Scientific Basis to Assess the Effects of Nutrients on San Francisco Bay Beneficial Uses

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EXECUTIVE SUMMARY

San Francisco Bay (SFB) has long been recognized as a nutrient-enriched estuary; however, until recently, it has exhibited resistance to symptoms of nutrient overenrichment due to a number of factors such as high turbidity, strong tidal mixing, and grazing by bivalves. Recent observations have reinforced the need to identify numeric water quality objectives and management actions to protect SFB from the potential effects of nutrient over-enrichment. The purpose of this work was to develop a quantitative framework, hereto referred to as an *assessment framework,* to assess eutrophication in the SFB, based on indicators of dissolved oxygen (DO), phytoplankton biomass (chlorophyll-a), gross primary productivity, the prevalence of harmful algal blooms (HAB) and toxins.

A group of experts in the ecology of SFB, as well as international experts in assessment frameworks (AF) and nutrient criteria, worked in concert to define core principles for the AF. These principles include the geographic scope, recommended Bay segmentation of subembayments for assessment, and the protocols and recommended spatial and temporal frequency of monitoring that would support use of the framework to assess nutrient effects on SFB. A quantitative scheme was developed to classify SFB subembayments in tiers of ecological condition, from very high to very low, based on risk of potential adverse effects of nutrient overenrichment and eutrophication. Decisions on classification bins were supported by a combination of existing literature and guidance, quantitative analyses of existing SFB data from the USGS research program, and expert best professional judgment. Analyses of two decades of phytoplankton species composition, chlorophyll-a, and dissolved oxygen (DO), and 3 years of toxin data from solid phase adsorption toxin tracking (SPATT) samplers were used to support decisions on the AF and demonstrated: 1) significant increases in chlorophyll-a, declines in DO, and a high prevalence of HAB species and toxins across most SFB subembayments and 2) strong linkage of increasing chlorophyll-a to declining DO and HAB abundance. Statistical approaches were used to define thresholds in chlorophyll-a relating to increased risks of HABs and declining DO. These thresholds were used, in combination with expert best professional judgment, to develop an AF classification scheme. A qualitative summary of uncertainty associated with each indicator was made for the purpose of focusing future research, monitoring, and modeling on AF refinement.

The AF is intended to provide a decision framework for quantifying the extent to which SFB is supporting beneficial uses with respect to nutrients. This AF is comprised of three important elements: 1) a set of conceptual models that defines what a problem would look like in SFB, if it occurred, 2) a set of core principles supporting the AF, and 3) classification tables. The AF supports and is supported through the other major science elements. The conceptual models and AF core principles provide a sound scientific foundation for informing modeling and monitoring. Through early interactions with the stakeholder community, these two components of the AF appear to have the greatest consensus and the least "uncertainty."

The classification scheme is a critical element of the AF, because it represents a quantitative and transparent mechanism through which SFB data can be interpreted to assess, nutrient-related beneficial use support. Given its importance, the authors of this document fully acknowledge the uncertainty in the AF classification scheme and need for refinement, through multiple iterations of basic research, monitoring, and modeling. We suggest that the near-term use of the AF classification system be focused on a scientific "test drive" focused on understanding how to collectively use and improve efficiencies for assessment, monitoring and modeling. The "test drive" of the AF can be conducted in tandem with research, monitoring, and modeling to improve the scientific foundation for the AF, aimed at the following six major recommended actions:

1. Improve the scientific basis for nutrient-related segmentation of SFB.

2. Reduce sources of uncertainty in chlorophyll-a, HAB abundance and toxin classification by: 1) Better assessment and characterization of the ecological and human risk of HABs in SFB, 2) Co-location of chlorophyll-a and monitoring of toxins in Bay surface waters, shellfish and SPATT to improve documentation of linkage of chlorophyll-a to HAB toxin concentrations, 3) Expand SPATT samplers to include other toxins and conduct better validation of SPATT toxin data relative to surface waters or mussel toxin tissues, 4) Assemble a scientific workgroup to evaluate and provide recommendations on the chronic effects of HAB toxins, and 5) Improve monitoring through better spatial and temporal coverage of HAB data to link chlorophyll-a to DO.

3. Optimize spatial and temporal sampling of AF indicators to best align quality of the information produced, while balancing costs, logistics, and power to detect trends.

4. Improve the scientific basis for dissolved oxygen classification and monitoring in future iterations of the AF. Current recommendations focus on indicators of phytoplankton. We recommend: 1) synthesis of DO expectations for SFB species types and the seasonal use of specific habitat types (deep channel, shallow subtidal, tidal sloughs, etc.) within SFB subembayments; 2) improved characterization of the diel variability of DO at key points within the deep water and shallow margin habitat of each subembayment in order to better characterize support of species and habitats; and 3) improved mechanistic understanding of the physical and biological factors influencing DO within and between the deep channel and shallow water margin habitat.

5. Include diked baylands, restored salt ponds and tidal sloughs in future iterations of the AF, which is currently focused on open water habitats.

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1 INTRODUCTION

1.1 Background and Purpose

The San Francisco Bay Regional Water Quality Control Board (Water Board) is developing nutrient water quality objectives for San Francisco Bay. Water Board staff favor an ecological risk assessment approach (EPA 1998), in which ecological response indicators (e.g. change in algal abundance and assemblage, dissolved oxygen) are used as the endpoints to assess whether the San Francisco Bay (SFB) is supporting designated uses. A model would then be used to link those endpoints to nutrients and other factors that comprise management options to (e.g. best management practices). In this risk-based approach, nutrients are considered a resource that should be managed at levels that support SFB beneficial uses. The key is managing nutrients at levels that pose a low risk of adverse effects, while ensuring the system doesn't become nutrient-limited. This approach is consistent with that being used for nutrient objective development for other waterbodies in California, including other estuaries (SWRCB 2014).

The process of selecting appropriate endpoints begins with a synthesis of science and the development of a framework for interpreting the endpoints that is ultimately based on policy decisions by the Water Board, taking into consideration advice from its advisory groups. In this document, we refer to the product of scientific synthesis as a **nutrient assessment framework (AF)**, defined as a structured set of decision rules that specify how to use monitoring data to categorize specific subembayments of SFB from very high to very low ecological condition, using indicators that have a direct linkage to nutrients and support of SFB beneficial uses. Thus, while the decision on regulatory endpoints should be informed by science, it is ultimately a policy decision. The ultimate goal of this effort is that the Water Board would propose numeric endpoints for SFB, based on the synthesis of science represented in the AF and feedback from the SFB stakeholders and scientific peer review.

The purpose of this document is to describe the SFB nutrient AF, the scientific synthesis upon which it is based, and key data gaps and recommendations for its future refinement.

1.2 Document Audience, Authorship, and Organization

This report was written to address the information needs of both scientists and technically-oriented decision makers and stakeholders involved in the SFB Nutrient Management Strategy. With that audience in mind, the report assumes a certain baseline familiarity with SFB as well as a basic understanding of the biology, nutrient cycling, biogeochemistry, and physical processes in estuaries. The scientific synthesis supporting this report was developed collaboratively with a team of co-authors consisting of scientists whose areas of expertise cover a range of relevant disciplines and much of whose work has focused on SFB.

This document is organized as follows:

Section 1	Introduction. Purpose, and Organization
Section 2	Context: Detailed Background, Process for AF Development, and Review of Existing Approaches
Section 3	Proposed AF Core Principles and Classification Tables
Section 4	Summary and Recommendations

Appendices Key definitions, supporting literatures reviews and quantitative analyses

2 CONTEXT FOR FRAMEWORK DEVELOPMENT: DETAILED BACKGROUND, PROCESS FOR DEVELOPMENT, AND REVIEW OF EXISTING APPROACHES

2.1 San Francisco Bay: A Brief History and Context for Nutrient Management

SFB encompasses several subembayments of the San Francisco Estuary, the largest estuary in California. SFB is surrounded by remnant tidal marshes, an array of intertidal and subtidal habitats, tributary rivers, the freshwater "Delta" portion of the estuary, and the large mixed-land-use area known as the San Francisco Bay Area. San Francisco Bay hosts an array of habitat types, many of which have undergone substantial changes in their size or quality due to human activities (Conomos (ed.) 1979). Urban residential and commercial land uses comprise a large portion of Bay Area watersheds, in particular those adjacent to Central Bay, South Bay and Lower South Bay. Open space and agricultural land uses comprise larger proportions of the areas draining to Suisun Bay and San Pablo Bay. The San Joaquin and Sacramento Rivers drain 40% of California, including agricultural-intensive land use areas in the Central Valley. Flows from several urban centers also enter these rivers, most notably Sacramento which is ~100 km upstream of Suisun Bay along the Sacramento River.

SFB receives high nutrient loads from 37 public owned wastewater treatment works (POTWs) servicing the Bay Area's 7.2 million people (Association of Bay Area Governments, www.abag.ca.gov). Several POTWs carry out nutrient removal before effluent discharge; however, the majority are designed to have secondary treatment without additional N or P removal. Nutrients also enter SFB via stormwater runoff from the densely populated watersheds that surround SFB. Flows from the Sacramento and San Joaquin Rivers deliver large nutrient loads, and enter the northern estuary through the Sacramento/San Joaquin Delta.

SFB nutrient loads and ambient nutrient concentrations are among the highest of the U.S. estuaries (2012), However, SFB has long been considered relatively immune to its high nutrient loads. For example, the first San Francisco Bay Regional Basin Plan from 1975 stated that only limited treatment for nutrients was necessary because the system was considered to be light-limited (SFRWQCB, 1975). Research and monitoring over the last 40 years have identified several factors that impart SFB with resilience to high nutrient loads, i.e., control on phytoplankton production (e.g., see Cloern and Jassby 2012; Cloern et al., 2007), including high turbidity, strong tidal mixing, and abundant filter-feeding clam populations.

However, recent studies indicate that the response to nutrients in SFB is changing. These shifts in nutrient responses may be triggered by one or more recently documented changes in SFB, including shifts in the timing and extent of freshwater inflow and salinity intrusion, decreasing turbidity, restructuring of plankton communities, and reduced metal contamination of biota, and food web changes that decrease resistance of the estuary to nutrient pollution (Cloern and Jassby 2012).

Since 1969, a USGS research program has supported water-quality sampling in the San Francisco Bay. This program collects monthly samples between the South Bay and the lower

Sacramento River to measure salinity, temperature, turbidity, suspended sediments, nutrients, dissolved oxygen and chlorophyll-a. The USGS data, along with sampling conducted by the Interagency Ecological Program (IEP), provide coverage for the entire San Francisco Bay-Delta system. Although these data are critical to our current understanding of the Bay-Delta Estuary, the USGS program is a research program and, thus, is not intended to serve as a comprehensive SFB nutrient monitoring program.

The Nutrient Strategy highlights the need to lay the groundwork for a regionally supported, long-term monitoring program that should be organized in such a way as to collaborate with ongoing research efforts to provide the information that is most needed to support management decisions in the Bay.

The technical approach underpinning the SFB Nutrient Management Strategy is compatible with a major statewide initiative, led by the California State Water Resources Control Board (State Water Board), to develop nutrient water quality objectives for the rest of the State's estuaries www.swrcb.ca.gov/water_issues/programs/nutrient_objectives/ .

2.2 SFB Nutrient Management Strategy: Management Questions, Major Work Elements, and Linkage to AF

To address growing concerns that SFB's response to nutrients is changing and that conditions may be trending toward adverse impacts due to elevated nutrient loads, the Water Board worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy (herein referred to as "the Strategy"; SFRWQCB 2012), which lays out an approach for gathering and applying information to inform management decisions. The Strategy identified four overarching management questions:

- Is SFB currently experiencing nutrient-related impairment, or are there signs of future impairment?
- What are appropriate guidelines for identifying a problem?
- What nutrient loads can the Bay assimilate without impairment of beneficial uses?
- What are the contributions of different loading pathways, and how do they vary in importance as a function of space and time?

To address these management questions, the Strategy identified five major work elements:

- Conceptual model development, scientific synthesis and basic research
- Nutrient assessment framework
- Modeling
- Monitoring and special studies
- Characterization of nutrient loads, sources and major pathways

This report consists of the proposed AF and the analyses and literature that supported its development. Other major elements exist and are in various stages of progress (http://sfbaynutrients.sfei.org/).

The nutrient AF is intended to provide a decision framework for quantifying the extent to which SFB is supporting beneficial uses with respect to nutrients. It also is integral to the other major elements by:

- Defining monitoring requirements (the core indicators, spatial and temporal frequency of sampling) needed to support routine assessments of SFB
- Identifying a set of management endpoints that should constitute the output of SFB water quality models that will improve the mechanistic understanding of the linkage of nutrients to adverse outcomes in SFB
- Contributing to key science needs and analyses needed to further refine the AF

<u>This last bullet point is a critical product of this effort, as the authors of this document fully acknowledge the considerable uncertainty in the AF classification scheme and need for refinement, through multiple iterations of basic research, monitoring, and modeling.</u>

2.3 Conceptual Approach, Desired Attributes of a Nutrient AF and Process for Development

Conceptual Approach to AF Development

Nutrient objectives are scientifically challenging because nutrients are required to support life and the assessment of how much is "too much" is not straightforward. Typical paradigms used to set thresholds for toxic contaminants do not apply, in part because the adverse effects of nutrient over-enrichment are visible at orders of magnitude below recognized toxicity thresholds for unionized ammonia and nitrate. In addition, the effects of nutrient discharges often occur via indirect exposure pathways, which are spatially and temporally disconnected from their points of discharge.

The conceptual approach for AF development is anchored in an ecological risk assessment approach (EPA 1998), which consists of multiple ecological response indicators (e.g., algal abundance and assemblage, dissolved oxygen) as endpoints to assess whether SFB is supporting beneficial uses (Tetra Tech 2006). A hydrodynamic and water quality model is then used to link those assessment endpoints to nutrients and other factors that comprise management options (e.g., best management practices). In this risk-based approach, nutrients are considered a resource that should be managed at levels to maintain SFB designated uses, while maintaining a low risk of adverse effects. If the nutrients present – regardless of actual magnitude – have a low probability of impairing uses, then water quality standards can be considered met. This approach is consistent with EPA guidance for nutrient criteria development (e.g., cause-effect approach; EPA 2001) and with guidance being used by the State Water Board for nutrient objective development for other waterbodies in California (SWRCB 2014), including other estuaries (Sutula 2011).

