Nutrient Management Strategy Science Program

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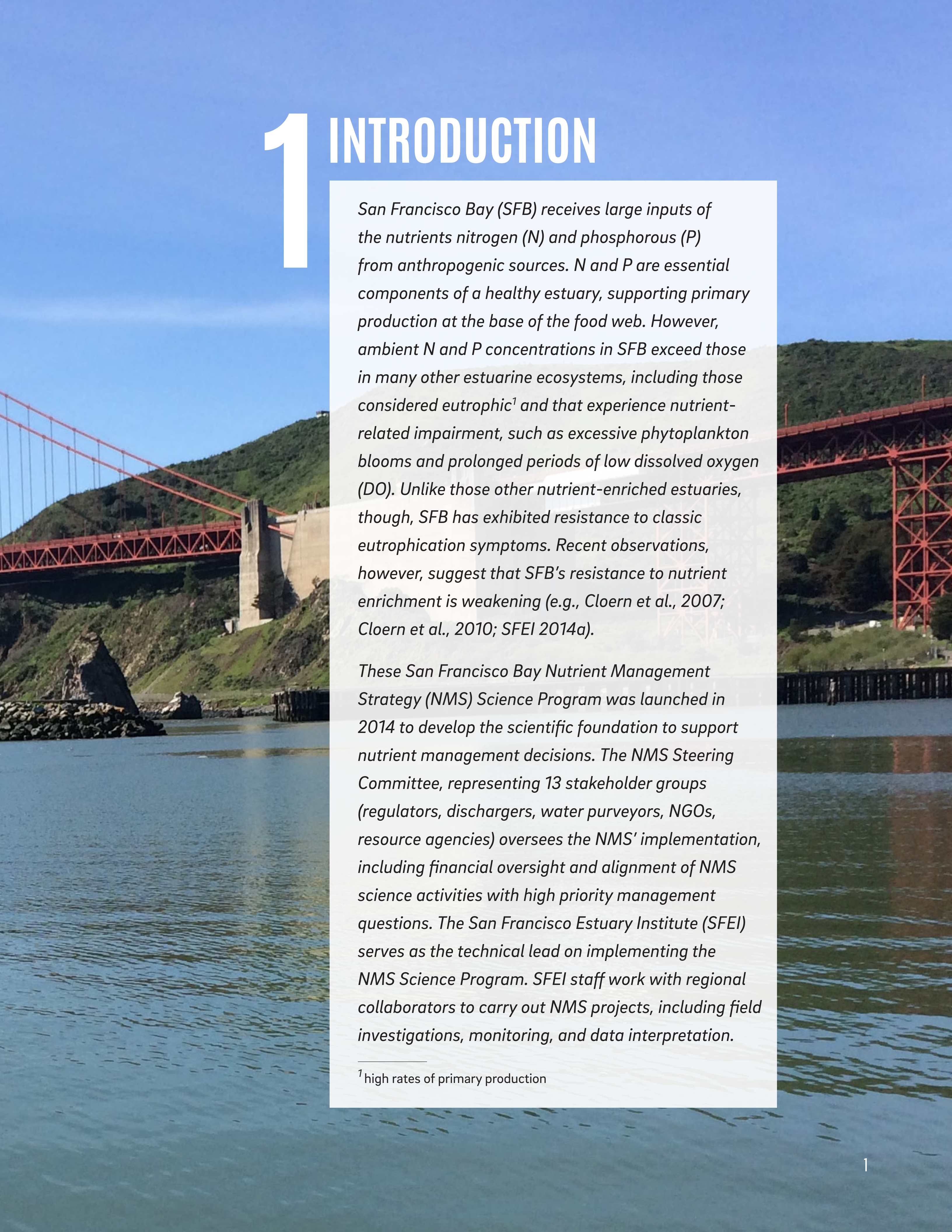

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INTRODUCTION

San Francisco Bay (SFB) receives large inputs of the nutrients nitrogen (N) and phosphorous (P) from anthropogenic sources. N and P are essential components of a healthy estuary, supporting primary production at the base of the food web. However, ambient N and P concentrations in SFB exceed those in many other estuarine ecosystems, including those considered eutrophic[1] and that experience nutrient-related impairment, such as excessive phytoplankton blooms and prolonged periods of low dissolved oxygen (DO). Unlike those other nutrient-enriched estuaries, though, SFB has exhibited resistance to classic eutrophication symptoms. Recent observations, however, suggest that SFB's resistance to nutrient enrichment is weakening (e.g., Cloern et al., 2007; Cloern et al., 2010; SFEI 2014a).

These San Francisco Bay Nutrient Management Strategy (NMS) Science Program was launched in 2014 to develop the scientific foundation to support nutrient management decisions. The NMS Steering Committee, representing 13 stakeholder groups (regulators, dischargers, water purveyors, NGOs, resource agencies) oversees the NMS' implementation, including financial oversight and alignment of NMS science activities with high priority management questions. The San Francisco Estuary Institute (SFEI) serves as the technical lead on implementing the NMS Science Program. SFEI staff work with regional collaborators to carry out NMS projects, including field investigations, monitoring, and data interpretation.

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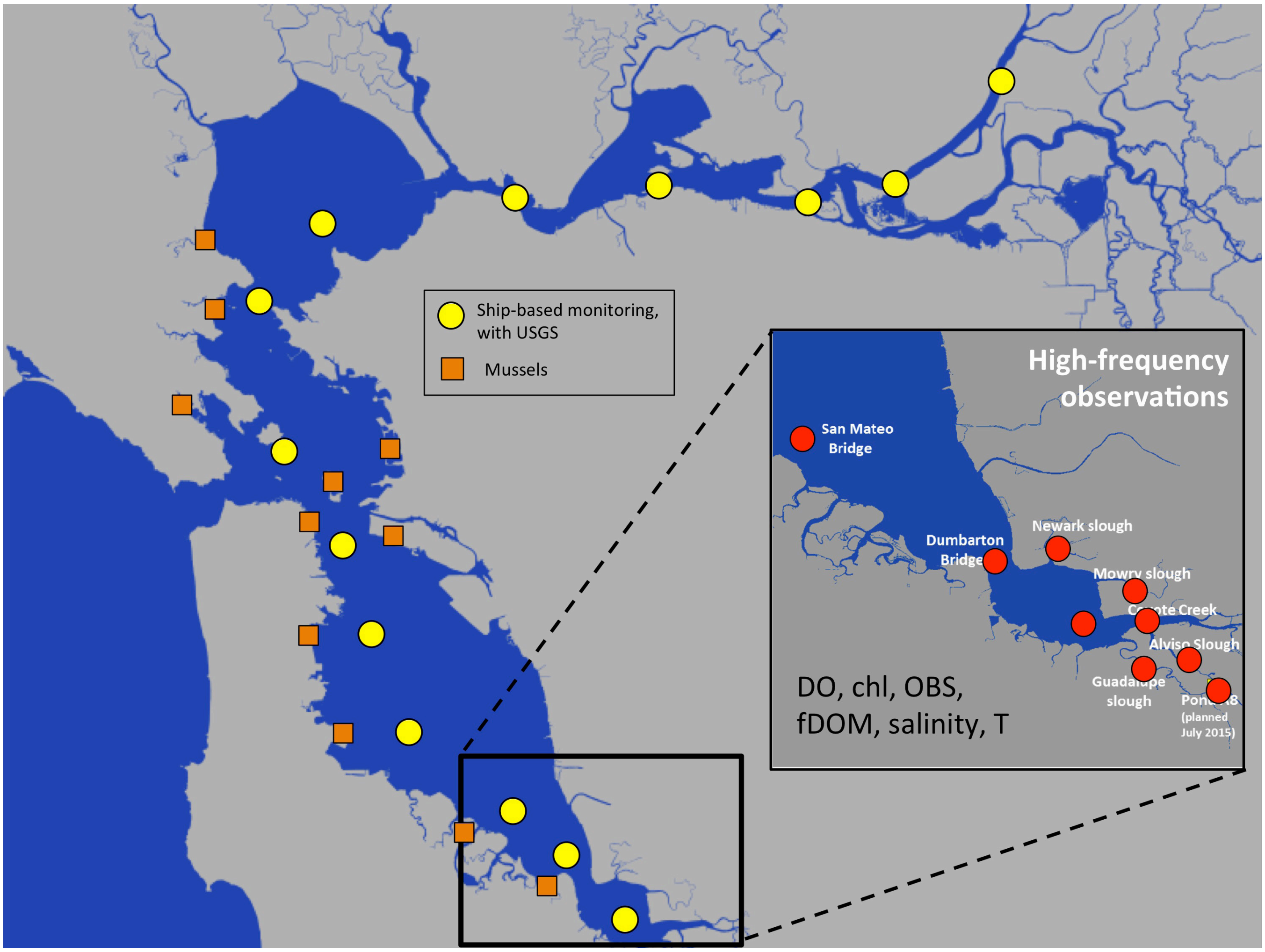
[1] high rates of primary production

NMS Science Program activities are guided by basic management questions that tie back to identifying what constitutes safe levels of nutrient loads to SFB (Table 1.1.a), and the focus of technical studies laid out in the multi-year NMS Science Plan (SFEI 2016a) and related technical reports (e.g, SFEI 2014; SFEI 2015; SFEI 2016b; Sutula et al., 2016). A major focus of the NMS effort over the past few years, shaped by these priorities, has been developing the NMS Observational Program (Figure 1.1), developing and applying biogeochemical models, and interpretation of long-term and new datasets.

This report provides an overview of major San Francisco Bay Nutrient Management Strategy (NMS) activities for Fiscal Year 2017 (FY17; July 2016- June 2017). Additional details are provided in this report's technical appendices. Other recent technical reports and workplans can be found at the NMS website (http://sfbaynutrients.sfei.org/books/reports-and-work-products).

Figure 1.1 The current NMS Observation Program. NMSOP work is carried out as a collaborative effort between SFEI, USGS, UC Santa Cruz, and other partners. USGS-Menlo Park has been monitoring chlorophyll-a, dissolved nutrients and other ancillary parameters at the numbered stations for several decades. To address NMS-specific needs, the spatial and temporal sampling frequency for several parameters nutrients were refined, and NMS funds now support the analysis of nutrients, phytoplankton assemblage, toxins from harmful algae. High frequency observations by SFEI (in collaboration with USGS-Sacramento) began in 2013. Mussel collection by SFEI (in collaboration with UCSC) began in 2015.



NAVIGATING THE REPORT

SECTION 2: Ship-based observations

SECTION 3: Harmful algae (HA) and toxins: water column and biota monitoring

SECTION 4: High-frequency observations

SECTION 5: Water quality modeling

SECTION 6: Exploring management options: wetland treatment opportunities

SECTION 7: Other NMS FY17 activities

TABLE 1.1 NMS SCIENCE PROGRAM OVERVIEW (SEE SFEI 2016)

MANAGEMENT QUESTIONS GUIDING NMS ACTIVITIES

1. What conditions indicate that beneficial uses are being protected? What conditions indicate that nutrient-related impairment is occurring?
2. Which habitats in SFB are currently supporting beneficial uses, and which are experiencing nutrient-related impairment?
3. Under what future scenarios could nutrient-related impairments develop?
4. What management actions are needed to mitigate or prevent nutrient-related impairment?

WORK CATEGORIES

- Monitoring
- Modeling
- Special studies
- Identify protective conditions

PROGRAM AREAS

- Nutrients loads/cycling
- High productivity / Low DO
- Phytoplantkon, Harmful Algae / toxins
- Management Alternatives

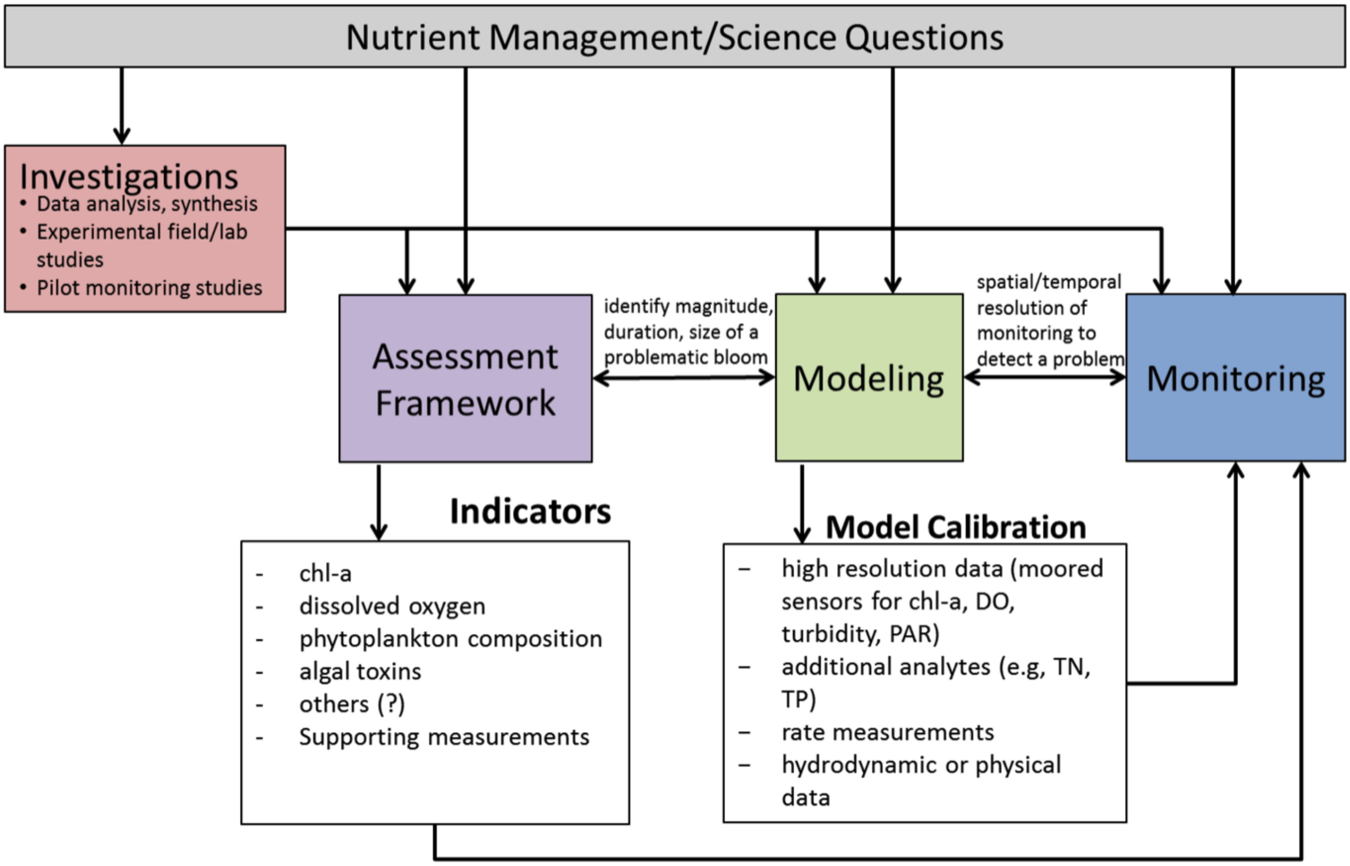
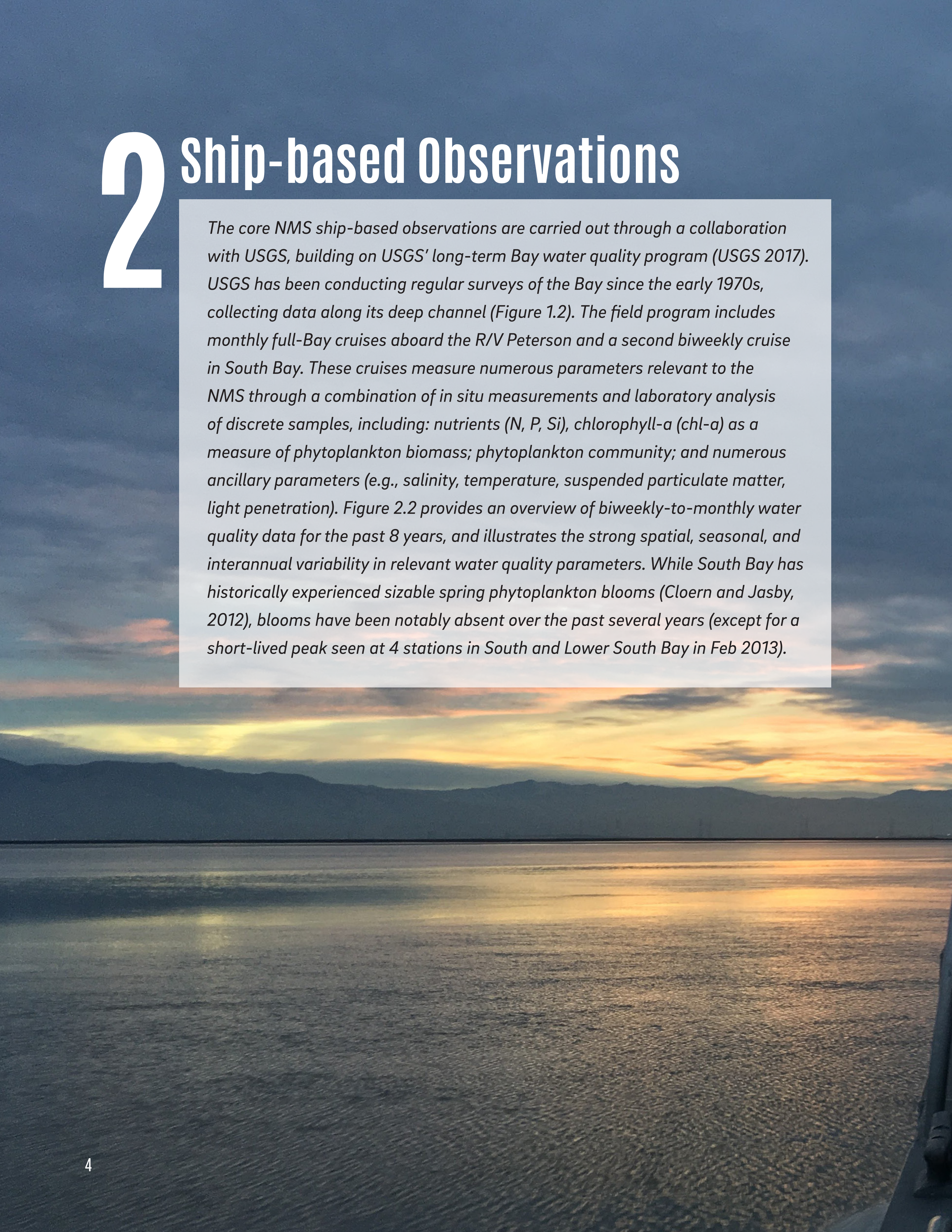


FIGURE 1.2 Connections and information flow between various components of the NMS.



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Ship-based Observations

The core NMS ship-based observations are carried out through a collaboration with USGS, building on USGS' long-term Bay water quality program (USGS 2017). USGS has been conducting regular surveys of the Bay since the early 1970s, collecting data along its deep channel (Figure 1.2). The field program includes monthly full-Bay cruises aboard the R/V Peterson and a second biweekly cruise in South Bay. These cruises measure numerous parameters relevant to the NMS through a combination of in situ measurements and laboratory analysis of discrete samples, including: nutrients (N, P, Si), chlorophyll-a (chl-a) as a measure of phytoplankton biomass; phytoplankton community; and numerous ancillary parameters (e.g., salinity, temperature, suspended particulate matter, light penetration). Figure 2.2 provides an overview of biweekly-to-monthly water quality data for the past 8 years, and illustrates the strong spatial, seasonal, and interannual variability in relevant water quality parameters. While South Bay has historically experienced sizable spring phytoplankton blooms (Cloern and Jasby, 2012), blooms have been notably absent over the past several years (except for a short-lived peak seen at 4 stations in South and Lower South Bay in Feb 2013).

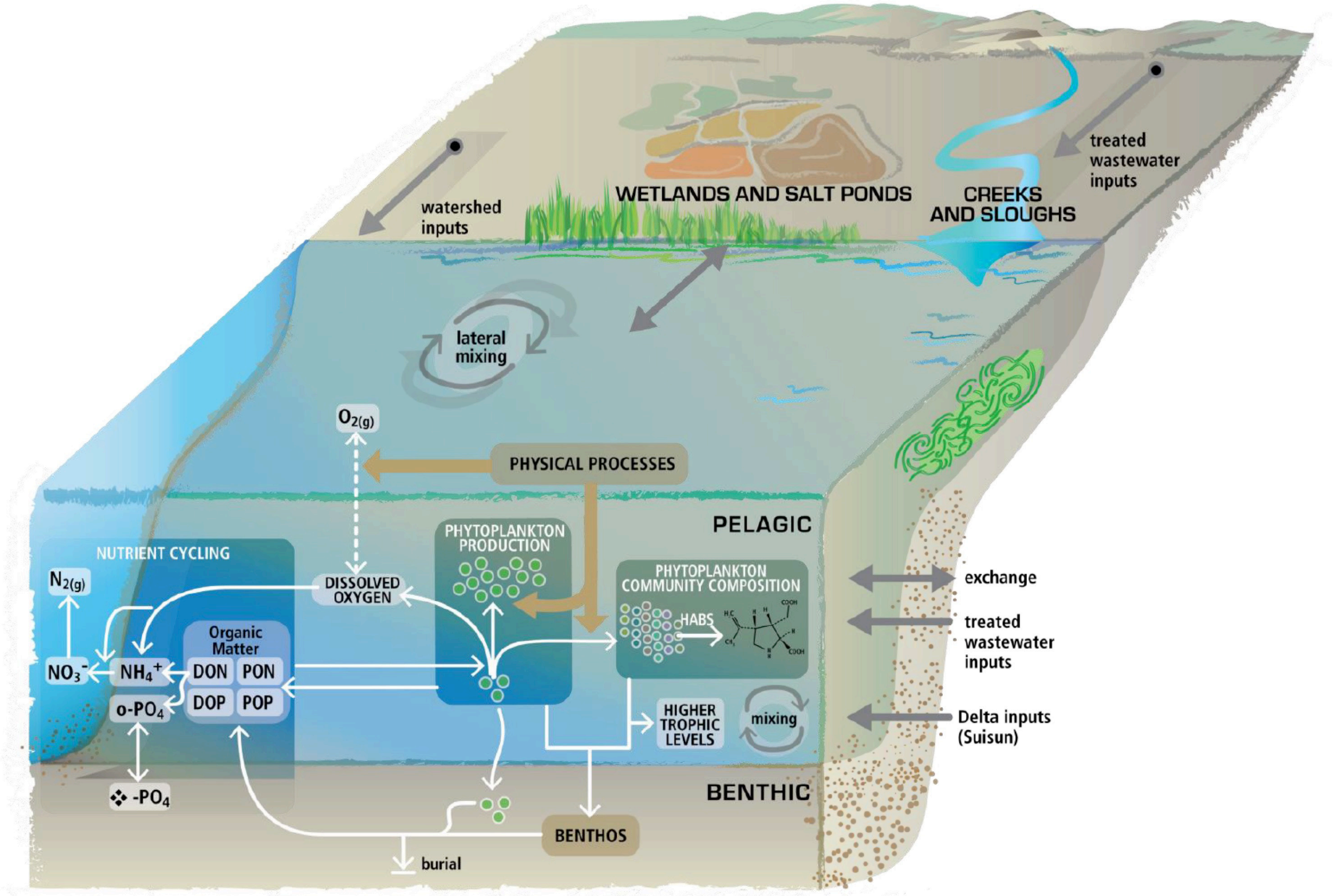

USGS
science for a changing world

AMBIENT WATER QUALITY

N and P are natural and vital components of healthy estuarine ecosystems. Sufficient nutrients levels are needed to support phytoplankton production that in turn serves as the base of the food web. Too much N or P, however, can yield unhealthy levels of phytoplankton, for example by leading to low dissolved oxygen levels, nuisance phytoplankton blooms, or increased numbers of toxin-producing species. Other factors, beyond nutrient concentrations, play important roles in regulating phytoplankton growth rates addition to nutrient levels (Figure 2.1: Therefore, additional data, beyond nutrient concentrations, are essential for assessing nutrient-related ecosystem health.

