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Development Plan 2014

Development Plan for the San Francisco Bay Nutrient Monitoring Program

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Contents

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1 Introduction

1.1 Background

San Francisco Bay (SFB) has long been recognized as a nutrient-enriched estuary (Cloern and Jassby 2012), but one that has not exhibited the classic impacts of high nutrient loads observed in other estuaries, such as high phytoplankton biomass and low dissolved oxygen. However, recent observations suggest that SFB's resistance to the harmful effects of nutrient overenrichment is weakening. Since 1999, the saline regions of SFB have experienced substantial increases in phytoplankton biomass (Cloern et al. 2007, 2010). An increased frequency of cyanobacteria blooms (Lehman et al. 2008) in the northern estuary and detection of harmful algae in the South Bay (J. Cloern, pers. com) also potentially signal changes in ecosystem response. Elevated nutrient concentrations and shifts in nutrient forms and ratios are hypothesized to have altered phytoplankton community composition (Glibert 2012) and, paradoxically, to be contributing to low productivity in Suisun Bay and the Delta (Dugdale et al. 2007; Parker et al. 2012a).

The combination of high nutrient concentrations and changes in environmental factors that regulate SFB's response to nutrients has generated growing concern that the Bay is trending toward, or may already be experiencing, adverse impacts from nutrients. The Nutrient Strategy for San Francisco Bay[1], developed through a collaborative effort of the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB), stakeholders, and dischargers, lays out a process for developing the scientific basis upon which to make informed decisions about managing nutrient loads to and maintaining beneficial uses within the Bay. Developing and implementing a nutrient-focused monitoring program for San Francisco Bay is one of several major work elements identified in the Nutrient Strategy.

1.2 Goals of this Report

The specific goals of this report, as an initial step in the SFB nutrient monitoring program development process, are to:

1. Articulate the goals of the nutrient monitoring program [Section 2]
2. Lay out the approach for developing the program [Section 3]
3. Assemble important background information, including:
    a. Summaries of historic and on-going monitoring activities [Section 4]
    b. Inventory potential elements of the future monitoring program – what, how, where and when to measure [Section 5]
4. Provide initial recommendations for program development, and identify next steps to address remaining questions related to future monitoring program structure [Section 6]

The monitoring program planning efforts described here focus primarily on the open bay subtidal and intertidal mudflat areas of SFB, including the main subembayments of Lower South Bay, South Bay, Central Bay, San Pablo Bay, and Suisun Bay. Margin habitats (wetlands, salt ponds, creeks and sloughs) are not discussed in this report. Program requirements for monitoring in those habitats will be developed through a separate effort. Since this report is one in a series of planning and synthesis reports, detailed background on nutrients in SFB is not presented here. The reader is referred to other reports for that information (McKee et al. 2011; Senn et al.,

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

2014a,b; Novick and Senn, 2014)

2 Goals of the SFB Nutrient Monitoring Program

Currently San Francisco Bay has no regionally-managed nutrient monitoring program. Nutrient-related data collection efforts in San Francisco Bay and the Delta (e.g., nutrients, phytoplankton, other water quality parameters) are currently carried out by several different research or monitoring programs, mainly the United States Geological Survey (USGS); Department of Water Resources-Interagency Ecological Program (DWR-IEP), Regional Monitoring Program (RMP), and researchers at San Francisco State University Romberg Tiburon Center (SFSU-RTC). Some of these programs have long data records (e.g., since 1970s), and the studies that generated those data have greatly informed our understanding of nutrient cycling and phytoplankton response in the Bay. However, there is limited coordination among these programs: each program has different goals and mandates, may use different or even incompatible methods, and may differ in their spatial and temporal sampling frequencies. Additionally, none of these programs was specifically designed to inform regulatory-driven nutrient management decisions. Furthermore, funding for the USGS water quality research program, which covers the largest area of the Bay, has decreased markedly over the past 20 years. The USGS is not mandated to carry out nutrient-related monitoring in SFB, and both the program's future direction and funding level are uncertain. Finally, current monitoring efforts rely mostly on ship-based measurements that focus on sites within the deep channel, carried out on a monthly basis. While these data provide valuable synoptic information, there is growing recognition of existing data gaps: monitoring is needed along the understudied shoals (>40% of SFB's total area) that flank the channel; higher temporal-resolution water quality data from continuous moored sensors is needed to improve assessment of Bay health and provide calibration for water quality models; and there are additional parameters or methods not currently employed that are needed to enhance the current suite of measurements.

The Nutrient Strategy articulates several overarching management questions (Table 2.1), and calls for a science program comprised of four major components through which information will be gathered and interpreted to inform management decisions: Assessment Framework; Modeling; Data/Experimental Investigations; and Monitoring. Figure 2.1 illustrates the relationship between the overarching management and science questions and nutrient strategy work elements, and how these combine to influence the monitoring program requirements. On the one hand, the monitoring program needs to measure the appropriate parameters that will be used to assess condition in SFB and make regulatory-based determinations about whether or not some areas are impaired, and measurements will need to be made at sufficient spatial and temporal resolution to detect an "event" that could be considered problematic. On the other hand, the determination of what size event would constitute a problem may require analysis through modeling (e.g., what concentration of phytoplankton biomass (chl-a) over what area might cause low dissolved oxygen in bottom waters?). Similarly, models are needed to determine the relative contributions from the range of sources to nutrients in different areas of SFB over time, and what degree of nutrient load reductions would be needed (and from which sources) to improve condition. Those models need to be calibrated with field data collected at sufficient spatial and temporal resolution. Finally, the monitoring program needs to collect appropriate data to inform whether ecological condition of the system is changing – this is especially true given the substantial changes in ecosystem response observed in SF over the past

15-20 years in South Bay, and over the past 30 years in Suisun Bay (Cloern and Jassby, 2012)

Table 2.1 Management questions from the Nutrient Strategy

MQ.1	Is there a nutrient problem or signs of a future problem in San Francisco Bay?
MQ.2	What are appropriate guidelines for identifying a problem?
MQ.3	What nutrient loads can the Bay assimilate without impairment of beneficial uses?
MQ.4	What are the relative contributions of loading pathways?

Broadly, the monitoring program must, in combination with the other Nutrient Strategy elements, yield sufficient data to allow regulators and stakeholders to confidently make decisions about how to best manage nutrient loads. More specifically, data collected through the monitoring program must: i. Allow regulators to determine whether the system is experiencing nutrient-related impairment; ii. Provide data at sufficient temporal and spatial resolution for model calibration/validation; iii. Allow managers and researchers to identify nutrient-related changes in ecological condition, or changes in factors that regulate ecosystem response to nutrients.

The approach taken to develop the monitoring program will involve exploring and incrementally defining these needs in more detail in terms of specific parameters to measure and the necessary spatial/temporal measurement frequency, and identifying the program structure that addresses those needs in a cost-effective manner.

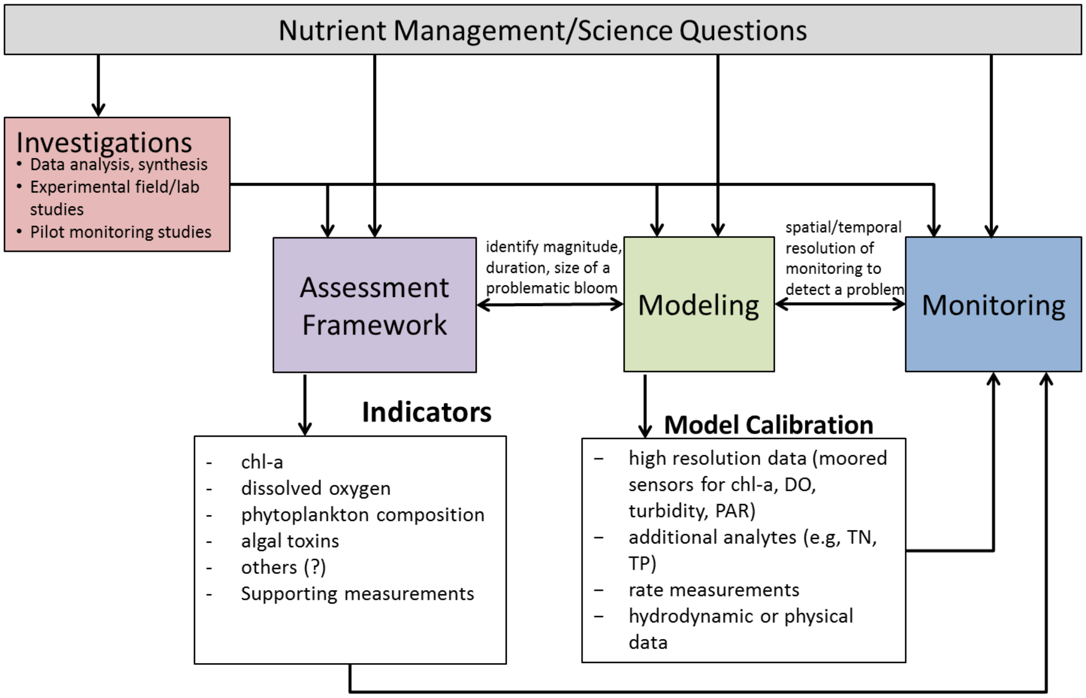

Figure 2.1 Conceptualization of the how Nutrient Strategy work elements influence monitoring program requirements

3 Approach and Timeline for Program Development

Table 3.1 presents the recommended approach and timeline for Monitoring Program Development. Program development is divided into 8 major components, summarized in Table 3.1. The timeline for program development depends both on the time required for the each component's tasks as well as the timelines for other work elements of the Nutrient Strategy that will inform nutrient monitoring program requirements (i.e., Assessment Framework, Modeling).The current goal is to develop draft and final recommended program structures in 2016 and 2017, respectively, with phased implementation beginning in 2017. Some new high-priority elements of the monitoring program will likely be implemented prior to the finalization of the new structure. In addition, some pilot studies to test new methodologies are already underway, and are expected to continue through the development process.

Regulator and stakeholder input will play an essential role in monitoring program development, in particular for identifying monitoring program goals, prioritizing among program components to meet those goals, and establishing institutional and funding agreements. A monitoring program technical advisory team will also be established to provide guidance on program development. The technical advisory team will consist of regional and national experts that have experience establishing and maintaining monitoring programs and/or expertise in SFB water quality. Regulator, stakeholder, and technical advisor input has already been received in multiple meetings over the past 2 years, as noted in the plan in Table 3.1 and is reflected in the recommendations in Section 6.