This ecological risk-based approach has two important advantages. First, it offers a more direct linkage with beneficial uses and is generally thought to lend itself to a more precise diagnosis of adverse effects. Second, the alternative approaches, such as stress-response or reference-based approaches, are particularly problematic in estuaries. SFB and other estuaries within California are highly variable in how they respond to nutrient loading, due to differences in physiographic setting, salinity regime, frequency and timing of freshwater flows, magnitude of tidal forcing, sediment load, stratification, residence time, denitrification, etc. This combination of "co-factors" results in differences in the dominant primary producer communities (i.e., phytoplankton, macroalgae, benthic algae, submerged aquatic vegetation, emergent macrophytes). It also creates variability in the pathways that control how nutrients cycle within the estuary. At times, these co-factors can play a larger role in mitigating estuarine response to nutrient loads or concentrations, blurring or completely obscuring a simple prediction of primary productivity limited by nutrients.

Thus, the Water Board is working to develop an AF based on the following key tenets:

1. *Ecological response indicators (e.g., dissolved oxygen, primary producer abundance, productivity and assemblages) should provide a more direct risk-based linkage to beneficial uses than to nutrient concentrations or loads.* The AF should be based on assessing eutrophication (or other adverse effects), rather than nutrient over-enrichment per se.
2. *A weight-of-evidence approach with multiple indicators can produce a more robust assessment of eutrophication.* Wherever possible, the use of multiple indicators in a "weight-of-evidence" approach provides a more robust means to assess ecological condition and determine impairment. This approach is similar to the multimetric index approach, which defines an array of metrics or measures that provide limited information on biological status on an individual basis, but when integrated, serve to inform overall biological condition.
3. *Models can be used convert response indicators to site-specific nutrient loads or concentrations.* A key premise of the NNE framework is the use of models to convert numeric endpoints, based on ecological response indicators, to site-specific nutrient goals appropriate for permitting and TMDLs. A key feature of these models is that they account for site-specific co-factors, such as light availability, temperature, and hydrology that modify the ecological response of a system to nutrients. Thus, nutrient forms and ratios are not an explicit element of the AF, but become linked to assessment endpoints through modeling of ecological processes.

Desirable Attributes of an AF

The goal of the nutrient AF is to provide a structured set of decision rules that specify how to use monitoring data to categorize specific subembayments of SFB, from very high to very low ecological condition, using indicators that have a direct linkage to nutrients and support of SFB beneficial uses.

To achieve this goal, a nutrient AF for SFB should offer the following features:

- The AF should employ indicator(s) that have a strong linkage to Bay beneficial uses. This linkage should be scientifically well-supported and easily communicable to the public.
- One or more primary indicators of the AF should have a predictive relationship with surface water nutrients and/or nutrient loads to the Bay.
- The AF should employ the indicator(s) that classify the Bay subembayments from very high ecological condition to very low ecological condition. It should be explicit as to how

the magnitude, extent, and duration of the effects cause the subembayments to be classified differently.

- The AF should be spatially explicit for different subembayments of the Bay and different habitat types (deep vs. shallow subtidal), as warranted by the ecological nature of response to nutrients.
- The AF should specify what appropriate methods are used to measure the indicator and the temporal frequency and spatial density of data required to make that assessment.
- It should provide guidance on how the data should be analyzed to categorize the Bay subembayments.

Methodology Used to Develop AF

The methodology used to develop the AF consisted of five main steps:

1. **Empanel a team of scientific experts to guide AF development.** These experts represented a diverse body of knowledge of SFB hydrology, estuarine ecology and nutrient biochemistry, as well as expertise in nutrient criteria and AF development. This team is listed as contributing authors on this document.
2. **Review existing approaches to nutrient AF development.** A white paper was completed identifying candidate indicators and metrics, summarizing existing literature for how those indicators have been used to assess ecological condition, and recommending a suite of options to consider for further exploration (Appendix 1).
3. **Identify AF core principles,** including geographic scope and key habitats, key indicators and recommended measures, and the spatial and temporal frequency of sampling required for assessment.
4. **Analyze existing data to develop supporting information to develop a classification scheme.** Existing data were utilized to test out existing classification schemes and to quantify relationships between key variables of interest. These analyses are summarized in Section 3, and additional methods and supporting information are provided in Appendix 2.
5. **Develop AF classification scheme and quantify/describe major uncertainties**. Existing literature and supporting analyses were used to develop the AF classification scheme. For each indicator, uncertainties corresponding to classification “bins” were summarized. Key science needs required for the refinement of the classification scheme and core principles were summarized.

Testing the AF with existing or newly collected monitoring data, and further refinement based on monitoring and modeling, are steps envisioned for the AF in subsequent phase(s) outside the scope of this document.

2.4 Review of Existing Frameworks to Assess the Effects of Nutrient Over-Enrichment on Estuaries

We reviewed the existing regulatory and non-regulatory approaches to the assessment of the effects of nutrient over-enrichment in estuarine waterbodies worldwide in order to consider an appropriate approach to AF development (see white paper in Appendix B). A wide variety of methodologies exist (Table 2.1). All of the conceptual models reviewed focused on ecological impacts (i.e., eutrophication), rather than on nutrients' direct effects on ecological condition (i.e., toxicity).

The white paper (Appendix B) arrived at the following conclusions:

- **The eutrophication AFs reviewed have a common set of conceptual models.** These conceptual models show linkages to nutrients and relevant co-factors, as well as the risk pathways of "impairment" of ecosystems services and beneficial uses. These pathways of impairment include **(**1) increased harmful algal blooms, which can produce toxins that adversely affect both human health and aquatic life, (2) hypoxia and anoxia triggered by frequent algal blooms, which change the long-term balance of organic matter cycling and accumulation within an estuary (Nixon 1995) and can adversely affect habitat and aquatic life, (3) shifts in the dominance assemblages and size class of phytoplankton, which lead to degradation of food quality for estuarine consumers, including commercial and recreational fisheries, and (4) overabundance of algae, which results in reduced light availability for benthic primary producers (e.g., seagrass).

- **A common set of response indicators are used, focusing on dissolved oxygen and primary producers (e.g., Bricker et al. 2003, Zaldivar et al. 2008), that link to these major conceptual models.** Among primary producer indicators used, phytoplankton biomass (water column chlorophyll-a) is the most common (Table 2.1). The frequency and magnitude of harmful algal blooms and toxin concentrations have also been used, either directly as an indicator or indirectly using chlorophyll-a as a proxy for the increased probability of occurrence of HAB events. Phytoplankton assemblage has been used in assessment of ecological condition, but only in estuaries that can use a reference approach to defining the envelope of reference assemblages. Where TN and TP are used (typically in regulatory programs), they have been determined as a proxy for primary productivity either through statistical or process modeling to primary producer numeric targets (e.g., regulatory programs such as Chesapeake Bay and Florida), or through a reference water body approach (Andersen et al. 2011).

- **Among non-regulatory AFs (Bricker et al. 2003, Zaldivar et al. 2008), estuarine subembayments are binned into multiple condition classes, representing a disturbance gradient of high to low ecological condition (e.g., Zaldivar et al. 2008) or trophic state (Bricker et al. 2003).** These condition classes are developed through a combination of scientific data analyses and expert best professional judgment.

- **There is some degree of convergence on the thresholds or ranges represented within the various classification scheme, particularly for chlorophyll-a (see white paper, Appendix B).** This suggests consensus among experts who developed these frameworks that the ranges representing condition classes correspond to real ecosystem decline. That said, two points are worth mentioning. First, there is great variability in the temporal statistic (e.g., annual average, season max, 90th percentile) used to make the assessment. Second, the differences in the ranges, while small, represent large differences in estuarine productivity, especially on annual timescales.

- **Inherent in these AFs are key differences in temporal statistic, spatial density of data used to make an assessment and, in some cases, the way that multiple indicators are combined into a single score (Table 2.2).** These details are less obvious, but can have large effects on scoring (McLaughlin et al. 2013).

Table 2.1 Methods of eutrophication assessment and examples of biological and physico-chemical indicators used and integration capabilities (pressure-state and overall; modified from Borja et al. 2009). From Ferreira et al. 2011.

Method Name	Biological indicators	Physico-chemical indicators	Nutrient load related to impairments	Integrated final rating
TRIX[b]	Chl	DO, DIN, TP	no	yes
EPA NCA Water Quality Index[a]	Chl	Water clarity, DO, DIN, DIP	no	yes
ASSETS[e]	Chl, macroalgae, seagrass, HAB	DO	yes	yes
TWQI/LWQI[c]	Chl, macroalgae, seagrass	DO, DIN, DIP	no	yes
OSPAR COMPP[g]	Chl, macroalgae, seagrass, phytoplankton indicator species	DO, TP, TN, DIN, DIP	yes	yes
WFD[f]	phytoplankton, Chl, macroalgae, benthic invertebrates, seagrass,	DO, TP, TN, DIN, DIP, water clarity	no	yes
HEAT[d]	Chl, primary production, seagrass, benthic invertebrates, HAB, macroalgae	DIN, DIP, TN, TP, DO, water clarity	no	yes
IFREMER[h]	Chl, seagrass, macrobenthos, HAB	DO water clarity, SRP, TP, TN, DIN, sediment organic matter, sediment TN, TP	no	yes
STI[i]	Chl, Primary Production	DIN, DIP	no	no

[a] USEPA, 2005, 2008.
[b] Vollenweider *et al.*, 1998.
[c] Giordani *et al.*, 2009.
[d] HELCOM, 2009.
[e] Bricker *et al.*, 1999, 2003, 2007.
[f] Devlin, pers.Com.
[g] OSPAR, 2002, 2008.
[h] Souchu *et al.*, 2000.
[i] Ignatiades, 2005.

Table 2.2. Summary of approaches used for assessment of eutrophication applicable to shallow and deepwater unvegetated subtidal habitat. Adapted from Devlin et al. 2011.

		UK WFD	OSPAR	TRIX	ASSETS	EPA NCA	TWQI/LWQF	HEAT	IFREMER
Grouping of Variables	Caus-ative Factors	Nutrient Load	DIN and DIP concentration, ratios, and loads	DIN and TP concentration	DIN and DIP loads	DIN, DIP conc	TN, TP, DIN and DIP conc.	DIN and DIP	PO4, NOX, NH4, TN, TP
Grouping of Variables	1^{ary} effects	Chl-a, PP indicator species, seasonal changes in cell abundance of diatoms/dinoflagellates, SAV, macroalgae	Chl-a, PP indicator species, macroalgae, microphytobenthos, SAV	Chl-A	Chl-a macroalgae	water clarity, chl-a	Chl a, SAV, macroalgae	Chl a, water clarity, SAV,	Chl a, turbidity
Grouping of Variables	2^{ary} effects	DO	DO, zoobenthos and/or fish kills, organic carbon	DO	Nuisance/toxic blooms	DO	DO	Benthic invertebrates	DO percent saturation
Grouping of Variables	Other		Algal toxins						
Temporal sampling framework		Annual chla and DO, winter DIN, monthly PP groups	Growing season chl-a (Mar-Sept), Winter DIN, summer DO	Annual	Annual	One sample per year (per station) within summer index period	Results can be derived based on one time or multiple periods	Growing season chl-a (Mar-Sept), Winter DIN, summer DO	Annual
Spatial sampling framework		Sampling in estuaries and nearshore defined by salinity, reported by waterbody	Sampling defined by salinity in estuaries, nearshore	Sampling mostly in larger offshore systems; results reported by region	Sampling in salinity zones, synthesized to waterbody, region, national, with reporting at all levels	Sampling is regional, synthesized to national level, reported at regional and national level	For shallow, benthic PP dominated. Can be applied to single stations or groups of stations.	Sampling defined by salinity in Baltic Sea	For shallow, benthic PP dominated. Can be applied to single stations or groups of stations.
Assessment of indicators		Deviation from reference conditions	Deviation from reference conditions	Placement on scale from 1-10 TRIX units	Deviation from reference conditions	Deviation from reference conditions	Deviation from reference condition	Deviation from reference condition	Deviation from reference
Comb-ination Method		Indicator scores are averaged within an indicator group. Final score gives classification status	One out, all out for individual categories and overall classification	Linear combo of logarithm of variables modified by scaling coefficient	Scores of avg. primary and secondary indicators combined in a matrix	Indicators assessed individually. WQI based on % of samples in 4 categories.	TWQI scores combined as the sum of weighted quality values for individual indicators.	One out, all out for individual categories and overall classification	One out all out

3 FRAMEWORK TO ASSESS THE EFFECTS OF NUTRIENTS ON SAN FRANCISCO BAY BENEFICIAL USES

3.1 AF Core Principles

Geographic Scope and Focal Habitats

The geographic scope for the SFB AF is defined by the Golden Gate Bridge as the oceanward boundary, and Broad Slough in the Sacramento River as the upstream boundary, which is just upstream of Winter Island (the boundary between the San Francisco and Central Valley Water Boards; Figure 3.1).

SFB is comprised of deep and shallow water subtidal habitats and intertidal wetlands, and remnant tidal marshes (Figure 3.1). Deepwater and shallow subtidal habitats are the focus of this AF.

Although diked baylands, restored salt ponds, and tidal sloughs also are present in SFB and are important, they are excluded in this initial assessment work. That said, preliminary data indicate that these habitats may be in questionable ecological condition (Topping et al. 2009, SFEI 2014a); thus, we recommend development of an AF targeting these habitats in a subsequent phase of framework development.

Segmentation

SFB has six subembayments with very different physical, biogeochemical, and biological characteristics that shape their individual responses to nutrients. For this reason, the AF should be spatially explicit for these regions (herein referred to as subembayments) of SFB, as warranted by the ecological nature of response to nutrients.

