Nutrient Management Strategy Science Program
FY2016 ANNUAL REPORT

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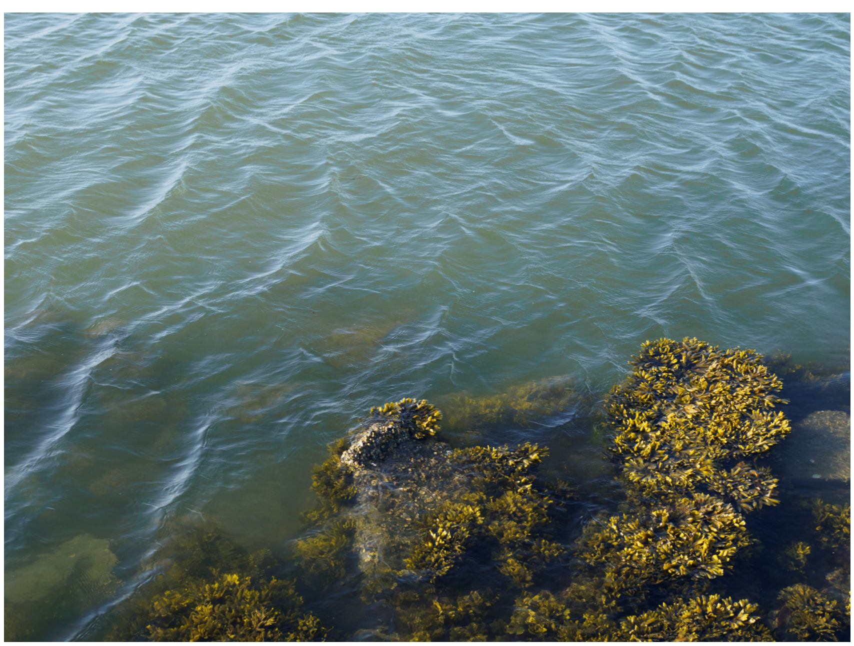

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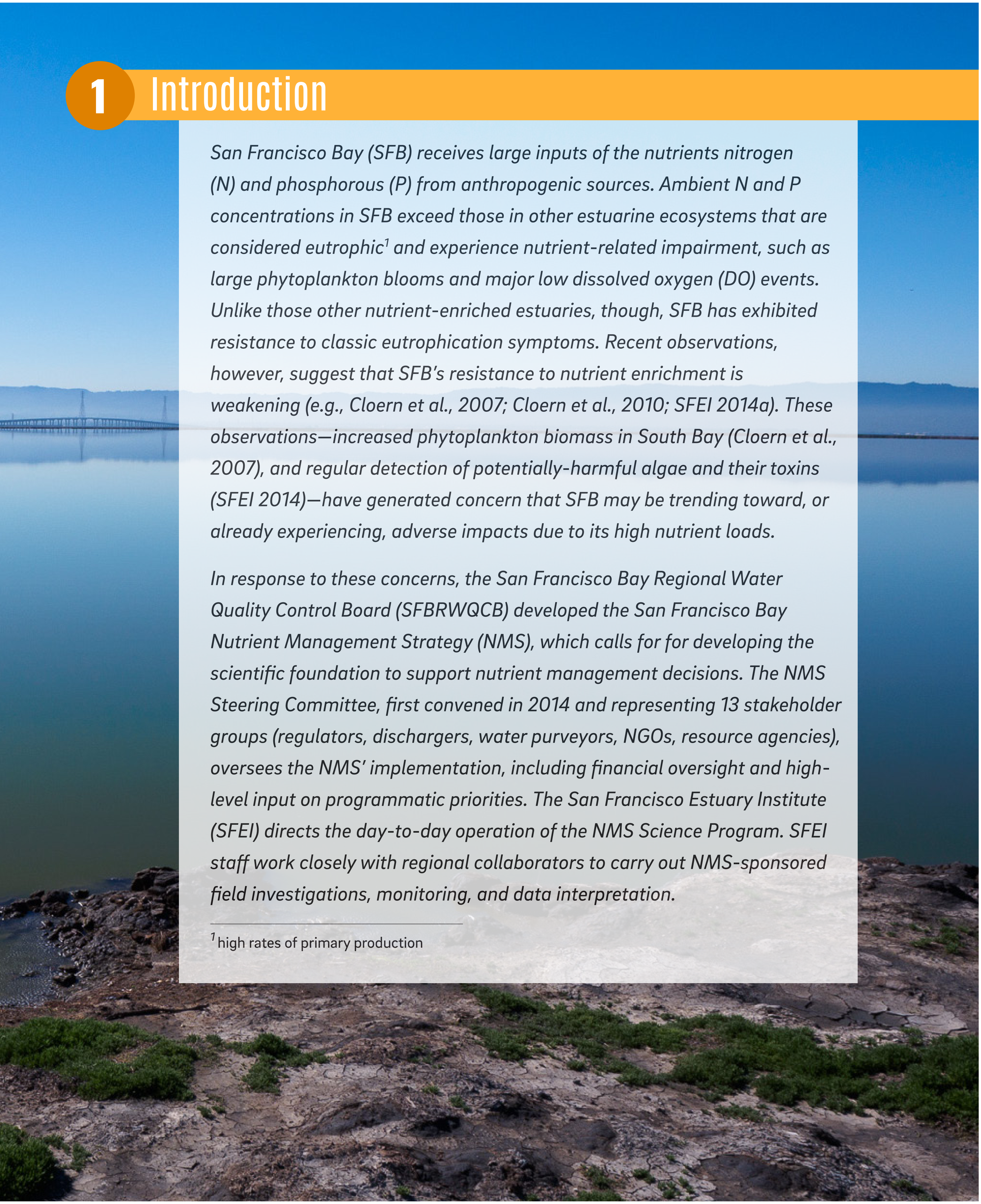

1 Introduction

San Francisco Bay (SFB) receives large inputs of the nutrients nitrogen (N) and phosphorous (P) from anthropogenic sources. Ambient N and P concentrations in SFB exceed those in other estuarine ecosystems that are considered eutrophic[1] and experience nutrient-related impairment, such as large phytoplankton blooms and major low dissolved oxygen (DO) events. 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 observations—increased phytoplankton biomass in South Bay (Cloern et al., 2007), and regular detection of potentially-harmful algae and their toxins (SFEI 2014)—have generated concern that SFB may be trending toward, or already experiencing, adverse impacts due to its high nutrient loads.

In response to these concerns, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) developed the San Francisco Bay Nutrient Management Strategy (NMS), which calls for for developing the scientific foundation to support nutrient management decisions. The NMS Steering Committee, first convened in 2014 and representing 13 stakeholder groups (regulators, dischargers, water purveyors, NGOs, resource agencies), oversees the NMS' implementation, including financial oversight and high-level input on programmatic priorities. The San Francisco Estuary Institute (SFEI) directs the day-to-day operation of the NMS Science Program. SFEI staff work closely with regional collaborators to carry out NMS-sponsored 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 determining safe levels of nutrient loads to SFB **(Table 1.1).** More detailed management and science questions, priority data gaps, and recommended activities were laid out in early technical documents (e.g., SFEI 2014) and in a recent 10-year NMS Science Plan (SFEI 2016). A major focus of the NMS effort over the past few years, shaped by these priorities, has been developing the NMS Observational and Forecasting program, and interpreting early results **(Figure 1.1).**

This report provides an overview of major San Francisco Bay Nutrient Management Strategy (NMS) activities for Fiscal Year 2016 (FY16; July 2015- June 2016).

- **SHIP-BASED MONITORING:** nutrients and phytoplankton community composition (Section 2)
- **HARMFUL ALGAE (HABs) AND TOXINS:** water column and biota monitoring (Section 3)
- **HIGH-FREQUENCY MONITORING:** for nutrient related parameters (Section 4)
- **MODELING:** hydrodynamics and biogeochemistry (Section 5)

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).

TABLE 1.1: 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?

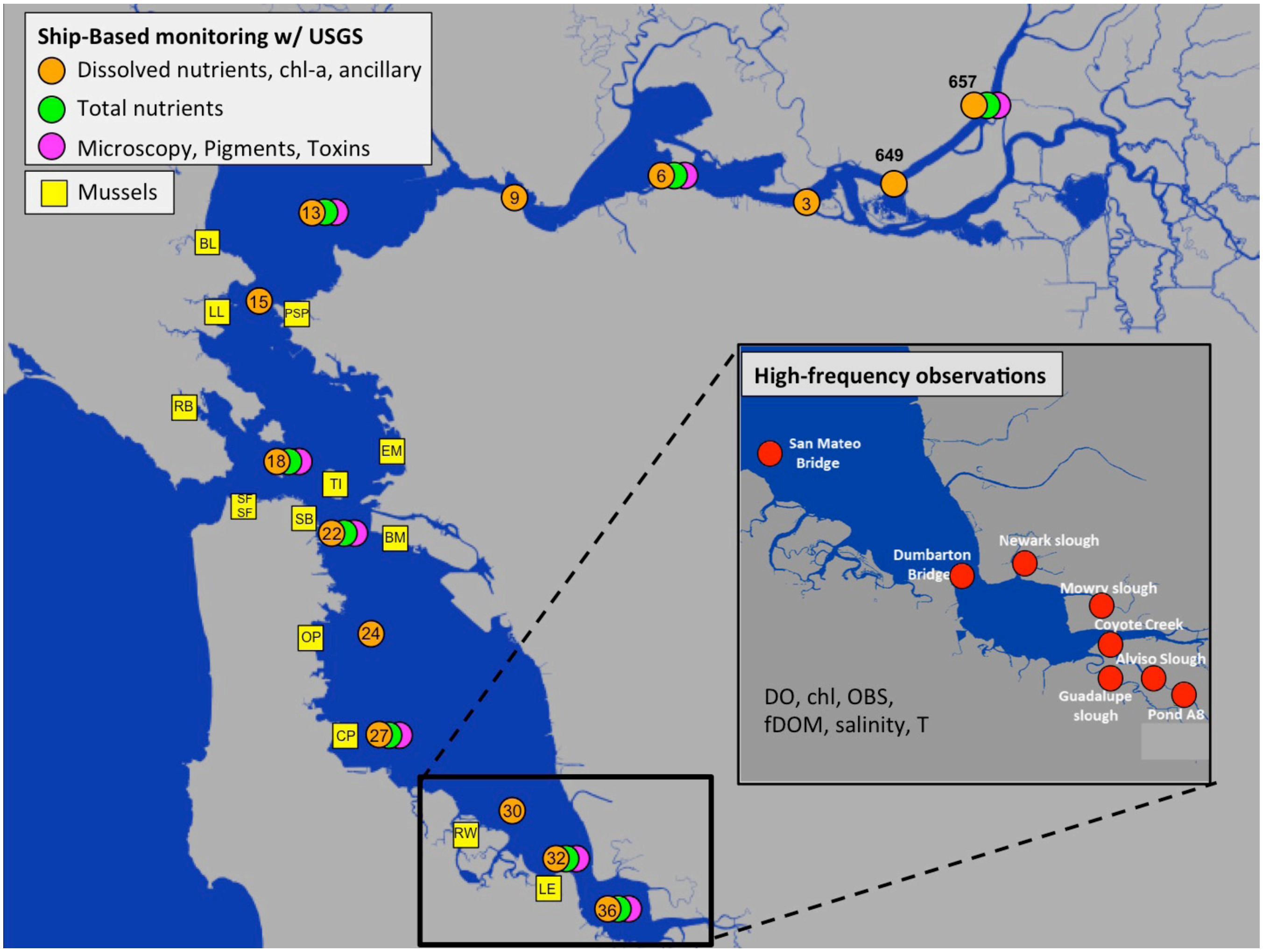
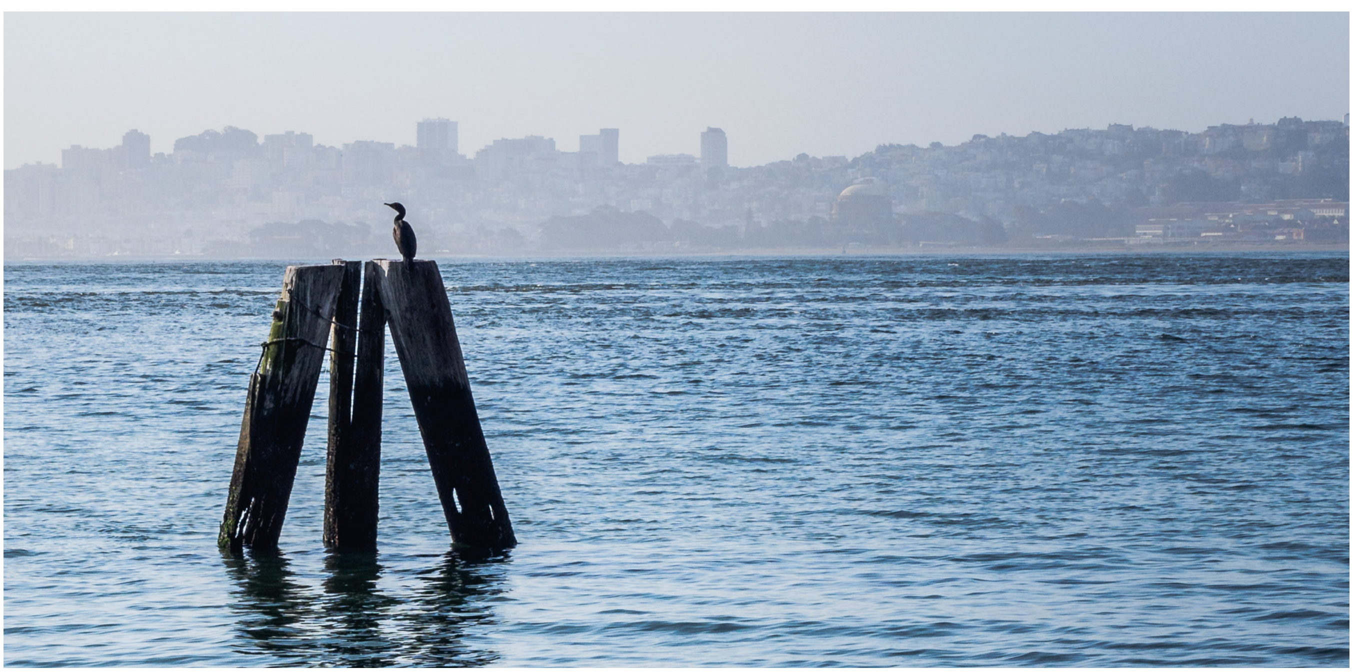


Figure 1.1 The current NMS observational network. USGS-Menlo Park has been monitoring chlorophyll-a, dissolved nutrients and other ancillary parameters at the numbered stations for several decades; toxins measurements were added in 2012, pigments were added in 2013 and total nutrients measurements were added in 2014. High frequency observations by SFEI (in collaboration with USGS-Sacramento) began in 2013. Mussel collection by SFEI (in collaboration with UCSC) began in 2015.



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2 Ship-Based Monitoring

OVERVIEW

NMS ship-based monitoring activities are carried out through a collaboration with USGS, building on USGS' long-term Bay water quality program. Work is supported through a combination of USGS program funding, funds from the SFB Regional Monitoring Program, and support from the NMS.

USGS has been conducting regular surveys of the Bay since the early 1970s, collecting data along its deep channel **(Figure 1.1).** The current field program includes monthly full-Bay cruises, augmented by one or more South Bay cruise each month. The *R/V Polaris* served as the USGS Bay program's workhorse **(Figure 2.1 A)** for over 40 years,. The *Polaris* was officially retired in May 2016, and is being replaced by the *R/V Peterson* **(Figure 2.1 B).** The *Peterson*, purchased by the USGS in fall 2015, is currently being retrofitted with a laboratory and oceanographic instrumentation, supported in part by NMS funds, and is expected to conduct its first Bay survey in August 2016.

USGS cruises measure numerous parameters relevant to the NMS efforts 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 and inexplicably 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). An increase in fall chl-a levels in South Bay, observed beginning in the late 1990s through 2005 (Cloern et al, 2007; **Figure 2.3)**, was among the original motivations for the Water Board to establish the NMS. This indicator continues to be tracked, and observations through 2015 suggest that fall chl-a levels have plateaued **(Figure 2.2;** SFEI #xxxx). A discussion of hypothesized factors contributing to these changes can be found in Cloern et al 2007 and SFEI 2015 (#xxx).

Figure 2.1 A. The 96' *R/V Polaris*...USGS workhorse for the past 40 years. Built in 1927, officially retired from service in the Spring of 2016. **B.** Replaced by the ***R/V Peterson***, 66'. New vessel, purchased by USGS. The NMS contributed funding to support the ship's retrofit.