Table 3.1. Major components and timeline of Monitoring Program Development

Task	***Description***	***2012***	***2013***	***2014***	***2015***	***2016***	***2017+***
1. Prepare a Monitoring Program Development Plan, v1.0, v2.0	Present monitoring program development approach that was developed with input from stakeholders and technical advisors			▨			
2a. Review past and on-going monitoring activities, and 2b. Inventory potential program components (habitats, compartments, analytes to measure spatial/temporal distribution measurement approaches)	Highlight ongoing research and monitoring efforts and inventory existing data that can be used to inform program development. Some potential program components are already well-monitored under the current efforts. These tasks will be the one of the primary purposes of this report, as well as proposing studies to inform program structure (Task 3)			▨	▨		
3. Carry out data analyses and special studies to inform program structure (spatial and temporal distribution; optimal approach; analytes to monitor)	There exists sufficient data for some habitats and/or parameters in SFB and a rigorous analysis of this data over the next 2-3 years will inform program structure. However, there are parameters or habitats that are currently understudied and pilot studies of experimental investigations are to evaluate their importance in a future monitoring program. Recommended analyses are included at the end of this report.		▨	▨	▨	▨	
4. Evaluation/prioritization of program elements	Potential program components (identified in Task 2) will be evaluated and prioritized based on results from Task 3.			▨	▨	▨	
5. Establish necessary programmatic/institutional agreements that bridge existing programs	As much as possible, the future monitoring program should build from and bridge across existing research and monitoring programs. There will need to be coordination across these programs with regard to funding, infrastructure and standard procedures.			▨	▨	▨	
6a. Draft program structure and 6b Final program structure	Technical experts will recommend a draft program structure based on the conclusions of Tasks 4 and 5. Stakeholders may need to further prioritize amongst these recommendations in light of financial or regulatory constraints.					▨	
7. Program implementation (in phases)	It is expected that the final program structure (Task 6b) will take several years to implement, as new elements are added to monitoring or common practices are enacted across agencies that continue existing monitoring.						▨
8. Technical advisor and stakeholder input	Dates listed here indicate meetings of technical experts that have informed monitoring program development approach and recommendations for program structure. There have also been numerous meetings with regulator and stakeholders over the same period.	May 2012	May 2013	Feb 2014	▨	▨	▨

4 Past and On-going Monitoring Activities in SFB

For nearly four decades, water quality research and monitoring have been conducted by various groups throughout SFB and the Delta. Major programs are summarized in Table 4.1. The longest and most consistent programs have been those run by USGS and DWR-IEP; the data from those two large and forward-thinking programs make SFB one of the best studied estuaries worldwide. In designing the nutrient monitoring program, substantial benefits and efficiencies would be gained by building upon and bridging across these two well-established programs with long historical records. While these programs have provided valuable data over a long period of time, they were not designed for nutrients and methods/field procedures are not coordinated across programs. It is therefore important that nutrient monitoring program design look afresh at the nutrient-specific requirements and identify the spatial/temporal sampling requirements, the necessary measurements, and the range of old-yet-reliable vs. newer technologies available to perform measurements and process data. In doing so, the abundant historic data can be analyzed to help inform the future program structure, and used to shed light on data gaps and monitoring needs. .

Data also exists from focused studies by USGS, universities (SFSU-RTC, among others), and other programs. While not included in Table 4.1, data from those studies may also be helpful for informing monitoring program development.

Table 4.1. Ongoing research and monitoring activities in SFB

Program	**Period of record**	**Frequency**	**where?**	**analytes**
USGS				
SFB Water Quality *PI: Cloern*	1969-present	Ship based 1-3x/month	San Francisco Bay and Sacramento River (to Rio Vista) Main Channel 38 active stations Surface to near bottom (CTD) Surface (2m) and near bottom (discrete) Surface (2m) (flow-though)	*CTD at all stations:* salinity, temperature, sigma-t (calculated), turbidity, photosynthetically active radiation (PAR), dissolved oxygen (DO), chl-a fluorescence *Discrete water samples at subset of stations:* chl-a, pheophytin, suspended particulate matter (SPM), DO, nitrite (NO_2^-), nitrate (NO_3^-), ammonium (NH_4^+), ortho-phosphate (o-PO_4^{-3}), silicate (SiO_2) *Surface water flow-through throughout cruise (5 second intervals):* salinity, temp, turbidity, chl-a fluorescence
SFB Phytoplankton *PI: Cloern*	1990-present	Ship based 20 -50 samples/year (typically only when chl-a > 5 ug/L)	San Francisco Bay and Sacramento River (to Rio Vista) Main Channel Up to 38 stations Near-surface (1-2m) and bottom	Microscopic enumeration to species level (density and biovolume) high-performance liquid chromatography (HPLC) for functional groups (pilot study 2011-present)
SFB Sediment *PI: Schoellhamer*	1989-present	Moored continuous 15 min intervals	San Francisco Bay Main Channel 10 active stations Surface (1-2m), mid-depth or near bottom	Salinity, temperature, turbidity (some sites), DO (some sites)
South SFB Benthos *PI: Thompson*	*South SFB* 1988-1996 2004-2009	Ship and small boat based Monthly (some sites) or 1-3x per year	South of San Mateo Bridge Main channel and shoals Variable number of stations	Benthic bivalve species, count, biomass filtration rate (calculated)
North SFB – Benthos *PI: Thompson*	1988-2008	Ship and small boat based Monthly (some sites, 1988-2008) or 1-3x per year (other sites, 2006-2008)	San Pablo and Suisun Bays Main channel and shoals Variable number of stations	Benthic bivalve species, count, biomass filtration rate (calculated)

Program	**Period of record**	**Frequency**	**where?**	**analytes**
North SF Bay/Delta – Carbon *PI: Bergamaschi*	2011-present	Moored continuous 15 minute intervals	Delta 6 active stations	Salinity, temperature, discharge, pH, DO, turbidity, fluorescent dissolved organic matter (fDOM), chl-a fluorescence, phycocyanin, NO_3^-, o-PO_4^{-3}
DWR-IEP				
Water quality	1975-present	Ship based Monthly	Delta through San Pablo Bay Main channel and shoals 21 active stations ~15 historic stations Surface (1m)	*CTD:* salinity, temperature, turbidity, secchi depth, DO, chl-a fluorescence Discrete water samples: suspended sediments chl-a, pheophytin-a, NO_2^-, NO_3^-, NH_4^+, total kjeldahl nitrogen (TKN), total organic nitrogen (TON), total phosphorous (TP), o-PO_4^{-3},SiO_2, other metals/organics
Continuous Water Quality	1978-present	Moored continuous 15-60 minute intervals	Delta through San Pablo Bay Main channel and shoals 13 active stations Surface (1m) or bottom	Salinity, temperature, depth, pH, DO, turbidity, chl-a fluorescence
Phytoplankton	1975-present (with significant methods change in 2008)	Ship based Monthly	Delta through San Pablo Bay Main channel and shoals 21 active stations ~15 historic stations Surface (1m)	*phytoplankton taxonomy:* Microscopic enumeration to species level (density and biovolume)
Zooplankton	1972-present	Ship based Monthly	Delta through San Pablo Bay Main channel and shoals 11 active stations	Taxonomic enumeration (to species level for some groups)
Benthos	1977-present	Ship based Monthly (since 1980)	Delta through San Pablo Bay Main channel and shoal 4 active sites	Taxonomic enumeration to species level
RMP				
Water Quality	1993-present	Ship based Annually (1993-2011) Biannually (2012-present) Dry season only	San Francisco Bay Main channel (1993-present) and shoals (2002-present) 22-31 active stations (fixed stations before 2002, randomized stations 2002-present) Surface	salinity, temperature, density, pH, hardness as CaCO3, DO, backscatter, suspended sediment, chl-a, pheophytin a, particulate organic carbon (POC), NO_2^-, NO_3^-, NH_4^+, o-PO_4^{-3},SiO_2, and other contaminants (e.g. pesticides, legacy pollutants)

Program	**Period of record**	**Frequency**	**where?**	**analytes**
Sediment	1993-present	Ship-based Annually (1993-2011) Biannually (2012-present) Alternate wet and dry season	San Francisco Bay Main channel (1993-present) and shoals (2002-present) 27 (wet season) and 47 (dry season) active stations (fixed stations before 2002, randomized stations 2002-present)	salinity, temperature, density, pH, DO, backscatter, Eh, % solids, grainsize parameters, total organic carbon (TOC), TN, and other contaminants (e.g. pesticides, legacy pollutants)
Other Monitoring Activities				
Historic LSB publicly owned treatment works (POTW) monitoring	1964-1993	Ship-based 1-2x per month	Lower South Bay and sloughs Up to 17 stations Main channel and sloughs Variable depths	Salinity, temperature, depth, pH, DO, turbidity, secchi depth, NO_2^-, NO_3^-, NH_4^+, TON, o-PO_4^{-3}
Current LSB POTW monitoring	2002-present	Ship-based Monthly	Lower South Bay and sloughs Up to 8 active stations Main channel and sloughs Variable depths	Salinity, temperature, depth, pH, DO, turbidity, secchi depth chl-a, NO_2^-, NO_3^-, NH_4^+, o-PO_4^{-3}
SFB Environmental Assessment and Monitoring Station (SF-BEAMS)	2002-present	Moored continuous ~6 minute intervals	San Pablo and Suisun Bay 2 active stations Deep subtidal Surface (1m)	Salinity, temperature, depth, pH, DO, turbidity, chl-a fluorescence

5 Inventory of Potential Monitoring Program Measurements

The primary goal of the SFB nutrient monitoring program development effort is to determine the highest-priority analytes and the most efficient and efficacious ways of obtaining the necessary data. This section discusses the range of potential parameters that could be incorporated into routine nutrient monitoring, and approaches for obtaining those measurements – the what, where, when, and how of the monitoring program. After this background is presented, Section 6 describes initial input from technical advisors on priority data gaps, recommendations for new monitoring program components, and recommended data analysis to inform program design and priorities.

5.1 Spatial and Temporal Sampling Considerations

As previously noted, this report focuses only on open-bay subtidal and intertidal areas, although it is expected that monitoring will need to occur in margin habitats and will be developed through a separate effort. The deep subtidal areas are referred to in this report as the deep channel, and shallow areas (both subtidal and intertidal) are referred to as the shoals, except where it is necessary to discuss the specific considerations of intertidal habitats.

The relative distribution of channel vs. shoal habitats in SFB varies within the estuary's 5 distinct subembayments (Figure 5.1). South Bay and Lower South Bay are characterized by a single deep (10-20m) channel that bisects broad shoals. Lower South Bay and areas of South Bay are connected to the decommissioned ponds of the South Bay Salt Pond Restoration Program, whose monitoring requirements are not specifically discussed in this program development; they are nonetheless an important consideration for monitoring the open-bay in this region. Central Bay is the deepest basin (up to 140m) and is directly connected to the Pacific Ocean through the Golden Gate. San Pablo Bay is characterized by a single deep channel (10-20m) and vast shoals north of the channel. Suisun Bay is distinguished from the other subembayments by its braided channels and the presence of two distinct shoal embayments: Grizzly Bay and Honker Bay. Mallard Island is considered the regulatory boundary between the Delta and San Francisco Bay. While flows and material transport from the Delta play an important role in shaping ecosystem function in northern SFB, monitoring needs in the Delta are not addressed in this report.

Currently, shipboard monitoring in SFB primarily occurs in the deep channel environments, with the exception of one IEP site in Suisun Bay that samples in Grizzly Bay (average depth ~ 3 m). However, several studies have demonstrated that there are strong lateral gradients in phytoplankton biomass during certain times of the year and that the shoal habitats are more productive than the channel due to their higher average light levels (Huzzey et al. 1990; Thompson, et al. 2008; Lucas et al. 2009). Both for assessing condition and calibrating models, stations may need to be established in these habitats.

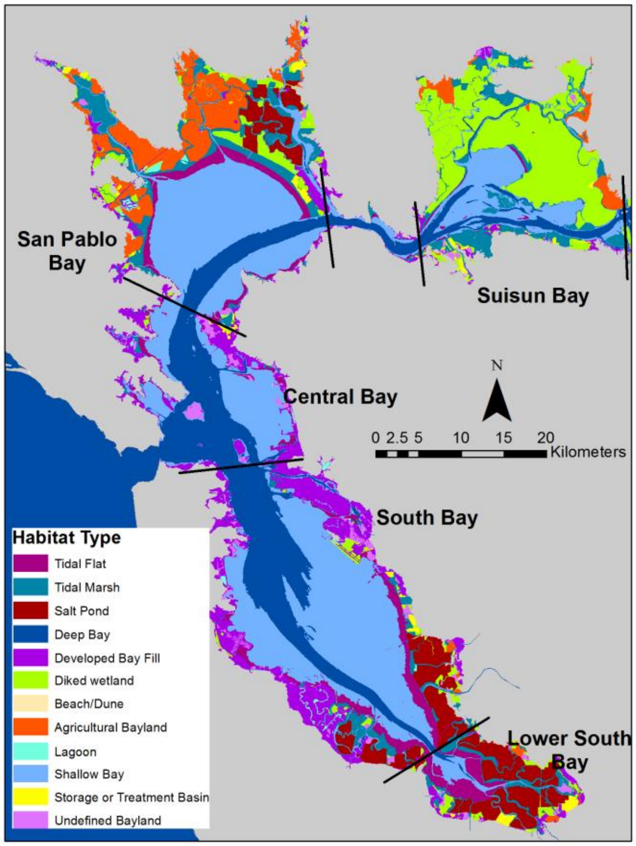

Figure 5.1: Habitat types in SFB's 5 subembayments. Monitoring planning described in this report is focused only on the habitats depicted here as Deep Bay, Shallow Bay and Tidal Flat.

