San Francisco Bay
Nutrient Management Strategy
Science Plan

March 15 2016

SFEI | AQUATIC SCIENCE CENTER

1. Introduction

The San Francisco Bay (SFB) estuary receives large inputs of the nutrients nitrogen and phosphorous from anthropogenic sources, and has the potential to suffer negative impacts from nutrient overenrichment. Nutrient concentrations in SFB exceed those in other estuarine ecosystems where degradation is strongly expressed. To date, SFB has shown resistance to some of the classic symptoms of nutrient over-enrichment, such as excessive phytoplankton biomass as chlorophyll-*a* (*chl-a*) and low dissolved oxygen (DO). Recent observations, however, suggest that SFB's resistance to nutrient enrichment is weakening, and have generated concern that SFB may be trending toward, or may already be experiencing, adverse impacts due to its high nutrient loads. In response to these concerns, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy (NMS).[1] The NMS lays out an overall approach for developing the underlying science to support nutrient management decisions.

This report presents a Draft Science Plan for implementing the SFB NMS. The report's main goals include:

1. Lay out a multi-year Science Plan representing a logical sequence of studies to inform major management decisions, assuming a time-line of 10+ years.
2. Develop an approach and rationale for sequencing and prioritizing among studies, and identify specific high-priority studies, in particular those that should proceed in FY2016-2018.
3. Provide realistic estimates of the time-frame and funding needed to support a Science Plan that will successfully inform management decisions.

The Draft Science Plan was developed in 2014-15 with input from science advisors (Table 1.1), the NMS Steering Committee, and the NMS Nutrient Technical Work Group (Fig. 1.1). Projects are described in more detail in the first 1-3 years, and in increasingly less detail over time, recognizing that the Science Plan will be iteratively refined based on new insights gained as work progresses.

Table 1.1 Science Advisors for NMS Science Plan

James Cloern, PhD	USGS
Lawrence Harding, PhD	UCLA
Wim Kimmerer, PhD	SFSU-RTC
Raphael Kudela, PhD	UC Santa Cruz
Mark Stacey, PhD	UC Berkeley
Martha Sutula, PhD	SCCWRP

The science advisor team was convened in December 2014 to provide initial input on the Science Plan, discuss priorities for specific studies, and recommend a sequence and time-line to address

[1]http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/Nutrient_Strategy%20November%202012.pdf

management questions. During two meetings (October 2014, February 2014), the NMS Steering Committee provided guidance on the approach for developing the Science Plan and science and management priorities. The Nutrient Technical Workgroup also provided input during a meeting in April 2014. Additional science advisor meeting is planned for Summer/Fall 2015 to help develop the plan's final draft, and provide input on specific projects for FY2016.

The Draft Science Plan is described in Section 2 and Appendix 1. Relevant background information on nutrient issues in San Francisco Bay, and a summary of major science needs and recommended priorities, are presented in Appendix 2-4 (Section 4). The background material and recommendations were originally presented in an earlier report (*Scientific Foundation for the San Francisco Bay Nutrient Management Strategy*; SFEI 2014).

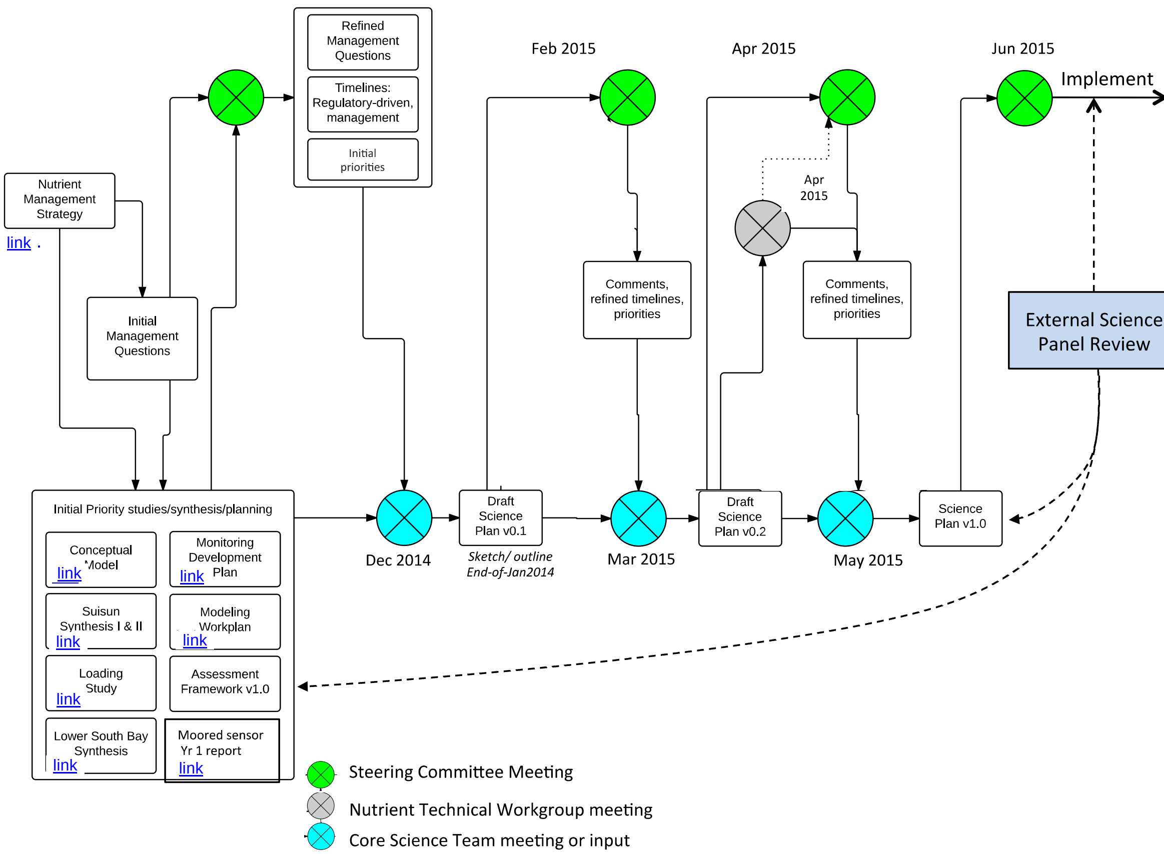


Figure 1.1 Proposed process and timeline for Science Plan development. Actual dates differ from those depicted. A draft Science Plan was used to guide FY16 funding decision in June 2015. Stakeholder comments were received in June/July 2015, and comments from two external peer reviewers in March 2016 (see Appendix 5). An External Science Panel Review will occur sometime in FY17 or later.

2. Science Plan

2.1 Management Questions and Knowledge / Data Gaps

The Science Plan aims to build the scientific foundation needed by regulators and stakeholders to answer the six management questions in Table 2.1. High priority knowledge and data gaps related to nutrient loads, nutrient cycling and ecosystem response to nutrients in SFB were identified in SFEI (2014), and are summarized in Appendix 4.

Table 2.1 Management questions targeted by the NMS Science Plan

1. What conditions in different SFB habitats would indicate that beneficial uses are being protected versus experiencing nutrient-related impairment?
2. In which subembayments or habitats are beneficial uses being supported? Which subembayments or habitats are experiencing nutrient-related impairment?
3.a To what extent is nutrient over-enrichment, versus other factors, responsible for current impairments? 3.b What management actions would be required to mitigate those impairments and protect beneficial uses?
4.a Under what future scenarios could nutrient-related impairments occur, and which of these scenarios warrant pre-emptive management actions? 4.b What management actions would be required to protect beneficial uses under those scenarios?
5. What nutrient sources contribute to elevated nutrient concentrations in SFB subembayments or habitats that are currently impaired, or would be impaired in the future, by nutrients?
6. When nutrients exit SFB through the Golden Gate, where are they transported and how do they influence water quality in the Gulf of Farallones or other coastal areas?
7. What specific management actions, including load reductions, are needed to mitigate or prevent current or future impairment?

2.2 Science Plan Structure

Activities in the Science Plan are organized by Major Program Areas and Work Categories (Table 2.3), based on the priority science needs detailed in Appendix 4 and in SFEI (2014). Program Areas 2, 3, and 4 address the five pathways for adverse impacts presented in Figure A.3.1. Program Area 1, *Nutrients*, is presented as a separate Program Area because defining the sources, fate, and transport of nutrients is essential to all elements of the Science Plan. Activities in each of the first four program areas are divided into 5 Work Categories (Table 2.3). Note that three Work Categories also appear as sub-headings under Program Area 5, *Program-wide Activities*. Monitoring, Modeling, and Protective Conditions / Asssessement Framework are essential components of Program Areas 1-4, but are also themselves major programmatic undertakings, with technical activities and coordination that are not well-placed under Program Areas 1-4.

Table 2.2 Science Plan structure

Major Program Areas	Work Categories
1. Nutrients (loads, cycling/transformations)	A. Synthesis B. Monitoring C. Special Studies D. Modeling (current conditions) F. Identify Protective Conditions F. Modeling condition under plausible future scenarios
2. High biomass and low dissolved oxygen	
2.1 Deep subtidal	
2.2 Shallow margin habitats	
3. Phytoplankton community composition	
3.1 HABs/toxins	
3.2 Food quality (due to N:P, NH4, etc.)	
4. Low productivity	
5. Program-wide Activities	
5.1 Monitoring	Future monitoring program design, including considerations of science requirements, logistics, institutional agreements, and funding
5.2 Modeling	Base model development, model documentation, model maintenance
5.3 Protective Conditions/Assessment Framework	Iteratively refine framework based on new data.
5.4 Program Management	Science communication, stakeholder engagement, coordination among projects, fundraising

Table 2.3 Work Categories within the Major Program Areas

Work Categories	**Types of activities**
A. Synthesis	• Analyzing/synthesizing new results from past studies, developing conceptual models, etc., to identify science needs • Analyzing/synthesizing new data from monitoring and special studies to inform next steps in science plan implementation • Workshops to identify highest priority science questions and experiments
B. Monitoring	• Current ship-based monitoring, Bay-wide…nutrients, phytoplankton biomass, phytoplankton composition, physical observations (salinity, temperature, SPM, etc.) • Moored sensors…biogeochemical data, physical data (T, salinity, stratification, velocities, etc.) • Future monitoring program design: data analysis and expert input on spatial/temporal resolution, blend of ship-based vs. fixed-station continuous monitoring, new measurements, etc.

C. Special Studies	• Field investigations to
	  ○ measure biogeochemical processes: e.g., primary production, nutrient transformations (water column, benthic), DO consumption (water column, benthic)
	  ○ collect physical observations (T, sal, velocities, light levels) to quantify mixing, transport, and stratification
	  ○ study processes or test hypotheses at the ecosystem-scale (e.g., factors that influence HABs or toxin production)
	• Mechanistic studies in the laboratory
	• Pilot studies related to monitoring program development, including data analysis

D. Modeling	• Biogeochemical (Water Quality) and hydrodynamic model development and application to quantitatively explore:
	  ○ Transport of nutrients and biomass
	  ○ Growth of phytoplankton, grazing by pelagic and benthic grazers, growth of different types of phytoplankton
	  ○ Nutrient and organic matter biogeochemical transformations and losses
	  ○ Hydrodynamics, effect of physics (e.g., stratification) on env'l processes

E. Identify Protective Conditions	• Levels of DO, chl, and toxins, or characteristics of phytoplankton assemblages that are protective of beneficial uses • Identify the beneficial uses potentially impacted by nutrients. In the case of aquatic life uses, specifically identify the organisms to be protected. • Literature review to identify these levels, modeling (trophic transfer, HAB or toxin bloom size) • Nutrients, loads or concentrations that will protect beneficial uses.
F. Future scenarios	• Identify high priority environmental change scenarios to test • Identify load reduction or management scenarios. • Simulate ecosystem response under future scenarios

2.3 Timeline and Budget Assumptions

In addition to the management questions and science needs, two practical constraints strongly influence the NMS Science Plan's structure and activities. The first is the proposed timeline for answering management questions. The second is the available funding to support science activities. Currently, both the Science Plan's timeline and its funding are uncertain. It was not possible to develop the Science Plan with the timeline and budget left fluid; therefore, two major assumptions were made.

First, a 10-year time horizon was identified as the goal for reaching sufficiently-confident answers to NMS management questions (Table 2.1). This 10-year time horizon, beginning in July 2014, was based on guidance from the SFBRWQCB. Tables 2.4 and 2.5 present approximate timelines for addressing the management questions in Table 1.1. Table 2.5 organizes management questions into specific questions based on the Major Work Areas in Table 2.2. The sequencing and timeline of Science Plan activities were designed to yield early provisional answers to management questions, and to refine those answers through further investigations that target major uncertainties. This iterative approach allows the Science Plan to be periodically refocused on the highest priority science needs. It would also help identify the need for any early management actions, e.g., if impairment becomes evident. The milestones and dates in Tables 2.4 and 2.5 are realistic in terms of the effort and time required to conduct investigations related to a particular line of inquiry. It is important to note, though, that the schedule assumes that all work proceeds in parallel

Second, with the timeline fixed, the Draft Science Plan budget was allowed to expand to match the proposed schedule. As with the schedule, the estimated funding needed to conduct a set of investigations are realistic. However, it became apparent early in Science Plan discussions that the current funding level ($1.38mill/yr) will be insufficient to address all the management questions (Table 2.1) for all potential adverse-impacts pathways (Figure A.3.1) at this pace, given the knowledge and data gaps that need to be addressed (Appendix 4). In addition, some amount of ramp-up time is needed to build a sustainable program. It should be noted that even with an "unlimited resources" approach, some questions remain unanswered at a final level of confidence in a 10-year period.

The Draft Science Plan in its current form is thus best considered as an idealized plan – technically feasible but unlikely to proceed as laid out because of funding constraints, and requiring either substantially increased funding or tough decisions about what lines of inquiry and types of investigations are most essential. A process or structure for prioritizing science activities has not yet been developed, and is a necessary upcoming step.

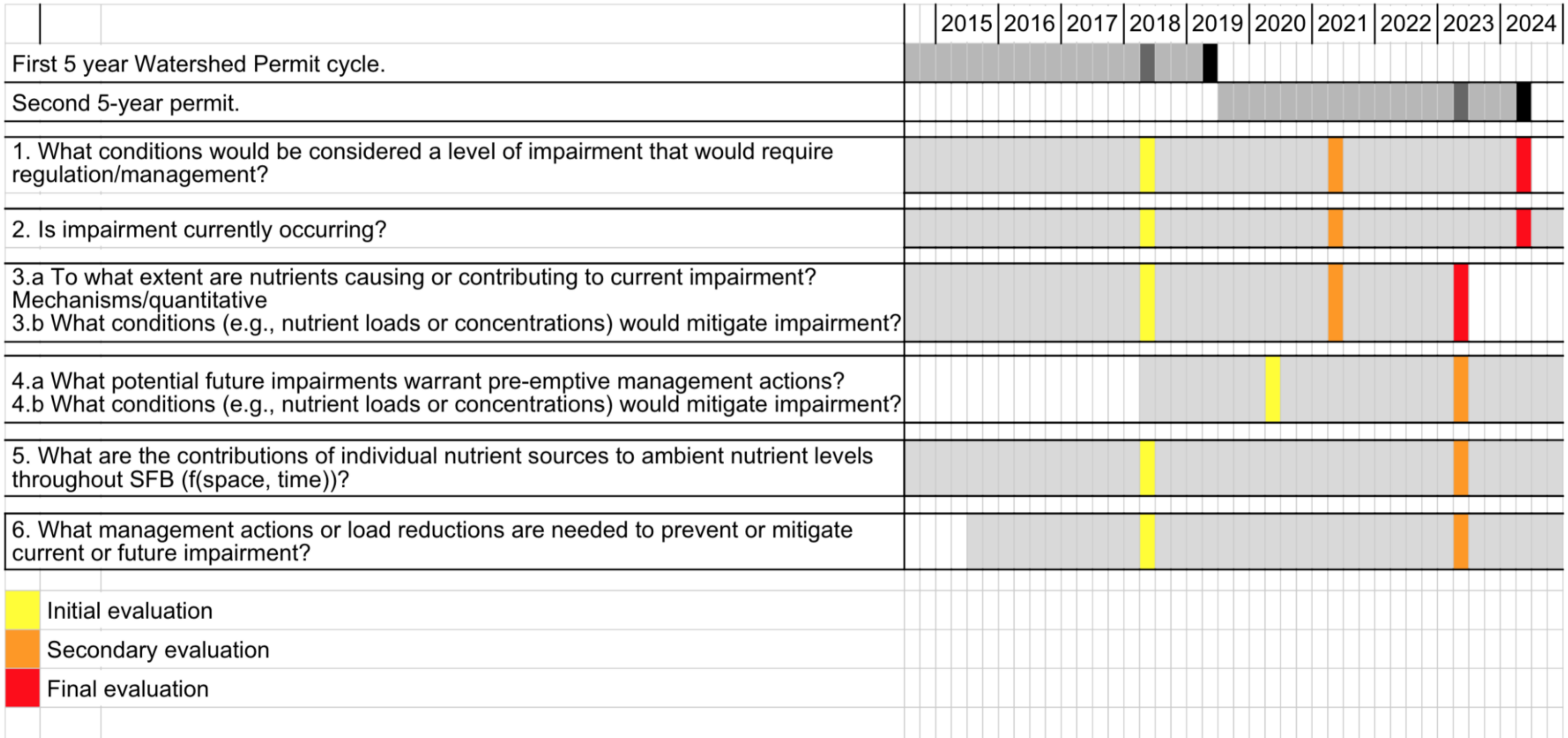


Table 2.4 Management questions and approximate timeline for iteratively reaching answers. The 10-year timeline is based on a Regional Water Board goal of establishing nutrient objectives for SFB by the end of the second Bay-wide nutrient permit (2024). See Table 2.5 for more detailed version

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
First 5 year Watershed Permit cycle. All information needed to inform next permit required by 4.5 year mark											
Second 5-year permit. All information needed to inform next steps beyond the 10 years needed by 9 year mark											
1. What conditions would be considered a level of impairment that would require regulation/management?					Initial evaluation			Secondary evaluation			Final evaluation
1.1 DO in deep subtidal, and chl-a leading to that DO		Initial evaluation			Secondary evaluation						Final evaluation
1.2 DO: shallow margin habitats					Initial evaluation			Secondary evaluation			Final evaluation
1.3 HAB abundance, toxin abundance (concentration, area, duration, frequency), community/food shifts		Initial evaluation						Secondary evaluation			Final evaluation
2. Is impairment currently occurring?					Initial evaluation			Secondary evaluation			Final evaluation
2.1 DO in deep subtidal, and chl-a leading to that DO					Initial evaluation			Secondary evaluation			Final evaluation
2.2 DO: shallow margin habitats					Initial evaluation			Secondary evaluation			Final evaluation
2.3 HAB abundance, toxin abundance (concentration, area, duration, frequency), community/food shifts					Initial evaluation			Secondary evaluation			Final evaluation
3.a To what extent are nutrients causing or contributing to current impairment? Mechanisms/quantitative 3.b What conditions (e.g., nutrient loads or nutrient concentrations) would mitigate impairment?					Initial evaluation			Secondary evaluation		Secondary evaluation	
3.1 DO in deep subtidal, and chl-a leading to that DO					Initial evaluation			Secondary evaluation		Final evaluation	
3.2 DO: shallow margin habitats					Initial evaluation					Secondary evaluation	
3.3 HAB abundance, toxin abundance (concentration, area, duration, frequency), community/food shifts					Initial evaluation					Secondary evaluation	
4.a What potential future impairments warrant pre-emptive management actions? 4.b What conditions (e.g., nutrient loads or nutrient concentrations) would mitigate impairment?							Initial evaluation			Secondary evaluation	
4.1 Effects of plausible physical and biological drivers on ecosystem dose:response (3.1-3.6)?							Initial evaluation			Secondary evaluation	
4.2 Scenarios with sufficiently high probability of occurring and large impact?							Initial evaluation			Secondary evaluation	
4.3 What conditions would mitigate or prevent impairment?							Initial evaluation			Secondary evaluation	
5. What are the contributions of individual nutrient sources to nutrient levels throughout SFB (f(space, time))?					Initial evaluation					Secondary evaluation	
5.1 Current magnitudes (f(t)) of individual nutrient loads at their point of entry to SFB?	Initial evaluation				Secondary evaluation					Final evaluation	
5.2 Anticipated load changes: environmental change, flow diversion, population, land-use, management?					Initial evaluation					Secondary evaluation	
5.3 Magnitudes of nutrient transformations and losses within SFB, space/time variability?					Initial evaluation			Secondary evaluation		Final evaluation	
5.4 Contributions of individual nutrient sources to loads/concentrations in "subregions" (f(t))?					Initial evaluation			Secondary evaluation		Final evaluation	
6. What management actions or load reductions are needed to prevent or mitigate current or future impairment?					Initial evaluation					Secondary evaluation	
6.1 What "local" reductions/changes are needed in subregions to mitigate current impairments (3.1-3.6)?					Initial evaluation					Secondary evaluation	
6.2 What external load reductions or other management actions can achieve the desired "local" effect(s)?					Initial evaluation					Secondary evaluation	
6.3 What are the optimal approaches for achieving the local effects?										Initial evaluation	

Initial evaluation (yellow)
Secondary evaluation (orange)
Final evaluation (red)

Table 2.5 Expanded version of Table 2.5 depicting schedule of iteratively answering management questions for the range of potential adverse impact pathways and nutrient loads/transformations.