The extremely wet conditions in Spring 2017 resulted in unusually low salinities throughout the Bay. Although a few episodes of elevated phytolankton levels were observed along the deep channel, major prolonged blooms did not occur. Those data have not yet been incorporated into Figure 2.2, but data presented in Section 4.4 from the South Bay's eastern shoal provide an interesting perspective on Spring 2017 conditions.

FIGURE 2.1 Conceptual model illustrating major nutrient cycling processes and factors influencing ecosystem response to nutrients and San Francisco Bay's response to nutrients. N and P utilization by phytoplankton (and other primary producers) and biomass accumulation depends on multiple factors: light levels in the water column (inversely related to suspended sediment concentrations); temperature; vertical mixing by winds and tides, which is strongly-regulated by differences in salinity;lateral mixing between shallow shoals and the deep channel; and grazing. See SFEI 2014 for more information. SFEI 2014



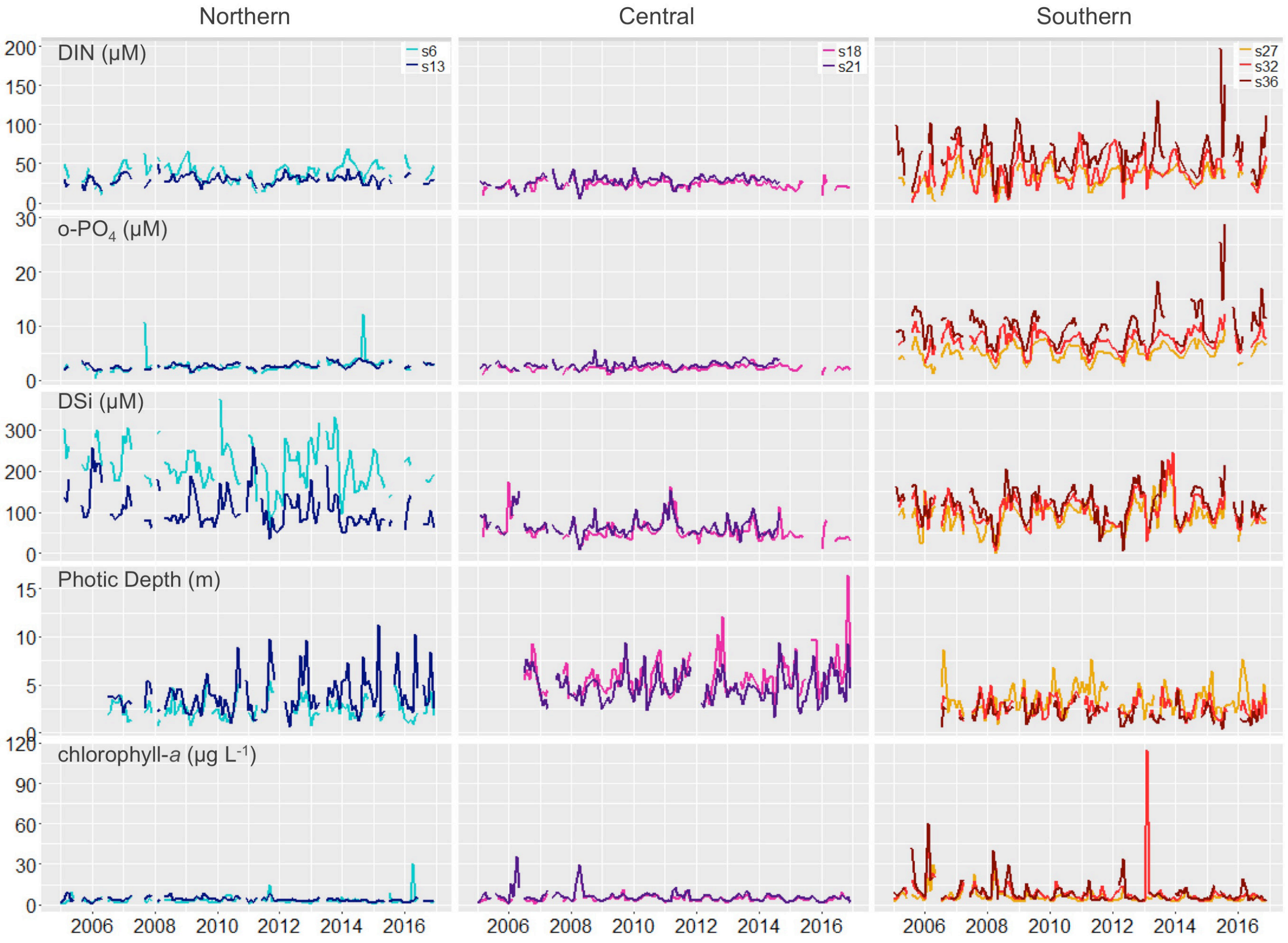


Figure 2.2 Water quality parameters recorded every two to four weeks along the axis of the Bay. South Bay and Lower South Bay regularly exhibits elevated N, P and chlorophyll-a relative to Central Bay and the the northern Bay. A wide range of spatial and temporal patterns are discernible from this rich dataset. Significant but intermittent blooms are evident in the chlorophyll-a signals, particularly in South Bay. Nutrient concentrations show recurring seasonal cycles, with the clearest cycle in phosphorus, and similar cycles visible in nitrogen and silicon. Photic depth (depth at which light levels equal 1% those at the surface) has a strong influence on phytoplankton growth and varies seasonally and spatially.

Onboard laboratory on the *R/V Peterson* (right).

NUTRIENT FORMS: EVALUATING THE IMPORTANCE OF ORGANIC N AND P

In nature, nitrogen and phosphorous occur within molecules having a diverse array of chemical structures that greatly influence their reactivity within the Bay. Those chemical structures also provide clues about the processes the N- and P-containing molecules have recently undergone. A quantitative understanding of nutrient "cycling" -- the magnitude of processes and the amount of nutrients in various pools -- is essential for interpreting and predicting the Bay's response to nutrients and estimating protective nutrient load. See Figure 2.3 caption for more discussion.

Although dissolved inorganic nutrients (NO3-, NH4+; and o-PO4) have been regularly sampled by the USGS program, organic N and P were not routine analytes. Beginning in late 2014 the NMS and USGS added measurements for additional analytes (dissolved organic N and P) with results to date for N summarized in Figure 2.3. (see Appendix X for P results).

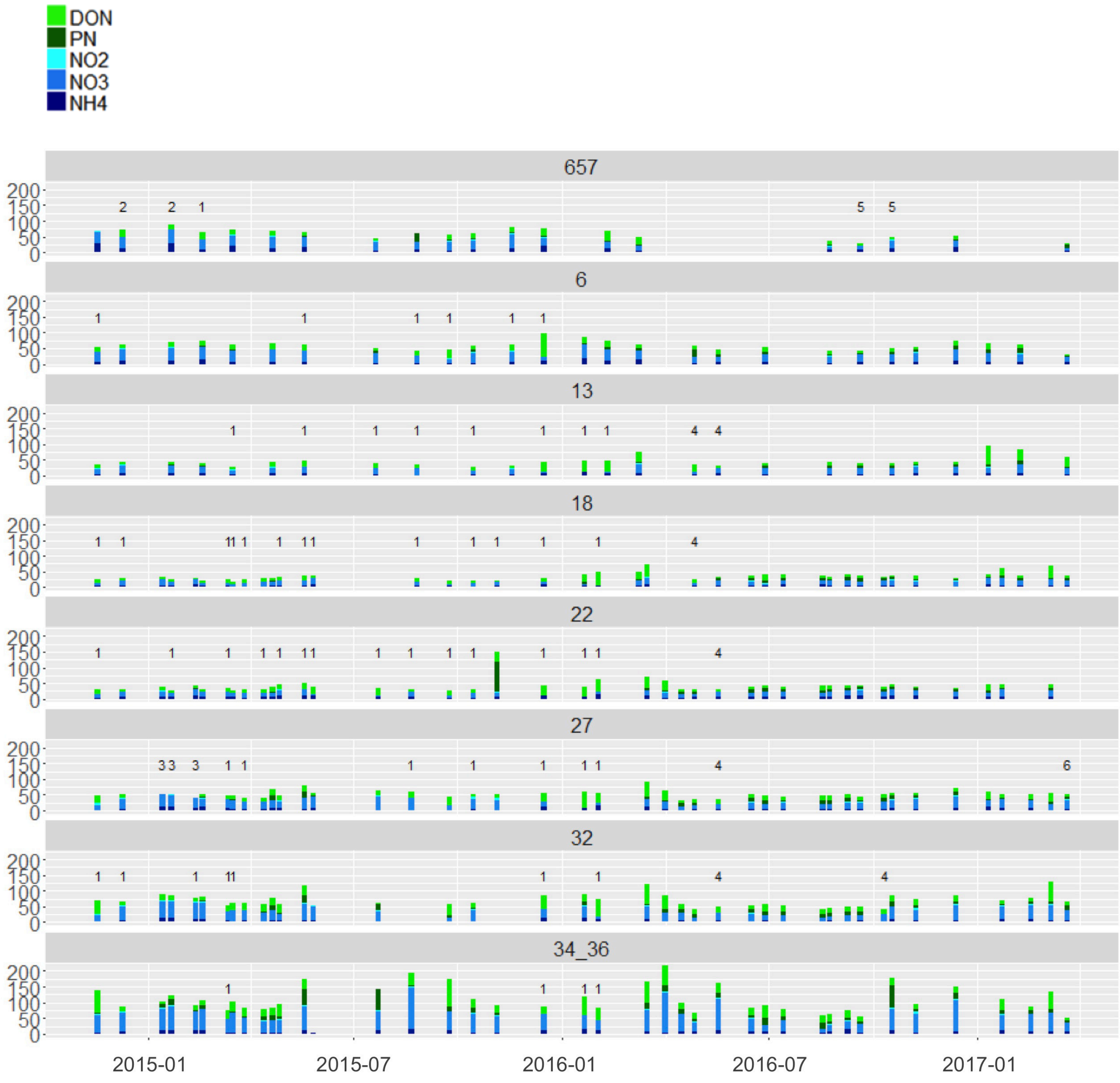
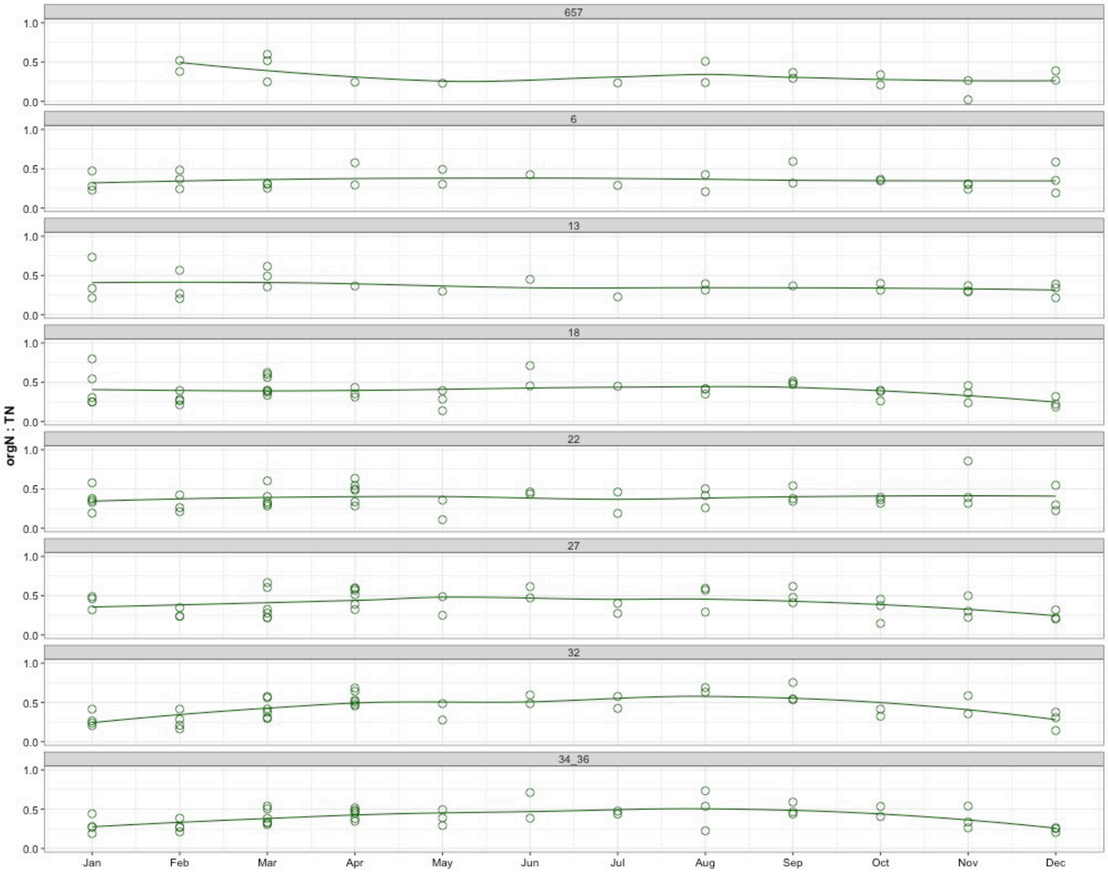


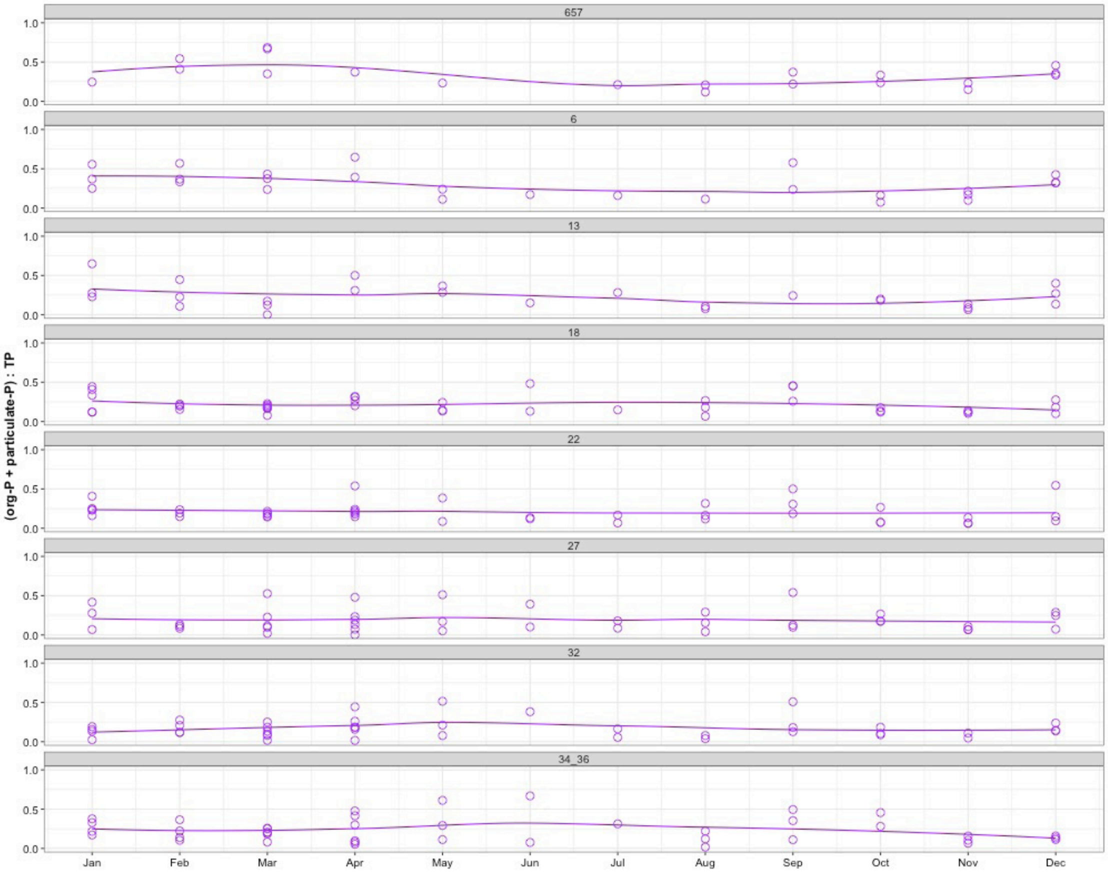
FIGURE 2.3 Nitrogen forms species by station (units in µM). DON = dissolved inorganic N; PN = particulate N (organic); DRP = dissolved reactive P (primarily o-PO4); DOP = dissolved organic P; TPP = total particulate P

Numbers within plot indicate...N: 1 = calculated PN was negative (i.e. small) and not shown; 2 = TN data unavailable; 3 = TDN data unavailable; 4 = calculated DON is negative, likely TDN and TN error; Stations: 34_36: Lower South Bay; 32: ~2km north of Dumbarton Bridge; 27: San Mateo Bridge; 22: ~5km south of Bay Bridge; 18: Central Bay; 13: San Pablo Bay; 6: Suisun Bay; 657: Sacramento River near Rio Vista

N and P entering the Bay via wastewater treatment plant discharges primarily occur as dissolved inorganic molecules: nitrate, NO3-; ammonium, NH4+; and ortho-phosphate, o-PO4). Dissolved inorganic N and P molecules are easily taken up by phytoplankton, benthic algae, and other plants, and convert them into organic molecules for cellular building blocks or metabolic processes. When phytoplankton and plant cells die, they are eventually degraded by microbes, releasing organic-N and organic-P molecules back to the surrounding water (or sediment). Some of those molecules are easily degraded (labile) , or “recyled”, back to inorganic N and P that can be assimilated by other primary producers, or experience other transformations (e.g., N loss via denitrification). Other compounds (refractory) break down slowly (see Figure 2.1): particulate forms settle and accumulate in sediments, while dissolved forms remain in the water column and undergo gradual transformations before eventually being flushed from the system. In addition, P has a tendency to sorb to inorganic particle surfaces, in which form it is both less bioavailable and prone to settling and burial.



orgN : TN
657
6
13
18
22
27
32
34_36
0.0
0.5
1.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



(org-P + particulate-P) : TP
657
6
13
18
22
27
32
34_36
0.0
0.5
1.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

With ~2.5 years of biweekly to monthly data, it is possible to offer some initial observations about the relative importance of org-N and org-P (%org-N, %org-P; Figure 2.4).

- %org-N and %org-P consistently approached or exceeded 50%, indicating that quantification of the organic forms is important for developing accurate nutrient budgets.
- There was substantial variability in both %org-N and %org-P within individual months. That said, the time window was short (2.5 years), and fell during a period defined by extreme climatic conditions (2014-2016 drought).
- Even with the variability, there appears to be a seasonal %org-N trend in South Bay (32, 34_36), with minimum %org-N in the coldest months (Dec, Jan, Feb) and increasing %org-N over spring and summer. However, seasonal %org-N trends can not be readily discerned for other regions. No obvious %org-P seasonal trends are evident at this point.As more data become available some of these observations will be explored more quantitatively. At present, these data are beginning to be used for tuning biogeochemical models.

As more data become available seasonal and spatial variability in %org-N and %org-P will be explored more quantitatively. At present, these data are beginning to be used for tuning biogeochemical models.

FIGURE 2.4 A Proportion of N as org-N (org-N:total N) vs. month. B. Proportion of P as org-P. Points represent individual dates. Curve is a LOESS smoother, and is intended to visually highlight central tendency values and any major seasonal patterns, not as a statistical model fit. See Figure 2.3 caption for station locations. Note: P complexed by inorganic particles is likely a nontrivial component of the non-oPO4 component.

PHYTOPLANKTON BIOMASS AND ASSEMBLAGE

Phytoplankton are key indicators of nutrient-related ecosystem health in SFB for two primary reasons:

- Elevated nutrients can promote low dissolved oxygen through excessive phytoplankton production (eutrophication). So tracking phytoplankton biomass is one way evaluate condition.
- Phytoplankton primary production accounts for the majority of Bay-wide food supply (Jassby et al. 2001). The amount of phytoplankton (biomass) and the “food quality” of the mixture present (assemblage) are therefore important for sustaining those food webs. Since nutrients can influence biomass [2] and assemblage, both can serve as relevant indicators of nutrient-related ecosystem health.

[2] biomass: the ‘concentration’ of phytoplanton, measured in units of μg C/L or μg chl-a / L, or presented as ‘biovolume’ in units of μm3/mL

Monitoring Trends in Phytoplankton Biomass – South Bay

The increase in fall chl-a levels in South Bay, observed beginning in the late 1990s (Cloern et al, 2007; Figure 2.4), was among the original catalysts for launching the NMS effort. Nutrient loads to South Bay did not change appreciably over this time period. In addition, phytoplankton growth and phytoplankton biomass in South Bay are generally not limited by nutrients, but instead by low light levels (turbid waters), efficient vertical mixing by strong tides (further limiting phytoplankton's access to light, compared to being in a light-rich surface layer), and strong grazing pressure by sediment dwelling organisms and benthos. Through analyzing several long-term datasets, Cloern et al. (2007, 2010) inferred that the Bay's responsiveness or sensitivity to nutrients was changin. We continue to track and interpret Fall chl-a levels in South Bay (SFEI 2015). Observations through 2016 suggest that fall chl-a levels have plateaued (Figure 2.5. Quantitatively exploring the changes to phytoplankton biomass and the causal factors are a major current focus of the NMS modeling program (Section 5). More discussion of the hypothesized factors contributing to these changes can be found in Cloern et al (2007, 2010) and SFEI (2014,2015 #xxx).

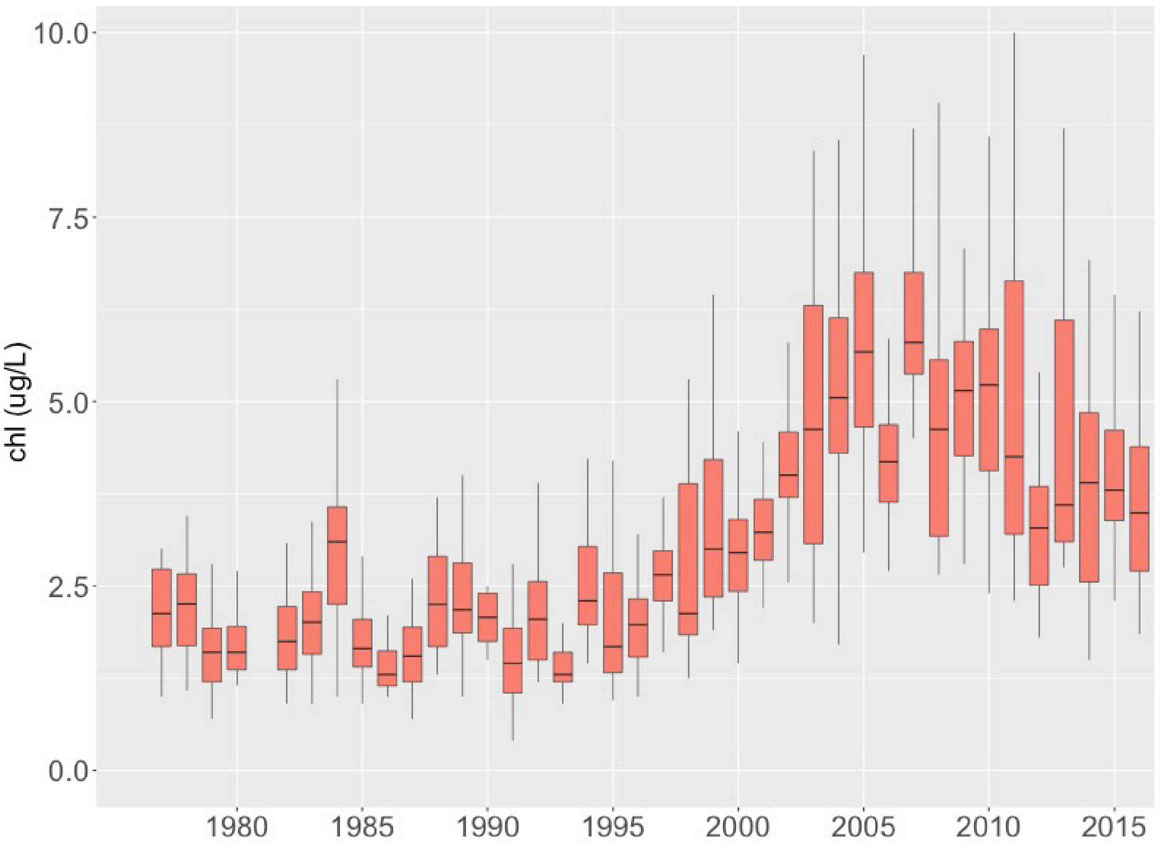


Figure 2.5 Annual average chlorophyll concentrations in South Bay during the months Aug-Dec. Black line = median; box = interquartile range; whiskers = 95% confidence interval. Averaging used here followed same approach as Cloern et al. 2007.