Measurements made as part of "routine" monitoring can be taken at a range of sampling intervals, depending on the management questions and relevant temporal scales for the processes or parameters of interest. Common sampling intervals for shipboard routine monitoring are weekly, bi-monthly (corresponding to the spring/neap tidal cycle), monthly, or seasonally. When sub-daily measurement frequencies are required over extended periods, shipboard sampling likely becomes cost-prohibitive. In those cases, high-temporal resolution data (e.g., continuous, 15 min, 30 min, hourly, etc.) can be collected using *in situ* instrument packages, deployed on moorings or attached to existing structures (e.g., bridge piers or navigation markers), assuming sensors are available for the parameters of interest. When there is a need for higher-frequency data for parameters that cannot be accurately measured by sensors, shipboard campaigns would fall into the category of "special studies" or "Investigations" (Figure 2.1), and are not discussed in this report.

5.2 Overview of measurement approaches

Given the range of potential parameters that could be part of routine monitoring, the relevant temporal and spatial scales for those parameters, and the different habitats in which they may need to be measured, a range of measurements approaches may need to be employed to collect data within the nutrient monitoring program. An overview of measurement approaches is presented below.

Shipboard sampling allows for the collection of samples for a wide array of parameters over large areas (i.e., subembayment or full bay). Shipboard sampling typically involves deploying a CTD[2] for vertical profiles, and collecting discrete water samples at one or more depths for measurement aboard the ship or for sample preparation in the ship's on-board laboratory for subsequent analysis when back on land. In addition, many research vessels have continuous flow-through systems that pump surface water into the ship's laboratory while the ship is underway; that water can be measured by in-line sensors for a range of parameters, or can be subsampled for analysis. The number of stations and area that can be covered in a day are constrained by the ship's speed and amount of time allocated for sampling. In SFB, shipboard sampling has generally been carried out at frequencies of spring/neap or longer (e.g. weekly-monthly). Samples for a wide range of measurements can be collected from research vessels, and space is often available for both sample preparation and on-board experiments. Ships that can accommodate these activities are commonly large (50-100') and have deep drafts (several feet), confining them largely to deep channel environments. However, some research vessels are available that have shallow drafts (e.g., catamaran-style), and can be used to sample in shallower areas. Small boats (i.e. motorboats 15-20' long) can be used to sample in even shallower areas, but typically have limited space for sample processing.

Moored instruments produce high-resolution near-continuous monitoring from a fixed location. Considerations around moored sensors include identifying which analytes can be accurately monitored with commercially-available sensors, determining the optimal location within the estuary and best water column depth at which to place the sensor package, required maintenance and calibration, and data quality. For parameters that require little or no in-situ calibration (e.g., salinity, temperature), moored instrumentation presents an excellent option for high frequency data collection. However, for other parameters (e.g. chl-a, dissolved oxygen, turbidity, fDOM, nitrate), measurements can be prone to substantial interferences or uncertainty, and extensive field calibration is often needed, increasing the effort and cost of their use. Additionally, sensors are prone to biofouling, and both frequent maintenance and rigorous QA/QC of large data streams are needed. A powerful feature of moored sensors is that they can be set up to telemeter data, creating the potential for near real-time monitoring. DWR-IEP maintains 3 moored stations in Suisun Bay with parameters such as chl-a, DO, etc., and SFSU-RTC maintains sensors at their dock in Central Bay. USGS maintains a number of stations Bay-wide for suspended sediments, temperature, and salinity (some of these stations also have DO). In addition, there are a few recently deployed pilot moored stations in South Bay and Lower South Bay with nutrient-related parameters (e.g., DO, chl-a, etc.)

Autonomous underwater vehicles (AUVs) can run continuously or be deployed to capture a specific event. AUVs are often deployed to follow a pre-programmed 3-dimensional path, and carry instrument packages similar to those deployed on a CTD, providing high frequency data along that path. AUVs can be either propeller-driven or buoyancy-driven (capable of moving

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[2] A sensor package that measure conductivity, temperature and depth as the instrument is lowered through the water column. Additional *in situ* sensors commonly integrated with CTDs included dissolved oxygen, chl-a fluorescence, turbidity, and photosynthetically active radiation (PAR).

vertically in the water column through internal buoyancy regulation), and are now commercially available; however, to date, no AUV efforts have been used in routine monitoring in SFB. The strong tidal currents in SFB could make AUVs difficult to deploy in terms of them being able to accurately follow a preprogrammed path, and increase the risk of expensive equipment loss or damage. However, if these issues could be overcome, AUVs could provide valuable and cost-effective data in areas of SFB that are difficult to access with research vessels. AUVs may also provide an excellent compromise between shipboard sampling and moored sensors: continuous data collection over an extended period of time on a moving platform.

Towed undulating instrument packages are pulled behind a ship and collect data from surface to deeper depths as the ship moves. Any number of sensors, such as those deployed on CTDs or at moorings, can be deployed on a towed package. They provide the same high-frequency transect data as a ship's flow-through system, but sample at multiple depths as it is towed to characterize vertical variability. Their use requires that a ship be outfitted with stern A-frame and winch. Use of towed undulating packages would be limited to SFB's deep channel.

Remote sensing data is available periodically (coincident with daytime satellite flyover), but gives a nearly continuous spatial picture within its swath. Considerations around remote sensing include feasible analytes, calibration and potential interferences, and image processing/interpretation expertise. Satellite imagery is commonly used in the open ocean and in some estuaries to infer chl-a concentration, sea-surface temperature, and other parameters. Remote sensing captures only surface blooms and many blooms dominated by HAB species are not easily distinguished using readily available, multi-spectral remote sensing products (e.g., MODIS). The potential utility or reliability of remote sensing for monitoring applications in SFB has been questioned because of frequent fog/cloud cover, high turbidity, and the low spatial resolution of the data compared to the size of SFB. However, remote sensing has arguably been underutilized to date in SFB, and there may be some applications for which it is uniquely well-suited.

Other In other estuaries, aerial surveys and seaplane-based sampling (i.e., deploying a CTD and collecting samples; e.g., Puget Sound) are used. In addition, CTD-like instrument and autosamplers have been deployed aboard ferries (e.g., Neuse River[3]) and used for monitoring. These approaches have not yet been used in SFB.

5.3 Parameters

This section presents an inventory of relevant parameters for potential inclusion in the SFB nutrient monitoring program, and briefly discusses spatial, temporal and methodological considerations for each. The broad set of starting parameters is based on initial considerations of measurements that are either already being made in SFB or commonly measured in other estuaries. Individual parameters are grouped by theme, and discussed in terms of their ecological significance and current understanding of spatial and temporal monitoring considerations. This starting set of parameters is not intended to be exhaustive nor serve as a recommendation. Instead, the goal was to provide a broad overview of possible parameters that give context for the initial recommendations that follow in Section 6. A more detailed set of parameters and

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[3] http://www.unc.edu/ims/paerllab/research/ferrymon/images/index.html

processes is presented in the Appendix (Tables A.1-A.5), which was developed with input from technical advisors on data availability in SFB. Some of the parameters in Tables A.1-A.5 might be considered part of routine monitoring, while others are better pursued as part of special studies, as noted. Rooted aquatic plants and fish abundance are not included here, but may be part of future program considerations

5.3.1 Phytoplankton Biomass and Production Rate

Ecological significance in SFB: Phytoplankton represent the largest component of living biomass in SFB, and their biomass fuels the SFB food web (Jassby and Cloern 2000). Through photosynthesis, phytoplankton transform inorganic elements into organic forms, and these transformations lead to measurable geochemical changes in estuarine systems (Cloern 1996). Phytoplankton biomass (commonly presented in units of µg chl-a L^{-1}) often serves as a sensitive indicator of nutrient availability in surface waters since phytoplankton growth rates are relatively rapid and depend on nutrient concentrations when nutrients are limiting. Moreover, phytoplankton can accumulate to high levels and cause adverse impacts when excessive levels of nutrients are present. For example, when biomass or production rates are extremely high, the respiration of dead biomass in bottom waters can lead to adverse impacts from low DO.

Coastal systems with primary productivity above 300 g C m^{-2} yr^{-1} are classified as eutrophic, and those below 100 g C m^{-2} yr^{-1} are considered oligotrophic (Nixon 1995). These productivity classifications, along with other measures (Table 5.1), are commonly used to characterize ecosystems and sometimes trigger regulatory actions. While phytoplankton biomass has historically been low in SFB, there have been statistically significant increases in all subembayments over the last 15 years, and our understanding of how both the different subembayments figure into this classification scheme and the how system is changing over time rely on measurements of both biomass and productivity.

Table 5.1 Phytoplankton biomass, productivity, and related parameters

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
Chlorophyll *a* (Chl *a*)	Proxy for phytoplankton biomass	Laboratory analysis of samples	Solvent extraction with analysis by fluorometer, spectrophotomer, or HPLC	Several USGS programs, DWR-IEP, RMP, SF-BEAMS
		Sensor (moored, CTD, flow-through or bench-top)	Chl *a* fluorometer calibrated using lab analyzed Chl *a*	Several USGS programs, DWR-IEP, SF-BEAMS
Particulate Organic Carbon/Nitrogen (POC/PON)	Measure of phytoplankton biomass	Laboratory analysis of samples	Elemental analyzer following combustion	Not currently monitored in SFB
Carbon fixation	Rate of carbon fixation can be used to infer phytoplankton growth	Laboratory analysis of samples	Carbon fixation is measured by ^{14}C incubation (often at different irradiances) or dissolved oxygen analysis (6-12 hours)	Not currently monitored in SFB

Spatial considerations: SFB has a relatively deep (10-20m) channel running along its spine, with broad shoals on either side. Chlorophyll-a concentrations vary laterally from shoal areas to the channel, with higher phytoplankton abundance commonly measured along the shoals (Cloern et al. 1985; Huzzey et al. 1990; Thompson et al. 2008). Blooms often begin on the shoals in SFB and spread into the channels, where the bloom can persist if the water column is stratified (Lucas et al. 1999). In general, light levels are thought to be too low for blooms to develop or be sustained in the deep channel unless the water column is stratified. In addition to lateral gradients, chl-a varies persistently along a longitudinal gradient, with the highest concentrations typically observed in Lower South Bay and the lowest in the northern estuary.

Despite the importance of production in shoals, there is limited systematic monitoring in those areas. Shipboard sampling is well suited for monitoring in the deep channel and most data are from these areas. Larger research vessels cannot access shoal areas where phytoplankton biomass tends to be higher than in the channel and these areas are currently undersampled in all subembayments.

Temporal considerations: In general, the largest phytoplankton blooms tend to occur in Spring (February-May). At channel sites, chl-a concentrations are typically highest during periods of minimum tidal mixing energy, which that allows the water column there to remain stratified for a sufficient period of time. Over the past ~15 years in South Bay and Lower South Bay, higher baseline biomass levels and/or modest blooms have been occurring in Summer and Fall. Phytoplankton biomass in the North Bay exhibits limited variability between months but considerable intra-annual variation (Cloern, Hieb et al. 2010) with some years exhibiting little bloom activity, and other years having substantial bloom events.