The physical features in SFB provide natural breakpoints for segmentation, as documented by Jassby et al. (1997) for chlorophyll-a, TSS and salinity. These breakpoints or subembayment boundaries are also obvious in other ecological data. The SFB Regional Monitoring Program (RMP) uses a segmentation scheme that differs slightly from that of Jassby et al. (1997); this segmentation scheme was derived based on a variety of different contaminant and environmental gradients not necessarily relevant for nutrients.

For the AF and supporting analyses, we used subembayment classification based on Jassby et al. (1997; Table 3.1., Figure 3.1). That said, we strongly recommend reanalysis of existing data in the Jassby et al. (1997) methodology, using newly available and relevant ecological data, to finalize this segmentation scheme.

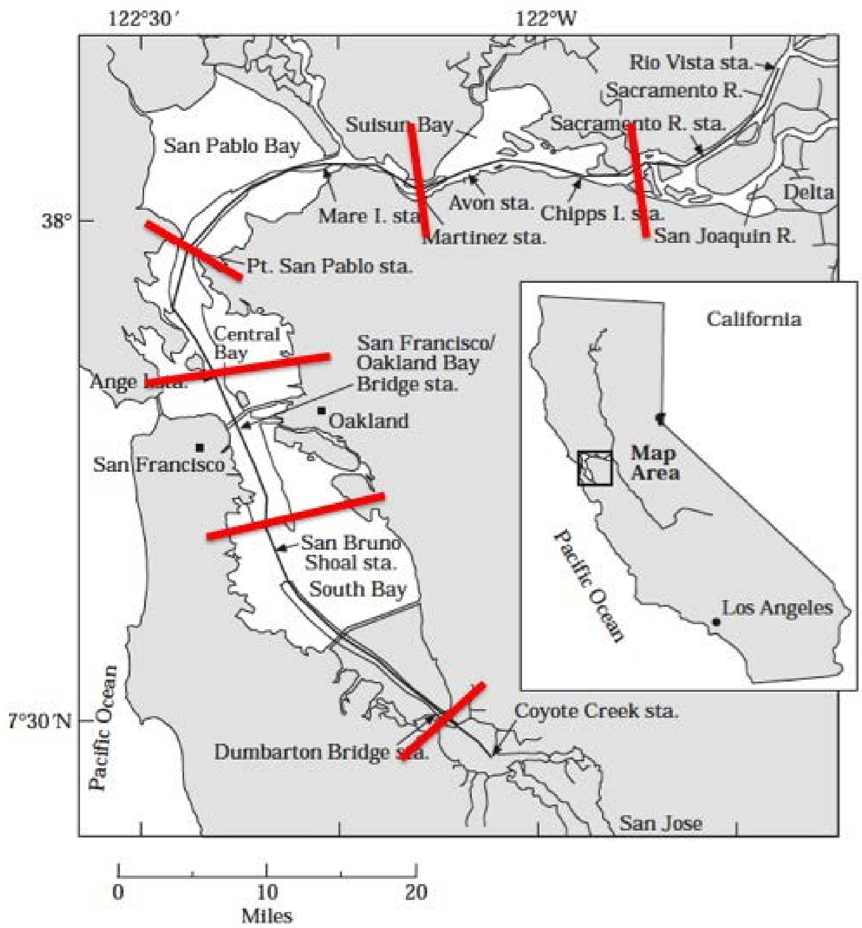

Figure 3.1 Map of SFB showing geographic scope of AF, focal habitats and subembayment boundaries. Subembayment names are designated on the map.

Table 3.1. Size and locations of boundaries defined by preliminary AF classification scheme (from Jassby et al. 1997).

Stratum no.	Description	Size ± SD (km)	Northing (km)	Easting (km)
1	South of Dumbarton Br.	6·9 ± 0·3	<151·4	
2	Dumbarton Br. to San Bruno Shoal	23·3 ± 0·6	151·4–165·3	
3	San Bruno Shoal to Angel I.	28·7 ± 0·7	165·3–188·8	
4	Angel I. to Mare I.	37·3 ± 2·2	≥188·8	<564·6
5	Mare I. to Martinez	13·1 ± 1·1	≥188·8	564·6–574·5
6	East of Martinez	51·8 ± 1·7	≥188·8	≥574·5

Key Indicators and Linkage to SFB Beneficial Uses

A core principle of the AF is the use of several indicators as multiple lines of evidence for potential adverse impacts (Figure 3.2), assuring a more robust assessment of the ecological condition of SFB subembayments. In the SFEI 2014b report, experts arrived at consensus regarding what undesirable conditions would plausibly manifest in SFB in response to adverse nutrient-related impacts – and how each undesirable state would impact beneficial uses (Table 3.2). The undesirable states were divided into seven categories that represent specific examples extending from more general adverse impact pathways (Figure 3.2).

The undesirable states can be measured by six key indicators representing the multiple lines of evidence within this AF:

1. Phytoplankton biomass (as chlorophyll-a)
2. Gross and net phytoplankton production (hereto referred to collectively as GPP)
3. Harmful algal bloom species abundance
4. HAB toxin concentrations
5. Phytoplankton assemblage, expressed as phytoplankton food quality, percent of biovolume < 0.5 microns, and other metrics of community change
6. Dissolved oxygen

The remainder of this section is devoted to analyzing the seven undesirable states and the role that the six condition indicators can play in assessing these undesirable conditions.

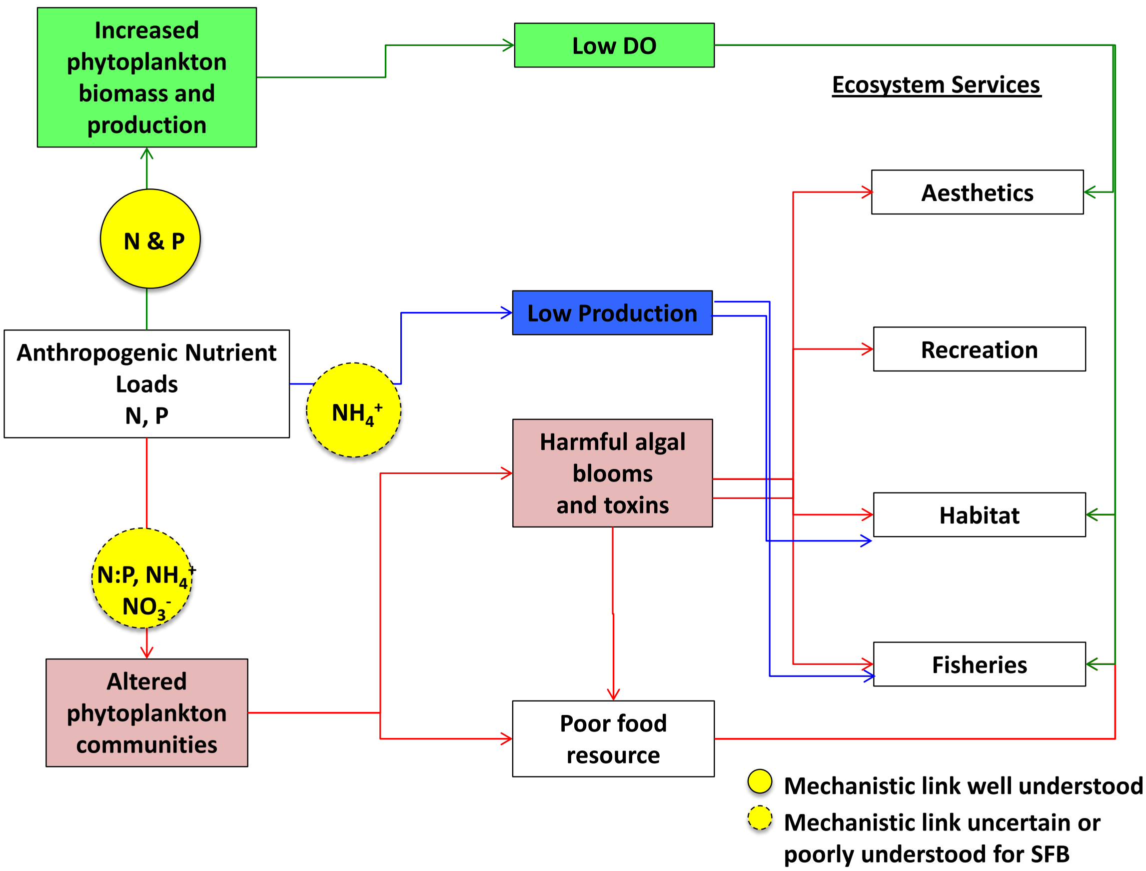

Figure 3.2 Potential adverse impact pathways: linkages between anthropogenic nutrient loads and adverse ecosystem response. The shaded rectangles represent indicators that are recommended for measurement along each pathway to assess condition. From SFEI 2014b).

Table 3.2 Plausible undesirable states and link to beneficial uses (adapted from SFEI 2014b).

Undesirable State (S)	Rationale or Link to Beneficial Uses
S1. High Phytoplankton Biomass and Productivity High phytoplankton biomass and productivity of sufficient magnitude, duration, and spatial extent that it impairs beneficial uses due to direct or indirect effects (S2-S3). This could occur in deep subtidal or in shallow subtidal areas.	Direct effects on noncontact water recreation (REC2) due to aesthetics via odors and surface scum. Other main concern is through increased organic matter accumulation causing low dissolved oxygen (S2-S3) and proliferation of pathogenic bacteria, leading to degraded contact and noncontact water recreation (REC1 and REC2).
S2 and S3. Low Dissolved Oxygen ***Deep subtidal:*** Low DO in deep subtidal areas of the Bay, over a large enough area and below some threshold for a long enough period of time that beneficial uses are adversely affected. ***Shallow/margin habitats***: DO in shallow/margin habitats below some threshold, and beyond what would be considered “natural” for that habitat, for a period of time that it impairs beneficial uses.	Fish kills, die-off of beneficial benthos, loss of critical habitat that result in lowered survival or spawning/reproductive success or recruitment success of fish and beneficial benthos. These consequences directly affects EST, RARE, etc. beneficial uses.
S4. HAB Abundance and Algal Toxins ***HABs and toxins:*** Occurrence of HABs and/or related toxins at sufficient frequency or magnitude of events that habitats reach an impaired state, either in the source areas or in areas to which toxins are transported. ***NABs:*** Occurrence of nuisance algal blooms with sufficient frequency and magnitude that they impair beneficial uses; for example, similar to the red tide bloom in Spring 2004	***HABs and toxins*:** Passive or active uptake of toxins, or ingestion of HAB-forming species and accumulation of toxins. Ingestion of bioaccumulated toxins is harmful to both wildlife and humans through consumption of toxins via shellfish or fish. Skin contact and inhalation can also be problematic. ***NABs*:** Some species are considered HABs for reasons other than toxins (e.g., directly impairing biota at very high levels, e.g., coating fish gills, birds wings, rapid biomass production leading to low DO). Impaired aesthetics, surface scums, discoloration, odors. These adverse effects directly impact EST, WILD, SHELL, RARE, and COMM beneficial uses.
S5. Low Phytoplankton Biomass and Productivity Low phytoplankton biomass in Suisun Bay or other habitats due to elevated NH_4^+, which would exacerbate food supply issues.	Suisun Bay is considered a food limited system, and low levels of phytoplankton biomass and productivity may contribute to impairment in this highly altered system. These adverse effects directly impact EST, SHELL, RARE, and COMM beneficial uses.
S6. Suboptimal Phytoplankton Assemblages that Impact Food Quality Nutrient-related shifts in phytoplankton community composition, or changes in the composition of individual cells (N:P), that result in decreased **phytoplankton food quality**, and have cascading effects up the food web.	Phytoplankton primary production is the primary food resource supporting food webs in SFB. Changes in the dominant assemblages and their relative size fractions would impact food quality. These adverse effects directly impact EST, SHELL, RARE, and COMM beneficial uses.
S7. Other Nutrient-Related Impacts Other direct or indirect nutrient-related effects that alter habitat or food web structure at higher trophic levels by other pathways. Several additional nutrient-related impacts on food webs in the northern estuary have been proposed that are not captured by S1-S6.	

High phytoplankton biomass and primary productivity (S1, Table 3.2) can have direct effects on REC2 in SFB via nuisance scums and odors.

However, among the most common and problematic impairments due to high phytoplankton biomass is **low dissolved oxygen** (S2 and S3, Table 3.2) in subtidal areas that results through metabolism of phytoplankton-derived organic matter by oxygen-consuming microorganisms (e.g., Figure 3.3). Because aquatic organisms rely on DO for survival, growth and reproduction, the consequences of sub-optimal DO in SFB include die-offs or low production of fish and benthos and loss of critical habitat due to lowered survival or spawning/reproductive success or recruitment success (Figures 3.4). These adverse effects directly impact EST, SHELL, RARE, and COMM beneficial uses.

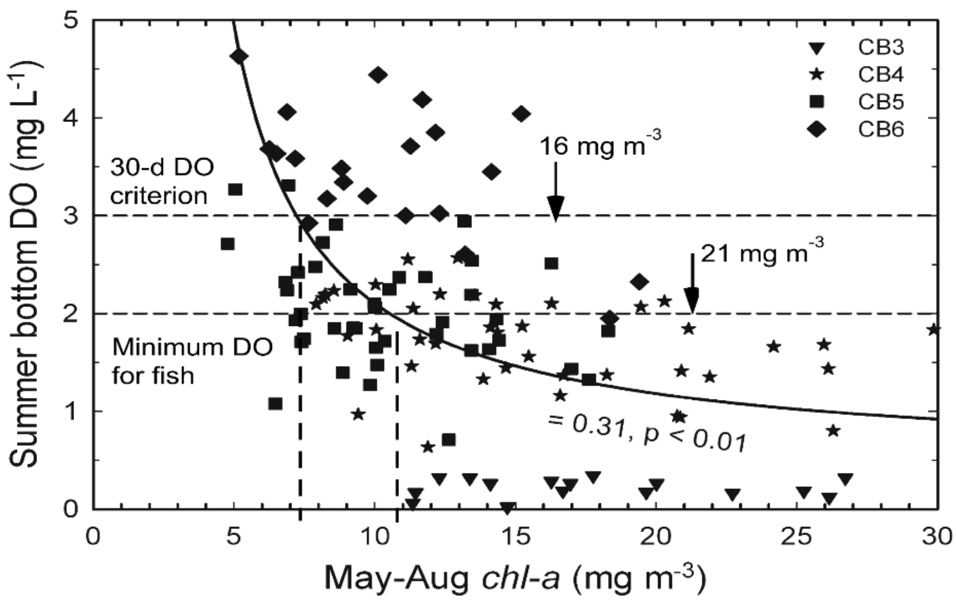

Figure 3.3. Example of dissolved oxygen as a function of chlorophyll-a in Chesapeake Bay. From Harding et al. 2013. Scientific bases for numerical chlorophyll criteria in Chesapeake Bay. *Estuaries and Coasts* doi:10.1007/s12237-013-9656-6

Elevated nutrient concentrations, or changes in relative abundance of nutrient forms, could increase the frequency with which **harmful algal blooms (HAB) and algal toxins** (S4, Table 3.2) occur, including abundance, duration, and spatial extent. Algal toxins, such as microcystin and domoic acid, bioaccumulate and can exert toxicity to consumers at all levels of the food web, including humans. Some HAB exudates also exert direct toxicity (e.g., skin contact). High nutrient loads may also increase the frequency of so-called nuisance algal blooms (NABs), which are not toxic but may degrade aesthetics due to surface scums or odors. Elevated phytoplankton biomass is typically correlated with increased probability of HABs (and NABs) and toxins (e.g., Figure 3.5).