2.4 Regulator and Stakeholder Priorities

Input was solicited from regulators, stakeholders, and the NMS Steering Committee at several points during the Science Plan development process to identify priorities and time-sensitive issues. Several themes emerged during these discussions and have been incorporated, to the extent possible, in this version:

1. The Science Plan must consider, and help define, the specific beneficial uses that are targeted for protection, including identifying the organisms and ecosystem services that management actions would aim to protect from nutrient-related adverse impacts.
2. Conditions protective of beneficial uses should be quantitatively identified: e.g., protective DO conditions for specific fish species; protective algal toxins concentrations for chronically-exposed marine biota.
3. Provisional answers to some questions are needed by June 2018 to inform permit renewal discussions:
    a. Source-attribution for nutrients in SFB as a function of space and time;
    b. Define regional demarcations / boundaries in SFB based on retrospective data analysis of relevant water-quality properties and modeling of sources;
    c. Initial indications of whether SFB is experiencing nutrient-related adverse impacts.
4. The Science Plan's implementation needs a process for prioritizing among science activities (Figure A.3.1) and assessing timeline/schedules, in order to achieve an appropriate balance between program cost, program duration, and the level of confidence in the answers to management questions.

2.5 Rationale/Criteria for Establishing Workflow and Priorities

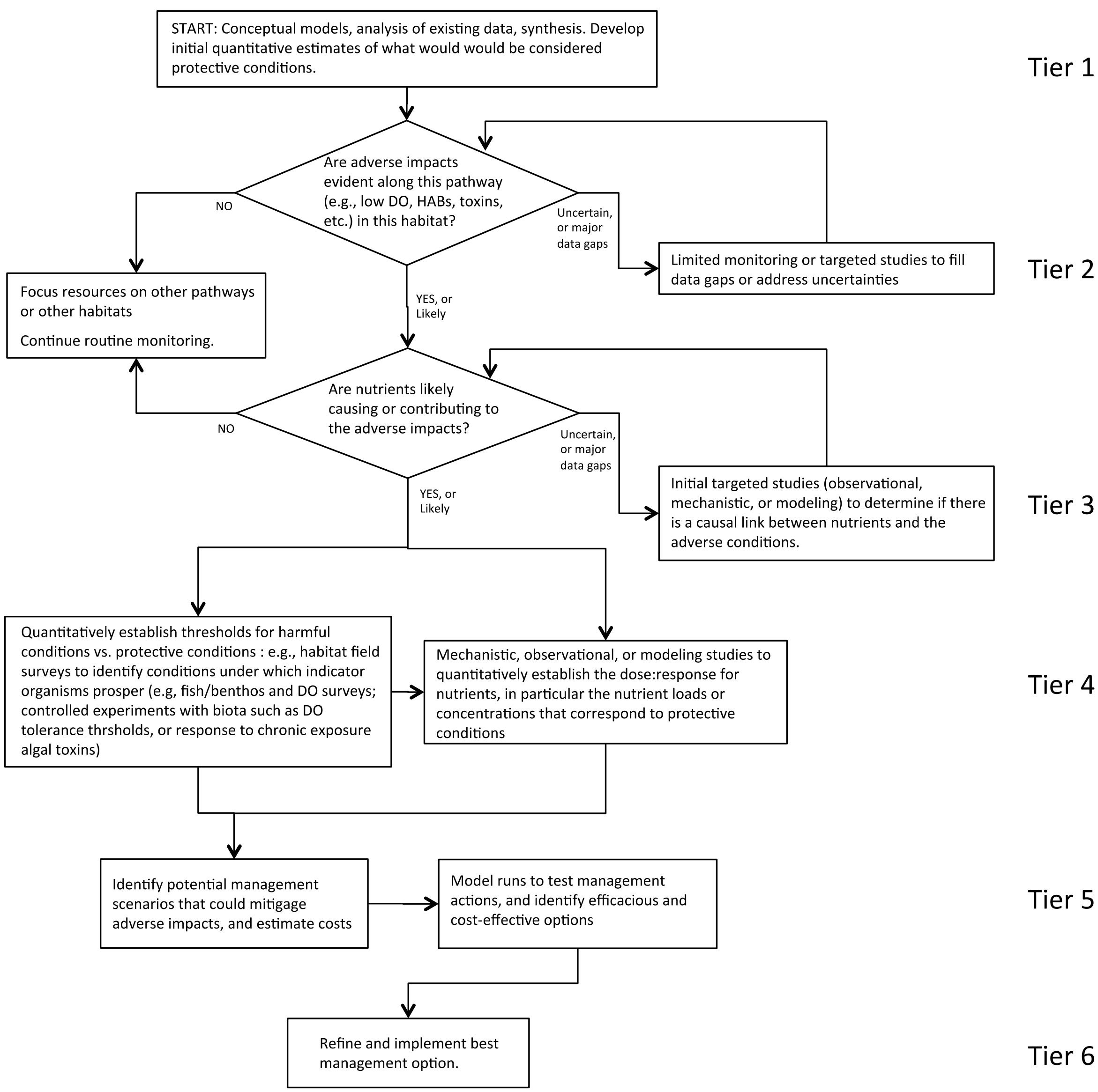
This section provides an overview of several criteria used to guide the development of the Science Plan using the structural elements defined in Tables 2.2 and 2.3.

1. Adopt an approach that produces early guidance, pursues studies to test priority knowledge gaps, and periodically refines guidance based on new information.

- Goals:
    - A Science Plan that targets the highest priority studies, with the expectation that priorities will evolve based on results from on-going work.
    - Provisional answers to management questions that can help inform any early decisions or planning.
- Build flexibility into the process through planned reassessments (e.g., 3 year cycles):
    - Periodically revisit the Science Plan, and refine priorities based on new data.
    - Refine earlier guidance, as necessary, based on new scientific information and their management implications.

2. To the extent possible, use a tiered approach to guide the sequencing or prioritization of projects. This is especially important in the first few years when a major focus needs to be on identifying which pathways (Figure A.3.1) and habitats are most concerning.

- The decision tree below illustrates a generalized workflow, organized into tiers. Following this logic, some of the more challenging, costly, and multi-year studies (Tiers 4, 5: e.g., quantitative/mechanistic studies to explore nutrient-HAB linkages; habitat field surveys to characterize DO tolerance) are pursued only after a problem has been identified and a causal link with nutrients established (Tiers 1, 2, 3). Table A.1 serves as an example of sequenced or tiered studies for exploring issues related to HABs/toxins.
- Work cannot always strictly follow such a tiered sequence. One example is the coupled hydrodynamic-biogeochemical modeling for SFB, which will take considerable time to develop. Work on model development needs to begin early, unlike what might be suggested by a strictly tiered approach.

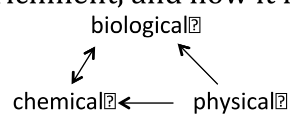


3. When possible, pursue projects that benefit more than one Program Area, and look for opportunities to leverage efforts in one program area to advance others.

- HABs exemplify an undesirable shift of phytoplankton species composition to a community including toxic forms. HAB-related studies (e.g., field investigations using microscopy, pigments, or genomic approaches) will also advance our understanding of factors that shape phytoplankton community composition and food quality more broadly.
- Many of the projects identified below have direct and indirect benefits for multiple program areas.

4. Organize field investigations spatially to ensure integrated and efficient collection of necessary data

- A diverse array of environmental data is needed to shed light on how SFB responds now to nutrient over-enrichment, and how it may respond in the future.



- These data are best collected simultaneously, both to aid in interpretations and maximize cost-effectiveness (i.e., relatively small incremental cost of adding measurements to a field program than launching a new study)

5. Target high-priority conceptual and data gaps through specific projects in FY2016-FY2018.

- Since nutrients have only emerged as a concerning issue in SFB recently, there are many priority needs, including (see also Section A.4.2 and Tables A.4.1-A.4.6):
  - Developing coupled hydrodynamic/biogeochemical models for SFB
  - Moored sensors for high-frequncy monitoring of nutrient-related parameters, both for assessing condition and calibrating models.
  - Field investigations to measure nutrient transformation rates
  - Improved characterization of HABs and algal toxins in SFB, and exploration of the risk they pose in
  - DO-related conditions in SFB's margin habitats and mechanistic investigations of causal factors.
- Other nutrient-related adverse impact pathways have received substantial investigation over the past several years. A number of ecosystem-scale studies and controlled experiments focused on NH_4^+ inhibition of phytoplankton growth rates and N:P or NH_4^+ impacts on phytoplankton food quality have proceeded during the past several years. Some of these studies are still underway but nearing conclusion. Therefore new studies related to NH_4^+ and N:P adverse impact pathways were not identified for FY2016-2018. As on-going studies are completed, the state of that science needs to be assessed, and at that point gaps can be identified and relevant studies prioritized.

6. This goal-setting version of the Science Plan should capture the full breadth of science needs. While it was developed with realistic funding levels in mind, it is not constrained by its current available funding (~$1.4mill yr^{-1}).

- The Science Plan is geared toward answering the major management questions within 10 years.
- Much more work is proposed to occur in parallel in the Science Plan than can be accomplished with current funding.
- Thus, the Science Plan can be thought of as a comprehensive science-needs road map. As such, it is also meant to concretely identify funding needs and help focus NMS fundraising efforts (e.g., national and regional RFPs).
- Some degree of prioritization will still be necessary, independent of fundraising. A prioritization effort should be a next step in the Science Plan development or update. External review of the Science Plan will also be helpful step for recruiting additional expert input on science priorities.

2.6 10-year Science Plan

This section presents the 10-year Science Plan at a few different resolutions. Figure 2.6 depicts the approximate timing of major activities within the main Work Categories across all Program Areas. Table 2.6 provides more detail, breaking down work into Program Areas, Work Categories, and major activities. A more granular version of Table 2.6 is presented in Table A.2, which illustrates the full breadth of science needs. Despite what may look like a very detailed portrayal of activities in Table A.2, the project descriptions are still quite general, and specific data needs will need to be identified on a year-by-year basis, and prioritized as the program progresses.

The Science Plan project timelines (Tables 2.6 and A.2) and milestone timing (Table 2.4-2.5) present realistic estimates of the time required to conduct investigations and reach reasonably confident answers to management questions. As noted in Section 2.4, the plan is not constrained by the current budget, which is ~$1.4mill yr^{-1}. Pursuing all of these topics in parallel would require a much higher funding level.

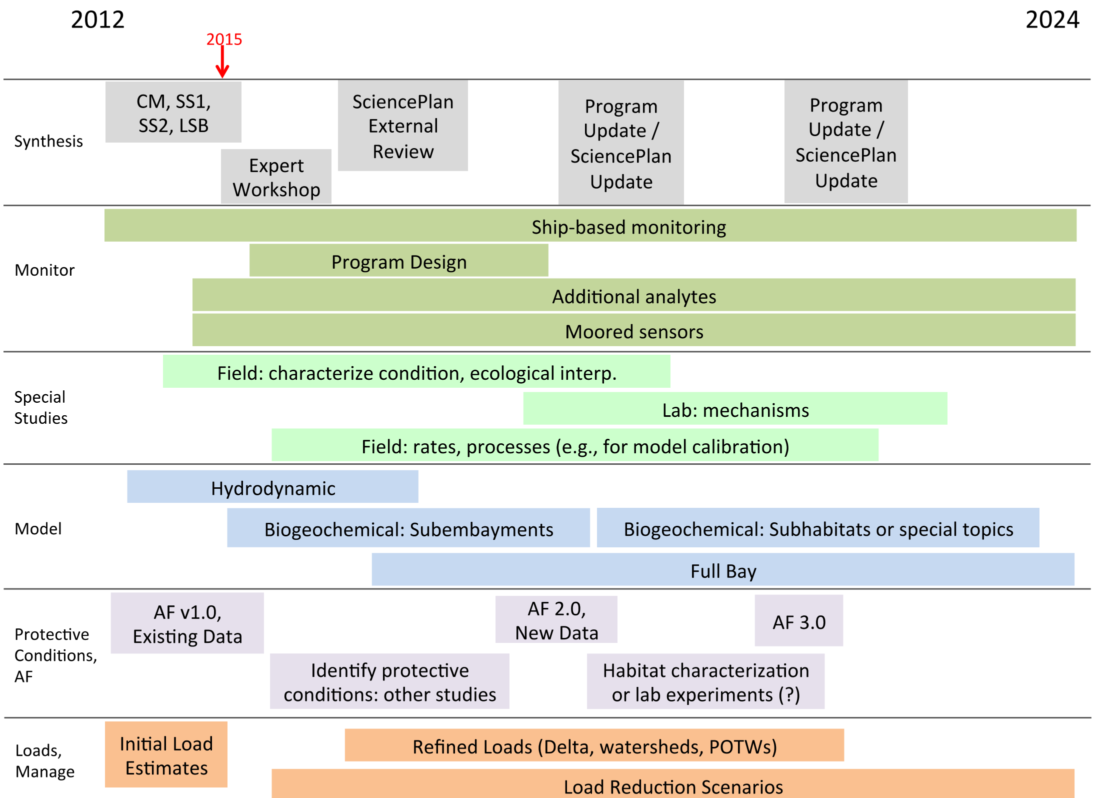


Figure 2.6 Approximate timing of major work categories over a 10 year Science Plan.

Although Figure 2.6 and Table 2.6 present the timing of work, and forecasted times for answering management questions, they do not convey the workflow or iterative nature of activities. Sidebar A provides three examples to better illustrate the Science Plan's workflow and iterative structure. The workflows in Sidebar A are analogous in structure to the tiered workflow example in Section 2.5, with those in Sidebar A providing some additional detail (specific to pathways) and illustrating the recommended iterative nature of the workflow.

Table 2.6 Overview of the 10-yr Science Plan. Dark Grey indicates a deliverable or end of project. Red/Yellow/Orange signify answers reached with similar confidence levels as in Tables 2.4 and 2.5

	Topic		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	**Nutrient: loads, transformations,**														
	Synthesis														
	Monitoring	Ship-based monitoring													
		Continuous, moored stations													
	Special Studies														
	Modeling	*Load estimates*													
		transport, transformation													
	Protective Conditions														
	Future Scenarios														
2.1	**High chl, low DO - Deep Subtidal**														
	Synthesis														
	Monitoring	Ship-based monitoring													
		Continuous, moored stations													
	Special Studies	Field investigations: biogeo, physics													
		Habitat assess (e.g., fish, benthos)							TBD						
	Modeling														
	Protective Conditions														
	Future Scenarios														
2.2	**High chl, low DO - Shallow Margin**														
	Synthesis														
	Monitoring										TBD				
	Special Studies	DO in shallow margin habitats									TBD				
		Field investigations: biogeo, physics													
		Habitat assess (e.g., fish, benthos)							TBD						
	Modeling														
	Protective Conditions														
	Future Scenarios														
3.1	**Phytoplankton community: HABs/Toxins**														
	Synthesis														
	Monitoring	Ship-based monitoring													
		Continuous, moored stations													
	Special Studies	Field investigations, data analysis													
		Experiments: HABs, toxin production													
		Experiments: biota toxicity										TBD			
	Modeling														
	Protective Conditions														
	Future Scenarios												TBD		
3.2	**Phytoplankton community: Food Quality**														
	synthesis	Suisun Synthesis II													
		Additional Synthesis, External Review													
	Monitoring	Ship-based monitoring													
		Continuous, moored stations													
	Special Studies	Complete funded projects, other funds													
		Field study, data analysis (w/ HABs)													
		Experiments:comm. comp. (w/ HABs)													
		Experiments: measure food quality									TBD				
	Modeling														
	Protective Conditions	expert input, lit. review: food quality													
	Future Scenarios												TBD		
4	**Low Biomass**														
	Synthesis	Suisun Synthesis I, II													
		Additional Synthesis, External Review													
	Monitoring	Ship-based monitoring													
		Continuous, moored stations													
	Special Studies	Complete funded projects, other funds													
		New field studies or experiments						TBD							
	Modeling														
	Protective Conditions														
	Future Scenarios										TBD				

Table 2.6 cont'd

	Topic	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
5	**Nutrient Program Coordination**													
	Synthesis: Bi-annual program updates, Science Plan updates													
	Monitoring: develop program, basic monitoring, infrastructure													
	Modeling: base model development, refinement, maintenance													
	Assessment Framework Development													
	Program Management													

2.7 Projects identified for FY2016-2018

Table 2.7 summarizes projects that were identified within the 10-year plan (Figure A.2) as beginning in FY2016-2018. Table 2.7 also notes the geographic focus of each investigations and the target Program Areas, as well as estimated costs.

A next important step is to prioritize among these projects to identify those projects that should go forward in FY2016, recognizing that their estimated total cost exceeds current funding.

Table 2.7 Projects Identified for FY2016-2018. Note, prioritization among projects has not been done. Costs are approximate. Symbols indicate the level of alignment between the project and each Program Area and Subembayment. ● Directly aligned; ⦿ Moderately aligned; ○ Limited alignment (e.g., knowledge transfer from one subembayments or project to another, but no data)

	Project	Cost/yr ($1000s)	Start Date	Length (yr)	Program Area Focus						Subembayment Focus				
					1	2.1	2.2	3.1	3.2	4	LSB	SB	CB	SPB	SUI
1	On-going ship-based monitoring. Costs for basic nutrient-related analytes (nutrients, phytoplankton community, ancillary)	100	Jul 2015	3+	●	●	●	●	●	●	●	●	●	●	●
2	Measure new analytes, core monitoring: pigments, toxins (filters, SPATT, biota/benthos)	150	Jul 2015	3+	●	●	●	●	●	⦿	●	●	●	●	●
3	Moored sensor monitoring: Field work/ maintenance, data interpretation, system-scale interpretations for DO, nutrients, biomass	200	Jul 2015	3+	●	●	●	⦿	⦿	○	●	●	⦿	○	○
4	DO in margin habitats: Field work/ maintenance, data interpretation, system-scale interpretations for DO, nutrients, biomass	200	Jul 2015	3	●	●	●	⦿	⦿		●	●		○	○
5	Biogeochemical modeling - LSB, South, Suisun focus in Year 1-3. - Bay-wide nutrient transport/cycling to identify zones of influence of nutrient sources	400	Jul 2015	3+	●	●	●	⦿	⦿	●	●	●	●	●	●
6	Monitoring Program Development: historical data analysis, specify types of analytes and spatial/temporal frequency	150	Sep 2015	3	●	●	●	●	●	●	●	●	●	●	●
7	Data analysis/interpretation of -phytoplankton community composition and physical/chemical factors (microscopy: 1992-2017) - pigment and toxin data and physical/chemical factors (2011-2017), and pigment, toxin, nutrient, and physical/chemical condition in LSB	150	Sep 2015	3	●			●	●		●	●	●	●	●
8	Integrated investigation in subembayments (start LSB/South Bay): Grazing, hydrodynamic data, phytoplankton production, sediments or light, MPB production, community/HABs/toxins, nutrient transformations, DO	400	Sep 2015	3	●	●	●	●	●	○	●	●	○	○	○

	Project	Cost/yr ($1000s)	Start Date	Length (yr)	Program Area Focus						Subembayment Focus				
					1	2.1	2.2	3.1	3.2	4	LSB	SB	CB	SPB	SUI
9	Intensive Bay-wide investigation: toxins/HABs, e.g., phytoplankton community, HABs, toxins, and/or toxins in bivalves	200	Jan 2016	3			●	●			●	●	●	●	●
10	Identifying protective DO levels for deep water and shallow margin habitats (desktop study: species to protect, DO tolerance (time, duration), expert input, comparison with ambient condition, monitoring gaps	150	Sep 2015	2		●	●				●	●	●	●	●
11	Identifying protective toxin levels for SFB habitats (desktop study: species to protect, food web, expert input, bioaccumulation and plume modeling, comparison with ambient condition, monitoring gaps	100	Sep 2015	2				●	●		●	●	●	●	●
12	Identifying protective food quality for SFB (desktop study: species to protect, feeding practices and requirements, consideration of potential past food quality, expert input), comparison with ambient condition, monitoring gaps, science gaps	50	Jan 2016	2					●		●	●	●	●	●
13	External review or workshop: N:P, NH4 inhibition	25	Sep 2015	1				●	●	●	○	○	○	●	●
14	AF data analysis: Update/analyze probability of HABs and toxins vs. chl-a, and low DO, new data	100	Jul 2017	2				●			●	●	●	●	●
15	Load estimates: Hydrological modeling to estimate inputs from local watersheds; Refined estimates of Delta Loads; updated loads from POTWs	150	Sep 20155	3	●	⊙	⊙	⊙	⊙	⊙	●	●	●	●	●
16	Science coordination and oversight across projects; Reporting; NMS Program Management: stakeholder coordination, project management	350	Jul 2015	3	●	●	●	●	●	●	●	●	●	●	●
	Estimated Total ($mill/yr)	~2800													

Sidebar A

Each major Program Area could be thought of as having its own sub-plan (Figure S.1 and S.2). Some projects or activities may be distinct to one program area, and others may contribute to multiple program areas (vertically).