Phytoplankton Assemblage

Phytoplankton assemblage is measured 1-2 times per month by microscopy at seven stations throughout SFB (Figure 1.1), continuing the 20+ year USGS phytoplankton record. Figure 2.5 presents assemblage data, at the class level, for 2014-2016. The y-axis extends from 0-1, and bars represent each classes' proportional contribution to total biovolume in the sample. Biovolume (µm^{3} L-1), estimated using dimensions measured during microscopy, is a surrogate for biomass (µg carbon L-1). Although the relative biovolumes do not convey information about actual biovolume, the chl-a plotted on top of the plots serves as a reasonable estimate of total biomass.

Bay-wide over this 2 year record, diatom-dominated assemblages were observed with the greatest frequency, consistent with past observations (Cloern and Dufford, 2005). However, cryptophyte- and dinoflagellate-dominated assemblages also occurred, including some dates when chl-a levels were moderately elevated (e.g., Lower South Bay, March 2016; San Pablo, Jun 2016), In South Bay and San Pablo Bay, cryptophytes commonly accounted for 30-50% of biovolume. Other classes (e.g., chlorophytes, cyanobacteria) were also present but contributed minimally to biovolume (usually <5%). See section 2.4 for more discussion of phytoplankton assemblage seasonal and spatial patterns.

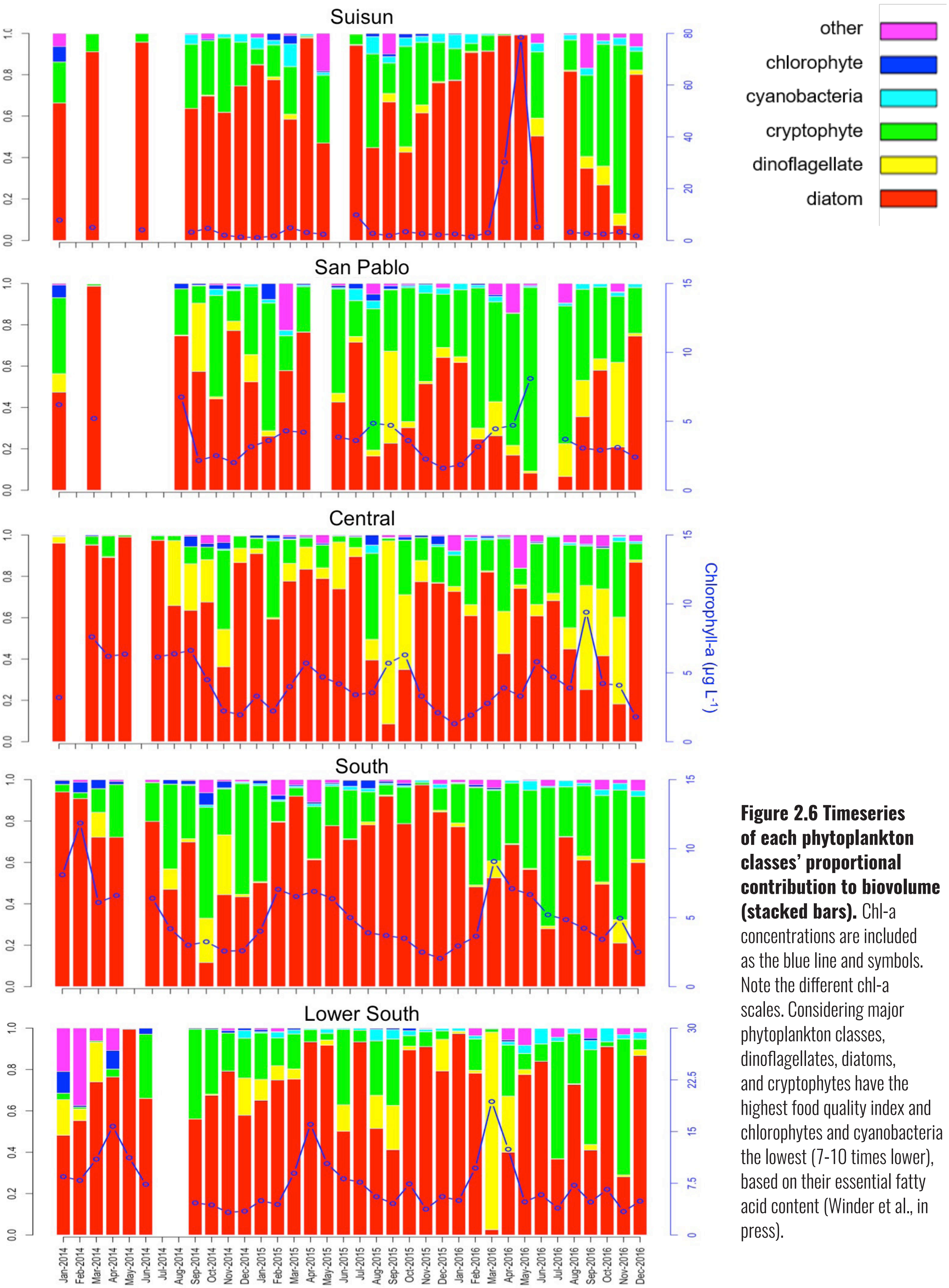


Figure 2.6 Timeseries of each phytoplankton classes' proportional contribution to biovolume (stacked bars). Chl-a concentrations are included as the blue line and symbols. Note the different chl-a scales. Considering major phytoplankton classes, dinoflagellates, diatoms, and cryptophytes have the highest food quality index and chlorophytes and cyanobacteria the lowest (7-10 times lower), based on their essential fatty acid content (Winder et al., in press).

EXPLORING SEASONAL AND SPATIAL VARIABILITY IN PHYTOPLANKTON ASSEMBLAGE

Phytoplankton growth rates and biomass accumulation are influenced by multiple regulating factors -- e.g., T, salinity, light attenuation, length of day, vertical mixing, horizontal, transport/dilution, grazing, nutrient concentrations -- all of which vary strongly in space and time in SFB. As a result, regions of SFB exhibit distinct seasonal biomass patterns (Figure 2.6), as well as interannual variability (Figure 2.6: width of interquartile range, some wide confidence intervals and outliers).

We hypothesized that these variability in these regulating factors would also cause pronounced spatiotemporal differences in phytoplankton assemblage in San Francisco Bay, by encouraging or discouraging growth of specific taxa due to strong inter-taxa differences in optimal growth conditions. In addition, we expected that other factors, such as proximity to distinct sources of "seed" organisms (e.g., coastal ocean, the Delta) would also influence observed assemblages. Developing the mechanistic understanding of factors that influence phytoplankton assemblage is highly relevant both from food quality and harmful algae perspectives.

To test these hypotheses we explored the long-term USGS phytoplankton data (1992-2014) to identify spatial and temporal patterns in phytoplankton assemblage at multiple taxa levels (class, genus, species). A small subset of the interpretations are presented here.

Looking Bay-wide and over 20 years of observations at class-level phytoplankton assemblage, several broad but strong patterns emerge (Figure 2.8).

- Although diatoms did commonly dominate biovolume (Cloern and Dufford 2005), other assemblage-types were consistently observed throughout the Bay.

- At least 3 regions in terms of distinct seasonal cycles. Two clear examples are

...Central Bay: strong dinoflagellate signal in Sep-Oct, consistent with coastal influence, and diatom or mixed-assemblages the remainder of the year.

....South Bay: frequent diatom dominance Feb-Mar-Apr, and strong cryptophyte signal May-Sep, (LSB and USB are similar):

- The variability in spatial-seasonal assemblages might best be thought of in terms of frequency or likelihood of occurrence:

....in some region-month bins, one assemblage type was encountered with high frequency over many years of observation (e.g., CEN: Oct-Nov, dinoflagellate dominance; LSB,SOU, USB: Feb-Mar-Apr, diatom dominance; SOU, USB: Aug, cryptophyte dominance)

...in other bins, 2 or more assemblage-types were encountered with comparable frequencies

...in both cases, those frequency patterns were punctuated by anomalies -- atypical assemblage for a given region-month bin, suggesting that interannual variability in physical or biological factors can substantially alter both biomass (Figure 2.6) and the types of phytoplankton that contribute to that biomass (e.g., rare dinoflagellate 'spikes' in SOU and LSB).

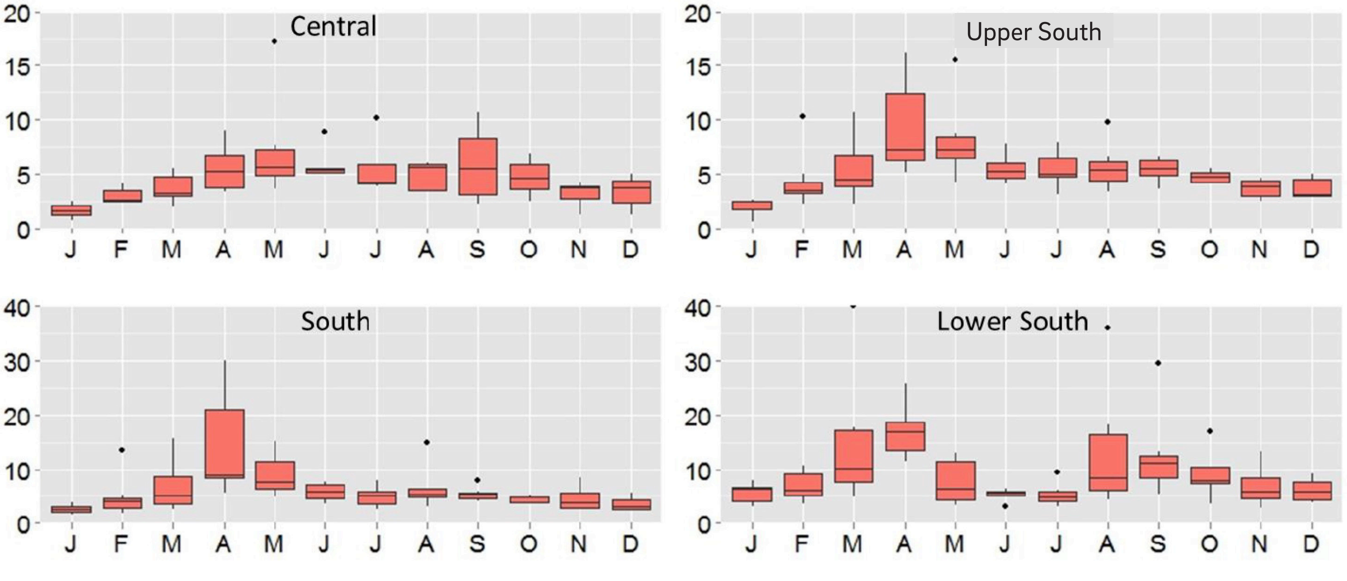


Figure 2.7 Seasonal chl-a levels in three regions of San Francisco Bay. Shaded area represents 25-75%ile of monthly pooled data for the period 2006-2011.Black line = median; box = interquartile range; whiskers = 95% confidence interval. Source: SFEI 2014; Data: USGS

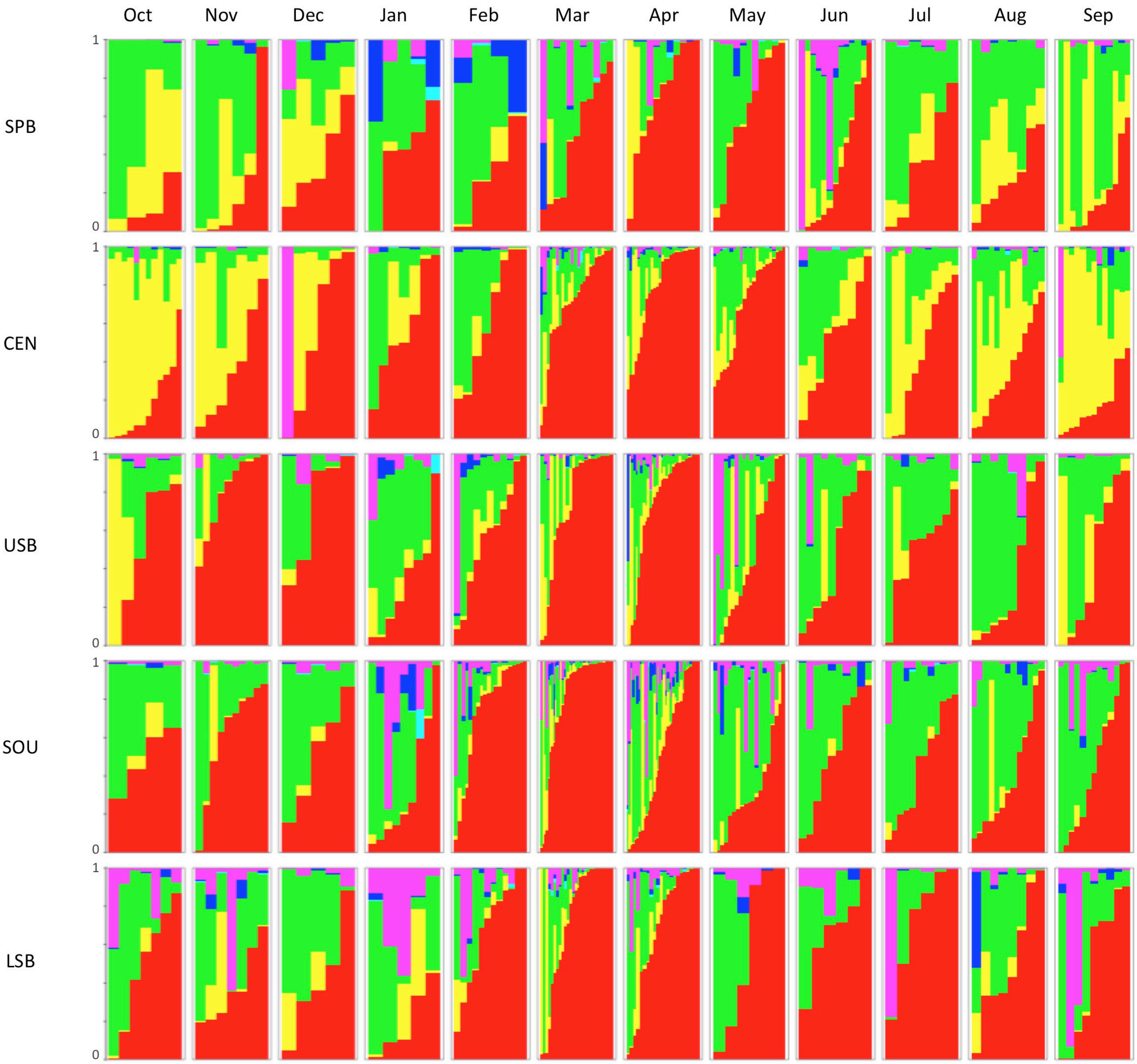
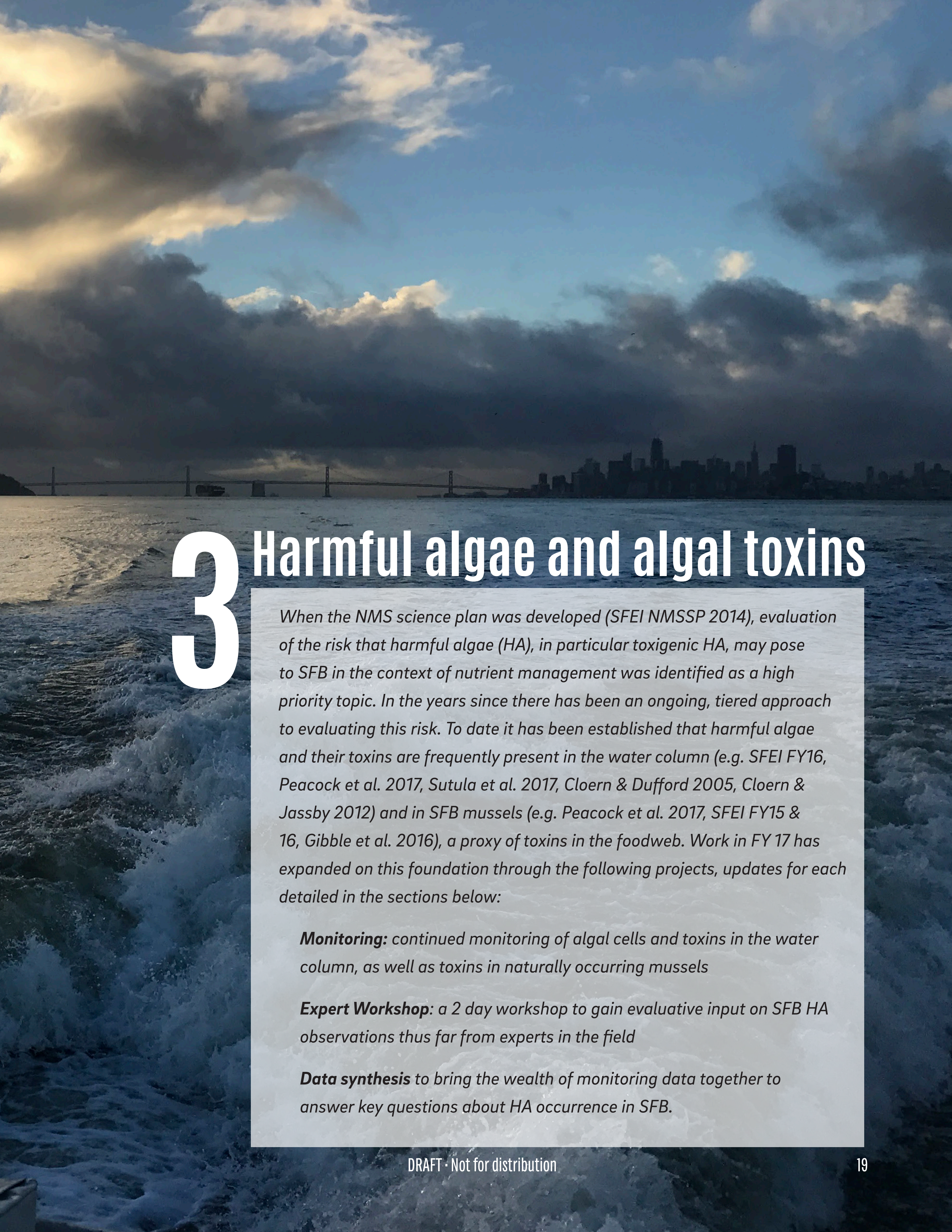


Figure 2.8 Relative contribution of phytoplankton classes to total biovolume, by region and month. For each region-month bin, data from all years were pooled; each multi-colored vertical bar represents one sample. The width of bars gives an indication of how densely a region-month bin was sampled, with Feb-Mar-Apr being the most densely sampled. For visual clarity, each bin was sorted by the diatom proportion.

LSB = Lower South Bay, south of Dumbarton Bridge (s34+s36); SOU = far South Bay, just north of Dumbarton Bridge (s32); USB = Upper South Bay, San Mateo Bridge (s27); CEN = Central Bay (s18+s21); SPB = San Pable Bay (s13).

SFEI, in prep.; Data: USGS

other 🟪
chlorophyte 🟦
cyanobacteria 🟦
cryptophyte 🟩
dinoflagellate 🟨
diatom 🟥



3 Harmful algae and algal toxins

When the NMS science plan was developed (SFEI NMSSP 2014), evaluation of the risk that harmful algae (HA), in particular toxigenic HA, may pose to SFB in the context of nutrient management was identified as a high priority topic. In the years since there has been an ongoing, tiered approach to evaluating this risk. To date it has been established that harmful algae and their toxins are frequently present in the water column (e.g. SFEI FY16, Peacock et al. 2017, Sutula et al. 2017, Cloern & Dufford 2005, Cloern & Jassby 2012) and in SFB mussels (e.g. Peacock et al. 2017, SFEI FY15 & 16, Gibble et al. 2016), a proxy of toxins in the foodweb. Work in FY 17 has expanded on this foundation through the following projects, updates for each detailed in the sections below:

***Monitoring:** continued monitoring of algal cells and toxins in the water column, as well as toxins in naturally occurring mussels*

***Expert Workshop**: a 2 day workshop to gain evaluative input on SFB HA observations thus far from experts in the field*

***Data synthesis** to bring the wealth of monitoring data together to answer key questions about HA occurrence in SFB.*

MONITORING HARMFUL ALGAE

Measures of both cellular abundance and toxin concentrations are the most common metrics used by harmful algal bloom (HAB) monitoring programs to assess HAB condition. These measures describe the presence, intensity, and frequency of occurrence of potentially HA and their toxins.