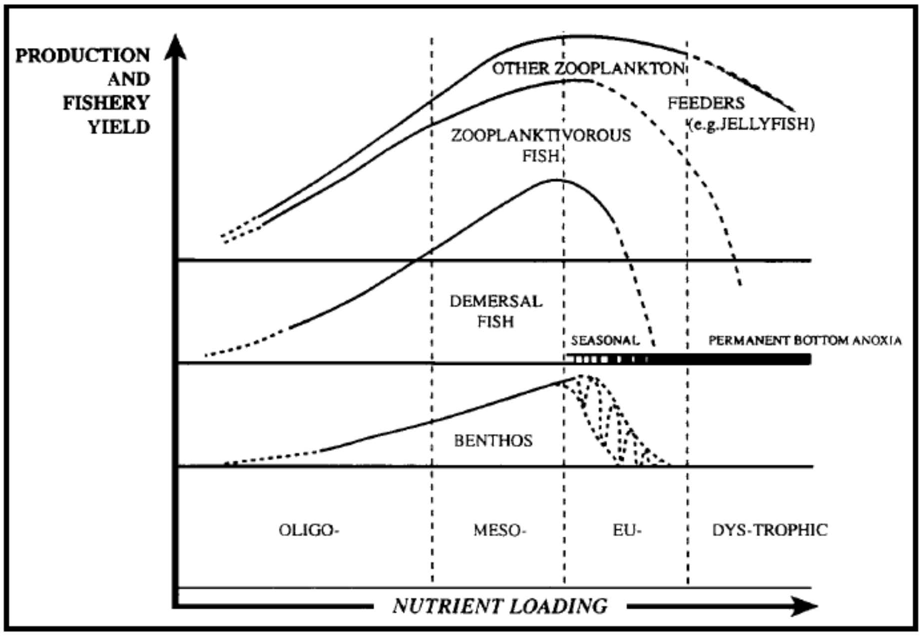

Figure 3.4. Comparative evaluation of fishery response to nutrients along continuum of oligotrophic, mesotrophic, eutrophic and dystrophic states of primary productivity (Nixon 1995). Although higher nutrient inputs initially increase the productivity of fisheries, ecological systems worldwide show negative effects as nutrient loading increases and hypoxic or anoxic conditions develop. Each generic curve in the lower half of the figure represents the reaction of a species guild to increasing nutrient supplies. From Diaz and Solow (1995).

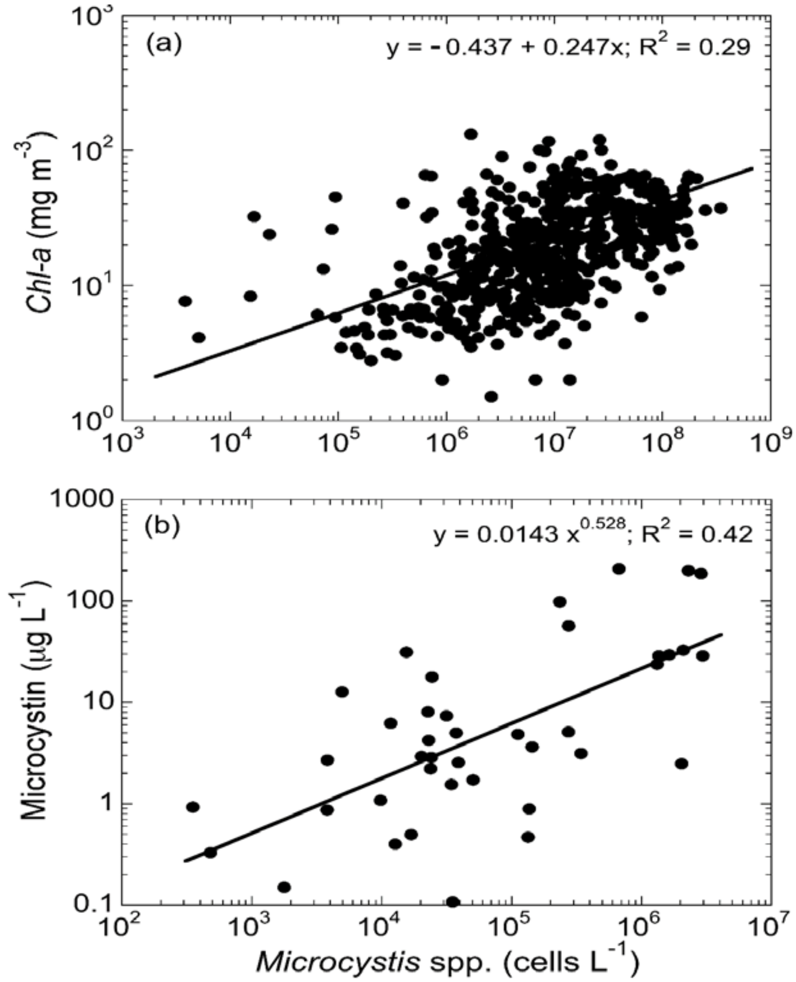

Figure 3.5. Example of relationships between chlorophyll-a, cyanobacteria Microsystis spp. abundance, and toxin concentrations, From L. W. Harding et al. 2013. Scientific bases for numerical chlorophyll criteria in Chesapeake Bay. ***Estuaries and Coasts*** **doi:10.1007/s12237-013-9656-6**

A number of factors can lead to **low phytoplankton biomass and productivity** (S5, Table 3.2) and **suboptimal phytoplankton assemblages that impact food quality** (S6, Table 3.2), a phenomenon marked by a shift in phytoplankton community composition away from assemblages found under minimally disturbed conditions, toward smaller, suboptimal compositions that do not adequately sustain organisms at higher trophic levels.

Two metrics have been discussed for measuring adverse changes to phytoplankton communities:

1) **Fraction of small-sized phytoplankton**: Fisheries yields are correlated to phytoplankton biomass (e.g., biovolume) and primary productivity (Friedland et al. 2012; Figure 3.6). When the portion of picophytoplankton (< 5 microns) grows, the result is a comparatively lower trophic transfer of energy and carbon up the food web (e.g., Figure 3.6) than is seen with other phytoplankton, which results in lower fisheries yields.

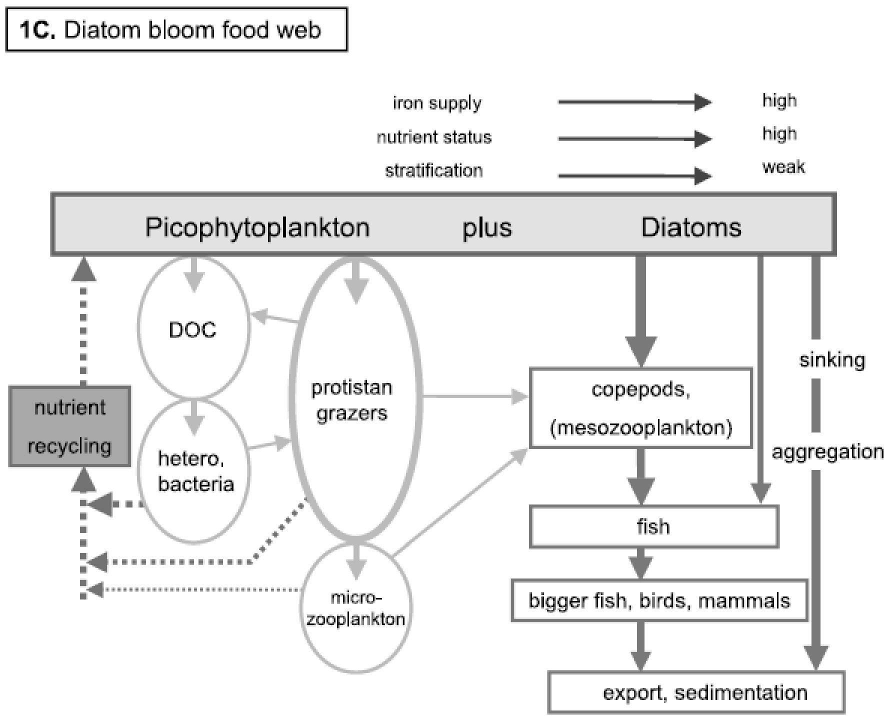

Figure 3.6. Example of a marine food web showing the complex pico-phytoplankton and diatom food web structure in diatom-dominated blooms. For simplicity, the regeneration paths are shown only on the left side of the figure (Source: Barber and Hisock 2006).

2) **Index of phytoplankton food quality**: This index utilizes data on phytoplankton composition to characterize the “food quality” that phytoplankton represent in supporting productivity of upper trophic levels. This is a key pathway to link phytoplankton composition to beneficial uses, such as commercial and recreationally important fisheries (i.e., EST, COMM, RARE). The concept of a phytoplankton food quality index is based on laboratory experiments showing that growth efficiency of crustacean zooplankton is highest when they are fed algae enriched in highly unsaturated fatty acids (cryptomonads and diatoms), and lowest when fed algae poor in these essential fatty acids (e.g., cyanobacteria; Brett and Müller-Navarra 1997).

Based on Galloway and Winder (2015), the fatty-acid food quality index (FQI) can be computed from the average composition of long chained essential fatty acids (LCEFA) at the algal taxonomic group level (Park et al. 2003, Galloway and Winder 2015).

The scale of the index (0–1; Equation 1) is defined by calculating the relative quality of each algal group (AGi) compared to the maximal LCEFA content of all AG:

Equation 1. FQI = AGcy*Pcy + AGgr*Pgr + Agdi*Pdi + AGcr*Pcr

where the FQI is the biovolume weighted average of the AGi for each individual group, and Pcy, Pgr, Pdi, and Pcr are the proportions of phytoplankton biovolume in a sample contributed by cyanobacteria, green algae, diatoms, and cryptomonads. Figure 3.7 shows the separation in AGi by phytoplankton taxonomic group. The concept has recently been applied to phytoplankton composition data collected by the USGS in the Lower Sacramento River through Suisun Bay from 1992 to 2014 (Cloern et al. 2015).

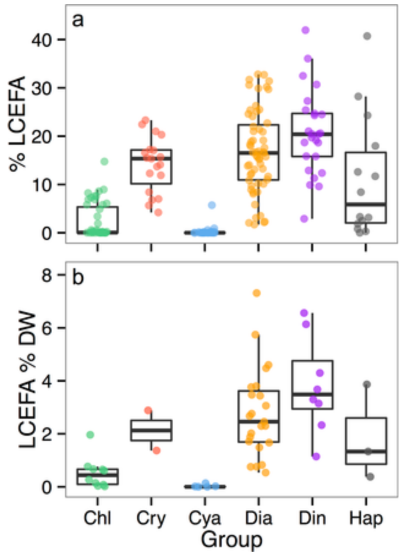

Figure 3.7. From Galloway and Winder 2015. Boxplots of species averages of Σ long-chain essential fatty acids (LCEFA) in six major phytoplankton groups. (a) Shows the percent total fatty acids (% FA) dataset, consisting of 208 averages from 666 raw profiles. (b) Shows the percentage of algal dry weight (FA % DW) dataset, consisting of 55 averages from 105 raw profiles. Group name abbreviations follow Fig 1. The heavy line is the median, box boundaries are the 25th and 75th percentiles, and whiskers extend to the most extreme value within 1.5*IQR (interquartile range). The y-axis is set to show the extent of whiskers; thus, some extreme outliers are not plotted (outliers were included in calculation of average group LCEFA).

We propose that a number of metrics for phytoplankton community composition be deployed in routine assessments of SFB. In addition to tracking HAB abundance and toxin concentrations, phytoplankton metrics should be developed with the intent to create classification schemes in the future, if warranted, as these metrics (in combination with chlorophyll-a and GPP, discussed in more depth in Section 3.2) can give a more robust understanding of SFB condition and ecological change.

One final note: Nutrient forms and ratios are not explicitly considered as metrics within the present AF, although they will most certainly be included within the framework of monitoring and mechanistic modeling. The reason is that while several authors have hypothesized that high nutrient concentrations, elevated NH_4^+, or altered N:P are currently adversely impacting food webs in SFB (Table 3.1, S6; Dugdale et al., 2007; Parker et al., 2012a,b; Dugdale et al., 2012), scientific consensus is lacking on the importance of these hypothesized pathways relative to other controls on phytoplankton production and community composition.

3.2 Protocols, Temporal and Spatial Frequency Recommended for Measurement of Key Indicators

An important attribute of an AF is clarity in the methods used to measure the indicators, as well as the temporal and spatial frequency in which they should be measured in order to make an assessment. Table 3.3 provides a list of six key indicators and the specific analytes associated with each. This table is not inclusive of the longer list of parameters required for data interpretation or for other Nutrient Strategy program elements. The SFB Monitoring Strategy (SFEI 2014c) provides a more comprehensive picture of those data needs, as well as specific recommendations on protocols for measurement of key indicators.