Figure S.3 is a general example, while Figure S.4 and Figure S.5 present the cases for HABs/toxins and Low DO in sloughs/creeks, respectively. Enter the diagram in the purple "Identify Protective Conditions" box, and proceed to the "Adverse Impact?" decision. For most of the Program Areas, there remains considerable uncertainty about whether adverse impacts are occurring and the dose:response with nutrients, which leads into the Monitoring and Special Studies box. The smaller rectangles illustrate the types of studies or activities that would be pursued during a pass through the Monitoring and Special Studies box. One pass through this box, carrying out multiple activities in parallel (e.g., monitoring, field investigations) to generate new data or test hypotheses, would take ~3 years. That new information would be used to provide provisional answers to management questions (Tables 2.4-2.5) and refine the Assessment Framework (AF).

The process repeats until the ambient condition data and AF have developed to the point where "Adverse Impact?" can be answered with sufficient confidence. Exactly what constitutes sufficient confidence is a regulatory decision or management decision. If there is an adverse impact, work moves to revising conceptual models, developing and implementing numerical models, investigating the quantitative importance of nutrients, and exploring load reduction scenarios that would mitigate impairment. As noted above, work would likely proceed on multiple fronts in parallel, not in series – for example, work will have been moving forward with model development, and when modeling is needed to answer a specific question, the Base Model will ready for use and customization for the specific questions being explored.

Figure S.1

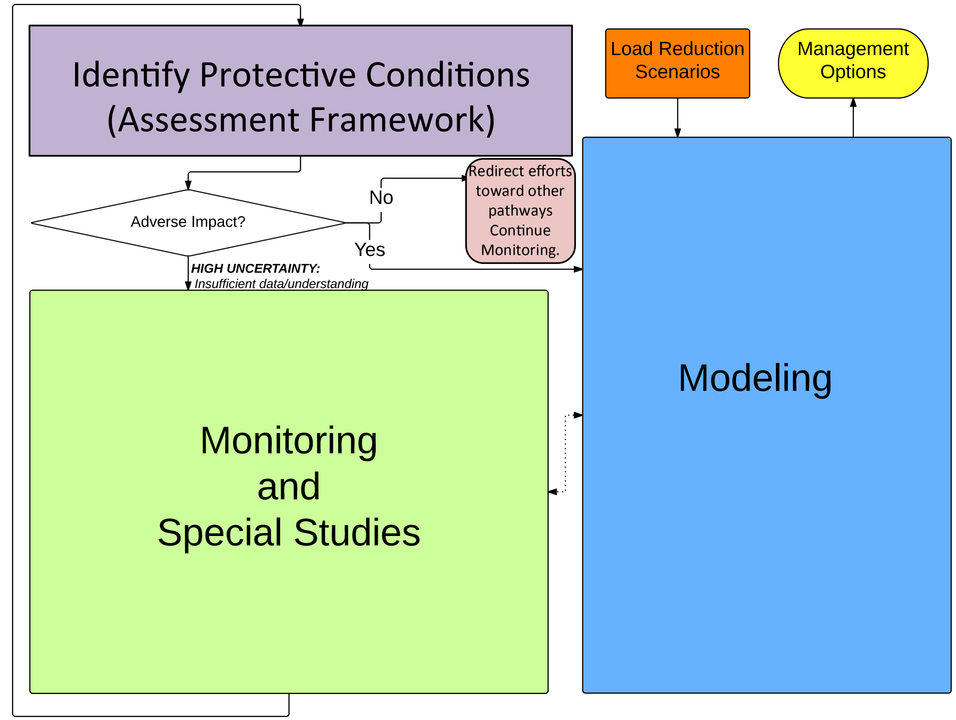


Figure S.2

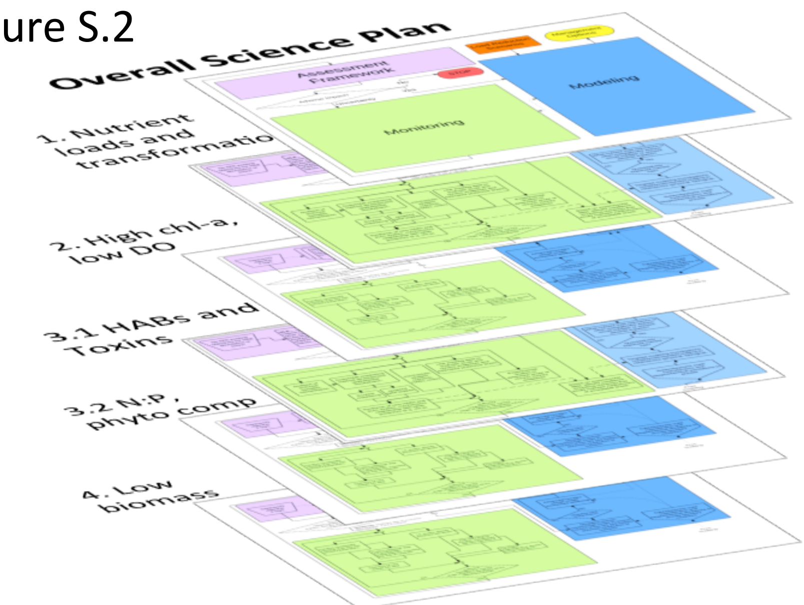


Figure S.3 General Case

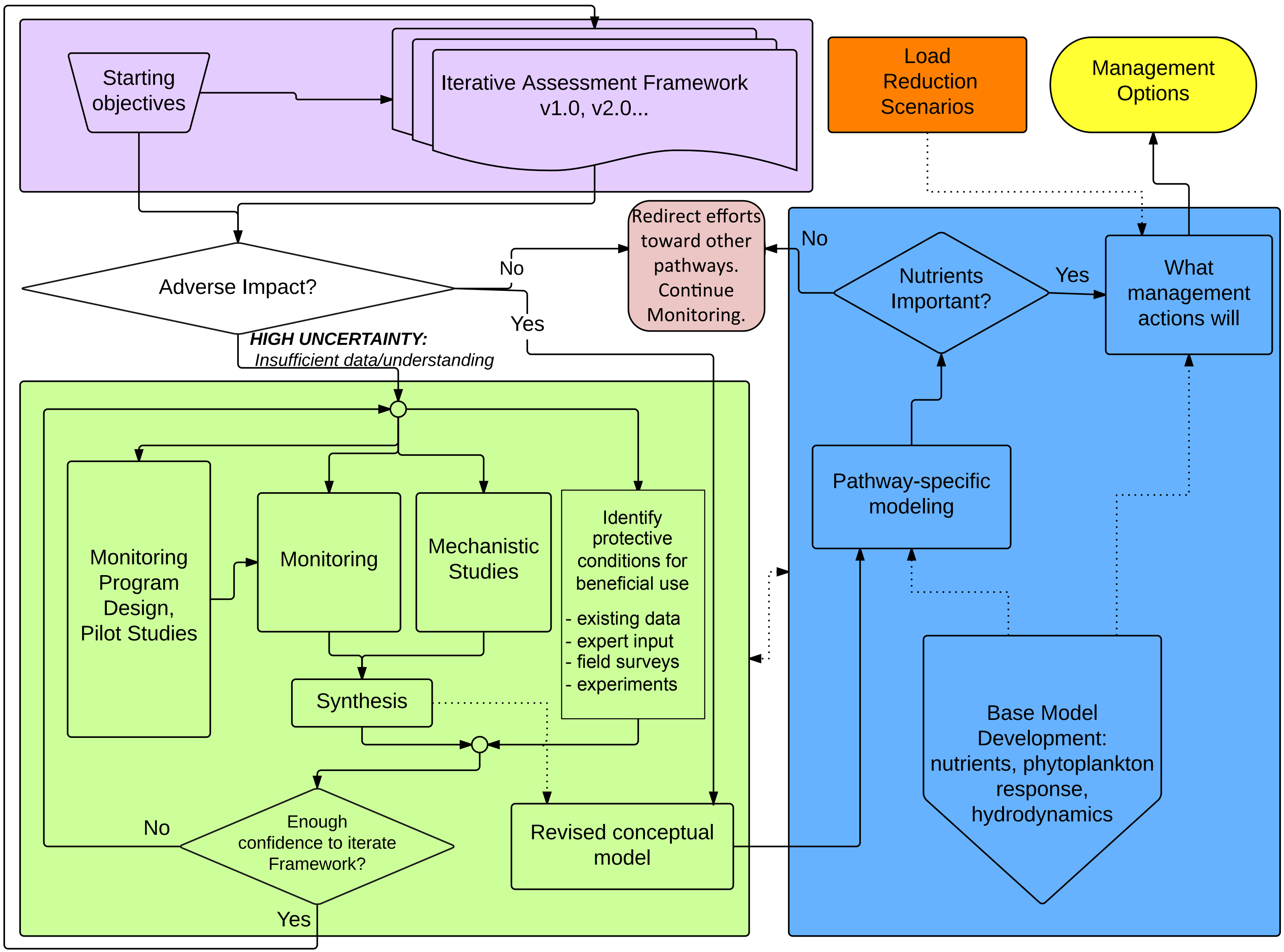


Figure S.4 HABs/toxins

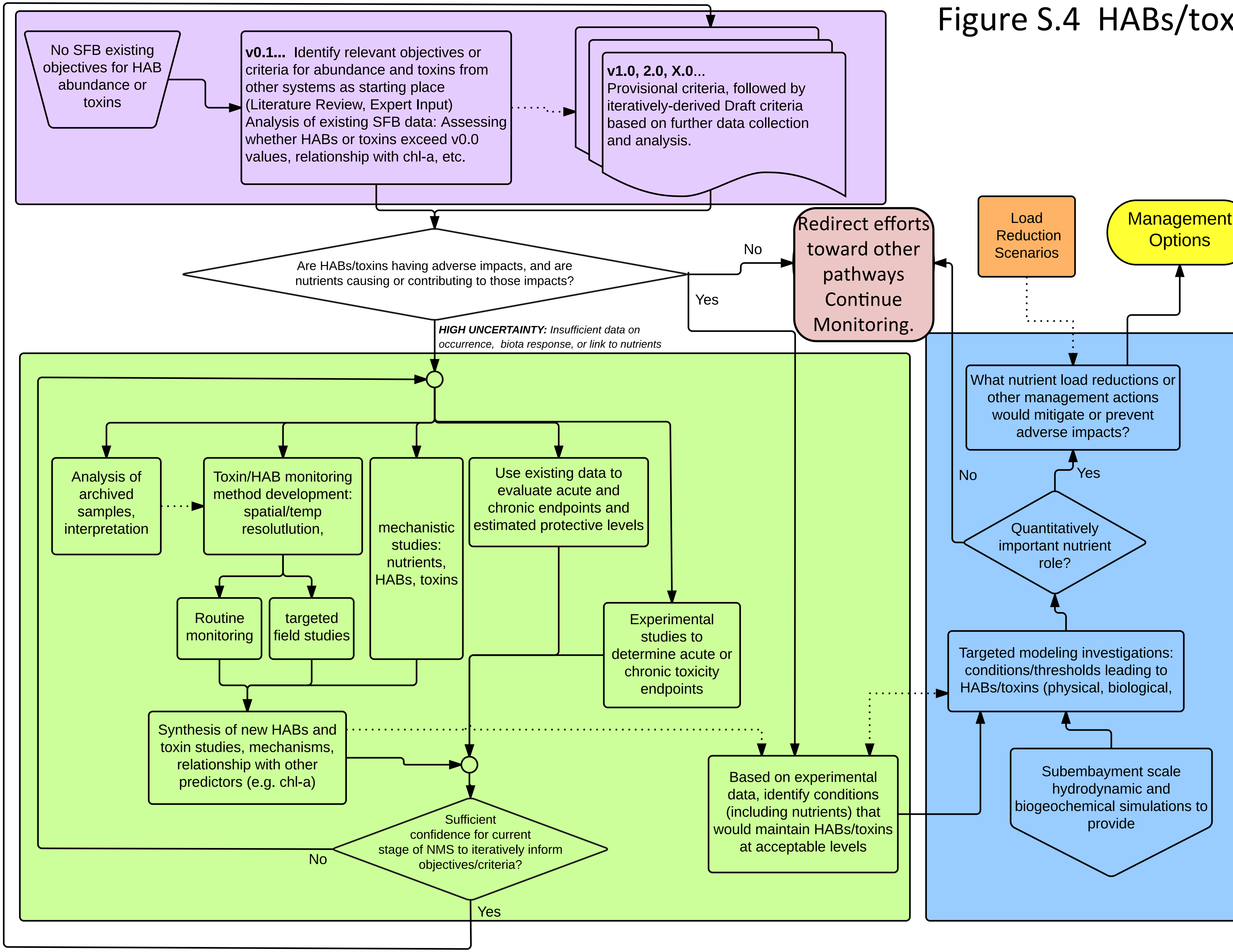
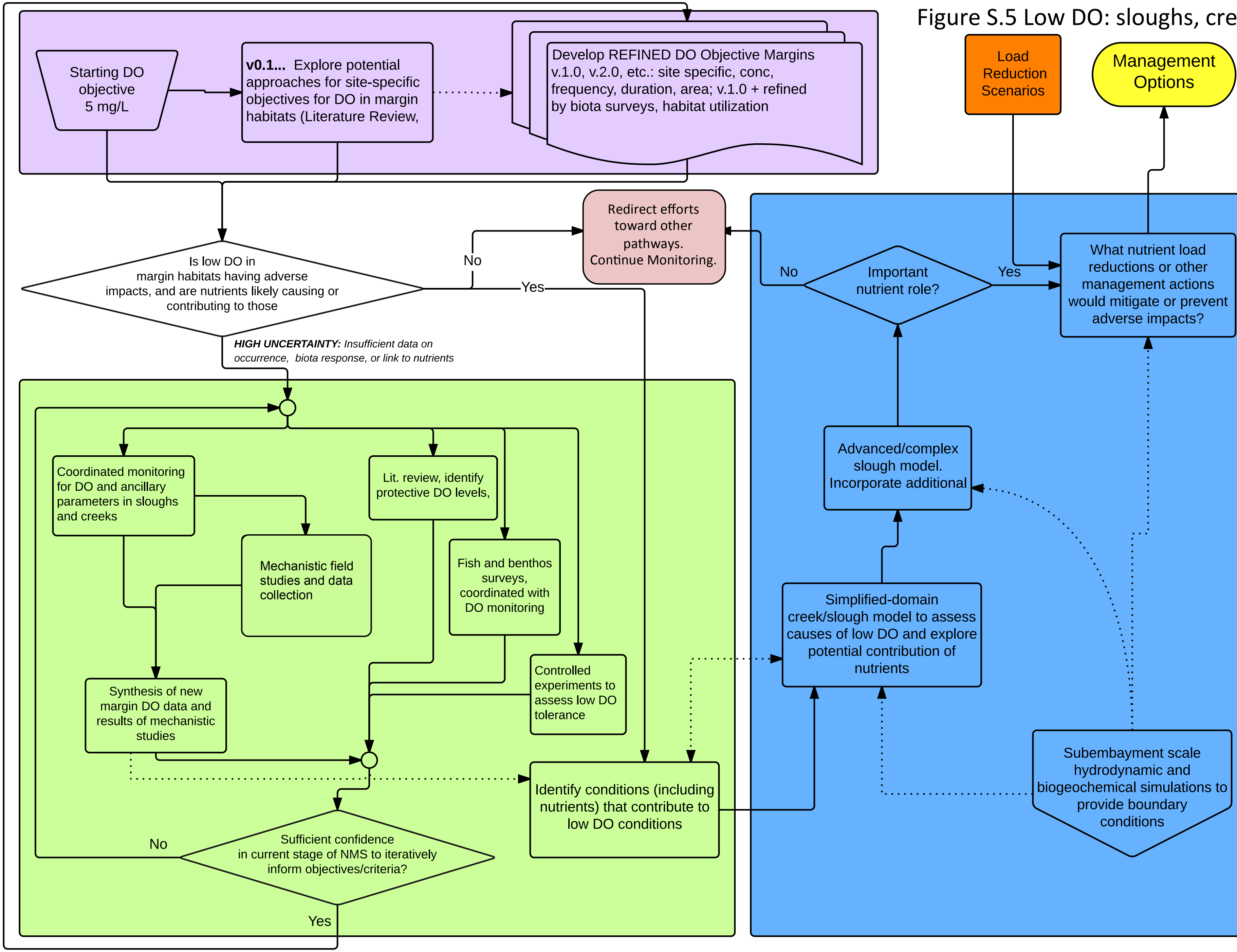


Figure S.5 Low DO: sloughs, creeks



Appendix 1 Additional Science Plan Tables

Table A.1 Tiered ordering of HABs/toxins questions and estimated effort associated with work. Note: In general the costs included here do not include the costs associated with routine monitoring (field work) to collect samples, or cost of ancillary data (nutrients, T, sal, light, etc.).

Tier	Question	Current level of completion	Confidence if answer given today	Cost and activity	Time to complete	Total Cost ($1000s)	Feasible to answer by 2024?
1	Are HABs/NABs/toxins present? If so which ones, how abundant?	20% Existing data show presence common detection of HAB species Toxins are ubiquitous but effect is unknown	High	$150/yr 1 more year of sample collection	1.5 yr	$225	Yes
2	Are HABs causing impairment, based on existing data on what causes adverse impacts elsewhere, and based on toxin concentrations in biota and water?	10% Toxins are ubiquitous in water. Toxins have also been detected in most bivalve samples analyzed to date, but are generally low relative to existing guidance levels.	Low	$200/yr Bivalve sampling, water column sampling. Additional 2-3 years of data.	4 yr	$800	Yes
3	What are the ecological drivers at a large scale, in particular the role of nutrients (alongside other physical/biological factors)?	10% Some data available, more needed. 3-5 additional years of data.	Low	$150/yr Additional sample analysis, data analysis and interpretation	3 yr	$450	Yes
4	What are the physiological drivers? In particular what roles do nutrients play, and what would be protective concentrations?	5% Based on studies in other systems	Low	$150-200/yr Substantial undertaking	6+ years e.g., 3 yr for each class of organisms	>$1000	Yes
5	Is acute or chronic impairment from toxins evident in resident organisms?	0% No data	Low	$100-200/yr Lab experiments or tissue from Bay animals	5+ yrs	>$1000	Yes
6	Predictive/statistical models: Is there a nutrient-related high risk? What levels of nutrients would be protective?	0% Need ecological and physiological results from 3 and 4, and data from 1 and 2.	Low	$150/yr	3 yrs	$450	Yes, but #2-4 would need to start early
7	Numerical simulation models: Is there a nutrient-related high risk? What levels of nutrients would be protective?	0% Need much data on growth conditions	Low	$200 Semi-quantitatively improved understanding of nutrient role and risk	5 years of model development	$1000	Not to completion

Table A.2 10-year Science Plan

o - - - - - - - x   Indicates a project that was/is funded and is completed or still underway

Dark grey squares indicate a deliverable or report (there are more deliverables than noted in table; just a subset here)

The yellow, orange and red cells indicate a milestone for answers being iteratively reached to questions that are closely tied to management questions (initial, medium, and final, respectively), corresponding to Tables 2.4 and 2.5.

