergistic adverse effects with pesticides and pesticide degradates."

"Mixed effects and interactions (e.g., temperature and contaminants, zooplankton feeding rates and contaminants)."

There is no comprehensive monitoring and assessment program looking at the relationship between contaminants and ecological processes.

"What drivers and/or mechanisms influence the fate and transport of these constituents? What are the impacts to listed fish and their habitat? At what temporal and spatial scale should we measure these constituents to support fisheries and aquatic beneficial uses? How does land use change (habitat restoration) play a role in supporting the ecological function of the Delta? Can we restore the healthy function of the system by studying 'only' these constituents; does the information we collect fit within a broader framework? What are the hot spots and hot moments at which these constituents occur and can we use this information to drive management decisions?”

“IEP (Interagency Ecological Program) Directors need to recognize the importance of water quality in ecosystem studies and commit to including more water quality expertise and integration into their studies.”

“For the most part, sufficient research has been conducted to show the importance of water quality impacts to the Delta ecosystem and organisms; however, there does not appear to be sufficient information for regulatory agencies to prioritize aquatic ecosystem health over anthropogenic interests. This may require numerical models to show that seemingly minor sublethal and indirect impacts to individual organisms can result in major population declines. Both numerical and conceptual models are needed to help understand how sources, pathways, transport, mechanisms (e.g., biological, chemical, and physical), and other management actions (e.g., land use and sediment management) affect water quality.”

“Nearly all of the parameters that are the focus of this review suffer from a lack of consistent and adequate temporal and spatial coverage.”

Pesticides and other chemicals at low levels are not being assessed adequately for sublethal effects or additive effects in concert with other stressors.

“What are the cumulative impacts of pesticide application to waterways with sensitive fish species? What are the direct and indirect, acute and sublethal effects of pesticides to fish and their aquatic habitat? What are the habitat effects of increased nutrient loading and algal toxins in the Delta? What are the hot spots and hot moments of pesticide, nutrient and methylmercury production in the Delta, and what are the key drivers? What modeling efforts are needed to improve our understanding of nutrient transport in the Delta; can we develop a nutrient modeling effort?”

“Toxicity testing, as well as other evaluations of xenobiotic impacts to aquatic life physiology, behavior, etc. is not adequate to support timely management decisions.”

“Toxicity testing and the other biological tools available that assess the health of organisms or biological effects of exposure are highly underused. Biological testing helps understand the dynamic, combined effects of multiple compounds present at any given time. Chemical analysis alone is often problematic because of unknown bioavailability, but toxicity testing innately provides the answer to whether or not something is bioavailable.”

“We need to fully understand the sublethal effects (from the whole organism to the molecular level) of contaminants and the interaction of chemicals and say a water quality stressor. What is that interaction of say the fish is starving because of inadequate food quality and supply, so what happens when they are exposed to a chemical stressor or immune disease? The system is a series of low-level effects that cumulatively have an adverse effect. USEPA had conducted an in-situ study at Hood on Sacramento River (see Biales et al. 2015). We need to continue this type of work.”

CECs will require increased vigilance and modifications of the water quality monitoring and analyses programs.

“As scientific research identifies risk thresholds for particular CECs, it would be useful to determine their occurrences and concentrations in Delta waterways. A selection process selecting candidate chemicals for future monitoring studies in the Delta would benefit from stakeholder input and a public review. Focus on ambient water quality first, then determine if problems exist.”

Although the Delta is one of the best studied estuarine systems in the world, research is needed in several areas.

1. ***Contaminants:***

   “What are the cumulative impacts of pesticide application to waterways with sensitive fish species? What are the direct and indirect, acute and sublethal effects of pesticides to fish and their aquatic habitat? What are the habitat effects of increased nutrient loading and algal toxins in the Delta? What are the hot spots and hot moments of pesticide, nutrient and methylmercury production in the Delta, and what are the key drivers? What modeling efforts are needed to improve our understanding of nutrient transport in the Delta; Can we develop a nutrient modeling effort?”

   “Overall, contaminant and toxicity monitoring in the Delta requires more consistency and thoroughness, and the studies need to be developed so they reflect impacts to key estuarine species.”

   “More than just measurement of chemicals, effects on organisms past standard chronic and acute testing should be done.”

   “Some key parameters that require more monitoring include the fate, transport, and ecological impact of sediment bound contaminants (e.g., pyrethroid pesticides and mercury), PPCPs, and the long-term toxicological effects (cumulative) of altered water quality.”

   “We need to examine potential water and sediment toxicity with a diverse suite of test species.”

2. ***Nutrients:***

   “More research is necessary for nutrient (e.g., forms and ratios) impacts to the Delta ecosystem. In addition, the exchange of nutrients and food sources between the upper estuary, lower estuary, near shore, and floodplains is likely necessary to support species recovery. Understanding how to maximize these exchanges of nutrients and primary and secondary production in these zones is necessary to improve the Delta ecosystem health.”

3. ***Need for research on nutrients and aquatic weeds:***

   “We don't really know how nutrients affect aquatic weed growth or the food web.”

   “You might have asked how water quality data could be integrated with biological data. For example, data integration that will help understand the role of nutrients in the distribution and growth of aquatic weeds and harmful algae.”

4. ***Need for more high frequency data, especially at locations where flow is measured:***

   “Measurements need to be made at higher frequencies at more flow stations to get at processes – a good long-term high frequency base monitoring network needs to be developed that should cover the entire estuary. Water quality parameter additions should be considered when new sensors become available – sensor technology is advancing rapidly. Of course, the data then also needs to be analyzed!

Shorter-term, smaller, but more spatially intense high frequency monitoring networks should augment this base high frequency monitoring network to address specific questions of management concern, e.g., about the effects of the upcoming SRWTP conversion or specific wetland restoration actions."

"Again, focusing on collection of in situ high-frequency data: before I would add parameters or stations, I would think about redirecting the current efforts. Between DWR and USGS, we have a good flow network, but we often do not collect water quality data at the same locations that flow is measured, which hampers our ability to correctly interpret that data. It seems to me that it would assist the monitoring that is done by collection of discrete samples would benefit from sampling at the same locations we are collecting continuous data, but this is often not done."

There is a need for improved collaboration among agencies.

"Agencies and programs tend to naturally be siloed. It takes time and effort to coordinate and integrate. The way to counter this is to present cohesive strategies on answering priority management questions in the Delta. This requires buy-in and agency or entity management commitment to the process. This can be done by addressing and prioritizing regulatory information needs, then grouping like purposes and missions. Work teams or study groups are then formed based on the grouping. Within each work team, individual program's mandates and needs are discussed and recognized. Resulting study efforts are designed to meet as many of the intersecting information needs, recognizing that some may not be met by an integrated monitoring or study effort and will need to exist outside the coordinated effort. There still should be a data connection where information can flow. Work teams need to include the appropriate multidisciplinary members, such as biologists, geologists, water quality experts, and data management resources."

Better linkages are needed between water quality monitoring that is done for regulatory compliance, with that being done for special studies and in research programs.

"Research priorities are determined by permits and environmental compliance."

"Because water quality regulations and management are primarily under the purview of the Water Boards, the Department often coordinates with Water Board staff to determine the kind of information they need to develop water quality criteria to protect natural resources. Yes, understanding and achieving the water quality conditions necessary to protect natural resources is important."

The CWQMC needs funding and additional staff to be more effective. Alternatively, there are other agencies that could coordinate monitoring programs.

"The CWQMC needs to focus on what they want to do – right now they are being opportunistic, which is good, but there needs to be a guiding strategy, and I think that is changing and a little unclear right now (likely because of a lack of funding)."

"A more Delta-focused group that actually does include hands-on monitoring might be better."

These other agencies that could coordinate monitoring include: "the Delta RMP and IEP." However, IEP will "need a better database system. They would need more contaminants experts, like aquatic toxicologists in their team. They are more fish centric."

"The Delta RMP provides the proper organizational structure to design, review, and report on new water quality monitoring activities in the Delta."

"The San Francisco Estuary Institute (SFEI) and its information management and accessibility services could be better utilized."

Data management needs to be improved.

"We are not making good use of the data we do collect and a key uncertainty is other people's QA/QC–there is a lot of data out there, whether or not it's useable is another question."

"Creation of data management plans should become standard operating procedures (SOPs) for all monitoring efforts to ensure that data and metadata are properly managed and stored for future use and access."

"Both the CWQMC and the IEP are potentially the best to coordinate data storage. The former is underfunded and understaffed. Alternatively, an NGO (such as SFEI) could do this."

"To share data means having a common way to link up the data geo-spatially. Therefore, first order is a minimum geo reference standard and SOPs should need to be developed and required for each record so data can be connected in the real world. Second, for years we have debated whose database platform water quality data should be housed in. This has always met both personal and agency philosophy challenges and resources issues. Third, existing systems have vocabulary comparability problems for similar categories of data, for example chemical name, or units of measure."