Harmful algae in the water column

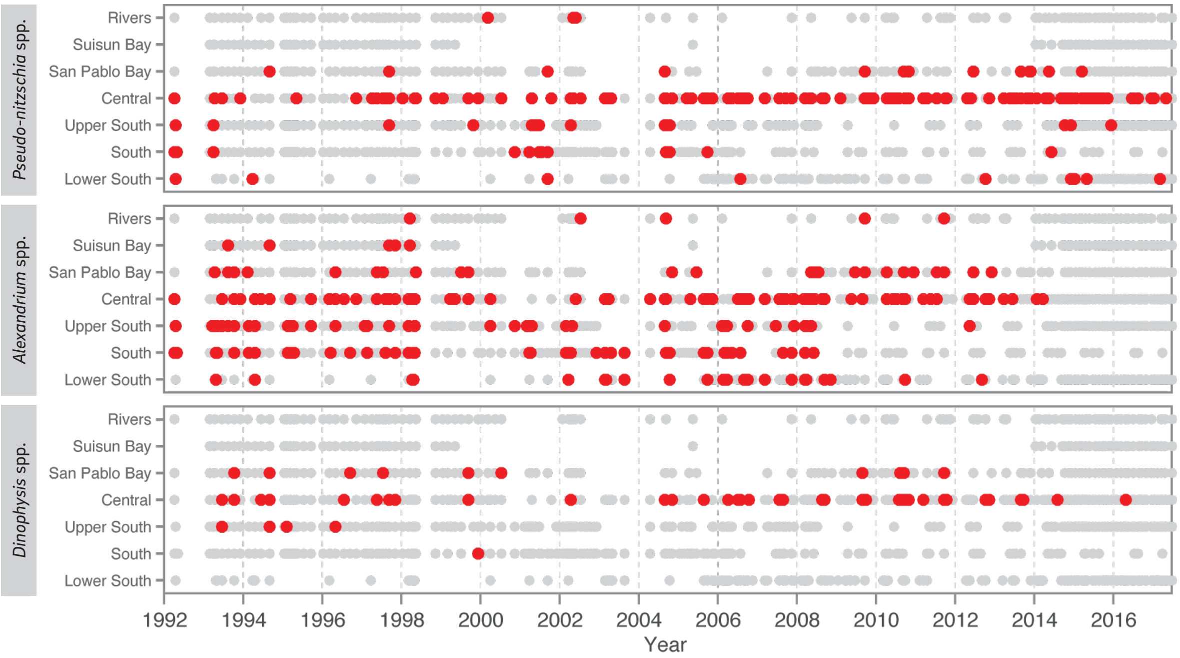
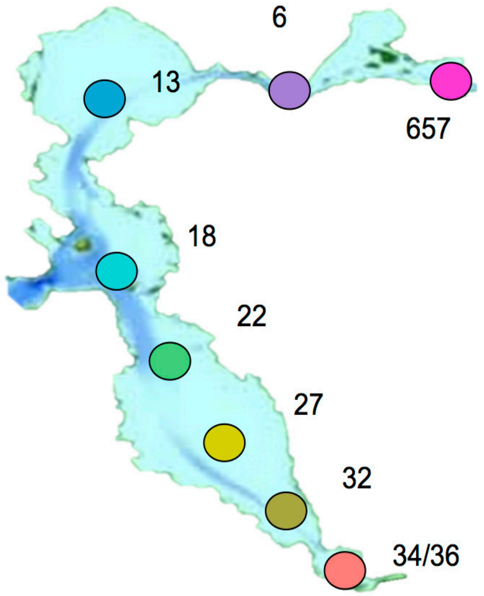


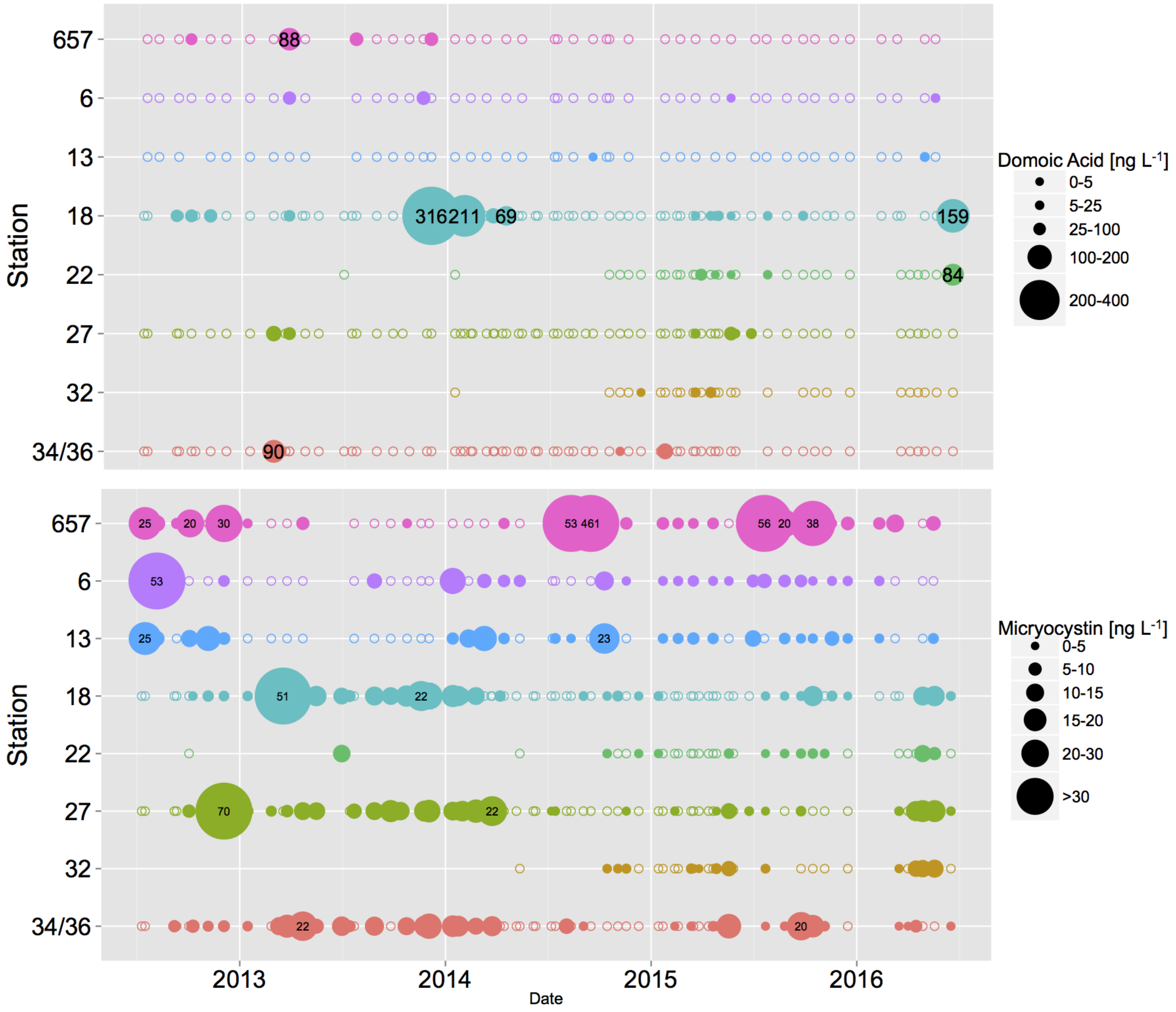
Figure 3.1 Approximately 25 years of presence (red) or absence (black) of 3 algal groups known to be potentially harmful. Samples were collected during routine shipboard monitoring at the stations shown in figure 1.2. (Data: USGS)

Algal bloom in south SF Bay, photo by Scott Conrad, USGS, published by SFEP.



Algal toxins in the water column

Figure 3.2 As of FY 17, particulate domoic acid (top) and microcystin (bottom) monitoring data have been updated to span late 2011 through early 2016 for all sampling stations. Samples were collected during routine shipboard monitoring at the stations shown in on the right. Numbers on plots indicate high values observed. Figure credit: Peacock et al. 2017, submitted.



ALGAL TOXINS IN SAN FRANCISCO BAY MUSSELS

Ongoing NMS mussel monitoring yields continuous, bi-weekly observations of domoic acid (DA), microcystins (MCY), and saxitoxins (STX) at several locations in central and south SFB (Figure 3.3). In FY17 processing of the first full year of NMS mussel monitoring program samples was completed (Figures Figures 3.4-3.6). This is notable dataset as all previous mussel toxin observations in SFB spanned shorter time frames and were sampled less frequently. Analysis of mussel samples spanning late October 2016 through mid 2017 will be completed by early fall 2017.

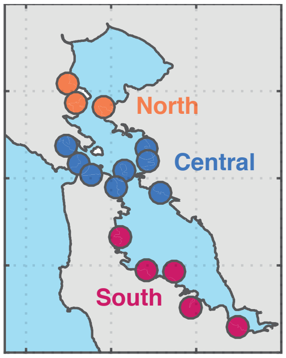


Figure 3.3: Locations of mussel sampling in SFB. Boxes indicate north, central, and south groupings applied to figures 3.4-3.6.

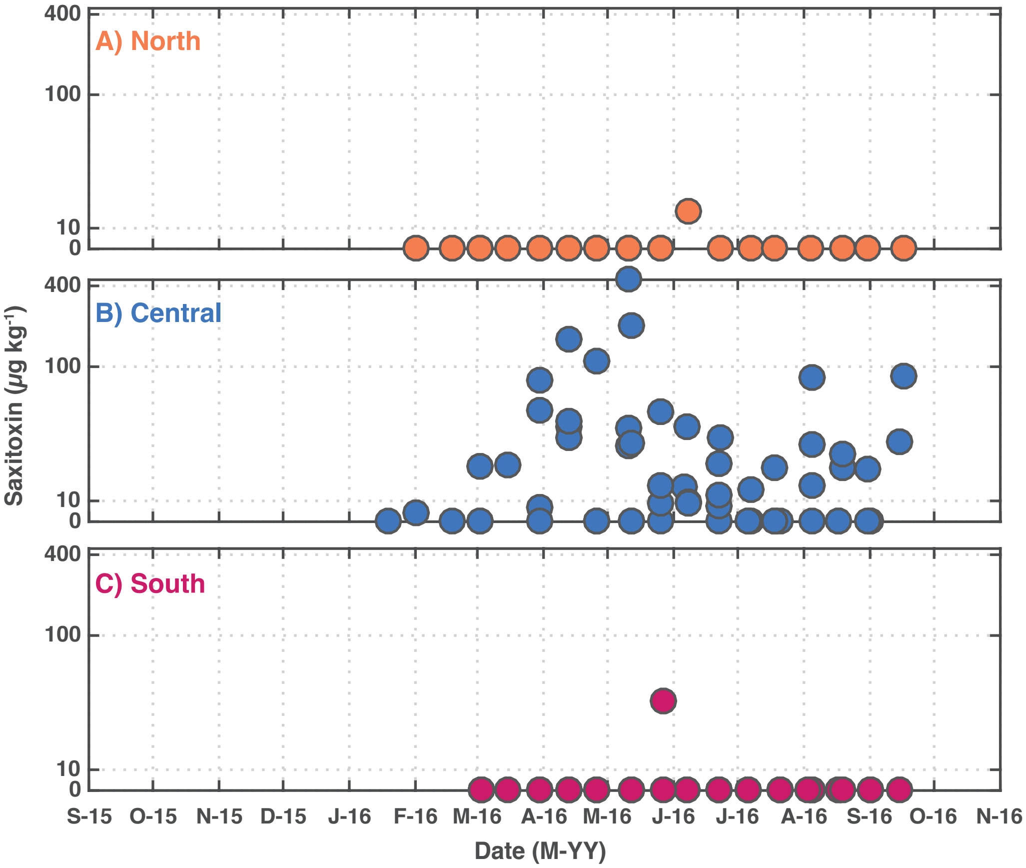


Figure 3.4 Saxitoxin (STX) in San Francisco Bay mussels over time at north (top) central (middle) and south (bottom) sampling sites from September 2015 - September 2016. The recommended safety threshold for STX in mussels is 800 µg/kg.

What does the first year of toxin levels in mussels tell us?

- **Over 60% of mussels tested positive for DA.** Similar to previous results, the DA maximum is two orders of magnitude lower than the regulatory threshold for ingestion of seafood. Seafood consumption safety thresholds are established for all 3 classes of toxins measured in our monitoring program, hence are used here as a descriptor of the severity of algal toxin levels observed.
- **Similar to DA, over 60% of mussels tested positive for MCY,** however MCY levels did surpass safety thresholds for seafood consumption. Some samples in south SFB reached over twice this threshold.
- **Over 30% of mussels tested positive for PST.** Maximum PST values reached roughly 1/2 of the regulatory threshold of 800 µg/kg.

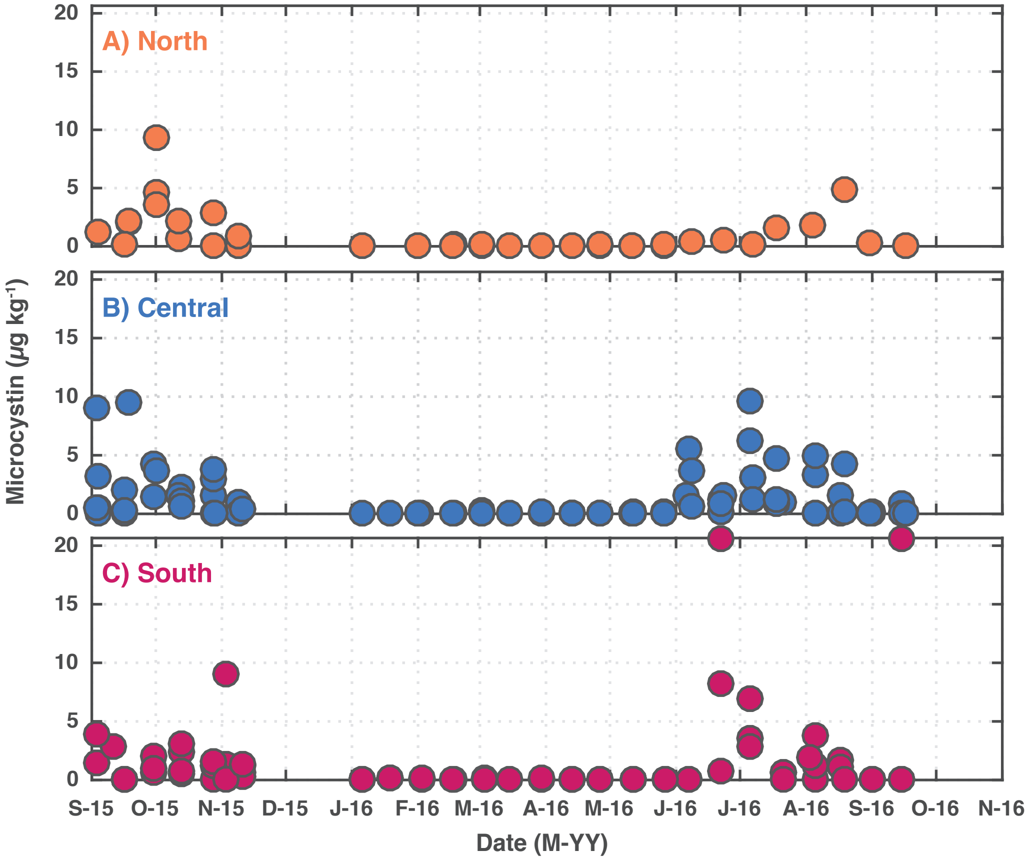


Figure 3.5 Microcystin (MCY) in San Francisco Bay mussels over time at north (top) central (middle) and south (bottom) sampling sites from September 2015 - September 2016. The recommended safety threshold for MCY in mussels is 10 µg/kg.

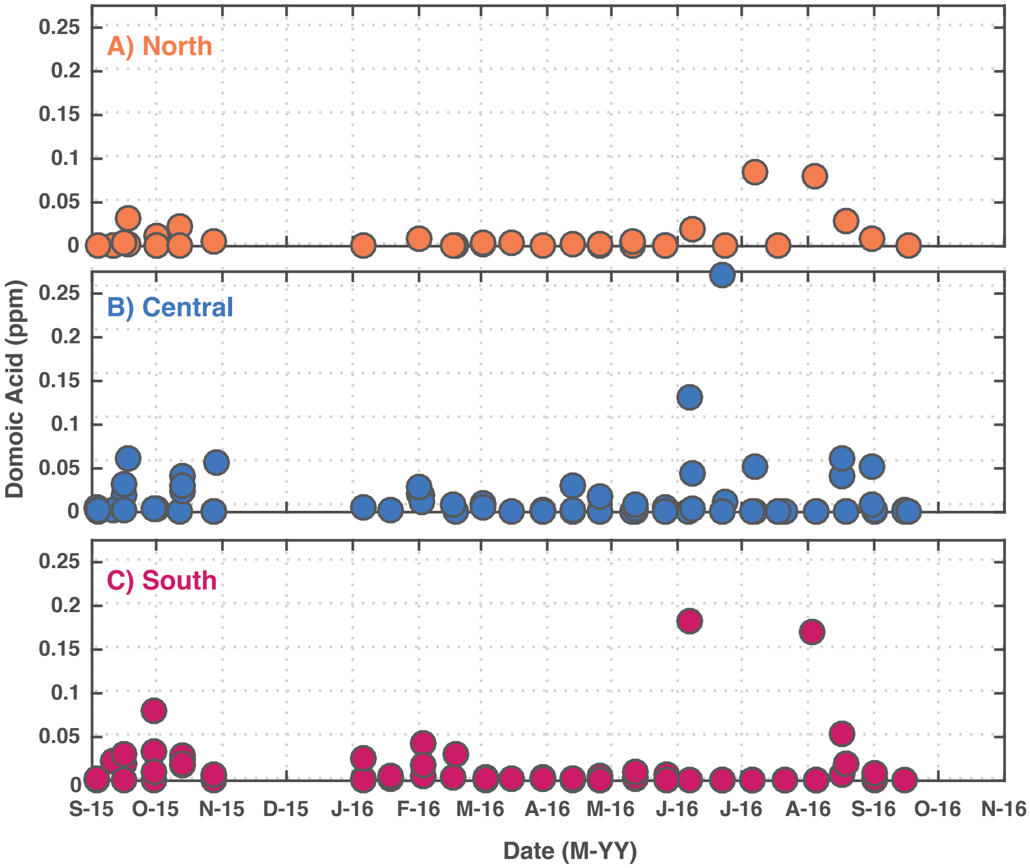


Figure 3.6 Domoic acid in San Francisco Bay mussels over time at north (top) central (middle) and south (bottom) sampling sites from September 2015 - September 2016. The regulatory threshold for DA in mussels is 20 ppm.

WORKSHOP ON HARMFUL ALGAE IN SAN FRANCISCO BAY

In June a panel of researchers that specialize in HAB investigations were invited to a 2-day workshop at SFEI to provide their input on HA observations in SFB thus far, as well as provide recommendations for future research priorities. Three main questions guided the workshop:

1. What do observations thus far in SFB of HAB-forming taxa or phycotoxins indicate about the potential for adverse impacts on SFB ecology?
2. What monitoring efforts and targeted studies are needed to investigate whether HABs are tied to nutrient condition in the SFB region?
3. What are the major uncertainties and data gaps relative to adequately answering the key questions above?

There was consensus that harmful algae and their toxins and have the potential to be a high priority ecological, and perhaps human, health issue in SFB. Adverse impacts, however, are difficult to assess due to incomplete information on wildlife and human exposure to algal toxins found in SFB. Several specific suggestions for priority action items to investigate uncertainties were developed during the workshop. As feasible and applicable to the NMSSP, these suggestions were incorporated into plans for ongoing and future NMS investigations.

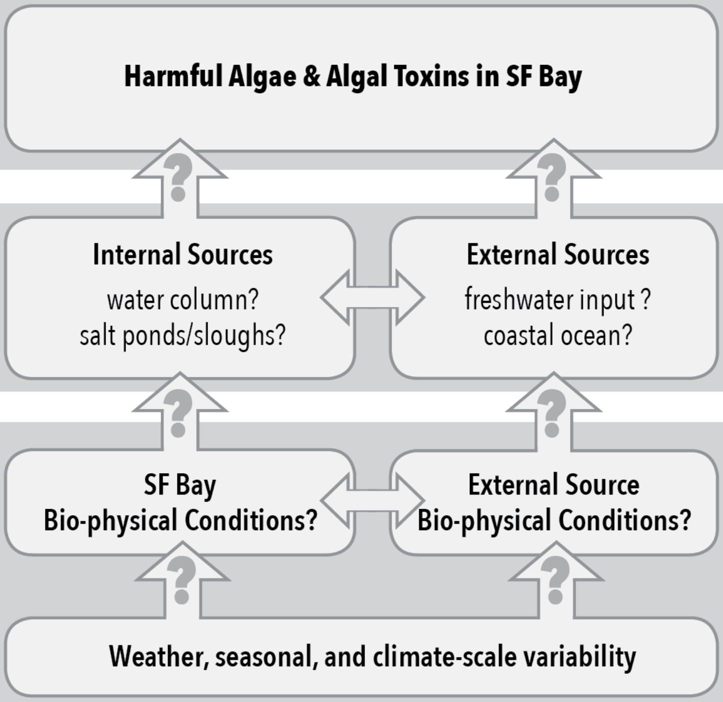
Identifying the potential sources of the HA and phycotoxins observed thus far was identified as a logical, tenable next step towards investigating whether HA in SFB are related to anthropogenic nutrient enrichment. Specifically, can these observations be attributed to populations that are potentially supported by SFB's nutrient-enriched waters? Alternatively, are the observed HA populations initiated in waters outside of SFB then introduced into the Bay, or some combination of these options? This work has begun and will be ongoing into FY18.

Approach: Post-Workshop Guiding Questions for NMS HAB Investigations

Are HA and phycotoxins present in SF Bay?
Ongoing monitoring has established they are present at potentially concerning levels. Now monitoring & environmental data are being applied to investigate:

What are the sources of HA in SF Bay?

What conditions may promote HA in SFB?
Where "conditions" includes a range of physical/biological parameters (e.g. temperature, salinity, community composition, etc.) and time/space scales.



BRINGING IT ALL TOGETHER: DATA SYNTHESIS

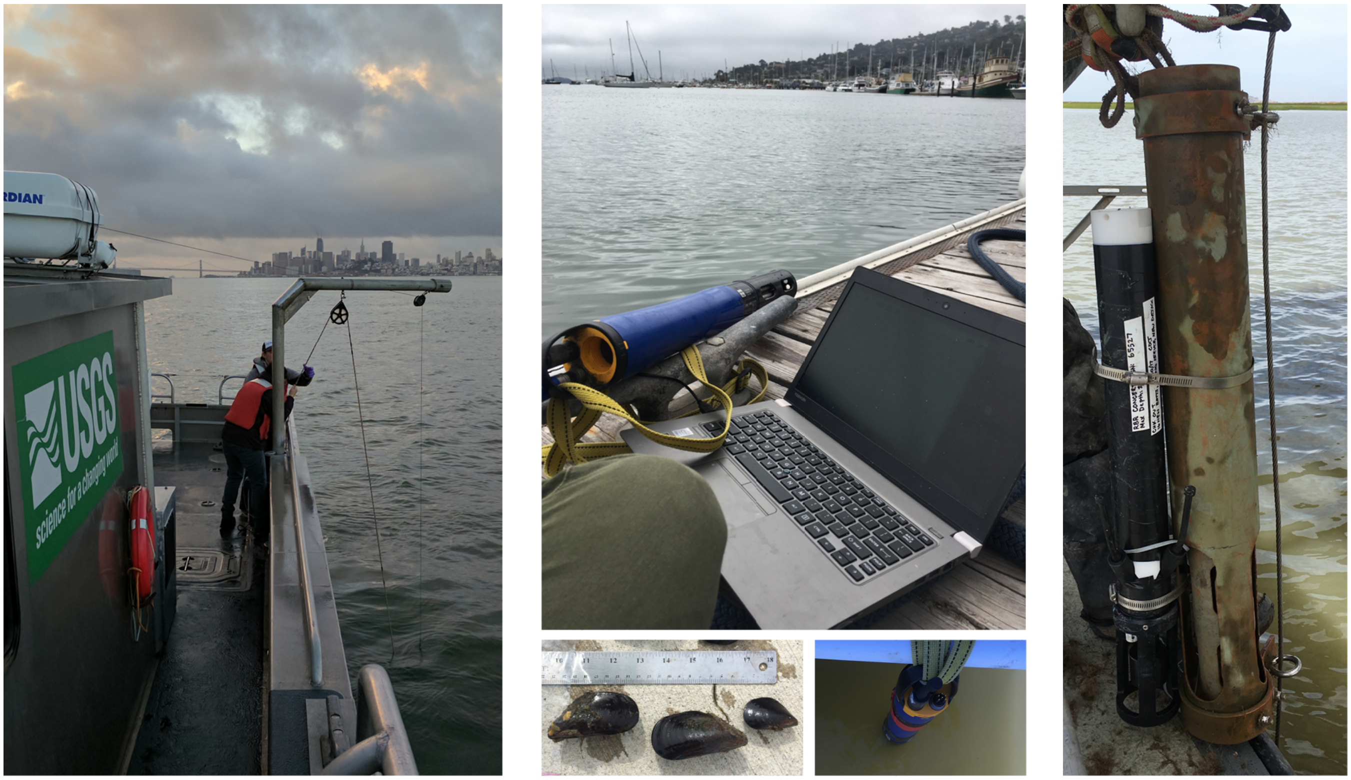
Algal toxin monitoring data have become comprehensive enough to describe the temporal/spatial frequency of toxin occurrence in the water column (e.g. Peacock et al. 2017) and now mussels as well (Figures X.1-4). These monitoring data, however, are roughly biweekly snapshots in highly time-variable and spatially-patchy estuarine ecosystem. To describe changes in the physical environment in between sampling events, high frequency monitoring data (hours to days) from moorings throughout SFB have recently been acquired. Ongoing work through FY18 will be using these datasets to investigate the overarching questions 1) what conditions associated with HA and/or toxin occurrence and 2) what are potential sources of HA and their toxins to SFB?