	Topic	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
	First 5 year Watershed Permit cycle.													
	Second 5-year permit.													
1.	**Nutrient: loads, fate, transport**													
1.A	***Synthesis_Nutrients***													
1	conceptual model	o - - - - - - - x												
2	LSB synthesis		o - - - - - - x											
3	Suisun Synthesis I	o - - - - - - x												
1.B	***Monitoring_Nutrients***													
1	Baseline Nutrient monitoring: monthly, bi-weekly, Bay-wide	- - - - - - - - - - - - - -												
2	Additional new parameters, shifting toward new nutrient program			o - - x										
3	Continuous, moored stations, LSB and South Bay focus, nutrients			o - - x										
4	Continuous, moored stations, other subembayments, nutrients													
1.C	***Special investigations: rates, physics, state variables_Nutrients***													
1	Biogeochemical Mapping, LSB focus				o - - x									
2	Physical data collection, interpretation, LSB and South Bay focus				o - - - x									
3	N and P transformations and uptake, field investigations, physical data, LSB and South Bay focus													
4	N/P transformations, field investigations, physical data, other subembayments													
1.D	***Modeling***													
	Load estimates													
1	Overall Loading estimates, v1.0, v2.0, ...	o - - - - - x												
2	Delta loads to Suisun, v1.0, v2.0			o - - - - - x										
3	Refined point source load estimates, v1.0, v2.0, ...													
4	Local watershed load estimates													
	transport, transformation													
5	Subsystem: LSB and South Bay, including sensitivity analysis				o - - x									
6	Subsystem: Suisun Bay, including sensitivity analysis													
7	Bay-wide nutrient transformations + transport; source tracking/attribution													
8	Exchange with coastal ocean, fate of exported nutrients													
1.E	***Protective Conditions: nutrients***													
1	Based on protective levels for DO, HABs, etc, determine protective nutrient concentrations or loads													
1.F	***Future Scenarios: Nutrients***													
1	Nutrient cycling/concentrations under future land uses													
2	Future scenarios for nutrient inputs (e.g., load reductions)													
2	**High chl, low DO**													
2.1	**2.1 DO: deep subtidal**													
2.1.A	***Synthesis***													
1	conceptual model	o - - - - - - - x												
2	LSB synthesis		o - - - - - - x											
2.1.B	***Monitoring: state variables/concentrations***													
1	Baseline biomass monitoring: monthly, bi-weekly, Bay-wide	- - - - - - - - - - - - - -												
2	Additional new parameters, shifting toward new nutrient program			o - - x										
3	Continuous, moored stations, LSB and South Bay focus, biomass/DO		- - - - - - - - x											
4	Continuous, moored stations, other subembayments, bioimass/DO													
2.1.C	***Special investigations: rates, physics, state variables, chl-DO deep***													
1	Biogeochemical Mapping, LSB				o - - x									
2	Physical data collection, interpretation, LSB				o - - - x									
3	LSB and South Bay focused field investigations: Biomass, productivity, respiration/oxygen demand in water column and sediments, grazing, physical observations (stratification, velocities, etc.)													
4	field investigations, other embayments: Biomass, productivity, respiration/oxygen demand in water column and sediments, grazing, physical observations (stratification, velocities, etc.)													
5	Habitat/condition assessments (e.g., fish surveys, benthos)													
6	Controlled studies on DO/T tolerance for target species									TBD				
2.1.D	***Modeling_chl-DO_deep***													

	Topic	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	Subsystem: LSB and South Bay, focus on explaining recent changes, including sensitivity analysis, relative imporantance of regulating factors (clams, light, etc.)				o - - x									
2	Subsystem: Suisun, focus on explaining past changes, relative importance of factors (light, NH4, clams, flushing), including sensitivity analysis													
3	Bay-wide biomass/production/DO													
4	Exchange with coastal ocean, fate of exported biomass, importance of imported biomass													
2.1.E	***Protective Conditions: DO,chl_deep***													
1	Assessment Framework Development, v1.0, v2.0, v3.0; Based on newly collected data, model simulations, habitat assessments, and any refinements to DO standards		o - - - - - - - - x											
2	Evaluating DO standards: literature review, desktop studies				o - - x									
2.1.F	***Modeling Future Scenarios: DO, deep subtidal***													
1	DO, productivity, biomass, etc., under environmental change scenarios													
2	Future scenarios for management actions (e.g., load reductions)													
2.2	**DO: shallow margin**													
2.2.A	***Synthesis***													
1	conceptual model	o - - - - - - - x												
2	LSB synthesis (including Analysis of existing DO data in Lower South Bay)		o - - - - - - x											
3	Suisun Marsh TMDL work (separate effort)													
2.2.B	***Monitoring: state variables/concentrations***													
1	On-going monitoring in sloughs, or special studies?									TBD				
2.2.C	***Special investigations: rate measurements, physics, state variables***													
1	DO in shallow margin habitats, LSB focus			o - - - x						TBD				
2	Biogeochemical Mapping, LSB				o - - x									
3	Physical data collection, interpretation, LSB				o - - - x									
4	LSB and South Bay focused field investigations: Biomass, productivity, respiration/oxygen demand in water column and sediments, grazing, physical observations (stratification, velocities, etc.)													
5	field investigations, other embayments: Biomass, productivity, respiration/oxygen demand in water column and sediments, grazing, physical observations (stratification, velocities, etc.)													
6	Habitat/condition assessments (e.g., fish surveys, benthos)													
7	Controlled studies on DO/T tolerance for target species									TBD				
2.2.D	***Modeling_chl-DO_shallow***													
1	Slough modeling: focus on one representative sloughs in LSB or South Bay, biomass/DO, nutrients; starting basic, adding complexity as needed													
2	Expand to other sloughs/creeks, as needed and feasible													
2.2.E	***Protective Conditions: DO_shallow***													
1	Assessment Framework Development, v1.0, v2.0, v3.0; Based on newly collected data, model simulations, habitat assessments, and any refinements to DO standards													
2	Evaluating DO standards: literature, desktop studies				o - - x									
2.2.F	***Modeling Future Scenarios: DO, deep shallow***													
1	DO, productivity, biomass, etc., under environmental change scenarios													
2	Future scenarios for management actions (e.g., load reductions)													
3	**Phytoplankton community**													
3.1	**HABs/toxins**													
3.1.A	***Synthesis: HABs/toxins***													
1	conceptual model	o - - - - - - - x												
2	Suisun Synthesis 2		o - - - - - - x											
3.1.B	***Monitoring: state variables/concentrations***													
1	baseline USGS program	- - - - - - - - - - - - - -												
2	integrative measurements (SPATT on Polaris, or at fixed sites)	- - - - - - - - - - - - x												
3	additional measurements (consistent set of stations under all conditions)			o - - x										
4	On-going water column sampling for toxins													
5	Benthos monitoring (natural organisms or e.g., mussel watch)													
3.1.C	***Special investigations***													
1	analysis of archived pigment samples; on-going analysis of samples collected during monitoring		o - - x											
2	analysis of archived toxin samples (11/2011-12/2014); on-going analysis of samples collected during monitoring			o - - x										

	Topic	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
3	Biogeochemical Mapping, LSB, in particular interpretation of pigments and toxins				o - -									
4	Physical data collection, interpretation				o - - - x									
5	data analysis/interpretation of historical HAB and community composition data, and recent data: statistical analysis, mechanistic interpretation													
6	data analysis/interpretation of pigment and toxin data (2012-2017): statistical analysis, mechanistic interpretation													
7	targeted/intensive field investigations to characterize spatial/temporal distribution of HABs/toxins and physical/chemical conditions: LSB, South													
8	targeted/intensive field investigations to characterize spatial/temporal distribution of HABs/toxins and physical/chemical conditions; Bay-wide and/or other embayments													
9	Controlled experiments: factors influencing HABs and toxin production													
10	Controlled experiments: toxicity to biota									TBD				
3.1.D	***Modeling_HABs***													
	simplified domain models for exploring factors that could favor HAB blooms or toxin production, HAB-promoting/toxin-promoting													
	predicting HAB occurrence													
3.1.E	***Protective Conditions: HABs/toxins***													
1	Assessment Framework Development, v1.0, v2.0, v3.0; Based on newly collected data, habitat assessments, etc.: HABs/toxins.		o - - - - - - - - - x											
2	Evaluating toxicity and HAB thresholds: which organisms to protect, existing data from other studies, lit review													
3	based on toxicity criteria, estimate size/concentration bloom or toxin plumes(bioaccumulation/exposure)													
3.1.F	***Modeling Future Scenarios: toxins/HABs***													
	simulations under future drivers									TBD				
3.2	**Food Quality**													
3.2.A	***synthesis***													
1	Suisun Synthesis II		o - - - - - - x											
2	Additional synthesis, External Review													
3.2.B	***Monitoring: state variables/concentrations***													
1	baseline USGS program	- - - - - - - - - - - - - -												
2	additional measurements (consistent set of stations under all conditions)			o - - x										
3	On-going water column sampling for appropriate measures of phytoplankton community													
3.2.C	***Special Studies***													
1	analysis of archived pigment samples (11/2011-6/2014)		o - - x											
2	analysis of additional archived pigment samples (through 6/2015) (along with HAB study)			o - - x										
3	Biogeochemical Mapping, LSB, jointly with HABs				o - -									
4	Physical data collection, interpretation				o - - - x									
5	data analysis/interpretation of historical community composition data, and recent data: statistical analysis, mechanistic interpretation; Jointly with HABs													
6	data analysis/interpretation of pigment and toxin data (2012-2017): statistical analysis, mechanistic interpretation; Jointly with HABs													
7	targeted/intensive field investigations to characterize spatial/temporal distribution of communities: LSB, South; jointly with HABs													
8	targeted/intensive field investigations to characterize spatial/temporal distribution of communities; Bay-wide and/or other embayments; Jointly with HABs													
9	Controlled experiments: factors influencing community composition, some overlap with HABs studies							TBD						
10	Controlled experiments: factors influencing cellular composition or effects at higher trophic levels (ecological stoichiometry)									TBD				
3.2.D	***Modeling***													
1	simplified domain models for exploring factors that shape community composition; some overlap with HAB modeling						TBD							
2	predicting phytoplankton composition and food quality, some overlap with HAB modeling									TBD				
3.2.E	***Protective Conditions: Food Quality***													
	literature review, healthy phtoplankton community													
	experimental work to identify optimal food quality						TBD							
3.2.F	***Modeling Future Scenarios: food quality***													
	simulations under future drivers									TBD				
4	**NH4 inhibition of primary production**													
4.A	***Synthesis***													
1	Suisun Synthesis I	o - - - - - - x												

	Topic	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
2	Suisun Synthesis II		o - - - - - - x											
3	Additional synthesis, External Review													
4.B	***Monitoring: state variables/concentrations***													
1	baseline USGS sampling	- - - - - - - - - - - - - -												
4.C	***Special investigations***													
1	Complete recent and current projects: Dugdale et al., Glibert et al.; Berg/Kudela et al; Kraus et al. (other funding)													
2	analysis/interpretation of existing data, alongside physical/chemical measurements													
3	New targeted/intensive field investigations							TBD						
4	New controlled experiments:							TBD						
4.D	***Modeling***													
1	Simplified domain, mechanistic model, NH4, light, clams, flow													
2	Further refined model for NH4 considerations													
4.E	***Protective Conditions:***													
1	Interpretation of experimental, field, modeling results, protective levels													
4.F	***Modeling Future Scenarios***													
1	simulations under future drivers									TBD				
5	**Nutrient Program Development and Maintenance**													
5.A	A. Synthesis: Bi-annual program updates, periodic updates of Science Plan, etc.		o - - - - - -											
5.B	B. Monitoring: program development, basic monitoring, infrastructure		o - - - x											
5.C	C. Special Studies													
5.D	D. Modeling: base model development, refinement, maintenance		o - - - - - - - x											
5.E	E. Assessment Framework: data assimilation, refinement		o - - - - - - - - - x											
5.F	F. Program Management													

Appendix 2. Background

A.2.1 San Francisco Bay and the Bay Area

San Francisco Bay (SFB) encompasses several subembayments of the San Francisco Estuary, the largest estuary in California (Figure A.2.1). SFB is surrounded by remnant tidal marshes, intertidal and subtidal habitats, tributary rivers, the freshwater "Delta" portion of the estuary, and the large mixed-land-use area known as the San Francisco Bay Area (Figure A.2.2.A). San Francisco Bay hosts an array of habitat types (Figure A.2.1), many of which have undergone substantial changes in their size or quality due to human activities. Urban residential and commercial land uses comprise a large portion of Bay Area watersheds, in particular those adjacent to Central Bay, South Bay and Lower South Bay (Figure A.2.2.A). Open space and agricultural land uses occupy larger proportions of the watersheds draining to Suisun Bay and San Pablo Bay. The San Joaquin and Sacramento Rivers drain 40% of California, including agricultural-intensive land use areas in the Central Valley. Flows from several urban centers also enter these rivers, most notably Sacramento which is ~100 km upstream of Suisun Bay along the Sacramento River.

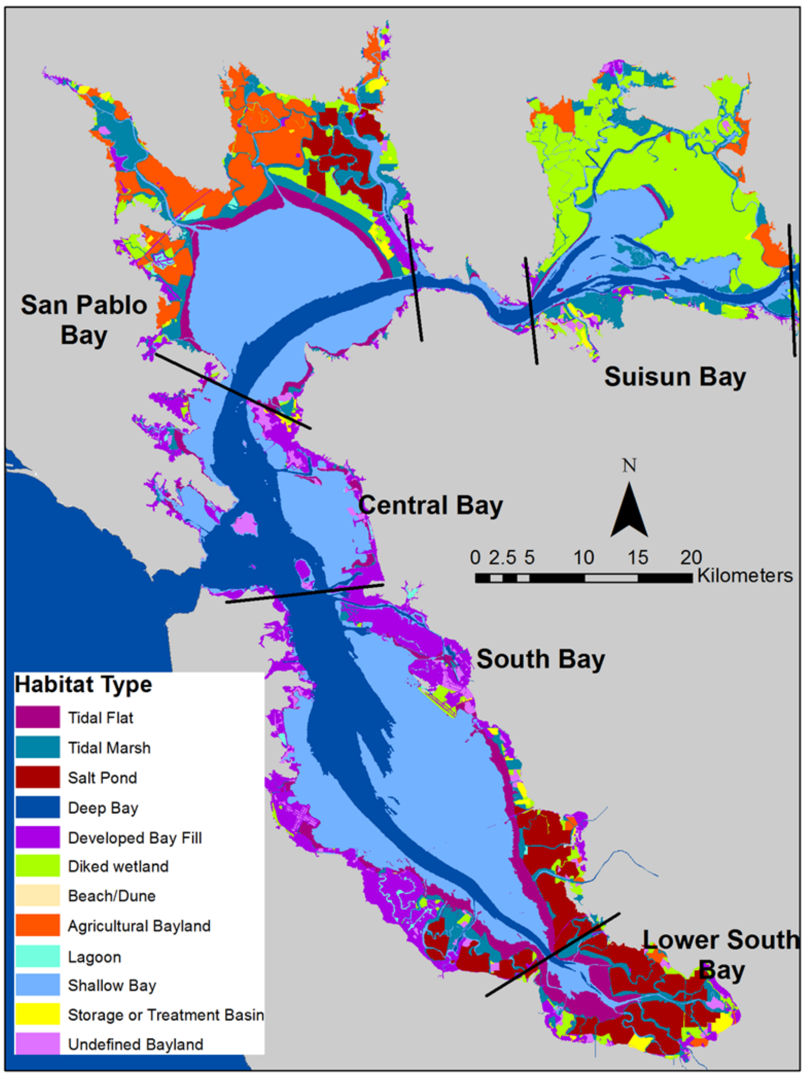


Figure A.2.1 Habitat types of SFB and surrounding Baylands. Water Board subembayments boundaries are shown in black. Habitat data from CA State Lands Commission, USGS, UFWS, US NASA and local experts were compiled by SFEI.

SFB receives high nutrient loads from 42 public owned wastewater treatment works (POTWs) servicing the Bay Area's 7.2 million people (Figure A.2.2.B). Several POTWs carry out nutrient removal before effluent discharge; however the majority perform only secondary treatment without additional N or P removal. Nutrients also enter SFB via stormwater runoff from the densely populated watersheds that surround SFB (Figure A.2.2.A). Flows from the Sacramento and San Joaquin Rivers deliver large nutrient loads, and enter the northern estuary through the Sacramento/San Joaquin Delta (not shown, immediately east of the maps in Figure A.2.1 and A.2.2).

A.2.1 San Francisco Bay Nutrient Strategy

Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) are essential nutrients for primary production that supports SFB food webs. However DIN and DIP concentrations in SFB greatly exceed those in other US estuaries where water quality has been impaired by nutrient pollution (Cloern and Jassby, 2012). SFB has long been considered relatively immune to its high nutrient loads. For example, the original San Francisco Bay Regional Basin Plan from 1975 stated that only limited treatment for nutrients was necessary because the system was considered to be light limited (SFBRWQCB, 1975). Research and monitoring over the last 40 years have identified several factors that impart SFB with its resistance to high nutrient loads (e.g., see Cloern and Jassby 2012; Cloern et al., 2007; Kimmerer and Thompson, 2014): high turbidity (low light), strong tidal mixing (breaks down stratification and fully mixes the water column, resulting in low light availability), and abundant filter-feeding clam populations (remove phytoplankton from the water column).

However, recent studies indicate that the response to nutrients in SFB is changing, indicate that the system is poised to potentially experience future impacts, or suggest that current nutrient levels are already causing adverse impacts. These observations include: a 3-fold increase in summer-fall phytoplankton biomass in South Bay since the late 1990s; frequent detections in SFB of algal species that have been shown in other nutrient-rich estuaries to form harmful blooms; detection of algal toxins Bay-wide; an unprecedented red tide bloom in Fall 2004; and studies suggesting that the chemical forms of nitrogen can influence phytoplankton productivity and composition. To address growing concerns that SFB's response to nutrients is changing and that conditions may be trending toward adverse impacts due to elevated nutrient loads, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy[1], which lays out an approach for gathering and applying information to inform management decisions. Overall, the Nutrient Management Strategy aims to answer four fundamental questions:

1. Is SFB experiencing nutrient-related impairment, or is it likely to in the future?
2. What are the major nutrient sources?
3. What nutrient loads or concentrations are protective of ecosystem health?
4. What are efficacious and cost-efficient nutrient management options for ensuring that Bay beneficial uses are protected?

The indications of changing SFB response to nutrients have come to the fore at a time when the availability of resources to continue assessing the Bay's condition is uncertain. Since 1969, a USGS research program has supported water-quality sampling in the San Francisco Bay. This USGS program collects monthly samples between the South Bay and the lower Sacramento River to measure salinity, temperature, turbidity, suspended sediments, nutrients, dissolved oxygen and chlorophyll a. The USGS data, along with sampling conducted by the Interagency Ecological Program (IEP), provide coverage for the entire Bay–Delta system (Figure A.2.3). The San Francisco Bay Regional Monitoring Program (RMP) has no independent nutrient-related monitoring program, but instead contributes approximately 20% of the USGS data collection cost. The Nutrient Strategy highlights the need for a regionally-supported, long-term monitoring program that provides the information that is most needed to support management decisions in the Bay.

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[1] http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/Nutrient_Strategy%20November%202012.pdf

The timing also coincides with a major state-wide initiative, led by the California State Water Resources Control Board (State Water Board), for developing nutrient water quality objectives for the State's surface waters, using an approach known as the Nutrient Numeric Endpoint (NNE) framework. The NNE framework establishes a suite of numeric endpoints based on the ecological response of a waterbody to nutrient over-enrichment and eutrophication (e.g. excessive algal blooms, decreased dissolved oxygen). In addition to numeric endpoints for response indicators, the NNE approach includes models that link the response indicators to nutrient loads and other management controls. The NNE framework is intended to serve as numeric guidance to translate narrative water quality objectives.

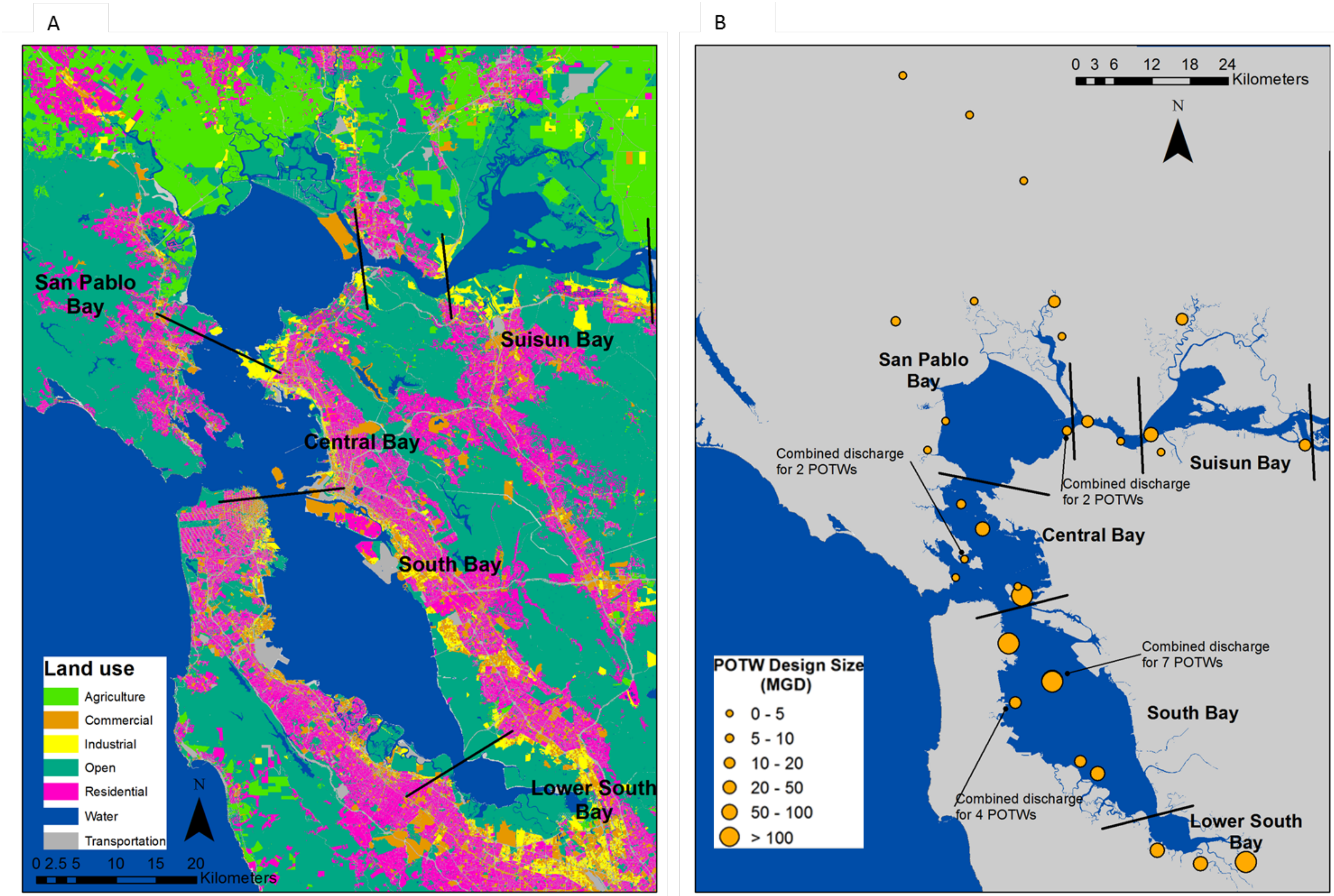

Figure A.2.2 A. Land use in watersheds that drain to SFB (Data from Association of Bay Area Governments, 2000). **B.** Location and design size (in million gallons per day) for POTWs that discharge directly in SFB or in watersheds directly adjacent to subembayments. In both figures, Water Board subembayment boundaries are shown in black.