"The CWQMC Portal for the Delta has made great strides in bringing data together, mostly through the work of 34 North and the IEP to integrate data into scientific visualization products. Technology advancements are allowing us to think differently. Open data platforms are the new and most promising approach. It allows groups to keep their data systems, but place data sets outside of firewalls for access by tools to integrate. Vocabulary challenges are being tackled by software that can look for compatibility with similar names and connect the values. Programs still need to have sustainable data systems that provide similar fields including the above mentioned spatial reference data, and metadata as a way to evaluate the quality of the data. Real time sensor data is on the rise and available publically, but data quality review of these large data sets and metadata describing the quality is problematic."

Data Visualization

"The improvement that I would like to see is in data visualization. I know that SFEI is making progress on data visualization with their EnVis portal, and that Bay-Delta Live is working on visualization tools as well. But both are still well short of what is possible using commercial products designed for visualization of large and complex data."

"I believe centralization of Delta data in a single data warehouse and linking that data to powerful and flexible visualization tools would be a great investment, and speed our understanding of Delta processes."

There are some positive comments related to existing data management efforts.

"Many recent advances in data sharing and good models for data sharing e.g., Water Quality Exchange jointly developed by USEPA and USGS under the National Water Quality Monitoring Council."

"Data sharing is good and could be improved, but the CDEC (California Data Exchange Center) program and portal does an outstanding job."

"There has been substantial progress in agency recognition and commitment to data sharing."

"There are some redundancies in water quality monitoring and programs but there are advantages to having redundancy in the system."

Adaptive management is, in general, not a part of water quality programs. However, some agencies/programs are using adaptive management and can provide models for integrating adaptive management into water quality.

"We do not currently use an adaptive management approach in collecting water quality data, or to inform management decisions."

"Adaptive management in collecting water quality data is not particularly relevant for our agency. We monitor what is required by law (i.e., even though we haven't found certain constituents, we must continue to monitor for them) and what is necessary to continue to deliver high quality of water to our customers."

"We use a simple adaptive management approach. Data is first collected at key locations for a period of time, analyzed, and the program is then adjusted as needed to reflect the needs of our Agency."

"We use an adaptive management approach to actively conserve and protect ESA listed species and their habitat to meet recovery goals and objectives. We accomplish these goals through our coordination on regional monitoring efforts and engagement with various water quality stakeholders (state, federal, local, etc.). Our data needs and monitoring efforts are tied directly to the current and future threats to our species such as pesticides, heavy metals, sediment, etc."

"A good example of adaptive management is the SWRCB, SPoT (Stream Pollution Trends) program. This is a model that should be examined. They have a technical scientific review panel and input from entities. It has goals, assessment questions, very good analytical team and uses a diverse suite of test species to assess attainment of the assessment questions. They have reduced pollutants such as the OCs, PAHs, and at the same time looking forward to what pollutants needs to be included in next monitoring cycle based on the panel inputs too. Additionally, they are coordinating with CDPR to have better coordination on focused monitoring to evaluate the effectiveness of management decisions, such as pesticide use restrictions."

Funding is necessary for improvements in water quality monitoring and analysis.

"The Delta RMP is the umbrella program regularly monitoring contaminants in the Delta, yet they are focused on pesticides (as is the Irrigated Lands Regulatory Program) with some proposed future work on nutrients and mercury. They only monitor five peripheral sites coming into the Delta monthly and this is not sufficient either spatially or temporally. This doesn't provide enough information to perform mass balance, identify sources and sinks, or generate trend data for quite some time."

"Additionally, data management has been poor and inconsistent across the multiple agencies of IEP. DWR management commitment to applied database needs at IEP for water quality and biological data has been under-resourced for years and based on (Microsoft) Access data platforms. This needs to be better. USGS groups receiving any state or federal Delta money for Delta or watershed work needs to be held to providing data into designated systems in a more timely manner, not only their NWIS (National Water Information System) system."

"Currently, the CWQMC and its work groups operate largely on voluntary contributions of staff time and other resources. "

There is a need to understand the effects of changing Delta conditions and intended management actions on water quality, especially as it is clear that climate change and other factors in the future will bring about numerous changes.

"I think in addition to the general questions, you could have asked some questions specific to some ongoing or intended management actions, e.g., WaterFix tunnels, specific habitat restoration projects, the SRWTP conversion, Yolo Bypass, etc. For example, will these actions affect water quality in a part of/the whole Delta? Is the current water quality monitoring network sufficient to monitor and assess changes in water quality in specific parts and/or the whole Delta that may result from these actions? What monitoring and research is needed to determine if changes in water quality are due to these specific actions or something else?"

"Proposed changes in water conveyance and changes in hydrology related to climate change are likely to affect water quality."

It is not clear how water quality data are being used in management decisions, and whether the data are sufficient to support management decisions and policies.

There are "some questions specific to some ongoing or intended management actions, e.g., WaterFix tunnels, specific habitat restoration projects, the SRWTP conversion, Yolo Bypass, etc. For example, will these actions affect water quality in a part of/the whole Delta? Is the current water quality monitoring network sufficient to monitor and assess changes in water quality in specific parts and/or the whole Delta that may result from these actions? What monitoring and research is needed to determine if changes in water quality are due to these specific actions or something else?"

V. Concluding Thoughts

Many of the comments that we received in interviews and questionnaire responses concerned issues surrounding water quality monitoring. The Delta ISB is in the initial stages of developing a review of the Delta's extensive monitoring enterprise. For this reason, we have not emphasized monitoring in this review of water quality. However, this present review has clarified the need for the Delta ISB to examine specific issues related to monitoring and water quality, and these topics will be included in the monitoring enterprise review.

Based on this present review, we clearly see the need to document and evaluate water quality components that are being monitored, who is monitoring them, and the way and reasons that these components are monitored. The upcoming monitoring review will also include information about how monitoring data are being stored, analyzed, synthesized, communicated, and used in decision making. Moreover, we anticipate that the response of the agencies to the information provided in this water quality review will enable the monitoring enterprise review to better identify additional components that should be monitored and efficiently used in decision-making. We also anticipate that the information in this water quality review will enable the Delta ISB to identify appropriate focused research in conjunction with monitoring to help address uncertainties in scientific understanding of Delta water quality.

Water quality has many meanings, depending on management interests and a variety of other factors ranging from societal values to economic considerations. The mandates and perspectives of the managers and users of water quality information will also determine which constituents may be of concern, whether their concern is for human health, fisheries, drinking water, agricultural water, or other purposes. Although this report has not dealt in detail with source reduction, great advances have been made in this area in recent decades. Attention to source reduction clearly should continue as a key research and management priority for both point and non-point source discharges.

VI. Next Steps

As with many of the topics that the Delta ISB has reviewed, water quality remains an active and ongoing area of study in the Delta for scientists, managers and policy makers. Information about pesticides, CECs, nutrients, and HABs, and their effects on aquatic organisms and ecosystems, as well as implications for human health, is evolving, and we anticipate new information and scientific understanding will become available to better assist decision makers and enhance policy development. As a result, the Delta ISB is committed to undertake an active outreach effort and to engage agencies, the scientific community, and the Delta Science Program in ongoing discussions about the topics and recommendations presented in this review. The Delta ISB also recognizes the need for more studies that consider interactions between water quality and societal issues, including human health, economic considerations, and social justice.

Following completion of this review, the Delta ISB will prepare a summary sheet that will communicate key findings and recommendations to the broader community. We plan to report results from this review at meetings of the Delta Stewardship Council, the Delta Plan Interagency Implementation Committee (DPIIC), and the Bay-Delta Science Conference. We also plan to discuss the recommendations presented in this review with local agencies and to identify the best strategies for implementing them. These discussions may take several forms including meetings with local agencies, panel discussions and follow-ups with agency personnel and the academic community at Delta ISB meetings, or partnering with the Delta Science Program to co-organize a team or workshop focused on implementation of the recommendations presented in this review. We are also considering a post-review survey of local and state agencies to find out what recommendations they might be interested in being involved in implementing.