Some sub questions currently under investigation:

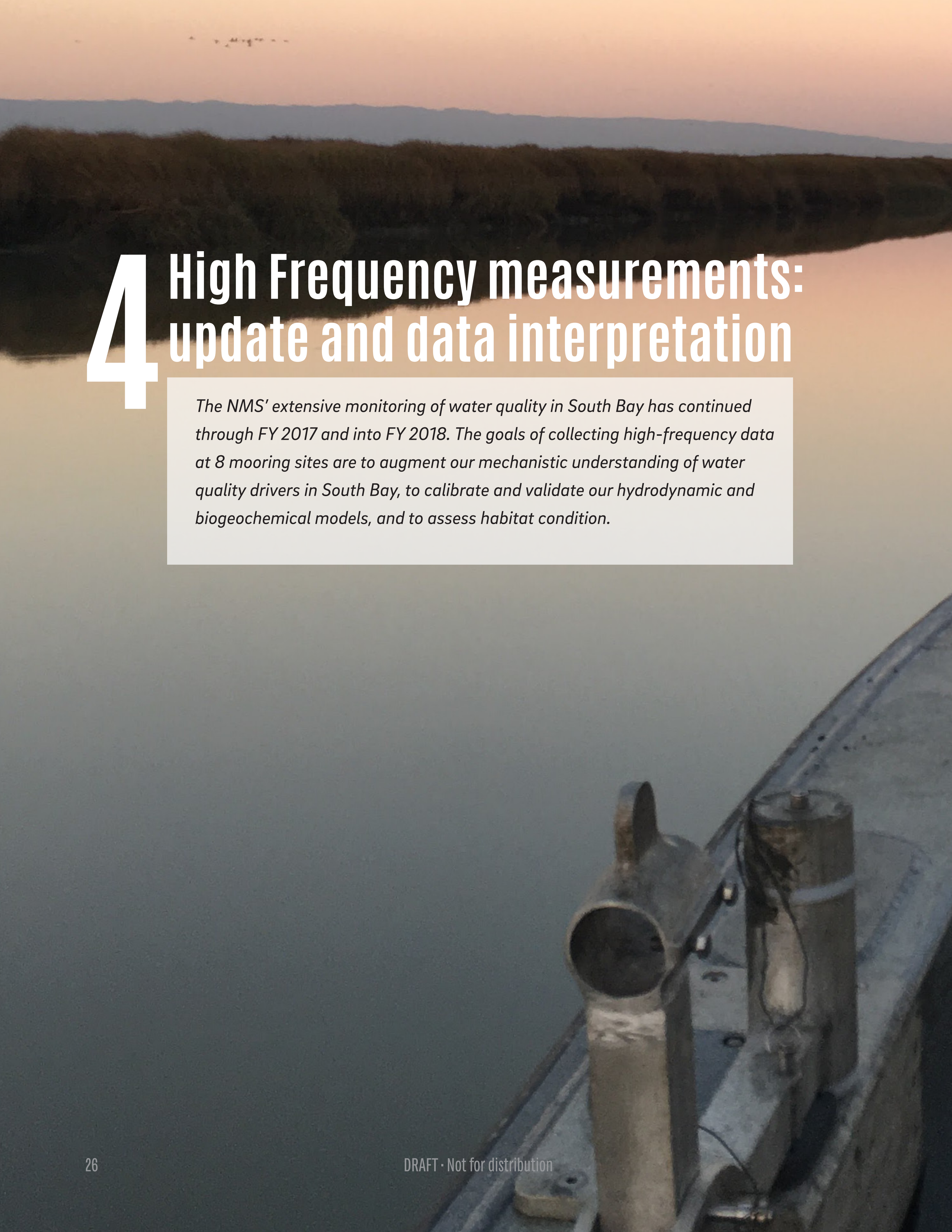
Seasonally, mussel MCY is present most often during warm summer months when rainfall is the lowest and salinity in central and south SFB is the highest. As MCY is generally considered a freshwater class of toxins, these observations further support the possibility (SFEI FY16) that there are sources of MCY to south SFB other than the Delta; can any potential sources be identified with existing data?

PST levels rise and fall from March through roughly August, primarily in central SFB mussels (Fig 3.Xx); is this indicative of a sustained PST-producing bloom event in or around central SFB? If so, was this bloom marine in origin? Or was it initiated, or sustained, in SFB?

There is evidence that trends in DA may follow trends in DA in the nearby marine environment (SFEI FY16), suggesting a marine source of DA to SFB. Are DA trends in SFB mussels similar to DA trends in nearby marine mussels collected at the coast?



Data collection from multiple platforms around SF Bay: routine shipboard sampling of discrete water samples and physical parameters in the water column (left); routine mussel collection at docks and marinas, including sensor deployment for coincident physical parameters (left); deployment of stationary moorings that collect high frequency physical observations (right).



4

High Frequency measurements: update and data interpretation

The NMS' extensive monitoring of water quality in South Bay has continued through FY 2017 and into FY 2018. The goals of collecting high-frequency data at 8 mooring sites are to augment our mechanistic understanding of water quality drivers in South Bay, to calibrate and validate our hydrodynamic and biogeochemical models, and to assess habitat condition.

MOORING NETWORK DATA: SUMMER 2016 UPDATE

The system is extremely dynamic, with strong tidal currents, active mixing, and discrete locations of strong primary productivity. In addition to the evident diurnal and spring-neap tidal signature in each of these constituents, the range of observed DO and chl-a values increases in the margin regions, such as the A8 feeder channel (which connects Pond A8 with Alviso Slough), Guadalupe, and Alviso Sloughs. The bridge sites show the narrowest range of DO and Chl-a.

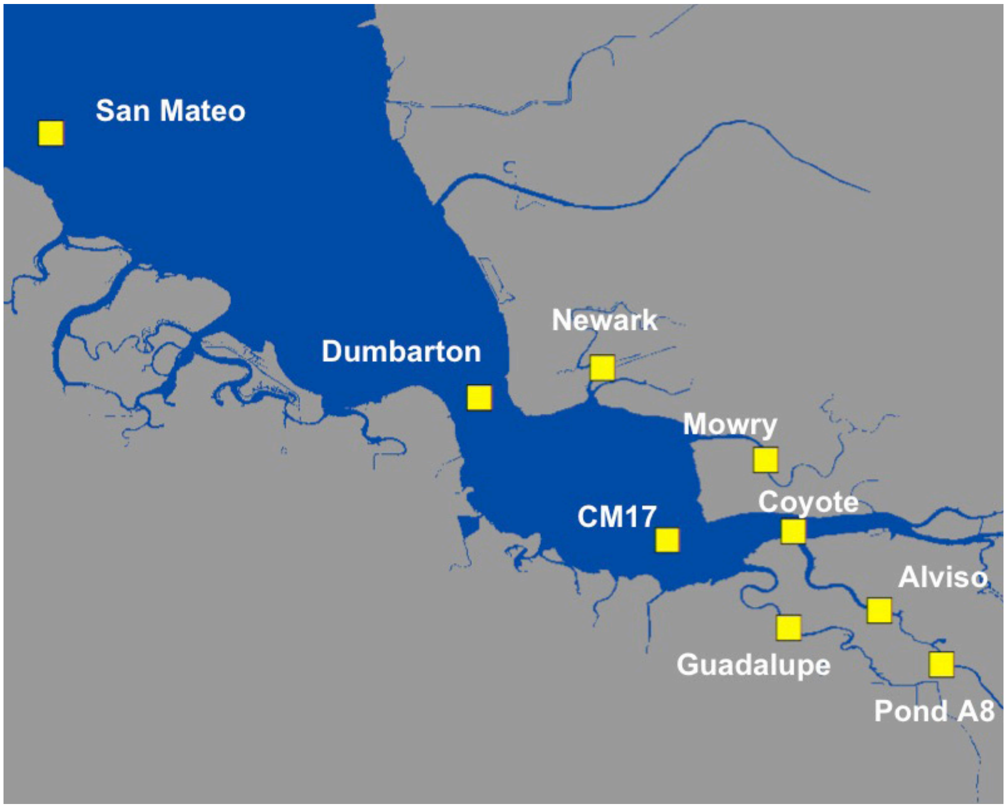
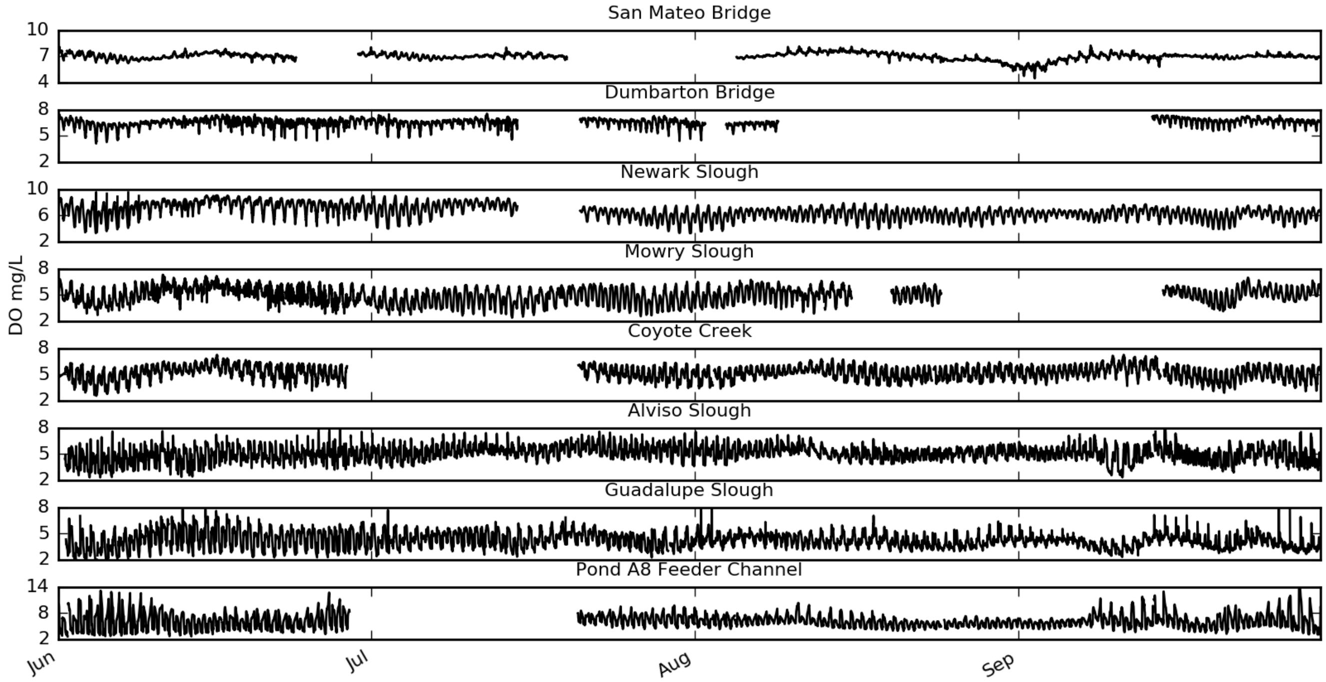
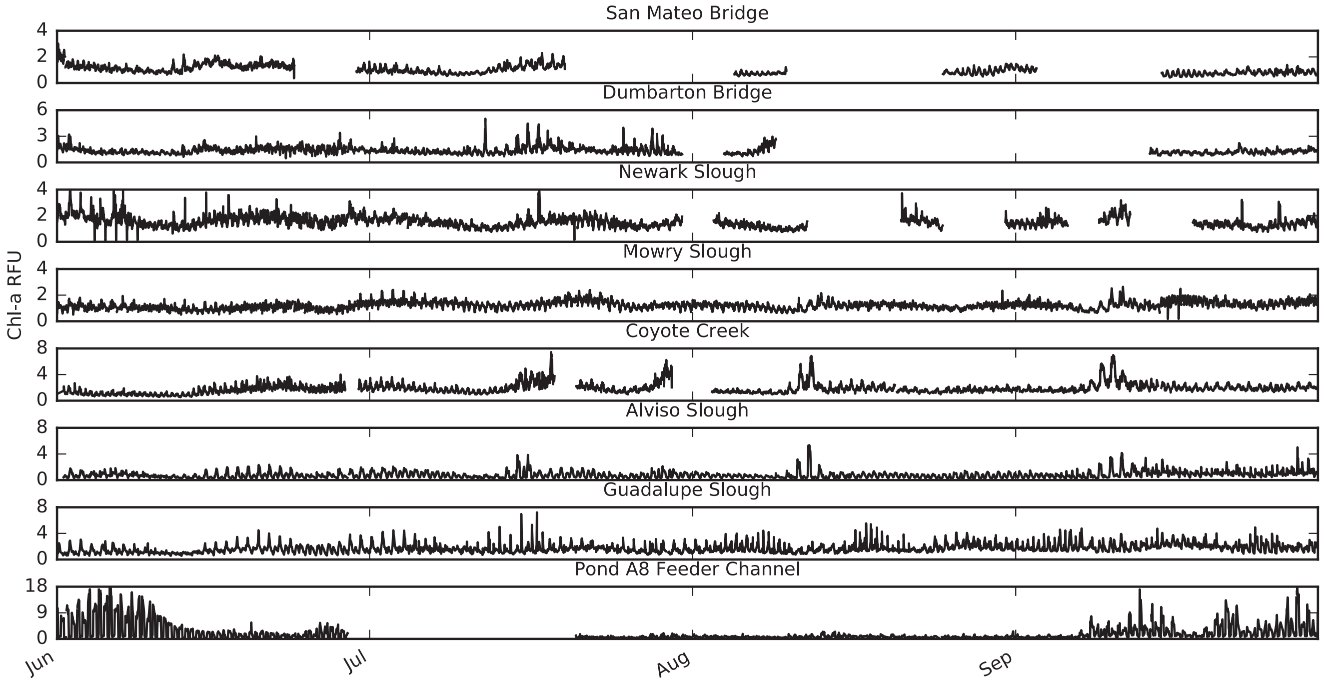


Figure 4.1 NMS mooring locations. Dumbarton, Alviso , and San Mateo were established in CY2013; All other stations were established in CY2015. In general, basic measurements include 15-min measurements for include sensors for salinity, T, dissolved oxygen, chl-a, turbidity, phycocyanin, and colored dissolved organic matter. Velocity data also collected at Alviso (USGS), Dumbarton (USGS), and CM17 (UC Berkeley)

Guadalupe Slough.

Dissolved Oxygen (DO, mg/L) and Chlorophyll-a (chl-a, in RFU) are shown for the summer of 2016. Data gaps are due to fouling of optical sensors. Note that the ranges represented by vertical axes vary between plots. Note also that comparisons of chl-a at different locations are not advisable due to differences in sensors. Temporal patterns are accurately shown.



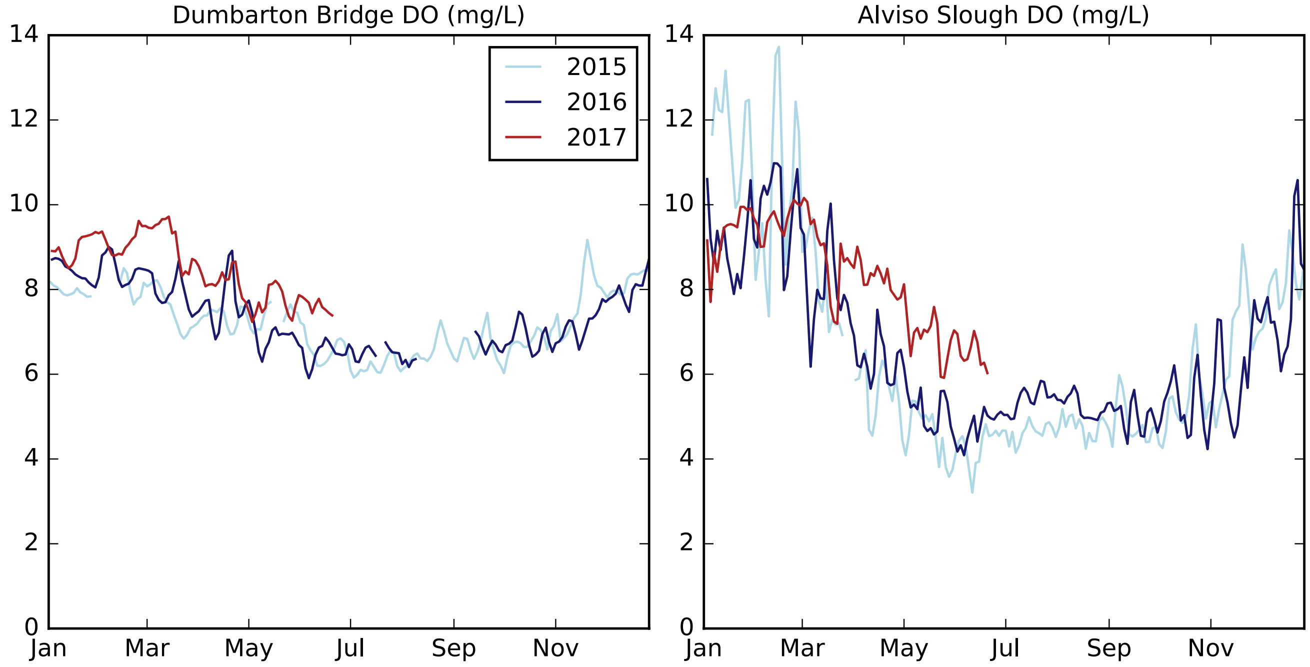


Dissolved Oxygen in the Open Bay and Margins

Examining DO at the Dumbarton Bridge (open Bay) and Alviso Slough (margin site) over multiple years allows us to examine the differences in these two environments. Daily averages of DO are shown below, for years 2015, 2016, and 2017. The seasonal pattern is clear at both locations, with DO highest in the winter and lowest the the warm, summer months, although there is variability between years. The spring and summer of 2017 demonstrate notably higher DO in the margins and open bay following the record-setting wet winter.

The differences between the two sites are also apparent. The range of daily averages of DO observed in the open bay, from about 6 to 10 mg/L, is narrow compared with the margin where levels span 4 to 14 mg/L. (The instantaneous variability is greater than what is captured in an average daily value, and DO sometimes dips below 4 mg/L in Alviso Slough for short periods of time.) Both locations see oxygen-enriched conditions in the winter months, but the elevated DO concentrations in Alviso Slough suggest a near-by source.

This difference points to the mechanisms controlling DO at these sites. At the Bridge, water from Lower South Bay as well as the broad South Bay shoals is mixed by wind waves and strong tidal currents. Alviso Slough receives water from former salt ponds, which are relatively warm and clear due to their shallow depths. This water can be oxygen-enriched as primary productivity grows during spring-time, or depleted as organic material respires during autumn months, leading to a vast range of observed DO values.



Daily averages of DO at the Dumbarton Bridge and Alviso Slough moorings.

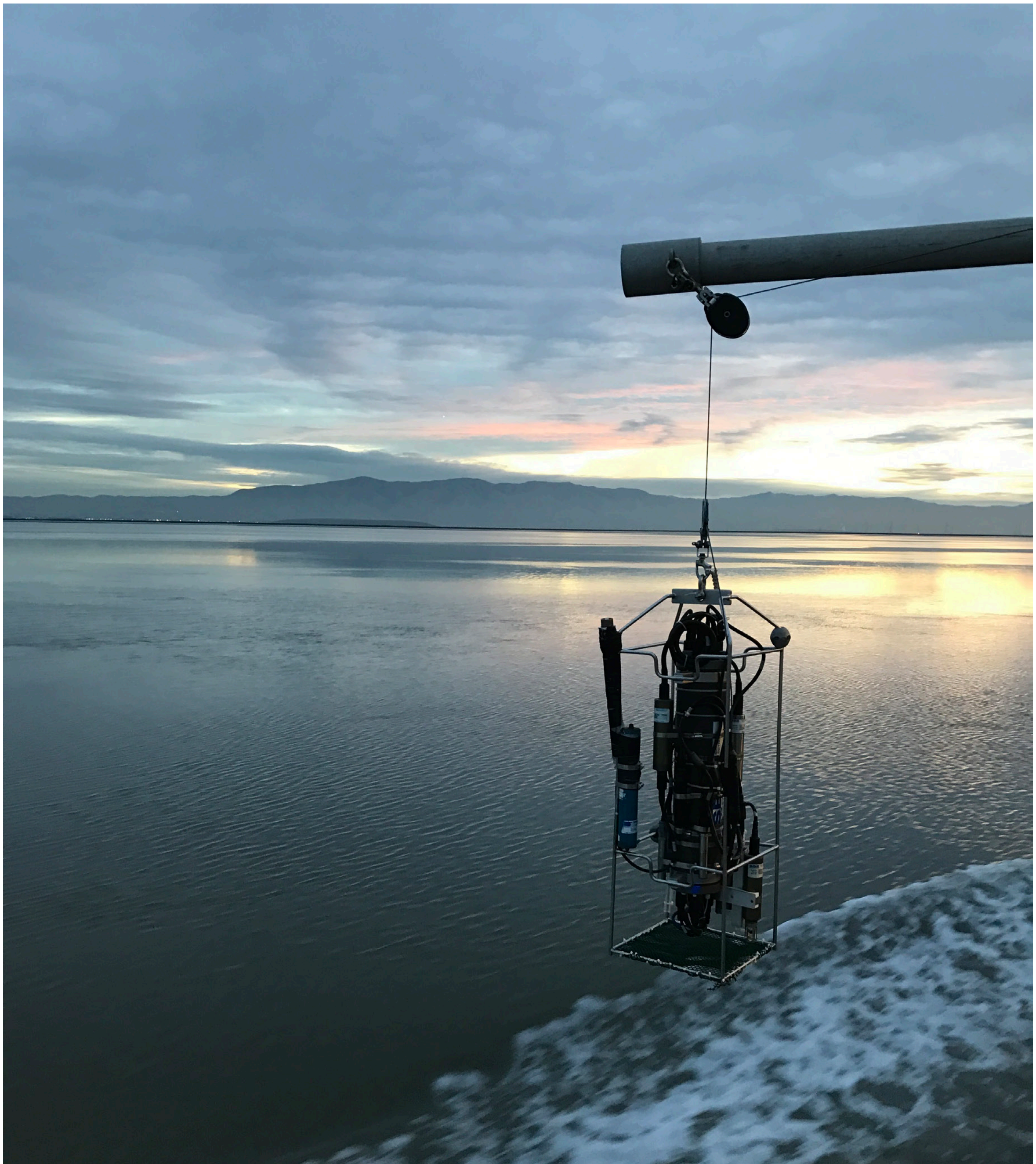
Mooring Network Data Management

We have implemented automated processes for cleaning the data to meet our QA/QC standards. These include:

- Identifying times when the sensors are out of the water.
- Extracting thermistor data from each sensor to minimize data gaps during fouling events.
- Outlier removal.
- Correcting DO concentration when temperature and/or conductivity data are missing or compromised.

Next steps include:

- Automating the identification of fouling due to sediment clogging and biological growth.