DO and metrics of phytoplankton quantity and quality are the two principal groups of indicators proposed for the SFB nutrient AF. The Water Board's basin plan already contains numeric objectives for DO, and Water Board staff has expressed interest in reviewing the existing DO objectives.

Table 3.3 Recommended indicators, analytes and basis for classification scheme.

Indicator	Analyte	Basis for Classification Scheme
Dissolved oxygen	Dissolved oxygen as % saturation and concentration	SF Water Board Basin Plan (2016)
Phytoplankton biomass	Water column chlorophyll-a	Analysis of existing data (Appendix C)
Depth integrated, annual gross and net primary production	Chlorophyll-a, photic depth and surface irradiance, recalibrated on a frequency to be determined by direct measures of GPP (per Cole and Cloern 1984)	Nixon (1995)
HABs abundance (Alexandrium spp, cyanobacteria[1], Pseudo-nitzchia spp., Dinophysis spp.)	Genus and/or species cell counts and biovolume	Existing state, federal or international guidance—Appendix C for specifics by HAB species
HAB toxin concentrations		Existing state, federal or international guidance
Phytoplankton composition	Genus and/or species cell counts	No classification scheme proposed.
	% of Biovolume < 0.5 microns	
	Phytoplankton Food Quality Index (Galloway and Winder 2015)	

[1] Cyanobacteria of interest include, but are not limited to, Cylindrospermopsis spp., Anabaena spp., Microcystis spp., Planktothrix spp., Anabaenopsis spp., Aphanizomenon spp., Lyngbya spp., Raphidiopsis spp., Oscillatoria spp., and Umezakia spp.

Review of the science supporting SFB DO objectives is beyond the scope of this initial phase of AF development. Thus, the present recommendations focus on phytoplankton indicators.

<u>Until further work is undertaken to consider and refine DO objectives and/or optimize sampling, assessments of DO are assumed to occur at the same frequency and location as those for the phytoplankton indicators.</u>

Because dissolved oxygen, phytoplankton biomass, productivity and phytoplankton composition are all extremely variable across both time and space, the following two sections outline recommendations regarding the temporal and spatial elements of the AF and how to align them with the monitoring program to optimize capturing this variability, while also balancing costs, logistics and power to detect trends.

Temporal Scales of Interest and Recommended Frequency

For phytoplankton indicators, four temporal components are of interest for documenting ecosystem change (Figures 3.8 and 3.9):

- Magnitude of spring blooms
- Emergence and magnitude of fall blooms
- Elevated baseline occurring during non-blooms periods (typically during June-September)
- Interannual variability and trends

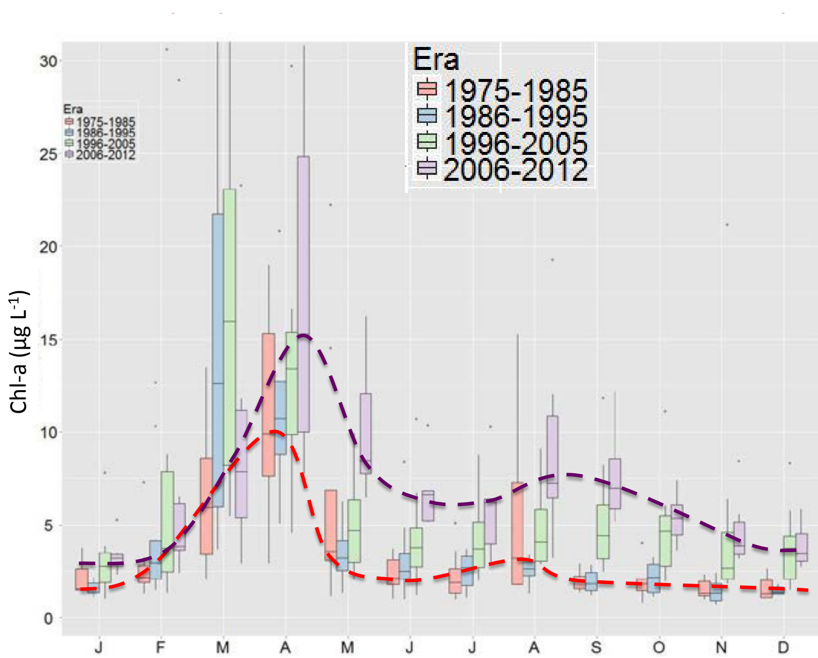

Figure 3.8. 10-year rolling average chlorophyll-a by month of the year in Lower South Bay, illustrating the four elements of interest in phytoplankton variability: (1) spring bloom, (2) fall bloom, (3) elevated baseline during non-bloom periods, and (4) interannual variablility. Source: Jim Cloern, USGS

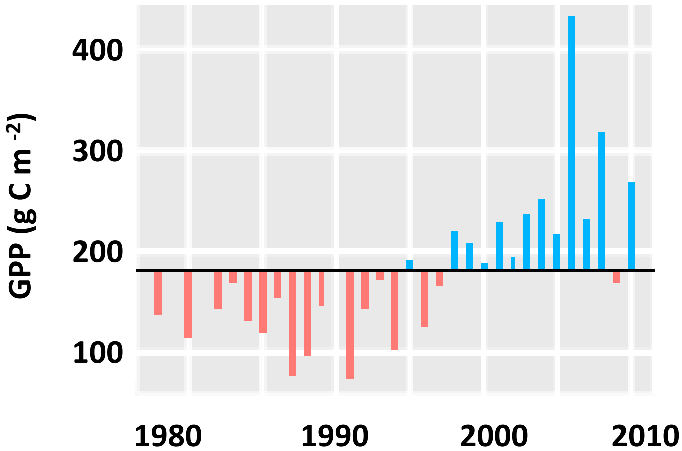

Figure 3.9. Trends in estimated annual GPP over time. From Cloern and Jassby (2012). Drivers of change in estuarine-coastal ecosystems: discoveries from four decades of study in San Francisco Bay. Rev. Geophys., 50, RG4001, doi:10.1029/2012RG000397.

Considering this variability, we recommend a sampling frequency of no less than monthly via ship-based sampling, with weekly sampling possible in order to better characterize bloom events.

Spatial Elements and Minimum Recommended Density

To adequately capture spatial gradients, we recommend sampling that encompasses (1) the SFB subembayments defined by Jassby et al. (1997), (2) both deep-channel parts and shallow parts of the Bay, (3) vertical gradients in the water column, either as grabs with depth or conductivity-temperature-depth (CTD) profiles, and (4) both the upstream, oceanic boundary conditions, as well as other potential “seed” sources of HABs, e.g., salt ponds.

We used best professional judgment to recommend preliminary placement of ship-based transects, water quality stations and moorings by subembayment (Figure 3.10). These locations should be considered provisional, subject to funding availability and optimization in concert with other nutrient strategy components that require monitoring (e.g., model development, etc.). Locations of historic USGS stations are preserved to maintain continuity of the long-term data set. Additional stations were added while balancing the logistics and cost of ship-based sampling. No stations are placed in tidal sloughs and restored salt ponds; consideration of monitoring in these habitats should be undertaken in a subsequent phase of AF development. Additional data analyses have been recommended to optimize the placement of stations (Senn et al. 2014).

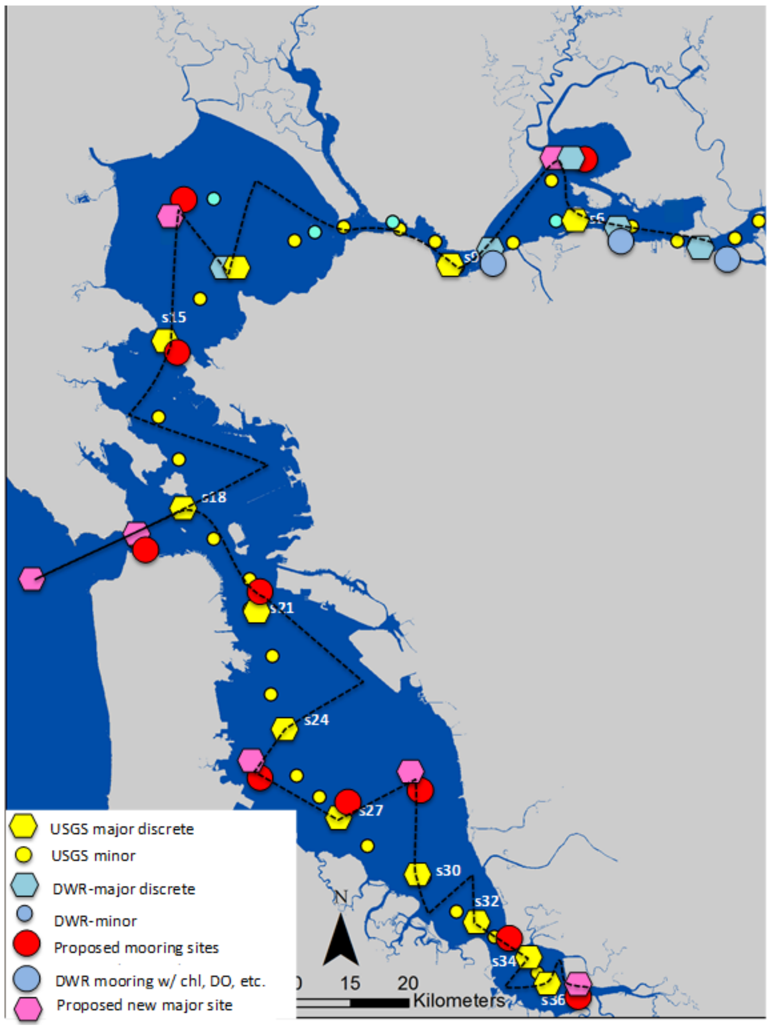

Figure 3.10. Recommendation of sampling stations representing minimum effort needed to support ambient nutrient assessment of SFB subembayments. Locations should be considered provisional, subject to funding availability and optimization in concert with other nutrient strategy components that require monitoring (e.g., model development, etc.).

3.3 Proposed AF Classification Tables, Justification, and Sources of Uncertainty

As noted above, we have proposed classification frameworks for five of the six indicators of SFB ecological condition: phytoplankton biomass (chlorophyll-a), gross primary productivity, HABs abundance, HABs toxins, and dissolved oxygen (Table 3.3).

For the sixth indicator – phytoplankton community composition – we explored two metrics that could be used to assess adverse changes (Section 3.1), and also made recommendations regarding temporal and spatial considerations (Section 3.2), but are stopping short of proposing a classification table for phytoplankton community composition.

Among the other five indicators, dissolved oxygen already has a classification table in use in SFB, and we recommend that the next step be a review of the need to refine the Basin Plan DO objectives (Section 3.2).

Our approach to developing classification tables for the four remaining indicators consisted of separating Bay subembayments into categorical bins of ecological condition, from high to low, based on indicators that are linked to ecosystem services (i.e., beneficial uses). An intent was made to be as explicit as possible on the precise metrics used to measure the indicators, as well as the temporal and spatial density of data required to make assessments and to specify how the data would be used to report on status and trends.

Existing guidance and the results of the quantitative analyses were synthesized, using expert opinion, into a classification scheme to assess ecological condition for multiple subembayments of SFB for each of the four indicators. For each indicator, a scheme was developed to parse SFB subembayments into a maximum of five ecological condition states (very high, high, moderate, low, very low), analogous to ecological condition frameworks developed for the European Union Water Framework Directive (Zaldivar et al. 2008). Existing guidance and quantitative analyses were used to inform the “thresholds” that define the range of values within each bin.

For most indicators, guidance exists in the form of established WQOs, state, federal or international guidance, or published studies that form the scientific foundation for their use in a classification scheme. For chlorophyll-a, we lacked confidence that an expert-derived existing guidance developed for estuaries around the world (e.g., Zaldivar et al. 2008) could be applied, without question, to SFB. For this reason, analyses of existing data were used to investigate the linkage between chlorophyll-a and potential pathways of impairment, detailed in Appendix C. Quantitative analyses and existing published guidance were supplemented by best professional judgment to address key data gaps and describe uncertainty and level of confidence in the classification.

For the purpose of reporting on status and trends, we recommend that classification occurs annually by subembayment, thus characterizing the spatial extent if the results are viewed on the whole for SFB or for each subembayment. The AF was designed to be applied using a data set that includes a minimum of monthly, ship-based discrete samples and CTD profiles, with spatial resolution given in Figure 3.10 (Senn et al. 2014a).

The following sections describe development of classification tables for each of the four indicators: phytoplankton biomass (chlorophyll-a), gross primary productivity, HABs abundance, and HABs toxins (the two HABs indicators are merged into one section). The final section offers recommendations regarding the future of indicator development work for dissolved oxygen.

Phytoplankton Biomass (Chlorophyll-a)

Chlorophyll-a has formed a cornerstone of standardized approaches to assess eutrophication (Bricker et al., 2003, Zaldivar et al. 2008) and to support regulatory water-quality goals in estuaries (Harding et al., 2013) because it is a well-recognized indicator that integrates nutrient loadings and represents adverse effects to ecosystems. Decisions based on quantitative endpoints can be based on deviations from “reference” conditions, or on quantitative relationships with ecosystem impairments (e.g., Harding et al. 2013). In SFB, records of chlorophyll-a prior to human disturbance are not available, complicating development of reference chlorophyll-a ranges. An extensive, multi-decadal dataset is available to explore quantitative relationships between chlorophyll-a and potential pathways of adverse effects, as a means for establishing chlorophyll-a endpoints.

We analyzed a multi-year dataset that included chlorophyll-a (1993-2014), phytoplankton species composition (1993-2014), DO (1993-2014), and algal toxins (2012-2014) to (1) explore trends in HAB abundance, toxins, and DO concentrations and their relationships with chlorophyll-a, and (2) quantify chlorophyll-a thresholds and related uncertainty that correspond to categories of “protected” and “at risk” in the context of current DO WQOs and HAB alert levels. Quantile regression and conditional probability analysis were used to identify thresholds of chlorophyll-a, corresponding to categories of increasing risk in the context of current DO WQOs (SFRWQCB 2015) and HAB alert levels (Appendix C).