VII. Citations

Ackerman, J.T., Eagles-Smith, C.A., Heinz, G., De La Cruz, S.E., Takekawa, J.Y., Miles, A.K., Adelsbach, T.L., Herzog, M.P., Bluso-Demers, J.D., Demers, S.A., and Herring, G. 2014. Mercury in Birds of San Francisco Bay-Delta, California: Trophic Pathways, Bioaccumulation, and Ecotoxicological Risk to Avian Reproduction. US Geological Survey Report No. 2014-1251. https://pubs.er.usgs.gov/publication/ofr20141251

Anderson-Abbs, B., Howard, M., Taberski, K., and Worcester, K. 2016. California Freshwater Harmful Algal Blooms Assessment and Support Strategy: Strategic Plan- Phase 1. Surface Water Ambient Monitoring Program. http://www.waterboards.ca.gov/rwqcb2/water_issues/programs/SWAMP/HABstrategy_phase%201.pdf

Baginska B. 2015. Total Maximum Daily Load Selenium in North San Francisco Bay: Staff Report for Proposed Basin Plan Amendment. Oakland, CA: San Francisco Bay Regional Water Quality Control Board. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/seleniumtmdl.shtml

Baldwin, D.H., Spromberg, J.A., Collier, T.K., and Scholz, N.L. 2009. A fish of many scales: extrapolating sublethal pesticide exposures to the productivity of wild salmon populations. Ecological Applications 19: 2004–2015. https://doi.org/10.1890/08-1891.1

Berg, M. and Sutula, M. 2015. Factors Affecting Growth of Cyanobacteria with Special Emphasis on the Sacramento-San Joaquin Delta. Southern California Coastal Water Research Project Technical Report No. 869. http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_nutrient_research_plan/science_work_groups/2015_08_cyano_wp_final.pdf

Bernhoft, R.A. 2012. Mercury toxicity and treatment: a review of the literature. J Environ Public Health. http://dx.doi.org/10.1155/2012/460508

Biales, A.D., Denton, D.L., Riordan, D., Breuer, R., Batt, A.L., Crane, D.B., and Schoenfuss, H.L. 2015. Complex watersheds, collaborative teams: assessing pollutant presence and effects in the San Francisco Delta. Integrated Environmental Assessment and Management 11: 674–688. https://doi.org/10.1002/ieam.1633

Central Valley Water Board (Central Valley Regional Water Quality Control Board). n.d. Fact Sheet: CV-SALTS Releases New and Innovative Plan to Address Salt and Nitrates in Groundwater. https://www.cvsalinity.org/

Cayan, D., Maurer, E., Dettinger, M., Tyree, M., and Hayhoe, K. 2008. Climate change scenarios for the California region. Climatic Change 87(Suppl 1): S21–S42. http://dx.doi.org/10.1007/s10584-007-9377-6

Chen, W-H, Haunschild, K., Lund, J.R., and Fleenor, W. 2010. Current and long-term effects of Delta water quality on drinking water treatment costs from disinfection byproduct formation. San Francisco Estuary and Watershed Science 8(3). https://escholarship.org/uc/item/0qf4072h

Chen, L., Meseck, S.L., Roy, S.B., Grieb, T.M., and Baginska, B. 2012. Modeling fate, transport, and biological uptake of selenium in North San Francisco Bay. Estuaries and Coasts 35:1551–1570. http://dx.doi.org/10.1007/s12237-012-9530-y

Cloern, J.E., Knowles, N., Brown, L.R., Cayan, D., Dettinger, M.D., Morgan, T.L., Schoellhamer, D.H., Stacey, M.T., van der Wagen, M., Wagner, W., and Jassby, A.D. 2011. Projected evolution of California's San Francisco Bay-Delta-river system in a century of climate change. PLoS ONE 6(9): e24465. https://doi.org/10.1371/journal.pone.0024465

Connon, R.E., Geist, J., Pfeiff, J., Loguinov, A.V., D'Abronzo, L.S., Wintz, H., Vulpe, C.D., and Werner, I. 2009. Linking mechanistic and behavioral responses to sublethal esfenvalerate exposure in the endangered delta smelt; *Hypomesus transpacificus* (Fam. Osmeridae). BMC Genomics 10: 608. https://doi.org/10.1186/1471-2164-10-608

Cooke, J. 2016. Using recent science to advise the Delta methylmercury TMDL. Bay-Delta Science Conference Mercury Special Session, November 17, 2016. http://scienceconf2016.deltacouncil.ca.gov/content/using-recent-science-advise-delta-mercury-tmdl

Cutter, G.A. and Cutter, L.S. 2004. Selenium biogeochemistry in the San Francisco Bay estuary: changes in water column behavior. Estuarine, Coastal and Shelf Science 61: 463–476. https://doi.org/10.1016/j.ecss.2004.06.011

CWQMC (California Water Quality Monitoring Council). 2016. CyanoHAB Triggers. http://www.mywaterquality.ca.gov/monitoring_council/cyanohab_network/docs/triggers.pdf

Dahm, C.N., Parker, A.E., Adelson, A.E., Christman, M.A., and Bergamaschi, B.A. 2016. Nutrient dynamics of the Delta: effects on primary producers. San Francisco Estuary and Watershed Science 14(4). https://doi.org/10.15447/sfews.2016v14iss4art4

David, N., Gluchowski, N. Leatherbarrow, D.C., Yee, J.E., and McKee, D. 2015. Estimation of contaminant loads from the Sacramento-San Joaquin River Delta to San Francisco Bay. Water Environment Research 87: 334–346. https://doi.org/10.2175/106143015X14212658613721

Delta ISB (Delta Independent Science Board). 2011. Memo Re: Addressing multiple stressors and multiple goals in the Delta Plan. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-isb-isb-products-products-stressors/final-memo-phil-isenberg-delta-isb-addressing

Delta ISB (Delta Independent Science Board). 2015. Flows and Fishes in the Sacramento-San Joaquin Delta. Research Needs in Support of Adaptive Management. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-isb-s-final-report-flows-and-fishes-sacramento-san-joaquin-delta-research-needs-support

Delta ISB (Delta Independent Science Board). 2017. Review of Research on the Sacramento-San Joaquin Delta as an Evolving Place. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-evolving-place-final-v2

Deng, D.F., Hung, S.S., and Teh, S.J. 2007. Selenium depuration: residual effects of dietary selenium on Sacramento splittail (*Pogonichthys macrolepidotus*). Science of the Total Environment 377: 224–232. https://doi.org/10.1016/j.scitotenv.2007.02.025

Diamond, J.M., Latimer, H.A., Munkittrick, K.R., Thornton, K.W., Bartell, S.M., and Kidd, K.A. 2011. Prioritizing contaminants of emerging concern for ecological screening assessments. Environmental Toxicology and Chemistry 30: 2385–2394. https://doi.org/10.1002/etc.667

Dugdale, R.C., Wilkerson, F.P., Hogue, V.E., and Marchi, A. 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Estuarine, Coastal and Shelf Science 73: 17–29. https://doi.org/10.1016/j.ecss.2006.12.008

Feyrer F., Herbold, B., Matern, S.A., and Moyle, P.B. 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco Estuary. Environmental Biology of Fishes 67: 277–288. http://dx.doi.org/10.1023/A:1025839132274

Fleck, J.A., Ackerman, J.T., Eagles-Smit, C.A., Windham-Myers, L., Stewart, R., and Fujii, R. 2016. Building a scientific foundation to manage mercury in the San Francisco Estuary. Bay-Delta Science Conference Mercury Special Session, November 17, 2016.

Fleenor, W., Hanak, E., Lund, J., and Mount, J. 2008. Delta Hydrodynamics and Water Quality with Future Conditions. Appendix C to Comparing Futures for the Sacramento-San Joaquin Delta. San Francisco, CA: Public Policy Institute of California. http://www.ppic.org/content/pubs/other/708EHR_appendixC.pdf

Fong, S., Louie, S., Werner, I., Davis, J., and Connon, R.E. 2016. Contaminant effects on California Bay-Delta species and human health. San Francisco Estuary and Watershed Science 14(4). https://doi.org/10.15447/sfews.2016v14iss4art5

Hamilton, S.J. 2004. Review of selenium toxicity in the aquatic food chain. Science of the Total Environment 326: 1–31. https://doi.org/10.1016/j.scitotenv.2004.01.019

Healey, M.C., Dettinger, M.D., and Norgaard, R.B. (eds). 2008. The State of Bay-Delta Science, 2008. Sacramento, CA: CALFED Science Program.

James, A.C., Brandenberger, J.M., Dutch, M., Hardy, J., Lester, D., Norton, D., O'Neill, S.M., Redman, S., Schultz, I.R., Sullivan, C., and West, J.W. 2015. Contaminants of Emerging Concern: A Prioritization Framework for Monitoring in Puget Sound. https://www.eopugetsound.org/sites/default/files/features/resources/CEC_Prioritization_White_Paper_2015-02-28.pdf

Jassby, A.D., Cloern, J.E., and Cole, B.E. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. Limnology and Oceanography 47: 698–712. https://doi.org/10.4319/lo.2002.47.3.0698

Jassby, A. 2008. Phytoplankton in the upper San Francisco Estuary: recent biomass trends, their causes, and their trophic significance. San Francisco Estuary and Watershed Science 6(1). https://escholarship.org/uc/item/71h077r1

Johns, C., Luoma, S. N., and Elrod, V. 1988. Selenium accumulation in benthic bivalves and fine sediments of San Francisco Bay, the Sacramento-San Joaquin Delta, and selected tributaries. Estuarine, Coastal and Shelf Science 27: 381–396. https://doi.org/10.1016/0272-7714(88)90095-9

Krabbenhoft, D.P., Gilmour, C., and Kidd, K. 2016. Overview of ISP's assessment of current mercury knowledge in the Bay-Delta. Bay-Delta Science Conference Mercury Special Session, November 17, 2016.