Since San Francisco Bay is California's largest estuary, it is a primary focus of the state-wide effort to develop NNEs for estuaries. Through the Nutrient Strategy, the SFBRWQCB is working with regional stakeholders and with the State Water Board to develop an NNE framework specific to SFB. That effort was initiated by a literature review and data gaps analysis that recommends indicators to assess eutrophication and other adverse effects of nutrient overenrichment in San Francisco Bay McKee et al., 2011)[2]. McKee et al. (2011) evaluated a number of potential indicators of ecological condition for several habitat types based on the following criteria:

- Indicators should have well-documented links to estuarine beneficial uses
- Indicators should have a predictive relationship with nutrient and hydrodynamic drivers that can be easily observed with empirical data or a model
- Indicators should have a scientifically sound and practical measurement process that is reliable in a variety of habitats and at a variety of timescales
- Indicators must be able to show a trend towards increasing or/and decreasing benefical use impairment due to nutrients

The report recommended focusing on subtidal habitats initially, and proposed the following primary indicators of beneficial use impairment by nutrients: i. phytoplankton biomass; ii. phytoplankton composition; iii. dissolved oxygen; and; iv. algal toxin concentrations. In addition, 'supporting indicators' and 'co-factors' were identified, and are summarized in Table A.2.1. Supporting indicators provide additional lines of evidence to complement observations based on primary indicators, and co-factors are essential information to help interpret and analyze trends in primary or supporting indicators.

Table A.2.1 Recommended indicators within the context of the SFB NNE. Excerpted from McKee et al 2011

Habitat	Primary Indicators	Supporting Indicators	Co-Factors
All Subtidal Habitat	Phytoplankton biomass, productivity and assemblage Cyanobacteria cell counts and toxin concentration Dissolved oxygen	Water column nutrient concentrations and forms[1] (C,N,P,Si) HAB species cell counts and toxin concentration	Water column turbidity, pH, conductivity, temperature, light attenuation Macrobenthos taxonomic composition, abundance and biomass Sediment oxygen demand Zooplankton
Seagrass Habitat	Phytoplankton biomass Macroalgal biomass & cover Dissolved oxygen	Light attenuation, suspended sediment concentration Seagrass areal distribution and cover Epiphyte load	Water column pH, temperature, conductivity Water column nutrients
Intertidal flats	Macroalgal biomass and cover	Sediment % OC, N, P and particle size Microphytobenthos biomass (benthic chl-a)	Microphytobenthos taxonomic composition
Muted Intertidal and Subtidal	Macroalgal biomass & cover Phytoplankton biomass Cyanobacteria toxin concentration	Sediment % OC, N, P and particle size Phytoplankton assemblage Harmful algal bloom toxin concentration	Water column pH, turbidity, temperature, conductivity Water column nutrients

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[2]http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/644_SFBayNNE_LitReview%20Final.pdf

Regions of SFB behave quite differently with respect to nutrient cycling and ecosystem response due to a combination physical, chemical, and biological factors. To facilitate the discussion of spatial trends in this report, SFB was divided into 5 subembayments, as depicted in Figure A.2.1: Suisun Bay, San Pablo Bay, Central Bay, South Bay and Lower South Bay (LSB). These subembayment boundaries were chosen based on geographic features and not necessarily hydrodynamic features, represent one of several sets of boundaries that could be used. The boundaries illustrated in Figure A.2.1 are similar to those defined by the SFBRWQCB in the San Francisco Bay Basin Plan, although we use different names for the subembayments south of the Bay Bridge.

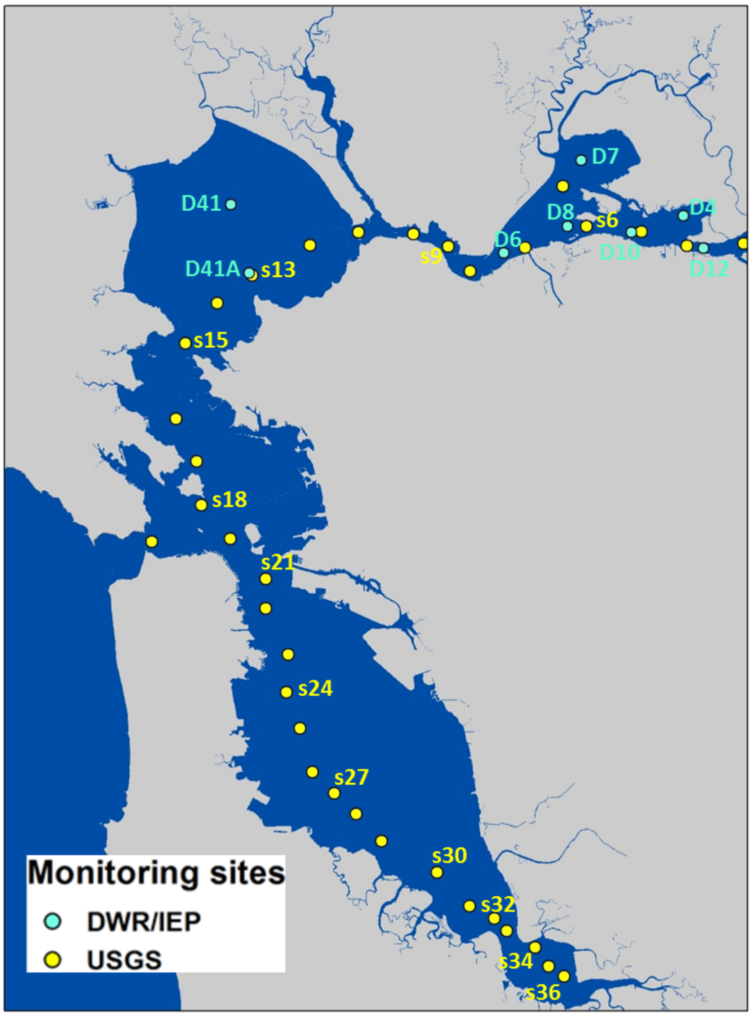

Figure A.2.3 Location of DWR/IEP and USGS monthly sampling stations. Data from labeled USGS Stations (s6, s15, s18, s21, s27, s36) are used in Figures 5.7, 6.3-6.7 and 7.11.

Appendix 3 Problem Statement

A.3.1 Recent observations in SFB

In estuarine ecosystems in the US and worldwide, high nutrient loads and elevated nutrient concentrations are associated with multiple adverse impacts (Bricker et al. 2007). N and P are essential nutrients for the primary production that supports food webs in SFB and other estuaries. However, when nutrient loads reach excessive levels they can adversely impact ecosystem health. Individual estuaries vary in their response or sensitivity to nutrient loads, with physical and biological characteristics modulating estuarine response (e.g., Cloern 2001). As a result, some estuaries experience limited or no impairment at loads that have been shown to have substantial impacts elsewhere.

Figure A.3.1 illustrates several potential pathways along which excessive nutrient loads could adversely impact ecosystem health in SFB. Each pathway is comprised of multiple linked physical, chemical, and biological processes. Some of those processes are well-understood and data are abundant data to interpret and assess condition; others are poorly understood or data are scarce. A recent conceptual model report (SFEI 2014a) describes the processes creating the pathways between loads and adverse response, and describes the current state of knowledge and data availability.

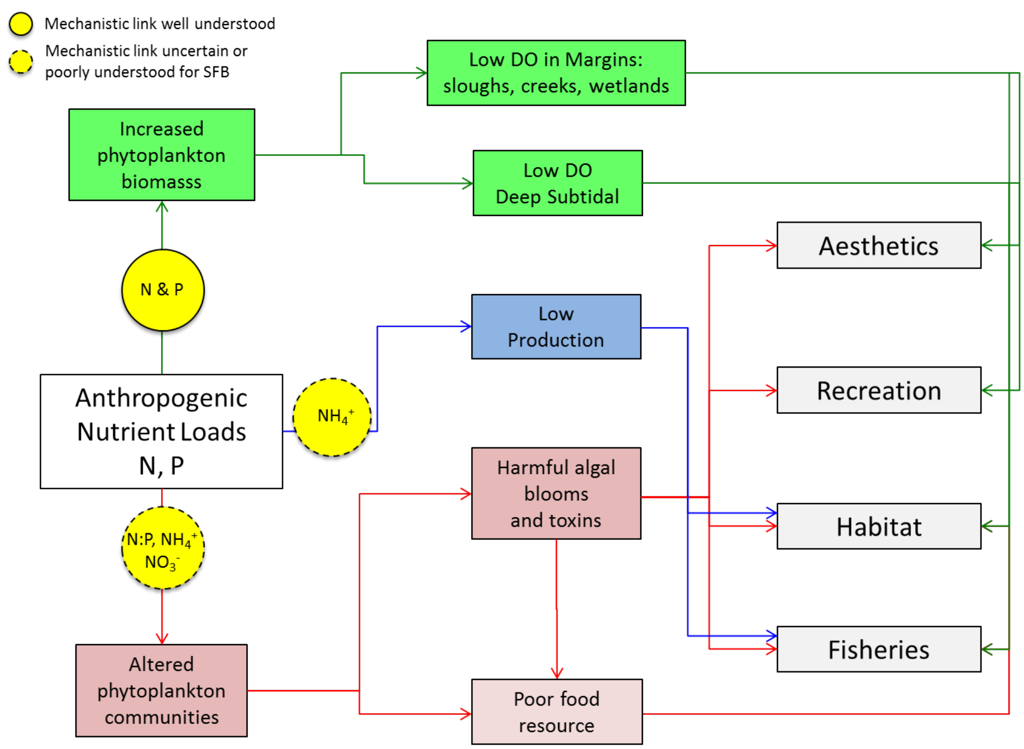

Figure A.3.1 Potential adverse impact pathways: linkages between anthropogenic nutrient loads and adverse impacts on uses or attributes of SFB. The shaded rectangles represent indicators that could actual be measured along each pathway to assess condition. Grey rectangles to the right represent uses or attributes of SFB for which water quality is commonly managed. Yellow circles indicate the forms of nutrients that are relevant for each pathway

Current nutrient loads to some SFB subembayments are comparable to or much greater than those in a number of other major estuaries that experience impairment from nutrient overenrichment (SFEI 2014). Consistent with its high loads, SFB has elevated levels of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous (DIP) relative to other estuaries (Figure A.3.2). Yet SFB does not commonly experience classic symptoms of nutrient overenrichment, such as massive and sustained phytoplankton blooms, or low dissolved oxygen over large areas in the subtidal zone. SFB has been spared the most obvious adverse impacts of high nutrient loads along these pathways due to a combination of factors (high turbidity; strong tidal mixing; large populations of benthic filter feeders) that have imparted SFB with some inherent resistance to these effects (Cloern and Jassby, 2012; SFEI 2014). However, several recent sets of observations indicate that nutrient-related problems may already be occurring in some areas of SFB, or serve as early warnings of problems on the horizon.

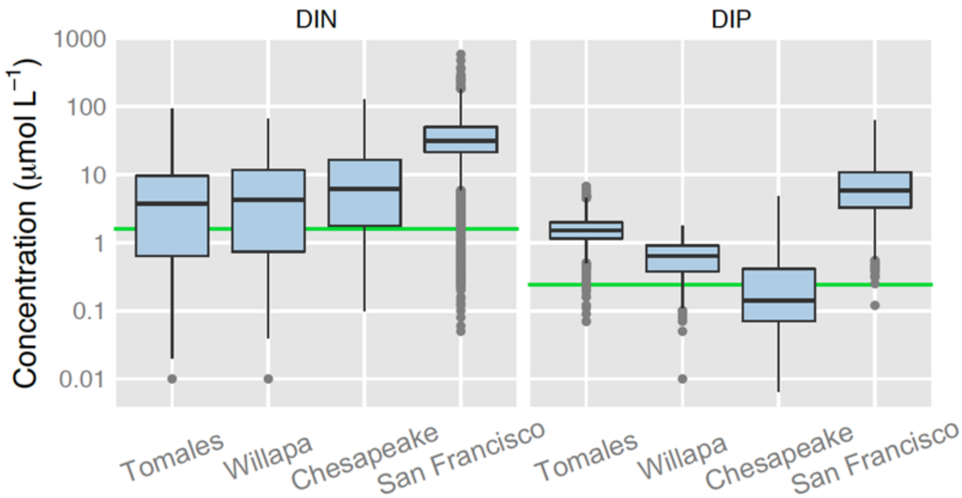

Figure A.3.2 Nutrient concentrations in South Bay compared to other estuaries. Source: Cloern and Jassby (2012)

Over the past 15 years, statistically significant increases in phytoplankton biomass have been observed throughout SFB. Most notably summer/fall phytoplankton biomass tripled between the mid-1990s and the mid-2000s (Figure A.3.3; Cloern et al., 2007) in South Bay and LSB, representing a shift in trophic status from oligo-mesotrophic (low to moderate productivity system) to meso-eutrophic (moderate to high productivity system) (Cloern and Jassby, 2012).

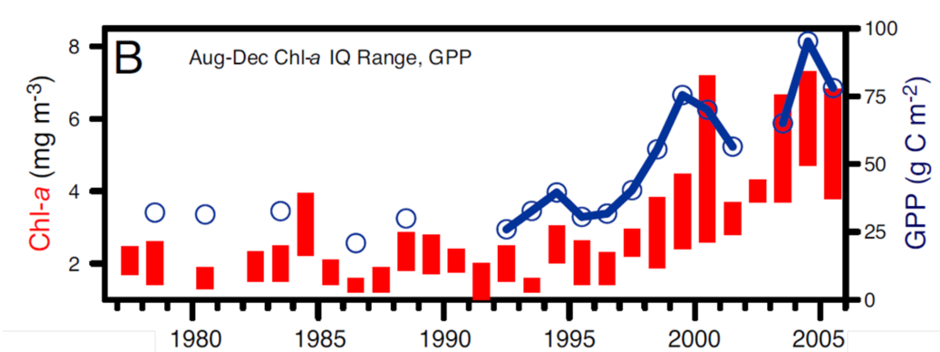

Figure A.3.3 Interquartile range of Aug-Dec chl-a concentrations averaged across all USGS stations between Dumbarton Bridge and Bay Bridge, 1977-2005. Source: Cloern et al., 2007

More recent data from South Bay suggest that, at least presently, biomass concentrations have plateaued at a new level instead of continuing to rise (Figure A.3.4). While the greatest magnitudes of biomass increase (i.e., in ug/L chl-a) have been observed in South Bay, other SFB subembayments have also experienced statistically significant increases in phytoplankton biomass (J Cloern, personal communication).

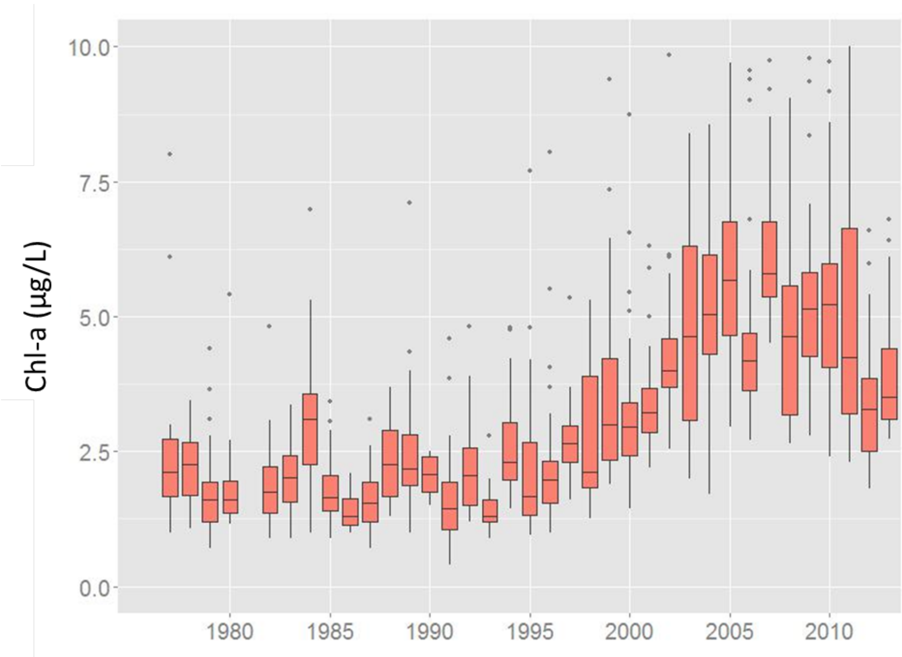

Figure A.3.4 Same stations as and data as presented Figure A.3.5, with data extended through 2013 (Interquartile range of Aug-Dec chl-a concentrations averaged across all USGS stations between Dumbarton Bridge and Bay Bridge, 1977-2013). Source: SFEI 2014c

In Suisun Bay, extremely low phytoplankton biomass has defined the system since 1987 (Figure A.3.8), coincident in time with the invasive clam, *Potamocorubula amurensis,* becoming widely established. The extended period of low phytoplankton biomass and low rates of primary production are considered to be among the factors contributing to long-term declines in upper trophic level production in Suisun Bay and the Delta by limiting food supply (Baxter et al., 2010; NRC 2012). While the low phytoplankton biomass and productivity in Suisun Bay have frequently been attributed to the impacts of *Potamocorbula* and low light levels due to high suspended sediments (e.g., Kimmerer and Thompson, 2014), recent studies have argued that elevated ammonium (NH_4^+) concentrations in Suisun Bay also limit primary production rates and play an important role in both creating the low biomass conditions and exacerbating food limitation (Dugdale et al., 2007; Dugdale et al., 2012; Parker et al. 2012a,b). Other studies have proposed that high ambient concentrations of nitrate (NO_3^-) and NH_4^+, and altered ratios of N:P cause shifts phytoplankton community composition toward

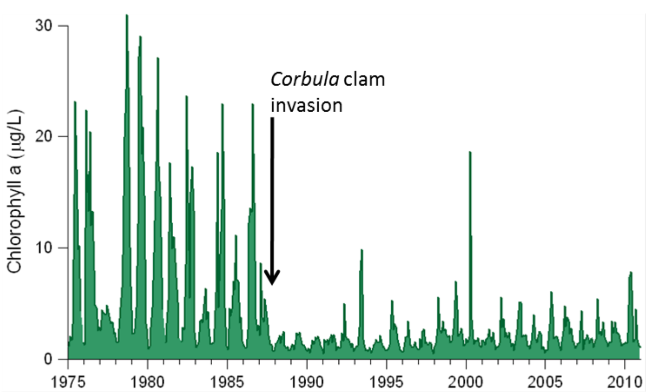

Figure A.3.5 Phytoplankton biomass in Suisun Bay, 1975-2010. Source: J Cloern, USGS; Data: USGS, DWR-EMP species having poor food quality, adversely impacting Delta food webs (Glibert 2010; Glibert et al., 2011).