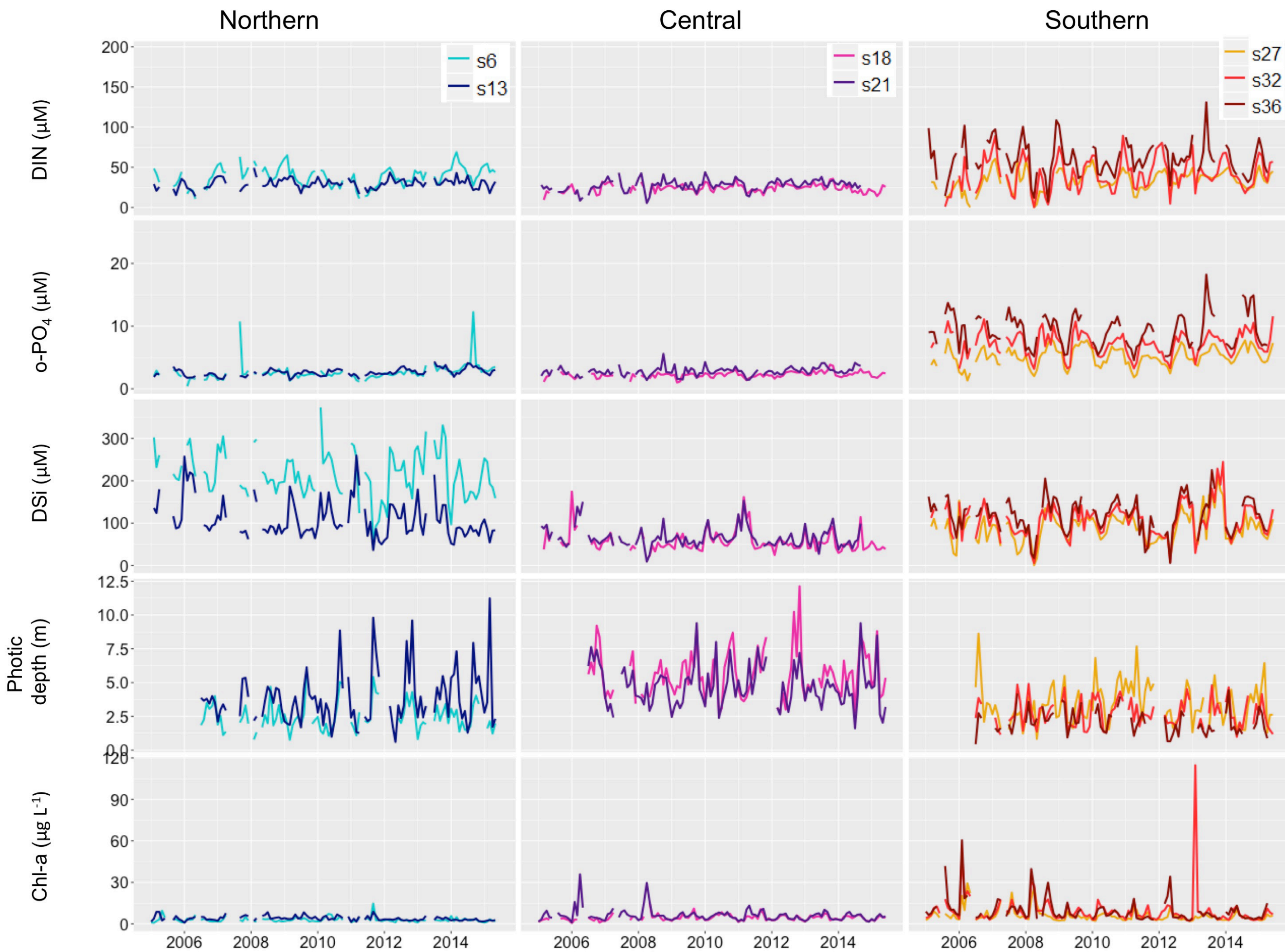


Figure 2.2 Water quality parameters recorded every two to four weeks along the axis of the Bay. South Bay and Lower South Bay regularly exhibits elevated N, P and chlorophyll-a relative to Central Bay and the the northern Bay. A wide range of spatial and temporal patterns are discernible from this rich 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.

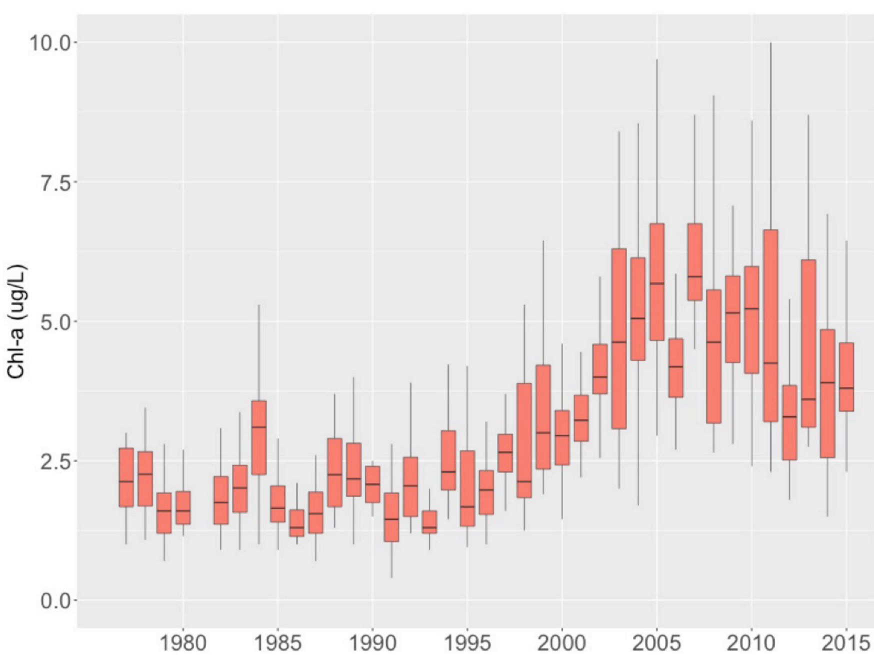


Figure 2.3 Cloern et al 2007 documented increasing fall biomass concentrations in South Bay, showing ~2.5-fold higher chl-a concentrations between 1995 and 2005. The increasing chl-a led to concerns that South Bay's resistance to nutrients was declining. At that point it was unclear whether biomass would continue increasing or stop. Data over the next 10 years suggest that fall biomass has plateaued, i.e., that the system has reached a new dose:response relationship for nutrients and chl-a in South Bay.

NUTRIENTS

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. Other factors, beyond nutrient concentrations, play important roles in regulating phytoplankton growth rates addition to nutrient levels: e.g. light levels in the water column (inversely related to suspended sediment concentrations), water temperature, vertical mixing, lateral mixing between shallow shoals and the deep channel. Therefore, the collection of additional data—for example the parameters in **Figure 2.2**—is essential for assessing nutrient-related ecosystem health.

Inorganic nutrients (e.g., nitrate, NO_3^-; ammonium, NH_4^+; ortho-phosphate, o-PO_4) have been a regular component of the USGS Bay program. In some cases, organic nutrients can represent sizable bioavailable fractions of total N and P, making observational data on both inorganic and organic forms of N and P necessary for nutrient mass balances, and for calibrating biogeochemical models. For these reasons, since 2014, the NMS and USGS have been collecting and analyzing samples for inorganic and organic forms of N and P **(Figures 2.4).**

With approximately 1.5 years of data now available, some general observations are possible:

- Sizable proportions of both N and P are present in forms other than the basic inorganic forms (i.e., NH_4^+, NO_3^-; o-PO_4). Organic-N was commonly ≥30% of TN , while organic (and particulate) P was in the range of 5-30% of TP.
- TN:DIN and TP: o-PO_4 vary substantially both in space and seasonally.

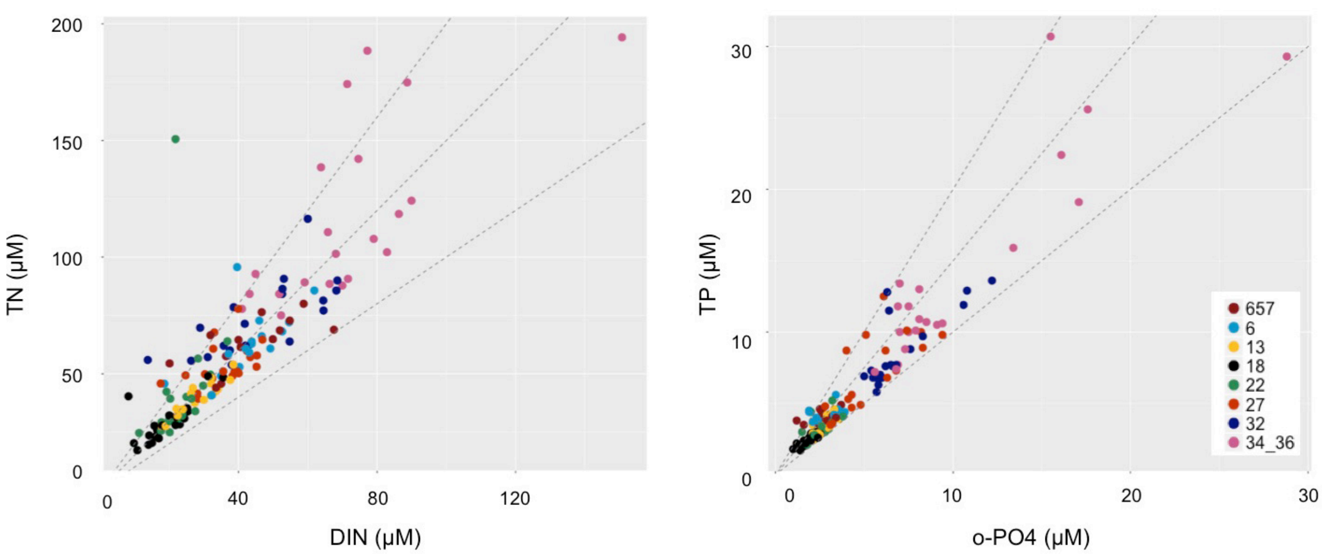
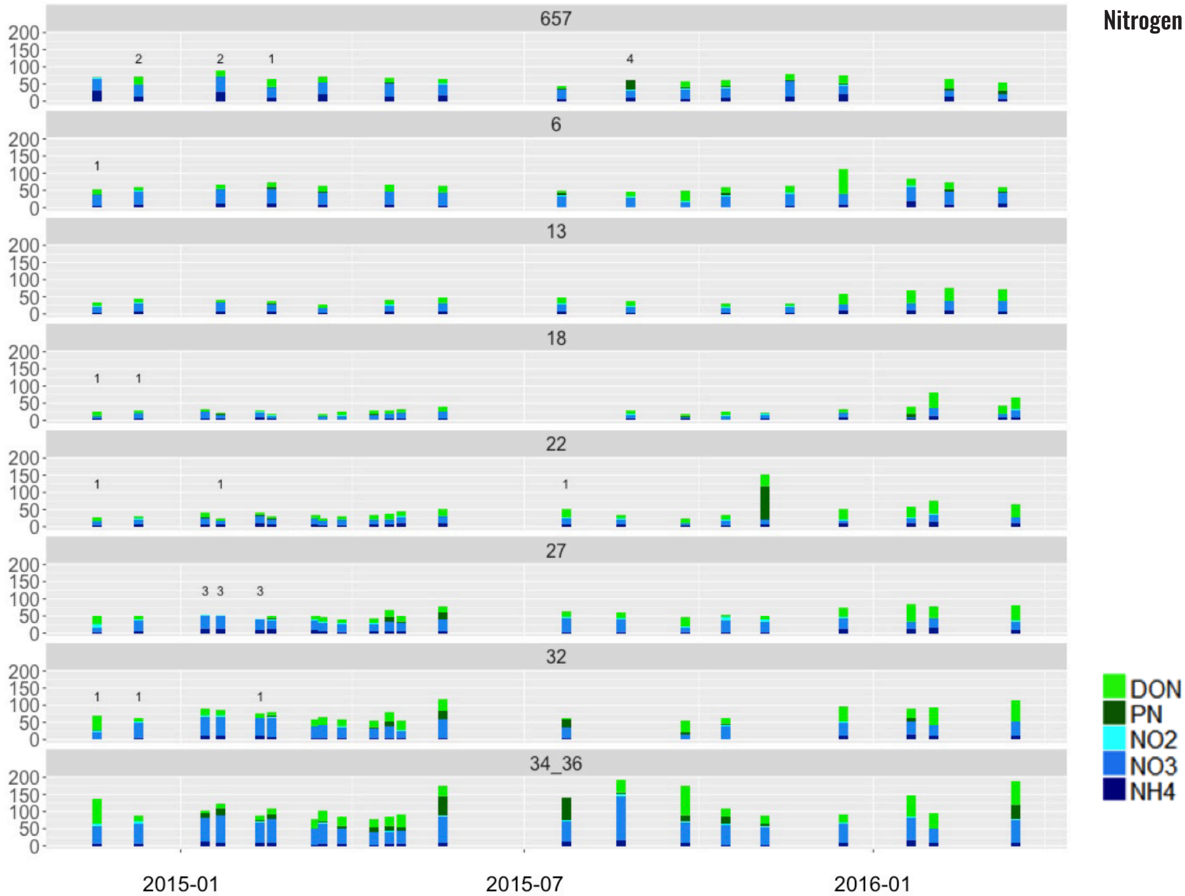


Figure 2.4 (above). TN vs DIN (NO_3 + NH_4, in µm) and TP vs. o-PO_4 for Nov 2014 - Mar 2016. Colors represent individual stations (see Figure 1.1 for locations). Dashed lines show slopes of 1:1, 1.5:1 and 2:1.

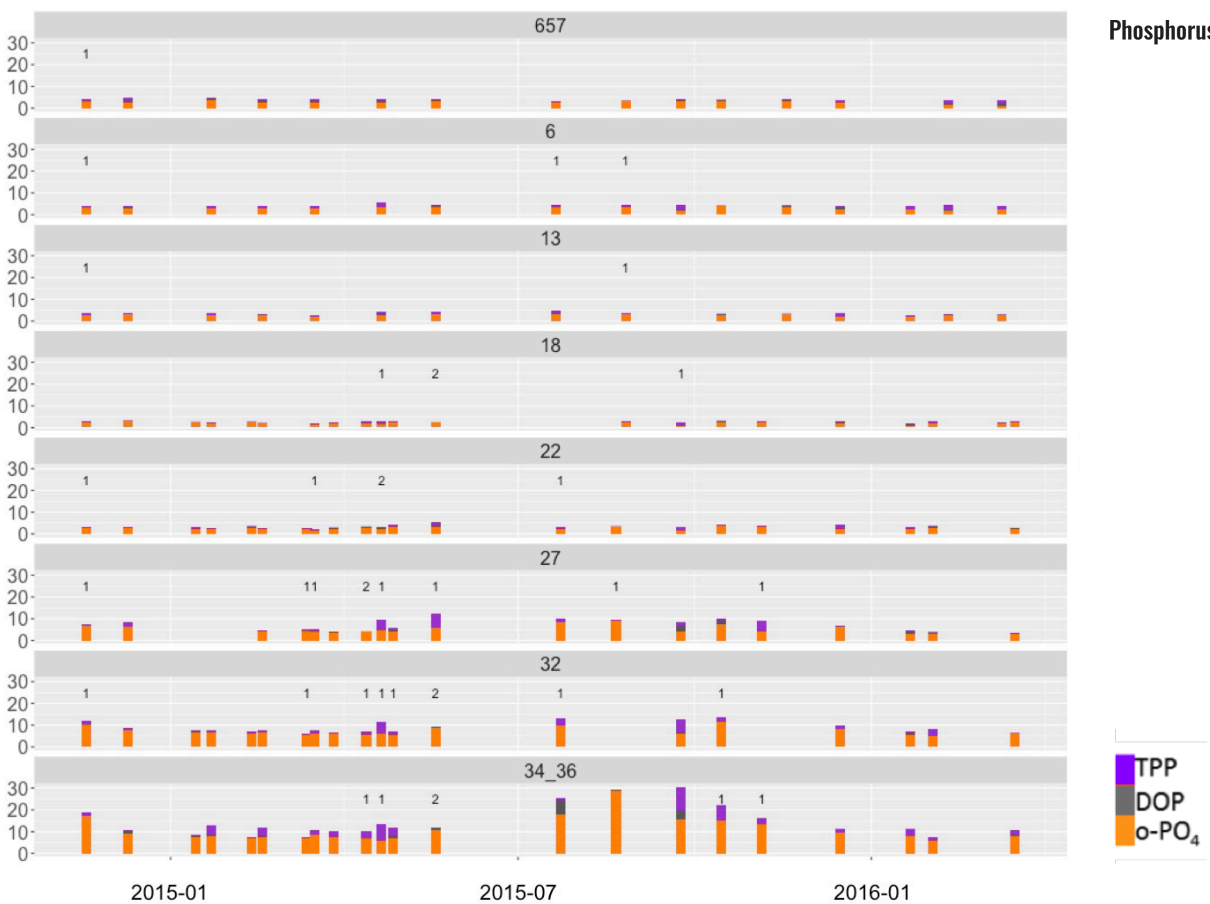
Next page: N (top) and P (bottom) species by station (in µM). DON = dissolved inorganic N; PN = particulate N (organic); DRP = dissolved reactive P (primarily o-PO4); DOP = dissolved organic P; TPP = total particulate P

