REGIONAL MONITORING PROGRAM
FOR WATER QUALITY IN THE SAN FRANCISCO BAY

External Nutrient Loads to San Francisco Bay

by
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i. Executive Summary

i.1 Background

San Francisco Bay (SFB) has long been recognized as a nutrient-enriched estuary (Cloern and Jassby 2012), but one that has not exhibited the classic impacts of high nutrient loads observed in other estuaries, such as high phytoplankton biomass and low dissolved oxygen. More recent observations, though, suggest that SFB's resistance to the harmful effects of nutrient overenrichment is weakening. Since the late 1990's, some regions of SFB have experienced substantial increases in phytoplankton biomass (Cloern 2007; Cloern 2010). An unprecedented red tide bloom in September 2004 (Cloern 2005), and increased frequency of cyanobacteria blooms (Lehman 2008) in the northern estuary also signal changes in ecosystem response. Recent studies in the northern SFB estuary (including the San Joaquin/Sacramento Delta) have also argued that the chemical forms of nutrients and their relative abundances (e.g., ammonia:nitrate, N:P) adversely impact phytoplankton productivity (Dugdale 2007, Parker, Dugdale 2012a, Parker 2012b, Dugdale 2012) and community composition (Glibert 2012).

The combination of high nutrient concentrations and changes in environmental factors that regulate SFB's response to nutrients has generated growing concern about whether the Bay is trending toward, or may already be experiencing, nutrient-related impairment. To address this concern, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy[1], which lays out an approach for gathering and applying information to inform key management decisions. Estimating nutrient loads, including evaluating how those loads vary spatially and temporally was recognized as an early priority in the Nutrient Management Strategy.

i.2 Main Goals and Approach

This report's main goals were to

1. Use the best available current information to quantify external nutrient loads to San Francisco Bay;
2. Explore how current loads vary spatially (at the subembayment scale) and seasonally;
3. Where data permits, assess long-term trends in nutrient loads; and
4. Identify major data needs and important uncertainties.

The report focuses on loads from publicly-owned wastewater treatment works (POTWs), refineries, stormwater runoff, and efflux from the Sacramento-San Joaquin Delta. Average annual loads and seasonal variations in loads were determined based on 2006-2011 data and recent POTW and refinery effluent characterization data that has been collected since July 2012 and covers a wide range of nutrient forms. For some POTWs and the Delta efflux, long-term trends in loads were also evaluated. Across all sources, the major nutrient forms considered were ammonium (NH_4^+), nitrate (NO_3^-), and dissolved inorganic phosphorous (DIP, largely present as HPO_4^{-2} at typical San Francisco Bay pH) due to data availability. Total-N and Total-P were

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

considered where possible. Net nutrient loads to SFB through oceanic exchange via the Golden Gate are not included in this analysis, although this source may be important under some conditions, and are addressed in a separate report. Direct atmospheric deposition of N to the Bay's surface was assumed to be small relative to other sources and was not included in estimates. However, the loads resulting from atmospheric deposition to Bay Area watersheds and the Central Valley were indirectly included through estimating fluvial loads from those sources. Insufficient information exists to constrain nutrient loads through groundwater inputs to the Bay; however, given the size of other sources, groundwater loads were also assumed to be small.

i.3 Main Findings

i.3.a Bay-wide loads overview

The San Francisco Bay Area has 42 POTWs that discharge approximately 500 million gallons per day (MGD) of treated effluent either directly to the Bay or to receiving waters in adjacent watersheds that drain to SFB (not including discharges east of Suisun Bay that enter through the Delta). While several POTWs carry out nitrification (conversion of NH_4^+ to NO_3^-), or further advanced treatment (e.g., biological nitrogen removal) to remove a portion of nutrients prior to discharge, most POTWs only employ secondary treatment, which generally removes little N or P. Bay-wide annual-average POTW loads were 34300 kg d^{-1} NH_4^+, 11500 kg d^{-1} NO_3^-, and 3900 kg d^{-1} DIP. The 5 largest POTWs accounted for approximately 75%, 50% and 45% of these loads respectively. NH_4^+ was the dominant form of DIN discharged Bay-wide, although NO_3^- was the dominant form for several POTWs where effluent is nitrified prior to discharging. Recently collected effluent characterization data from POTWs (see Appendix 4) showed that 89% of total-N was discharged as dissolved inorganic nitrogen (DIN; DIN = $NH_4^+ + NO_3^-$) and 78% of total-P was discharged as DIP, and that [DIN]:[DIP] was highly variable among plants.

Loads from 6 refineries, located in Suisun and San Pablo Bays, were also quantified based on effluent data. The total load from refineries was estimated to be 970 kg d^{-1} DIN and 60 kg d^{-1} DIP.

Stormwater nutrient loads were estimated using the Regional Watershed Spreadsheet Model (RWSM), a modeling tool that is under development for the Bay Area for other contaminants (Mckee and Lent 2011; Lent 2012). We used the RWSM-calculated annual runoff volumes for 331 watersheds that ultimately drain to the Bay, based on rainfall, land-use, and slope (Lent 2012), and combined these runoff flow estimates with land-use specific nutrient concentrations to compute annual loads. To date, limited effort has been directed toward modeling stormwater nutrient loads in the Bay Area; in addition, only limited stormwater nutrient data existed to validate landuse-specific nutrient concentrations and model results. Thus, the stormwater loads are highly uncertain, but nonetheless serve as order of magnitude estimates for comparison with other sources. Annual-average stormwater loads to the Bay were estimated to be 10800 kg d^{-1} DIN (mostly as NO_3^-) and 1300 kg d^{-1} DIP. The load magnitudes varied substantially on a seasonal basis. The calculated nutrient yields (kg d^{-1} m^{-2}) from individual watersheds showed strong spatial variation, with moderate yields from high-density residential areas, and the highest yields from agriculturally-dominated areas draining to San Pablo and Suisun Bays. As a result, the majority of the estimated stormwater nutrient loads, came from watersheds draining into San Pablo Bay and Suisun Bay. However, these loads need to be interpreted cautiously because of limited field data.

Flows emanating from the Delta and entering Suisun Bay at its eastern edge deliver large amounts of nutrients to SFB. Loads from the Delta were estimated using flow and concentration data at select locations near where the Delta transitions into Suisun Bay. Annual average loads were 5800 kg d^{-1} NH_4^+, 10400 kg d^{-1} NO_3^-, and 950 kg d^{-1} DIP, all of which exhibited strong seasonal and interannual variability.

i.3.b Seasonal variations of loads and relative importance of sources

To evaluate the seasonal variability in the importance of nutrient sources, average monthly loads were calculated for the period 2006-2011 at the subembayment scale. For these initial estimates, SFB was segmented into subembayments using the SFBRWQCB's subembayment boundaries (see Figure 2), which are reasonable boundaries, but may not be the most hydrodynamically-meaningfully delineations for addressing some management or scientific questions. Other boundaries were also considered, but the use of different boundaries did not appreciably influence the relative importance of sources within subembayments.

POTW and refinery loads showed some, but relatively limited, seasonal variability in all subembayments, while stormwater and Delta efflux loads showed strong seasonal variability. In Lower South Bay, South Bay and Central Bay, discharge from POTWs was the dominant source of DIN and DIP year-round. While the relative contribution of stormwater-derived DIN to overall DIN loads at the subembayment scale were minimal in these three subembayments, stormwater DIP loads had the potential to be nontrivial during some months. Compared to those three subembayments, stormwater nutrient loads to San Pablo Bay/Carquinez Straits comprised a relatively greater proportion of total direct loads (i.e., not including exchange between subembayments). However, nutrient loads transported from Suisun Bay, which include inputs from the Delta, appear to be an important, if not dominant, nutrient source to San Pablo Bay throughout most of the year. In Suisun Bay, load estimates suggest that the Delta was the largest source of NH_4^+ for as much as half the year, but that direct POTW loads to Suisun Bay dominated NH_4^+ loads during the rest of the year. The Delta contributed the largest loads of NO_3^- year-round to Suisun Bay, and the majority of DIP during half the year.

i.3.c Long-term trends in loads

Long-term data records were available for some POTWs, including most of the largest dischargers, and also for Delta efflux loads, allowing loading patterns to be examined over recent decades. Since data analysis and modeling efforts will focus on investigating changes in ambient water quality and ecosystem response over the past few decades, changes in nutrient loads (or load composition) over that period also need to be examined. Visual inspection of NH_4^+ loads from some POTWs suggest that loads have increased substantially (30-40%) over the past 10-20 years. Others have remained relatively constant, or substantially decreased due to treatment upgrades. NH_4^+ loads from the Delta efflux have increased in all months over the last 35 years, including a near tripling in April and May.

i.4 Data gaps and major uncertainties

Aside from several POTWs that had been measuring multiple nutrient forms, for most POTWs only NH_4^+ concentration data was readily available prior to 2012. For plants that do not nitrify, NH_4^+ concentrations provide a reasonable surrogate for estimating total DIN loads. However, DIP concentrations and [DIN]:[DIP] were highly variable among POTWs (based on 2012 data). Furthermore, there is limited total N and total P data. The current effluent characterization program will be valuable for addressing these gaps for current loads, and may also help with filling historic gaps, to the extent that concentrations or ratios at individual POTWs have not changed substantially.