Harmful phytoplankton species also represent a growing concern. The harmful algae, *Microcystis spp.*, and the toxin they produce, microcystin, have been detected with increasing frequency in the Delta and Suisun Bay since ~2000 (Lehman et al., 2008). In addition, the HAB toxins microcystin and domoic acid have been detected Bay-wide (Figure A.3.6). The ecological

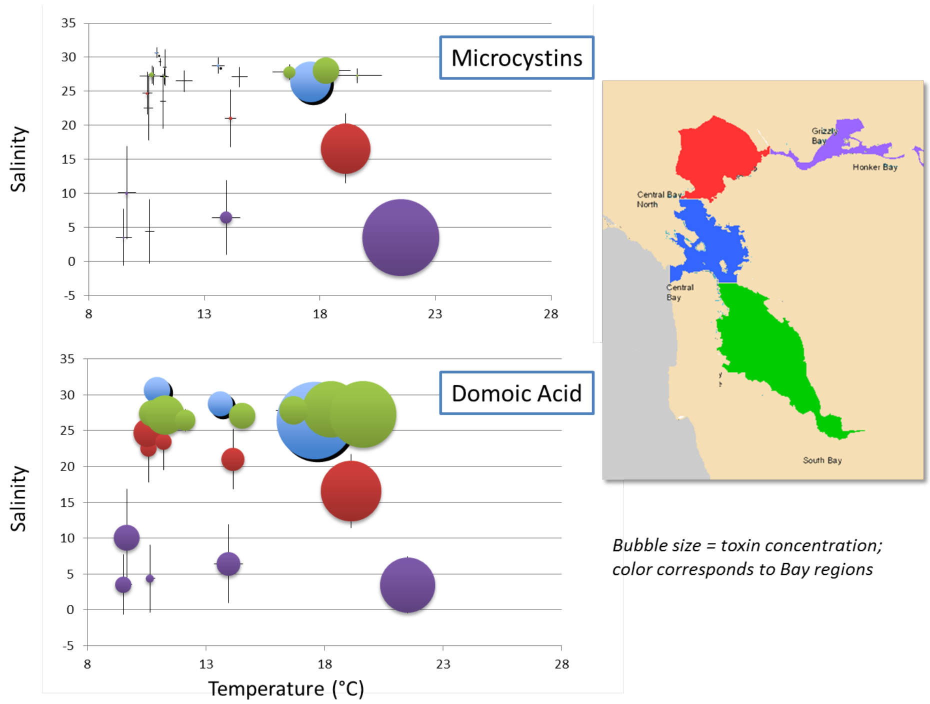

Figure A.3.6 HAB toxins detected in SFB during 2011. Bars represent 1 SD for salinity and temperature Source: R. Kudela

significance of observed toxin levels in the Bay are not yet known. A number of phytoplankton species that have formed harmful algal blooms (HABs) in other systems have been detected throughout SFB (Figure A.3.7 and Table A.3.1). Although the abundances of HAB-forming organisms in SFB have not generally reached levels that would constitute a major bloom, they do periodically exceed thresholds established for other systems (Sutula et al., in prep), and major *Microcystis spp* blooms and elevated microcystin levels have been observed with some regularity in the Delta (Lehman et al., 2008). Moreover, since HAB-forming species are present in SFB and nutrients are abundant, HABs could readily develop should appropriate physical conditions create opportunities that HABs can exploit. In fact, an unprecedented large red tide bloom occurred in Fall 2004 following a rare series of clear calm days during which the water column was able to stratify, and chl-a levels reached nearly 100 times their typical values (Figure A.3.8; Cloern et al. 2005). In addition, harmful-bloom forming species have been detected at elevated abundances in salt ponds in LSB undergoing restoration (Thebault et al., 2008), raising concerns that salt ponds could serve as incubators for harmful species that could then proliferate when introduced into the open bay

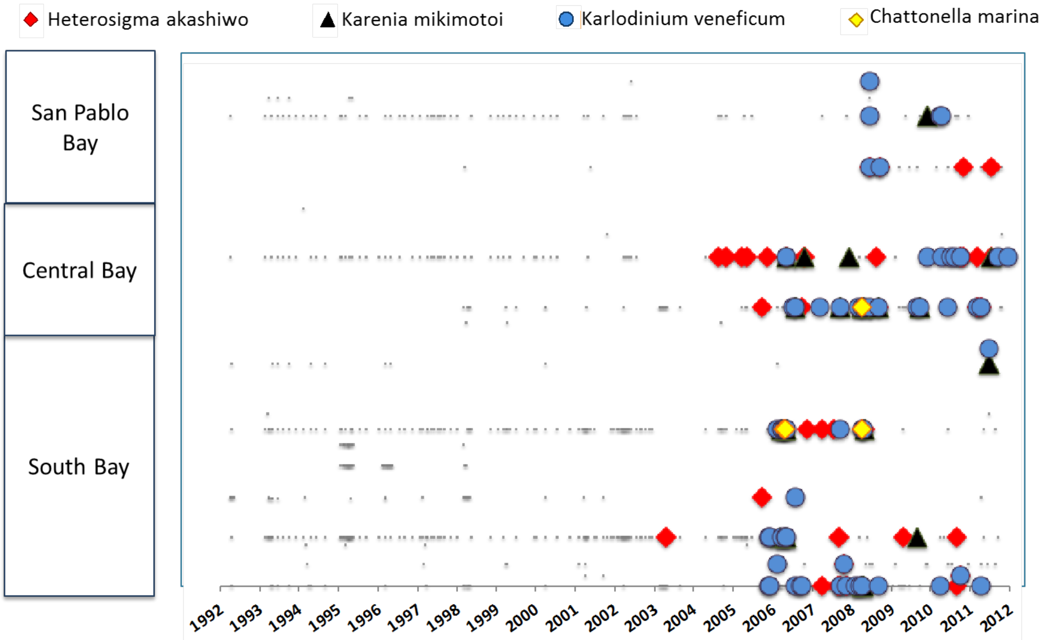

Figure A.3.7 Several potentially harmful algal species detected in South Bay, Central Bay, and San Pablo Bay over the past 20 years. Y-axis represents distance to USGS stations from Lower South Bay. Grey dots represent sample collection/analysis, colored dots represent one of the 4 species detected in a collected sample. Source: T Schraga, USGS

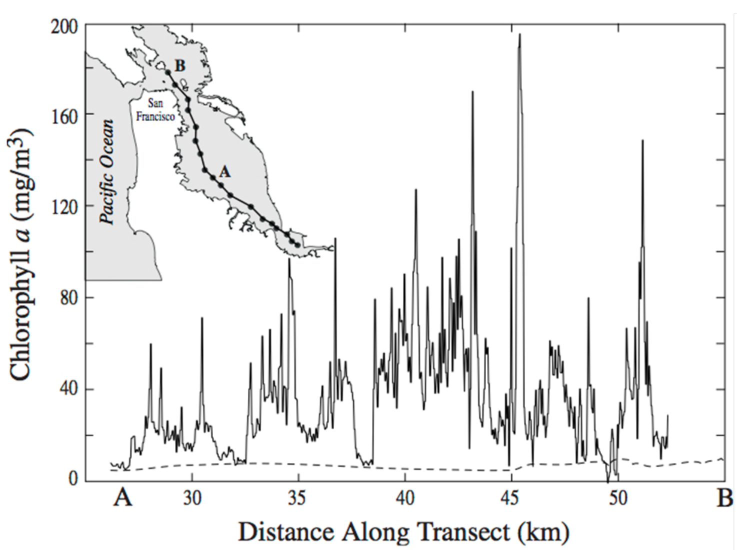

Figure A.3.8 Phytoplankton biomass South and Central Bays. Measurements taken during a red tide on 8 September 2004 (solid curve). Phytoplankton biomass returned to typical seasonal levels on 14 September (dashed curve). Inset map shows location of the sampling transect A-B. Source: Cloern et al. 2005

Table A.3.1 Potentially harmful algal species detected through USGS science program in SFB: 1992-2012. Source: T Schraga, USGS

Genus/Species	Division/ Phyla	1st observed	Most recent observed	# of times observed	Toxin**	Impact	Location and timing of observations
Alexandrium	Dinoflagellate	1992	2011	247	saxitoxin	neurotoxin, fish kills	South, Central, and San Pablo Bays - Spri and Fall
Amphidinium	Dinoflagellate	1996	2008	36	compounds with haemolytic and antifungal properties	fish kills	South Bay - spring bloom (March-April) a occasionally fall bloom (September-Octob
Dinophysis	Dinoflagellate	1993	2011	51	okadaic acid		Central bay
Heterocapsa	Dinoflagellate	1992	2012	394		food web hab, kills shellfish	Found throughout year, but mostly seen in spring and summer, South and Central Bay occasionally up to San Pablo Bay
Karenia mikimotoi *	Dinoflagellate	2006	2011	22	gymnocins, compounds similar to brevetoxin	kills benthic organisms, fish, birds, + mammals	South bay + Central Bay
Karlodinium veneficum *	Dinoflagellate	2005	2012	63	compounds with hemolytic, ichthyotoxic, and cytotoxic effects	kills fish, birds + mammals	South bay + Central Bay
Heterosigma akashiwo *	Raphidophyte	2003	2011	39	neurotoxin	fish kills	South bay + Central Bay
Pseudo-nitzschia	Diatom	1992	2011	132	domoic acid		Large blooms occurred in central and soutl Bay (stn 27) in 1990s
Anabaena	Cyanobacteria	1993	2011	24	PSTs		Sacramento River and confluence.
Aphanizomenon flos-aquae	Cyanobacteria	1995	2011	13	PSTs		Sacramento River and confluence. Low #s South Bay

Table A.3.1 continued

Genus/Species	Division/Phyla	1st observed	Most recent observed	# of times observed	Toxin**	Impact	Location and timing of observations
Aphanocapsa	Cyanobacteria	1993	2011	22			South Bay 2005+6, 2011 Delta confluence (San Joaquin source most likely)
Aphanothece sp.	Cyanobacteria	1992	2011	32			South Bay 2005+6, 1990s and 2010-11 Suis and Sac River
Cyanobium sp.	Cyanobacteria	1999	2008	79	microcystin		South and Central Bay
Lyngbya aestuarii	Cyanobacteria	2011	2011	1	saxitoxin	human health impacts (skin, digestion, respiratory, tumors) and paralytic shellfish poisoning	September 2011 - large bloom in Suisuin are (stn 3)
Planktothrix	Cyanobacteria	1992	2011	23	PSTs		South Bay 2005-2007, 1990s, 2010-11 Suisu and Sac River
Synechococcus sp.	Cyanobacteria	1992	2011	66			South Bay spring (March/April)
Synechocystis	Cyanobacteria	1997	2011	224	microcystin		South Bay and San Pablo Bay, mostly in fall

All of these species have had high biomass in SFBAY. Multiple species are grouped within a genera. If it's a single species, it is listed as such
*Known as exceptionally harmful in temperate estuaries such as in Japan and Atlantic coast estuaries. All were detected for the first time in SFb in the past 10 years and have persisted
** Not all toxins are known. Genera with PST have two or more Paralytic Shellfish Toxins = microsystin, cylindrospermopsin, anatoxin, saxitoxin. All cause Paralytic Shellfish Poisoning. PSTs microcystin and cylindrospermopsin cause liver damage in mammals, anatoxin and saxitoxin damage nerve tissues in mammals (humans, dogs, etc.)

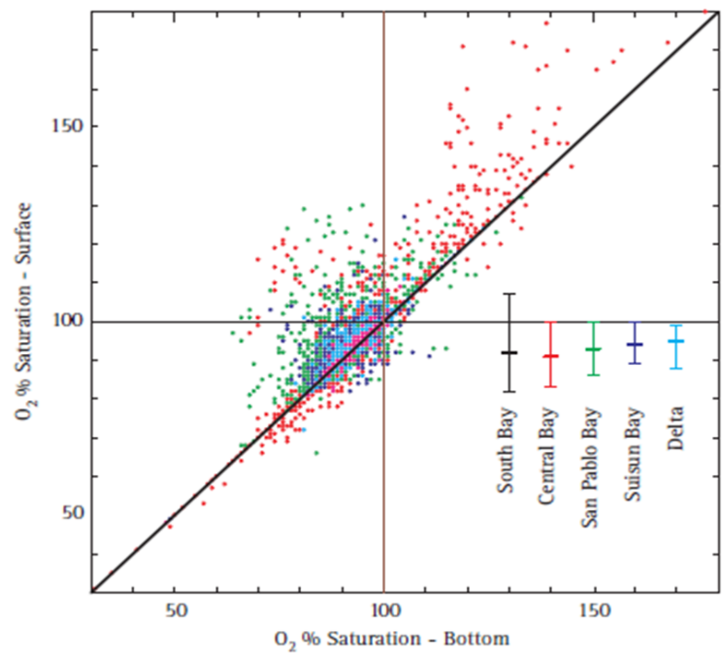

Figure 32. Oxygen concentration as percent saturation in near-surface and near-bottom samples. Color indicates region, and error bars give medians and 10th and 90th percentiles of the data. Data from USGS monitoring program, which focuses on channel stations and the portion of the Delta in the lower Sacramento River.

Figure A.3.9 DO in deep subtidal areas of SFB. Source: Kimmerer 2004

DO concentrations in deep subtidal habitats throughout the Bay typically remain at levels above 5 mg L^{-1}, (Figure A.3.12), the San Francisco Bay Basin Plan standard. However, in LSB, open-Bay sampling has most frequently occurred at slack high tide. Recent continuous measurements at the Dumbarton Bridge indicate that DO levels at low tide are commonly 1-2 mg/L lower than at high tide during summer months (e.g., Figure A.3.10.A), and can occasionally dip below, 5 mg L^{-1} (SFEI, unpublished data). During Summer 2014, USGS sampling cruises detected DO < 5 mg/L at other deep subtidal stations south of the Dumbarton Bridge during two cruises[3].

Low DO commonly occurs in some shallower margin habitats (Figure A.3.10B and Figure A.3.11). For example, studies of salt ponds undergoing restoration in LSB show that they experience large diurnal DO fluctuations (Topping et al., 2009) and occasionally experience sustained periods of anoxia (Thebault et al., 2008). In some slough habitats of LSB, DO regularly dips below 5 mg L^{-1}, frequently approaches 2 mg L^{-1} (Shellenberger et al., 2008). At a site in Alviso Slough, DO remained near or below 2 mg L^{-1} for sustained periods (up to 10-12 hours) during Summer 2013 (Figure A.3.10.B) and Summer 2014 (SFEI, 2015). Low DO has also been observed in Suisun Marsh, although whether that low DO is linked to nutrient issues in SFB is still being investigated (effluent from managed duck ponds is presumed to be a major cause; Tetra Tech 2013). Under natural conditions, shallow subtidal and tidal wetland habitats commonly experience low DO, and plants and animals native to these habitats are often well-adapted to these DO swings. However, there is a paucity of DO data in margin habitats, and the

[3] http://sfbay.wr.usgs.gov/access/wqdata/query/easy.html

severity of low DO (frequency, duration, spatial extent, concentration), whether it is impacting biota, and the extent to which excess nutrients cause or contribute to the low DO conditions are all poorly known.

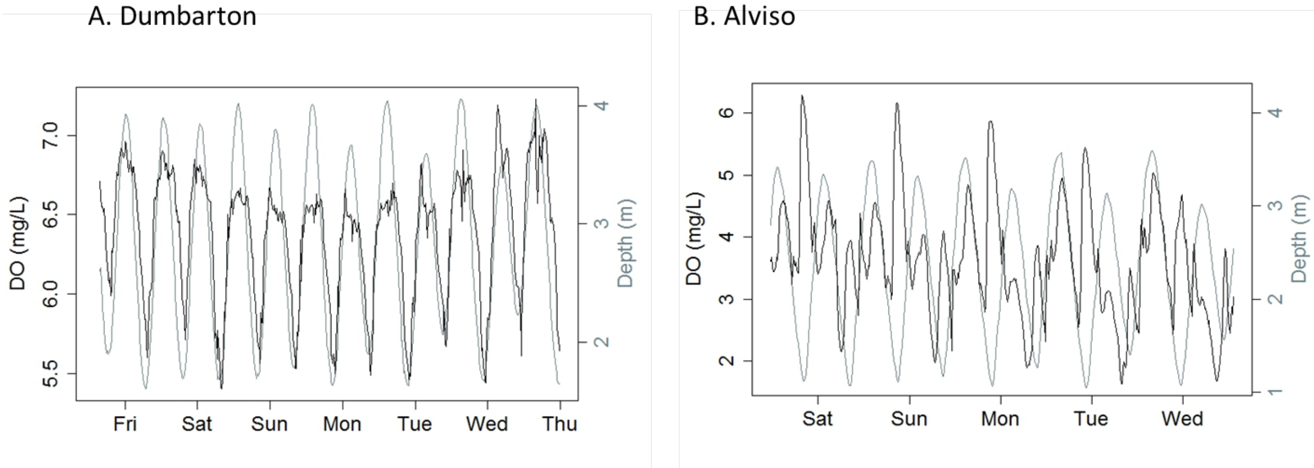

Figure A.3.10 Time series of DO (mg/L) and depth at **A.** Dumbarton Bridge and **B.** Alviso Slough, Sep 5-12 2013.

In addition to characterizing and addressing any current nutrient-related problems in SFB, there is a need to anticipate potential future adverse impacts. The highly elevated DIN and DIP concentrations Bay-wide provide the potential for impairment to occur in the future if the physical and biological factors that provide SFB with resistance to high nutrient loads continue to change. Any major reductions in nutrient loads to SFB will take years-to-decades to implement. Thus, if future problems are to be averted, potential impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed in advance of their onset. A proactive approach to characterizing and managing potential problems – while they are on the somewhat-distant horizon, as opposed to imminent – will allow greater flexibility in the management options that can be pursued.

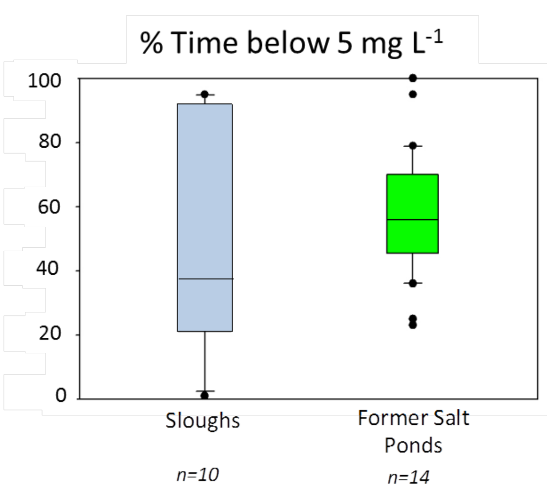

Figure A.3.11 Percentage of time DO less than 5 mg/L in sloughs and salt ponds rimming Lower South Bay, based on a review of all available multi-program continuous sensor measurements. Source: SFEI 2014c

Appendix 4 Key Observations and Recommendations

The following observations and recommendations are excerpted from *"Scientific Foundation for the San Francisco Bay Nutrient Management Strategy"* (SFEI 2014), and serve as the starting set of recommendations for the Science Plan.

A.4.1 Key observations

1. Changes in SFB's response to nutrient loads over the past decade, combined with the Bay's high nutrient loads and concentrations, justify growing concerns about elevated nutrients.
2. The future trajectory of SFB's response to nutrients is uncertain. One plausible trajectory is that SFB maintains its current level of resistance to the classic effects of high nutrient loads and no further degradation occurs. A second, equally plausible scenario is that SFB's resistance to nutrients continues to decline until adverse impacts become evident. The highly elevated DIN and DIP concentrations Bay-wide provide the potential for future impairment. Any major reductions in loads to SFB will take years-to-decades to implement. Thus, if future problems are to be averted, potential impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed in advance of their onset.
3. By considering current conditions in SFB, trends of changing ecosystem response, and a conceptual model for SFB's response to nutrients, we identified the following highest priority issues:
    a. Determine whether increasing biomass signals future impairment. This issue is most pertinent for Lower South Bay and South Bay.
    b. Determine if low DO in shallow habitats causes adverse impacts, and quantify the contribution of excess nutrients to that condition.
    c. Characterize/quantify the extent to which excess nutrients contribute now, or may contribute in the future, to the occurrence of HABs/NABs and phycotoxins.
    d. Further evaluate other hypotheses for nutrient-related adverse impacts to ecosystem health, including nutrient-induced changes in phytoplankton community composition and ammonium inhibition of primary production. That evaluation – to include expert workshops, data analysis/synthesis, or modeling – should aim to identify high priority investigations that are needed to help determine protective nutrient levels, and assess their potential quantitative importance.
    e. Test future scenarios that may lead to worsening conditions through the use of numerical models.
    f. Quantify the contributions of individual nutrient sources to ambient concentrations in different areas of the Bay, considering both their transport and in situ transformations and losses.
    g. Evaluate the potential effectiveness of various nutrient management strategies at mitigating or preventing adverse impacts.
4. Although concern related to changing ecosystem response in SFB is warranted, widespread and severe nutrient-related impacts do not currently appear to be occurring, based on existing sampling locations and parameters commonly measured. This apparent lack of current severe impacts translates into time for conducting investigations to improve understanding of SFB's response to nutrients and allows for sound, science-based management plans to be developed

and implemented. That said, the considerable amount of time required to implement any management strategy raises the level of urgency such that work should move forward expeditiously.

5. Given the stakes of no action - and the time required for data collection, analysis, and modeling tools to reach a useable state - work needs to move forward in parallel on implementing multiple aspects of the Nutrient Strategy. A well-coordinated program is needed to maximize the effectiveness and efficiency of this effort. That program needs to integrate seamlessly across what might otherwise be (or become) semi-independent program areas. Specifically, we recommend the following set of highly-integrated program areas:
    a. Monitoring: Develop and implement a sustainably-funded and regionally administered monitoring program that continues routine monitoring, and fills newly-identified data gaps relevant to nutrients;
    b. Modeling: Develop and apply linked hydrodynamic and water quality models to integrate observations, identify critical data gaps (to be addressed through monitoring or experimental studies), quantify processes at the ecosystem scale, and evaluate future scenarios (including management alternatives);
    c. Observational and Experimental Studies: Undertake special studies (field investigations, controlled experiments) to address the highest priority knowledge and data gaps identified in #3; and
    d. Data Synthesis and Interpretation: Analysis of existing and newly collected data (from monitoring and experimental studies), incorporatingmodels, to improve understanding of linkages between nutrients and ecosystem response and to inform the development of an assessment framework.
6. The Delta/Suisun boundary, while an important regulatory boundary, is not meaningful from ecological and loading standpoints. Nutrient loads to and transformations within the Delta exert considerable influence over nutrient loads to and ambient concentrations within Suisun, San Pablo, and Central Bays. Furthermore, the ecology and habitat quality of the Delta and Suisun Bay are tightly coupled. A unified approach – one that spans the Bay-Delta continuum - for evaluating the impacts of nutrients on beneficial uses will best serve both ecosystem health in the Bay-Delta and the information needs of environmental managers.

A.4.2 Recommendations for Addressing Priority Knowledge Gaps

Section A.4.2.1 provides an overview of the recommended highest priority work efforts over the next 1-5 years to address knowledge and data gaps to, in a targeted way, inform nutrient management decisions in SFB. The process consisted of (see SFEI 2014)

- Identifying the highest priority scenarios for potential impairment along one or more pathways, and high priority science questions that need to be addressed related to those scenarios (Tables A.4.1 and A.4.2);
- Prioritizing data or knowledge gaps related to the key processes that control ecosystem response to nutrients along the pathways of the near-term highest priority scenarios (Tables A.4.3-A.4.6.

Recommendations presented in Section A.4.2.1 are organized around several major themes or types of work. Not all high priority data gaps are discussed in the text below, and the reader is also referred to Tables A.4.1-A.4.6. Section A.4.2.2 takes a broader view, and describes knowledge gaps and data needs in terms of a set of ecological and management challenges that lie ahead.