USING DATA TO ESTIMATE DO CONSUMPTION RATES

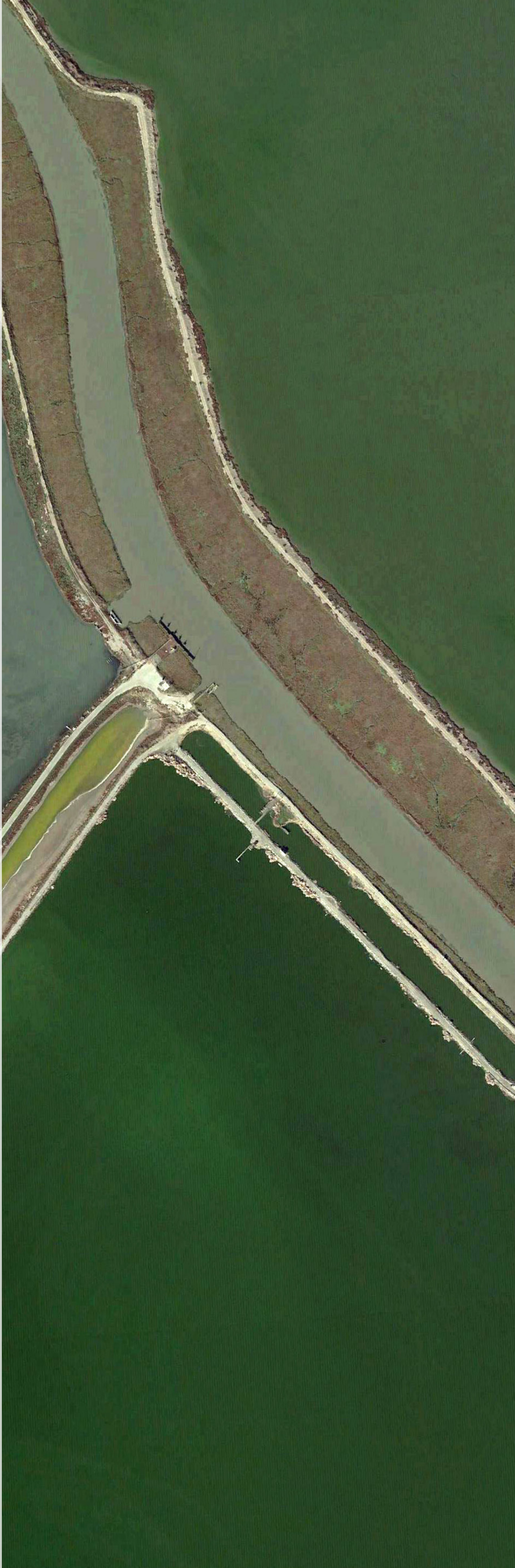
Mooring data were used to estimate rates of net oxygen flux throughout LSB. This quantity, shown in red, includes all respiration and production, as well as air-sea exchange. Positive values indicate net production, and negative values are net consumptive. Published values for estuarine pelagic and benthic respiration are typically on the order of -1 to -3 g O2 m-2 day-1. Net oxygen consumption near the Alviso complex and in Mowry Slough was estimated to be far greater (more negative) than those values, implying that respiration alone would be greater still. DO consumption values at the Dumbarton Bridge, Newark Slough, and Coyote Creek are more consistent with published ranges.

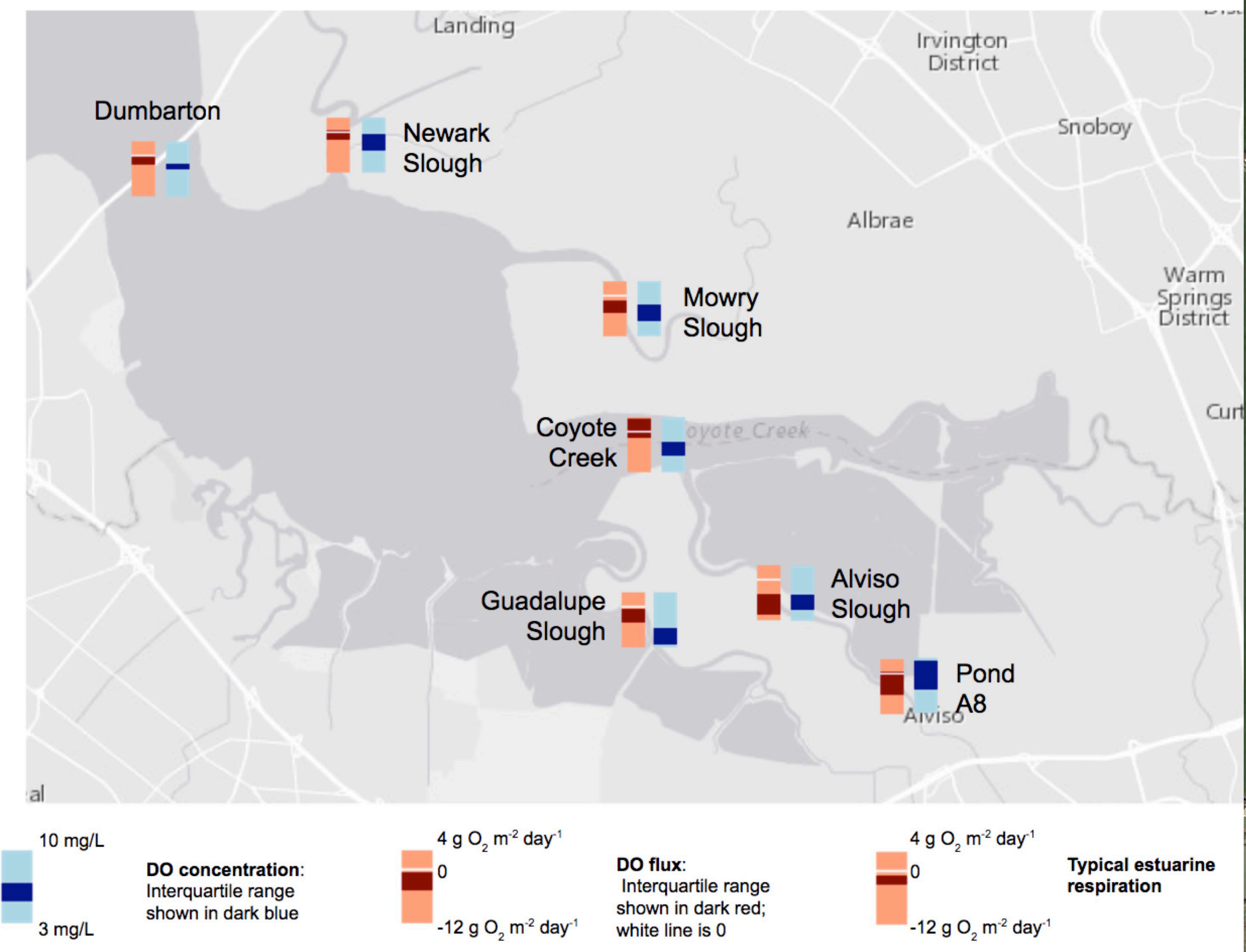
Although these locations exhibit very high rates of oxygen consumption, concentrations of DO are not frequently problematic (with the exception of Guadalupe Slough) and evidence of extreme biological stress, such as fish kills, is rare. Our working hypothesis is that this is due to the influence of local primary-productivity “hot spots”, such as the Alviso pond complex, located between Alviso and Guadalupe sloughs.

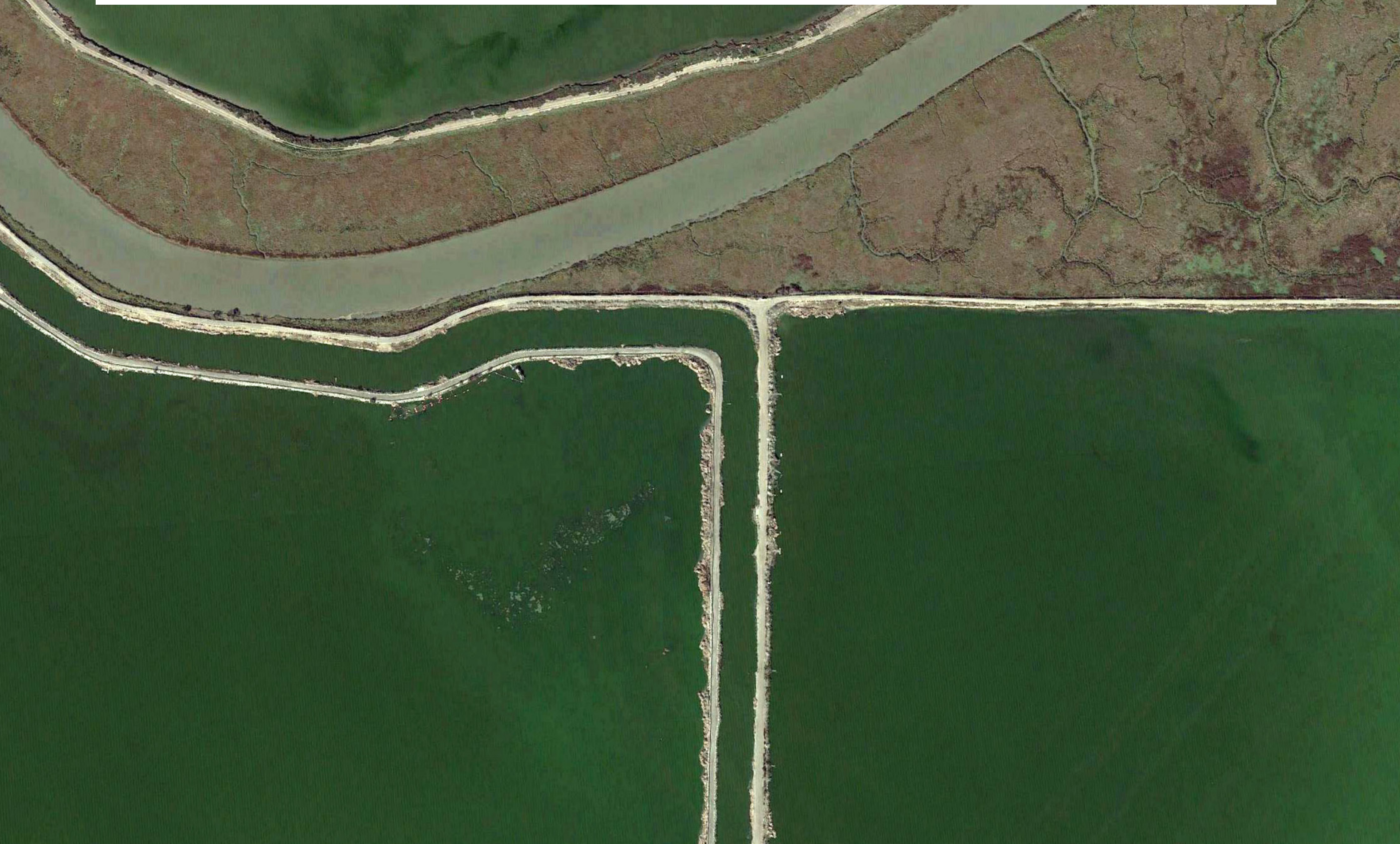
During a typical year:

- In spring time, as the shallow, quiescent ponds begin to warm, phytoplankton blooms develop and are dispersed throughout near-by sloughs.
- Photosynthetic production of DO and respiration are active during the phytoplankton growing phase resulting in oxygen enrichment at the outlet of Pond A8.
- As summer begins and temperatures rise, phytoplankton begins to die, and the ponds and sloughs are seeded with decaying organic material, consuming oxygen at rapid rates.
- DO doesn’t plummet, however, due to the continued supply of oxygen to the system via production.

Guadalupe has anomalously low levels of DO, which could be explained by transport of DO from Pond A8 being inadequate to offset the effects of the decaying organic material that has been deposited in the slough over many previous tidal cycles, and/or stratification inhibiting turbulent transport of oxygen due to the influence of freshwater.




Landing
Irvington District
Snoboy
Albrae
Warm Springs District
Curt
Dumbarton
Newark Slough
Mowry Slough
Coyote Creek
Coyote Creek
Guadalupe Slough
Alviso Slough
Pond A8
Alviso
10 mg/L
3 mg/L
DO concentration: Interquartile range shown in dark blue
$4\ g\ O_2\ m^{-2}\ day^{-1}$
0
$-12\ g\ O_2\ m^{-2}\ day^{-1}$
DO flux: Interquartile range shown in dark red; white line is 0
$4\ g\ O_2\ m^{-2}\ day^{-1}$
0
$-12\ g\ O_2\ m^{-2}\ day^{-1}$
Typical estuarine respiration

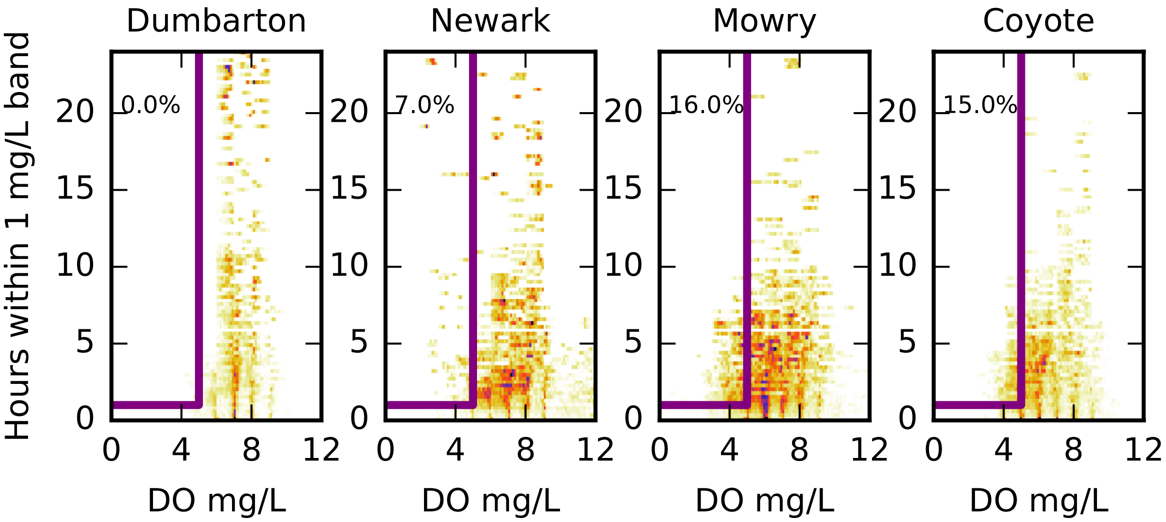


DO AND HABITAT QUALITY IN LOWER SOUTH BAY

Given the wide range of DO concentrations observed in the South and Lower South Bay since 2013, the question of its implications for habitat quality is a pressing one. Linking the effects of DO variability on the health and behavior of animals to conditions in the environment was the subject of an SFEI workshop in April, 2017. Scientists from the US and Canada, as well as local stakeholders, met to map out a methodology for characterizing the dependence of habitat quality on DO.

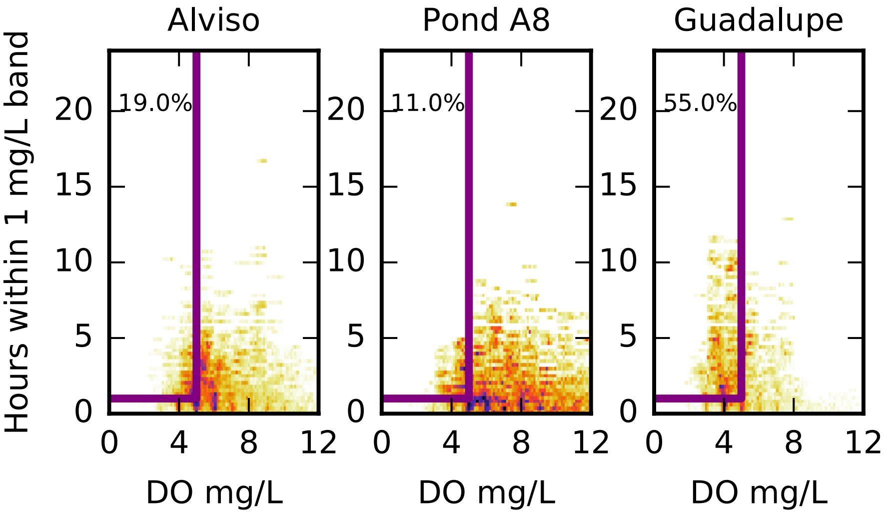
The key components are:

1. Use fish and benthic surveys, along with co-located measurements of water quality, to determine biological DO requirements.
2. Quantify the DO condition among habitat types (e.g. sloughs, mudflats, open bay), including the range of DO concentrations and persistence of low-DO events, as shown below.



Histograms at LSB sites in 2016 of measurements binned by DO concentration and duration at or below each concentration interval. Darker colors indicate that many measurements were observed at or below that DO concentration for the specified length of time (consecutively).

The purple box indicates the percentage of DO measurements falling below 5 mg/L for 1 hour or longer. The Dumbarton Bridge station saw almost no measurements in that box, while in Guadalupe, over half of measurements were < 5mg/L for 1 hour or more.



MONITORING PILOT: STUDYING CONDITIONS ALONG SOUTH BAY'S SHOALS

What are biogeochemical conditions outside the view of current monitoring?

Past studies have shown that chl-a levels are often higher along SFB's shoals than measured along the adjacent deep ship channel (e.g, Cloern 1995; Thompson et al, 2008), in part due to the shallower water column allowing phytoplankton to experience greater light levels. Given the large areal extent of the shoals (in South Bay, San Pablo Bay, and Suisun Bay) improved quantitative understanding of the biogeochemical processes along the shoals is needed both to predict conditions (i.e., calibrating models) and to accurately assess condition.

In Spring 2017 the NMS launched a pilot study to characterize conditions along South Bay's broad eastern shoal. Working with researchers from USGS-Sacramento, a multi-sensor mooring was deployed on the shoal in where depth was ~2m (at low tide), ~2km north of the San Mateo Bridge. In addition, high-frequency biogeochemical "mapping" cruises measured a range of parameters using a flow-through water system and optical sensors, while the boat cruised at ~15 knots.

Preliminary data from the mooring (Figure 4.6) and mapping (Figure 4.7) indicate that a relatively high-biomass bloom developed along the shoal. [Note: chlorophyll-a and NO3- concentrations are approximate, pending calibration data]

Mooring data indicate:

- chl-a levels reached and remained at 50 µg/L (daily average) for approximately 2 weeks before the bloom dissipated. The hourly time-scale variability in chl-a is actually an indication of spatial variability in chl-a concentration, with the twice daily high and low tides moving water with different concentrations past the sensor.
- Nitrate concentrations varied inversely with chl-a, both the multi-day signal and hourly time-scale variations. This pattern is consistent with nitrate being assimilated by phytoplankton.
- The ~10-day cycle in daily turbidity peaks is due in part to the spring-neap tidal cycle, and provides insights into very different light conditions that phytoplankton experience.

The biogeochemical mapping data provides highly complimentary information:

- Chl-a max/min concentrations concided with nitrate min/max concentrations. Elevated chl-a and lower nitrate (relatively to channel) were generally observed further east along the shoal. The distribution of chl-a levels on 3/23/2017 and 4/5/2017 were comparable to the concentrations detected by the mooring.

Further interpretation of this dataset is planned in the coming year, including the use of velocity data (ADCP) also collected at the mooring, and initial use in model calibration.

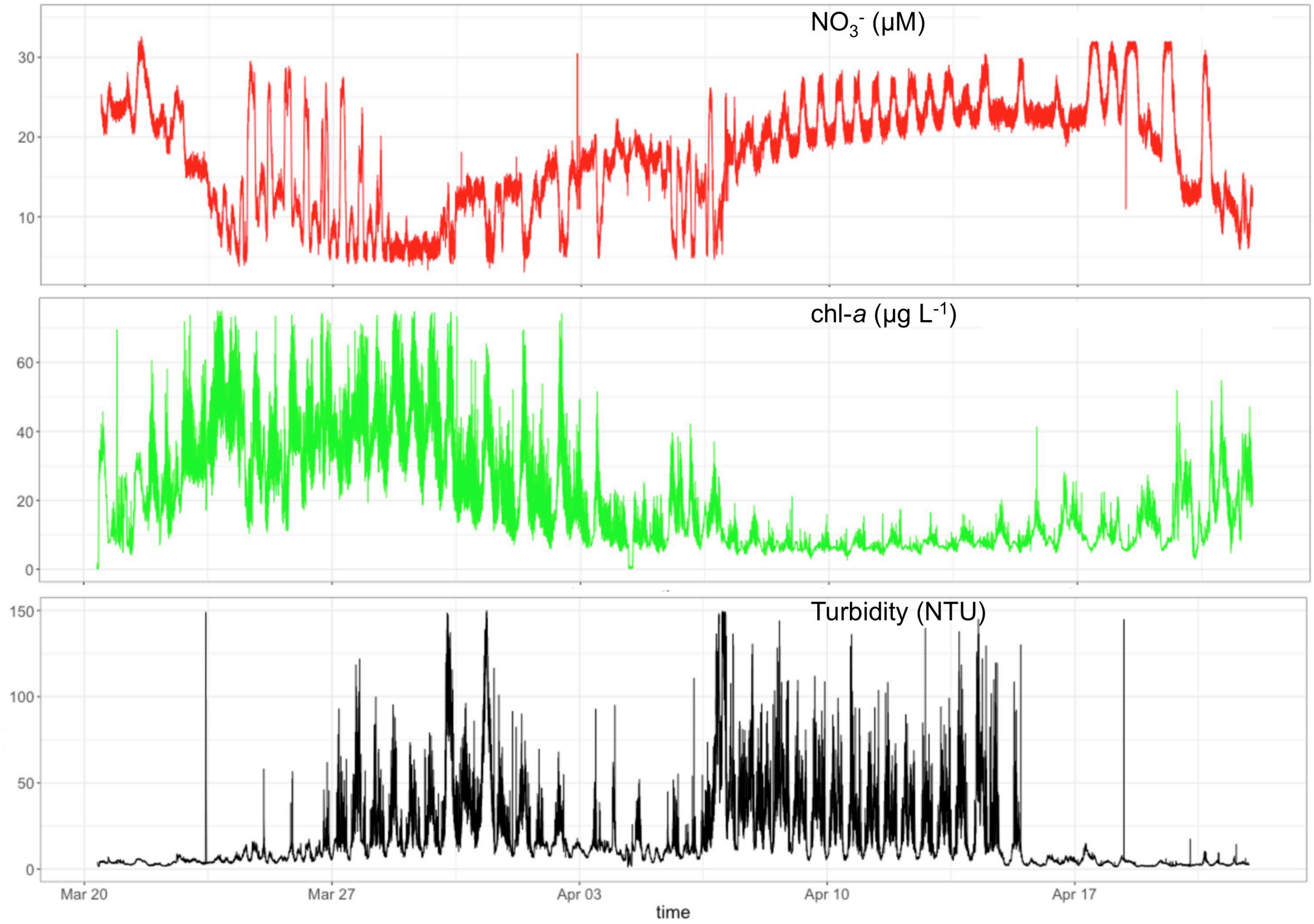
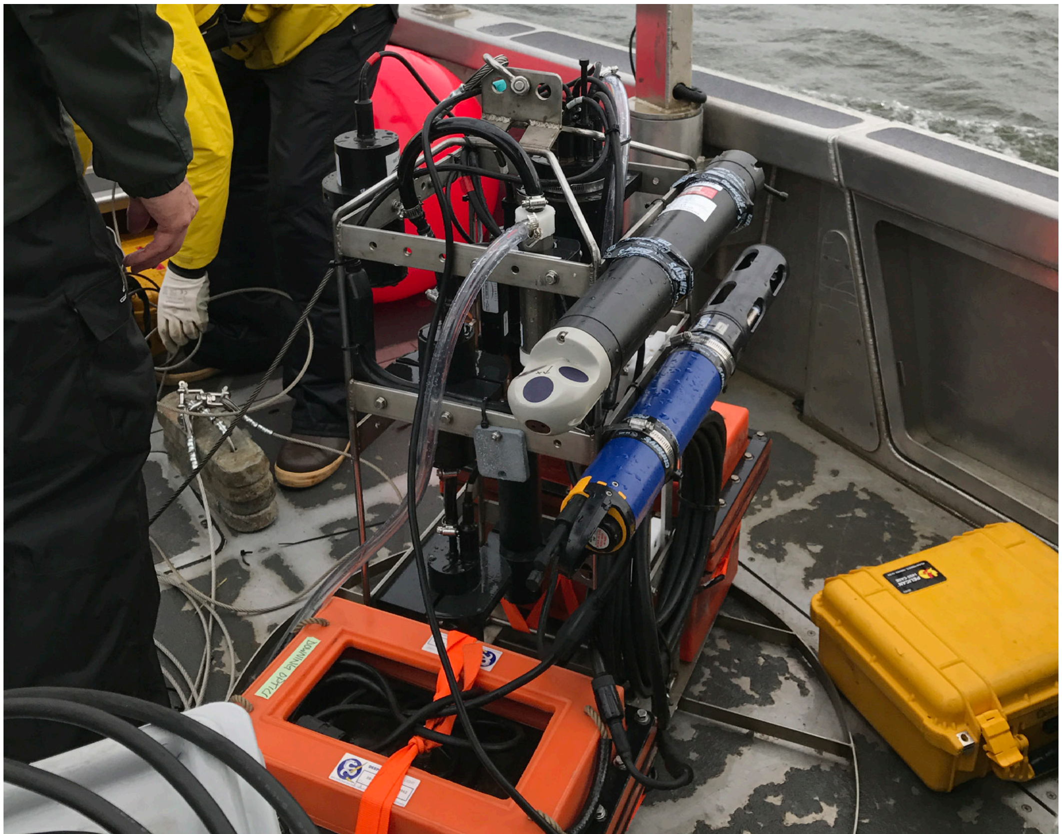


Figure 4.6 Nitrate, chlorophyll-a, and turbidity measurements during a one month mooring deployment on the South Bay eastern shoal. Concentrations approximate, pending validation with discrete sample data.