Delta efflux loads have the potential to be a dominant source of nutrients to Suisun Bay and San Pablo Bay during much of the year. The approach used for developing the time-series of monthly-average loads is based on a peer-reviewed approach that was applied for other compounds exiting the Delta (Jassby and Cloern 2000), and is a reasonable approach for a first set of estimates. However, the approach has limitations, both because it uses an imperfect combination of historic data (collected for other purposes, as opposed to flow and concentration specifically collected to quantify nutrient loads) and due to gaps in that data. Hydrodynamic and reactive transport models for the Delta need to be calibrated, validated, and applied to generate improved Delta nutrient load estimates, and to quantify uncertainties and the influence of upstream factors that regulate loads (e.g., flow routing, residence time, changes in nutrient loads and nutrient forms from SRCSD). Additional monitoring data, in particular during high flow periods, may also be needed to calibrate such models. Loads exchanged between subembayments, such as those entering San Pablo Bay from Suisun Bay, also need to be more rigorously evaluated.

The stormwater load estimates in this report are highly uncertain. That said, they provide useful order-of-magnitude estimates for assessing the potential importance of stormwater contributions. These estimates suggest stormwater does not contribute substantially to loads at the subembayment scale in Lower South Bay, South Bay, and Central Bay. However, stormwater may contribute nontrivially to DIN and DIP loads in San Pablo and Suisun Bays during some times of the year. Furthermore, the importance of stormwater loads at spatial scales finer than the subembayment-scale (e.g., in shallow margin habitats) should not be ruled out. While the Regional Watershed Spreadsheet Model was the best available tool for estimating stormwater nutrient loads for this report, the nutrient load estimates it generated are highly uncertain because the model has not been calibrated for nutrients. In particular, loads from watersheds that have high proportions of agricultural land-use (primarily draining to San Pablo and Suisun Bays) need to be critically evaluated. Better constraining stormwater load estimates will require improved hydrological and loading models as well as additional field data to calibrate and validate those models.

Finally, in this report, loads were combined and analyzed at subembayment spatial scales and at monthly time scales so that seasonal variation in the relative importance of sources could be evaluated. For these calculations, the SFBRWQCB's subembayment boundaries were used. However, other boundaries may be just as appropriate for such an analysis. We tested the sensitivity of basic interpretations to the set of boundaries selected by also using the Regional Monitoring Program's standard boundaries (as described in Lowe 2005). While moving the boundaries, of course, yielded different results in terms of the loads that fell within individual segments, the relative importance of sources was not sensitive to the choice of boundaries. In reality, any set of boundaries that divides SFB into such large areas may be too coarse to meaningfully address management questions. More highly resolved longitudinal and lateral segmentation is likely needed. Hydrodynamic and water quality models will be essential for determining what levels of resolution are most appropriate for addressing which management questions.

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1. Introduction

1.1 Context

Nutrient concentrations in subembayments of San Francisco Bay (SFB) are comparable to or greater than those in other estuaries that experience beneficial use impairment due to nutrient overenrichment (Cloern and Jassby 2012). SFB has historically been resistant to many of the adverse effects of nutrient overenrichment because of strong tidal mixing, light limitation due to high turbidity, and benthic grazing that help maintain low phytoplankton biomass. However there are signs that the factors regulating SFB's response to nutrients may be changing, and that its resistance to high nutrient loads is weakening (Cloern and Jassby 2012, Senn 2012) .

The combination of high nutrient concentrations and changes in environmental factors that regulate SFB's response to nutrients has generated growing concern about whether areas of SFB are trending toward, or may already be experiencing, nutrient-related impairment. To address this concern, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy[2], which lays out an approach for gathering and applying key information to inform management decisions. Estimating nutrient loads, including evaluating how those loads vary spatially and temporally was identified as an early priority in the Nutrient Management Strategy.

1.2 Goals and General Approach

The main goals of this project were to:

1. Use the best available current information to quantify external nutrient loads to San Francisco Bay;
2. Explore how current loads vary spatially (at the subembayment scale) and seasonally;
3. Where data permits, assess long-term trends in nutrient loads; and,
4. Identify major data needs and important uncertainties.

The report focuses on loads from publicly-owned wastewater treatment works (POTWs), refineries, stormwater runoff, and efflux from the Sacramento-San Joaquin Delta. Average annual loads and seasonal variations in loads were determined based on 2006-2011 data and recent POTW and refinery effluent characterization data that has been collected since July 2012 and covers a wide range of nutrient forms. For some POTWs and the Delta efflux, long-term trends in loads were also evaluated. Across all sources, the major nutrient forms considered were ammonium (NH_4^+), nitrate (NO_3^-), and dissolved inorganic phosphorous (DIP, largely present as HPO_4^{-2} at typical San Francisco Bay pH) due to data availability. Total-N and Total-P were considered where possible. Net nutrient loads to SFB from oceanic exchange through the Golden Gate are not included in this analysis, although this source may be important under some conditions, and is addressed in a separate report (Largier and Stacey, 2014). Direct atmospheric deposition of N to SFB's surface was assumed to be small relative to other sources and was not included in estimates. However, the loads resulting from atmospheric deposition to Bay Area

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

watersheds and the Central Valley were indirectly included through estimating fluvial loads from those sources. Insufficient information exists to constrain nutrient loads through groundwater inputs to the Bay; however, given the size of other sources, groundwater loads were also assumed to be small.

2. Methods

We estimated the following, according to the methods described in Sections 2.1-2.3:

1. Annual average current loads from all sources Bay-wide (using 2006-2011 data, as well as 2012 POTW and refinery effluent data)
2. Monthly average loads for all sources, compiled at the subembayments scale
3. Long-term time series of loads for select subembayments and sources (when sufficient data was available).

All load estimates made in this report are "end of the pipe", and do not consider mixing, transport, or transformation of nutrient loads once they enter SFB. Details of the SFB study area, including subembayment boundaries and characteristics, are shown in Figure 1 and Table 1.