Kratzer, C.R., Kent, R., Seleh, D.K., Knifong, D.L., Dileanis, P.D., and Orlando, J.L. 2011. Trends in Nutrient Concentrations, Loads, and Yields in Streams in the Sacramento, San Joaquin, and Santa Ana Basins, California, 1975–2004. Denver, CO: US Department of the Interior, US Geological Survey. Scientific Investigations Report 2010-5228. http://pubs.usgs.gov/sir/2010/5228/pdf/sir20105228.pdf

Kraus, T.E.C., Bergamaschi, B.A., Hernes, P.J., Spencer, R.G.M, Stepanauskas, R., Kendall, C., Losee, R.F., and Fujii, R. 2008. Assessing the contribution of wetlands and subsided islands to dissolved organic matter and disinfection byproduct precursors in the Sacramento-San Joaquin River Delta: a geochemical approach. Organic Geochemistry 39: 1302–1318. https://doi.org/10.1016/j.orggeochem.2008.05.012

Laetz, C.A., Baldwin, D.H., Collier, T.K., Herbert, V., Stark, J.D., and Scholz, N.L. 2009. The synergistic toxicity of pesticide mixtures: implications for risk assessment and the conservation of Pacific salmon. Environmental Health Perspectives 117: 348–353. https://doi.org/10.1289/ehp.0800096

Laetz, C.A., Baldwin, D.H., Hebert, V.R., Stark, J.D., and Scholz, N.L. 2014. Elevated temperatures increase the toxicity of pesticide mixtures to juvenile Coho salmon. Aquatic Toxicology 146: 38–44. https://doi.org/10.1016/j.aquatox.2013.10.022

Laetz, C.A., Hecht, S.A., Incardona, J.P., Collier, T.K., and Scholz, N.L. 2015. Ecotoxicological risk of mixtures in: C. Amiard-Triquet, J.-C. Amiard, and C. Mouneyrac (eds) Aquatic Ecotoxicology: Advancing Tools for Dealing with Emerging Risks. Elsevier. pp 441–462. https://doi.org/10.1016/B978-0-12-800949-9.00018-8

Lehman, P.W., Boyer, G., Hall, C., Waller, S., and Gehrts, K. 2005. Distribution and toxicity of a new colonial *Microcystis aeruginosa* bloom in the San Francisco Bay Estuary, California. Hydrobiologia 541: 87–90. https://doi.org/10.1007/s10750-004-4670-0

Lehman, P.W., Teh, S.J., Boyer, G.L., Nobriga, M.L., Bass, E., and Hogle, C. 2010. Initial impacts of *Microcystis aeruginosa* blooms on the aquatic food web in the San Francisco Estuary. Hydrobiologia 637: 229–248. https://doi.org/10.1007/s10750-009-9999-y

Lehman, P.W., Marr, K., Boyer, G.L., Acuna, S., and Teh, S.J. 2013. Long-term trends and causal factors associated with *Microcystis* abundance and toxicity in San Francisco Estuary and implications for climate change impacts. Hydrobiologia 718: 141–158. https://doi.org/10.1007/s10750-013-1612-8

Linares-Casenave, J., Linville, R., Van Eenennaam, J.P., Muguet, J.B., and Doroshov, S.I. 2015. Selenium tissue burden compartmentalization in resident white sturgeon (*Acipenser transmontanus*) of the San Francisco Bay Delta estuary. Environmental Toxicology and Chemistry 34: 152–160. http://dx.doi.org/10.1002/etc.2775

Lund, J.R. 2016. California's agricultural and urban water supply reliability and the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 14(3). http://dx.doi.org/10.15447/sfews.2016v14iss3art6

Lund, J., Hanak, E., Fleenor, W., Howitt, R., Mount, J., and Moyle, P. 2007. Envisioning Futures for the Sacramento-San Joaquin Delta. San Francisco, CA: Public Policy Institute of California. http://www.ppic.org/publication/envisioning-futures-for-the-sacramento-san-joaquin-delta/

Luoma, S.N. and Presser, T.S. 2004. Forecasting Selenium Discharges to the San Francisco Bay-Delta Estuary: Ecological Effects of a Proposed San Luis Drain Extension. U.S. Geological Survey Open-File Report 00-416. https://pubs.usgs.gov/pp/p1646/

Luoma, S., Anderson, S., Bergamaschi, B., Holm, L., Ruhl, C., Schoellhamer, D., and Stewart, R. 2008. Chapter 3. Water Quality. The State of Bay-Delta Science. p. 55.

Luoma, S.N., Dahm, C.N., Healey, M., and Moore, J.N. 2015. Challenges facing the Sacramento-San Joaquin Delta: complex, chaotic, or simply cantankerous? San Francisco Estuary and Watershed Science 13(3). http://dx.doi.org/10.15447/sfews.2015v13iss3art7

Medellin-Azuara, J., Hanak, E, Howitt, R.E., Fleenor, W.E., and Lund, J.R. 2014. Agricultural losses from salinity in California's Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 12(1). https://escholarship.org/uc/item/4b7295m9

Mehinto, A. 2017. Test-driving a new CEC framework to effectively screen for chemical occurrence and effects in aquatic environments. Presented at SWAMP Watershed Health Indicator and Data Science Symposium, June 29-30, 2017. https://www.waterboards.ca.gov/resources/data_databases/docs/wq_science_sym/agenda_day1/alvine_mehinto_abstr.pdf

Moore, M.T., Denton, D.L., Cooper, C.M., Wrysinski, J., Miller, J.L., Werner, I., Horner, G., Crane, D., Holcomb, D.B., and Huddleston, G.M. 2011. Use of vegetated agricultural drainage ditches to decrease pesticide transport from tomato and alfalfa fields in California, USA. Environmental Toxicology and Chemistry 30: 1044–1049. http://dx.doi.org/10.1002/etc.474

Mount, J., Bennett, W., Durand, J., Fleenor, W., Hanak, E., Lund, J., and Moyle, P. 2012. Aquatic ecosystem stressors in the Sacramento-San Joaquin Delta. San Francisco, CA: Public Policy Institute of California. http://www.ppic.org/content/pubs/report/R_612JMR.pdf

Mount, J., Twiss, R., and Adams, R.M. 2006. The Role of Science in the Delta Visioning Process. Draft report of the Delta Science Panel of the CALFED Bay-Delta Science Program.

Noon, B.R., Raimondi, P., MacWilliams, M., and Stewart-Oaten, A. 2017. Independent Panel Review of the Delta Regional Monitoring Program (Delta RMP) Monitoring Design. Phase II: Final Review. http://deltacouncil.ca.gov/docs/final-report-2017-independent-review-panel-delta-regional-monitoring-program-delta-rmp

NRC (National Research Council). 2012. Sustainable Water and Environmental Management in the California Bay-Delta. Washington, DC: The National Academies Press. https://doi.org/10.17226/13394

NRC (National Research Council). 1980. Drinking Water and Health, Volume 2. Washington, DC: The National Academies Press. https://doi.org/10.17226/1904

Nichols, F.H., Cloern, J.E., Luoma, S.N., and Peterson, D.H. 1986. The modification of an estuary. Science 231: 567–573. https://doi.org/10.1126/science.231.4738.567

Orlando, J.L., McWayne, M., Sanders, C., and Hladik, M. 2013. Dissolved pesticide concentrations in the Sacramento-San Joaquin Delta and Grizzly Bay, California. 2011-12: U.S. Geological Survey Data Series 779. https://pubs.er.usgs.gov/publication/ds779

Parker, A.E., Dugdale, R.C., and Wilkerson, F.P. 2012. Elevated ammonium concentrations from wastewater discharge depress primary productivity in the Sacramento River and the Northern San Francisco Estuary. Marine Pollution Bulletin 64: 574–586. https://doi.org/10.1016/j.marpolbul.2011.12.016

Presser, T.S. and Luoma, S.N. 2013. Ecosystem-scale selenium model for the San Francisco Bay-Delta Regional Ecosystem Restoration Implementation Plan. San Francisco Estuary Watershed Sciences 11(1). http://dx.doi.org/10.15447/sfews.2013v11iss1art2

Ralston, N.V. and Raymond, L.J. 2010. Dietary selenium's protective effects against methylmercury toxicity. Toxicology 278: 112–123. https://doi.org/10.1016/j.tox.2010.06.004

Raimondi, P., Noon, B., MacWilliams, M., Stewart-Oaten, A., and Valoppi, L. 2016. Independent Panel Review of the Delta Regional Monitoring Program (Delta RMP) Monitoring Design. Phase I: Initial Review. http://deltacouncil.ca.gov/docs/science-program-product/independent-panel-review-delta-regional-monitoring-program-delta-rmp