A.4.2.1 Recommendations

R.1 Develop a regionally-administered and sustainably-funded nutrient monitoring program

Major research and monitoring efforts in San Francisco Bay and the Delta include the USGS research program[4] and the IEP Environmental Monitoring Program.[5] The data generated through these programs, and the related interpretations, form much of the foundation for current understanding of SFB's response to nutrients. However, the focus and mandates of these programs are not necessarily aligned with those of a program designed program to inform nutrient management decisions. Furthermore, future funding of the USGS program is uncertain.

Developing a regionally-administered and sustainably-funded nutrient monitoring program needs to be a major priority. Effort needs to be directed toward developing the institutional and funding frameworks for the program, and developing its primary science goals and activities. Several initial recommendations are presented below.

R.1.1 Program development

R.1.1.1 Develop institutional and funding agreements

Developing and implementing a regional nutrient monitoring program will be a major undertaking in terms of logistics and cost, and long-term institutional support will be needed. There are several entities currently involved in ship-based and continuous (moored sensors) monitoring (e.g., USGS, IEP, CA Department of Water Resources, CA Department of Fish and Game). To avoid unnecessary duplication of effort and maximize resources, there may considerable advantage to achieving some monitoring program goals through fostering close coordination among on-going programs, and augmenting those efforts with additional monitoring. Activities distributed across independent programs need to be well-coordinated, especially in terms of methods, QA/QC, data management and data sharing, synthesis, and reporting.

R.1.1.2 Develop the monitoring program science plan: management questions, goals, priorities, and approaches

A nutrient monitoring program science plan needs to be developed that lays out the management questions, and the program's goals and priorities relative to those management questions. Detailed plans for achieving those goals also need to be developed. A number of the goals and data needs may differ considerably from those of the current research and monitoring activities (i.e., USGS, IEP). When evaluating the future program's needs relative to current efforts, particular attention needs to be given to the following issues:

- The optimal distribution of effort and resources among broad monitoring categories (water column vs. benthos, shoals vs. channel, open bay vs. margins, physical/hydrodynamic vs. biological vs. chemical)
- Key parameters or processes to be measured within these categories;
- Spatial and temporal resolution of sampling; and

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[4] http://sfbay.wr.usgs.gov/access/wqdata/

[5] http://www.water.ca.gov/iep/activities/emp.cfm

- The distribution of monitoring effort between ship-based sampling and moored sensors for continuous monitoring.

For some of these issues, considerable data resources already exist from long-term monitoring in SFB. A major component of the monitoring program design effort should include analyzing this data to inform decisions (e.g., about the necessary spatial and temporal density of sampling). Pilot studies should also be part of planning, to inform which parameters provide important additional information, test methods that provide less expensive approaches for essential data collection, and select moored sensor sites and parameters.

R.1.2. Initial monitoring program science recommendations

Several clear monitoring program recommendations emerged through developing the conceptual model (SFEI 2014), and identifying data/knowledge gaps related to priority scenarios (Tables 6.3-6.6).

R.1.2.1 Continue shipped-based monitoring along SFB's deep channel

The long-term record provided by the USGS research program has yielded important insights into the mechanisms that shape SFB's response to nutrients, including physical and biological processes that regulate that response, and how that response has changed over time. Maintaining and building upon this program will be critical for anticipating future changes, and for assessing the effectiveness of any management actions. New parameters may be needed informative, such as size-fractionated chl-a and C:chl-a, organic forms of N and P, as well as others noted below.

R.1.2.2 Develop a moored sensor sub-program for high temporal resolution data

Data collection at higher temporal resolution for chl-a, DO, nutrients, turbidity, and other parameters is needed at multiple locations to assess condition and to improve our quantitative understanding of ecosystem response to nutrients, including the processes that influence phytoplankton blooms, influence oxygen budgets, and regulate nutrient fate. High temporal resolution data will be essential for accurately calibrating water quality models. Continuous monitoring with moored sensor systems is feasible for a wide range of water quality parameters. Techniques for some parameters are becoming increasingly well-established and reliable (e.g., salinity, T, turbidity, chl-a, DO), while others are advancing (e.g., nitrate, phosphate, ammonium, phytoplankton counts and identification). Moored sensor systems can telemeter data, allowing for near real-time assessment of conditions. The data from moored sensors are not a substitute for ship-based sampling, but rather provide strongly complementary information about physical and biological processes that influence key water quality parameters (chlorophyll, DO, T, SpC) over time-scales (hours) that are too short to effectively monitor or study through ship-based sampling. While there are currently multiple stations in Suisun Bay and the Delta that measure some nutrient-related parameters, there are only 3 newly-added stations south of the Bay Bridge for measuring chl-a or nutrients (added in September 2013), and few that measure DO and other parameters (T, SpC, turbidity).

R.1.2.3 In addition to monitoring along the channel, monitoring is needed in shoal environments, including lateral transects

Sampling along the shoals is needed for improved understanding of phytoplankton and nutrient processes, and for model calibration. Most of the water quality data available in SFB is from stations along the deep channel. The shoals are important areas for phytoplankton and MPB production, and large lateral heterogeneities in phytoplankton biomass (and SPM, which influences light availability and growth rates) are common in SFB (Thompson et al., 2008;

Cloern, 1995). In addition, a substantial proportion of nutrient transformations likely take place along the shoals (benthic nitrification and denitrification). Shoal monitoring can be accomplished both through boat/ship-based transects or with moored sensors, and the best approach will vary depending on the questions being addressed. Using autonomous underwater vehicles (AUVs) outfitted with sensors may also be a possibility. AUVs are commonly employed in research studies, and some AUV-sensor systems are already commercially-available. Pilot studies that test AUVs in SFB would be useful for assessing the feasibility and cost effectiveness of this approach, and to inform planning.

R.1.2.4 Coordinated monitoring in shallow subtidal habitats.

Some agencies (e.g., stormwater, wastewater) carry out periodic monitoring in shallow habitats, and several focused studies have been conducted in Lower South Bay systems (Thebault et al., 2008; Shellenbarger et al. 2008; Topping et al., 2009). However, there is currently no systematic monitoring in shallow margin habitats either at the subembayments scale or Bay-wide. Data collection on productivity (e.g., chl-a, light levels) and DO concentrations in select systems would help inform whether adverse impacts are occurring in these systems due to low DO, and help ascertain the causes of low DO. Before embarking on this effort, it would be worthwhile to examine existing data from current or recent studies (e.g., studies in LSB) to assess the need for monitoring and identify the best approaches to pursue.

R.1.2.5 Increased focus HAB/NAB-forming species, phycotoxins, and phytoplankton community composition in general

Given the prevalence of HAB-forming organisms in the Bay and the frequent detection of phycotoxins Bay-wide, it would be prudent to more closely monitor phytoplankton composition, the occurrence of HAB-forming organisms and phycotoxins within San Francisco Bay. Composition and biovolume data collected for HAB-related work would also support assessment and improved mechanistic understanding of other hypothesized nutrient-related shifts in phytoplankton community composition. The abundance and forms of nutrient are two among many factors that can influence phytoplankton community composition and the occurrence of HABs. The relative contributions of those factors toward causing adverse shifts in composition or HAB occurrences are poorly understood. More frequent (in space and time) analysis of phytoplankton composition and phycotoxins, in combination with special studies, (see Recommendation 4.1) will be needed to better understand these mechanisms and assess potential linkages to nutrients.

Determining taxonomy and biomass by microscopy is expensive and time consuming, which limits the amount of data that can be collected. Some amount of manual microscopy ground-truthing will always be needed. However, other techniques, in combination with microscopy, may allow for increased data collection of at lower costs. Carrying out pilot studies will help inform which techniques provide valuable and cost-effective information. Measuring phytoplankton-derived pigments is one such approach. Different classes of phytoplankton have distinct pigment fingerprints. It is possible, with sufficient calibration (relative to microscopy) and training of software to quantify phytoplankton biomass within specific classes. Flow cytometers and digital imaging tools are also available. These systems - which measure optical properties and capture images of individual cells, and employ image-recognizing software to identify and count phytoplankton down to the species level - can be deployed at moored stations for continuous monitoring, used on a monitoring vessel as it cruises along a transect, or used in the laboratory. Moored applications can telemeter data, allowing for near real-time information.

One such system provided early warning of a toxic algal bloom in the Gulf of Mexico.[6] An additional advantage of digital imaging approaches is that an archive of phytoplankton image data would be developed: if a phytoplankton species eventually becomes important, the digital archive could be mined to determine when that species first appeared.

Pilot projects have been initiated recently that are measuring phycotoxins in SFB, and an algal pigment pilot study is underway. Continuation of similar pilot studies, and testing a variety of methods, will help identify the most informative and cost-effective options, all the while establishing baseline concentration data against which future data can be compared. The feasibility of measuring algal toxins in archived benthos samples should also be considered in order to generate longer time series of algal toxins and look for changes over the past decade or more (if well preserved samples exist).

R.1.2.6 Benthos monitoring to quantify spatial, seasonal, and interannual variability in grazer abundance

Grazing by benthic filter feeders is considered to be one of the main controls on phytoplankton biomass accumulation in several subembayments. To estimate the influence of the benthic grazing, and track its changes in space and time, benthos surveys are needed on a regular basis in some subembayments, most importantly Lower South Bay, South Bay, San Pablo Bay, and Suisun Bay. In recent years there has been ample benthos monitoring in Suisun Bay and the Delta (and some in San Pablo Bay), although the fate of this program is not known. There are currently no sustained programs in the other subembayments. However, there are some years during which intensive benthic sampling has taken place (e.g., Thompson et al. 2008), and along with opportunistic sampling efforts (in some cases, samples have been archived but not yet analyzed for biomass; J Thompson, personal communication). Benthos monitoring could occur less frequent than water quality monitoring, e.g., three times per year (spring, summer, fall). Sorting, counting, and weighing benthos samples is time consuming and costly. A pilot study to test the feasibility of using benthic cameras may also be worth considering (alongside traditional sample collection for calibration/validation), since its use could potentially allow for more cost-effective benthos surveys.

R.1.2. 7 Zooplankton abundance/composition

Monitoring data on zooplankton are needed to quantify pelagic grazing rates. Zooplankton abundance and composition may also serve as an important indicator of food supply and quality for higher trophic levels. Long term zooplankton monitoring has been carried out in Suisun Bay and the Delta. However, zooplankton abundance and composition are not currently measured in other subembayments.

R.1.2.8 Allocate sufficient funding for data interpretation and synthesis

Data analysis and data synthesis are essential components of a monitoring program. Allocating sufficient funds for these activities will allow field results to be efficiently translated into management-relevant observations that inform decisions, and allow the monitoring program to nimbly evolve to address emerging data requirements. Annual reports will be needed that not only compile and present data, but that also evaluate and interpret trends. More detailed special studies will also be needed periodically to generate scientific synthesis reports on complex data sets (e.g., spatial and seasonal trends in phytoplankton community composition).

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[6] http://www.whoi.edu/oceanus/viewArticle.do?id=46486

R.2. Develop and implement a science plan for SFB that targets the highest priority management and science questions

The size of SFB, and the complexity and diversity of its nutrient-response issues, create a situation in which there are numerous science questions that need to be addressed to improve our understanding of the system. Addressing the management and science questions will require a combination of field studies, controlled experiments, monitoring, and modeling across the topics of nutrient cycling, phytoplankton response (biomass and community composition), and hydrodynamics. It will not be feasible to explore all the relevant science questions – that would take longer than management decisions can wait, and would outstrip any reasonable budget. To best target science efforts, there would be considerable benefit to developing and implementing a science plan that: identifies the highest priority management issues, and associated science questions; and identifies the sets of studies and data collection/monitoring needs that efficiently target those questions. In some cases, the management issues, science questions, data gaps, and studies may be similar Bay-wide. In other cases, the science questions or data gaps may be subembayment- or habitat-specific. The science questions listed in Tables A.4.1-A.4.2 and the recommendations in this section could serve as a starting point in what would be an iterative Science Plan development process.

Analysis of existing data from SFB, combined with broader critical literature review, would be useful early steps in science plan development, to articulate what is well-understood - in other estuaries and SFB - and focus scientific studies and monitoring on addressing the most critical knowledge and data gaps.

R.3. Develop hydrodynamic, nutrient cycling, and ecosystem response models

Tables A.4.1-A.4.2 illustrate that modeling will play a central role in addressing a wide range of science questions. Models can also be used to prioritize data collection needs. While there are multiple hydrodynamic models available for SFB, there are currently no integrated hydrodynamic-phytoplankton-nutrient models. Considerable progress could be made toward addressing several important science questions through using "simplified-domain" models that are built upon simplified (spatially-aggregated), but still accurate, hydrodynamics. Potential applications of these simplified domain models include (not an exhaustive list):

R.3.1 Quantitative analysis of nutrient budgets (including losses/transformations of nutrients);

R.3.2 Quantifying the relative importance of major processes that control primary production in Suisun Bay (light, clams, flushing, NH_4^+ inhibition), and explore which factors may explain the changes in phytoplankton biomass in South Bay over the past ~20 years.

R.3.3 Performing sensitivity/uncertainty analysis, and identifying highest priority monitoring activities, process level studies, or rate measurements to minimize model uncertainty.

R.3.4 Forecasting ecosystem response under future scenarios, and narrowing the list of high priority scenarios;

In developing such models, there is a benefit to "starting simple", and adding complexity as needed. LSB/South Bay and South Bay could serve as good initial focus areas for basic model development and application, because of the abundance of data for those systems and since these two subembayments are where concerns about adverse impacts from nutrients are greatest. Lessons learned through applying basic models will be useful for informing larger-scale or more complex model development.

Higher spatial resolution models, or larger spatial scale models (e.g., full Bay as opposed to individual subembayments) will be needed to explore several important issues, including:

R.3.5 Determine the zones of influence of individual POTWs under a range of hydrodynamic forcings and estimated transformations/losses

R.3.6 Test future scenarios under which adverse impacts may develop Bay-wide or in individual subembayments

R.3.7 Evaluate the effectiveness of different nutrient control strategies for achieving desired reductions in ambient concentrations as a function of space and time.

R.3.8 Quantify loads from the Delta to Suisun Bay under seasonally- and interannually-varying hydrological conditions, and the influence of these loads in Suisun and down-estuary subembayments under a range of forcings.

R.3.9 Quantify the importance of net nutrient loads from the coastal ocean to SFB under a range of commonly-occurring forcing scenarios, and explore the fate of the nutrient-rich SFB plume leaving the Golden Gate, and the potential influence of those nutrients on coastal ecosystems.

R.4. Carry out special studies to address key knowledge gaps about mechanisms that regulate ecosystem response, and inform whether or not impairment is occurring

The draft list of priority science questions in Tables A.4.1-A.4.2, viewed alongside the data/knowledge gap priorities in Tables A.4.3-A.4.6, present an initial picture of the types of data collection and studies that are the most important in the near term. A number of priorities have been discussed above in the context of monitoring program development (*R.1.2.1-1.2.8*) and modeling (*R.3.1-R.3.9*). An overview of special study priorities is provided below; however, the reader is also referred to the Tables A.4.1-A.4.6.

Nutrient cycling

R.4.1 Controlled field/lab experiments to measure pelagic nutrient transformations (pelagic nitrification, nutrient uptake rates)

R.4.2 Controlled field/lab experiments to measure benthic nutrient transformations (benthic nitrification, denitrification, mineralization and N and P fluxes from sediments)

R.4.3 Quantify the importance of internal nutrient transformations using models.

Productivity of phytoplankton and MPB

R.4.4 Controlled experiments that further test the proposed "NH_4^+-paradox" mechanism of lower productivity when NH_4^+ is elevated, determine relevant thresholds, and allow its effect to be better parameterized and compared to other regulating factors in models (*R.3.2*).

R.4.5 Through analysis of existing data or through field studies, assess the variability or uncertainty in the Cole and Cloern (1987) productivity relationship due to factors such as different phytoplankton assemblages, temperature, light levels, etc.

R.4.6 Field measurements to quantify MPB primary production rates and biomass.

R.4.7 Compare MPB production and biomass with phytoplankton production and biomass, consider how MPB's relative importance would change (or already has changed) due to ecosystem change (lower suspended sediments, benthic grazers), and explore how those changes influence nutrient cycling, oxygen budgets, and food webs.

Dissolved O_2

R.4.8 Controlled field experiments to quantify sediment oxygen demand in a range of depositional environments. These can be carried out in conjunction with the benthic nutrient transformation special studies as part of the same experimental protocol (*R.4.2*).

R.4.9 Monitoring and targeted mechanistic studies of DO in shallow margin habitats to assess the severity of low DO (concentration, spatial extent, frequency, duration).

R.4.9 In cooperation with other efforts or as special nutrient-related studies, determine the degree to which low DO in margin habitats (or in open water areas of some areas of the Bay, specifically LSB) adversely impact biota. To a certain degree, this work could be carried out based on existing data from other studies on DO tolerances of key organisms. Field surveys of fish or benthos abundance may also be warranted.

R.4.10 Through field experiments and modeling, quantify the degree to which anthropogenic nutrients contribute to occurrences of low DO.

HABs, toxins, and phytoplankton community composition

R.4.12 Rigorous analysis of existing phytoplankton community composition data – for HAB-forming species and composition more broadly – to test qualitative and quantitative agreement with various conceptual models, and refine those conceptual models as needed.

R.4.13 Field studies (collecting phytoplankton composition data at higher temporal or spatial resolution) to test mechanisms of HAB development and phytoplankton community succession in response to physical, chemical, and biological drivers.

R.4.14 Field studies to evaluate the potential importance of salt ponds as incubators of HAB-forming species.

R.4.15 Controlled experiments, using mixed cultures and monocultures from SFB, that mechanistically explore the interactive effects of nutrient availability (including variability in concentrations and forms), light, and temperature on HAB/NAB development and phycotoxins production, or other shifts toward assemblages that poorly support food webs. The goals of such studies would be to identify conditions that favor some classes or species of phytoplankton over others under the prevailing conditions in SFB (light limitation, excess nutrients), and enable predictions about assemblage response. Such information is also essential for identifying nutrient concentrations or loads that would decrease the risk of HAB occurrences or other adverse assemblage shifts.

R.4.16 Apply the information from R.4.1.5 within models to, among other issues, evaluate the magnitude of the nutrient component of stress, and explore potential composition responses to changing conditions, including those due to potential management actions (e.g., nutrient load reductions).

A.4.2.2 Grand Challenges

During the conceptual model development and identification of knowledge gaps, data gaps, and monitoring needs, four so-called "Grand Challenges" emerged related to understanding and managing SFB ecosystem health. While there is overlap between the underlying management issues that motivated the more specific recommendations above and those that motivated the Grand Challenges, the Grand Challenges represent a somewhat different, more holistic perspective or framework for considering science and data collection needs. In so doing they highlight connections between nutrient issues and other ecosystem health concerns, and provide an additional impetus for addressing those data collection needs.

Grand Challenge 1: What do we need to know in 10-20 yrs to make improved decisions related to water quality management or ecosystem health, including those related to nutrients? 1-2 decades is approximately the time scale over which large capital improvement projects are planned and implemented. 10-20 years is also a long enough time period for trends to become evident, e.g, the changes in phytoplankton biomass in South Bay and LSB since the late 1990s. What information needs to be collected now, to serve as baseline condition data, so that changes in important indicators can be confidently identified and attributed to the correct causal agent(s), whether those changes lead to improved or worsened condition?

Grand Challenge #2: The northern estuary is poised to experience major changes due to management actions and environmental change. Anticipated changes include: nitrification and nutrient load reductions at Sac Regional wastewater treatment plant; numerous large scale restoration projects and changes in water management in the Delta; changing climate patterns altering the timing, residence time, and amount of water passing through the Delta. What do we need to be measuring now in order to determine if these changes have positive, negative, or no impacts on ecological health in SFB and the Delta? How will phytoplankton respond to changes in nutrient loads/speciation? How will the food web respond?

Grand Challenge #3: Large areas along the margins of South Bay and LSB are slated to undergo restoration. Given the size of these areas compared to the adjacent water surface area, it is reasonable to expect that proposed restorations along the margins will have measurable impacts on water quality and ecological health in the open Bay. Some of these effects may be positive, including increased habitat for fish, birds and other organisms. It will be desirable to document those changes; in order to do so, baseline data is needed for these higher trophic level indicators of ecosystem health. Those changes could also encourage more denitrification and decreased N within the Bay, which could be considered within integrated nutrient management plans. As discussed earlier, there may also be unintended and undesirable consequences, including: restored/reconnected salt ponds acting as incubators for HAB-forming phytoplankton species; exceedingly high primary production rates and high biomass, causing periodic low DO in wetlands and sloughs; and increased duration of stratification due to dampening of tidal mixing energy. What hypotheses of adverse impacts need to be tested, as part of restoration planning, so that the risks of severe unintended consequences can be minimized?

Grand Challenge #4: Similar to Grand Challenges 1-3, what baseline observational data is needed to detect climate-related changes in habitat quality in SFB and to disentangle them from other anthropogenic drivers? What types of modeling simulations should be done to anticipate effects? The CASCaDE II[7] project is exploring these issues, largely focused in the Delta. Similar studies may be warranted in the Bay.