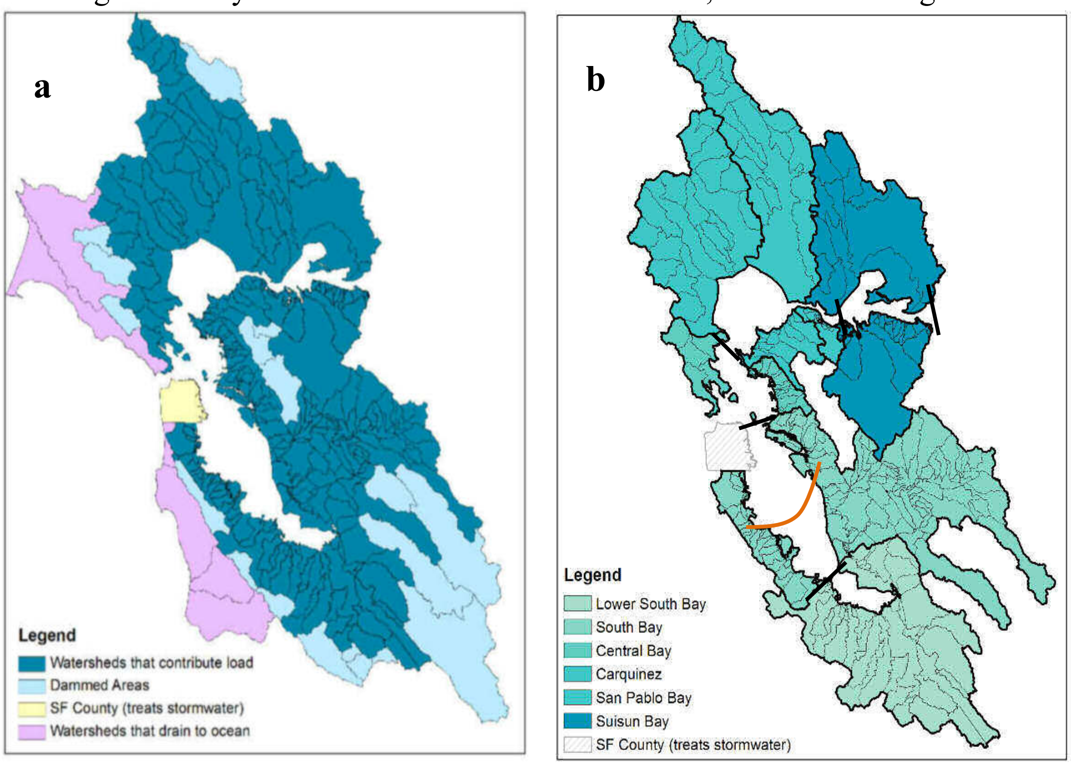

Figure 1 San Francisco Bay Study Area (a) A map of the entire Bay Area watershed, including watersheds that drain to the ocean (pink), watersheds that are dammed (light blue), San Francisco County (which treats stormwater along with wastewater, in yellow), and watersheds considered to contribute load to SF Bay (dark blue). (b) Watersheds that contribute load to SF Bay, with colors indicating the subembayment to which they contribute load. Subembayment classifications were based drainage of major hydrologic features into Bay segments as defined by SF Regional Water Quality Control Board, shown in black (San Pablo Bay and Carquinez Straits are combined, the boundary between shown as dotted line). The Regional Monitoring Program for SF Bay (RMP) agrees with the Water Board with the exception of the South Bay/Central Bay boundary (shown in orange)

Table 1 Relevant physical features of each subembayment. Subembayments are based on boundaries defined by the SF Regional Water Quality Control Board (with San Pablo Bay and Carquinez Strait combined for simplicity)

	Boundary	**Bay area[1] (km^2)**	**Sources considered**	**# POTWs[2] (% total flow Bay-wide)**	**Watershed area (sq. km)**	**% surface water[3]**	**% open[3]**	**% agriculture[3]**	**% commercial[3]**	**% industrial[3]**	**% residential[3]**	**% transportation[3]**
Lower South Bay	Below Dumbarton	30	POTW, stormwater	3 (24%)	1320	1%	37%	2%	11%	5%	30%	14%
South Bay	Dumbarton to Bay Bridge	460	POTW, stormwater	10 (33%)	1685	1%	55%	2%	8%	3%	21%	10%
Central Bay	Bay bridge to Richmond Bridge	200	POTW, stormwater	7 (17%)	255	1%	33%	0%	10%	4%	36%	16%
San Pablo Bay + Carquinez	Richmond Bridge to Benicia Bridge	310	POTW, refineries, stormwater	13 (13%)	2180	3%	42%	33%	3%	2%	13%	4%
Suisun Bay	Benicia Bridge to Mallard Island	100	POTW, refineries, stormwater, delta	4 (13%)	1465	4%	51%	18%	4%	2%	14%	7%

[1] Smith and Hollibaugh (2006)

[2] Number of POTWs that discharge to the Bay or one of its tributaries. Some subembayments may have additional POTWs that drain to different receiving waters

[3] Based on data from Association of Bay Area Governments (2000)

In general, data were most abundant for NH_4^+, NO_3^- and DIP; total nitrogen (TN) and total phosphorous (TP) were considered when possible. Throughout this report, NH_4^+ is used to refer to NH_3 and NH_4^+. At typical pH values for SFB, nearly all ammonia is expected to be present as NH_4^+ and nearly all DIP is expected to be present as HPO_4^{-2}. All loads are reported as kg d^{-1} N or P.

2.1 Annual average current loads from individual sources

2.1.1 POTWs and Refineries

42 POTWs and 6 refineries were considered (referred to collectively hereafter as dischargers). Approximate discharge locations are shown in Figures 2a and 2b.

Two main datasets were used in this report and were obtained through data collection that resulted from a 2012 order issued by the SFBRWQCB. To satisfy the first part of the order, dischargers submitted all available nutrient effluent data from 2004-2011. While 100% of dischargers monitored NH_4^+ during this time because of numeric permit limits, far fewer measured NO_3^- (n=17) or DIP (n=3) (Table 2). For the second part of the order, dischargers began a 2-year monitoring program (beginning July 2012) for multiple nutrient forms, including NH_4^+, NO_3^-, DIP, and total N and total P.

Table 2 provides an overview of data availability. Given that 2004-2011 data was not in a uniform format across all dischargers, and was of variable completeness, a rigorous analysis of that data was only performed for the largest dischargers to ensure that the majority of loads were being considered, based on the following criteria: three largest dischargers in each subembayments, and any additional dischargers necessary to cover 75% of effluent flow in each subembayment (based on combined POTW and refinery effluent flow). Loads from smaller dischargers were estimated based on an approach described below. In some cases multiple POTWs discharge to SFB through a single combined outfall (as noted in Table 2). In the case of the East Bay Dischargers Authority (EBDA), the combined flow rate and loads placed EBDA among the largest dischargers to the Bay, and, for the purposes of this report, the combined EBDA flows and loads were considered, as opposed to the individual POTWs.

Current loads were determined using both the 2012 and 2004-2011 datasets. At the time of this report's first draft, only 6 months of data (July-December 2012) were available; therefore only that subset of the data was used in load calculations. The full first year of data has since become available (see Appendix 4). Table A.4.3 summarizes differences between effluent concentrations and loads calculated based on 6 month and 12 month data for each individual POTW. While loads from some individual POTWs differed between the first 6 month averages and the full first year averages, the total POTW loads varied by less than 5% Bay-wide and by less than 10% in any individual subembayment. Therefore, load calculations presented in this report's figures and tables are based on the first 6 months of data. A brief analysis of year 1 data at a subset of POTWs is presented in Appendix 4.