Sandheinrich, M.B. and Wiener, J.G. 2011. Methylmercury in freshwater fish: recent advances in assessing toxicity of environmentally relevant exposures. Boca Raton, FL: CRC Press. http://dx.doi.org/10.1201/b10598-6

Schoellhamer, D.H., Wright, S.A., Monismith, S.G., and Bergamaschi, B.A. 2016. Recent advances in understanding flow dynamics and transport of water-quality constituents in the Sacramento-San Joaquin River Delta. San Francisco Estuary and Watershed Science 14(4). https://doi.org/10.15447/sfews.2016v14iss4art1

SFEI (San Francisco Estuary Institute). 2013. The Pulse of the Bay: Contaminants of Emerging Concern. SFEI Contribution #701. Richmond, CA. http://www.sfei.org/sites/default/files/biblio_files/Pulse_2013_CECs.pdf

Shilling F., White, A., Lippert, L., and Lubell, M. 2010. Contaminated fish consumption in California's Central Valley Delta. Environmental Research 110: 334–344. https://doi.org/10.1016/j.envres.2010.02.002

Sinha E., Michalak, A.M., and Balaji, V. 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science 357: 405–408. https://doi.org/10.1126/science.aan2409

Slotten, D., Ayers, S.M., Suchanek, T.H., Weyand, R.D., Liston, A.M., Asher, C., Nelson, D.C., and Johnson, B. 2002. The Effects of Wetland Restoration on the Production and Bioaccumulation of Methylmercury in the Sacramento-San Joaquin Delta, California. Assessment of Ecological and Human Health Impacts of Mercury in the San Francisco Bay-Delta Watershed, A CALFED Bay-Delta Program Project. October 1999 – March 2003. DRAFT FINAL REPORT.

Sobczak, W.V., Cloern, J.E., Jassby, A.D., Cole, B.E., Schraga, T.S., and Arnsberg, A. 2005. Detritus fuels ecosystem metabolism but not metazoan food webs in San Francisco Estuary's freshwater Delta. Estuaries 28: 124–137. https://doi.org/10.1007/BF02732759

Stewart, A.R., Luoma, S.N., Elrick, K.A., Carter, J.L., and van der Wegen M. 2013. Influence of estuarine processes on spatiotemporal variation in bioavailable selenium. Marine Ecology Progress Series 492: 41–56. https://doi.org/10.3354/meps10503

Stewart, A.R., Windham Myers, L., Fleck, J.A., Lucas, L., Bishop, J., Martyr, R., Marvin-DiPasquale, M., Knowles, N., van der Wegen, M., and Minikowski Achete, F. 2018. 3D modeling of methylmercury as a conservative tracer in San Francisco Bay-Delta: lessons learned about the Delta Doughnut and critical processes of fate and transport. Delta Tributaries Mercury Council.

Stewart, A.R., Luoma, S.N., Schlekat, C.E., Doblin, M.A., and Hieb, K.A. 2004. Food web pathway determines how selenium affects aquatic ecosystems: a San Francisco Bay case study. Environmental Science & Technology 38(17): 4519–4526. https://doi.org/10.1021/es0499647

Sutton, R. and Sedlak, M. 2015. Contaminants of Emerging Concern in San Francisco Bay: A Strategy for Future Investigations. 2015 Update. SFEI Contribution #761. Richmond, CA.

SWRCB (State Water Resources Control Board). 2015. Annual Compliance Report. Sacramento, CA. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/dwdocuments/2015/2015_acr.pdf

Tetra Tech. 2017. Proposed Plan for Enhanced Selenium Monitoring in the Delta to Track Future Loading Changes Associated with the California WaterFix Project. Prepared by Tetra Tech for the Western States Petroleum Association.

USEPA (United States Environmental Protection Agency). 2016. Aquatic Life Criteria-Selenium Documents. Washington DC. https://www.epa.gov/wqc/aquatic-life-criterion-selenium-documents

USEPA (United States Environmental Protection Agency). 2017. CyanoHAB Guidelines and Recommendations. https://www.epa.gov/nutrient-policy-data/guidelines-and-recommendations

Ward, A.K. and Paerl, H.W. 2017. Delta Nutrients Forms and Ratios Public Workshop: Role of Nutrients in Shifts in Phytoplankton Abundance and Species Composition in the Sacramento-San Joaquin Delta. Nutrient Stakeholder & Technical Advisory Group. http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_nutrient_research_plan/science_work_groups/20170530_phyto_wp.pdf

Wiener, J.G., Gilmour, C.C., and Krabbenhoft, D.P. 2003. Mercury Strategy for the Bay-Delta Ecosystem: A Unifying Framework for Science, Adaptive Management, and Ecological Restoration. Final Report to the California Bay-Delta Authority.

Windham-Myers, L., Fleck, J.A., Lucas, L., Bishop, J., Stewart, A.R., Martyr, R., and Marvin-DiPasquale, M. 2016. The Delta Doughnut: a persistent pattern for methylmercury metrics. Bay-Delta Science Conference Mercury Special Session, November 17, 2016. http://scienceconf2016.deltacouncil.ca.gov/content/delta-doughnut-persistent-pattern-methylmercury-metrics

Wood, M.L., Foe, C.G., Cooke, J., and Louie, S.J. 2010. Sacramento-San Joaquin Delta Estuary TMDL for Methylmercury. Staff Report. Rancho Cordova, CA: Central Valley Regional Water Quality Control Board. https://www.waterboards.ca.gov/rwqcb5/water_issues/tmdl/central_valley_projects/delta_hg/archived_delta_hg_info/april_2010_hg_tmdl_hearing/apr2010_tmdl_staffrpt_final.pdf

Yang, D-Y., Chen, Y-W., Gunn, J. M., and Belzile, N. 2008. Selenium and mercury in organisms: interactions and mechanisms. Environmental Reviews 16: 71–92. https://doi.org/10.1139/A08-001

Zegura, B., Sedmak, B., and Filipi, M. 2003. Microcystin-LR induces oxidative DNA damage in human hepatoma cell line HepG2. Toxicon 41: 41–48. https://doi.org/10.1016/S0041-0101(02)00207-6

VIII. Appendices

Appendix A: Perceptions about Water Quality in the Delta: Responses to the Delta ISB Questionnaire

Quantitative Evaluations and Comments
The Delta ISB developed and sent out a questionnaire about the current state of water quality analysis being conducted in the Delta. Twenty-three respondents filled out the questionnaire and several others were interviewed in person. Questions were scored numerically in terms of a series of choices from strongly disagree with the statement to strongly agree. Respondents were also asked to make narrative comments for each question if they wished. A graphical presentation of responses received and examples of representative supportive comments follows below. Because perceptions about water quality can influence actions, consideration of these comments is helpful in making this report complete and useful.