5.3.2 Phytoplankton Community Composition

Ecological significance in SFB: Phytoplankton taxa come in a large variety of cell sizes, abilities, and nutritional quality. Each of these characteristics has implications for consumers (zooplankton, clams, fish) and the health of the ecosystem. A recent decline in the abundance of native pelagic fish species in northern SFB and the Delta has raised questions about whether the phytoplankton community is of appropriate quality to support these higher organisms and about the role that nutrients may play in shaping this community (Glibert 2012). Another important reason for both understanding and monitoring phytoplankton composition is to detect the presence of harmful algal bloom (HAB) forming phytoplankton. The high available dissolved nutrient concentrations, persistent presence of potentially-harmful species, and large seed-stocks of cyanobacteria in the Delta make SFB a potential initiation site and incubator for HABs.

Table 5.2 Phytoplankton community composition and related parameters

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
Phytoplankton species abundance and biovolume	Information on types of species and cell sizes present- which have implications for consumers and the health of the ecosystem	Laboratory analysis of samples	Inverted microscopy for enumeration of all phytoplankton to species level	USGS SFB Water Quality, DWR-IEP
		Laboratory analysis of samples	High-performance liquid chromatography (HPLC) for phylogenetic divisions of algal taxa present	USGS SFB Water Quality (pilot program[4] since 2011)
		Sensor (moored, CTD, flow-through or benchtop)	Imaging flow cytometer with high frequency, flow-though sampling for semi-automated enumeration of phytoplankton species	Grant application in process, not calibrated for SFB at this time.
Picoplankton abundance and biovolume	Informs size structure of the phytoplankton community	Laboratory analysis of samples	Epifluorescent microscopy for enumeration of smallest phytoplankton	Not currently monitored in SFB
Presence of HAB species	Detection of harmful, toxic and nuisance phytoplankton species	Laboratory analysis of samples	Inverted microscopy for quick scan without enumerating the entire sample	Not monitored except when detected though regular phytoplankton composition monitoring (USGS, DWR-IEP)
		Sensor (moored, CTD, flow-through or benchtop)	Imaging flow cytometer with high frequency, flow-through sampling for semi-automated enumeration of phytoplankton species	Grant application in process, not calibrated for SFB at this time
		Laboratory analysis of samples or sensor	Immunofluorescent probes, for rapid detection of single species	Not currently monitored in SFB
		Laboratory analysis of samples or sensor	RNA probes for detection of single species	Not currently monitored in SFB
Phytotoxin concentration	Determine presence of algal toxins (threat to humans and wildlife)	Laboratory analysis of samples	Liquid chromatography–mass spectrometry (LC/MS) to detect toxin concentration in water	USGS SFB Water Quality pilot program since 2011, no results at this time
		Laboratory analysis of samples	Solid Phase Adsorption Toxin Tracking (SPATT) to detect toxin concentrations in water	USGS SFB Water Quality pilot program since 2012

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[4] Footnote: ‘pilot program’ means that samples have been collected at a subset of stations and dates and are stored awaiting analysis or are in the process of being analyzed. Unless a pilot program is completed (e.g. urea), the results have not been systematically interpreted in a report or other product.

Spatial considerations: Algal blooms, whether harmful or benign, are produced in the photic zone, the upper water layer from the surface to the depth of 1% of light penetration. Different functional groups may dominate at different water depths; e.g., dinoflagellates are able to move vertically below the photic zone and back while cyanobacterial filaments and colonies tend to remain at the very surface of the water column. Blooms often have a patchy distribution, and may be spatially isolated or spread across miles. In SFB, phytoplankton blooms in general tend to initiate along the shallow shoals and then spread to deeper regions. Detection of HAB-forming species has varied by subembayment. *Microcystis aeruginosa* blooms have occurred in the Delta and the North Bay during July through November of each year since 1999. Algal toxin monitoring over the last several years has detected microcystin Bay-wide (R. Kudela, pers. com.). In addition, the USGS sampling program has observed an increased detection frequency of potentially-harmful species in South Bay over the past ~10 years. Appearances of some taxa were surprising because they had not been detected in the previous 2 decades of sampling (Cloern and Dufford 2005). One hypothesis for these observations, made after the first commercial salt ponds were opened in 2004, is that the salt ponds might function as incubator habitats and a source of toxic phytoplankton to San Francisco Bay as they are opened to tidal exchange. Oceanic or riverine end-members may also introduce seed populations to SFB; for example, an unprecedented red tide occurred in Fall 2004 that may have been advected into SFB from the Pacific Ocean (Cloern et al. 2005).

Temporal considerations: San Francisco Bay exhibits both seasonal and decadal cycles in community composition. During periodic blooms (primarily spring and fall), phytoplankton biomass is typically dominated by large-celled diatoms (Cloern and Dufford 2005; Wilkerson, et al. 2006; Kimmerer et al. 2012). Lehman (2000) identified stream flow as an important interannual indicator of community composition in the northern estuary: i. Periods of low light, turbulence, and short residence times were associated with pennate and single-celled centric diatoms; and ii. Cryptophytes and flagellates were associated with "critically dry" periods of increased residence time, increased light intensity, and higher water temperature. Within the Delta, low streamflow has also been associated with enhanced *Microcystis* blooms (Lehman et al. 2010), attributed to reduced turbulence and prolonged residence time. Basin-scale decadal oscillations also profoundly impact the coastal plankton assemblage. Since the oceanic end-member can serve as a seed population for the estuary, San Francisco Bay is also indirectly influenced by El Niño, the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and other mesoscale changes (Cloern and Dufford 2005; Cloern et al. 2010). Both seasonal and decadal trends would be captured by monthly monitoring.

Microscopy is a time-tested method of enumerating phytoplankton community composition but is not rapid and can be expensive. New technologies are emerging that would potentially allow more frequent and less costly sampling. USGS, UC Santa Cruz and SFEI are collaborating on a pilot study of HPLC pigment analysis for functional group identification. If the pigment-derived composition results agree with co-located samples analyzed by microscopy, this approach may prove viable, in particular because it is less expensive than microscopy and could allow more samples to be measured. Imaging flow cytometers take pictures of individual phytoplankton cells in a sample, and those images and other spectral data that is collected can be compared to image libraries to identify phytoplankton down to species level. These imaging cytometers can be used on the benchtop, aboard an underway research vessel, or deployed in situ at a moored station.

Other emergent technologies that are not yet in use for monitoring could eventually be of use in SFB in the future if a particular HAB species becomes an increasing concern (including immunofluorescent and RNA probes that detect specific gene sequences to identify single species of interest). Some of these instruments can also be deployed in situ or used in bench-top mode with discrete samples and can be used to fill the gaps (in time) between microscopic samples.

5.3.3 Other basic water quality parameters

Ecological significance in SFB: There are numerous physical properties and chemical characteristics of water samples that are relevant for a nutrient monitoring program, and they are summarized briefly in Table 5.3. Some physical properties can be measured to determine if stratification is occurring (vertical gradients in temperature or salinity). Photosynthetically active radiation (PAR) provides a direct measurement of light availability for phytoplankton growth, while suspended sediments/turbidity attenuate the light available in the water column. Both stratification and light availability influence whether or not a bloom is likely to develop. Nutrient concentration provides an indication of the growth potential for phytoplankton in an estuary. Dissolved oxygen concentration is an important indicator of ecosystem metabolism and health, and low DO in bottom waters is a common adverse impact of excess nutrient loads.

Table 5.3 Basic water quality parameters

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
Temperature (T)	Fundamental water quality parameter affecting the growth rate of organisms and ecosystem function; also used to calculate density of water	Sensor (moored, flow-through or benchtop)	thermistor probe	Several USGS programs, DWR-IEP, RMP, SF-BEAMS, South Bay Dischargers monitoring
Conductivity, Salinity	Fundamental water quality parameter effecting ecosystem and biotic function; also used to calculate density of water	Sensor (moored, CTD, flow-through or benchtop)	electrode-based probe	Several USGS programs, DWR-IEP, RMP, SF-BEAMS, South Bay Dischargers monitoring
Dissolved Oxygen (DO)	Fundamental water quality parameter necessary for biotic life and ecosystem function	Laboratory analysis of samples	Winkler titration	Several USGS programs, DWR-IEP, RMP, SF-BEAMS, South Bay Dischargers monitoring
		Sensor (moored, CTD, flow-through or benchtop)	optical DO probe	
Dissolved inorganic nutrients (ammonium, nitrate, nitrite, ortho-phosphate, silicate)	Essential nutrients for growth of phytoplankton	Laboratory analysis of samples	Colorimetric analysis (Autoanalyzer)	Several USGS programs, DWR-IEP, RMP, South Bay Dischargers monitoring
		Laboratory analysis of samples	fluorometric derivatization	Several USGS programs, DWR-IEP, RMP, South Bay Dischargers monitoring

Parameter	*Why it is monitored*	*Approach*	*Example of a commonly used method*	*Monitored by*
		Laboratory analysis of samples	wet oxidation	Several USGS programs, DWR-IEP, RMP, South Bay Dischargers monitoring
		Sensor (moored, CTD, flow-through or benchtop)	Ultraviolet (NO3) or wet-chemistry (PO4) sensors	USGS North SFB/Delta Carbon
urea (dissolved organic nutrient)	Essential nutrient for growth of phytoplankton, can be used by HAB organisms for growth	Laboratory analysis of samples	Colorimetric analysis	Not currently monitored in SFB (USGS SFB Water Quality pilot study 2011-2012)
Total nitrogen (TN), total phosphorus (TP)	For monitoring total nutrient loads to a system and calculating dissolved organic nitrogen and phosphorus fractions.	Laboratory analysis of samples	Kjeldahl digestion, wet oxidation, UV, combustion	Not currently monitored in SFB
Photosynthetically Active Radiation (PAR)	PAR profiles are used to calculate light attenuation and light energy available to phytoplankton for photosynthesis	Sensor (moored, CTD, flow-through or benchtop)	PAR sensor	USGS SFB Water Quality
Turbidity, or suspended particulate matter	Indicator of sediment load and degree of sediment resuspension	Laboratory analysis of samples	Suspended particulate matter (SPM) or Total Suspended Solids (TSS)	Several USGS groups, DWR-IEP, RMP
		Sensor (moored, CTD, flow-through or benchtop)	optical backscatter (OBS) or nephelometer sensor, Can be calibrated to SPM or TSS using discrete lab-analyzed samples	Several USGS groups, DWR-IEP, SF-BEAMS
pH	Used for inferring water chemistry	Sensor (moored, CTD, flow-through or benchtop)	pH probe	USGS North SFB/Delta Carbon, DWR-IEP, RMP, SF-BEAMS

Spatial considerations: Salinity distribution in northern SFB varies seasonally and with water diversion (Kimmerer 2002) and can impact habitat extent of plants and animals. Vertical salinity and temperature distributions occur infrequently as wind and tidal energies typically keep the water column well-mixed, except during periods of low mixing energy when blooms commonly develop (Cloern et al. 2005, Lucas et al. 2009). Dissolved nutrients vary longitudinally by subembayment and laterally due to input by point-sources, remineralization of organic matter, and uptake by phytoplankton. When the water column is well mixed, vertical gradients in nutrient concentrations rarely occur. In contrast, PAR decreases exponentially with depth and the rate of this decrease, or light attenuation, is a key factor in promoting or limiting primary productivity and biomass accumulation (Alpine and Cloern 1988). Compared with other estuaries in the United States, SFB has high rates of light attenuation due to high suspended particulate matter (SPM), severely limiting primary productivity (Cloern 1999). Dissolved oxygen concentrations occasionally exhibit a vertical gradient, with greater concentrations near the surface.

Parameters that are easily sampled using CTD (e.g. salinity, temperature, DO, turbidity, PAR, and chl-a fluorescence) are currently reasonably-well sampled along SFB's main channel at monthly time scales. Sampling along the shoals occurs infrequently. Discrete samples are collected at main USGS and DWR-IEP stations on a monthly basis for nutrients, chl-a, and other parameters.