[7] http://cascade.wr.usgs.gov/

Table A.4.1 Highest priority adverse impact scenarios, science questions, and types of studies needed to address those questions

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling	Assessment Framework	Technology, cost-benefit analysis
1 High phytoplankton biomass and low DO in LSB and South Bay									
a. What level of phytoplankton biomass (and over what area, for what period of time) would result in adverse impacts in LSB and South Bay habitats?	x	x			x	x		x	
b. What are the relative importances of the fundamental drivers that underlie recent changes in phytoplankton biomass in LSB (decreased SPM, loss of benthic grazers, other)?		x	x		x	x			
c. What is the importance of organic matter produced in margin habitats to biomass and DO budgets in LSB and South Bay deep subtidal habitats?			x		x	x			
d. What will be the response of phytoplankton biomass and DO if suspended sediments continue decreasing at rates similar to the past 20 years? Do adverse impacts become increasingly likely at environmentally-relevant SPM values? Or are adverse impacts unlikely along this pathway under this scenario?			x		x	x			
e. What scenarios could lead to worsened conditions and adverse impacts? - Longer periods of stratification due to salt pond and wetland restoration efforts, higher production/biomass? - Changes in climate patterns, longer periods of stratification, higher T, higher production/biomass? - Salt pond and wetland restoration, greater biomass production in margin habitats that is transported to deep subtidal habitats? - Multiple changes in parallel (lower SPM, longer stratification, biomass from margins, low grazing rates)?		x	x	x	x	x			
f. Based on this analysis, what are likely future trajectories in LSB and South Bay? Will biomass concentrations level off or continue increasing? What will be the response of DO?		x	x		x	x			
g. What reductions in nutrient loads are necessary to prevent adverse impacts?			x		x	x			
2 High phytoplankton biomass and low DO in margin habitats									
a. What low DO 'severity' would cause adverse impacts: spatial extent within individual sub-habitats (e.g., %age of slough), DO deficit, frequency, duration? Individual sub-habitats vs. overall condition (e.g., individual slough(s) impacted vs. percentage of total slough kilometers impacted)?	x	x						x	
b. How common (spatially) are low DO occurrences in these habitats? What is the severity of the low DO in each sub-habitat and collectively (within individual sloughs/creeks/salt-ponds, and collectively, what is the spatial extent (e.g., small stretch vs. entire slough), frequency, duration, DO deficit, bottom layer or full water column)?		x	x						

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling	Assessment Framework	Technology, cost-benefit analysis
c. Are relevant biota adversely impacted by low DO? Field surveys, potentially controlled studies. Avoidance, stress/toxicity, death	x	x	x	x					
d. What mechanisms act to cause the periodicity of low DO, including causing it to develop and dissipate? New organic matter sources (e.g., *in situ* production within sloughs or inputs from adjacent habitats, microphytobenthos vs. phytoplankton), on-going sediment oxygen demand, residence time, stratification, freshwater inputs, tidal exchange		x	x	x	x	x			
e. To what extent do anthropogenic nutrient loads contribute to or cause increased severity of low DO (spatial extent, DO deficit, frequency, duration)?		x		x	x				
f. Based on observed (or modeled) conditions relative to conditions that have adverse impacts, are these habitats (subset or as a whole) adversely impacted by low DO?		x	x		x	x		x	
3. HABs/NABs and phycotoxins									
a. What frequency or magnitude of HABs/NABs or HAB-toxins would cause adverse impacts?	x	x			x			x	
b. How do the abundances of phycotoxins and the HAB-forming species vary in space and time within the Bay? Have there been detectable changes over time, based on existing data? What are the sources of phycotoxins (in situ production vs. transport into SFB or subembayments)?		x	x	x					
c. What causes/contributes to increased frequency or elevated abundances of HAB/NAB-forming organisms? To what extent do nutrients cause, contribute to, or enable increased abundance/blooms? Seeding rates from the coast, seeding rates from adjacent habitats (including salt ponds), role of physical drivers (T, light, mixing/stratification) and chemical conditions (nutrients) favoring higher *in situ* production specifically of HAB/NAB forming organisms	x		x	x	x	x			
d. What causes/contributes to production of *in situ* phycotoxins production? To what extent do nutrients cause, contribute to, or enable increased phycotoxins production? role of physical drivers (T, light, mixing/stratification) and chemical conditions (nutrients) favoring higher *in situ* production	x		x	x					
e. What future scenarios could increase the frequency or severity of HAB/NAB events or increase phycotoxin abundance? - restoration and reconnection of salt ponds/wetlands? high-light, warm, nutrient-replete incubators? - future water management practices in the Delta (withdrawals, longer residence times) ? - changes in climate patterns? How likely are those changes in the 20-30 yr time horizon?		x	x	x	x				

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling	Assessment Framework	Technology, cost-benefit analysis
h. Based on a comparison of observed conditions and conditions considered to induce adverse impacts, are regions/subembayments/habitats of SFB experiencing HAB/NAB related adverse impacts, or will they in the future?			x					x	
i. What decreases in nutrient loads or ambient nutrient concentrations would decrease adverse impacts, or the risk of adverse impacts, from HABs/NABs?					x	x			
4. Other Nutrient Impact Pathways: Low phytoplankton biomass (NH_4^+ inhibition), Suboptimal phytoplankton community composition									
a. What is the underlying mechanism by which NH_4^+ slows or inhibits primary production? Characterize NH_4^+ concentrations and magnitude of effect. At what NH_4^+ concentrations are primary production rates substantially impacted?	x	x		x					
b. What is the relative contribution of elevated NH_4^+ compared to other factors that maintain low phytoplankton biomass in Suisun Bay (clam grazing, light limitation, flushing)?					x	x			
c. Are current NH_4^+ loads or concentrations adversely impacting biomass levels in Suisun Bay?		x	x		x	x		x	
d. What nutrient load reductions would prevent or mitigate adverse impacts due to NH_4^+ inhibition of primary production?					x	x			
e. What constitute optimal, or healthy, phytoplankton assemblages in SFB's subembayments? Conversely, what assemblages would be considered to poorly support desirable food webs?	x	x						x	
f. How have phytoplankton community compositions changed within SFB subembayments over recent years?		x	x						
g. Based on what is known from other systems or from prior experimental/field work (Bay-Delta or elsewhere), what hypothesized mechanisms are most likely to influence phytoplankton community composition in the Bay-Delta, based on ambient conditions (nutrient concentrations, light, temperature, stratification, etc.)? What controlled experiments or observations in SFB are needed to further evaluate these proposed mechanisms in SFB?	x	x							
h. What is the magnitude (or relative importance) of the role that current ambient nutrient concentrations play in shaping phytoplankton community composition?	x	x		x	x	x			
i. What changes to nutrient availability would mitigate or prevent adverse impacts of nutrients on phytoplankton community composition?	x	x		x	x	x			
i. What other adverse impact pathways may require further attention in SFB (aquatic macrophytes, macroalgae, SAV habitat)?	x	x							

Table A.4.2 Highest priority mitigation scenarios, science questions, and types of studies needed to address those questions

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay/Delta	Watershed Modeling:	Assessment Framework	Technology, cost-benefit analysis
5. Reductions in nutrient loads from POTWs and nutrient loads from the Delta									
a. What are the magnitudes of loads from individual POTWs?		x	x						
c. How do internal processes shape nutrient concentration within SFB, how do they vary in space/time: mixing/flushing, nitrification, denitrification, uptake/assimilation, regeneration from sediments, etc.				x	x	x			
b. What are the zones of influence and magnitude of contributions of individual POTWs and Delta loads, and how do these vary seasonally and interannually?					x	x			
d. How do Delta loads to Suisun Bay vary seasonally and interannually? What portions of the loads that enter Suisun Bay from the Delta originate from Regional San, others POTWs? What portions of the loads come from Central Valley agriculture? What are the load contributions from agriculture within the Delta?		x	x		x	x	x		
f. What will Delta loads to Suisun Bay be under future scenarios: restoration, changes to water management practices, changes in agricultural practices?					x	x			
i. Considering areas of influence, zones where impairment may be occurring, and internal processes, what combination of load reductions are needed to mitigate or prevent impairment?					x	x			
g. What is the range of options for achieving various levels of nutrient load reductions from POTWs? What are the costs and multiple benefits (nutrients + other benefits, e.g., recycled water) of individual POTW efforts, and of longer-term integrated sub-regional plans?									x
h. Given the necessary load reductions and cost-benefits, what are the best options for achieving load reductions?									x
6. Reductions in stormwater nutrient loads									
a. Are stormwater nutrient loads potentially important sources to some margin habitats in some subembayments, or at the subembayments scale, and do they warrant further consideration?		x	x		x	x	x		
b. If yes, what are the loads from priority watersheds? What is their contribution to nutrient loads, or organic matter/BOD loads, to margin habitats?		x	x				x		
c. What are the magnitudes of stormwater nutrient contributions to deep subtidal habitats in other subembayments?					x	x			

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay/Delta	Watershed Modeling:	Assessment Framework	Technology, cost-benefit analysis
7. Other mitigation strategies: wetland restoration/treatment and shellfish beds									
a. What is the potential for wetland restoration/treatment to mitigate adverse impacts of nutrients?	x				x	x			
b. What is the potential for managed shellfish beds to mitigate adverse impacts of nutrients?	x				x	x			
b. If wetlands or managed shellfish beds appear to be promising nutrient management options – what do pilot studies, advanced modeling, and economic considerations suggest about their potential to be part of an integrated management program?					x	x			x
8. Influence of nitrification at Regional San and Suisun direct POTWs on NH_4^+ inhibition of primary production or other adverse impacts									
a. What is NH_4^+ fate within the Delta and how does this change as a function of season, flow, etc.?					x	x			
b. What load reductions are necessary to reduce NH_4^+ to ambient concentrations that would not inhibit production or have other adverse impacts?					x	x			

Table A.4.3 N and P loads and cycling: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of Knowledge about magnitude, composition, or controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
Loads				
POTWs	**High**	**Moderate: C**omprehensive effluent monitoring is currently underway. Prior to 2012, data availability varies by POTW and in general is fairly sparse for several nutrient forms (NO_3^-, o-PO4, TN, TP)	**Very High**	**Very High**
Stormwater runoff	**Uncertain**	**Low**: Limited stormwater data and limited modeling effort	**High**	**High**
Delta	**High**	**Low:** Initial estimates suggest Delta loads may be a large source but they need to be validated, and time-series of loads are needed.	**Very High**	**Very High**
Groundwater	**Low**	**Low:** Poorly quantified but not expected to be major source because of relatively high loads from other sources	**Low**	**Low**
Direct atmospheric deposition	**Low**	**Low**: Poorly quantified but not expected to be major source because of relatively high loads from other sources, including from the large Central Valley watershed	**Low**	**Low**
Exchange through GG	**Uncertain**	**Low:** Has the potential to be large, but highly uncertain	**High**	**High**
Processes				
Benthic denitrification	**High**	**Low**: see OM mineralization and NH4 and PO4 release below	**Very High**	**Very High**
Pelagic denitrication	**Low**	**Low**: not expected to be important because of oxic water column	**Low**	**Low**
Benthic nitrification	**High**	**Low**: see OM mineralization and NH4 and PO4 release below. Potentially large, but limited field measurements, and need for both field and model-based estimates.	**Very High**	**Very High**
Pelagic nitrification	**High**	**Low**: Potentially large, but limited field measurements, and need for both field and model-based estimates.	**Very High**	**Very High**
N fixation	**Low/Uncertain**	**Low**	**Moderate**	**Low**

Process or Parameters	Importance for quantitative understanding	Current Level of Knowledge about magnitude, composition, or controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
OM mineralization and release of NH4 and o-PO4 from sediments, and in the water column	**High**	**Low**: Potentially a substantial source from the sediments to the water column. Limited data from two studies in SFB, but well-studied in other systems and at least initially may be able to use that information. Field studies aimed at exploring this issue will also inform sediment oxygen demand, benthic primary production, benthic denitrification, and benthic nitrification.	**Very High**	**Very High**
Settling/burial of N and P	**High**	**Low/Moderate**: limited field estimates to date, although could be estimated based on other sedimentation data.	**Moderate**	**Low**
Rates of NH4, NO3, and o-PO4 uptake by phytoplankton	**High**	**Moderate**: field measurements exist for NH4 and NO3 in northern estuary, limited data in South Bay and LSB. Uptake rates for P are not well-studied. Both N and P uptake rates can be partially constrained by knowing phytoplankton C:N:P and productivity	**Moderate**	**Moderate**
Other processes: DNRA, ANAMOX	**Low**	**Low**: but expected to be relatively small	**Low**	**Low**
N and P budgets for subembayments: loads, transformations, sources/sinks, export	**High**	**Low**: The ability to quantify these will provide important information on the subembayments' ability to process/assimilate N and P. Basic modeling work needed.	**Very High**	**Very High**
Ambient concentration data				
Phytoplankton C:N:P	**High**	**Low**: Currently not routinely measured during monitoring	**Very High**	**Very High**
Concentration of NO3, NH4, and PO4	**High**	**Moderate**: monthly data available at ~15 stations Bay-wide but finer spatial and temporal resolution needed to inform process level understanding and modeling	**Very High**	**Very High**
Concentrations of NO_2^- and N_2O	**Low/Moderate**	**Moderate**: not needed for nutrient budgets, but informative as diagnostic of processes	**Moderate**	**Moderate**
Concentration of DON, PON, DOP, POP within and loaded to the system	**Moderate/ uncertain**	**Low:** Little current data, and information is needed. Given the high DIN and DIP concentrations, abundance organic forms may be relatively low.	**High**	**High**

Table A.4.4 Phytoplankton and MPB productivity / biomass accumulation: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
PHYTOPLANKTON - Processes				
Primary production rates	**High**	**Low/Moderate**: Basic understanding about light limitated production is well modeled. Recent studies suggest that the relationship may have shifted, and revisiting this may be important for estimating system productivity.	**Very High**	**High**
Pelagic grazing	**High**	**Low**: Long-term program in Suisun Bay/Delta for macrozooplankton, but limited micro-zooplankton data, which may be more quantitatively important in terms of overall grazing rate. No systematic zooplankton sampling in LSB, South Bay, Central Bay.	**Very High**	**High**
Benthic grazing	**High**	**Low**: good data to support estimates in Suisun Bay. Limited data in LSB South Bay. Monitoring of benthos abundance would inform this.	**Very HIgh**	**Very High**
Sinking, respiration, burial	**High**	**Moderate**: Discussed within context of Dissolved Oxygen	**Low**	**Low**
Inhibition of primary production rates by elevated NH_4^+	**High/ Uncertain**	**Low**: Several studies have been completed and others are underway. Uncertainty remains about mechanism and relative importance of the process. Field/lab studies and modeling work can be done in parallel, with the former designed to further elucidate the mechanism and thresholds and the latter to quantify its role relative to other factors.	**Very High**	**Very High**
Production in the shoals vs. channels (during stratification), and physical or biological controls on bloom growth/propagation	**High**	**Low**: Considered to be an important process but limited data available. Data needed to better predict bloom magnitudes.	**Very High**	**Very High**
Germination of resting stages	**Low**	**Low:** Not considered among the highest priority processes to study	**Low**	**Low**
PHYTOPLANKTON – Ambient concentration data				
High frequency data in channel	**High**	**Low**: Very limited high temporal resolution (continuous) phytoplankton biomass data beyond of Suisun Bay. Needed to better predict blooms.	**Very High**	**Very High**
High temporal resolution data in shoals	**High**	**Low:** Very limited high temporal resolution (continuous) phytoplankton biomass data beyond of Suisun Bay. Needed to better predict blooms.	**Very High**	**Very High**
d	**High**	**Moderate/High**: USGS program has been collecting monthly data at along the channel for the past 35 years, and needs to be continued.	**Very High**	**Very High**
Phytoplankton C:N ,C:chl-a,	**High**	**Low:** Valuable information to inform understanding of processes and for	**Very High**	**Very High**

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
and size-fractionated chl-a		modeling		
Microphytobenthos - Processes				
Primary production rates	**Moderate**	**Low:** may be able to predict productivity based on light levels and chl-a, although needs to be confirmed	**Moderate**	**Moderate**
Grazing	**Moderate/ Unknown**	**Low:** Potentially important as a sink, but difficult to study.	**Low**	**Low**
Microphytobenthos – Ambient abundance data				
Basic biomass information, seasonal, spatial	**High**	**Low:** Very limited data on MPB abundance and productivity, despite the fact that MPB productivity may be comparable in magnitude to phytoplankton productivity.	**High**	**High**

Table A.4.5 Dissolved Oxygen: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
Processes or loads				
Atmospheric exchange	**High**	**Moderate**: Difficult to measure but readily modeled (albeit with substantial uncertainty)	**Low**	**Low**
Pelagic and benthic nitrification (for O2 budget)	**Low/Moderate**	**Moderate**: NH4 loads/concentrations provide an upper bound on this oxygen sink. It is not expected to be a major DO sink, or	**Low**	**Low**
Sediment oxygen demand (Benthic respiration + oxidation of reduced compounds).	**High**	**Low**: This set of processes is particularly important for understanding O_2 budget in shallow margin environments. The mechanisms are well understood but rates are poorly constrained and likely are highly variable in space/time. Field experiments are possible. Increased (high spatial/temporal resolution) monitoring of DO will also allow "average" demand to be quantified by difference/modeling.	**Very High**	**Very High**
Pelagic and benthic primary production rates	**High**	**Low**: Benthic production rates, in particular are particularly poorly constrained and would require field surveys. Pelagic rates can be reasonably well-estimated based on phytoplankton biomass and light. As noted above, high spatial/temporal resolution monitoring of chl-a will help refine estimates	**Very High**	**Very High**
Pelagic respiration	**Moderate**	**Moderate**: In shallow areas, sediment oxygen demand will be of much greater importance than pelagic respiration. Pelagic respiration rates by viable phytoplankton can be reasonably well-estimated based on biomass. Respiration of dead OM is a function of OM abundance and quality, and water temperature.. In deep channel areas of the Bay, where pelagic respiration will be more important than sediment oxygen demand, low DO does not appear to be a major issue, and thus constraining these rates are not among the highest priorities.	**Low**	**Low**
DO – Ambient concentration data				
High spatial resolution DO data in deep channel	High	**Low**: USGS research program provides an excellent long-term record along the Bay's spine. This work needs to be continued.	**Very High**	**Very High**
High temporal resolution DO data in deep channel	High	**Low**: Limited DO data available from continuous sensors, in particular in South Bay and LSB. A network of sensors is installed in Suisun Bay and the Delta.	**Very High**	**Very High**

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
High temporal resolution data in shoals and shallow margin habitats	High	**Low**: Some special studies have been performed, and some on-going monitoring by POTWs and others (e.g., USGS studies in salt ponds). While these individual efforts have valuable information and some reports are available, a meta-analysis of this data has not been completed, and there is currently no overarching regional program.	**Very High**	**Very High**

Table A.4.6 Phytoplankton community composition and HABs: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of Certainty about magnitude, composition, or controls	Need for additional or on-going data collection or process studies	Priority for study in next 1-5 years
Processes				
Pelagic grazing rates (size-selective)	**High**	**Low**: No systematic zooplankton sampling in LSB, South Bay, Central Bay. Only 1 station in San Pablo.	**Moderate**	**Moderate**
Size-selective benthic grazing rates	**High**	**Low**: Good data to support estimates in Suisun Bay. Limited data in LSB South Bay. Monitoring of benthos abundance would inform this.	**Very High**	**Very High**
Temperature, light, and nutrient (concentration, N:P, form of N) preferences of phytoplankton PFTs specific to SFB subembayments	**High**	**Low**: Limited understanding of how these factors/preferences may shape phytoplankton community composition, in particular in a light-limited nutrient-replete system.	**Very High**	**Very High**
Effects of trace metals, organics or pesticides	**Moderate/ Uncertain**	**Low:** Limited information on vitamins, trace-metals, and the influence of anthropogenic contaminants such as pesticides that may be influencing community composition. competition with diatoms.	**Moderate**	**Moderate**
Effect of physical forcings, including exchange between subembayments, oceanic and terrestrial (including wetlands, salt ponds) end-member inputs, large scale climate forcings	**High**	**Moderate:** Data on community composition over the past 20 years (Bay wide) and up to 40 years (Suisun and Delta) to explore different explanations.	**Very High**	**Very High**
NH4 inhibition: diatom productivity	**High/ Uncertain**	**Low:** Several studies completed, others underway.	**Very high**	**Very high**
Ambient composition data				
Size-fractionated chl-a	**High**	**Low:** Provides a coarse measure of in which classes phytoplankton biomass resides, which is a useful albeit coarse surrogate for food quality. Not currently being collected but could be easily added to monitoring.	**HIgh**	**High**

Process or Parameters	Importance for quantitative understanding	Current Level of Certainty about magnitude, composition, or controls	Need for additional or on-going data collection or process studies	Priority for study in next 1-5 years
Phytoplankton community composition, monthly time-scales, at sufficiently high spatial resolution, and higher temporal/spatial resolution to test mechanisms	**High**	**Moderate:** 20 year near-monthly Bay-wide record from USGS and ~40 year record for Suisun and Delta. But few higher resolution data sets or special studies.	**Very high**	**Very high**
Frequency and magnitude of detection of HABs or HAB toxins	**High**	**Low**: Limited data on HABs and toxins, and	**Very high**	**Very high**
Phytoplankton community composition in salt ponds, particularly HAB-forming species	**High**	**Low:** Limited data to date, but of high concern.	**Very High**	**Very High**
Surrogate measures for phytoplankton composition	**Low**	**Low:** The use of phytoplankton pigments or digital image recognition approaches could be piloted that would eventually increase the amount of composition data that could be collected	**Very High**	**Very High**