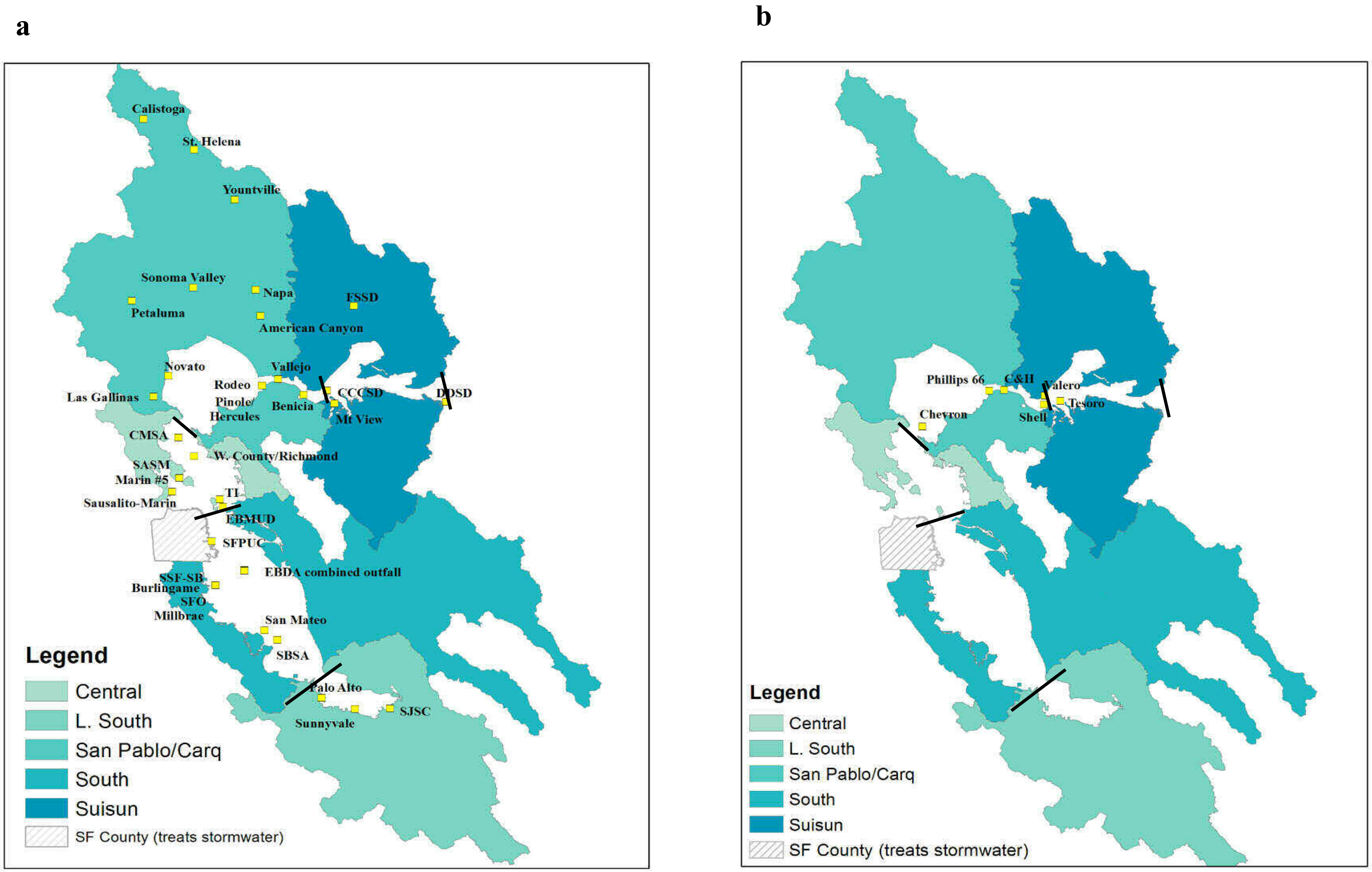

Figure 2 POTW (a) and Refinery (b) outfall locations in San Francisco Bay. Colors indicate to which subembayment watersheds contribute load, based on the boundaries of the SF Regional Water Quality Control Board (shown in black). See section 2.2 for a discussion of subembayment groupings. SF County, which treats stormwater with wastewater, is shown here for reference.

Table 2 Historic POTW and refinery data used in this report. This includes available nutrient data from 2004-2011 (submitted to the Water Board as part of a 2012 13267 order) as well as additional data directly requested for specific plants. Beginning in 2012, all plants began monitoring for NH_4^+, NO_3^- and DIP (among other nutrients). See section 2.2 for a discussion of subembayment groupings.

			Flow		NH_4^+		NO_3^-		DIP	
			Dates	# samples	Dates	# samples	Dates	# samples	Dates	# samples
Lower South Bay	Large dischargers	City of San Jose/City of Santa Clara (SJSC)	1957-2011	636	1965-2011	564	1975-2011	440	1974-2011	435
Lower South Bay	Large dischargers	City of Palo Alto	1994-2011	6326	1994-2011	845	1994-2011	220	1994-2011	204
Lower South Bay	Large dischargers	City of Sunnyvale	1988-2011	2648	1988-2011	2527	1988-2011	1237		
South Bay	Large dischargers	East Bay Dischargers Authority (EBDA) combined outfall[1]	1999-2011	4473	1999-2011	411				
South Bay	Large dischargers	City and County of SF-Southeast Plant (SFPUC)	1996-2011	5368	1996-2011	415	1996-2011	154	1996-2011	127
South Bay	Large dischargers	South Bayside System Authority (SBSA)	1990-2011	8033	1990-2011	1005				
South Bay	Large dischargers	City of San Mateo	1999-2011	2378	1996-1999 2008-2011	192 36				
South Bay	Large dischargers	Cities of South SF and San Bruno (SSF-SB)[2]	2004-2011	2922	2004-2011	2215				
South Bay	Large dischargers	City of Burlingame[2]								
South Bay	Large dischargers	City of Millbrae[2]								
South Bay	Large dischargers	San Francisco International Airport (SFO)[2]								
Central Bay	Large dischargers	East Bay Municipal Utility District (EBMUD)	1999-2011	4473	2007-2011	150				
Central Bay	Large dischargers	Central Marin Sanitation Agency (CMSA)	1998-2011	4932	1998-2011	708				
Central Bay	Large dischargers	West County/Richmond	2003-2011	2951	2008-2011	55				
Central Bay	Small dischargers	Sewage Agency of Southern Marin (SASM)[3]	Loads estimated using design flow and 2012 concentrations							
Central Bay	Small dischargers	Sausalito-Marin City Sanitation District								
Central Bay	Small dischargers	U.S. Department of Navy - Treasure Island								
Central Bay	Small dischargers	Sanitary District of Marin County #5[3]								
San Pablo Bay/Carquinez	Large dischargers	Napa Sanitation District	2000-2011	2311	2000-2011	149				
San Pablo Bay/Carquinez	Large dischargers	Vallejo Sanitation and Flood Control District	2000-2011	1654	2000-2011	1652	2000-2011	136		
San Pablo Bay/Carquinez	Large dischargers	Chevron, Richmond Refinery	2004-2009	1068	2004-2009	44				
San Pablo Bay/Carquinez	Large dischargers	Shell Oil, Martinez Refinery	1998-2011	4563	2004-2009	135	2004-2009	47		
San Pablo Bay/Carquinez	Large dischargers	Novato Sanitary District	2005-2011	878	2005-2011	272				
San Pablo Bay/Carquinez	Large dischargers	Sonoma Valley County Sanitation District	1996-2011	5844	1996-2011	808	1996-2011	802		
San Pablo Bay/Carquinez	Large dischargers	Conoco Phillips66 Rodeo Refinery	2004-2011	150	2004-2009	72	2007-2008	14		
San Pablo Bay/Carquinez	Large dischargers	City of Pinole/Hercules[4]	2002-2011	104	2002-2011	62	2007-2009	26		
San Pablo Bay/Carquinez	Small dischargers	City of Petaluma	Loads estimated using design flow and 2012 concentrations							
San Pablo Bay/Carquinez	Small dischargers	City of Benicia								
San Pablo Bay/Carquinez	Small dischargers	City of American Canyon								
San Pablo Bay/Carquinez	Small dischargers	Rodeo Sanitary District[4]								
San Pablo Bay/Carquinez	Small dischargers	Valero, Benicia Refinery								
San Pablo Bay/Carquinez	Small dischargers	Las Gallinas Valley Sanitary District								
San Pablo Bay/Carquinez	Small dischargers	C&H Sugar Company								
San Pablo Bay/Carquinez	Small dischargers	City of Calistoga								
San Pablo Bay/Carquinez	Small dischargers	Town of Yountville								
San Pablo Bay/Carquinez	Small dischargers	City of St. Helena								

Table 2 (continued)

			Flow		NH_4^+		NO_3^-		DIP	
			Dates	# samples	Dates	# samples	Dates	# samples	Dates	# samples
Suisun Bay	Large dischargers	Central Contra Costa Sanitary District (CCCSD)	1975-2011	10374	1975-2011	10293	1993-2011	927		
		Fairfield-Suisun Sewer District (FSSD)	2004-2011	1204	2004-2077	373	2004-2011	315		
		Delta Diablo Sanitation District (DDSD)	1991-2011	252	1992-1993 2007-2011	179 47	1992-1993 2007	179 5		
		Tesoro, Golden Eagle Refinery	2000-2011	3960	2000-2011	164				
	Small dischargers	Mt. View Sanitary District	Loads estimated using design flow and 2012 concentrations							

While estimated discharger loads based on the 6 months of 2012 effluent data are accompanied by fairly low uncertainty, there was considerable uncertainty about how well those loads apply to previous time periods or under other conditions (e.g., low, medium, and high flow). To address this uncertainty, loads were also computed using the latest five years (2006-2011) of the 2004-2011 data. While this dataset was less complete in terms of parameters measured, it represented a much longer record. Depending on data availability, a time series of load estimates was made for 2006-2011 in one of the following two ways:

1. For analytes actually measured during 2006-2011, paired flow and concentration data from a given sampling event were combined to calculate loads:
$$Load_{date=i(2006-2011)} = Flow_{date=i(2006-2011)} * Concentration_{date=i(2006-2011)}$$
This calculation was mainly limited to NH_4^+, except for the few dischargers that also measured NO_3^- and DIP.

2. For analytes not measured during 2006-2011, average concentrations determined from the 2012 dataset were combined with actual flows during that time period to calculate loads:
$$Load_{date=i(2006-2011)} = Flow_{date=i(2006-2011)} * Concentration_{2012}$$

The latter calculation introduces uncertainty related to how representative the 2012 dataset is as an average for the period 2006-2011, recognizing that the analyte's concentration may have varied among the sampling events during 2006-2011, either due to changes in operation or seasonal changes. Certain special cases arose in which a major treatment change occurred between 2006 and 2012 that made the above approach inappropriate. Revised estimates for these plants were dealt with on a case-by-case basis as noted in the Results.