We found that HAB toxins and species can be routinely detected in SFB subembayments. Increased occurrences of HAB species and declining DO were correlated with increased chlorophyll-a over the 20-year period. Monthly chlorophyll-a “thresholds” corresponding to increased risk of HABs were identified, aggregating across all subembayments. The analyses were also sufficiently robust to estimate chlorophyll-a thresholds relating to DO for South Bay and Lower South Bay. Taken together, these analyses were used to support a preliminary set of chlorophyll-a assessment thresholds aimed at defining a gradient of ecological condition (from low to high risk) for increased HAB events and low DO in SFB subembayments.

Classification of chlorophyll-a linked to HABs is based on a monthly timescale because the HAB alert guidance is based on acute risk. In contrast, classification based on the linkage to dissolved oxygen was based on the mean concentration of monthly values from February to September, the time period in which biomass has been observed to be changing over the last two decades in SFB. This difference in temporal statistic reflects a more contemporaneous linkage between chlorophyll-a and HABs, as compared to the lagged response of organic matter production and the eventual increased potential for DO depletion. For DO, the differences in classification by subembayment reflect regional differences in hydrogeographic factors affecting DO dynamics.

Classification of Chlorophyll-a Linked to HABs. Categorization of monthly mean chlorophyll-a is directly linked to the outcome of quantile regressions and CPA relating the acute risk of HABs as a function of increased chlorophyll-a (Table 3.4, Appendix C: Figures 6-8). The highest category of ecological condition is defined by monthly mean chlorophyll-a values < 13 mg m^{-3}, which represents a baseline probability of ~0.39 to 0.4 for HAB abundance and ~0.3 for domoic acid and microcystins. Ecological condition is downgraded as monthly values in the range of 13-25 mg m^{-3} show increased probabilities of exceeding HAB alert values to up to 0.44 for HAB abundance and 0.6 or greater for toxins. Chlorophyll-a concentrations in the range of 40 mg m^{-3} represent a 0.5 to 0.68 probability of a HAB event; while there are only two data points for toxins between 20-60 mg m^{-3}, the CPA suggests a probability of 0.6-0.7 within this range of chlorophyll. Occurrence of HABs on a more frequent basis represents a potentially chronic exposure to toxins (e.g. Ger et al. 2009; Goldstein et al. 2008), and thus, condition is downgraded as the annual frequency of occurrence in monthly samples increases (Table 3.4).

For context, on a Bay-wide scale, 13 mg m^{-3} corresponds to the 90th percentile of monthly surface chlorophyll-a over the last 20 years. On a sub-embayment scale, Central, North Central, San Pablo and Suisun Bay stations were below 13 mg m^{-3} for greater than 95% of the time over the last 20 years. The range of chlorophyll-a at Lower South Bay and South Bay stations was slightly higher. The ranges were below 13 mg m^{-3} 74% and 85% of the time, respectively, in Lower South Bay and South Bay, and below 25 mg m^{-3} 88% and 93% of the time, respectively (Figure S3, supplemental materials in Appendix C).

Table 3.4. Chlorophyll-a Classification Table Linked to HAB Abundance, Based on Annual Frequency of Occurrence in Monthly Samples. Classification should be applied to each subembayment.

Subembayment Monthly Mean Chlorophyll-a Linked to HAB Abundance (µg L^{-1})	Ecological Condition Based on Annual Frequency of Occurrence in Monthly Samples			
	1 of 12	2-3	4-6	6+
≤ 13	Very high	Very high	Very high	Very high
>13 – 25	Good	Moderate	Moderate	Low
>25 – 40	Moderate	Moderate	Low	Very Low
>40 – 60	Moderate	Low	Very Low	Very Low
>60	Low	Very low	Very low	Very low

Classification of Chlorophyll-a Linked to DO. While chlorophyll-a was negatively correlated with DO in all subembayments, only in South Bay and Lower South Bay were these relationships consistently significant to quantify thresholds supporting classification decisions. Conceptually, the mechanism resulting in an expected negative relationship between summer DO and February-September mean chlorophyll-a is that high primary production during this time scale is expected to promote increased abundance of planktonic and benthic detritus, which during summer leads to an increasing probability of net ecosystem heterotrophy (Caffrey 2003). In some areas of San Francisco Bay, and at some times in all subembayments of the Bay, biological effects on DO are dominated by physical processes such as fluvial transport, stormwater and treated wastewater inputs, water exchange between subembayments, and mixing or exchange between habitats within a subembayments (Smith and Hollibaugh, 2006). The modulating factors are generally very important in both Central and Suisun Bays, which are most proximal to and have greater exchange with the coastal ocean and the Delta, respectively. It may still be possible to establish chlorophyll-a thresholds at which DO will begin to decline to unacceptable levels in the Central and North SFB subembayments, using other modeling approaches than what was employed by Sutula et al. (in prep, Appendix C).

In developing a chlorophyll-a classification scheme linked to DO for South and Lower South Bays, we relied principally on the predicted chlorophyll-a thresholds produced from quantile regressions of DO concentration that represent a range of ecological condition, from 7 to 4 mg L^{-}

^{1} (Table 3.4, Appendix C: Tables 1-2). We note that the three-month median percent saturation WQO of > 80% is ~ 7 mg L^{-1} at summertime mean temperature and salinity in South SFB. According to the proposed European Union Water Framework Directive (EU WFD) for classification of estuarine waters based on DO (Best et al. 2007), 5.7 mg L^{-1} at marine salinities is equivalent to 7 mg L^{-1} in freshwater criteria, with chronic values considered to be supportive of salmonid reproduction and survival, which is not a designated use in South SFB. Thus, the "very high" tier of 7.0 mg L^{-1} is roughly equivalent to meeting the three-month median percent saturation objective, while the "moderate" condition category has 90% probability that the 5 mg L^{-1} concentration objective would be met (Table 3.5). This approach is comparable, though with higher expectations, than is used in Best et al. (2007). Without specific analyses that clarify the seasonal and habitat-specific DO acute and chronic criteria required to support beneficial uses, we have more heavily weighted our DO classification bins to align with existing SFB WQOs. We used the lower 95% confidence interval of the predicted 0.1 Tau quantile of February to September mean chlorophyll-a (Sutula et al., in prep, Appendix C) as the basis for the classification bin, because it gives greater confidence that chlorophyll-a falls above the predicted lower end of the classification bin.

Table 3.5. Chlorophyll-a Classification Table Based on Risk of Falling Below DO Water Quality Objectives, Based on Annual February-September Mean Chlorophyll-a, for South Bay and Lower South Bay only.

Classification of ecological condition based on mean February - September chlorophyll-a (mg m^{-3}) linked DO benchmarks - South Bay and Lower South Bay Only		
Category	**Lower South Bay**	**South Bay**
Very high)	≤23	≤14
High		>25 - 32
Moderate	>23 - 35	>32 - 44
Low	>35 - 51	>44 - 58
Very Low	>51	>58

In South Bay, quantile regression results provided in Appendix C suggest that a February to September mean chlorophyll-a of 13-16 mg m^{-3} is "protective" of the three-month median DO percent saturation WQO (80% or ~7 mg L^{-1} at summertime mean temperature and salinity in South SFB). At a February-September mean of 13 mg m^{-3}, 90% of the DO is predicted to be above 7 mg L^{-1}, while at 42 mg m^{-3}, 90% of the DO is predicted to be above 5.0 mg L^{-1} (Appendix C: Table 2). Ninety-five percent of the February-September mean chlorophyll-a measured at South Bay sites over the 20-year record is below 14 mg m^{-3} (Appendix C: Figure A4), reflecting the fact that primary production in combination with physics in the deep channel habitat of South Bay promotes largely normoxic conditions – greatly improved from the periods of hypoxia recorded prior to implementing advanced wastewater treatment in the 1970s (Cloern and Jassby, 2012). Uncertainty in this classification is low (see 95% confidence intervals, Appendix C: Table 2), given the significance of the quantile regression. However, we note that existing data were limited to ship-based data that do not capture a diel curve, contributing to uncertainty that existing relationship does not capture true DO minima. These analyses should be repeated with continuous DO data that better characterizes physical and biological exchanges with the shallow water margin habitat. Such data do not exist and we recommend that they be collected.

CPA and quantile regressions were also used to support a chlorophyll-a classification scheme for Lower South Bay, albeit with more uncertainty than for South Bay. The reasons for this greater uncertainty are two-fold. First, biological and physical exchanges between Lower South Bay and the adjacent shallow margin habitats are unquantified. While CPA analyses could only be used to suggest a threshold in which the subembayment is “at risk” of falling below the 80% percent saturation WQO (~13 mg m^{-3}), neither CPA nor quantile regression could be used to derive a chlorophyll-a value that would be “protective” of the percent saturation WQO. It is likely that an additional source of DO water < 80% saturation (from either the tidal slough or restored salt ponds) is exchanging with Lower South Bay deep channel habitat. These margin habitats have been documented to routinely fall below 5 mg L^{-1} DO on diel timescales (Thebault et al, 2008; Shellenbarger et al, 2008, SFEI 2014a). Considering that these intertidal habitats rich in organic carbon may have natural sources of low DO water, the expectations for DO in these habitats and their physical and biological exchanges with Lower South Bay need to be considered in setting appropriate expectations for Lower South Bay deep channel habitat (Sutula et al. 2012, Bailey et al. 2014). Second, it is noteworthy that while these data show that Lower South Bay is meeting the 3-month median DO saturation objective only 72% of the time, it is above 5 mg L^{-1} 97% and above 5.7 mg L^{-1} 90% of the time over the past 20 years, with 95% of the February to September mean chlorophyll-a less than 25 mg m^{-3}. Best et al. (2007) have proposed > 5.7 mg L^{-1} as a benchmark to represent the highest ecological condition category for estuaries assessed under the European Union Water Framework Directive. Given this, it will be helpful to review the science supporting existing DO WQOs in SFB specifically with respect to both deep water and shallow margin habitats, as is currently being done for Suisun Marsh as part of development of a DO TMDL (Bailey et al. 2014).

Major Sources of Uncertainty in Chlorophyll-a Classification. Overall, uncertainty exists in this proposed chlorophyll-a classification framework and our ability to quantify that uncertainty is constrained. Five major types of uncertainties exist in the chlorophyll-a framework linked to HABs and DO impairment pathways: (1) significance of the ecological and human risk of HABs in SFB, (2) linkage of chlorophyll-a to HAB cell counts, rather than toxin concentrations, as the foundation for the risk paradigm; SPATT toxin data were used to supplement the analyses, but the calibration of SPATT relative to particulate or mussel toxin tissues is still ongoing and should be a continued management focus, (3) uncertainty in the risk to aquatic life, since the HAB alert levels are focused on risk to human health rather than aquatic life, (4) uncertainty in capturing risks of chronic exposure to HABs, stemming from the fact that alert levels are based on acute toxin exposure, (5) the underlying mechanism of the correlation between February-September chlorophyll-a and summer DO, and (6) appropriate DO expectations for shallow water margins, tidal sloughs and intertidal wetland habitat, and portions of the SFB open water habitat that are strongly linked to the margins (e.g. LSB).

Our classification tables for chlorophyll-a are somewhat distinct from the other indicators in that they rely on relationships with other SFB attributes (e.g. HAB abundance and DO). We know from other long-term observational programs that changes can also include shifts in the efficiency with which nutrients are assimilated into algal biomass (Riemann et al. 2015). SFB’s high nutrient concentrations imply a potential to produce phytoplankton biomass at levels that impair water quality. To illustrate this point we computed median concentrations of dissolved inorganic nitrogen (DIN) and chl-a a across four subembayments of the estuary (Appendix C: Table 3). We then computed potential chl-a as the sum of measured chl-a plus the quantity of chl-a that could be produced if all remaining DIN was assimilated into phytoplankton biomass, assuming a conversion factor of 1 g chl-a per mol N (Eppley et al. 1971). If this potential is realized then the median chl-a concentrations in all Bay subembayments would increase by an order of magnitude. Given the uncertainty in SFB's trajectory amidst global change, it is this potential for high biomass production that motivates establishment of chl-a thresholds to support nutrient management in SFB. Though we like to think of these relationships as fixed, in reality, these chl-a thresholds can change as fundamental drivers such as oceanic exchange, top-down grazing, light limitation, etc. that control the nature of the relationship between chl-a, HAB cell density and DO can change with climate variability and climate change, (Cloern et al. 2014, Riemann et al. 2015).

This point underscores the critical need to continuously reevaluate these relationships through a long-term consistent monitoring program in SFB. A consistent monitoring program would go a long way to reduce some of the remaining uncertainties in the existing data, given the large data gaps and inconsistent available data between sites, for the analyses conducted here (Sutula et al, (in prep), Appendix C).

Gross and Net Primary Production

Annual GPP is proposed as an AF indicator, to be measured via an empirical method utilizing chlorophyll-a, photic depth, surface irradiance (per Cole and Cloern 1984), recalibrated with specified direct, discrete measures of GPP (e.g., Cloern et al. 2014). GPP is complementary to chlorophyll-a, which does not provide a direct measure of the internal supply rate of biological oxygen demand, nor the rate of turnover of phytoplankton carbon. Annual GPP would be assessed based on the identical temporal and spatial data collected to support chlorophyll-a.

Decisions on classification thresholds for GPP were based on Nixon (1995), who proposed definitions of the trophic state of estuaries as oligotrophic (< 100 g C m^{-2} yr^{-1}), mesotrophic (100-300 g C m^{-2} yr^{-1}), eutrophic (>300-500 g C m^{-2} yr^{-1}), and hypereutrophic (> 500 g C m^{-2} yr^{-1}). For the purposes of assessment of SFB subembayments, we collapsed these into three categories (Table 3.6). Hypereutrophic represents the boundary between moderate and low/very low ecological condition (>500 g C m^{-2} yr^{-1}). Oligotrophic and mesotrophic are combined into one category (very high/high ecological condition), expressly to avoid categorizing very low production values as indicative of very high ecological condition, since some level of production is considered important.

Nixon did not specify a method for measurement of GPP; Cloern et al. (2014) documented how differences among methodologies can have a large impact on estimated GPP. We propose confirming proposed GPP classification boundaries using the SFB water quality model, once calibrated for DO, in order to provide an additional confirmation of these proposed classification thresholds.