Temporal considerations: Higher frequency measures may give a more accurate picture of flow-mediated versus biologically mediated changes in nutrient concentration at key locations.

5.3.4 Zoobenthos

Ecological Significance: Benthic organisms reflect the state of environmental quality over their lifetime (particularly relevant because most species are stationary) and can affect the ecosystem by disproportionately consuming pelagic and benthic food resources, by accumulating contaminants, and by releasing nutrients (either as a byproduct of food consumption or by stirring the sediments). Benthic organisms are also a valuable food resource for birds, fish, and larger invertebrates. Benthic communities are described by enumerating the number of individuals of each species present, which allows us to understand their life history, position in the food web and their seasonal cycles. By estimating biomass of certain groups of species or for the entire community we are able to convert count data into carbon units which are comparable to those calculated for pelagic flora and fauna. When combined with laboratory derived filtration/grazing rate estimates, zoobenthos biomass can be converted into field-scale grazing rates. It is also important to identify species present because each species has the potential to accumulate contaminants in differing tissue and in differing amounts. Therefore the ability to trophically transfer contaminants is species dependent.

Table 5.4 Zoobenthos parameters

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
Zoobenthos abundance	Used for determining community diversity, determining seasonal patterns and for understanding relative dominance of species.	Laboratory analysis of samples	Macroscopic or microscopic counting of each species.	USGS Benthos, DWR-IEP
Zoobenthos composition	Used for determining community structure and diversity, determining the possible trophic transfer of contaminants, and the emergence of new non-indigenous and invasive species.	Laboratory analysis of samples	Taxonomic identification of each species.	USGS Benthos, DWR-IEP

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
Bivalve Grazing rate	Grazing rate of pelagic organisms can be sufficiently high that benthic filter feeders can reduce the biomass of phytoplankton and zooplankton larvae that are available in the water column. The benthos can therefore structure the foodweb of the ecosystem.	Laboratory analysis of samples	Biomass is estimated for each species and converted using a feeding rate that is available for some species.	USGS Benthos

Spatial Distribution: Benthic communities in estuaries usually organize along the salinity gradient with species having varying tolerance for fresh and salt water. A benthic community is found in all oxic environments and species composition can be a result of environmental conditions that stress some species and not others (eg. intertidal organisms have increased tolerance for temperature changes and extremes). Sampling design is therefore dependent on the question being posed and frequently results in a compromise of understanding spatial variability and temporal (short and long term) variability. While zoobenthos found in channel and shoal sites may filter/graze at the same rates, their relative impact on phytoplankton biomass is greater in shoal environments because of the shallower water column.

Temporal Distribution: Benthic communities in temperate climates can be ecologically important during all seasons. The frequency of sampling is dependent on the reason for monitoring or the question being posed. DWR-IEP has found that seasonal sampling has not been successful at frequencies of less than bimonthly and that monthly to near monthly is best. Intensive spatial sampling has been done around the annual phytoplankton blooms (before, during and after) to determine the trophic interaction of the benthic and pelagic systems.

5.3.5 Zooplankton

Ecological significance in SFB: Zooplankton abundance and composition serve as important indicators of food supply and quality for higher trophic levels. The food web of northern SFB has suffered a long-term decline in productivity at nearly all trophic levels, including zooplankton such as rotifers, cladocera, and some copepods (Kimmerer and Orsi 1996) (Widner and Jassby 2010). The decline in copepod biomass and changes in copepod species composition have been identified as potentially contributing to a decline in native pelagic fishes observed since the early 2000s (Baxter 2010). There are several hypotheses about what could be driving this long-term decline in zooplankton, including predatory species introductions and limited phytoplankton production in northern SFB. Zooplankton monitoring in SFB has mainly been limited to northern SFB and most of the interpretation has focused on larger zooplankton taxa, although limited data is available from research studies in other areas of SFB and on microzooplankton.

Table 5.5 Zooplankton parameters

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
Zooplankton abundance and composition	Zooplankton constitute an important food resource for fish	Laboratory analysis of shipboard samples	Field collections with mysid and Clark bumpus nets, and pumps, followed by lab identifications	IEP at 11 stations in Suisun and San Pablo Bays (1972-present) USGS SFB Water Quality (from 1999-2003 by Bollens)
Zooplankton Grazing rate	Zooplankton grazing could be an important control on phytoplankton biomass accumulation	Laboratory analysis of shipboard samples	Grazing rates are determined through special study, and then used to convert on-going biomass measurements into estimates of grazing rates	Not currently monitored in SFB

Spatial considerations: Zooplankton tend not to stay in one geographic location, but instead live in a moving frame of reference based on temperature and salinity preferences. This is particularly important in northern SFB, where salinity is strongly influenced by flow from the Delta. As a result, in northern SFB, there often exists a gradient of dominant zooplankton species from the Golden Gate north through the Delta (Ambler et al. 1985). This was not found to be the case in South Bay, where *Acartia* species dominated throughout the region and during most months of the year. *Acartia* are typically undersampled in SFB because of lack of regular sampling south of the Golden Gate. Zooplankton biomass tends to be higher in areas where phytoplankton biomass is also higher, i.e. South Bay and shoal habitats (Ambler, et al. 1985).

Most zooplankton monitoring has occurred in the main channel in northern SFB, yet many nearshore habitats are feeding grounds for fishes of concern and could be sinks for zooplankton because of higher relative consumption by clams. One study of zooplankton composition in the shoals found that in all subembayments, the same zooplankton taxa usually existed between the channel and the shoals (Ambler et al. 1985). There were some zooplankton taxa (e.g. *Acartia*) who were found more often in the channel that in the shoals because of their preference for deeper water, particularly during the ebb tide (a retention mechanism, Kimmerer et al. 1998) or during high light periods (reduces predation, Fancett and Kimmerer 1985).

Temporal considerations: Zooplankton abundance varies seasonally and can increase by over two orders of magnitude from winter to summer months in freshwater, sometimes at rates of 10% d^{-1} (Senn et al., 2014b). This is likely due to changes in temperature, food abundance and residence time. In the South Bay, zooplankton biomass was found to be highest during winter-spring, possibly due to warmer temperatures during these months than in northern SFB (Ambler et al. 1985). The dominant zooplankton species has also been shown to vary seasonally. *A. clausi and Tintinnopsis* spp. were dominant during wet months, and *A. californiensis* were dominant during dry, warm months (Ambler et al. 1985). Introduction of exotic zooplankton species can be an important driver of long-term variability in zooplankton abundance and composition.

5.3.6 Microphytobenthos

Ecological significance: Microphytobenthos (MPB; i.e., benthic algae) primary production has received little attention in SFB relative to phytoplankton production. However, given the broad shallow shoals in several of SFB's subembayments, primary production by benthic microalgae could be important. Jassby et al. (1993) suggested that MPB production could account for as much as 30% of overall primary production in SFB and therefore could have a substantial influence on food web structure (by favoring organisms and pathways that utilize benthic microalgae), dissolved oxygen budgets, and nutrient cycling. Benthic diatoms (mainly pennate, but some centric) have been the major MPB taxa identified in the limited studies carried out to date in SFB .

While MPB production is potentially important in terms of its overall contribution to primary production, and some estimates of its magnitude have been made, little is known about how much it influences the food web, the net effect it has on dissolved oxygen budgets, or how it might respond to system perturbations (e.g, decreases in SPM).

Table 5.6 Microphytobenthos parameters

Parameter	***Why it is monitored***	***Approach***	***Example of a commonly used method***	***Monitored by***
MPB abundance and productivity	Rates of primary production can be high leading to thick mats on sediments exposed to high light	Laboratory analysis of samples	Chl *a* analysis for abundance and ^{14}C incubation for carbon fixation	Not currently monitored in SFB
MPB composition	To determine relative contributions of diatoms and cyanobacteria	Laboratory analysis of samples	Microscopy	Not currently monitored in SFB

Spatial distribution: Unvegetated intertidal habitats account for ~10% of SFB's area, and are currently believed to be dominated by microphytobenthos. As water depth increases, or turbidity increases, microphytobenthos give way to phytoplankton as the dominant producer because phytoplankton are able to position themselves in the photic portion of the water column. Phytoplankton is considered the dominant producer overall in the system (Jassby and Cloern 2000), but microphytobenthos could be still contribute substantially to biomass (Jassby et al. 1993), particularly in certain subembayments with a higher proportion of intertidal regions. MPB productivity could be nearly four times as large in South Bay as in Suisun Bay, possibly due to spatial differences in MPB assemblage or bathymetry-induced differences in light exposure to intertidal areas (Guarini et al. 2002).

Temporal Frequency: MPB residing on intertidal mudflats experience unattenuated incident light levels during low tide and productivity would be greatest during these times. A recent study has documented the seasonal variability in MPB production in SFB. Direct measurements of sediment chl-*a* (mg chl-a m^{-2}) were made in September 2011 and March 2012 at sites in the Delta and open Bay (Cornwell and Glibert, in progress). Benthic chl-a abundance was roughly 30% larger in September than in March at both locations, and about 4 times larger in the Delta than in the open Bay at both time points, with the latter difference likely due in part differences in depth and light availability.

6 Initial Recommendations

Over the subsequent 1-2 years, the overall goal for nutrient monitoring program planning is to develop and broadly vet - through expert teams, technical review, and stakeholder and regulator input - a monitoring program structure that meets the data requirements of the Nutrient Strategy's Assessment Framework and Modeling activities, as illustrated in Figure 2.1. That proposed program structure would undoubtedly include a number of the stations and parameters that are currently part of the USGS or DWR-IEP programs. The ~40-year data record provided by these programs (Table 4.1) has allowed researchers and managers to develop important insights into the mechanisms that regulate SFB's responses to nutrients and other stressors, and how those responses have changed over time. Continuing these programs will be essential for assessing current condition, trends in ecosystem response, and in assessing the effectiveness of any management actions. However, there remain several data gaps, and filling these gaps will be important for a future nutrient-driven monitoring effort (see Tables A.1-A.5). Some of these data gaps may only need to be addressed by one-time or periodic special studies, while others will result in new stations, new parameters, and new methods for data collection augmenting existing USGS and DWR-IEP programs to address specific nutrient-related data needs.

This section summarizes initial recommendations and proposes next steps for monitoring program development, informed by input to date from stakeholders and experts. We begin with a set of monitoring program recommendations from technical experts (Senn et al, 2014a). These recommendations are intended to be provisional and will not necessarily be enacted immediately. Rather, they serve as a starting place for further prioritization based on needs and guidance from the Assessment Framework and Modeling projects. We then identify investigations or special studies needed to address outstanding questions related to program structure, e.g. exact location/timing/methodologies for monitoring (see Sections 6.7, 6.8 and 7). Aside from the technical aspects of monitoring program structure, there are also remain questions around programmatic/institutional considerations, in particular the potential degree of inter-institution collaboration. Those points are discussed in Section 6.11.

6.1 Develop a monitoring program science plan

A monitoring program science plan is needed that lays out a framework for systematically evaluating the numerous data needs emerging from various aspects of the Nutrient Strategy, prioritizing among those needs, identifying the specific analytical approach for measurements, and proposing tiers of program components. Some of the prioritization may happen through other components of the Nutrient Strategy (e.g., sensitivity analysis through modeling). Other prioritization, e.g., the longitudinal spacing of monitoring stations or the balance between moored and shipboard stations, may involve data analysis carried out within monitoring program development.

This current document - including the initial recommendations for additional measurements, data analysis, and special studies below - is a first step in the process of specifying the program's essential components. Initial recommendations about essential program components discussed below are based on a combination of technical expert and stakeholder input gathered from a number of meetings over the prior few years. Fortunately, considerable data resources exist from long-term monitoring in SFB. A major component of the monitoring program design effort should include analyzing this data to inform decisions about program structure (e.g., about spatial and temporal density of sampling). Pilot studies should also be part of planning, to inform which parameters could provide important additional information and to test methods that provide less expensive approaches for essential data collection.