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; P: 1 = DOP (calculated) was negative (i.e., small) and is not shown; 2 = TPP data not available

Nitrogen (µm)



Phosphorus (µm)



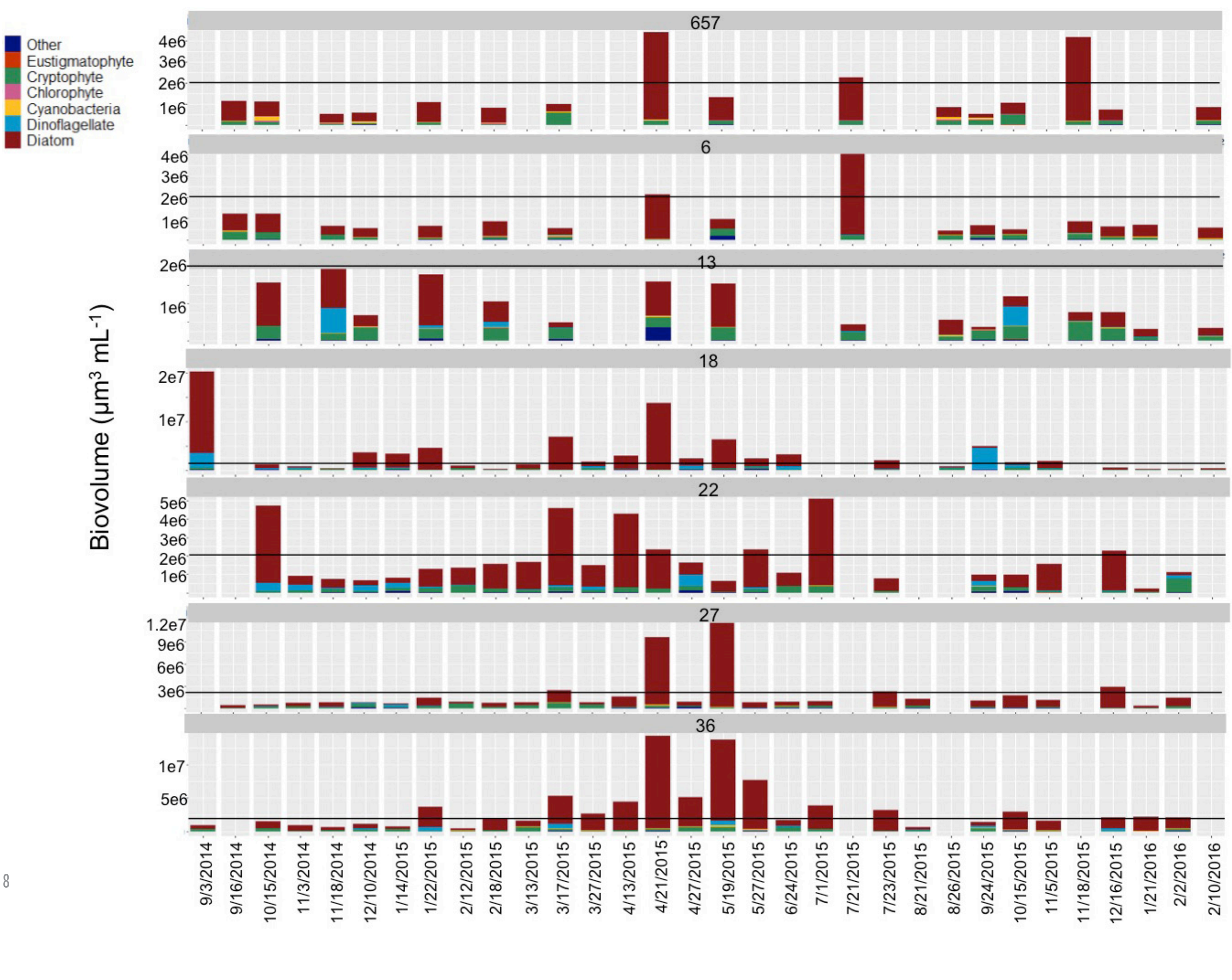
PHYTOPLANKTON COMMUNITY COMPOSITION

Phytoplankton community composition is measured 1-2 times per month by microscopy at seven stations throughout SFB **(Figure 1.1).** On-going work, supported by NMS and in-kind USGS funds, is extending the 20+ year USGS record (Cloern and Dufford 2005).

Figure 2.5 presents the most recent ~1.5 years of phytoplankton community data, through February 2016, quantified as biovolume (μm^3 mL^{-1}) and grouped into major classes.

- Biovolume is a more ecologically-meaningful way to describe community than density (e.g., cells mL^{-1}), because individual phytoplankton cells can differ in size (and organic carbon content) by several orders of magnitude.
- Diatoms contributed most of the total biovolume across all sites, and even greater proportions during blooms. San Pablo Bay assemblages departed somewhat from this generalization, with dinoflagellates accounting for nearly a third of phytoplankton biovolume during blooms.
- Other phytoplankton classes (cryptophytes, dinoflagellates) tended to represent a larger proportion of the overall biovolume Bay-wide during non-bloom conditions.

Figure 2.5 Timeseries of phytoplankton biovolume (in μm^3/ mL^{-1}), by major class and station. Note the different scales on the y-axes. The black line on each plot represents total biovolume of 2 x 10^{-6} μm^3 mL^{-1}, which corresponds to approximately 10 μg L^{-1} of chl-a and would constitute a bloom in SFB.



Importance of community composition?

Phytoplankton community composition influences ecosystem health.

- Nutritional quality differs among phytoplankton taxa
- Some phytoplankton produce toxins that impact biota

Multiple factors influence how the phytoplankton community varies seasonally, spatially, and interannually.

- Light
- Temperature
- Salinity
- Nutrients
- Seeding of organisms
- Preferential grazing

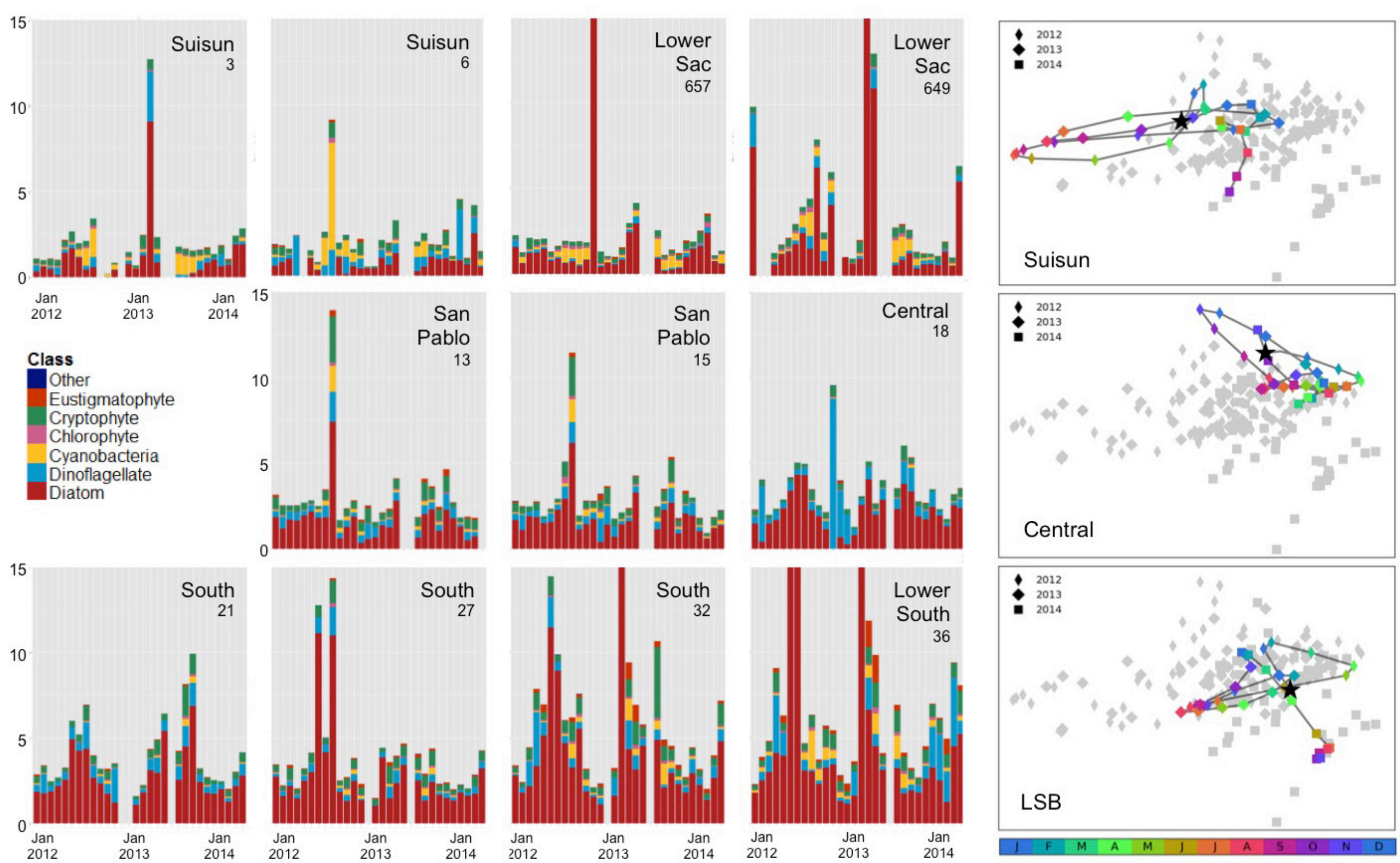
Role of nutrients relative to other factors?

- Role of nutrients poorly understood in SF Bay
- N and P concentrations rarely dip to growth-limiting levels (i.e. there's enough of N and P that no class outcompetes another)

HYPOTHESIS: *Community varies in coherent patterns—spatially, seasonally, and episodic events—driven by an inferable set of mechanisms.*

We are currently testing the above hypothesis, using a rich phytoplankton community dataset recently produced, through the NMS in collaboration with UCSC and USGS researchers **(Figure 2.6).** Initial analysis, using a technique that translates composition into two dimensions (nMDS), suggest that coherent seasonal and spatial patterns are evident (**Figure 2.6, right side).** See the electronic appendix (http://sfbaynutrients.sfei.org/content/phytoplankton-nmds) for more background and animations illustrating change over time.

Figure 2.6 (below, left): Phytoplankton community composition at 11 stations throughout SFB, in units of µgL^{-1} chl-a, and divided into 5 major classes (and 'other'). See Figure 1.1 for station locations. (below right) Results of nMDS for LSB, Central, and Suisun Bay, see electronic appendix. Data: Peacock et al., in prep.

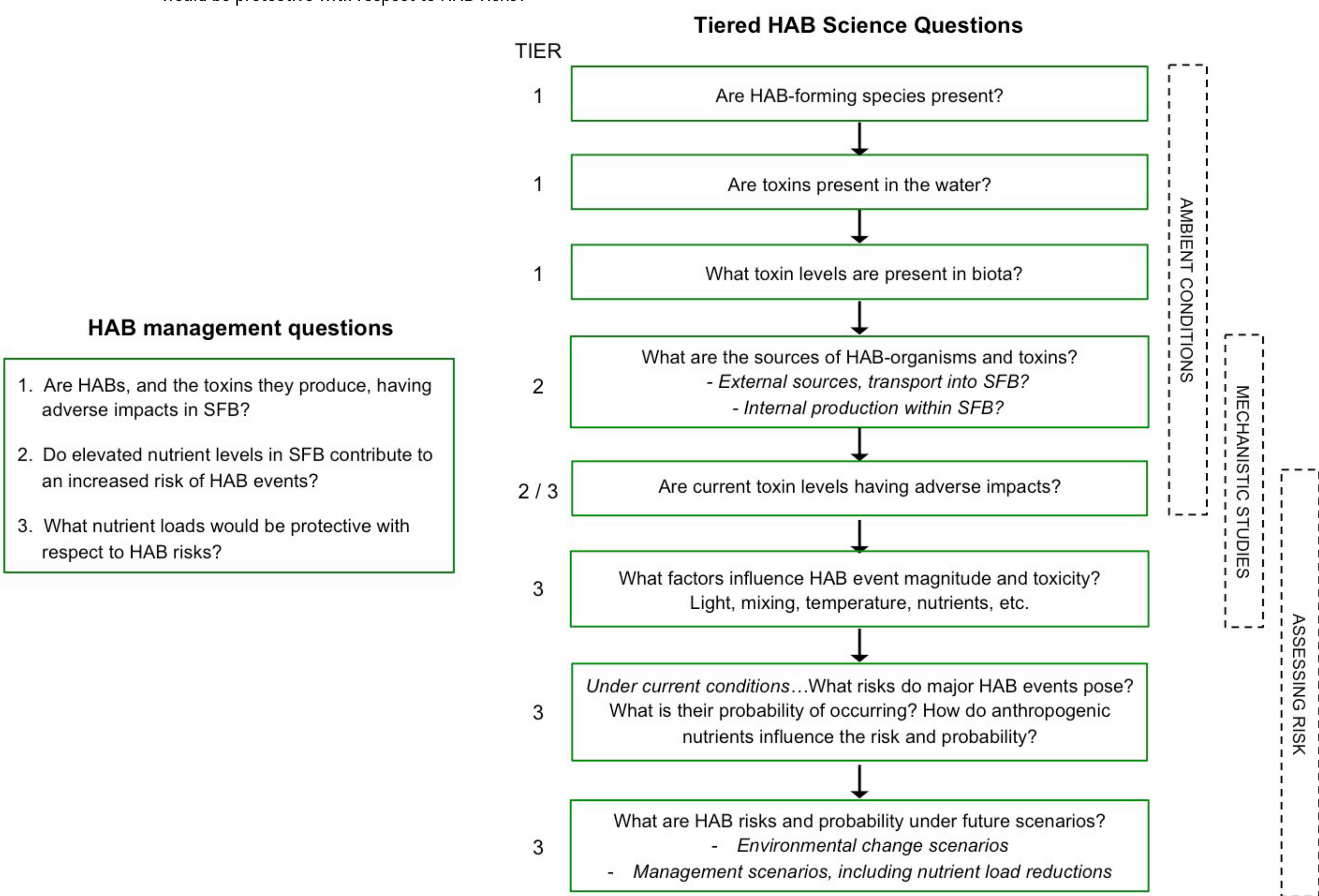


3 Harmful algae and algal toxins

The record-setting *Pseudo-nitzchia* bloom in Spring/Summer 2016 along the US west coast provided a close-to-home example of how HABs can both severely impact marine biota and regional economies (ref). That event also demonstrated how multiple factors that trigger harmful algal blooms (HABs), and the difficulty in predicting when and where they will develop.

Assessing the risk that HABs pose in SFB is a high-priority topic for the NMS (SFEI 2014; SFEI 2016). HAB risk assessment, in a nutrient management context, poses major scientific challenges because it requires disentangling the multiple physical, chemical, and biological factors that regulate HAB-organism growth in order to identify protective nutrient levels. The NMS Science Plan lays out a tiered approach to studying HABs, tackling increasingly complex science questions as it becomes clear those answers are essential for informing management decisions **(Figure 3.1).** NMS studies to date have focused mostly on Tier 1 science questions. Several FY17 projects will begin exploring Tier 2 and 3 questions.

Figure 3.1 Tiered approach to exploring HABs and toxins within the NMS. Activities to date have primarily focused on Tier 1 questions, characterizing ambient conditions with respect to occurrence of HAB-forming organisms and toxin levels in water and biota. Field observations indicate that several HAB-forming organisms are commonly detected. Several toxins are also regularly observed in water and biota: Domoic Acid, Microcystins, and Saxotoxin. Upcoming work, targeting Tier 2 and 3 science questions, will focus on developing an improved understanding of the factors that influence HAB occurrence and toxin production—in particular the role played by anthropogenic nutrients—and the risks posed by HABs. Answers to the Tier 2 and 3 science questions will provide guidance related to the management question "What nutrient loads would be protective with respect to HAB risks?"



TOXIN-PRODUCING ALGAL SPECIES IN THE BAY?

Phytoplankton data from 1992 through early-2015 illustrate that two HAB-forming genus, *Pseudo-nitzchia* spp. and *Alexandrium* spp., are commonly detected in SFB **(Figure 3.2).** *Pseudo-nitzchia* and *Alexandrium* produce the toxins domoic acid (DA) and saxitoxin (SAX), respectively, both potent neurotoxins. Other harmful algae have also been regularly detected **(Figure A.X;** see also Cloern and Dufford, 2005; Cloern and Jassby, 2012; SFEI 2014; Sutula et al, submitted).