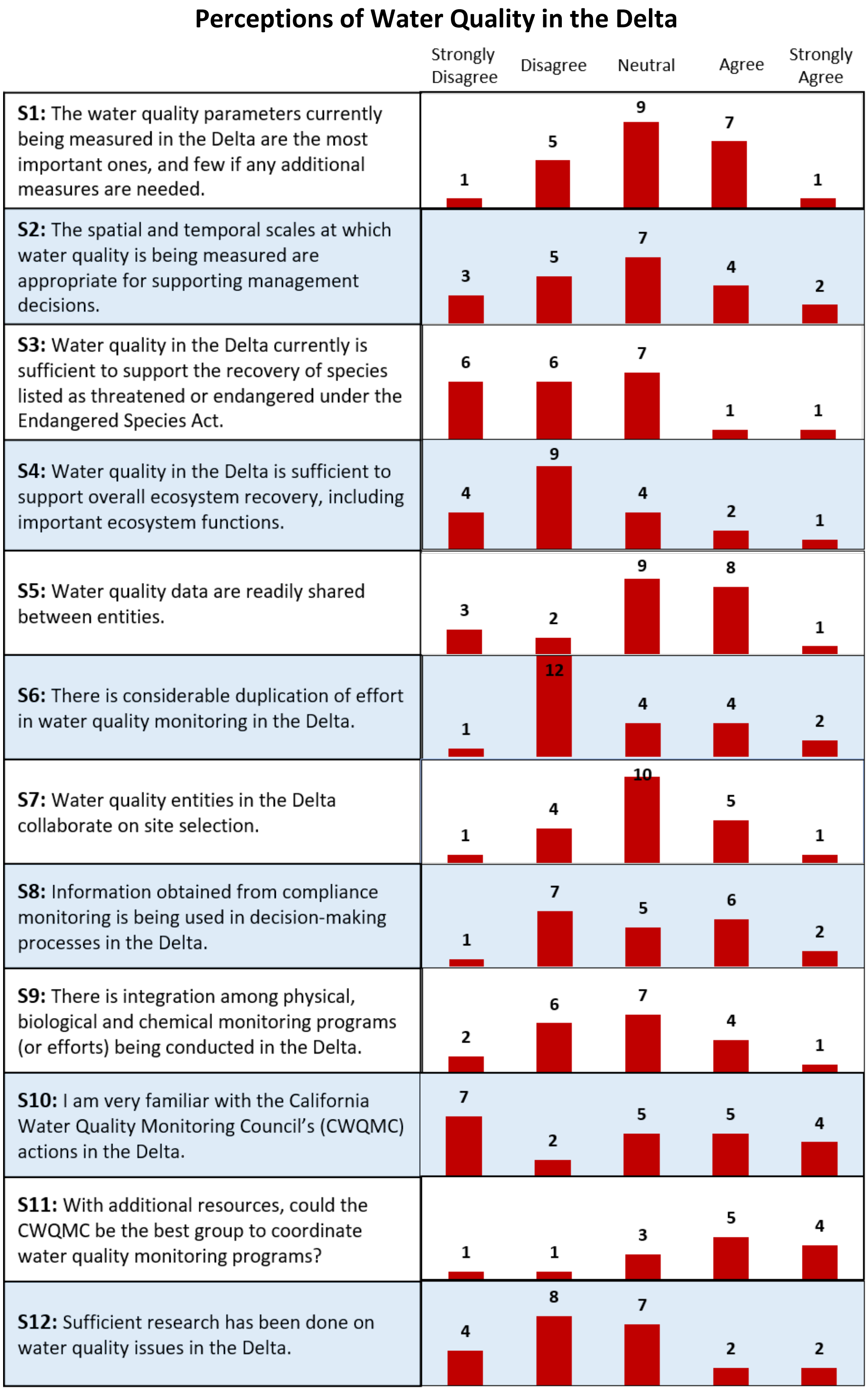

Figure 1. Summary of responses to the questionnaire that the Delta ISB distributed to assess perceptions about water quality across agencies and programs. As many as 23 responses were provided. The figure illustrates the diverse perspectives across the entities that are involved in water quality issues.

Question 1. The water quality parameters currently being measured in the Delta are the most important ones, and few if any additional measures are needed.

The responses to this question produced a normal distribution with the range among five categories of strongly disagree to strongly agree being 4%, 22%, 39%, 30%, and 4%, respectively. This question produced many responses about the need for additional components to be examined:

- "Sucralose;"
- "The fate, transport, and ecological impact of sediment bound contaminants (e.g., pyrethroid pesticides and mercury), PPCPs, and the long-term toxicological effects (cumulative) of altered water quality;"
- "Toxicity testing, as well as, other evaluations of xenobiotic impacts to aquatic life physiology, behavior, etc." are needed;
- pyrethroids: "Adverse impacts to aquatic life (e.g., LC50s, reduced fecundity) have been observed at pyrethroid concentrations 2-5 times lower than analytical methods can quantify;"
- "In situ ammonium and phosphate; strategically-placed continuous sensors that provide information about phytoplankton size and rudimentary taxonomic class" are needed; as are "multi-wavelength fluorescence sensors that permit tracking of wastewater. But, perhaps most importantly, sensors that can actually see the main HABs we have here;"
- "Aggregate sampling, or more important bioassay work at the boundary conditions and sources should be conducted;"
- "FDOM (Organic Carbon), Chlorophyll a;"
- "Methylmercury, pharmaceuticals, nutrients, algal toxins" should be measured at more sites;
- "Metals, e.g., Cu, Ni, which are naturally occurring and have anthropogenic sources, not because of water quality concern but to help understand presence and sources of other pollutants of concern" should be examined;
- "*Hyalella* and *Chironimus* toxicity testing. CECs (pharmaceuticals and personal care products, flame retardants). Sublethal fish effects."

Clearly, both the numerical responses and comments to this question indicate that there are different perceptions about whether current parameters being measured in the Delta are sufficient. Responses may reflect interests of either the agencies or the person responding to the questionnaire. However, several respondents mentioned a need for more mercury and pesticide testing.

Question 2. The spatial and temporal scales at which water quality is being measured are appropriate for supporting management decisions.

Responses again indicated a normal distribution with the range among five categories of strongly disagree to strongly agree being 14%, 24%, 33%, 19%, and 10%, respectively. Specific responses included:

- "For salinity and flow, measurements are adequate, which are in the permits. For toxicity and sublethal effects, there is inadequate spatial and temporal measurements. Discrete grab samples do not adequately capture the heterogeneity of the system;"

- "Pesticides (e.g., pyrethroids) should be measured at higher temporal resolution; nutrients fate and transport (nitrates and ammonia) and methylmercury production should be measured at higher spatial and temporal scales to identify when and where hot spots and hot moments occur, as well as what the drivers are that influence the pools and fluxes of these constituents in the Delta;"
- "We need to test key indicator sites with a much higher frequency. We need to understand the tributaries which are the inputs to the Delta…We should conduct more frequent sampling here to ascertain the major inputs to the system;"
- "Nearly all of the parameters that are the focus of this review suffer from a lack of consistent and adequate temporal and spatial coverage;"
- "Depending on what you want to do and what your goal is – modeling requires more. I don't think we are in a situation where any parameter is measured too much (at this point);"
- "We have insufficient nutrients and CECs data. We probably can cut back on mercury and methylmercury monitoring given our understanding of their presence, sources, and management actions;"
- "Measurements need to be made at higher frequencies at more flow stations to get at processes – a good long-term high frequency base monitoring network needs to be developed that should cover the entire estuary;"
- "Focusing on collection of in situ high-frequency data; before adding parameters or stations, I would think about redirecting the current efforts;"
- "We also have yet to make an effort to harmonize instrument calibration and data collection between the agencies that collect continuous water quality information in the Delta;"
- "Ammonium, phosphate and additional phytoplankton parameters were measurements that would help us better manage the system, but they should be deployed strategically. They will help us assess in real time the effects of management decisions on aquatic food webs;"
- "Additional frequency for SWAMP's SPoT monitoring would be beneficial. Their current monitoring frequency was deemed adequate for a relatively stable system, but the Delta is very dynamic;"
- "Spatial and temporal sampling methodology needs to take into account the hydrodynamics of the system."

Question 3. Water quality in the Delta currently is sufficient to support the recovery of species listed as threatened or endangered under the Endangered Species Act.

Responses were skewed in the direction of strongly disagree with the five categories from strongly disagree to strongly agree being 29%, 29%, 33%, 5%, and 5%, respectively. Many of the comments on this question refer back to the answers given above for Question 2. Specific responses included:

- "2 areas that need exploring–>timing of first flush (and what's in it and what the effects are) as it lines up with migration, and spraying for aquatic veg and the effects of the spraying;"
- "There are currently only about 10 water quality objectives or criteria for pesticides in the

Central Valley, while over 1000 pesticide active ingredients are used in California… Herbicides likely reduce primary productivity in the Delta;”

- “USGS pesticide monitoring of the Sacramento and San Joaquin river inputs in the Delta showed that all samples contained mixtures of 3 to 14 pesticides. Pesticides reduce the benefit of the already limited aquatic life habitat in the Delta. Most of the Delta and tributaries are currently 303(d) listed for unknown toxicity, pesticides, and metals;”
- “Dissolved oxygen objectives (6 mg/L) in the Stockton Deep Water Ship Channel were developed to be barely adequate to allow salmonid passage during fall-run adult migration;”
- “The POD has occurred concurrently with reduced phytoplankton and zooplankton abundance, which make up the food web. The cause of the decline of these lower trophic levels is unknown; however, some of the hypothesized causes include invasive clams, ammonia discharges from Sacramento Regional San or adjustments to nutrient ratios, and pesticide discharges. Monitoring will be necessary to partition the possible impacts of these and other factors to food web and fish declines;”
- “Until about a decade ago, fish were thought to be insensitive to mercury toxicity; however, research has found that they are as sensitive, if not more sensitive as humans;”
- “The impacts of current pesticides used primary in agricultural landscapes; pollutants in urban stormwater runoff; production of methylmercury as a result of land use disturbance, and pharmaceuticals are aspects of water quality that hinder recovery;”
- “Nutrients are probably the biggest water quality issue for endangered species recovery. Pesticides probably have more localized impacts but cumulatively may be important;”
- “Sublethal effects (i.e., endocrine disruption) of pharmaceuticals and contaminants of emerging concern should be evaluated more;”
- “We know that sometimes, in some places, water in the Delta is toxic to test organisms which means it's likely one factor that's hindering recovery. What continues to be unclear because of insufficient monitoring is how widespread and severe (by itself, and relative to other stressors) this problem really is and how it affects the habitats favored by endangered species. We also don't always know what caused the observed toxicity;”
- “It is my understanding that folks currently believe species declines in the Bay-Delta are related to disruption in food webs consequent to a change in phytoplankton community composition. If we seek to restore these food webs, we need better information about them then can be obtained in weekly or monthly grab sampling programs;”
- “Whether contaminants helped shift the ecosystem to favor invasive weeds is yet unknown, but it seems clear that these weeds have increased clarity, reduced DO and flow, and provided cover for predators; all hindering the recovery of these fish;”
- “Pesticides and CECs having sublethal or food web effects. Low DO in back sloughs. Also physical habitat and temperature are hurting resiliency;”

Question 4. Water quality in the Delta is sufficient to support overall ecosystem recovery, including important ecosystem functions.