The recommendations presented below are based on the perceived science needs of the nutrient monitoring program. While they are individually all reasonable, non-frivolous recommendations, the combined set of recommendations may exceed available budget. In addition, all the recommendations can not be implemented simultaneously. In the science plan, the rationale for prioritizing among elements and for the phasing-in of new components can be discussed.

6.2 Maintain and augment shipboard monitoring at existing stations along SFB's deep channel

Major portions of the current shipboard water column sampling programs of USGS and DWR-IEP will be important to maintain as part of the nutrient monitoring program. Since much of the cost associated with shipboard sampling is related to boat use/maintenance, adding new parameters to already existing stations could be a relatively low-cost way to gain additional data. This subsection outlines several recommended sets of important additional data that could be collected at existing stations.

6.2.1 Additional basic water quality parameters

These parameters are relatively straightforward to measure, but nonetheless have costs associated with sample collection/processing, sample analysis, and data management.

TN and TP, and potentially TDN and TDP: Total N (TN) and total P (TP) are necessary parameters for nutrient mass balances and for modeling. Total dissolved N and total dissolved P could be considered somewhat lower priority than TN and TP, but nonetheless provide valuable information. By subtracting the relevant inorganic nutrient forms from TN and TP, estimates for total organic N and P (TON, TOP) can be obtained. Similarly, by subtracting the inorganic forms from total dissolved N and P (TDN and TDP), concentrations of dissolved organic N and P (DON, DOP) be can be obtained. In both cases, the additional effort for sample collection is trivial, and the analysis method is fairly routine.

Inorganic nutrients: Inorganic nutrient samples (primarily NO_3^-, NH_4^+, and o-PO_4) need to be collected at all major stations and analyzed with comparable methods. Inorganic nutrients have been collected consistently at DWR-IEP stations, but the USGS data has some gaps in space or time for these parameters as a result of changing research focus and limited funding. Comparing methods, detection limits, and QA/QC between USGS and DWR-IEP would be worthwhile.

Phytoplankton C, N, chl-a, size-fractionated chl-a: These parameters, and their ratios, provide important information about the physiological state of phytoplankton, the types of organisms that are making up the bulk of their biomass, and their nutrient requirements. C:chl-a can be highly variable among species and among physiological states within a species. Since chl-a is the most commonly used parameter for measuring phytoplankton biomass, knowledge of this ratio is essential for accurately translating measured chl-a into actual biomass; uncertainty associated with C:chl-a can be among the most important/sensitive uncertainties in modeling phytoplankton response. C:N is subject to similar inter-species and physiological state variability, but it varies over a narrower range than C:chl-a. Size-fractionated chl-a provides information on both the types of phytoplankton that are growing and serves as an indicator of the community's value as a food resource (phytoplankton < 5µm are generally considered lower food quality).

While the basic measurements of C, N, chl-a, and size-fractionated are chl-a are straightforward, they require additional filtering effort in the field. In addition, they are subject to some bias because some portion of the particulate organic matter will be detrital or vascular plant-derived as opposed to viable phytoplankton cells. In some cases stable C isotope rates can be used to verify whether the majority of the organic matter is derived from phytoplankton (i.e., produced within the Bay).

While this data will be valuable, it may not be needed at the same spatial or temporal frequency as other parameters.

6.2.2 Primary Production rates (e.g., ^{14}C uptake incubations)

Rates of primary productivity (PP, g C m^{-2} d^{-1}) provide important information on phytoplankton growth. When coupled with chl *a*, the relationship between phytoplankton biomass and productivity can be used to inform ecosystem models. While a number of PP rate measurements have been done in SFB, the bulk of those were completed prior to the 1990s (except a modest number completed in the past 10 years; Kimmerer et al. 2012, Parker et al. 2012). It is possible to estimate PP in SFB based on the amount of phytoplankton present (e.g., as measured by chl-a), incident light, and light attenuation as a function of depth, using a conversion factor referred to as ψ obtained experimentally via ^{14}C incubations (Cole and Cloern 1984). ψ varies depending on T and community composition; therefore, ^{14}C incubations need to be repeated to capture a range of conditions in space and time to calibrate the SFB-specific ψ, but only at low frequency because the incubations require substantial effort (e.g., quarterly or twice per year, at only several stations across a range of conditions). To inform how frequently updates/calibration-checks are needed, historic data could be analyzed to determine how sensitive ψ is to differences in T and phytoplankton community composition.

6.2.3 Phytoplankton community composition and algal toxins

Given the prevalence of HAB-forming organisms in SFB, increased frequency in *Microcystis* blooms in the northern estuary, SFB-wide detections of algal toxins, and other hypothesized shifts in phytoplankton community composition, phytoplankton community composition and related parameters need to be more systematically monitored. Currently, the USGS program only performs taxonomical analysis of phytoplankton at its main stations when phytoplankton biomass is elevated (i.e., chl-a > 5 µg L^{-1}) because of budgetary constraints. DWR-IEP sampling sites have a long phytoplankton composition record, collected independent of biomass on a monthly basis. However, the DWR-IEP counting methodology differs appreciably from that employed by USGS, and limits the comparability across the two data sets. Algal toxin samples are currently not part of routine monitoring, although samples have been collected more recently as part of pilot studies by USGS, in collaboration with UC Santa Cruz and the RMP. To date, most algal toxin measurements have been either space-integrated samples at the sub-embayment scale, or time-integrated samples at fixed stations over a the period of ~1month, using a solid phase extraction (SPE) approach that extracts a portion of toxin from the surrounding fluid. While these pilot studies have provided important results, the sampling technique limits the interpretability of the results in terms of the size or duration of a toxin plume and plume concentration, because of both the integrated nature of the technique and uncertainty in the correspondence between measured (i.e., extracted) and ambient concentrations.

The factors that regulate phytoplankton community composition and toxin production in SFB are poorly understood. Higher spatial and temporal monitoring of phytoplankton composition and toxin levels, in combination with special studies, will be needed to better understand these mechanisms and assess potential linkages to nutrients. However, determining community composition by microscopy is expensive ($175-500/sample). Pilot studies are needed to help inform which techniques, beyond microscopy, provide the most valuable and cost-effective information (see Section 6.8). The bullets below identify important data needs, but do not recommend specific techniques.

- Collect samples at multiple stations Bay-wide on at least a monthly basis, independent of phytoplankton biomass (i.e., chl-a) concentration. The major USGS historic stations, plus continuation of the DWR-IEP stations in San Pablo and Suisun Bays, can serve as a reasonable initial set of stations. Other stations, or more frequent sample collection during some times of the year, may be needed, and the exact sampling program will need to be determined by on-going data analysis. Both cell numbers and dimensions (for determining biovolume) are needed.
- Determine taxonomy in surface and bottom samples at some locations or times. Gradients in light and density can result in vertical gradients in phytoplankton. In addition, dense coastal waters can enter SFB as bottom layers and carry coastal organisms (including some potentially harmful species) into SFB where, when mixed to the surface, could take advantage of warmer waters and high nutrient concentrations.
- If data collected from both USGS and DWR-IEP are going to be used as part of the nutrient monitoring program, the approach to counting and dimensioning cells needs to be harmonized among the programs.
- Incorporate algal toxin measurements into the routine monitoring program. Current toxin monitoring is funded on a pilot basis, and needs to be sustained.

6.2.4 Zooplankton abundance/composition

Zooplankton abundance and composition serve as important indicators of food supply and quality for higher trophic levels and are also used to calculate basin-wide pelagic grazing rates. Long-term zooplankton monitoring has been carried out by DWR-IEP at several stations in Suisun Bay, one station in San Pablo Bay, and multiple stations in the Delta. However, zooplankton abundance and composition are not currently measured as part of routine monitoring in other subembayments. Monitoring for both macro- and microzooplankton may be important, because microzooplankton grazing rates may exceed those of macrozooplankton.

The actual experimental quantification of grazing rates is an additional activity, and if needed would be considered a special study, not part of routine monitoring. However, the systematic monitoring of zooplankton (species, size, and abundance) would be essential information for extrapolating lab-derived grazing rates to field-scale grazing estimates.

6.3 Expand shipboard monitoring to shoal sites

Sampling along the shoals is needed to improve 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 are common in SFB (e.g., Thompson et al., 2008, Huzzey et al. 1990). In addition, suspended particulate matter, which influences light availability and growth rates, exhibits strong lateral variability. Shoal monitoring can be accomplished both through shipboard or small boat transects, although a vessel with a shallow draft is needed. Moored sensors can also be useful for some parameters. Using autonomous underwater vehicles (AUVs) outfitted with sensors may also be a possibility. AUVs are commonly employed in research studies, and some are commercially available. The pros and cons of the different approaches need to be considered in detail, potentially including pilot studies.

To the extent that monitoring along the shoals is carried out using a fully-equipped research vessel (i.e., if a new vessel was obtained with shallow draft), the data gathered using its flow-through system during transects would be of additional value.

6.4 Utilize moored stations for continuous data collection

Data collection at higher temporal resolution for chl-a, DO, nutrients, turbidity, and other parameters is needed at multiple locations to identify the onset of events (e.g., large blooms) and to calibrate water quality models so that processes can be better understood and effects under future scenarios can be forecasted. 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 composition using flow-through digital imaging and flow cytometry). Moored sensor systems can also telemeter data, allowing for near real-time assessment of conditions.

Although moored sensors may address some questions better than shipboard sampling, they are not a substitute, but rather a strong complement that provides important additional information about processes operating on shorter time-scales. While there are currently multiple stations in Suisun Bay and the Delta that measure some of these parameters (e.g., DO, salinity, T, chl-a), there are only 2-3 pilot stations south of the Bay Bridge for measuring chl-a or nutrients, funded by the RMP and recently installed as part of the nutrient monitoring effort. Specific data needs include:

- High temporal resolution DO, chl-a, turbidity, and ancillary data (e.g., T, conductivity) at key sites and multiple depths (minimum of surface and bottom) along main channel
- High temporal resolution DO, chl-a, turbidity, and ancillary data at key sites along the

shoals

- Additional sensors at a subset of sites may be warranted, including nitrate, phosphate, ammonium (when reliable sensors become available), phytoplankton community composition, and, if possible, algal toxins

6.5 Benthos Monitoring

Zoobenthos: 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 benthic grazing, and track its changes in space and time, benthic surveys are needed on a regular basis in some subembayments, i.e., Lower South Bay, South Bay, San Pablo Bay, and Suisun Bay. In recent years there has been ample zoobenthos monitoring in Suisun Bay and the Delta, and some in San Pablo Bay, although the future of that program is not known. Sampling in other subembayments has been less consistent or absent entirely. However, there are some years during which intensive benthic sampling has taken place (e.g., Thompson et al. 2008), and some opportunistic semi-continuous sampling efforts in South Bay (in some cases, samples have been archived but not yet analyzed for biomass; J Thompson, personal communication).

Benthos monitoring could occur less frequently than water quality monitoring, e.g., three times per year (spring, summer, fall). Sorting, counting, and weighing benthos samples is time consuming and thus costly. In designing a benthos sampling program, the use of benthic cameras could be considered (alongside some traditional sample collection for calibration/validation), and be the focus of a pilot study, since its use could potentially allow for more cost-effective benthic surveys.

Microphytobenthos: Microphytobenthos (MPB) may account for a substantial fraction of primary production in some habitats of SFB, in particular along the broad intertidal mudflats of some subembayments. As such, MPB production could influence the nutrient, carbon, and oxygen cycles or budgets in those habitats. The abundance of MPB is poorly known, and some level of systemic sampling, either as part of routine monitoring or special studies, may be needed.