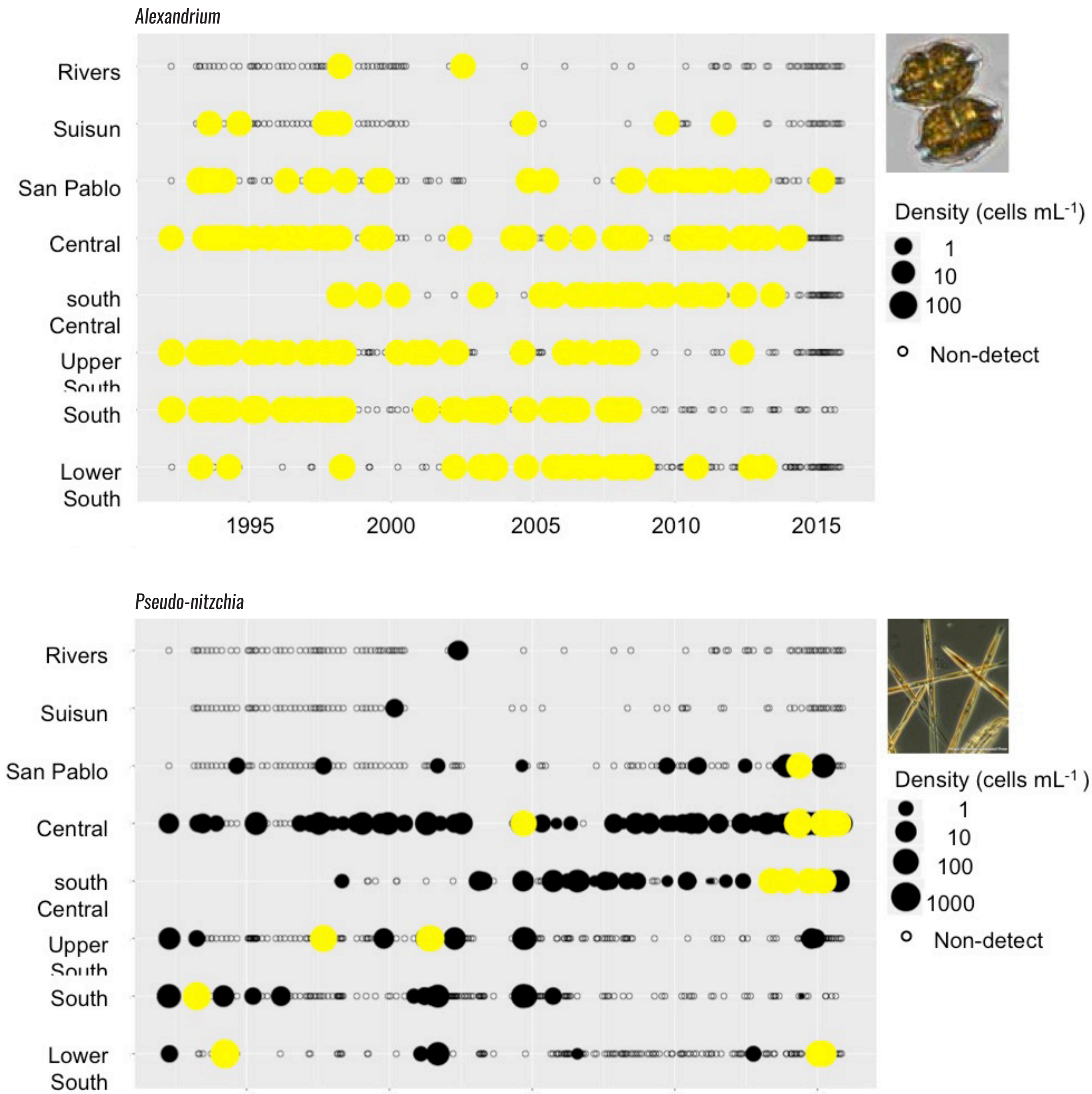


Figure 3.2 *Alexandrium* spp. and *Pseudo-nitzchia* spp. densities, 1992 through early-2015. Circle size is proportional to density (cells/mL). Yellow symbols indicate when densities exceeded those considered to be potentially concerning (P-N = 100 cells/mL; Alexandrium = presence; see Sutula et al., 2016). The low threshold for Alexandrium (detect vs. non-detect) is due to the potent toxicity of the toxin it produces, saxitoxin. Data: USGS

TOXINS IN THE WATER COLUMN? SPATIALLY INTEGRATED MEASUREMENTS

In collaboration with USGS and UCSC, the NMS is employing a cost-effective and sensitive screening-level approach (SPATT) for measuring spatially-averaged toxin levels in SFB **(Figure 3.3).**

Domoic acid (DA): produced by the marine diatom Pseudo-nitzchia spp.

- Detected year-round and within all Bay segments over the past 4 years
- The widespread detection, including in freshwater zones such as Suisun Bay, is noteworthy given that *Pseudo-nitzchia* is a marine diatom.
- DA was generally elevated across all segments during late-winter and spring of 2015, possibly indicating that DA and *Pseudo-nitzchia* entering the Bay from the large coastal bloom.
- Maximum level observed across the full record was in Central Bay in fall 2014

Microcystins (MCY): produced by the freshwater cyanobacteria Microcystis spp. and other organisms

- Detected throughout the Bay and year-round, albeit with more nondetects than DA
- Assuming Microcystis is the most likely MCY source, the widespread detections in saline areas suggest non-trivial freshwater sources, and that MCY is not easily degraded or lost.

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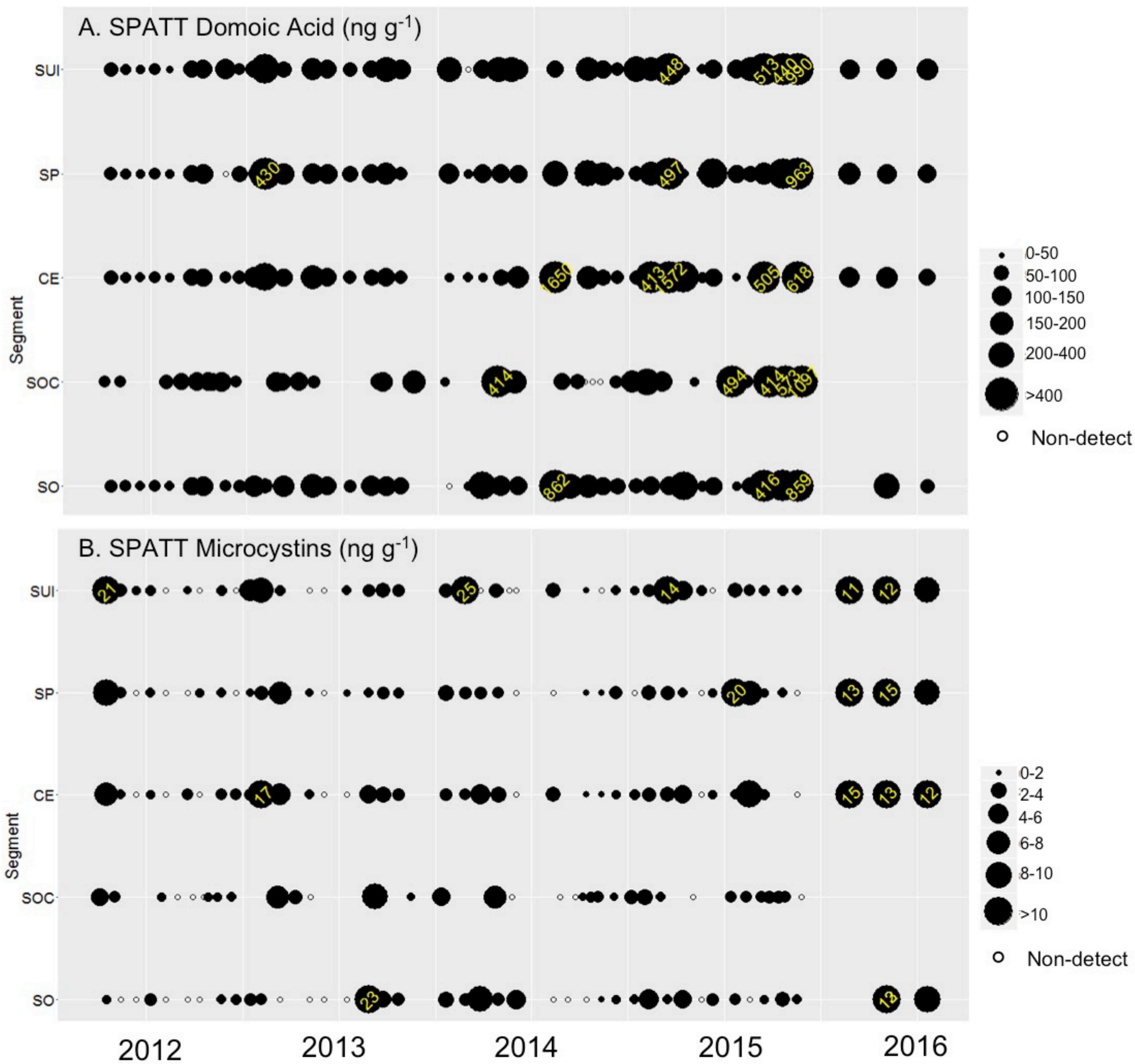

Figure 3.3 Spatially-integrated toxin measurements using SPATT, late 2011 through early 2016. A. Domoic Acid. B. Microcystins. Toxin levels were quantified by placing packets of toxin-trapping resin (SPATT) in a stream of water continuously pumped from the Bay while the USGS research vessel cruised along its sampling transect (see Kudela 2015) Circle size is proportional to concentration (ng g^{-1} resin). Rows correspond to Bay segments: SO = Lower South Bay and South Bay; SOC = SO plus Central Bay; CE = Central Bay; SP = San Pablo; SUI = Suisun and lower Sacramento River. SPATT collection occurred less consistently beginning in the second half of CY2015 because of limited access to research vessels with a flow through system. Sampling is expected to return to the pre-2015 frequency in the second of half of CY2016. While there remains some uncertainty associated with back-calculating from SPATT to ambient water concentrations, side-by-side comparisons of SPATT with other measures (particulate toxins, mussels) indicate that SPATT provides a reliable semi-quantitative measure of ambient DA and MCY (see Kudela, 2015; Kudela et al., 201x). Data: Peacock et al., in prep

TOXINS IN THE WATER COLUMN? DISCRETE SAMPLES

- ***Toxins were also measured at specific locations in SFB*** by filtering surface grab samples and trapping particle-associated toxins (PTOX) on filters. This is a standard approach for measuring water column toxin concentrations because the majority of toxin produced by HAB-organisms generally remain inside the cells while the cells are living.
- ***In 2013, USGS began collecting and archiving filter samples for PTOX.*** Over the past two years, collaborators at UCSC analyzed a subset of the archived samples from Lower South Bay, South Bay, and Central Bay for DA_{PTOX} and MCY_{PTOX} **(Figure 3.4).** DA_{PTOX} was detected sporadically over the period March 2013-March 2016, with maximum concentrations observed in Central Bay (300 ng L^{-1}) in late-2013/early-2014. While MCY_{PTOX} was detected with greater frequency than DA_{PTOX}, nondetects were common.
- ***On first glance, the PTOX results may seem inconsistent with the SPATT results.*** However, the techniques provide highly-complementary information, especially in these early stages of the NMS monitoring program development. The strength of SPATT is as a screening level tool—sensitive, integrating over large areas and therefore cost-effective. SPATTs shortcomings are related to geographic specificity and in translating back to ambient concentrations. PTOX measurements provide precise information about ambient concentration at a specific location, but will tend to "miss" the story when toxin concentrations are either very low or spatially-patchy.

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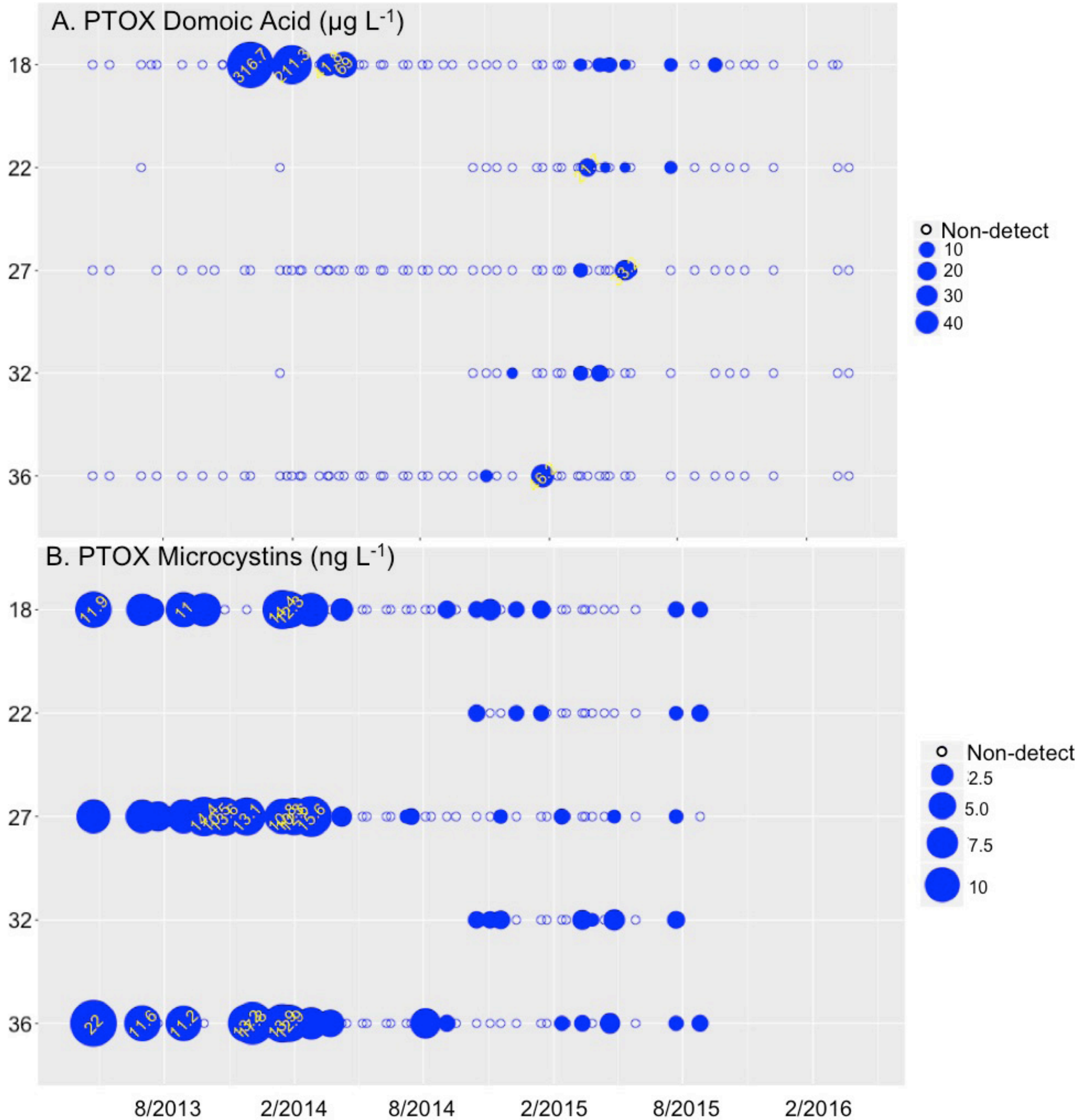


Figure 3.4 Particle-associated (PTOX) domoic acid (µg L-1) and microcystin concentrations (ng L-1) from grab samples, May 2013 through March 2016 (DA) or September 2015 (MCY). Numbers on y-axis correspond to station number. Central Bay = 18; South Bay = 22, 27, 32; Lower South Bay = 36. Note the different time periods covered by discrete samples compared to SPATT.

Data: Peacock et al., in prep.

from Coyote Hills, August 2016, Shira Bezalel (SFEI)

TOXINS ENTERING THE FOOD WEB?