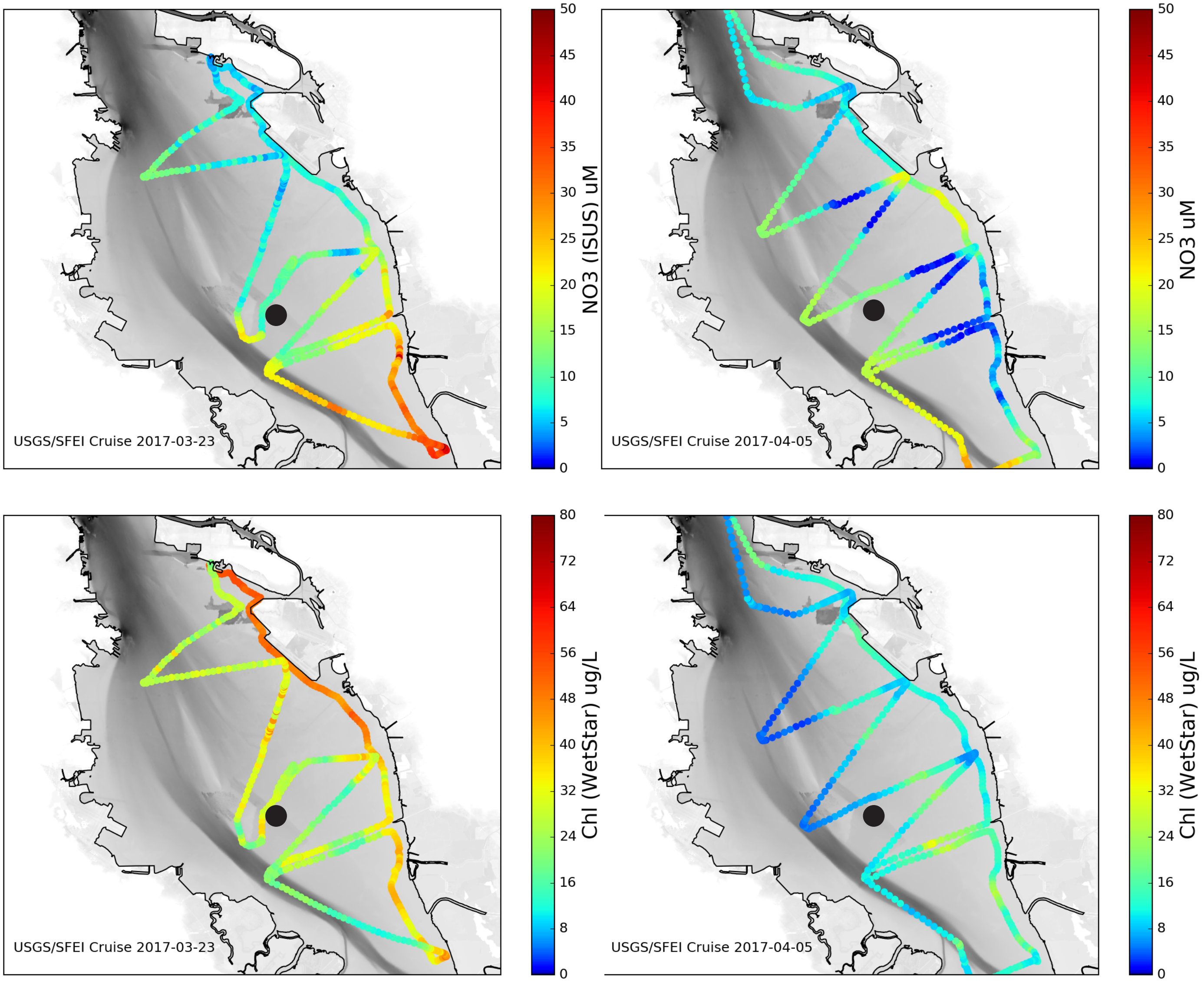
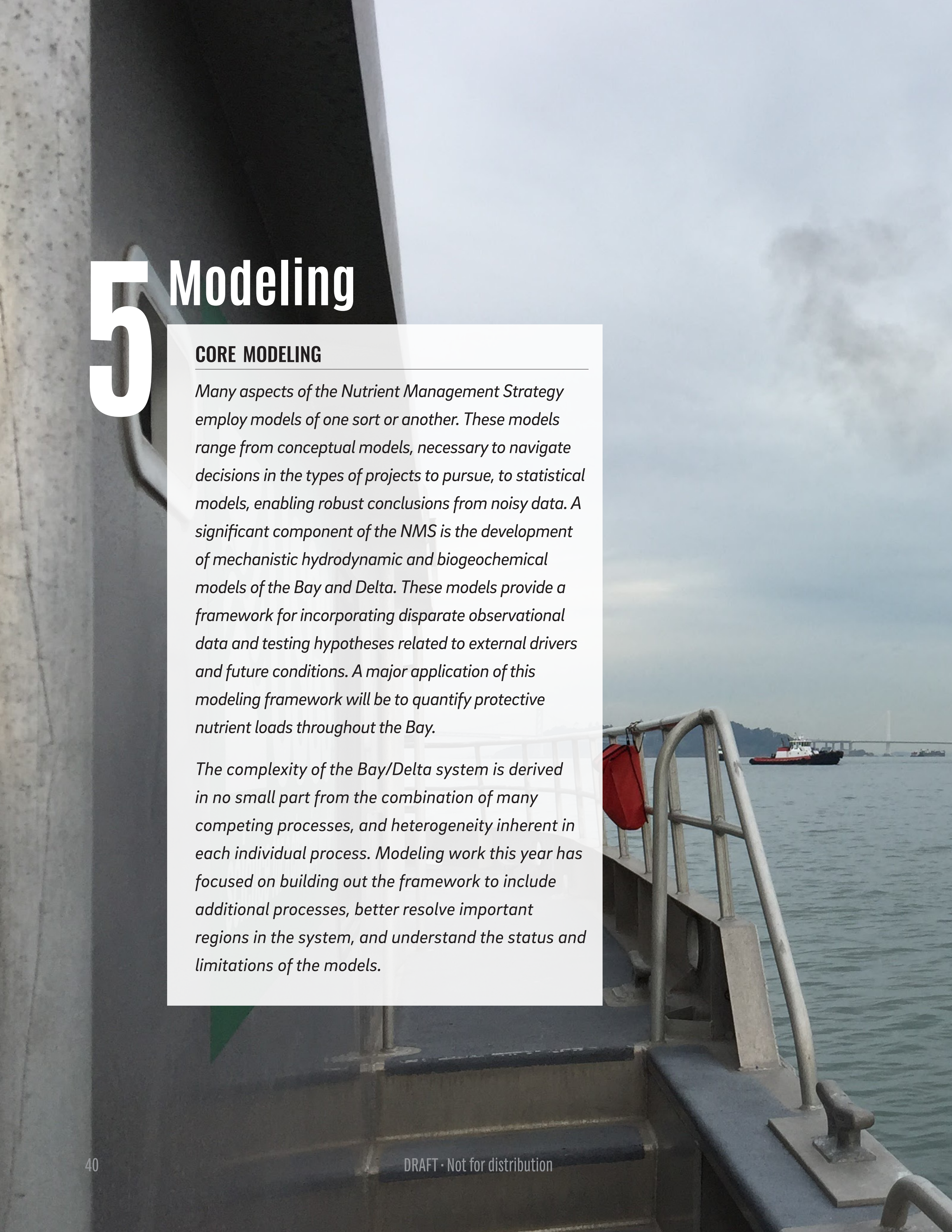


Figure 4.7 Nitrate and chlorophyll-a measured with flow-through sensors while cruising at ~15 knots during two cruises. Total elapsed time during data collection on both days was ~2 hours, beginning at slack-high / early-ebb. Concentrations approximate, pending validation with discrete sample data.


USGS



5 Modeling

CORE MODELING

Many aspects of the Nutrient Management Strategy employ models of one sort or another. These models range from conceptual models, necessary to navigate decisions in the types of projects to pursue, to statistical models, enabling robust conclusions from noisy data. A significant component of the NMS is the development of mechanistic hydrodynamic and biogeochemical models of the Bay and Delta. These models provide a framework for incorporating disparate observational data and testing hypotheses related to external drivers and future conditions. A major application of this modeling framework will be to quantify protective nutrient loads throughout the Bay.

The complexity of the Bay/Delta system is derived in no small part from the combination of many competing processes, and heterogeneity inherent in each individual process. Modeling work this year has focused on building out the framework to include additional processes, better resolve important regions in the system, and understand the status and limitations of the models.


MAERSK LINE

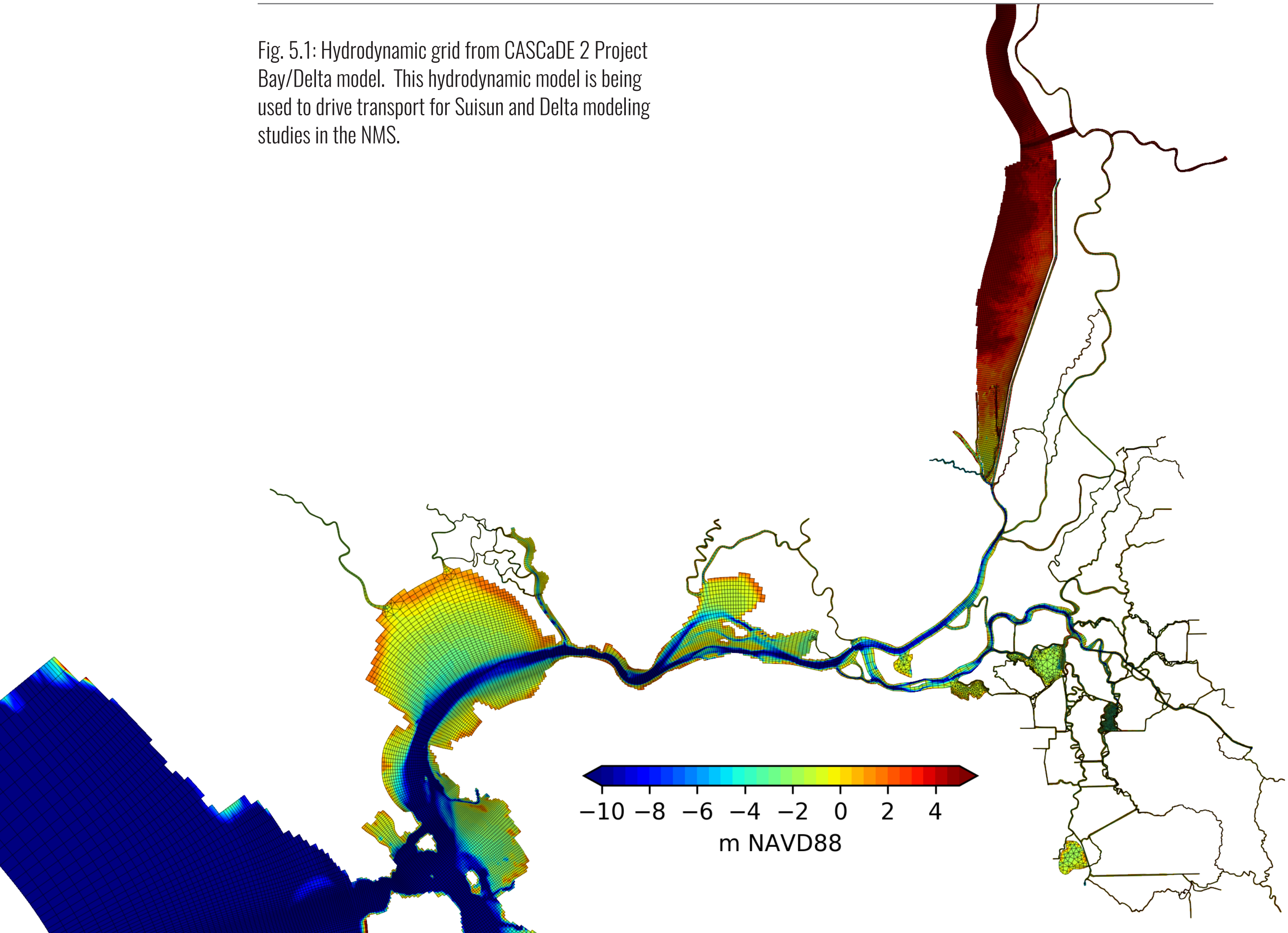
Hydrodynamics

At the start of the modeling project, the intended modeling platform, Deltares Flexible Mesh (DFM), was still under heavy development and testing. Early NMS applications relied on a SUNTANS-based model while DFM development was ongoing. The past year has seen this phase wrap up, with a significant milestone achieved in the publication of the initial SF Bay/Delta application of this model (Martyr et al, 2017).

This initial application, developed as part of the USGS CASCaDE project with supplemental funding from the NMS, focused on the Delta and North Bay. NMS efforts in collaboration with colleagues at Deltares extended that model to include a richer representation of South Bay (fig. 5.2), including validation of tides, currents, and the salinity field. Work is underway to add the remaining nutrient and freshwater sources to this model, as well as some additional physical processes such as evaporation. A key advance has been the inclusion of a hydrologic model to derive ungaged flows, rather than a more simplistic scaling approach used in previous model iterations. This change is expected to improve model skill during high-flow periods, as well as position the biogeochemical model to accept stormwater loads in addition to the wastewater loads currently implemented.

This phase of development will culminate in a three-way intermodel comparison to understand the relative strengths and weakness of the original SUNTANS model, the original DFM model, and the refined DFM model with additional sources and processes.

Fig. 5.1: Hydrodynamic grid from CASCaDE 2 Project Bay/Delta model. This hydrodynamic model is being used to drive transport for Suisun and Delta modeling studies in the NMS.



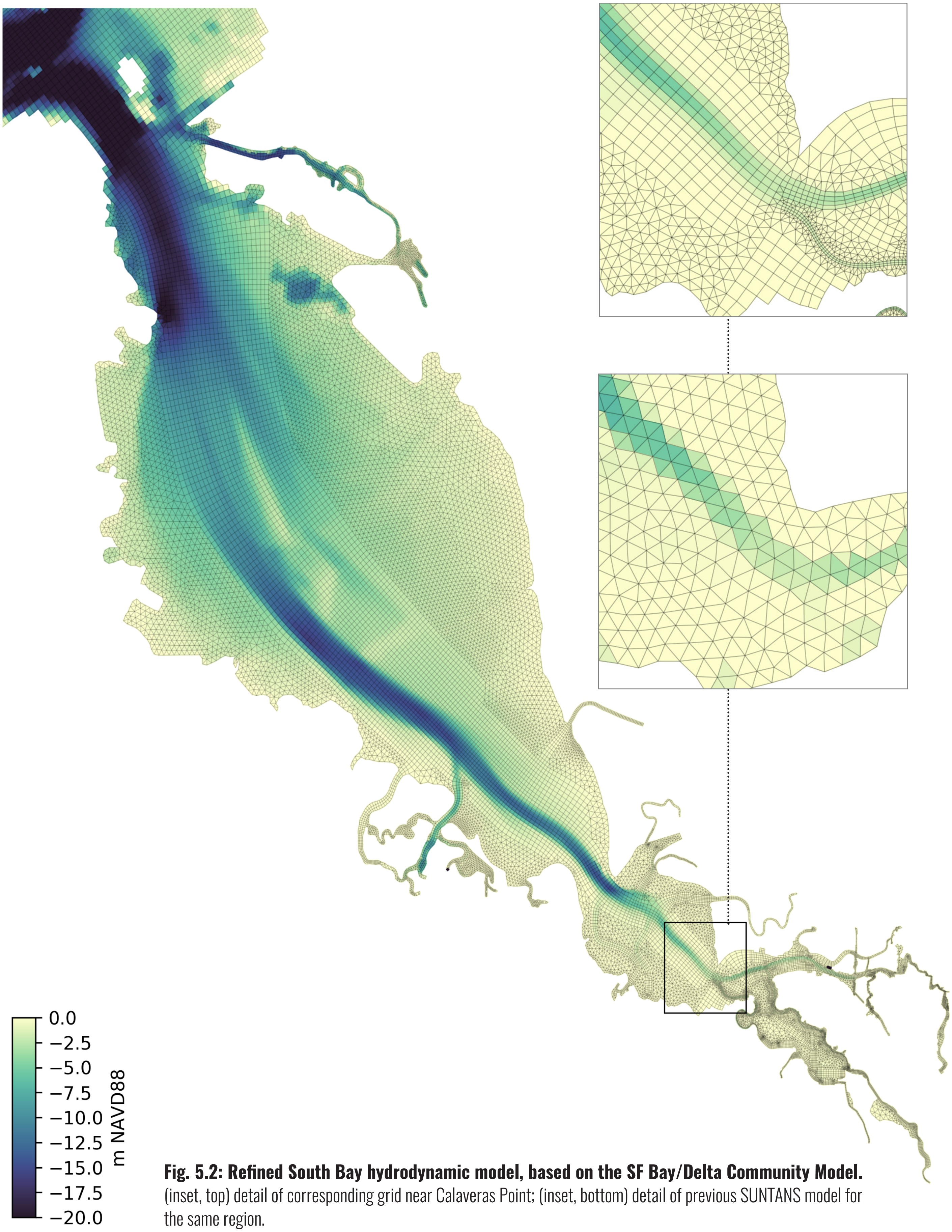


Fig. 5.2: Refined South Bay hydrodynamic model, based on the SF Bay/Delta Community Model. (inset, top) detail of corresponding grid near Calaveras Point; (inset, bottom) detail of previous SUNTANS model for the same region.

Nitrogen Budgets

While many parts of the coupled hydrodynamic- biogeochemical model are still being developed, some initial, if tentative, applications are already underway. One such early-phase application is estimating nitrogen budgets in the Bay at the sub-embayment scale.

For this project, nitrate and ammonia loads were added to the transport model, representing over 40 discharges as well as Delta-sourced nutrients. Transport of dissolved nitrogen is driven by the modeled hydrodynamics, and along the way subject to simplified estimates of nitrification and denitrification. Baseline validation of nitrate and ammonium concentrations show that the model captures a significant amount of the observed variance in nutrient concentrations.

Loads, transport and loss (via denitrification) of these nutrients were estimated and summarized in the form of regional nitrogen budgets. These budgets resolve the major pathways of nitrogen through the Bay on a monthly time scale, such as the snapshots of January, 2013 and August, 2013 in figure 5.3. Delta outflows in January lead to a transport-dominated flux of nitrogen through North Bay, and the model suggests a relatively minimal role of denitrification processes during this colder portion of the year. Lower flows and warmer temperatures in August allow for greater denitrification within the Bay, and a significantly smaller flux of nitrogen to the coastal ocean.

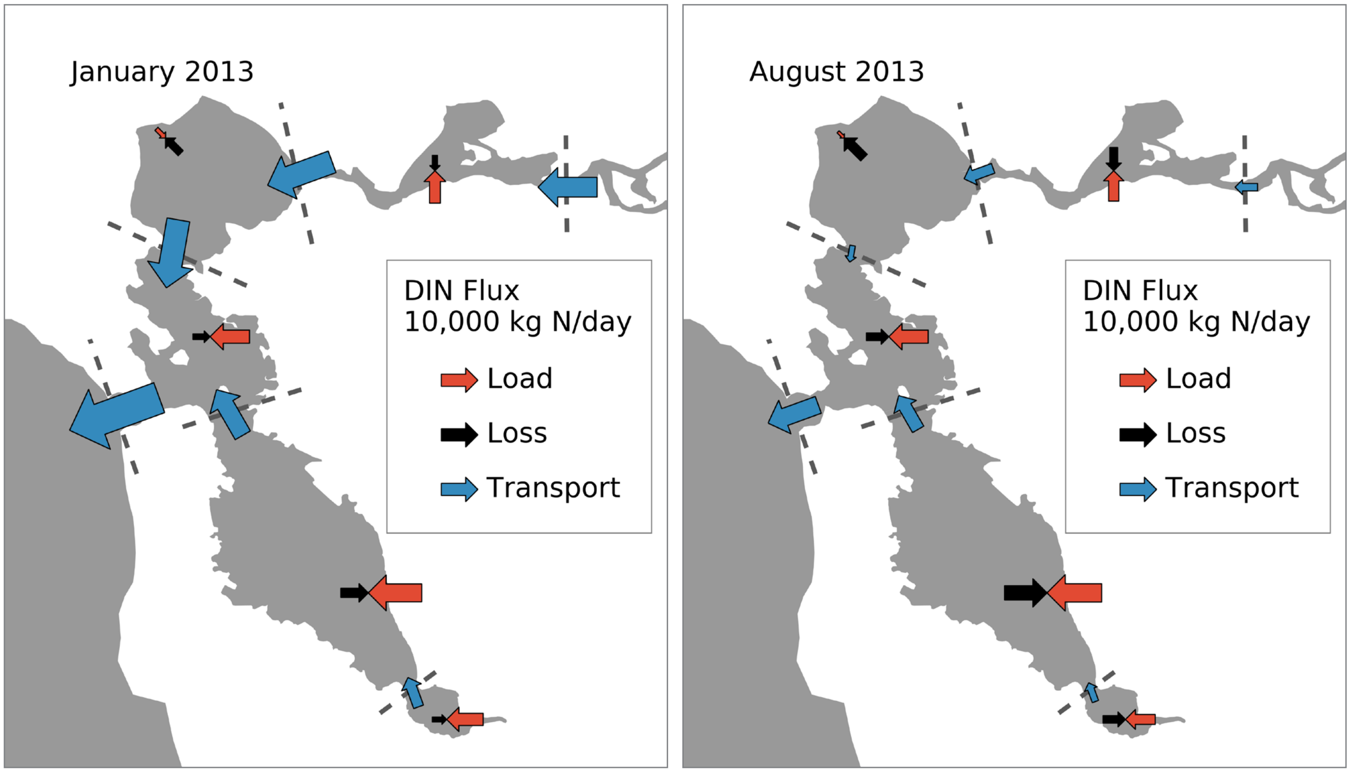


Fig. 5.3: Estimated loads, transport and loss of dissolved, inorganic nitrogen for a wet month (left) and a dry month (right). Arrows indicate the direction of the fluxes, with the size of the arrow scaled to the magnitude of the flux. Reference arrows in the legend correspond to a flux of 10,000 kg/day.