Rather than develop individual time-series of loads from smaller dischargers, loads were assumed constant and were estimated as:
$$Load = \tfrac{2}{3} Q_{design} * Concentration_{2012}$$

This method assumes that plants generally operate at two-thirds of their design capacity, and that 2012 concentrations were representative of typical conditions at this plant. Any uncertainty introduced by this estimation method, while potentially large for an specific POTW, is likely to be inconsequential to overall loads given the relative importance of these smaller dischargers.

2.1.2 Stormwater

The data available to estimate stormwater loads is much more limited than what was available for estimating POTW and refinery loads, and the relative uncertainties in the stormwater estimates are expected to be larger. Stormwater loads were calculated using the Regional Watershed Spreadsheet Model (RWSM) (Mckee and Lent 2011; Lent 2012) , which is under development by the San Francisco Estuary Institute (SFEI) and the Regional Monitoring Program (RMP) in coordination with the Bay Area Stormwater Management Agencies Association (BASMAA) to quantify stormwater loads of contaminants of concern to SFB. The spreadsheet model is designed to estimate runoff and loads on an annual basis, and is currently being calibrated for several contaminants (Cu, PCBs, Hg). While the RWSM has not yet been calibrated for nutrient loads, it was selected because it has appropriate spatial resolution for subembayment analysis, is sensitive to land-use (a major driver of watershed loads), and it is currently the best readily-available tool for generating order-of-magnitude estimates.

The RWSM combines land-use, soil type, slope, rainfall, and land-use specific nutrient concentrations to compute nutrient loads from 331 distinct watersheds. The model does not consider watersheds that contribute to dammed regions, watersheds that drain to the ocean, or watersheds in San Francisco County, which treats stormwater along with wastewater (Figure 1a). A schematic of the calculation, including input data sources is shown in Figure 3. The input precipitation dataset was an annual average of 1971-2000. The land-use specific nutrient concentrations used were the geometric means of 1-5 literature values for each nutrient form within 5 land-use categories (residential, commercial, industrial, transportation, open and agriculture; Table 3). For both NH_4^+ and NO_3^-, the agriculture runoff concentrations used were 3-10 times higher than those for other land-uses. The variability among the literature values was small (NO_3^- = 10, 7.3, 9.8 mg L^{-1}; NH_4^+ = 1.3, 1.1 mg L^{-1}). The type of agricultural practices may be quite different in these Bay area watersheds than in those from which the literature values were derived, and the stormwater loads should be critically evaluated. However, these agriculture runoff concentrations may not be unreasonable, considering that they are only 3-fold higher than has been measured in limited wet season sampling in Napa River and Sonoma Creek and their tributaries, downstream of mixed land-uses (McKee and Krottje 2005), and are within the range of values measured in runoff from vineyards in Australia (Cox 2012) and Spain (Ramos and Martinez-Casasnovas 2006).

Direct POTW discharges into tributaries were accounted for within the POTW loads, and were not considered stormwater loads.

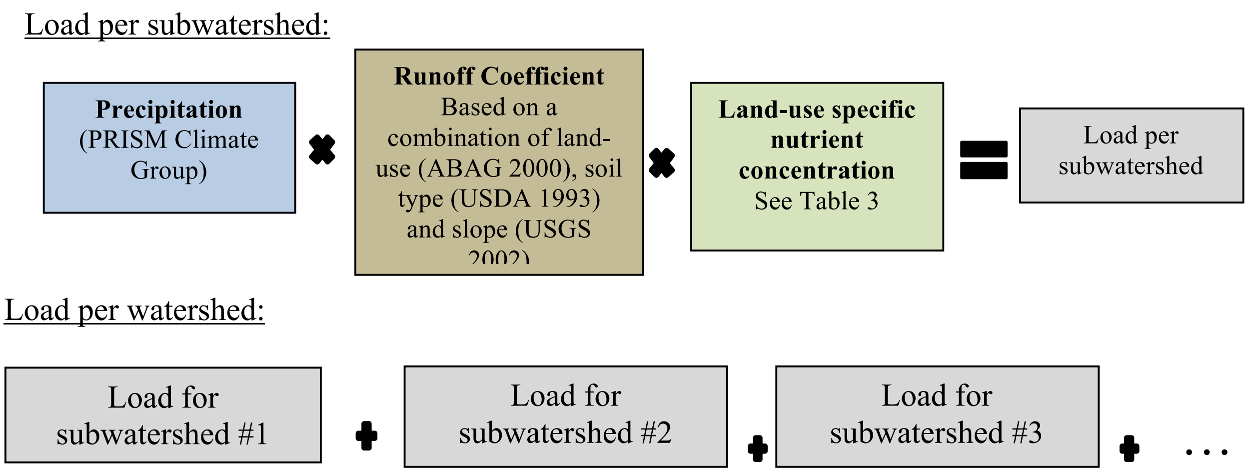

Figure 3 A schematic of the Regional Watershed Spreadsheet Model, the tool used to estimate stormwater nutrient loads. Several publicly available datasets were used as input variables to this model, including rainfall data from the PRISM Climate Group, land-use data from Association of Bay Area Governments (ABAG), soil data from USDA, slope data from USGS and nutrient concentration data from a variety of literature sources (see Table 3).

Table 3 Land-use specific nutrient concentration values (mg/L) used in the Regional Watershed Spreadsheet model. Values used were the geometric mean of values from the indicated literature sources. No DIP value was available for transportation, so TP was used.

	NH_4^+		NO_3^-		DIP	
	Value used	# Literature values available	Value used	# Literature values available	Value used	# Literature values available
Open	0.1	3[3,5,6]	0.3	5[1,2,3,5,6]	0.1	2[1,5]
Agriculture	1.3	2[3,6]	8.9	3[2,36]	0.6	2[2,3]
Commercial	0.4	2[3,6]	0.6	5[1,2,3,4,6]	0.5	3[1,2,3]
Industrial	0.3	2[3,6]	0.5	4[2,3,4,6]	0.4	2[2,3]
Residential	0.4	1[3]	0.7	4[1,2,3,4]	0.4	4[1,2,3,4]
Transportation	0.2	1[6]	0.4	1[6]	0.4	1[6]

Literature Referenced:

[1] Woodward-Clyde, 1991a
[2] Davis 2000
[3] Ackerman and Schiff 2003
[4] Sengupta 2013
[5] Yoon and Stein 2007
[6] Willardson 2008

2.1.3 Delta load approach

Suisun Bay and other down-estuary embayments are directly affected by loads flowing from the Sacramento-San Joaquin Delta. Although these loads have the potential to be substantial, no seasonally- or temporally-varying load estimates were available. To address this data gap, we developed monthly time-series of NH_4^+, NO_3^-, and DIP loads to Suisun Bay from the Delta, following an approach similar to that used by Jassby and Cloern (2000) to estimate organic matter loads from the Delta. The approach combines daily flow estimates at Rio Vista (Q_{rio}) and Twitchell Island (Q_{west}) (DAYFLOW[3]) and water quality data from nearby long-term monitoring stations (DWR[4], USGS[5]) to estimate nutrient loads (Figure 4, Appendix 2). The stations used by Jassby and Cloern (2000) were not operational after 1995, so we substituted nearby operational stations to estimate loads from 1996-2011. All stations used in load calculations were between 10km and 30km upstream from Suisun Bay and it is possible for nutrient concentrations and loads to change along this distance due to transformation or loss. To explore the sensitivity of load estimates to station location, we calculated loads using both these upstream stations and one closer to the mouth of Suisun Bay for a period when data were available at both sites. While some amount of conversion of NH_4^+ to NO_3^- occurs along this distance, overall computed DIN and DIP loads differed negligibly between these two locations (Figure A.2.3). NH_4^+ and DIP were measured at all water quality stations used in the calculations. For NO_3^-, however, the reported data is actually nitrate + nitrite (NO_2^-) for most dates. For dates when nitrite was also measured it accounted for <5% of $NO_3^- + NO_2^-$, so $NO_3^- + NO_2^- \sim NO_3^-$ is a reasonable assumption. Load estimates for 2006-2011 were averaged for comparison to annual averages from other sources. However, flow and loads from the Delta exhibited intense seasonality, and seasonally- or monthly-averaged results more accurately reflect the magnitude of the Delta loads relative to other loads (see Section 2.2).