Responses were somewhat skewed in the direction of strongly disagree in five categories from strongly disagree to strongly agree, with responses being 20%, 45%, 20%, 10%, and 5%, respectively. Several of the responses referred back answers given to previous questions. Additional comments included:

- “Continued support of the clear water lake concept to maintain low salinity at the pumps has created an altered ecosystem that eliminates natural tidal flux. The loss of seasonal flooding of wetlands and subsequent drainage has created greater water clarity and loss of transported organic matter and food chain organisms. The lower estuary looks like a freshwater lake, not a tidal marsh;”
- “Ecological function in the Delta is altered by dramatic changes in land use, such as increased pesticide application and nutrient inputs to salmonid-bearing streams, that far exceed the rate of storage or the ability of the Delta to 'process' these constituents. Some of the underlying aspects/mechanisms (hydrology, habitat, climate change) that drive these ecological processes are poorly understood. How do these drivers affect listed species and what are the effects at various level (sublethal); and spatial and temporal scales;”
- “Endangered species depend on a functioning ecosystem/ecosystem functions that support the reproduction, growth, and survival...;”
- “The Delta's water quality is not sufficient to support overall ecosystem recovery;”
- “There is reduced abundance of key species: some due to food web effects and some to direct effects of contaminants (e.g., straying, inhibiting olfactory queues for ripe females and predators, reduced fecundity). The energetic cost of coping with contaminants can decrease food intake and this is particularly concerning for species already known to be starving;”
- “The effects of multiple compounds and the effects of these compounds combined with other abiotic stressors (e.g., increased temperature, increased salinity, reduced habitat range) needs more attention along with the sublethal effects that can lead to decreased abundance or genetic diversity.”

Several respondents indicated that high nutrient loads, eutrophication, methylmercury, pesticides, and CECs are very important in preventing recovery.

Question 5. Water quality data are readily shared between entities.

Responses were skewed in the direction of strongly agree in the five categories of strongly disagree to strongly agree, with the range being 13%, 9%, 39%, 35%, and 4%, respectively. Several comments were provided in the responses:

- “To share data means having a common way to link up the data geo-spatially. Therefore, first order is a minimum geo reference standard and SOPs should need to be developed and required for each record so data can be connected in the real world. Second, for years we have debated whose database platform water quality data should be housed in. This has always met both personal and agency philosophy challenges and resources issues. Third, existing systems have vocabulary comparability problems for similar categories of data for example chemical name, or units of measure. The CWQMC for the Delta has made great strides in bringing data together, mostly through the work of 34 North and the IEP to integrate data into scientific visualization products. Technology advancements are allowing us to think differently. Open data platforms is the new and most promising approach. It allows groups to keep their data systems, but place data sets outside of firewalls for access by tools to integrate. Vocabulary challenges are being tackled by software that can look for compatibility with similar names and connect the values.

Programs still need to have sustainable data systems that provide similar fields including the above mentioned spatial reference data, and metadata as a way to evaluate the quality of the data. Real time sensor data is on the rise and available publically, but data quality review of these large data sets and metadata describing the quality is problematic;"

- "Need a central repository that is more regularly updated. MWQI is good but QA/QC slows time for data to be posted. CDEC is real time but a big problem is that data gaps (due to problems with the radio telemetry) or "typos" are not subsequently added or corrected;"
- "Data is not shared or easily available by (i) the universities and (ii) local agencies. This is often a result of no readily available public platform to submit/upload this data to;"
- "Sharing is increasing, particularly between Bay and Delta monitoring efforts for nutrients, but improvements needed to support nutrient water quality modeling. We could improve sharing of Bay CECs monitoring with the Delta;"
- "The improvement that I would like to see is in data visualization;"
- "Generally, groups seem to have less politically-induced inhibition when it comes to sharing water quality data than biological survey data, but how that data is shared needs facilitation."

Question 6. There is considerable duplication of effort in water quality monitoring in the Delta.

Responses were skewed in the direction of strongly disagree in five categories of strongly disagree to strongly agree with the range being 4%, 52%, 17%, 17%, and 9%, respectively. Strong opinions were expressed in the comments received:

- "This is a reoccurring fallacy I have heard about all monitoring programs across the state. The point is each entity develops Data Quality Objectives based on mandates and management questions, and these determine frequency, location, data quality, and parameters. Rarely do these match someone else's needs. Some of the categories include research, compliance, and ambient for trends, with each one requiring different species;"
- "There is redundancy throughout the Delta for some water quality constituents by different state and federal agencies;"
- "There is some duplication, but I actually find some (but not too much) redundancy to be a good thing. I think a bigger problem is inefficient coordination of field runs to service moored stations;"
- "There is so little contaminant monitoring, I no longer see the duplication there once was."

Question 7. Water quality entities in the Delta collaborate on site selection.

Responses fell into a normal distribution in a range of strongly disagree in five categories of strongly disagree to strongly agree being 5%, 19%, 48%, 24%, and 5%, respectively. No additional comments were received for this question.

Question 8. Information obtained from compliance monitoring is being used in decision-making processes in the Delta.

Responses were skewed in both the direction of strongly disagree and strongly agree in five categories of strongly disagree to strongly agree being 5%, 33%, 24%, 29%, and 10%, respectively. However, no additional comments were added in response to this question.

Question 9. There is integration among physical, biological and chemical monitoring programs (or efforts) being conducted in the Delta.

Responses were slightly skewed to disagree with this statement with a range in five categories from strongly disagree to strongly agree being 10%, 30%, 35%, 20%, and 5%, respectively. Several comments were received:

- "Top down management direction" is needed;
- "Agencies and programs tend to naturally be siloed. It takes time and effort to coordinate and integrate. The way to counter this is to present cohesive strategies on answering priority management questions in the Delta. This requires buy-in and agency or entity management commitment to the process. This can be done by addressing and prioritizing regulatory information needs, then grouping like purposes and missions. Work teams or study groups are then formed based on the grouping. Within each work team, individual program's mandates and needs are discussed and recognized. Resulting study efforts are designed to meet as many of the intersecting information needs, recognizing that some may not be met by an integrated monitoring or study effort and will need to exist outside the coordinated effort. There still should be a data connection where information can flow. Work teams need to include the appropriate multidisciplinary members, such a biologists, geologists, water quality experts and data management resources;"
- There is a need for "(1) continued support of cross-discipline workshops like the Bay-Delta Science Conference, (2) a public data repository for local agencies or universities to submit data, and (3) development and support of a easy to use searchable water quality platform that links to the share repository and various State/federal databases;"
- There is a "Need to have good discussions and recommendations about (1) timing of samples evaluated (coverage over a range of seasons) to capture the breadth of potential chemicals, (2) location of the samples in relationship to the discharge from point sources and the runoff from agriculture, and (3) sample type to be more representative in relation to the frequency of the parameter" under investigation;
- "Integration might be improved by having a third party evaluate the monitoring programs, make recommendations for better integration, and facilitating discussions among monitoring entities;"
- "In some cases, the integration is great. In other cases, I read papers on water quality that lack recognition of the physical processes and misinterpret the data because transport and mixing are neglected."

Question 10. I am very familiar with the CWQMC actions in the Delta.

Responses were somewhat evenly distributed over the range of the five categories from strongly disagree to strongly agree being 30%, 9%, 23%, 22%, and 17%, respectively. No additional comments were received for this question.

Question 11. With additional resources, could the CWQMC be the best group to coordinate water quality monitoring programs? If not, what is needed to make them even more effective? If the

CWQMC is not the best group to coordinate water quality monitoring programs, is there an entity that could better perform this function?