A FY2015 pilot NMS study found that domoic acid, microcystins, and saxitoxin were commonly detected in mussels deployed throughout the SFB (see Figure 2.12 in FY15 Annual report). Subsequently, beginning in September 2015, naturally-occurring mussel samples were collected biweekly from floating docks around Central Bay and South Bay (see locations in **Figure 1.1)** to continue this work and explore several important questions: What toxin concentrations are entering the food web, and how do they vary seasonally and spatially? Where, and under what conditions, do toxin-producing blooms develop? Can naturally-occurring mussels serve as reliable time-integrated bioindicators of toxin levels? Initial results are presented in **Figure 3.5.**

- Domoic acid and microcystins detected with high frequency throughout Central and South Bays.
- Domoic acid concentrations were always 100-fold less than threshold levels for human consumption of shellfish (20 ppm).
- Microcystin concentrations were closer to the human consumption threshold (10 ppb).
- Work is underway to measure other toxins (e.g., saxitoxin)

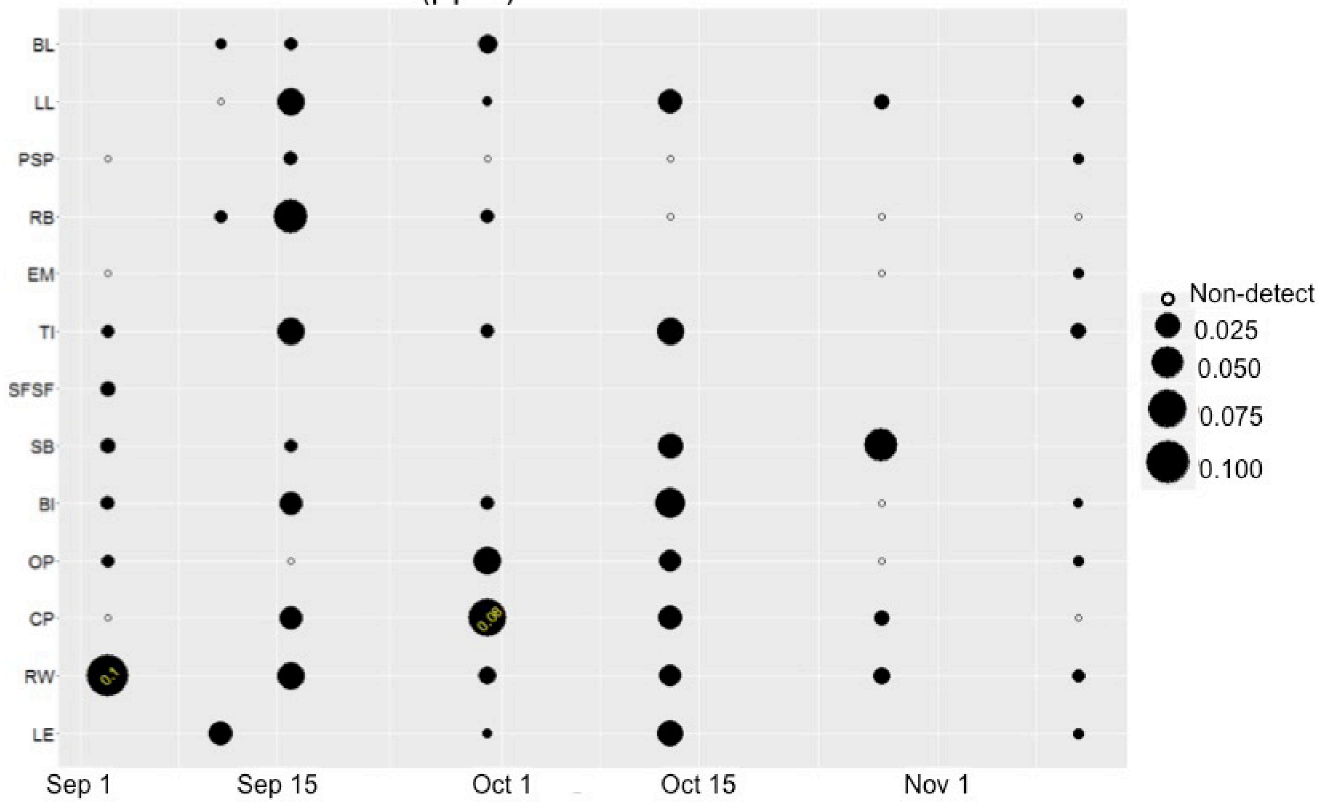
Figure 3.5 A. Domoic acid and B. Microcystins concentration in naturally occurring mussels, Sep-Dec 2015 on an approximately bi-weekly basis. See Figure 1.1 for sample locations. At each site, three mussels were individually homogenized and analyzed for toxins by LC-MS. Circle size is proportional to the mean of the triplicate analyses. While the toxin concentrations are relatively low compared to acutely toxic doses to humans, the potential impact of low-level exposure

Domoic Acid: Mussels excrete domoic acid rapidly (in some species the half-life is only a few days). Thus, the relatively high frequency of detection across all sites, and from late summer through early-winter, is generally consistent with observations from the SPATT measurements. The data are not suggestive of a major domoic acid event having occurred in Central Bay or South Bay during this time.

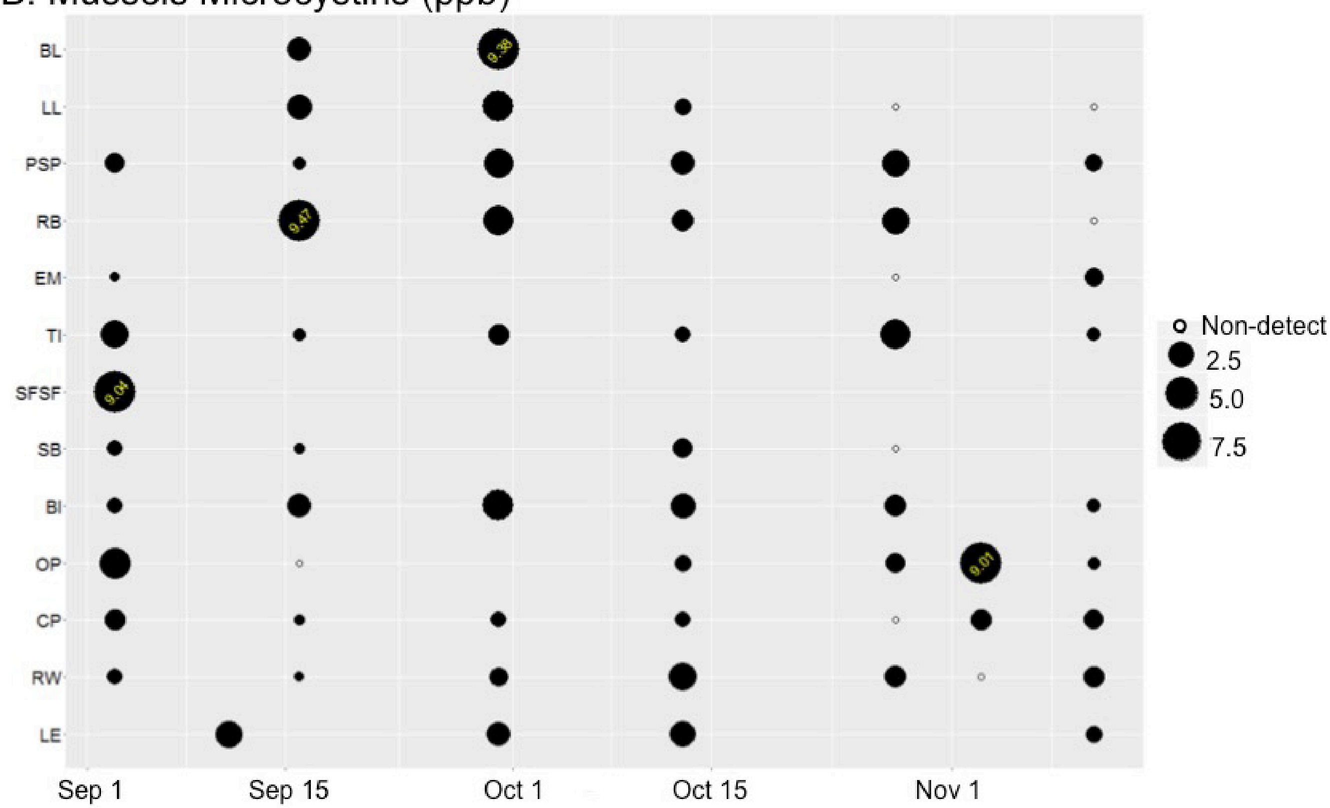
Microcystins: The high-frequency detection of *microcystins* is somewhat surprising given that the freshwater cyanobacteria *Microcystis* are commonly considered to be the main source. All samples were collected on structures near the Bay's edge where freshwater-sourced toxins could be present at higher levels.

Data: Peacock et al., in prep.

A. Mussels Domoic Acid (ppm)



B. Mussels Microcystins (ppb)



Two FY16 NMS pilot studies explored questions related to HAB and toxin sources to SFB.

Did the 2015 coastal Pseudo-nitzchia bloom spread to Central Bay?

Collaborators at UC Santa Cruz collected naturally-occurring mussels from multiple sites around Central Bay from April-August 2015. DA concentrations in late-May 2015 were 4-7 times greater than those in mid-April **(Figure 3.6).** Although increases were evident at all sites, the May 2015 tissue concentrations were still 100-300 times lower than human health thresholds for shellfish consumption (20ppm). DA concentrations decreased over the subsequent 3 months, suggesting that water column toxin levels decreased and that mussels gradually excreted their DA burden. Overall, the data are suggestive of some DA entering Central Bay from the coastal ocean during the Spring-Summer 2015 event. Interestingly, however, they do not suggest that a major toxin-producing bloom developed within Central Bay. The reason(s) why a *Pseudo-nitzchia* bloom did not develop within SFB are important motivators for work beginning in FY17, i.e., to understand what factors helped stymie a HAB event, as that understanding is integral to quantifying the risk of future HAB events.

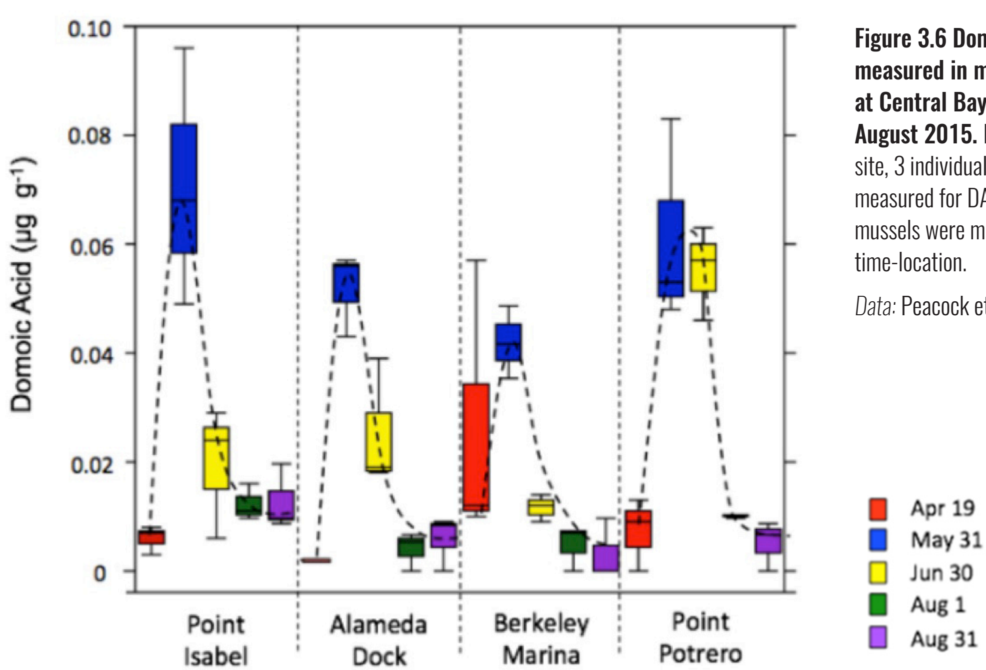


Figure 3.6 Domoic acid (DA) measured in mussels collected at Central Bay stations, April-August 2015. For each date and site, 3 individual mussels were measured for DA. Three individual mussels were measured for each time-location.

Data: Peacock et al, in preparation.

Can archived clam samples from Suisun Bay be used as bioindicators of microcystins exported from the Delta to Suisun Bay?

Archived samples of *Potamocorbula amurensis* clams were analyzed for microcystins to generate a 7-year monthly time-series **(Figure 3.7).** The results are encouraging: seasonal patterns consistent with warm-weather production of microcystins (Microcystis does not grow well when T < 20 C); and evidence of strong interannual variability. Beyond the potential utility of using *Potamocorbula* as bioindicators of algal toxins, the observed tissue concentrations exceed levels shown to cause organ damage in chronically-exposed fish (ref).

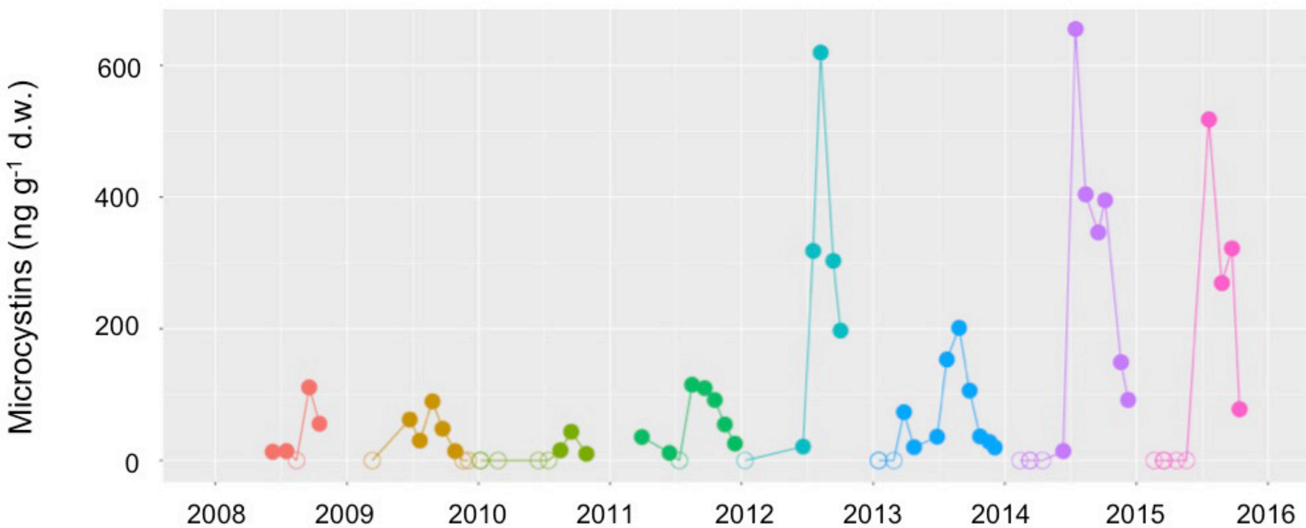
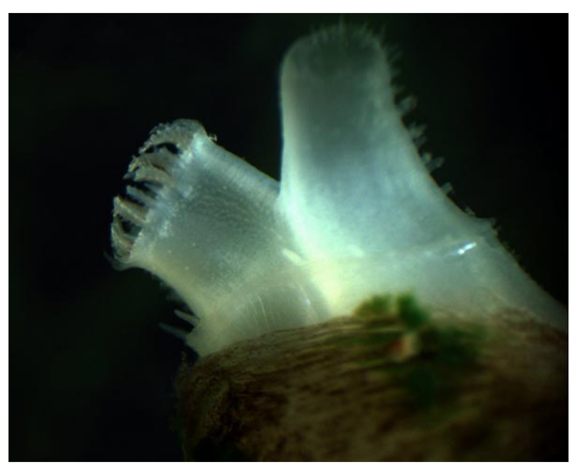


Figure 3.7 Microcystins (MCY) measured in the invasive clam, *Potamocorbula amurensis*, collected near Chips Island (eastern Suisun). Note: Concentrations are µg g^{-1} dry weight. Samples were originally collected by USGS (R. Stewart) as part of selenium monitoring work (e.g., Stewart et al., 2013).

MCY measurements performed by ELISA at Bend Genetics (T. Otter).



Left, ***Potamocorbula amurensis.*** Right, ***Potamocorbula amurensis siphons.*** Courtesy USGS.

4 High-frequency water quality measurements

In 2013 the NMS began developing a program for high frequency water quality measurements, guided by the following goals:

1. ***Develop improved mechanistic and quantitative understanding of the factors influencing water quality*** (e.g., dissolved oxygen levels, phytoplankton biomass, nutrient concentrations).
2. ***Collect high-frequency data for calibrating and validating water quality and hydrodynamic models,*** which will be used for interpreting system behavior and forecasting conditions under future scenarios, including nutrient management scenarios.
3. ***Monitor water quality at sufficient resolution to accurately assess condition,*** in particular in areas where water quality parameters vary with high-temporal frequency (diurnal, semidiurnal, and hourly or sub-hourly time-scales) or sharp spatial gradients, or that have historically received limited monitoring attention.

This section provides an overview of three sets of FY15 activities: Moored sensor network expansion in Lower South Bay, and Summer 2015 results; high-resolution water quality mapping to characterize spatial variability in biogeochemical processes, and early work to incorporate data from existing sensors in Suisun Bay and the Delta.

LOWER SOUTH BAY AND SOUTH BAY MOORINGS

To date, the majority of NMS moored sensor work has been focused in LSB and South Bay. Three moored sensor stations were established in 2013, and 6 additional stations installed in 2015 **(Figure 4.1),** through collaborative projects between SFEI, USGS, and UC Berkeley. Time series for dissolved oxygen, chl-a fluorescence, and turbidity are presented in **Figures 4.2, 4.3, and 4.4,** respectively, for Summer 2015 at a subset of stations. Moored sensor results will be presented in more detail in a forthcoming FY17 technical report. However, the importance of collecting high-frequency data is already becoming evident:

- ***Highly-variable signals at hourly time-scales,*** only detectable with high-frequency measurements
- ***Dominant periodicities of the signals hint at important underlying drivers:***
  - Semidiurnal/diurnal (~6 hr) minima and maxima suggesting a strong influence of the twice-daily flood and twice-daily ebb tides
  - Fortnightly (~14 day) "envelope" around daily max and min values, suggesting influence from spring (strong) and neap (weak) tides.
- ***Inter-site variability:***
  - Large differences in the signal magnitude (max, min, or average), indicating very different water quality conditions over relatively short distances.
  - Large differences in the relative strength of some high- or low(er)-frequency drivers, suggesting that the relative importance of underlying drivers varies spatially.