Table 3.6. Gross Primary Productivity Classification Table Based on Annual Rate (g m^{-2} yr-^{1}). Classification should be applied to each subembayment.

Category	**Gross Primary Productivity (g m^{-2} yr-^{1})**
Very high/High	≤300
Moderate	>300 - 500
Low/ Very Low	≥ 500

Major Sources of Uncertainty in Classification of GPP. The greatest source of uncertainty in the proposed GPP classification is the lumping of highly oligotrophic GPP into the highest category. We acknowledge that, while it would be desirable to identify some level of GPP that is too low, the Expert Workgroup felt that we did not have the scientific basis to determine at what level that is. This remains a source of uncertainty in this classification. Another source of uncertainty is the use of an indirect approach to estimate GPP. Although other sources of uncertainty in estimates of GPP exist (e.g. short term pulses missed by monthly sampling programs, Gallegos and Neele, 2015), we feel that if these indirect estimates are calibrated on a frequent basis with direct measures, this uncertainty will be constrained.

HAB Abundance and Toxins

Classification of HAB cell counts and toxins is based on the assumption that values exceeding thresholds or alert levels used in comparable systems (Table 3.7), or trends of increasing occurrence, are evidence of reduced water quality. This is consistent with findings from the U.K. Undesirable Disturbance Study Team (Tett et al. 2007) and is supported by recent syntheses examining the relationship between HABs and coastal water quality (Heisler et al. 2008; Anderson et al. 2008).

Table 3.7. Potential HABs from San Francisco Bay, and alert levels used in other regions.

Organism	***Alert Level (cells/L)***	***Reference***
Alexandrium spp.	Presence	http://www.scotland.gov.uk/Publications/2011/03/16182005/37
Blue-Green Algae	100,000	WHO, 2003; California Guidance (OEHHA, 2012)
Dinophysis spp.	100-1,000	http://www.scotland.gov.uk/Publications/2011/03/16182005/37; Vlamis et al. 2014
Heterosigma akashiwo	500,000	Expert opinion
Karenia mikimotoi	500,000	Expert opinion
Karlodinium veneficum	500,000	Expert opinion
Pseudo-nitzschia	10,000-50,000	Cal-HABMAP ; Shumway et al. 1995; Anderson et al. 2009

The classification scheme assumes data collection similar to the USGS monitoring program data described above, and includes regular (monthly) monitoring of phytoplankton species and total (particulate and dissolved) toxin from the top 2 m of the water column using grab samples, deployment of SPATT or similar integrative samplers as part of Bay-wide surveys, and targeted collection of tissue samples from bivalves and marine mammals. For the assessment, the expert working group assumed maximum toxin concentration and maximum cell abundance by Bay subembayment would be used as a metric because of the potential risk to human and ecosystem health, and the likelihood of undersampling given the relatively coarse temporal and spatial scales. As with the classification scheme for chlorophyll-and DO, we consider this initial set of recommendations to be hypotheses that should undergo further testing and refinement when more data are available.

Classification of HAB Toxins. Guidance for toxins is currently restricted to domoic acid, microcystins, and paralytic shellfish toxins (PSTs) since those three classes of toxins are both persistent and regulated in the State of California. The scheme could be extended to other toxins given sufficient information about acceptable levels. Since existing guidance is based on acute exposure or Tolerable Daily Intake (e.g. World Health Organization guidelines for microcystins), we did not include a "duration" of exposure, and consider chronic effects to be an area of emerging concern (e.g., Ger et al. 2009; Goldstein et al. 2008; Hiolski et al. 2014) that should be considered as more data become available.

For toxin concentrations, progressions among classification bins are treated the same, based on existing alert levels, where we classify 50% of the regulatory closure level as a "warning level" and the closure limit as a (regulatory) action level. Ecological condition states are therefore: non-detect to 10% of the warning level, 10-100% of the warning level, above the warning level and below an action level, and above an action level. Since there is no direct correlation between SPATT toxin concentrations and grab sample concentrations, we assigned categories based on historical data from the region, corresponding to those categories and based on comparison of SPATT with grab and tissue samples (Lane et al. 2010; Kudela 2011). We acknowledge that this is a weak point of the classification scheme and a major source of uncertainty, but the advantages of SPATT for routine monitoring (Mackenzie et al. 2004) outweigh these concerns.

Tables 3.8, 3.9, and 3.10 provide classification schemes for microcystins, domoic acid, and saxitoxins. Note that SPATT is not routinely used for saxitoxins and has been omitted from Table 3.10. For microcystins, water concentrations are based on OEHHA 2012 guidance, which sets the alert level for recreational contact, domestic animals, and livestock at 0.8 ppb for microcystins LR, RR, YR, and LA. For mussel tissue, values are based on WHO guidance of 0.04 µg/kg body weight per day, assuming 100 g consumption of tissue and a 60 kg individual; it is assumed that these values can be scaled to other organisms. Tables 3.9 and 3.10 provide the same classification scheme for domoic acid and paralytic shellfish toxins. Alert levels are based on California Department of Public Health guidelines for tissue of 20 ug/g for domoic acid and 80 ug/100g for PSTs for protection of human health. For all three toxins, annual assessment of ecological condition would be based on the lowest rating for the year to provide the most protective classification.

Table 3.8. Toxin Classification Table for Microcystin. Classification should be applied to each subembayment. If multiple occurrences in different media (particulate, SPATT, tissue) are detected within a subembayment on an annual basis, the lowest rating for the year should be applied.

Toxin Concentration	Ecological Condition Based on Annual Frequency of Occurrence in Monthly Samples			
	1 of 12	2-3	4-6	6+
Particulate concentration				
Non-detect	Very high	Very high	Very high	Very high
Detectable, but < 0.8 ppb	High	Moderate	Moderate	Low
0.8 - 20 ppb	Moderate	moderate	Low	Very Low
>20 ppb	Low	Very Low	Very Low	Very Low
SPATT				
Below the warning level <100 ng/g)	Very high	Very high	Very high	Very high
100-250 ng/g	Moderate	Low	Very low	Very Low
>250 ng/g	Low	Very Low	Very Low	Very Low
Mussel Tissue				
Non-detect	Very high	Very high	Very high	Very high
Detectable, but < 12 ng/g	High	Moderate	Moderate	Low
12-24 ng/g	Moderate	moderate	Low	Very Low
> 24 ng/g	Low	Very Low	Very Low	Very Low

Table 3.9. Toxin Classification Table for Domoic Acid. Classification should be applied to each subembayment. If multiple hits in different media (particulate, SPATT, tissue) are detected within a subembayment on an annual basis, lowest rating for the year should be applied.

Toxin Concentration	Ecological Condition Based on Annual Frequency of Occurrence in Monthly Samples			
	1 of 12	2-3	4-6	6+
Particulate concentration				
Non-detect	Very high	Very high	Very high	Very high
0-100 ug/L	High	Moderate	Moderate	Low
100 - 1000 ug/L	Moderate	moderate	Low	Very Low
> 1000 ug/L	Low	Very Low	Very Low	Very Low
SPATT				
<30 ng/g	Very high	Very high	Very high	Very high
30-75 ng/g	Moderate	Low	Very low	Very Low
>75	Low	Very Low	Very Low	Very Low
Mussel Tissue				
Non-detect	Very high	Very high	Very high	Very high
< 10 ppm	High	Moderate	Moderate	Low
10-20 ppm	Moderate	moderate	Low	Very Low
> 20 ppm	Low	Very Low	Very Low	Very Low

Table 3.10. Toxin Classification Table for Paralytic Shellfish Toxins. Classification should be applied to each subembayment. If multiple hits in different media (particulate, SPATT, tissue) are detected within a subembayment on an annual basis, lowest rating for the year should be applied.

Toxin Concentration	Ecological Condition Based on Annual Frequency of Occurrence in Monthly Samples			
	1 of 12	2-3	4-6	6+
Particulate Concentration				
Non-detect	Very high	Very high	Very high	Very high
Detectable	Low	Very low	Very low	Very Low
Mussel Tissue				
Non-detect	Very high	Very high	Very high	Very high
< 40 µg/100 g	High	Moderate	Moderate	Low
40-80 µg/100 g	Moderate	moderate	Low	Very Low
> 80 µg/100 g	Low	Very Low	Very Low	Very Low

Classification of HAB Abundance. The classification scheme for presence of HAB organisms is based on a similar metric as for toxins (Table 3.11). An alert level is defined based on existing monitoring programs, and condition is graded based on expert opinion relative to those alert levels. For *Alexandrium* specifically, because all monitoring programs consider presence of *Alexandrium* to be a potential impairment, only three cell abundance categories are used (not detected, detected at up to 100 cells/L, and more than 100 cells/L). For BGA, the criteria are restricted to stations or locations where salinity is less than or equal to 2, and the alert level is based on OEHHA 2012 guidance of 1E6 cells/mL (i.e., scum-forming blooms). Given the prevalence of BGA toxins in SFB (Appendix C-Figure 3), more conservative cell abundances were chosen for transitions from high Very High to Very Low condition compared to an alert threshold of 1E6 cells/mL.

Table 3.11. HAB Abundance Classification Table. Classification should be applied to each subembayment. If multiple HABs are detected within a subembayment on an annual basis, lowest rating for the year should be applied.

Cell Count By Taxonomic Group	Ecological Condition Based on Annual Frequency of Occurrence in Monthly Samples			
	1 of 12	2-3	4-6	6+
Cyanobacteria[1]. Applies at salinities ≤ 2 ppt.				
Absent to < 20,000 cells per ml	Very high	Very high	Very high	Very high
20,000 – 10^5 cells per ml	High	Moderate	Low	Very Low
10^5 – 10^7 cells per ml	Moderate	Low	Very Low	Very Low
> 10^7 cells per ml	Low	Very Low	Very Low	Very Low
Pseudo-nitzchia spp.				
<100 cells per l	Very high	Very high	Very high	Very high
100 to 10,000 cells per l	High	High	Moderate	Low
10,000 -50,000 cells per l	Moderate	Low	Low	Very Low
> 50,000 cells per l	Low	Very Low	Very Low	Very Low
Alexandrium spp.				
Non detect	Very high	Very high	Very high	Very high
Detectable to < 100 cells	High	Moderate	Low	Very low
>100 cells	Low	Very low	Very low	Very Low

[1] Cyanobacteria include: Cylindrospermopsis, Anabaena, Microcystis, Planktothrix, Anabaenopsis, Aphanizomenon, Lyngbya, Raphidiopsis, Oscillatoria, and Umezakia

Uncertainty Associated with HAB Abundance and Toxin Classification. There are three major sources of uncertainty associated with the classification of HAB abundance and toxin concentrations. The first source derives from the use of existing guidance on cell counts and toxin concentrations. Standard guidelines have not been adopted at the State or federal level. Second, while HABs represent a palatable risk to human and ecological threat in SFB, uncertainty exists in the significance of that threat. For humans, the uncertainty lies in the level of risk given the amount of contact and noncontact recreation that occurs, as well as consumption of shellfish from SFB. Improved data on the concentrations of toxins in mussel tissue and shellfish consumption survey may help to better quality that risk. For aquatic organisms, this risk is difficult to characterize, particularly because existing guidance is oriented towards human health rather than ecological endpoints and on acute rather than chronic exposure to toxins. Because of the high baseline of HAB occurrence in SFB, uncertainty about values corresponding to this pathway of chronic exposure becomes a significant concern. The third source of uncertainty is the inclusion of SPATT-derived toxins in the classification scheme. SPATT as a tool has not undergone rigorous calibration. Because of its utility as a monitoring tool, calibration of SPATT relative to particulate or mussel toxin tissues should be a continued management focus.

Dissolved oxygen

Dissolved oxygen (DO) is considered to be keystone indicator within the AF. DO is necessary to sustain the life of all aquatic organisms that depend on aerobic respiration and, thus, it has a direct linkage to aquatic life and beneficial use protection (see Sutula et al. 2012 for comprehensive review). Eutrophication produces excess organic matter that fuels the development of hypoxia and, in some cases, anoxia as that organic matter is respired (Diaz 2001). Low dissolved oxygen (DO) has direct effects on the reproduction, growth and survival of pelagic and benthic fish and invertebrates (USEPA 2000, Bricker et al. 2003, Best et al. 2007). The response of aquatic organisms to low dissolved oxygen will depend on the intensity of hypoxia, duration of exposure, and the periodicity and frequency of exposure (Rabalais and Harper 1992). Thresholds for assessment of effects of DO are derived from criteria deemed to be protective of the most sensitive species from acute (timescales of days) and chronic (time scales of weeks to months) exposures to low dissolved oxygen.

In this work, we chose explicitly to defer work on a classification scheme for DO, citing the need to prioritize the development of classification for phytoplankton related indicators and the fact that DO objectives already exist for SFB. The following recommendations are intended to encourage future discussion of DO classification schemes for SFB, given that no scheme is being proposed at this time.

Existing DO WQOs exist for SFB, based on a combination of DO concentration and percent saturation objectives. The SFB Water Board staff is considering revising the Basin Plan to allow for deviation from these numeric objectives in Suisun Marsh (Howard et al. 2014) and is entertaining a similar undertaking for shallow margin and intertidal habitats in South and Lower South Bay. Once this has been established, modeling could be used to refine expectations for the deep channel habitats of South SFB. Considering that these intertidal habitats rich in organic carbon may have natural sources of low DO water, and may experience natural conditions of low DO, the expectations for DO in these habitats and their physical and biological exchanges with open water habitat need to be considered in setting appropriate expectations for the deep channel habitat.