Suisun and the Delta

Initial modeling efforts of the NMS have focused on San Francisco Bay, and South Bay in particular. The geographic scope of recent NMS modeling projects, though, has extended into Suisun Bay and the Delta. In this early phase of the project, efforts have focused on integrating hydrodynamic data from the CASCaDE Project into the water quality model, and building the necessary databases of nutrient loads. One of the early outputs from this effort is a synthesized, 16 year dataset covering loads from significant wastewater treatment plants in the Delta and estimated contributions from the Sacramento River and San Joaquin River. Given the incomplete nature of observed nutrient concentrations, we have developed methods to fill data gaps based on seasonal cycles and long-term trends, yielding time series data such as in figure 5.4.

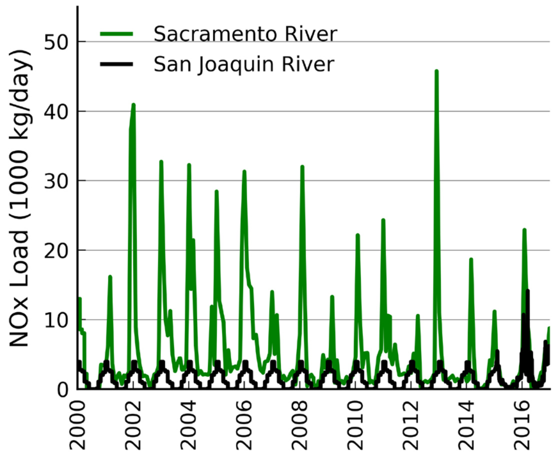
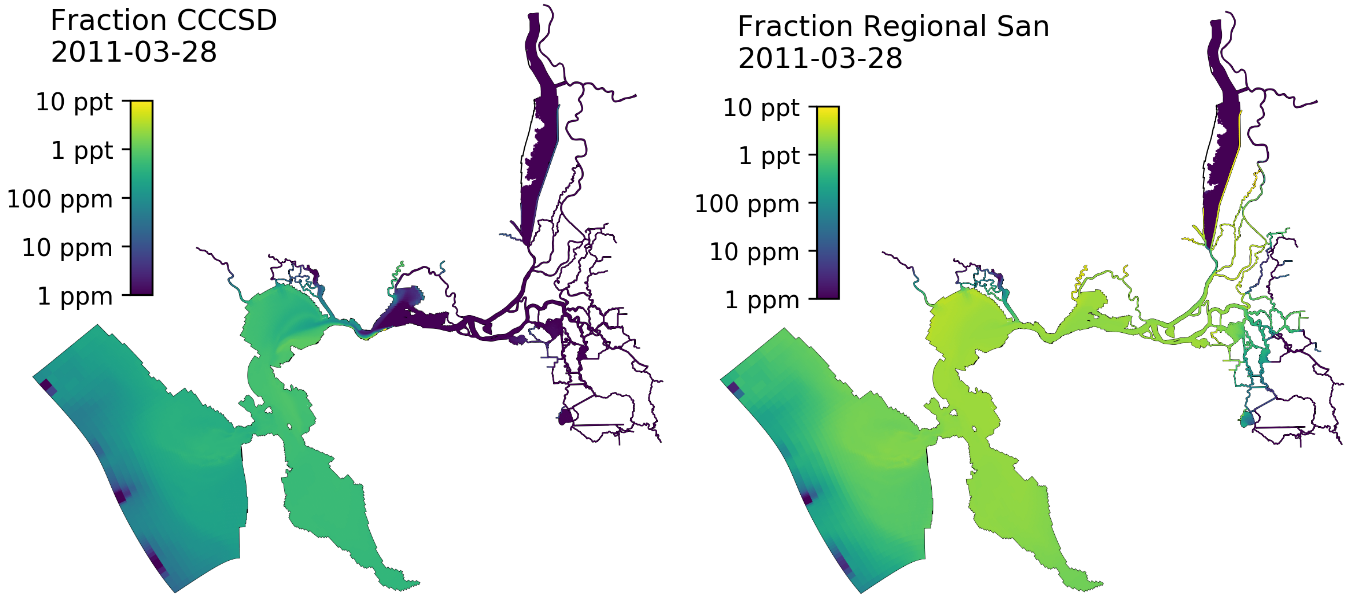


Fig. 5.4: Estimated NO3+NO2 loads on the Sacramento and San Joaquin Rivers. (above) While daily Sacramento River data has been processed for much of the period, San Joaquin data falls back to monthly climatologies for most of the period.

Figure 5.5 depicts an example of the initial tests of the coupling between hydrodynamics and nutrient loads. (below) Flows from two significant discharges are numerically labelled at the source and transported by the modeled currents. The plots are in terms of dilution ratios, i.e. 1000 ppt at the discharge.

This particular moment represents a high-flow period, with most of the open areas of Suisun Bay flushed by Delta outflows. Under these conditions, the influence of Central Contra Costa Sanitary District (CCCSD) is limited to a narrow strip in Suisun Bay before being diluted in downstream portions of the Bay.

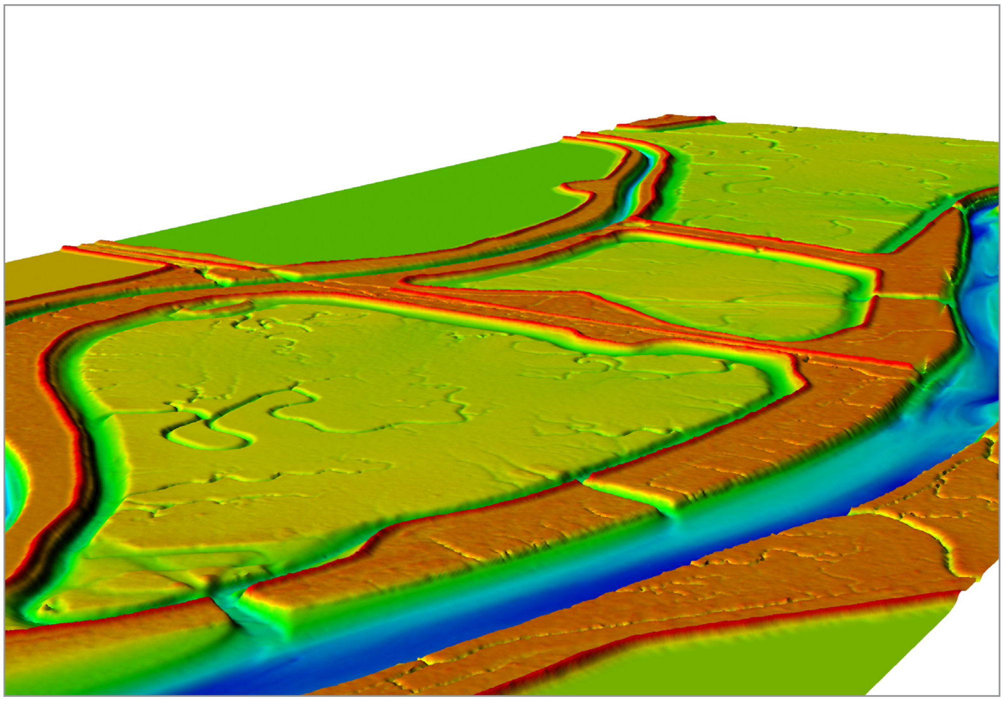
The corresponding distribution for Regional San in Sacramento is shown in the second plot. The discharge location is just visible on the mainstem Sacramento River. Compared to the distribution for CCCSD, here the model captures the influence of Regional San on the Delta, as well as the greater mean discharge, evidenced by higher concentrations throughout the model domain.

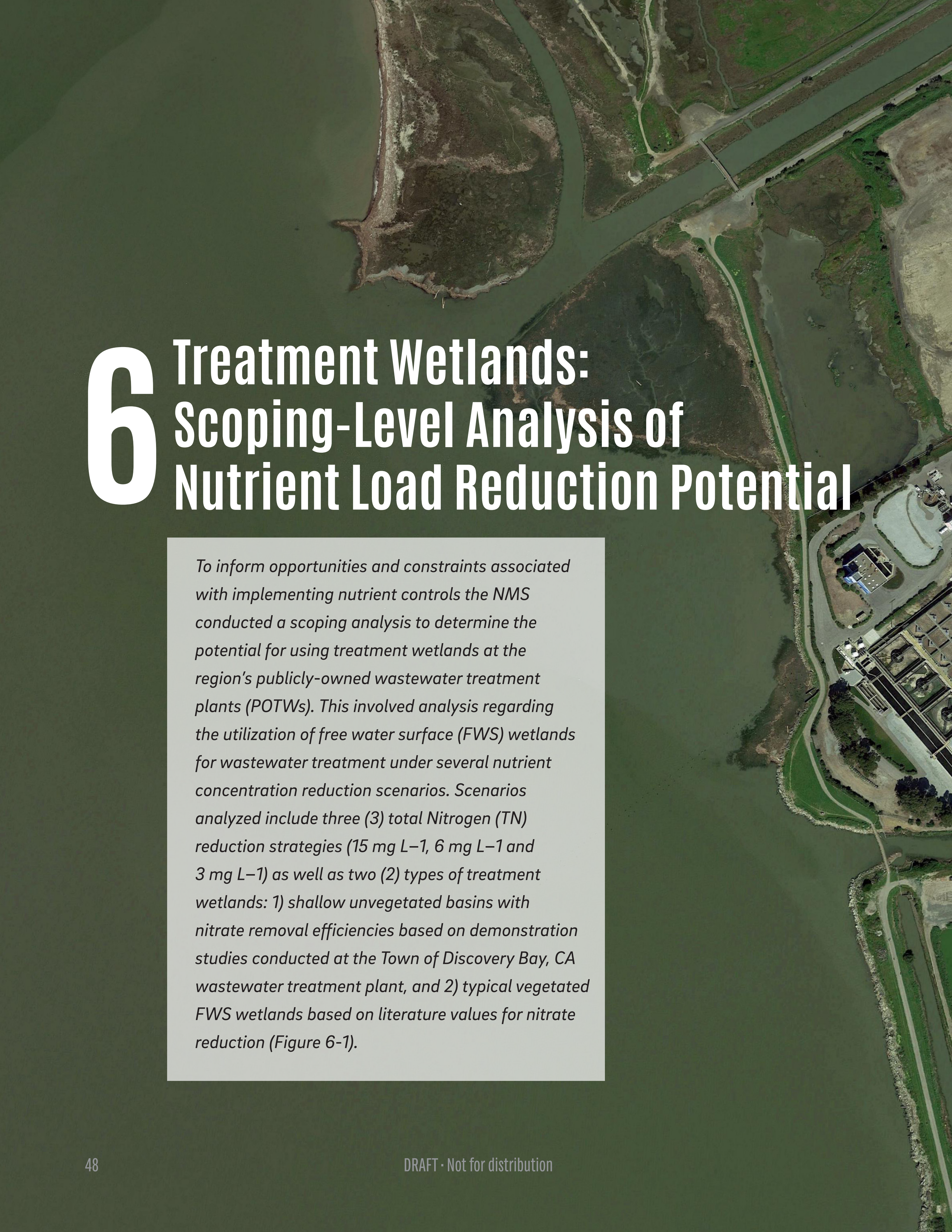


Lower South Bay

Another project taking the NMS modeling efforts into new geographic contexts is the Lower South Bay model. This work is also in a relatively early phase, with the bulk of the efforts to date focused on bathymetry processing, grid development, and hydrodynamic calibration. Given the complex configuration of sloughs and ponds, and significant influences of three nearby discharges, the Lower South Bay model will be an important tool for understanding transport and biogeochemical processes in this dynamic setting.

Fig. 5.6: Visualization of the bathymetry database assembled for modeling Lower South Bay. A 2m master bathymetry map, targeting the hydraulic configuration of the sloughs and ponds, has been completed for the study area. A portion of the Island Ponds is shown from a Cris Benton kite photo (left) and in a rendered bare-earth view of the bathymetry database (below).





6

Treatment Wetlands: Scoping-Level Analysis of Nutrient Load Reduction Potential

To inform opportunities and constraints associated with implementing nutrient controls the NMS conducted a scoping analysis to determine the potential for using treatment wetlands at the region's publicly-owned wastewater treatment plants (POTWs). This involved analysis regarding the utilization of free water surface (FWS) wetlands for wastewater treatment under several nutrient concentration reduction scenarios. Scenarios analyzed include three (3) total Nitrogen (TN) reduction strategies (15 mg L–1, 6 mg L–1 and 3 mg L–1) as well as two (2) types of treatment wetlands: 1) shallow unvegetated basins with nitrate removal efficiencies based on demonstration studies conducted at the Town of Discovery Bay, CA wastewater treatment plant, and 2) typical vegetated FWS wetlands based on literature values for nitrate reduction (Figure 6-1).

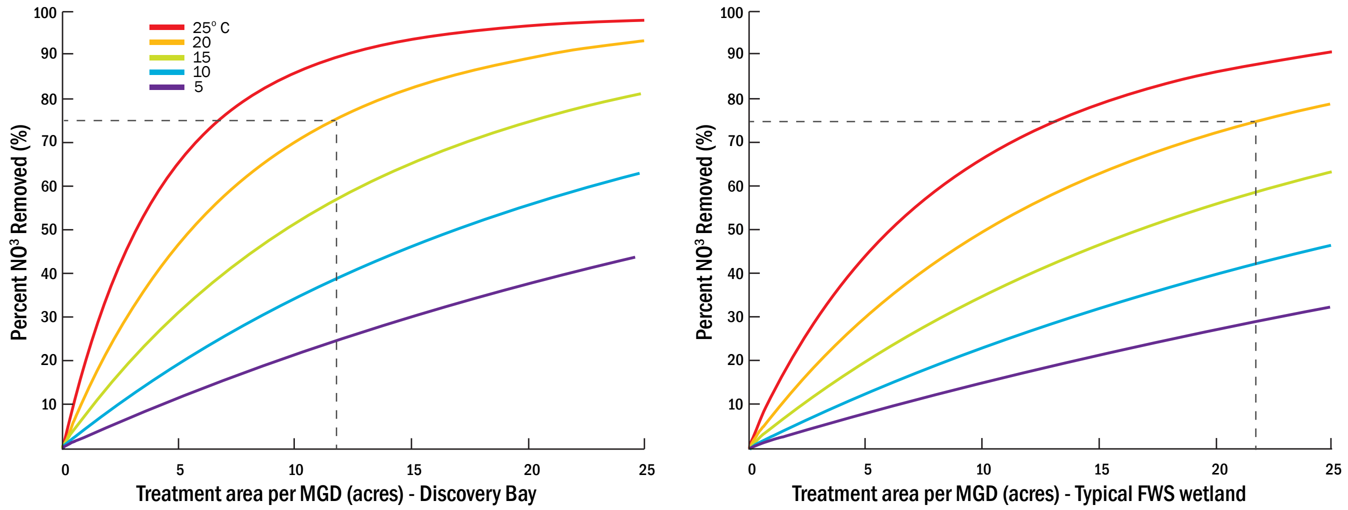


Figure 6-1. Comparison of literature-based nitrate removal rates indicating acres of treatment wetlands required to achieve corresponding rates of removal from 1 MGD of secondary wastewater effluent (Jasper et al, 2014; Kadlek 2011).

This analysis involved the estimation of potentially suitable land area for conversion to treatment wetlands within a two-mile radius of wastewater sources (Figure 6-2); calculation of TN removal requirements for each Permittee of the 2014 San Francisco Bay Nutrient Watershed Permit; and comparison of TN removal rates potentially achievable via utilization of the two treatment wetland types identified versus that required to meet each of the three TN concentration reduction scenarios (Figure 6-3). Cost estimates were also provided, based on literature values, though actual values are site specific and can vary widely from suburban regions with access to unutilized land versus urban areas with multiple environmental and land use conflicts.

Based on land constraints alone, 13 of the 34 wastewater facilities subject to the Nutrient Watershed Permit could meet a hypothetical 15 mg L-1 TN standard and 7 could meet a 3 mg L-1 effluent limitation for TN using FWS wetlands. This assumes full utilization of potentially available lands in proximity to a given facility and nitrification of wastewater effluent prior to discharge. Assuming all facilities are acting individually to meet TN reduction scenarios, the acreages presented in Table 6-1 could achieve corresponding rates of TN reduction, which are substantially less than the reductions needed to fully satisfy the three TN reduction scenarios.

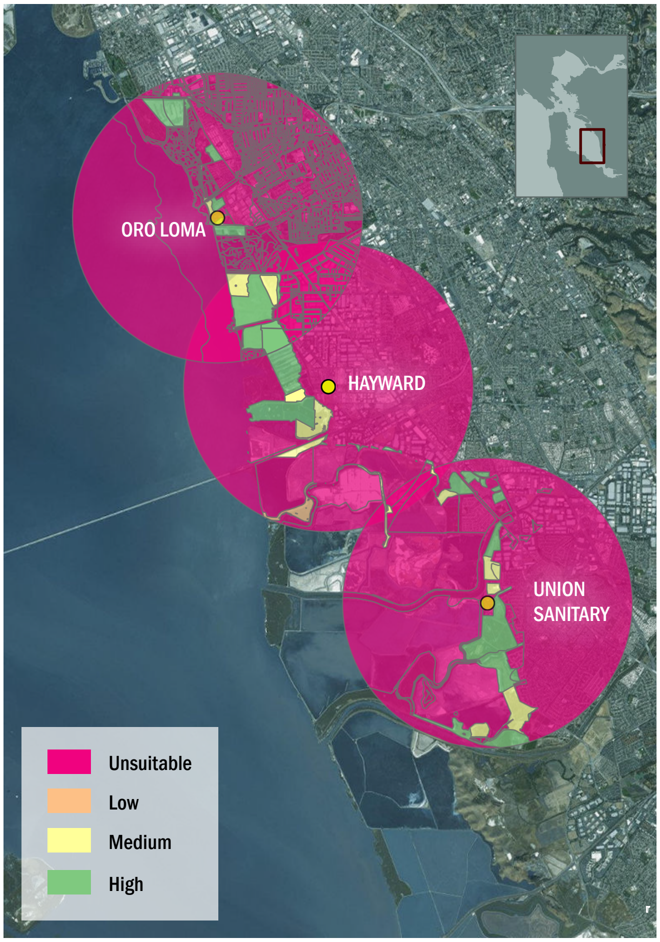


Figure 6-2. Scoping-level survey of lands considered potentially suitable for conversion to treatment wetlands within a 2-mile radius of three POTWs along the East Bay shoreline. Similar analysis was performed for the entire Bay shoreline.

	Level 2 (15 mg L–1)	Level 3 (6 mg L–1)	Advanced (3 mg L–1)
Sum of potentially available area of vegetated FWS treatment wetlands available to meet scenario (region-wide)	2,100 ac	4,500 ac	6,400 ac
Region-wide TN reduction potential, assuming implementation of FWS wetland acreage provided above	29%	41%	45%
Estimated TN reduction if the same acreage was used entirely for Discovery Bay-like systems	47%	58%	59%
Region-wide TN reductions needed to meet scenario	58%	83%	92%
Average present value cost per pound nitrate removed	$1.27	$2.75	$2.54

As indicated above, diminishing rates of TN reduction are observed despite significant addition of acreage, due to the uneven availability of sites potentially suitable for conversion to treatment wetlands. On a regional scale, this analysis suggests a reasonable rate of TN load reduction achievable through treatment wetlands FWS is 40-50%. Higher reduction requirements would necessitate optimization and upgrades of facilities and or other multi-benefit solutions, such as wastewater recycling and nutrient recovery. Treatment wetlands show great promise for helping achieve potential nutrient reduction needs, in addition to ancillary benefits, at substantially less cost compared with grey-infrastructure based technologies.

Further analysis is needed to refine land acquisition/utilization potential in the vicinity of wastewater sources, identify most appropriate treatment wetland designs and generate site-specific cost estimates. In preparation of potential nutrient load reduction requirements, additional recommendations include development of consistent permitting rules; identification of desired outcomes for multi-benefit treatment wetlands; development of an appropriate subembayment-scale nutrient credit trading structure; and a conceptual strategy for addressing technical, financial and outreach-based requirements for deploying a regional-scale program for multi-benefit treatment wetlands.

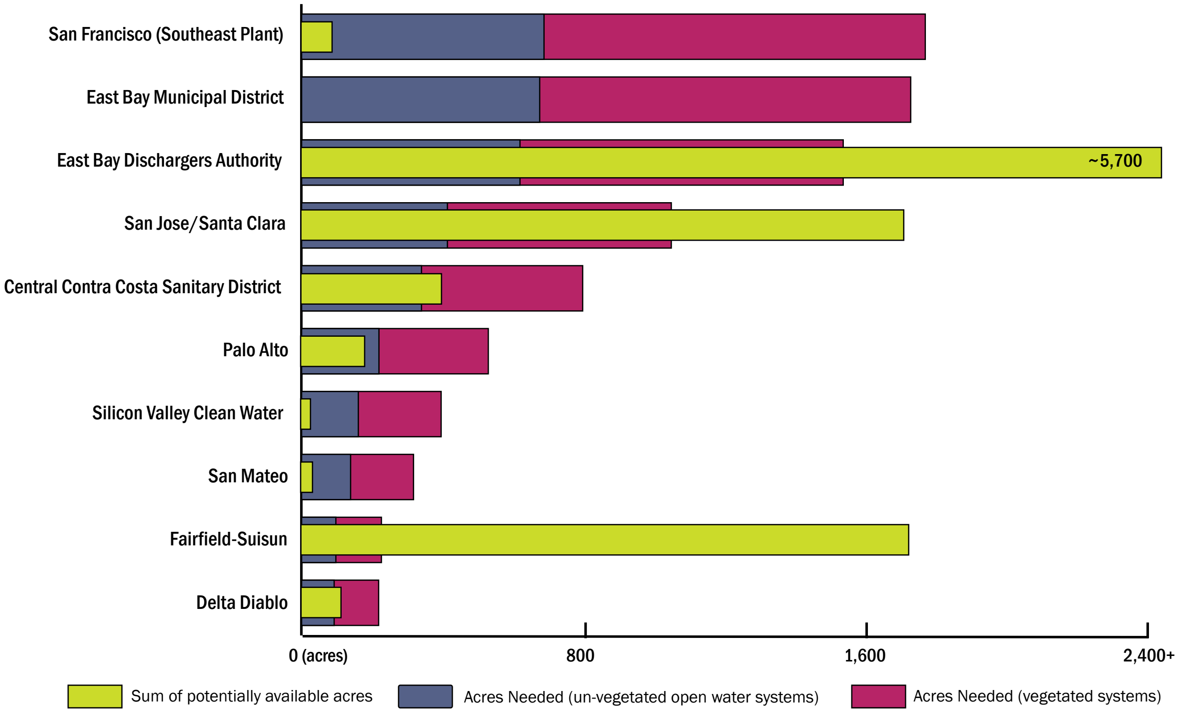


Figure 6.3: Summary of potentially available acres versus estimated treatment wetland acreage to meet 6 mg L-1 TN concentrations, from the 10 POTWs with the greatest concentration reduction needs.