6.6 Provisional recommendations for station locations

Expert input was solicited on the geographic structure of the future monitoring program at a February 2014 technical team meeting related to assessment and monitoring. The group was asked: ‘If you had to select stations on a map today, what is your best estimate of how the network would look?’ The team generated a first-draft hypothesized structure, taking into consideration the existing USGS shipboard stations and the DWR-IEP shipboard and moored stations, based on what is known about SFB’s hydrodynamics and ecosystem response, and on current (albeit incomplete) knowledge about data requirements for assessment and modeling (Fig 5.1).

Figure 6.1 illustrates the proposed program structure. The structure was intended as a hypothesis, and one that would be tested and adjusted through data analysis and pilot studies such as those identified in Sections 6.7, 6.8, and 6.10. Currently, USGS monthly cruises travel along the spine of SFB and occupy all of the yellow stations. At the minor stations, an instrument package (CTD, DO, chl-a, turbidity, PAR, etc.) is lowered through the water column and a profile of data is collected, but no discrete samples are collected. At the major stations, the instrument package is lowered and discrete samples are collected for multiple analytes. The hypothesized new structure would include all the USGS major stations, and augment those with up to 7 new stations, 5 of which are along the shoals and 2 of which would provide a clearer picture of water quality at stations more influenced by the coastal ocean. Some of the USGS minor stations might not be essential components of the nutrient monitoring program, in particular if the cruise track (dashed line) follows a zig-zag pattern in order to perform underway measurements along the shoals. Up to 10 moored stations were also included, with most of those in regions that currently have few or no nutrient-related sensors. Co-locating new major shipboard monitoring sites with these moored sensor sites would maximize the value of sensor servicing trips. In setting this station distribution, it was assumed that DWR-IEP shipboard and moored stations would continue, and that the data collected at those sites could be used as part of the nutrient monitoring program. As discussed above, for that to be the case, methods would need to be harmonized across the programs.

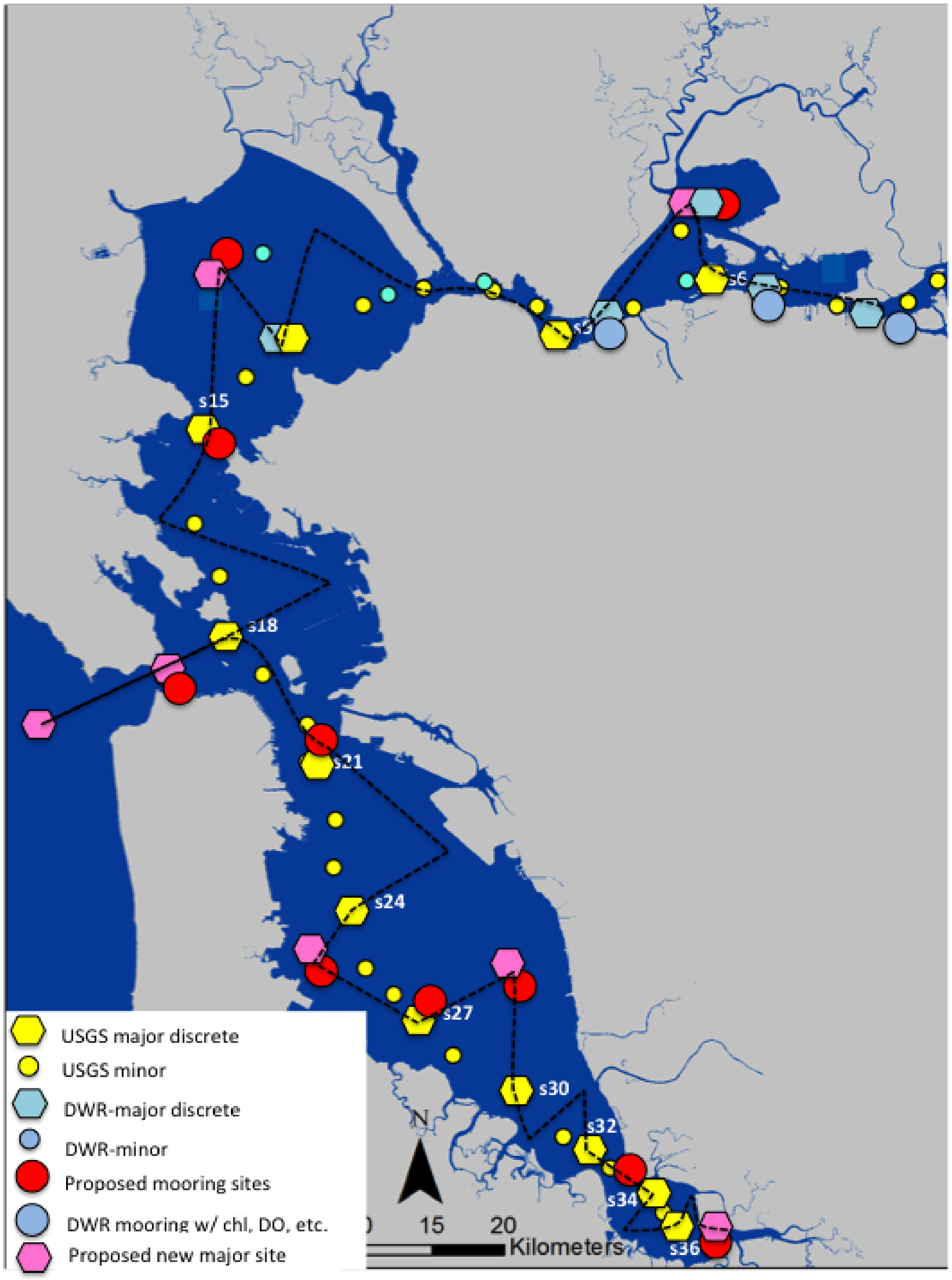

Fig 6.1: Current and hypothesized future monitoring stations for shipboard water column sampling and moored sensor sites. Dashed line illustrates an example cruise track that would allow data to be collected using flow-through system out to the shoals.

6.7 Recommended Data Analysis to inform Program Structure

This section identifies recommended data analysis activities that could be pursued in the near term to inform nutrient monitoring program structure.

6.7.1 Identifying spatial/temporal resolution of priority "events"

One major requirement of the nutrient monitoring program is that it assess condition based on parameters determined to be key indicators of ecosystem health (e.g., chl-a, DO, phytoplankton community composition, algal toxins) and determine when conditions are meeting standards and when they are below standards. The program's spatial and temporal sampling frequency must be sufficient to detect an "event" during which standards are not met. Exactly what constitutes an event will be informed by both science and policy, and will be developed through the Nutrient Strategy's Assessment Framework. The questions below are intended to help frame the discussion from the science side, inform the data requirements, and illustrate the close relationship between the monitoring program and assessment framework. While the assessment-related issues will have a strong influence over the monitoring program, it should be noted that they are not the only requirements.

6.7.1.1 What level of production/chl-a would lead to DO-related adverse impacts?

Measurements to date indicate that SFB does not experience low DO in subtidal, open water areas. Thus, unlike in some other estuaries, it is not possible to draw inferences from periods of low DO and antecedent phytoplankton biomass. Instead, it is recommended that basic estimates be made about the magnitude of a potential bloom (concentration of chl-a, area and depth of the bloom), that, when it settles into a bottom layer of the water column, could result in DO consumption down to levels that could have adverse impacts. Initial calculations could be quite basic (e.g., 1-2 box mass balance) to determine under what conditions a problem is feasible. If warranted, additional layers of complexity could be added to these calculations (up to a coupled hydrodynamic/water quality model).

In the end, these calculations would reveal the concentration and spatial extent of a bloom that could cause low DO to develop, which would inform the spatial and temporal resolution of monitoring that would be needed to detect such a bloom.

6.7.1.2 What duration/severity/frequency of low dissolved oxygen would adversely impact biota?

The answer to this question would provide information about the spatial and temporal frequency of DO sampling needed to identify a problematic low DO event. In addition, the answer would also inform calculations in 6.7.1.1. Experiments are not needed to begin address this question. There is sufficient information available in the scientific literature about effect-levels of low DO; instead, the DO standards can be specified based on the DO requirements of the organism(s) one is aiming to protect.

6.7.1.3 What levels of toxin concentration are problematic? How do these translate into spatial, concentration, and duration scales?

This question is similar to 6.7.1.2 in that it requires identifying the toxicity thresholds for organisms of concern, and working backward (including factors such as bio-concentration in the food web) to ambient concentrations and necessary spatial extent in the water column that would result in exceedence of those thresholds.

6.7.2 Optimizing spatial/temporal resolution of sampling

6.7.2.1 What sampling spatial resolution is needed along the longitudinal axis of the Bay (or what density is redundant)?

To explore this question, USGS data collected over the past 10-20 years at stations along SFB's deep channel, and flow-through underway data between these stations, can be analyzed to identify the degree of similarity/dissimilarity among stations, and identify the optimal placement of stations. The analysis can be performed for individual parameters and for multiple parameters simultaneously. A similar analysis was done by Jassby et al. (1997), but that work did not include nutrient parameters, and did not capture changes in biomass and other parameters that became evident beginning in the late 1990s. DWR-IEP data may also be relevant for this type of calculation for San Pablo Bay, Suisun Bay, and Delta.

Once the calibration/validation of the SFB biogeochemical model is complete, we could perform simulations to inform the suitability of the placement of stations, particularly for potential future conditions or parameters not historically monitored.

6.7.2.2 What sampling spatial resolution is needed laterally, as a function of subembayment and season?

Less lateral data exists than longitudinal data in SFB. However, there are several datasets that can be used to explore this question, notably 1 year of monthly continuous lateral transects collected in 1980 by USGS for the full Bay. Additional lateral data collected by the USGS is available for periods in the 1990s. Underway data is also available from multiple spring, summer, and fall sampling campaigns in San Pablo Bay and Suisun Bay by SFSU-RTC researchers aboard *R/V Questuary*. As noted above, model output could also be used to explore these questions, once that output data becomes available.

6.7.2.3 In South Bay, what is the minimum temporal sampling during important periods (e.g., spring blooms)?

During spring months, USGS typically samples on a weekly basis in South Bay to capture bloom events. This data could be analyzed to determine if similar observations would have been made if sampling had occurred at lower frequency (e.g., monthly, or every two weeks). The year 1982 could be a particularly interesting period because of weekly sampling in the deep channel plus sampling in shallow areas.

6.7.2.4 What are characteristic scales (space/time) of phytoplankton blooms in Suisun Bay?

To explore this issue, underway data from SFSU-RTC spring and fall sampling campaigns aboard the *R/V Questuary* could be used. Data from DWR-IEP moored sensors (outfitted with chl-a fluorometers) in Suisun Bay could also be used.

6.7.2.5 What spatial and temporal scales are integrated by measurements made at current monitoring stations? What spatial distribution of stations would maximize our ability to capture events (e.g., a bloom of certain magnitude, or a plume of algal toxin) or efficiently capture as much variance in condition as possible?

Monitoring at current stations in SFB does not measure conditions in a static water volume at those locations. Instead, the water volumes at those stations are actually changing mixtures of water that originated from multiple locations. In that sense, measurements made at monitoring stations throughout SFB are actually integrated biogeochemical signals from a range of locations. To explore this range, existing hydrodynamic model output data could be used to "backtrack", and identify which water masses contributed to the observed concentrations on a particular date when measurements were taken. In addition, by running such a model forward again, it would be possible to determine where sampling stations would need to be placed to capture events of specified magnitudes.

6.7.2.6 Where should moored sensors be placed? What is the optimal blend of ship-based sampling and moored sensors?

Moored sensors provide high-frequency data at a single point in space, and this location should appropriate for identifying problematic events in SFB (section 6.7.1) and, in combination with shipboard sampling, should capture the greatest ecosystem variability. While some aspects may be answered through analysis of existing data, the use of model output combined with monitoring data may be most informative.

6.7.2.7 What parameters are most important to measure in terms of their quantitative influence on predictions or model interpretations?

Sensitivity analysis of water quality parameters need to be performed using water quality models. The results of these analyses will help prioritize which parameters are more important to monitor for model development.