[3] http://www.water.ca.gov/dayflow/

[4] http://www.water.ca.gov/bdma/meta/Discrete/data.cfm

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

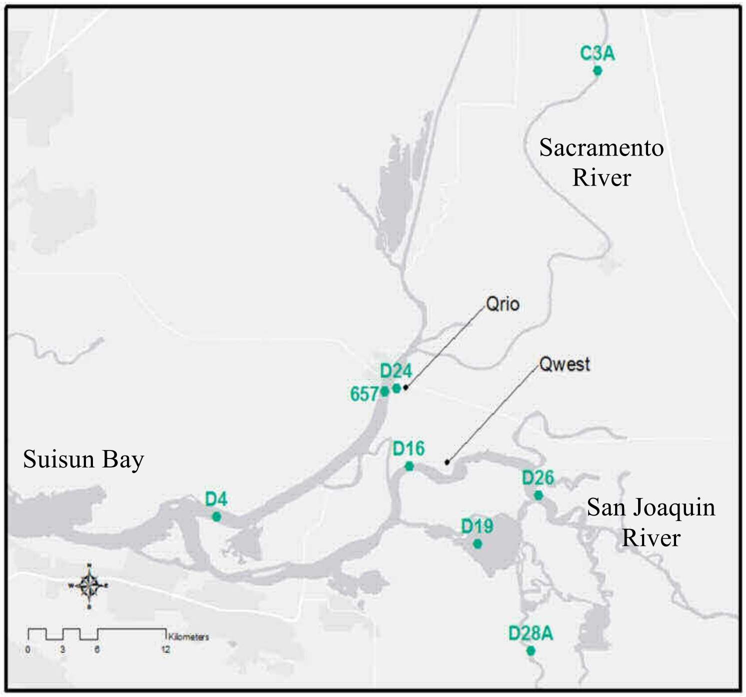

Figure 4 Flow and water quality stations used to calculate efflux loads from the Sacramento-San Joaquin Delta into Suisun Bay. Flow values (Q_{rio}, Q_{west}) were multiplied by water quality data from surrounding IEP or USGS monitoring stations (indicated by green dots) to estimate load. Detailed explanation of this method can be found in Appendix 2

2.2 Spatial, seasonal, and temporal load variability

To evaluate the seasonal variability and relative importance of nutrient sources, loads from each source type were averaged by month over the period 2006-2011 and combined within each of 5 subembayments based on discharge location. The subembayment boundaries used in this report coincide with those used by SFBRWQCB (Figure 1, Table 1):

- *Suisun Bay*: Mallard Island to Benicia-Martinez Bridge
- *Carquinez Strait/ San Pablo Bay*: Benicia-Martinez Bridge to Richmond Bridge
    - These two regions were combined for simplicity. Loads discharged into Carquinez Strait are assumed to, on average, be transported downstream to San Pablo Bay.
- *Central Bay*: Richmond Bridge to Bay Bridge
- *South Bay:* Bay Bridge to Dumbarton Bridge
- *Lower South Bay:* South of the Dumbarton Bridge

Although the boundaries are the same as those used by the SFBRWQCB, the names assigned here for subembayments south of the Bay Bridge differ from the SFBRWQCB names. Locations of POTW and refinery discharges relative to these boundaries are shown in Figures 2a and 2b. Watersheds were attributed to one of these subembayments based on drainage of major hydrologic features (Figure 1b).

This grouping into subembayments is an approximation, used to allow the relative importance of load categories to be assessed on monthly time scales. Other boundaries could have been used. For example, the Regional Monitoring Program (RMP) for San Francisco Bay defines Bay segments differently (Lowe 2005) based on a statistical analysis of field data and expert opinion. Lowe (2005) also acknowledges that boundary locations may vary depending on the substance of interest or by season. To assess the sensitivity of interpretations to the set of boundaries selected, we also evaluated the importance of load sources when the RMP boundaries were used. While changing the boundaries shifts the segments to which some sources are assigned, it does not substantially influence interpretations about the relative importance of loads (see Section 4.3). Appropriate boundaries for on-going nutrient studies have not yet been determined. The most appropriate or meaningful set of boundaries – and the acceptable degree of resolution vs. aggregation within subembayments - will depend on the specific science or management questions being addressed, and hydrodynamic and reactive-transport models will be needed both to help determine those boundaries and quantify or interpret processes within those boundaries.

The subembayment-scale seasonal analysis focused primarily on direct loads to subembayments (Table 1), including POTWs discharging to tributaries that drain to a subembayment. Exchange between subembayments was not considered because of the Bay's complex hydrodynamics precluded reasonable estimates; the one exception is exchange from Suisun Bay to San Pablo Bay (see Section 3.2.4). To assess seasonal variability in POTW and refinery contributions, NH_4^+, NO_3^-, and DIP loads from all dischargers (both small and large) were averaged by month and combined by subembayment. For the larger POTWs, the 2006-2011 load estimates were calculated as described in Section 2.1.1 and averaged by month. The estimation method for smaller dischargers assumed constant loads throughout the year, which is unlikely to substantially influence estimates given both the relative importance of their loads and the fact that POTW and refinery loads appear are to be relatively constant (compared to stormwater or loads from the Delta). Monthly stormwater nutrient loads were estimated by distributing the RWSM's annual nutrient loads over the year in proportion to the monthly distribution of rainfall (Western Regional Climate Center 2006). These monthly estimates were therefore dependent only on variation in rainfall, and do not account for baseline tributary flow during months of no precipitation, and also are not sensitive to seasonally-varying nutrient abundance or nutrient leachability at the source (e.g., differences in fertilizer application, tiling practices). Watersheds were assigned to subembayments based on drainage of major hydrologic features in each watershed, and loads were aggregated by subembayment (Figure 1b). Land-use within subembayments is shown in Figure 5. Finally, Delta load estimates were calculated on a monthly basis as described above for 2006-2011, and then averaged across years.

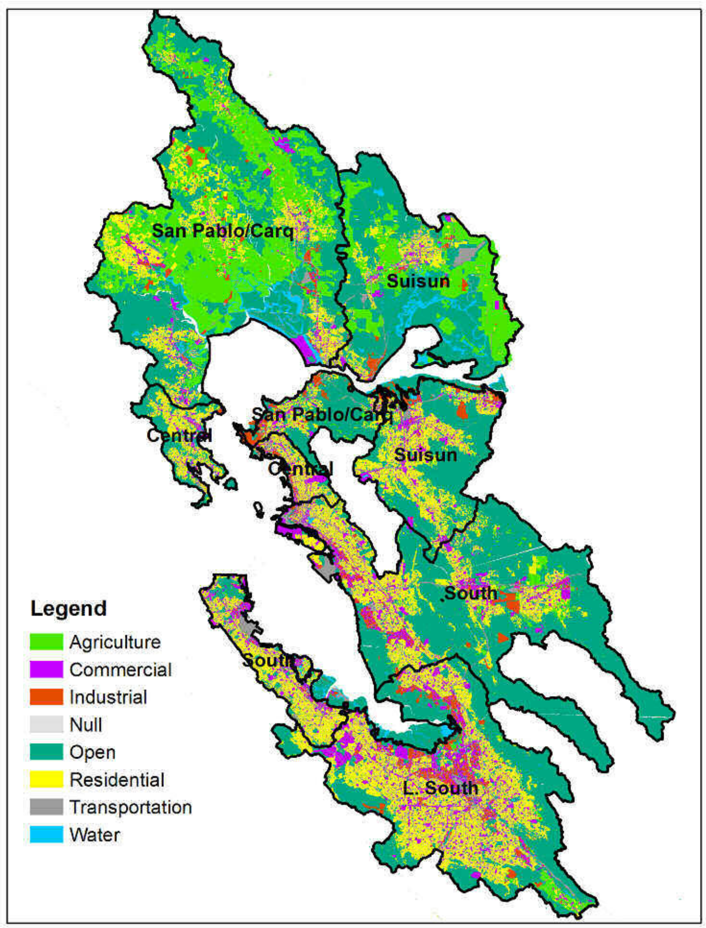

Figure 5 Land-use in watersheds that contribute load to San Francisco Bay, based on data from the Association of Bay Area Governments (2000). High frequency of agricultural activity in San Pablo Bay/Carquinez watersheds may explain high, calculated stormwater loads for that region.

2.3 Long term trends in loads

Nutrient loads were also estimated over longer time periods for Lower South Bay (3 POTWs) and Suisun Bay (3 POTWs plus Delta loads), and for 3 other large POTWs (EBDA combined outfall, EBMUD, SFPUC). Up to 30 years of data were used for some POTWs, but in some cases only NH_4^+ loads could be calculated during this period. For Delta efflux, sufficient data existed to develop load time series for NH_4^+, NO_3^-, and DIP back to 1975.