One question that should be addressed in future iterations of the SFB AF is the need to develop a DO AF that captures a fuller gradient in condition than expressed through binary classification associated with meeting established WQOs (i.e., above or below established objectives). Best et al. (2007) have proposed a DO classification scheme for European Union Water Framework Directive (EU-WFD) based on observed impacts of hypoxia on benthic and demersal fauna, as well as expert opinion, that is targeted to be relevant in a wide range of estuarine environments (Vaquer-Sunyer and Duarte 2008). The thresholds proposed by Best et al. (2007) are similar to those calculated for California species, including those found in SFB (5.7 mg L^{-1} as chronic-effects criteria protective of 95% of the non-salmonid population and 2.8 mg L^{-1} as acute effects criteria; Sutula et al. 2012). For salmonids, Sutula et al. (2012) calculated 6.3 mg L^{-1} as chronic effects criteria and 4.0 mg L^{-1} as acute effects criteria, but notes that the effects data used to calculate these criteria were based of freshwater exposure studies. Thus, applying fixed criteria to habitats that represent a continuum along a salinity gradient can be problematic. The Best et al. (2007) thresholds have the advantage of incorporating the effects of salinity on oxygen solubility and, thus, can reconcile a threshold protective of all life history stages for salmonids from 7 mg L^{-1} in freshwater to 5.7 mg L^{-1} at marine salinities. The ASSETS upper threshold of 5.0 mg L^{-1} is roughly equivalent to this threshold but does not take into account salinity (Bricker et al. 2003). Both ASSETS and EU-WFD (Bricker et al. 1999, 2003) utilize the 5th and 10th percentile, respectively, to integrate over time, similar to the SFB Basin Plan calculation of 10% frequency of non-compliance. The use of the percentile approach integrates the duration and frequency of low DO events and doesn't distinguish between high frequency short duration events and low-frequency but long-duration events. The effect of these two examples can be very different on biota, depending the timing and number of reproductive cycles in the year, number per brood, etc.

Estuarine subtidal habitat and associated intertidal margin habitats are prone to development of density-driven stratification, precluding diffusion and mixing of oxygen to bottom waters (Largier et al. 1991, 1996). Sutula et al. (2012) note that natural hypoxia in bottom waters of stratified estuaries is an issue for interpretation of existing Water Boards' DO objectives. Stacey (2015, Appendix D) analyzed the frequency of stratification events in South Bay; he found that: (1) salinity-stratification most often occurs during periods of peak freshwater flow to SFB (winter-spring), (2) duration of stratification seldom persists for periods greater than two weeks due to tidal mixing associated with spring tides, and (3) observed periods of low DO in South Bay do not typically coincide with stratification events. Incursions of low DO water into SFB is possible when oceanic deep waters upwell at the mouth of SFB (J.E. Cloern, personal communication). Although these are currently rarely observed, it is possible that these events will occur with increased frequency due to rising coastal hypoxia (Booth et al. 2013).

Finally, in the first phase of AF development, we chose not to recommend a prescribed monitoring program for DO. Such recommendations were outside the scope of our current effort, yet we believe that this is an important issue – one that should be coupled to a better characterization of the seasonal DO requirements of the most sensitive species and their important habitats in SFB. Future science plans related to DO should address this important aspect.

3.4 AF Indicators as Multiple Lines of Evidence

A core principle of the AF is that it be comprised of several indicators that should be used as multiple lines of evidence in the determination of overall ecological condition. In this preliminary AF, we have chosen not to specifically address combining each indicator into a multi-metric index, pending refinement of the classification through improved monitoring, modeling and other research. However, we can offer some simple guidance on the relative weight that these indicators can be given in view of their status and relative degree of associated uncertainty. This relative importance, presented as multiple lines of evidence, can be revised as uncertainties are reduced and our understanding of risk to beneficial uses from each impairment pathway improves.

Three indicators should be given strong weight in motivating management attention the near term, given their strong linkage to beneficial uses: (1) dissolved oxygen, (2) HAB toxins, particularly if found to be accumulating to levels of concern in shellfish or other aquatic organisms, and (3) gross and net primary productivity. We note that DO already serves as an independent line of evidence, as it is already in the SFB Water Board Basin plan.

HAB abundances should be given moderate weight in motivating management action. For HAB abundances, this weight could be refined pending better characterization of HAB risk in SFB.

Chlorophyll-a should be given moderate weight in motivating nutrient management action in the short term, because of the considerable uncertainty in the linkage of chlorophyll-a with HAB toxins and DO, particularly in shallow margins with SFB. The trend in chlorophyll-a should be given as much weight as the absolute magnitude. However, given the importance of the linkage of chlorophyll-a and GPP with nutrient loads, reduction in the uncertainty surrounding chlorophyll-a classification should be a high priority in the SFB Nutrient Science Plan.

Finally, for metrics of phytoplankton composition, emphasis should be on research and data visualization to communicate the ecological significance of trends over time. We would expect that a classification system for phytoplankton food quality index should be forthcoming after a period of piloting and demonstration in SFB. However, poor phytoplankton food quality, as well as other shifts in phytoplankton composition, can be driven by factors other than nutrients. For this reason, this indicator will likely serve as a supporting rather than primary line of evidence going into the future.

4 SUMMARY OF FINDINGS, VISION FOR NEAR-TERM USE, AND RECOMMENDATIONS FOR AF REFINEMENT

4.1 Summary of Findings

San Francisco Bay has long been recognized as a nutrient-enriched estuary; however, it has exhibited resistance to some of the classic symptoms of nutrient overenrichment, such as high phytoplankton biomass and hypoxia, due to a number of factors such as high turbidity, strong tidal mixing, and grazing that limit organic matter accumulation within the estuary. These observations have reinforced the need to identify numeric WQOs or a specific implementation plan for the existing narrative objective to protect the estuary from the potential effects of nutrient over-enrichment, especially following recent documentation of shifts in the timing and extent of freshwater inflow and salinity intrusion, decreasing turbidity, restructuring of plankton communities, elimination of hypoxia and reduced metal contamination of biota, and food web changes that decrease resistance of the estuary to nutrient pollution.

In this study, we utilized an expert workgroup to develop a quantitative framework to assess eutrophication in the SFB, based on indicators of phytoplankton biomass (chlorophyll-a), gross primary productivity, the prevalence of harmful algal blooms (HAB) and toxin, and DO. Experts defined core principles including geographic scope, recommended Bay segmentation, linkage of key indicators to beneficial uses, and the protocols and recommended spatial and temporal frequency of monitoring that would support a core assessment of nutrient effects on SFB.

We discussed a quantitative scheme to classify SFB subembayments in tiers of ecological condition, from very high to very low, based on risk to adverse effects of nutrient overenrichment and eutrophication. Decisions on classification bins were supported by a combination of existing literature and guidance, quantitative analyses of existing SFB data from the USGS research program, and expert best professional judgment.

Analyses of two decades of phytoplankton species composition, chlorophyll-a, and dissolved oxygen (DO), as well as three years of toxin data from solid phase adsorption toxin tracking (SPATT) samplers, were used to demonstrate (1) significant increases in chlorophyll-a, declines in DO, and a high prevalence of HAB species and toxins across most SFB subembayments, and (2) strong linkage of increasing chlorophyll-a to declining DO and HAB abundance. Statistical approaches were used to define thresholds in chlorophyll-a related to increased risks of HABs and low DO. In development of the AF classification scheme, a qualitative summary of uncertainty associated with each indicator was made for the purpose of focusing future research, monitoring, and modeling on AF refinement.

4.2 Vision for Near-Term Use of AF

The nutrient AF is intended to provide a decision framework for quantifying the extent to which SFB is supporting beneficial uses with respect to nutrients. This AF is comprised of three important elements: (1) a set of conceptual models that defines what a problem would look like in SFB, if it occurred, (2) a set of core principles supporting the AF, and (3) classification tables. The AF supports and is supported through the other major elements through:

- Defining monitoring requirements (the core indicators, spatial and temporal frequency of sampling) needed to support routine assessments of SFB
- Modeling to identify a set of management endpoints that should constitute the output of SFB water quality models and improve mechanistic understanding of the linkage of nutrients to adverse outcomes in SFB
- Informing science by identifying analyses needed to further refine the AF and highlighting areas in which monitoring, modeling and core synthesis should be improved

Given this philosophy, we feel that it is important to provide a statement of the appropriate use of the AF, given existing uncertainties.

The conceptual models and AF core principles provide a sound scientific foundation for informing modeling and monitoring. Through early interactions with the stakeholder community, these are the components of the AF that appear to have the greatest consensus and the least "uncertainty."

The classification scheme is a critical element of the AF, because it represents a quantitative and transparent mechanism through which SFB data are interpreted to assess, ultimately, nutrient-related beneficial use support. Given its importance, the authors of this document fully acknowledge the uncertainty in the AF classification scheme and need for refinement, through multiple iterations of basic research, monitoring, and modeling.

We suggest that the near-term use of the AF classification system be focused on a scientific "test drive" that seeks to understand how to collectively use and improve efficiencies for assessment, monitoring and modeling. This "test drive" should also consider whether or how to combine indicator results into multiple lines of evidence, particularly for communication to the public. Finally, this test drive should be conducted in tandem with research, monitoring and modeling to refine the AF.

4.3 Recommendations for Refinement of the AF

From this initial work, a number of recommendations emerge for refining and potentially expanding the AF. Please note that these recommendations have not been prioritized, and that early discussions to incorporate these needs into the SFB Nutrient Management Science Plan have already begun.

1. **Improve scientific basis for nutrient-related segmentation of SFB.** Our recommendation that the preliminary segmentation be based on Jassby et al. (1997) is a departure from the existing subembayments used by the SFB Water Board for assessments and permit-related activities. We strongly recommend reanalysis of existing data to be repeated using the Jassby et al. (1997) methodology, using newly available and relevant ecological data, to finalize this segmentation scheme.

2. **Include diked baylands, restored salt ponds and tidal sloughs in future iterations of this AF.** Deepwater and shallow subtidal habitats are the focus of this AF; diked baylands, restored salt ponds, and tidal sloughs are excluded in this first phase of work. We believe that these shallow water margin habitats are critical components of the SFB ecosystem and should be include in future iterations of the AF.

3. **Include dissolved oxygen classification and recommendations for monitoring in future iterations of the AF.** Current recommendations for AF focus on indicators of phytoplankton. We recommend science and synthesis to accomplish the following:

    a. Improve understanding of what species, representative of different beneficial uses, are the most sensitive to low DO and what are the temporal and spatial scales of their use of SFB subembayments as habitat
    b. Identify DO criteria representing acute and chronic tolerances to low exposure, and individual and population scales
    c. Improve characterization of the diel variability of DO at key points within the deep water and shallow margin habitat of each subembayment in order to better characterize support of species and habitats
    d. Improve mechanistic understanding of the physical and biological factors influencing DO within and between the deep channel and shallow water margin habitat

4. Optimize spatial and temporal sampling of AF indicators to best align quality of the information produced, while balancing costs, logistics, and power to detect trends. Dissolved oxygen, phytoplankton biomass, productivity and phytoplankton composition are all extremely variable across both time and space. The temporal and spatial elements of the AF and the monitoring program must be aligned and optimized to capture this variability in a manner that is also cost-effective. This could be done by conducting an intensive field observation program coupled interpolated with hydrodynamic model simulations, then conducting power analyses to understand how to best capture variability, given real constraints in available resources. Another approach is to invite subject matter experts to provide perspective about how this was done in systems of similar size and complexity (e.g. Chesapeake Bay).

5. **Reduce sources of uncertainty in chlorophyll-a, HAB abundance and toxin classification.** Three major recommendations are given to reduce uncertainty in the chlorophyll-a classification. These include:

    e. Better characterization of the significance of the ecological and human risk of HABs in SFB through more intensive monitoring of subembayments
    f. Co-location of chlorophyll-a, particulate, shellfish and SPATT monitoring to improve linkage of chlorophyll-a to HAB toxin concentrations, rather than cell counts as the foundation for the risk paradigm
    g. Expansion of SPATT samplers to include other toxins, particularly PSTs
    h. A work element to better validate SPATT toxin data relative to particulate or mussel toxin tissues: While this has historically been difficult, precedence exists (Lane et al. 2010), and because SPATT were originally designed for lipophilic toxins (Mackenzie et al. 2004), an obvious next step would also be to analyze SPATT samplers for okadaic acid, dinophysistoxins, and yessotoxins.
    i. Assembly of a scientific workgroup to synthesize scientific understanding of chronic effects of HAB toxins on SFB food webs and human health
    j. Monitoring improvements through better spatial coverage and temporal coverage of data to link chlorophyll-a to DO, focused specifically on South SFB, coupled with improved understanding of DO expectations for shallow water margins, tidal sloughs and intertidal wetland habitat (see Recommendation C above).

6. **Link HABs more specifically to nutrients.** Although deliberately excluded from this analysis, sufficient data exist to develop more complex multidimensional statistical models for harmful algal species and toxins (e.g. Kudela 2012) or to apply existing estuarine and coastal models to SFB (e.g. Lane et al. 2010; Anderson et al. 2009, 2010). This would also more directly link condition to nutrients.

7. **Fund a Nutrient Monitoring Program.** Since 1969, a USGS research program has supported water-quality sampling in SFB. This USGS program collects monthly samples between the South Bay and the lower Sacramento River to measure salinity, temperature, turbidity, suspended sediments, nutrients, dissolved oxygen and chlorophyll a. The USGS data, along with sampling conducted by the Interagency Ecological Program, provide coverage for the entire San Francisco Bay –Delta system. The San Francisco Bay Regional Monitoring Program (RMP) has no independent nutrient-related monitoring program, but instead contributes approximately 20% of the USGS data collection cost. Thus, there is currently an urgent need to lay the groundwork for a locally-supported, long-term monitoring program to provide information that is most needed to support nutrient-related management decisions in the Bay.

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APPENDIX A. DEFINITIONS OF KEY TERMS AND SFB BENEFICIAL USES

APPENDIX B REVIEW OF APPROACHES TO ASSESSMENT OF NUTRIENT EFFECTS ON ESTUARIES

Appendix C Quantitative Analyses Supporting Decisions on Chlorophyll-a Assessment Endpoints (Sutula et al. Manuscript in prep for Submission to a Scientific Journal)

APPENDIX D. SUPPLEMENTAL ANALYSES SUPPORTING DISCUSSION OF THE IMPORTANCE OF STRATIFICATION ON THE RELATIONSHIP BETWEEN DISSOLVED OXYGEN AND CHLOROPHYLL-A IN SF BAY (STACEY AND SENN, 2015 TECHNICAL MEMO)