Responses were skewed in the direction of strongly disagree in the range of five categories from strongly disagree to strongly agree being 20%, 45%, 20%, 10%, and 5%, respectively. The many comments received reflect the diversity of opinions on this issue:

- "Currently the CWQMC only has 1.3 staff to work towards achieving the goal of improved coordination of monitoring efforts. Additional resources (staff and funding) would most certainly help to improve the CWQMC's ability to work towards this goal;"
- "Dedicated funding is needed to allow each relevant agency to participate in the CWQMC's work group efforts and resources to enhance data management, documentation, and sharing between agencies. The CWQMC would be more effective if its membership were to be expanded to include additional governmental organizations that serve key roles in water quality and ecosystem health monitoring, assessment, and reporting;"
- "A Google search barely finds anything on the CWQMC. Clearly, there is much work to be done if this is to be a public WQ portal for the Delta;"
- "The CWQMC is a great platform for allowing multiple entities to address statewide issues, such as data quality, data sharing, and emerging problems such as CyanoHABs. The portal approach for the Delta is a good platform for access and visualization. I believe IEP is the best entity but water quality issues in the ecosystem are underrepresented in the IEP study design, which is decided largely by fisheries and food chain biologists. Additionally, the SWRCB's Division of Water Rights' scientific participation technically needs to be stronger, since flow and salinity are often brought up in the hearings, versus other potential water quality issues;"
- "Yes, if they would add links to DWR water quality and other agency's websites;"
- "The CWQMC has a much broader scope than just the Delta and doesn't do any hands-on monitoring itself. A more Delta-focused group that actually does include hands-on monitoring might be better, e.g., the evolving Delta RMP or the long-established IEP. Also, water quality monitoring should be closely coordinated and integrated with all other monitoring in the Delta; I don't think the CWQMC is in the best position to do this, the IEP is probably a better group for this. I think the CWQMC may have the biggest impact by bringing together and making all monitoring data available and visualizing and interpreting it in a publicly accessible way, and putting it in a statewide context. Another important role might be to guide and advise on water quality monitoring in the Delta;"
- "One of the CWQMC goals is to improve coordination of monitoring programs in the Delta and statewide. There are few (if any) organizations whose main purpose is to try and improve coordination of monitoring efforts (and access to data);"
- "Currently, the CWQMC and its work groups operate largely on voluntary contributions of staff time and other resources. Even with this obstacle, the CWQMC and its work groups have made tremendous progress toward standardizing methods and bringing data and information together from multiple agency programs."

Question 12. Sufficient research has been done on water quality issues in the Delta.

Responses were skewed in the direction of strongly disagree in five categories of strongly disagree to strongly agree being 17%, 34%, 30%, 9%, and 9%, respectively. Comments received include:

- “For the most part sufficient research has been conducted to show the importance of water quality impacts to the Delta ecosystem and organisms; however, there does not appear to be sufficient information for regulatory agencies to prioritize aquatic ecosystem health over anthropogenic interests. This may require numerical models to show that seemingly minor sublethal and indirect impacts to individual organisms can result in major population declines. Both numerical and conceptual models needed to help understand how sources, pathways, transport, mechanisms (e.g., biological, chemical, and physical), and other management actions (e.g., land use and sediment management) affect water quality;”
- However, “More research is necessary for nutrient (e.g., forms and ratios) impacts to the Delta ecosystem. In addition, the exchange of nutrients and food sources between the upper estuary, lower estuary, near shore, and floodplains is likely necessary to support species recovery;”
- “More research is necessary to understand the role of reduced turbidity (or increased water clarity) on Delta species declines; whether it has been caused by reduce sediment inputs, reduced phytoplankton growth, increased submerged aquatic species, increased residence time (sedimentation), etc.; and, whether it can and needs to be mitigated;”
- “More research is necessary to determine the impacts to individuals and population from the interaction of contaminants and other stressors (e.g., altered temperature, predation, and mixtures);”
- “Sublethal effects, additive effects of contaminants in the Delta. In vivo exposure studies at boundary conditions. Lab studies of threshold effects of related contaminants. Gene expression and behavioral effects. CEC monitoring. Determining relative sources of contributions of pesticides (Ag islands versus upstream watershed loading)” are topics needing additional examination;
- “Understanding the fate and transport of emerging contaminants (i.e., hormones, medicines), pyrethroids, and other constituents from urban storm water runoff into the Delta;”
- “There is much to learn about the impacts of pesticides, nutrients, algal toxins, and methylmercury in the Delta. Questions to consider include: What drivers and/or mechanisms influence the fate and transport of these constituents? What are the impacts to listed fish and their habitat? At what temporal and spatial scale should we measure these constituents to support fisheries and aquatic beneficial uses? How does land use change (habitat restoration) play a role in supporting the ecological function of the Delta? Can we restore the healthy function of the system by studying 'only' these constituents; do the information we collect fit within a broader framework? What are the hot spots and hot moments at which these constituents occur and can we use this information to drive management decisions?;”
- There is a need to better understand “Phytoplankton community structure, size and productivity; beneficial phytoplankton bloom inception, propagation and transport; harmful phytoplankton bloom inception, propagation and transport; nutrient forms, sources and sinks; wetland nutrient utilization as well as phytoplankton and dissolved organic carbon evolution; non-phytoplankton sources of energy available to Delta food webs; wastewater effects; nutrient uptake and transformation rates in both pelagic and benthic environments; nutrient and constituent exchange that occurs when water is circulated through Delta peat islands; mixed

effects and interactions (e.g., temperature and contaminants, zooplankton feeding rates and contaminants);"

- "Additional research regarding the ecological effects of contaminants and nutrients is possibly needed. The need for additional sediments in the Delta is a topic that needs more research, especially the composition and size of sediments needed for aquatic organisms. Suspended sediments versus bed sediments."

Appendix B: Respondents to the Delta ISB Questionnaire about Water Quality in the Delta

Respondent entities[7] (in alphabetical order):
California Department of Fish and Wildlife, Water Branch
California Department of Water Resources
California Department of Water Resources, Municipal Water Quality Program Branch
California Parks and Recreation, Division of Boating and Waterways
California Water Quality Monitoring Council (Two individuals)
Central Valley Regional Water Quality Control Board, Irrigated Lands Program
Contra Costa Water District
Delta Science Program
National Oceanic and Atmospheric Administration, National Marine Fisheries Service
Sacramento-San Joaquin Delta Conservancy
San Francisco Bay Regional Water Quality Control Board
Solano County Water Agency
State and Federal Contractors Water Agency
State Water Resources Control Board, Division of Drinking Water
State Water Resources Control Board, Office of Information Management and Analysis
State Water Resources Control Board, Pesticide Permitting Program
United States Environmental Protection Agency, Region 9
United States Geological Survey
United States Geological Survey, California Water Science Center

Plus two individuals reporting for themselves and an anonymous respondent.

[7] Respondents were not asked to represent the views of their respective entity.

Appendix C: Entities of Individuals that We Spoke with During this Review. In some cases, we spoke with individuals different from those who responded to the questionnaire.

Respondent entities (in alphabetical order):
California Department of Water Resources
California State Water Resources Control Board
Central Valley Regional Water Quality Control Board
California Water Quality Monitoring Council
Delta POD – Contaminants Work Team
Delta Nutrients Forms and Ratios Public Workshop
Delta Regional Monitoring Program
Delta Science Program
Sacramento Regional County Sanitation District
State and Federal Contractors Water Agency
University of California, Berkeley
University of California, Davis
United States Environmental Protection Agency
United States Geological Survey

IX. Other Delta ISB Reviews

Water quality is just one of the topic areas or themes that the Delta ISB has reviewed to meet its legislative mandate of providing oversight of the scientific research, monitoring, and assessment programs that support adaptive management in the Delta. Other "thematic" reviews by the Delta ISB are below and are on the Delta ISB's product webpage: http://deltacouncil.ca.gov/science-board/delta-isb-products.

Restoration
Delta Independent Science Board. 2013. Habitat Restoration in the Sacramento-San Joaquin Delta and Suisun Marsh: A Review of Science Programs. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-isb-isb-products/delta-independent-science-board-final-report-habitat-restoration

Flows and Fishes
Delta Independent Science Board. 2015. Flows and Fishes in the Sacramento-San Joaquin Delta. Research Needs in Support of Adaptive Management. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-isb-s-final-report-flows-and-fishes-sacramento-san-joaquin-delta-research-needs-support

Adaptive Management
Delta Independent Science Board. 2016. Improving Adaptive Management in the Sacramento-San Joaquin Delta. Sacramento, CA. http://deltacouncil.ca.gov/docs/final-delta-isb-adaptive-management-review-report

Delta Independent Science Board. 2017. Facilitating Adaptive Management in California's Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 15(2). https://doi.org/10.15447/sfews.2017v15iss2art3

Levees
Delta Independent Science Board. 2016. Workshop Report – Earthquakes and High Water as Levee Hazards in the Sacramento-San Joaquin Delta. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-isb-isb-products-levee-levees-products/final-levee-workshop-meeting-report-v9-30-16

Delta as an Evolving Place
Delta Independent Science Board. 2017. Review of Research on the Sacramento-San Joaquin Delta as an Evolving Place. Sacramento, CA. http://deltacouncil.ca.gov/docs/delta-evolving-place-final-v2

The Sacramento Regional County Sanitation District is undertaking a major upgrade of the Sacramento Regional Wastewater Treatment Plant, which is shown in this recent aerial photograph. The commitment to further reduce nutrient loadings is an excellent example of regional efforts to address water quality concerns in the Delta.

Photo Credit: Sacramento Regional County Sanitation District

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