3. Results

3.1 Bay-wide annual average loads

Current load estimates for POTWs and refineries are summarized in Table 4 and Table 5, respectively. For certain large dischargers, major plant upgrades occurred between 2006 and 2012 and standard methods described in Section 2.1.1 were adjusted accordingly based on conversations with plants managers (as noted in Table 4).

San Francisco Bay has 42 POTWs that discharge approximately 500 MGD of treated effluent either directly to the Bay or to receiving waters in adjacent watersheds that drain to the Bay (Figure 2a; not including discharges east of Suisun Bay that enter through the Delta). While several POTWs carry out nitrification (conversion of $NH_4^+$to NO_3^-), or further advanced treatment (e.g., biological nitrogen removal) to remove a portion of nutrients prior to discharge, most POTWs only employ secondary treatment, which generally removes little N or P. Bay-wide, POTWs discharge (annual average) 34300 kg d^{-1} NH_4^+, 11500 kg d^{-1} NO_3^-, and 3900 kg d^{-1} DIP (Table 6). Although SFB's large area, multiple subembayments, and complex hydrodynamics place practical limits on the interpretability of Bay-wide loads, they are nonetheless informative as a broad overview.

The 5 largest POTWs (EBMUD, EBDA combined outfall, SFPUC, SJSC, CCCSD) accounted for approximately 75% of NH_4^+ loads, 50% of NO_3^- loads and 45% of DIP loads from all POTWs Bay-wide. NH_4^+ was the dominant form of DIN discharged Bay-wide, although NO_3^- was the dominant form for several POTWs who nitrify effluent prior to discharging. The 6 months of detailed effluent characterization data from POTWs showed that 89% of total-N was being discharged as dissolved inorganic nitrogen (NH_4^++NO_3^-) and 78% of total-P was discharged as DIP. [DIN]:[DIP] was highly variable among POTWs.

Loads estimated based on the 2006-2011 and 2012 datasets agreed reasonably well (Table 4). The 2012 data was much more complete in terms of nutrient forms analyzed, and the weaker coverage of NO_3^- and DIP in the 2006-2011 dataset limited the number of comparisons that could be made. Data was most plentiful for NH_4^+. Loads agreed best when the dominant form of N in effluent was compared (i.e., NO_3^- vs. NH_4^+), and, not surprisingly, less well for the minor form of N.

Bay-wide, NH_4^+ accounted for approximately 75% of total DIN loads in both the 2012 dataset and the 2006-2011 when both NH_4^+ and NO_3^- data were available (Table 4). On average, DIN comprised 89% ± 12% of TN loads and DIP comprised 78% ± 16% of TP loads, based on the 2012 dataset in which TN and TP were measured by all plants. Several plants reported more DIP than TP in effluent (compared to only one plant that reported more DIN than TN in effluent). (Note: The instances in which DIN or DIP represented greater than 100% of TN or TP were removed when calculating the above means and standard deviations).

[DIN]:[DIP] varied substantially among POTWs (Table 4). The variability was generally due to large differences in DIP concentrations, as opposed to large variations in DIN concentrations. Thus, historical DIP load estimates, if based on either best engineering estimates of DIP concentration or [DIN]:[DIP], will have large uncertainties, unless those estimates can be constrained using newly collected data (assuming plant operation has not changed) or existing historic data that has not yet been evaluated.

Loads from 6 refineries, located in Suisun and San Pablo Bays, were also quantified based on effluent data (Table 5). The total load from these refineries was estimated to be 970 kg d^{-1} DIN and 70 kg d^{-1} DIP. Most refinery loads (in terms of DIN and DIP) were small compared to POTW loads, although the Chevron refinery loads cannot be readily dismissed relative to POTW load in San Pablo Bay/Carquinez. This is in part due to the relatively low direct POTW nutrient loads to San Pablo Bay. It is difficult to say if the relatively high NO_3^- effluent concentrations in 2012 (used to fill 2006-2011 data gap) are representative of typical Chevron plant operations, given the recent accident at this refinery and lack of historical data for comparison. Refinery DIP concentrations tended to be lower than those of POTWs, while DIN concentrations were comparable to POTWs, leading to high DIN:DIP in refinery discharges. DIN accounted for 82% ± 15% of refinery TN loads, and DIP accounted for 52% ± 30% of refinery TP loads.

Annual-average stormwater loads to the Bay were estimated to be 10800 kg d^{-1} DIN, mostly as NO_3^-, and 1300 kg d^{-1} of DIP (Table 6). The load magnitudes varied substantially on a seasonal basis and are best evaluated in a seasonal context (see Section 3.2). The calculated nutrient yields (kg d^{-1} m^{-2}) from individual watersheds showed strong spatial variation (Figure 6), with moderate yields from high-density residential areas, and the highest yields from agriculturally-dominated areas draining to San Pablo and Suisun Bays. As a result, the majority of the estimated stormwater nutrient loads, especially DIN, came from watersheds draining into San Pablo Bay and Suisun Bay. As noted in Section 2.1.2, because of uncertainty around the land-use specific nutrient concentrations used, these stormwater loads need to be critically evaluated.

Freshwater entering Suisun Bay from the Delta delivered substantial nutrient loads to SFB. Annual average loads were 5800 kg d^{-1} NH_4^+, 10400 kg d^{-1} NO_3^-, and 240 kg d^{-1} DIP (Table 6). As with stormwater, these loads exhibited strong seasonal and interannual variability and are best evaluated in a seasonal context (see Section 3.2.5)

Table 4 A summary of POTW loads. All values are kg d^{-1} N or P. Loads from small POTWs (shaded grey) were always calculated using two-thirds design flow and 2012 concentration data. Loads from large POTWs were calculated for both the 2006-2011 dataset and the 2012 dataset. Where needed, data gaps in the 2006-2011 dataset were filled using 2012 data (shaded purple). Deviations from these methods were necessary for certain plants and are noted above. See section 2.2 for a discussion of subembayment groupings.

		Flow (MGD)		NH_4^+ (mg L^{-1})		NH_4^+ (kg d^{-1})		NO_3^- (mg L^{-1})		NO_3^- (kg d^{-1})		DIN (kg d^{-1})		DIP (mg L^{-1})		DIP (kg d^{-1})		[DIN]:[DIP]		DIN/TN (%)	DIP/TP (%)
		2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2012	2012
Lower South Bay	SJSC	102	92	0.6	0.8	241	277	10.0	11.3	3860	3930	4101	4207	0.7[1]	0.4	215[1]	159	15	28	93%	72%
	Palo Alto	23	22	0.8	0.1	69	12	22.7	26.4	1953	2156	2022	2168	4.2	4.2	359	338	6	6	97%	96%
	Sunnyvale	12	10	2.2	7.2	114	371	12.4	18.3	568	629	682	1000	6.7[2]	6.7	184[2]	244	2	4	93%	96%
South Bay	EBDA combined outfall[3]	69	67	24.8	27.5	6275	6919	2.3	2.3	611	617	6886	7536	1.7	1.7	436	407	16	18	90%	71%
	SFPUC	58	54	34.0	34.5	7386	7032	0.8	1.8	188	357	7574	7389	1.9	1.4	420	291	18	25	93%	140%
	SBSA	16	13	32.0	40.1	1886	2036	0.6	0.6	34	30	1920	2066	4.0	4.0	243	202	8	10	98%	115%
	San Mateo	13	11	18.7[4]	29.2	906[4]	1160	1.6[4]	1.6	80[4]	79	986[4]	1239	2.6[4]	2.6	129[4]	106	8	12	91%	88%
	SSF-SB	9	9	29.8	29.4	1041	1015	1.9	1.9	67	65	1108	1080	3.0	3.0	106	101	11	10	93%	73%
	Burlingame	4		22.7		315		4.5		63		378		2.5		34		11		84%	46%
	Millbrae	2		39.2		297		0.1		1		298		2.6		20		15		94%	82%
	SFO	2		40.5		230		3.8		21		251		2.3		13		19		85%	94%
Central Bay	EBMUD	69	65	35.3	35.2	8510	8088	4.5	4.5	1165	1074	9675	9162	2.9	2.9	760	695	14	14	89%	67%
	CMSA	10	9	26.4	32.2	775	825	2.9	2.9	105	90	880	915	3.3	3.3	120	111	9	10	96%	119%
	West County/Richmond	11	8	13.2	20.9	581	571	3.2	3.2	130	114	711	685	1.6	1.6	65	47	10	15	92%	88%
	SASM	2		3.7		34.0		15.8		144		178		4.4		40		4		89%	90%
	Sausalito	1		8.8		40		12.2		56		96		3.6		16		6		90%	83%
	Treasure Island	1		0.4		2		7.4		36		38		3.1		15		3		71%	137%
	Marin District 5 (Tiburon)	1		21.0		52		0.5		1		53		2.5		6		9		91%	69%