This data, along with data from other sites and time periods, can be explored further at www.enviz.org, an interactive tool developed to host and visualize NMS high-frequency data.

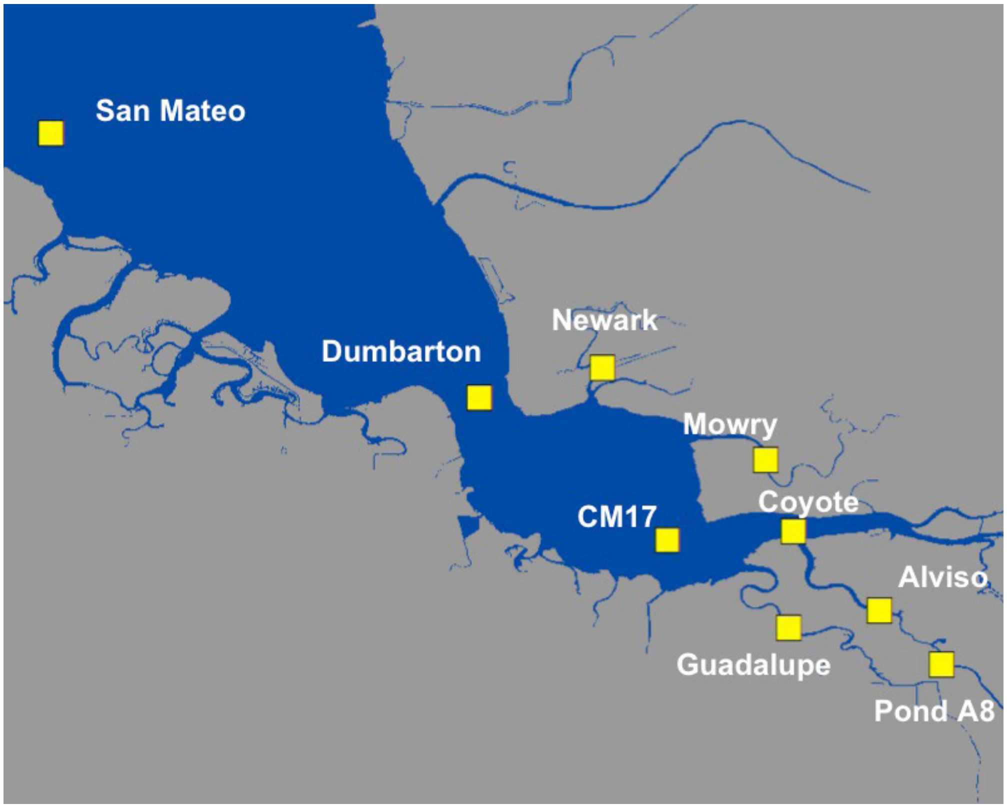
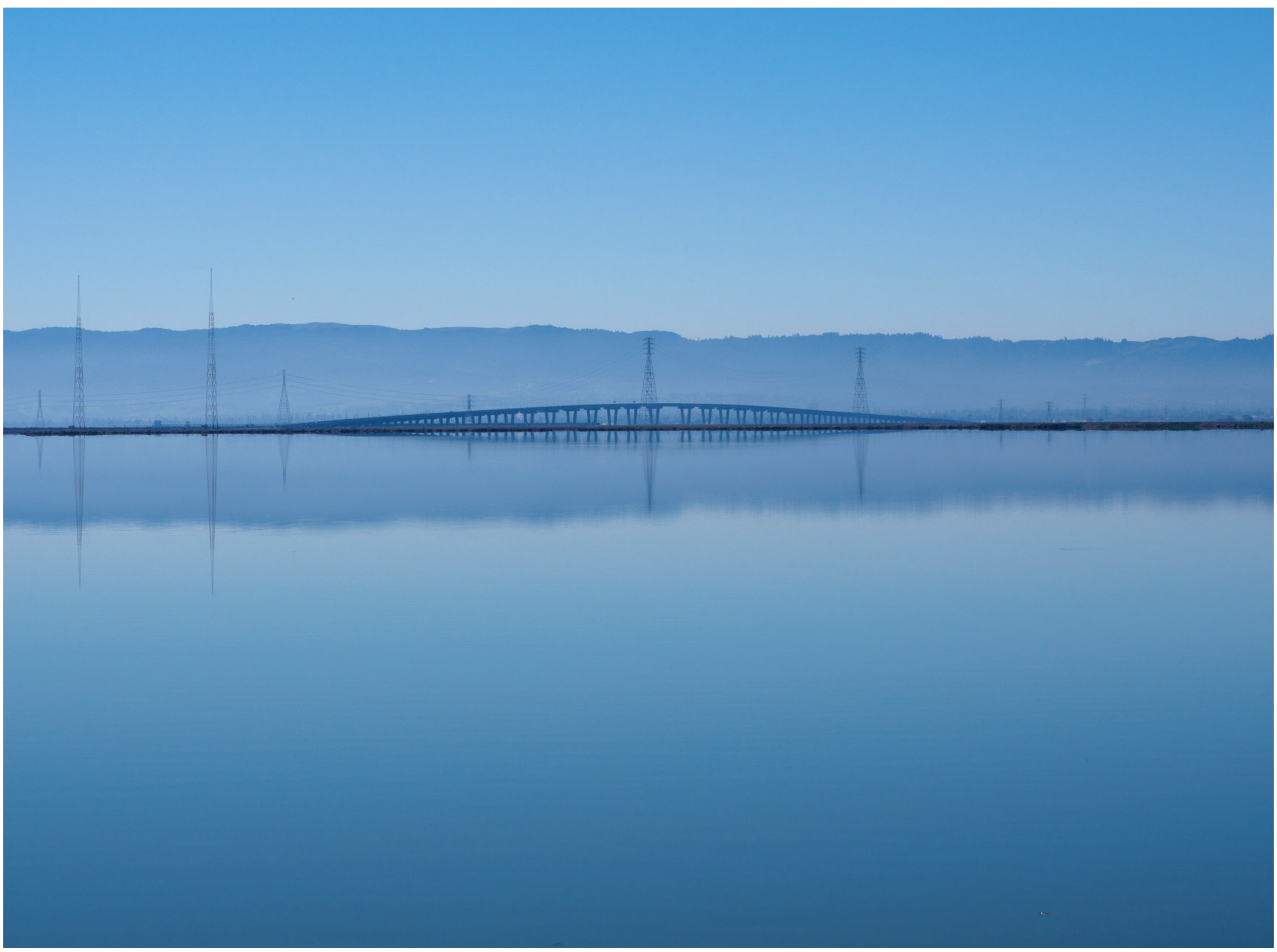


Figure 4.1 NMS mooring locations. Dumbarton, Alviso , and San Mateo were established in CY2013; All other stations were established in CY2015. In general, basic measurements include 15-min measurements for include sensors for salinity, T, dissolved oxygen, chl-a, turbidity, phycocyanin, and colored dissolved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



Dumbarton Bridge, Shira Bezalel (SFEI)

Dissolved Oxygen (DO)

- ***Open Bay sites (San Mateo, Dumbarton):***
  - – DO typically remained above the 5 mg L^{-1} SFB Basin Plan standard
  - – Daily and fortnightly variations: At Dumbarton, substantial DO decrease occurred during ebb tides, with smallest and largest dips during neap and spring tides, respectively.

  Hypothesis: Decreases were caused by mixing of lower-DO water from the Bay's margins into the open Bay during ebb tide, with greater exchange occurring during spring tides (SFEI 2015, Section 6).

- ***Slough and creek sites:,***
  - – DO regularly fell below 5 mg L^{-1}, with large daily variations (2-4 mg L^{-1}). Timing is consistent with tidally-driven variations, as opposed to diel variations in oxygen production.
  - – Large inter-site variability in DO concentrations
  - – Strong spring-neap signal at some sites (Newark, Coyote, Guadalupe)
  - – Each sites conditions represent a unique dynamic balance of multiple processes: water column metabolism (DO consumption and production); sediment oxygen demand; air–water exchange; vertical stratification causing DO depletion in bottom layer; vertical mixing during periods of stronger tidal energy (i.e., spring tides, flood tides); exchange between salt ponds and sloughs; and increased/decreased wetland:slough and slough:Bay exchange during spring/neap tides.

- ***Underlying causes and ecological impacts?*** FY17 projects will focus on quantifying the role of anthropogenic nutrients and salt pond exchange, and identifying healthy conditions for biota.

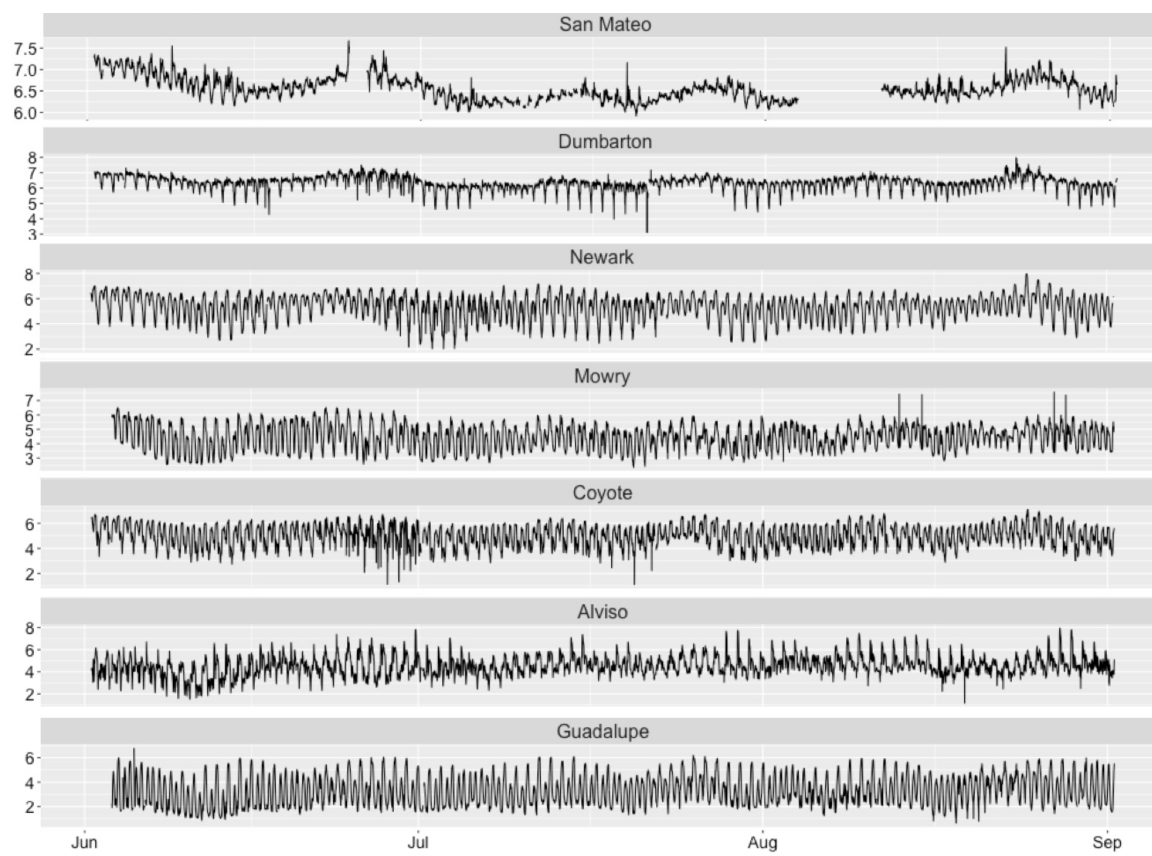


Figure 4.2 Dissolved oxygen (mg/L) collected at seven locations in South Bay and Lower South Bay. Note different y-axis scales. Visit www.enviz.org to explore the data during different time periods.

Chlorophyll-a as a measure of phytoplankton biomass

- Chl-a concentration is used as a measure of phytoplankton biomass. The relationship between μg L^{-1} and RFU is ~4:1 at open Bay sites, and ~2:1 at slough and creek sites.
- At San Mateo and Dumbarton, daily max chl-a concentrations co-occurred with ebb tides, indicating spatial heterogeneity in algal biomass concentrations (differences of ≥ 5 μg L-1), due either to greater production along the broad shoals or mixing of higher-biomass water masses from margin habitats.
- Sloughs with no salt pond connections (Mowry, Newark) had low chl-a levels.
- ***Salt pond exchange:***
  - Alviso Slough has multiple salt pond connections through which higher biomass waters enter the slough. Chl-a levels fluctuated between high (30-40 μg L^{-1}) and relatively low (2-4 μg L^{-1}) levels,with minimum chl-a coinciding with flood tides, as lower biomass-containing water masses from the open Bay dominated conditions in the channel.
  - Conditions at Coyote Creek are likely influenced by a mixture of open-Bay water and salt-pond-influenced waters (e.g., draining from Alviso Slough)
  - Chl-a levels in Guadalupe Slough spiked for short periods but remained low on average
  - The influence of organic matter flux from the salt ponds on water quality in the sloughs and open Bay requires further investigation and is being explored within FY17 projects.

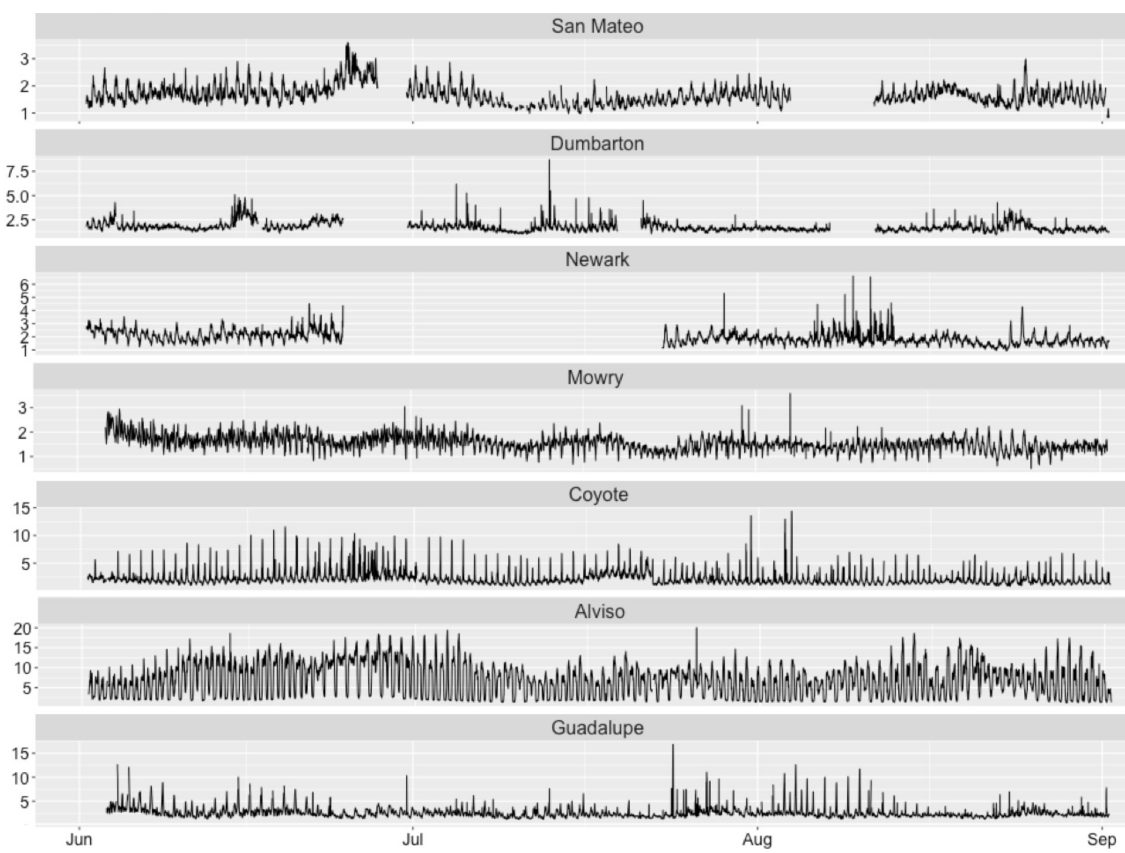


Figure 4.3 Chlorophyll-a, in units of relative fluorescence units (RFU) collected at 7 sites. Note: different y-axes