6.7.2.8 How frequently (and under what conditions) does the relationship used to estimate productivity in SFB (based on chl-a concentration and PAR, i.e., Cole and Cloern 1987) need to be validated/calibrated?

This relationship, while often assumed to be a constant, may actually be sensitive to changes in phytoplankton community composition, temperature, light intensity, and potentially other factors. There is ample data from a number of studies within different subembayments and the Delta that could be used to explore these sensitivities and inform calibration procedures.

6.8 Pilot studies

Pilot studies should be carried out throughout the program development period to identify the best techniques

6.8.1.1 What combination of techniques represents the best approach to measuring phytoplankton community composition for the needs of SFB?

Currently, a pigment-based approach is being piloted (CHEMTAX), with results being compared to samples analyzed by microscopy for method validation. In addition, a grant proposal was recently submitted to obtain 2 Imaging Flow Cytobots. If the proposal is successful, one of these instruments would be deployed aboard the USGS research vessel and used while underway to measure phytoplankton composition at high frequency. The second instrument would be deployed at a moored station, for example, at Dumbarton Bridge (Lower South Bay).

6.8.1.2 What approaches and spatial/temporal resolution are needed for measuring algal toxins?

Pilot studies are currently underway that employ solid-phase extraction to obtain subembayment-scale integrated measures of toxin. This technique is attractive in that it provides an integrated impression of toxin abundance. However, the correspondence of these measurements to ambient concentrations remains highly uncertain. In addition, the subembayment-scale measurements do not provide sufficient spatial resolution to identify localized toxin plumes. This limitation could be addressed through doing finer-scale integrated samples.

As part of another pilot project, USGS collected filter samples for toxin measurements, co-located with phytoplankton composition sample collection (both pigments and microscopy). There are currently ~2 years of monthly samples collected at ~10 or more stations per cruise, amounting to 200-250 samples. Analyzing these samples will provide high-spatial resolution toxin concentration along with the dominant phytoplankton communities, and will provide valuable information about both the spatial resolution of toxin plumes and factors that may explain their varying levels. In addition, it will provide a valuable complement to the spatially-integrated samples, and allow for consideration of what spatial aggregation is appropriate for this indicator.

6.8.1.3 Deploy pilot moored stations

The goal of this set of pilot studies is to inform where to best place sensors, and to begin developing the maintenance program and local-knowledge for sensor maintenance and data interpretation. Work on this topic is underway, with 3 stations deployed in South Bay and Lower South Bay, and needs to continue for another 2-3 years.

6.9 Coordinated monitoring needed in shallow margin habitats, including sloughs, creeks, and wetlands.

Some agencies (e.g., stormwater, wastewater) carry out monitoring in shallow habitats, and several studies have been conducted in Lower South Bay systems (Thebault et al. 2008, Shellenbarger 2008, Topping 2009). However, there is currently no Bay-wide systematic approach to monitoring in shallow marsh habitats. Data collection on productivity and DO concentrations in select systems may help inform whether impairment is occurring in these systems due to low DO, and to help ascertain the causes of any impairment. Before embarking on this effort, it may be helpful 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.

6.10 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).

6.11 Broad considerations about ecosystem change

During discussions of monitoring needs with technical advisors, four so-called "Grand Challenges" related to understanding and managing SFB ecosystem health were identified. These Grand Challenges represent a somewhat different perspective or framework for considering science and data collection needs than the considerations already outlined in this report. 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.

6.11.1 Grand Challenge #1:

What do we need to know in 10-20 years to make improved decisions water quality management or ecosystem health issues, including those related to nutrients?

1-2 decades is approximately the time scale over which large capital improvement projects are planned and implemented. 1-2 decades 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 show improved or worsened condition?

6.11.2 Grand Challenge #2

The northern estuary is poised to experience major changes due to management actions and environmental change. Anticipated changes include:

- Nitrification of effluent combined with N removal at Sacramento Regional County Sanitation District wastewater treatment plant, which will change both the form of N and total N concentrations discharged
- Numerous large scale restoration projects in the Delta
- Changes in water withdrawals and flow routing
- 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?

6.11.3 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 (Figure 5.1), it is reasonable to expect that effects will extend to the open water. 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 indicators of ecosystem health. Those changes may also encourage much higher rates of denitrification, which should be considered as part of an integrated nutrient management plan.

As discussed earlier, there may also be unintended and undesirable consequences of this restoration, including salt ponds acting incubators for HAB-forming phytoplankton species, exceedingly high primary production and low DO environments in light-rich, long-residence time habitats, and increased duration of stratification due to dampening of tidal mixing energy. What hypotheses of adverse impacts need to be tested so that the risks of severe unintended consequences are minimized?

6.11.4 Grand Challenge #4

While the exact ways that climate change will manifest itself in SFB habitats are unknown, the scientific consensus is that some of those changes have already started arriving, and that combinations of others are on the way. Changes to multiple climate-related drivers are feasible, and the combined effects are uncertain. Similar to Grand Challenges 1-3, what baseline observational data is needed in order to see these changes and disentangle them from other anthropogenic drivers? What types of modeling simulations should be done to anticipate effects?

The CASCaDE II project is exploring these issues, largely focused in the Delta.[5] Similar approaches may be worth considering for the Bay.

6.12 Program management considerations

Implementing a regional nutrient monitoring program will be a major undertaking in terms of logistics and cost. Long-term institutional support will be needed. As discussed above, there are several entities currently involved in ship-based and continuous (moored sensors) monitoring (e.g., USGS, DWR-IEP). To avoid unnecessary duplication of effort and maximize what can be accomplished with available resources, when developing the future nutrient monitoring program there will likely be considerable advantage to fostering close coordination among on-going programs toward achieving some of the monitoring program goals, and augmenting those efforts with additional monitoring as needed. In addition to broad institutional cooperation, there needs to be coordination at the level of sampling and analytical methodologies, data QA/QC, data sharing, synthesis, and reporting.

Along these lines, in the relatively near term (next 1-3 years), the USGS plans to replace its research vessel. The purchase of a new vessel represents an interesting opportunity for collaboration and joint funding between regional entities and the USGS. Based on initial estimates, it may also prove a wise investment on the part of the region, and a highly cost-effective way of ensuring ship access and sustaining the underlying program upon which the nutrient monitoring program will likely be built.

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

7 Next steps

This report is intended to serve as an initial step in monitoring program development. Important next steps include:

1. Begin development of a monitoring program science plan

2. Through this plan prioritize among proposed data analysis, pilot studies, no-regrets recommended new parameters, and new parameters that require further consideration.

3. Begin recommended data analysis, pilot studies, and new parameters

4. Estimate costs of parameters or new components of program

5. Based on above, develop a set of recommendations for phasing in new measurements or components of program

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Appendix

Table A.1 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 confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years	Routine Monitoring or Special Study
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**	**Routine monitoring**
Stormwater runoff	**Uncertain**	**Low**: Limited stormwater data and limited modeling effort	**High**	**High**	**Special study**
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**	**Special study**
Groundwater	**Low**	**Low:** Poorly quantified but not expected to be major source because of relatively high loads from other sources	**Low**	**Low**	**Special study**
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**	**Special study**
Exchange through GG	**Uncertain**	**Low:** Has the potential to be large, but highly uncertain	**High**	**High**	**Special study**
Processes					
Benthic denitrification	**High**	**Low**: see OM mineralization and NH4 and PO4 release below	**Very High**	**Very High**	**Special study**
Pelagic denitrication	**Low**	**Low**: not expected to be important because of oxic water column	**Low**	**Low**	**Special study**
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**	**Special study**
Pelagic nitrification	**High**	**Low**: Potentially large, but limited field measurements, and need for both field and model-based estimates.	**Very High**	**Very High**	**Special study**
N fixation	**Low/Uncertain**	**Low**	**Moderate**	**Low**	**Special study**

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**	**Routine Monitoring or Special Study**
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**	**Special study**
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**	**Special study**
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**	**Special study**
Other processes: DNRA, ANAMOX	**Low**	**Low**: but expected to be relatively small	**Low**	**Low**	**Special study**
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**	**Special study**
Ambient concentration data					
Phytoplankton C:N:P	**High**	**Low**: Currently not routinely measured during monitoring	**Very High**	**Very High**	**Special study**
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**	**Routine monitoring**
Concentrations of NO_2^- and N_2O	**Low/Moderate**	**Moderate**: not needed for nutrient budgets, but informative as diagnostic of processes	**Moderate**	**Moderate**	**Routine monitoring**
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**	**Routine monitoring**

Table A.2 Phytoplankton productivity and 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 <u>additional or continued</u> data collection, process studies, modeling	Priority for study in next 1-5 years	Routine Monitoring or Special Study
Processes					
Primary production rates	**High**	**Low/Moderate**: Basic understanding about light limited 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**	**Routine Monitoring**
Pelagic grazing	**High**	**Low**: Long-term program in Suisun Bay and 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**	**Special study**
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**	**Routine monitoring**
Sinking, respiration, burial	**High**	**Moderate**: Discussed within context of Dissolved Oxygen	**Low**	**Low**	**Special study**
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**	**Special study**
Production in the shoals vs. channels), 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**	**Special study**
Germination of resting stages	**Low**	**Low:** Not considered among the highest priority processes to study	**Low**	**Low**	**Special study**
Phytoplankton – Ambient concentration data					
High temporal resolution 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**	**Routine monitoring**
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**	**Routine monitoring**
Biomass data along the Bay's deep channel	**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**	**Routine monitoring**

Process or Parameters	**Importance for quantitative understanding**	**Current level of confidence about magnitude or mechanistic controls**	**Need for <u>additional or continued</u> data collection, process studies, modeling**	**Priority for study in next 1-5 years**	**Routine Monitoring or Special Study**
Phytoplankton C:N, C:chl-a, and size-fractionated chl-a	**High**	**Low:** Valuable information to inform understanding of processes and for modeling	**Very High**	**Very High**	**Routine monitoring**

Table A.3 Microphytobenthos productivity and biomass: 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	Routine Monitoring or Special Study
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**	**Special study**
Grazing	**Moderate/ Unknown**	**Low:** Potentially important as a sink, but difficult to study.	**Low**	**Low**	**Special study**
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.	**Very High**	**Very High**	**Special study**

Table A.4 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 <u>additional or continued</u> data collection, process studies, modeling**	**Priority for study in next 1-5 years**	**Routine Monitoring or Special Study**
Processes or loads					
Atmospheric exchange	**High**	**Moderate**: Difficult to measure but readily modeled (albeit with substantial uncertainty)	**Low**	**Low**	**Special study**
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**	**Special study**
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**	**Special study**
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**	**Routine monitoring**
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**	**Special study**
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**	**Routine monitoring**

Process or Parameters	**Importance for quantitative understanding**	**Current level of confidence about magnitude or mechanistic controls**	**Need for <u>additional or continued</u> data collection, process studies, modeling**	**Priority for study in next 1-5 years**	**Routine Monitoring or Special Study**
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**	**Routine monitoring**
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**	**Routine monitoring**

Table A.5 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**	**Routine Monitoring or Special Study**
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**	**Special study**
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**	**Special study**
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**	**Special study**
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**	**Special study**
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**	**Special study**
NH4 inhibition: diatom productivity	**High/ Uncertain**	**Low:** Several studies completed, others underway.	**Very high**	**Very high**	**Special study**

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	Routine Monitoring or Special Study
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**	**Routine monitoring**
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**	**Routine monitoring**
Frequency and magnitude of detection of HABs or HAB toxins	**High**	**Low**: Limited data on HABs and toxins, and	**Very high**	**Very high**	**Routine monitoring**
Phytoplankton community composition in salt ponds, particularly HAB-forming species	**High**	**Low:** Limited data to date, but of high concern.	**Very High**	**Very High**	**Routine monitoring**
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**	**Routine monitoring**