Turbidity

- In SFB, low light levels in the water column are a primary factor limiting phytoplankton growth rates and affecting nutrient utilization. The low light levels are caused mostly by high suspended sediment concentrations (SSC): as SSC increase, light is scattered or absorbed, instead of penetrating deeper into the water column. *In situ* turbidity measurements can be used to approximate SSC and to estimate light attenuation in the water column (see **Figure 4.4** caption).
- The high turbidity levels at these LSB and South Bay sites has a major effect on light penetration, or the photic depth (depth at which the light level is 1% of incident light):
- Turbidity exhibited large variability over hourly time-scales, and highly-periodic behavior across all sites: daily max and min relative to tidal stage, and spring-neap envelopes around daily max-min (~14-day periodicity) caused by stronger tidal mixing energy (spring vs. neap) resuspending more particles from the bed.
- ***But complex inter-site variability…***
  - Large intersite differences in max, min, and median turbidity.
  - Time lag, or timing shift, between sites because of transport—e.g., sediments resuspended along the shoals during flood tide appear later as ebb-tide peaks at channel sites.
  - Strong winds and wind waves also resuspend sediments in shallow areas

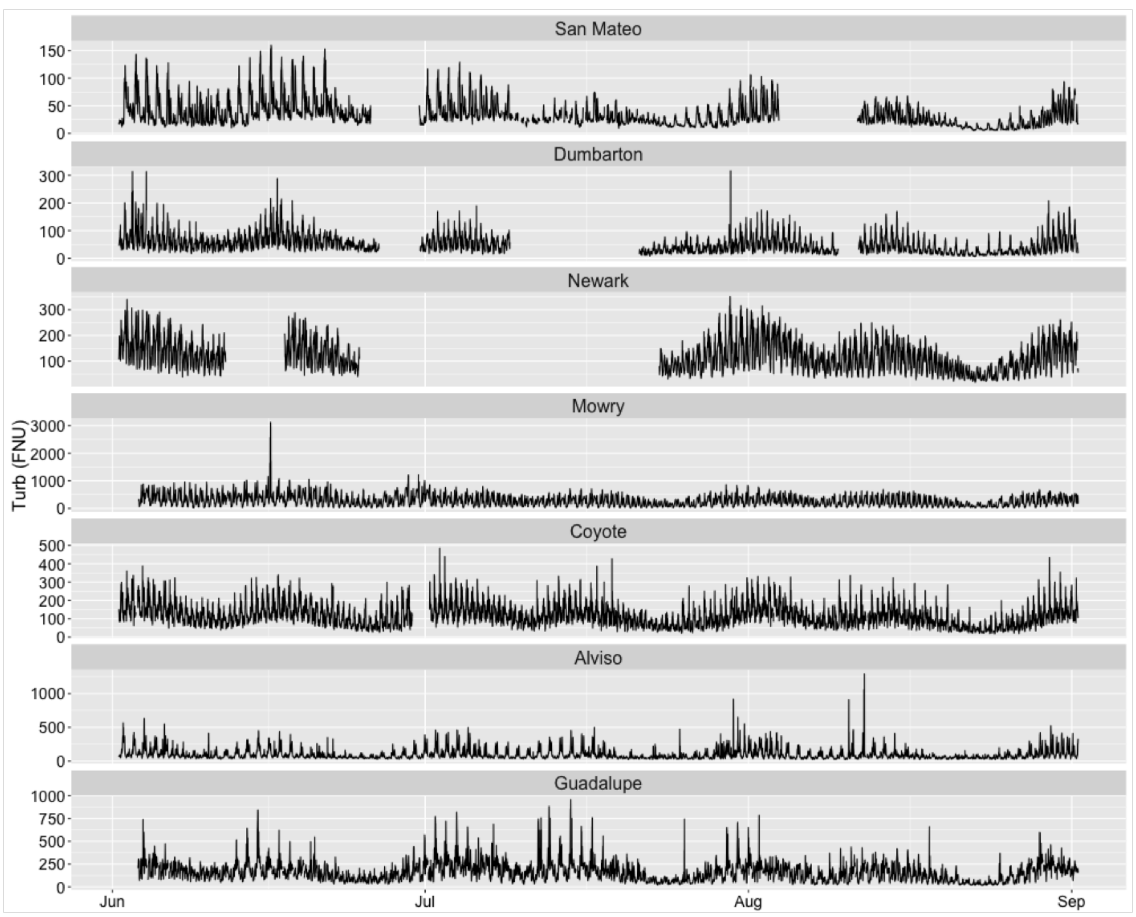


Figure 4.4
Turbidity (FNU) measured at 7 sites, Jun-Aug 2015.

Shira Bezalel (SFEI)

HIGH RESOLUTION MAPPING — LOWER SOUTH BAY

Based on early moored sensor data (SFEI 2015a; SFEI 2015b), we hypothesized that Lower South Bay had strong spatial gradients in water quality. To test this hypothesis, we worked with USGS researchers (Bergamaschi, Downing) to assemble high-resolution and near-synoptic water quality maps in the open-Bay, sloughs, and creeks of LSB **(Figure 4.5).** Discrete samples **(Figure 4.6, map)** were also analyzed to explore whether phytoplankton community composition varied along these gradients (in collaboration with M Peacock, UCSC, and Totten, Bend Genetics).

Biogeochemical parameters – highlights (Figure 4.5)

- Strong spatial gradients in important water quality parameters, most evident during ebb tides.
- Clear evidence of salt pond influence on adjacent slough and near-field open-Bay water quality

Phytoplankton community

- Diatoms comprised the majority of phytoplankton biovolume in all samples (by microscopy; not shown)**.**
- Beyond diatoms, DNA-based characterization revealed two broad types of composition **(Figure 4.6):**

See Figure 4.6 caption for cautionary note on interpreting the DNA-based results

Chlorophyte-enriched: Majority of these samples were slough/creek during ebb tide. ← **Hypothesis:** Salt-pond signature, enriched in phytoplankton produced in salt pond.

Cryptophyte-enriched: Majority of these samples were open Bay, or slough/creek during flood tide. ← **Hypothesis:** Open Bay signature, phytoplankton grown under Open Bay.

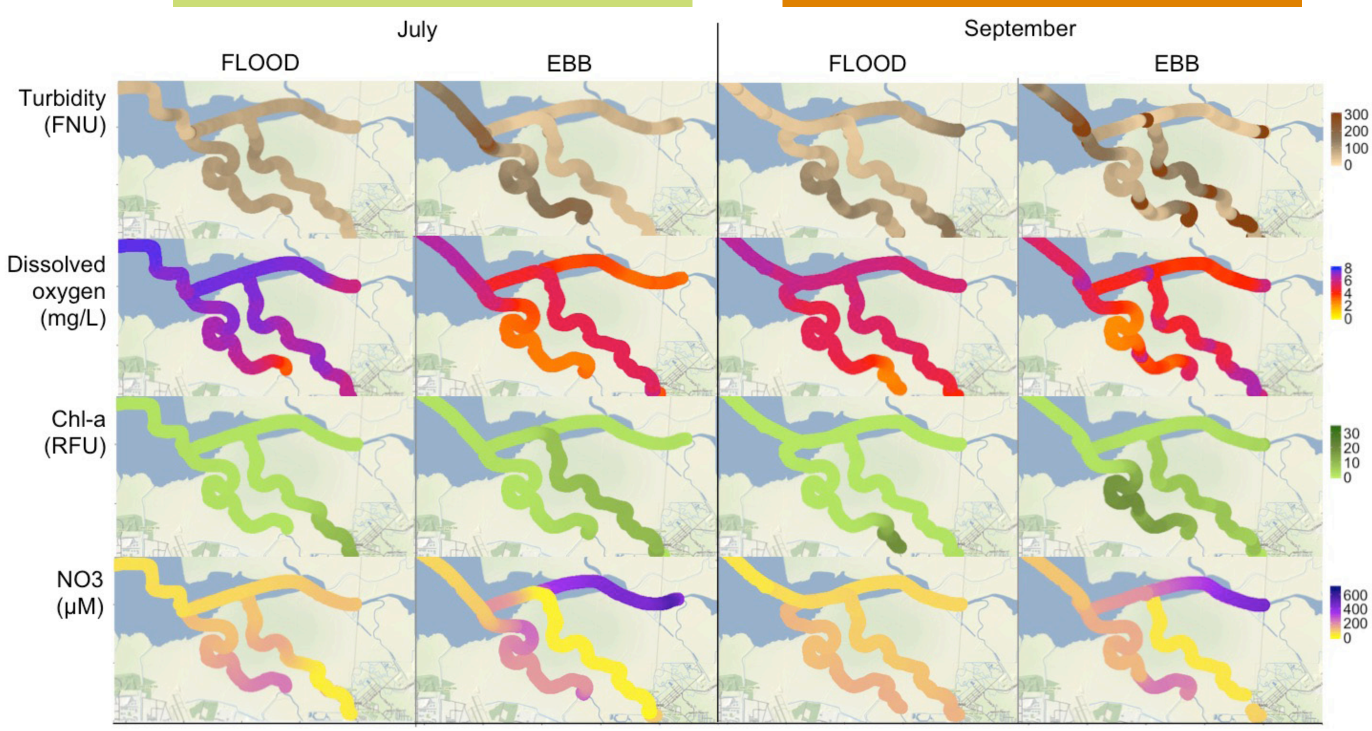


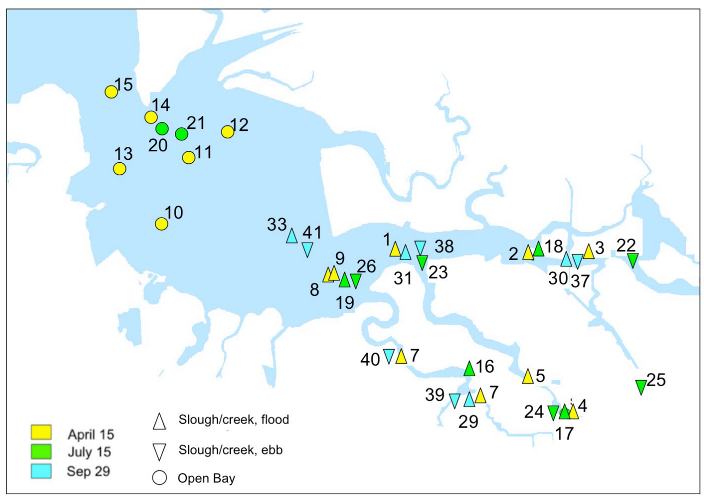
Figure 4.5 During mapping campaigns (mid-April, mid-July, and mid-September 2015), measurements were made within 1.5-hour windows centered on slack flood and ebb tides. While the boat cruised at ~20 mph, Bay water was pumped past a set of optical sensors recording measurements each second, yielding ~10m-resolution water quality data. Key observations: Large differences in water quality between flood and ebb; >5-fold variability in turbidity during ebb tides; Extended stretches of DO < 5 mg L^{-1} along sloughs and Coyote Creek; elevated chl-a in sloughs during ebb tide due to salt pond exchange (Alviso in July; Guadalupe in September); elevated NO_3^- along Coyote during ebb, and Guadalupe (ebb and flood) due to wastewater loads.

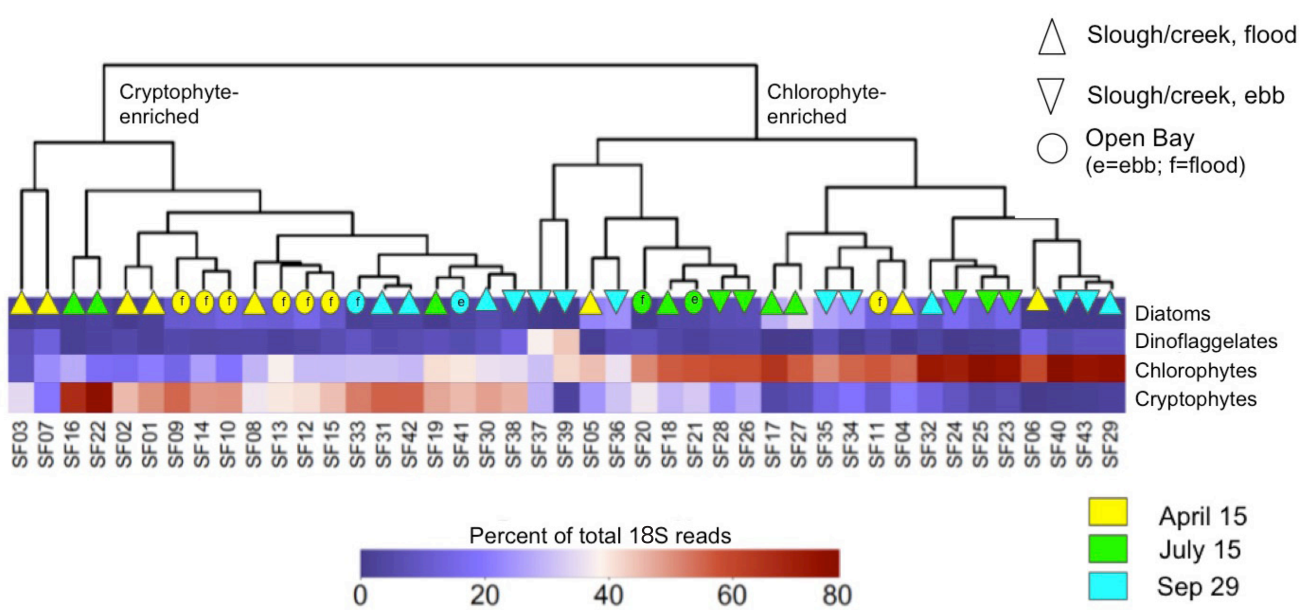
- HAB-forming organisms detected (see Appendix X for more details).
  - DNA: Alexandrium, Karlodinium, Gymnodium, Anabaena
    Microscopy: Karenia, Gymnodinium, Anabaena
  - September sampling occurred shortly after a salt pond gate connected to Guadalupe Slough was opened that delivered high levels of algal biomass to the slough, and counts (18s reads) for Alexandrium and Karlodinium were markedly higher at the Guadalupe sites than at other locations in September compared to other dates.

- Algal Toxins
  - Domoic acid: not detected; Microcystins: detected at low levels in several samples
  - Saxitoxin is being analyzed, but results not yet available.
  - Further work needed to explore the importance of salt pond influence on phytoplankton community: Substantial influence food quality? Source of HAB-forming organisms and toxins?

Figure 4.6 Discrete sample locations (right) and results from amplicon 16s sequencing (below). Sequencing results are presented as both a dendrogram (depicting similarity among samples) and a heat map of percent total 18s reads in the four classes comprising the largest amount of reads interpreting the sequencing data in terms of phytoplankton abundance is not straightforward because: some phytoplankton classes have more genome copies than others; and cyanobacteria are not included.

Therefore it would not be legitimate to make quantitative inferences between rows (i.e. greater 16s for chlorophytes does not mean chlorophyte biomass was greater than diatom biomass). However, it is reasonable to infer differences in overall community composition by comparing columns (comparing samples).

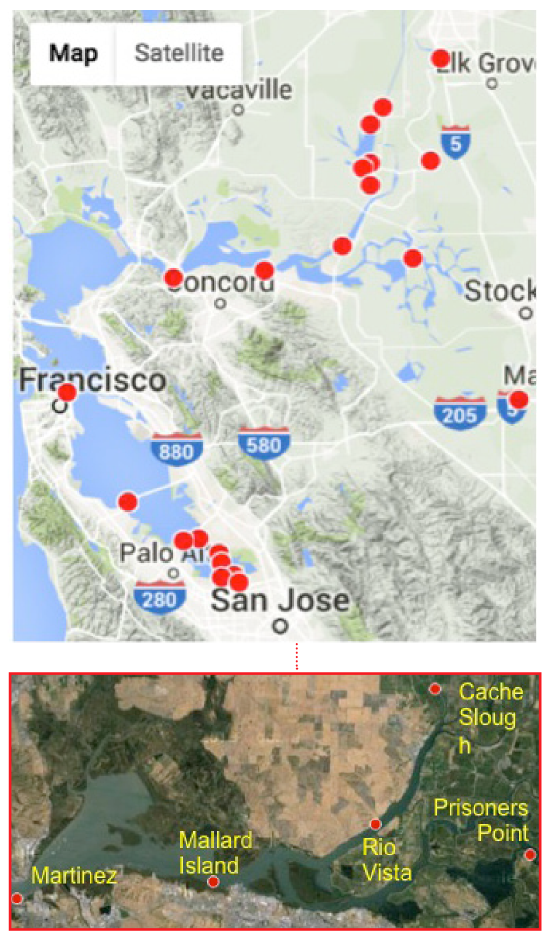




High Frequency moorings in the northern Bay-Delta

- Unlike South Bay and Lower South Bay, Suisun Bay and the Delta already had a number of moored sensors, maintained by other entities (CA Department of Water Resources (DWR); USGS).
- The NMS' near-term strategy for the northern Bay-Delta is to incorporate publicly available data from these sensors; assess the degree to which existing sensor locations and data quality address NMS needs for those areas; and begin exploring the possibility for collaborations and/or cooperative agreements between the NMS and other entities to efficiently achieve shared objectives.
- As a first step, we have begun pulling data from multiple stations operated by DWR and USGS into the www.enviz.org database and visualization tool **(Figure 4.7).** These stations telemeter data back to their individual agencies' data portals. The enviz site now periodically downloads this data from their separate data portals, and automatically populates the enviz database with the most recent data. The potential utility of these data sources is already becoming evident. For example:
  - A multi-week phytoplankton bloom event in the Sacramento River and within the Delta was clearly captured at four stations, operated by separate agencies, providing information about the magnitude of the bloom (chl-a concentration), its spatial extent, and its duration (Figure 4.7B).
  - Data from Martinez illustrates how, although a sustained bloom occurred in the lower Sacramento River and western Delta as far west as Mallard Island, the bloom apparently did not propagate throughout Suisun Bay.

A



B

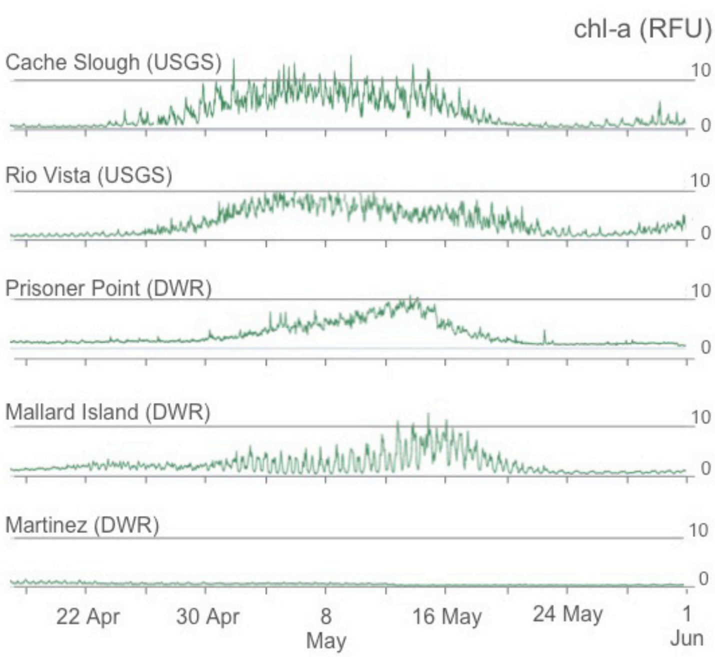


Figure 4.7 A. Stations currently included in www.enviz.org. B. Time series of chl-a sensor responses at 5 stations at five stations from Suisun and the Delta.

from Coyote Hills, August 2016, Shira Bezalel (SFEI)

5 Modeling

See also the online materials (http://sfbaynutrients.sfei.org/modeling/map.html)

The development and application of numerical models is an essential step in understanding the past, present and potential future conditions of San Francisco Bay. The recently-completed NMS Modeling Work Plan (insert link) lays out a phased approach to the modeling effort, including tasks and goals motivated by a suite of priority questions (see sidebar).

Priority Modeling Questions

Management questions that can be answered based on conservative transport studies,such as

- *What is the spatial extent of nutrient contributions from each nutrient source?*

Technical questions centered on reproducing nutrient-related phenomena in the Bay and understanding the strengths and limitations of the models. In particular, how complex must the models be to reproduce

- *Seasonal and basin-scale trends in nutrient concentration?*
- *The large bloom of 2003 in South Bay?*
- *Decadal trends of increasing chlorophyll in the Bay?*
- *Semidiurnal dips in dissolved oxygen at the Dumbarton Bridge?*

Ecosystem and broader scientific questions, including

- *How important are clams vs. light limitation in controlling blooms in the bay?*
- *How do sloughs and ponds affect water quality in the margins and open bay?*
- *How sensitive are conditions in the bay to forcing factors like nutrient loads, turbidity, temperature and benthic grazing?*

MAJOR ACTIVITIES

Hydrodynamics

The long-term plan for hydrodynamic modeling is to use the Delft Flexible Mesh (DFM) model, developed by Deltares and applied in San Francisco Bay in the USGS CASCaDE project. The initial focus of NMS biogeochemical modeling is on South Bay and Lower South Bay, areas found to be under-represented in the CASCaDE model. Work is underway to refine the DFM model in South Bay, building upon the CASCaDE model, and we anticipate switching to this platform in FY17. While the DFM hydrodynamic model was undergoing refinement in FY16, we utilized a previously-developed hydrodynamic model for South Bay, created in another hydrodynamic platform (SUNTANS), to make progress on early biogeochemical model development, including the work described below.

Passive Tracer Studies

To gain a better understanding of how individual nutrient sources contribute to concentrations at specific locations, we conducted a passive tracer study for WY2013. Flows from 36 POTWs, 5 refineries , and 70+ rivers and creeks were included as inputs to the hydrodynamic model. Each flow was numerically tagged in the water quality model with the source identity, and tracked as it was transported and mixed throughout the Bay during a 1 year simulation (WY2013). The resulting tracer distributions can be explored in the on-line materials (http://sfbaynutrients.sfei.org/modeling/map.html#conservative).

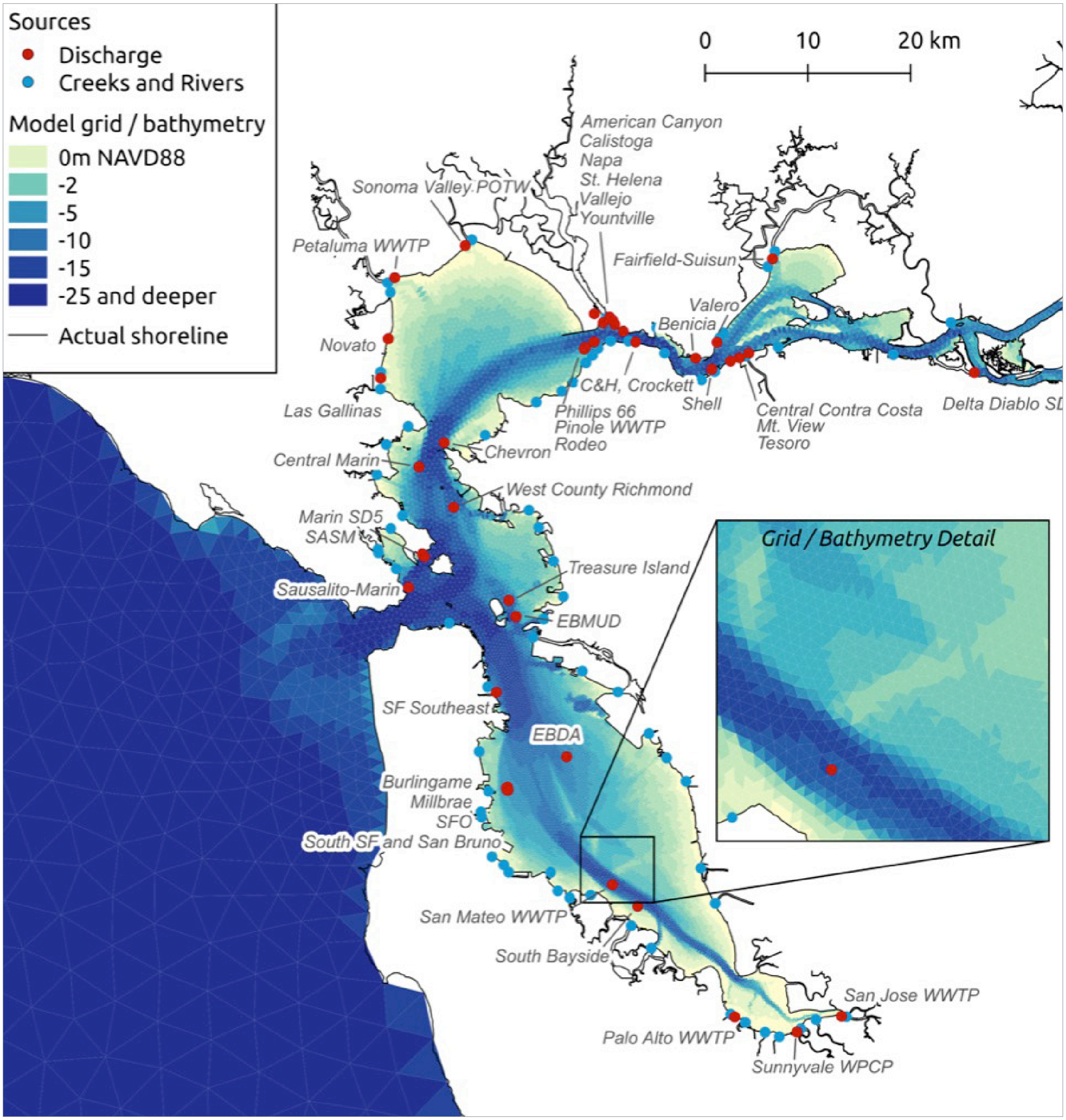


Figure 5.1 Figure 5.1 SUNTANS model grid and bathymetry in South Bay. The coastal ocean is the coarsest area, with individual grid cells visible in the map. The highest resolution is in South Bay, where the model can resolve variability at spatial scales down to 200m. Tides are introduced to the model 100km out from the Golden Gate, based on tide gage data, while freshwater is added to the model at over 100 locations representing wastewater discharges, refineries, creeks and rivers. The grid has 25,000 2-D cells, which translate to 200,000 3-D cells across 31 z-layers, resolving vertical scales as small as 0.5m. Estimated flows and nutrient loads are included for 36 POTWs, 5 refineries, and 73 rivers and creeks. Evaporation, precipitation and wind are also included. The model runs approximately 70 times faster than realtime on a desktop computer (i.e. a year simulation takes ~5 days).

Reactive Nutrient Simulations

The next step in the phased biogeochemical model development was a streamlined simulation focused on nitrogen as a 'reality check' to compare with observed data. Each source **(Figure 5.1)** was assigned estimated time-varying loads (kg d^{-1}) of nitrate (NO_3^-) and ammonium (NH_4^+). These inputs were transported and mixed, and allowed to undergo transformations, specifically nitrification and denitrification. Uptake by algae was not included in the simulation, which is likely an important oversimplification during some times of the year (spring, summer) and a reasonable assumption during others (fall, winter). **Figure 5.2** presents a subset of model results. **Figure 5.3** compares observed dissolved inorganic nitrogen (DIN; NO_3^- + NH_4^+) and modeled DIN concentrations. Additional model output can be explored in the online materials (http://sfbaynutrients.sfei.org/modeling/map.html#reactive).

NEXT STEPS

Biogeochemical modeling is progressing on a number of fronts. The major activities planned for FY17 are

- Skill assessment of SUNTANS and and Delft Flexible Mesh hydrodynamic models
- Prepare and run additional water years: 2003, 2006, and spring 2016.
- Addition of phytoplankton and more nutrient forms to the water quality model.
- Targeted comparisons between model results and specific, observed phenomena as outlined in the modeling work plan.

from Coyote Hills, August 2016, Shira Bezalel (SFEI)

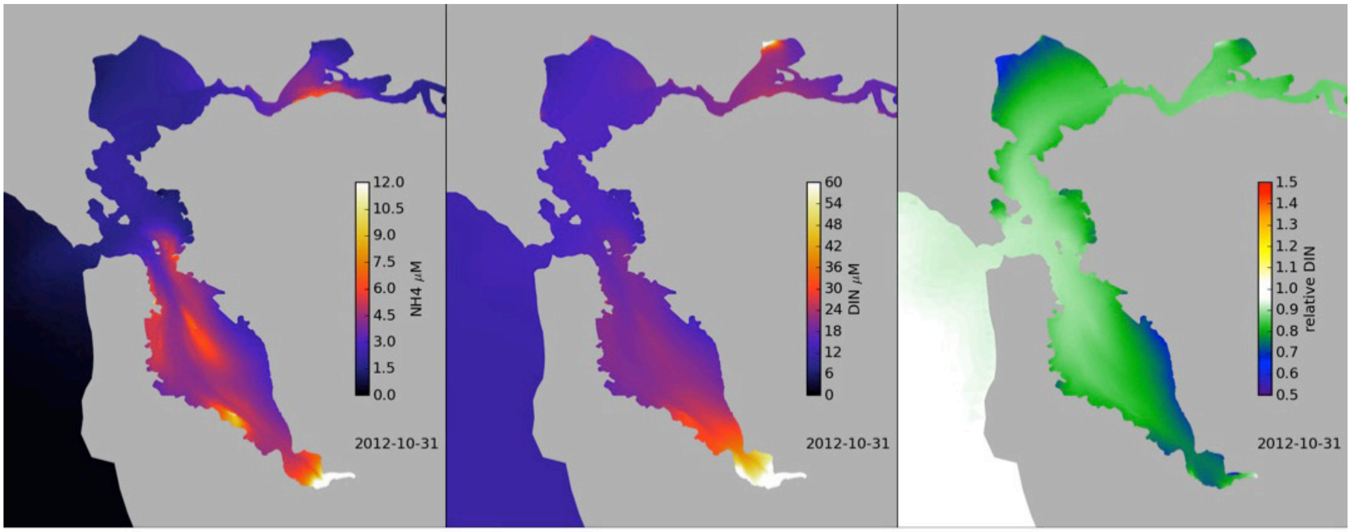


Figure 5.2 A snapshot of predicted nitrogen concentrations after a one month simulation. The left panel shows NH4 concentrations, with hot spots highlighting the locations of several wastewater discharges. In the model NH4 is slowly nitrified to produce NO3, which, in turn, is slowly lost to the atmosphere via denitrification. The center panel shows DIN, the sum of NH4 and NO3 (note the significantly larger scale compared to NH4 alone). Predicted DIN concentrations are the result of loads, dilution, transport, and loss via denitrification. Estimated DIN losses by denitrification can be inferred from the right panel, relative DIN: a value of 1.0 indicates no loss/reaction, while a value of 0.6 (blue), indicates that ~40% of DIN was lost by denitrification.

Nutrient loads were estimated based on the External Nutrient Loads report, and were added to the water quality model as concentrations associated with POTW flows. Nitrification and denitrification were enabled within the water quality model, using the default, temperature- and oxygen-dependent rate constants. Dissolved oxygen was modeled with a constant sediment oxygen demand and a variable reaeration rate. The temperature field was estimated from observations (USGS and DFW), as the present hydrodynamic model does not include temperature.

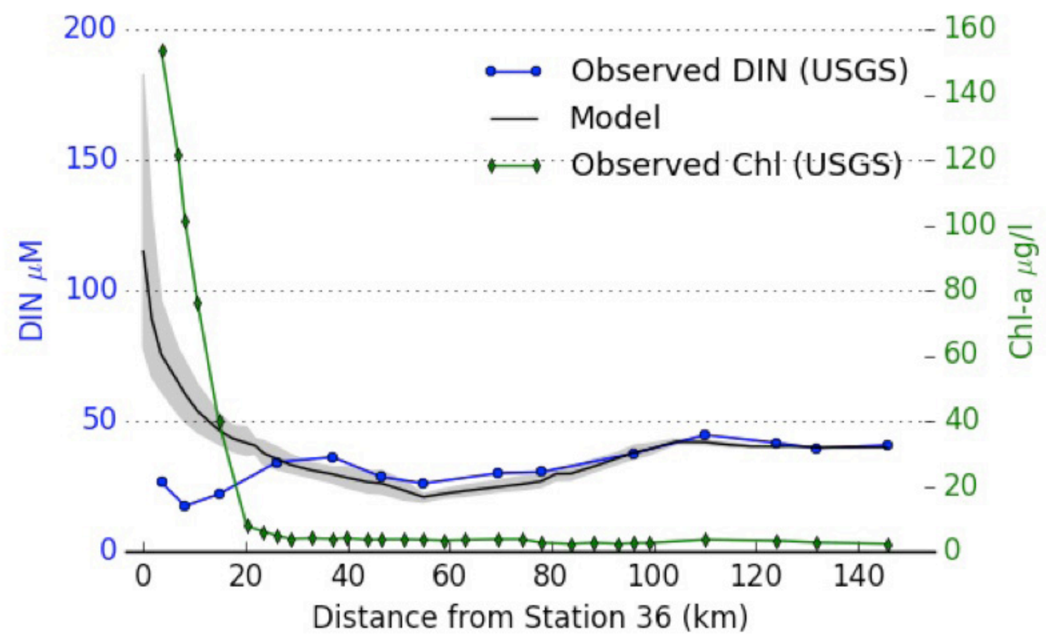


Figure 5.3 Comparison between modeled and measured DIN, plotted from South Bay (left) to Suisun Bay (right), reflecting conditions on February 26, 2013. The greatest departure occurs in Lower South Bay, where a large peak in measured chlorophyll indicates the presence of a bloom. Consistent with this bloom, observed DIN is drawn down in LSB relative to model predictions. While the present simulations do not include numerous nutrient processes (notably nutrient draw-down by phytoplankton as seen here), the initial results suggest that the model still captures most of the spatial trends in nutrient concentrations. The best agreement is generally in the winter months, while summer months tend to show greater differences between modeled and measured data, potentially attributable to phytoplankton, uptake, and sediment-sourced nutrients. Additional model-observation comparisons are available in the online materials (http://sfbaynutrients.sfei.org/modeling/map.html#comparisons).