[1] San Jose upgraded DIP treatment in 2007 so historic analysis was limited to 2007-2011

[2] Sunnyvale dredged nitrification ponds in early 2012 and 2012 DIP levels may be artificially high. DIP loads were calculated using 2006-2011 flow, 2006-2011 TP and DIP:TP from 2012

[3] Includes EBDA member agencies (Hayward, Oro Loma, Castro Valley and San Leandro, and Union Sanitary District), as well as Dublin-San Ramon Services District and the City of Livermore

[4] San Mateo changed sludge operations in 2009 and recommended restricting historical analysis to 2009-2011

Table 4 (con't)

		Flow (MGD)		NH_4^+ (mg L^{-1})		NH_4^+ (kg d^{-1})		NO_3^- (mg L^{-1})		NO_3^- (kg d^{-1})		DIN (kg d^{-1})		DIP (mg L^{-1})		DIP (kg d^{-1})		[DIN]:[DIP]		DIN/TN (%)	DIP/TP (%)
		2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2012	2012
San Pablo and Carquinez	Napa	13	16	4.2[5]	2.2	192[5]	137	6.3[5]	6.3	361[5]	371	553[5]	508	1.1[5]	1.1	61[5]	63	10	8	79%	80%
	Vallejo	11	12	11.9	9.3	462	392	7.2	7.0	281	307	743	699	2.7	2.7	111	108	7	6	87%	84%
	Novato	5	5	4.5	0.2	89	4	11.0	11.0	225	193	314	197	0.4	0.4	8	7	39	31	90%	60%
	Sonoma	3	5	0.3	0.2	4	5	22.6	13.5	253	188	257	193	2.6	2.6	34	43	9	5	93%	105%
	Pinole/Hercules	3	3	15.1	22.8	178	243	7.0	7.0	87	74	265	317	3.2	3.2	40	34	7	9	92%	100%
	Petaluma	3		0.4		6		1.0		14		20		2.4		32		1		45%	84%
	Benicia	3		25.0		284		0.9		11		295		2.8		32		9		110%	82%
	American Canyon	3		0.3		3		9.6		97		100		3.8		38		3		91%	80%
	Rodeo	1		2.5		7		11.2		30		37		3.7		10		4		92%	97%
	Las Gallinas	2		2.7		20		20.3		150		170		3.6		27		6		95%	85%
	Calistoga	1		2.8		6		11.0		23		29		2.2		5		6		95%	96%
	Yountville	0		6.3		9		13.0		18		27		3.0		4		7		97%	96%
	St. Helena	0		8.3		10		0.1		1		11		3.1		4		3		44%	32%
Suisun Bay	CCCSD	41	37	21.9	25.1	3282	3435	1.1	1.0	155	155	3437	3591	0.5	0.5	79	72	46	50	92%	56%
	FSSD	15	14	0.1[6]	0.0	7[6]	2	16.5[6]	27.7	896[6]	1416	903[6]	1418	3.9[6]	3.9	213[6]	191	2	7	98%	92%
	DDSD	9	7	32.1	27.8	1049	693	1.8	36.3	54	895	1103	1588	0.8	0.8	26	20	42	81	100%	57%
	Mt View	2		0.6		5		21.3		170		175		3.6		29		6		97%	140%

[5] Napa began denitrification in 2010 so historical analysis was limited to 2010-2011

[6] Fairfield-Suisun began sludge recycling in 2010 so historical analysis was limited to 2010-2011

Table 5 A summary of refinery loads. All values are kg d^{-1} N or P. Loads from small refineries (shaded grey) were always calculated using two-thirds design flow and 2012 concentration data. Loads from large refineries were calculated for both the 2006-2011 dataset and the 2012 dataset. Where needed, data gaps in the 2006-2011 dataset were filled using 2012 data (shaded purple). See section 2.2 for a discussion of subembayment groupings.

		Flow (MGD)		NH_4^+ (mg L^{-1})		NH_4^+ (kg d^{-1})		NO_3^- (mg L^{-1})		NO_3^- (kg d^{-1})		DIN (kg d^{-1})		DIP (mg L^{-1})		DIP (kg d^{-1})		[DIN]:[DIP]		DIN/TN (%)	DIP/TP (%)
		2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2006-2011	2012	2012	2012
San Pablo and Carquinez	Chevron	8	6	0.5	0.7	11	12	14.7	14.7	433	330	342	342	1.8	1.8	54	60	8	6	87%	75%
	Shell	6	6	1.6	2.5	37	51	3.5	2.5	75	65	116	120	<0.1	<0.1	0.2	0.2	> 50	>50	79%	8%
	Phillips 66	4	3	0.5	0	8	0	12	23.3	130	225	225	237	0.4	0.4	5	4	31	58	96%	61%
	Valero	2		0.3		3		20.8		154		157		<0.1		1		>200		93%	20%
	C&H	1		4.7		17		2.9		10		27		1.4		5		5		52%	66%
Suisun Bay	Tesoro	4	4	6.9	4.4	116	84	0.8	0.8	14	15	130	99	0.1	0.1	1	1	77	52	87%	84%

Table 6 Annual average loads by subembayment (and Bay-wide) and source for the period 2006-2011. All loads are in kg d^{-1} N or P. Loads exchanged from Suisun Bay to San Pablo Bay/Carquinez are not included here, but are estimated to be approximately 4000 kg d^{-1} NH_4^+, 17000 kg d^{-1} NO_3^- and 2500 kg d^{-1} DIP. See section 2.2 for a discussion of subembayment groupings.

		NH_4^+					NO_3^-					DIN					DIP				
		POTW	Refinery	Storm-water	Delta	Total	POTW	Refinery	Storm-water	Delta	Total	POTW	Refinery	Storm-water	Delta	Total	POTW	Refinery	Storm-water	Delta	Total
LSB	Jan avg	637	n/a	399	n/a	1036	5517	n/a	914	n/a	6431	6154	n/a	1313	n/a	7467	865	n/a	496	n/a	1361
	Jul avg	250	n/a	2	n/a	252	3473	n/a	4	n/a	3477	3723	n/a	6	n/a	3729	717	n/a	2	n/a	719
	Annual avg	**424**	**n/a**	**164**	**n/a**	**588**	**6381**	**n/a**	**375**	**n/a**	**6756**	**6805**	**n/a**	**539**	**n/a**	**7344**	**758**	**n/a**	**203**	**n/a**	**961**
South	Jan avg	17788	n/a	486	n/a	18274	1182	n/a	1149	n/a	2331	18970	n/a	1635	n/a	20605	1513	n/a	599	n/a	2112
	Jul avg	18032	n/a	2	n/a	18034	912	n/a	6	n/a	918	18944	n/a	8	n/a	18952	1297	n/a	3	n/a	1300
	Annual avg	**18336**	**n/a**	**199**	**n/a**	**18535**	**1065**	**n/a**	**471**	**n/a**	**1536**	**19401**	**n/a**	**670**	**n/a**	**20071**	**1401**	**n/a**	**145**	**n/a**	**1546**
Central	Jan avg	10368	n/a	135	n/a	10503	1976	n/a	253	n/a	2229	12344	n/a	388	n/a	12732	1228	n/a	178	n/a	1406
	Jul avg	9469	n/a	1	n/a	9470	1373	n/a	1	n/a	1374	10842	n/a	2	n/a	10844	846	n/a	1	n/a	847
	Annual avg	**9998**	**n/a**	**55**	**n/a**	**10053**	**1669**	**n/a**	**104**	**n/a**	**1773**	**11667**	**n/a**	**159**	**n/a**	**11826**	**1031**	**n/a**	**73**	**n/a**	**1104**
San Pablo/ Carq	Jan avg	1319	74	2589	n/a	3982	1594	970	15653	n/a	18217	2913	1044	18242	n/a	22199	443	71	1520	n/a	2034
	Jul avg	938	47	11	n/a	996	335	690	75	n/a	1100	1273	737	86	n/a	2096	199	49	7	n/a	255
	Annual avg	**1149**	**88**	**1062**	**n/a**	**2299**	**1080**	**754**	**6422**	**n/a**	**8256**	**2229**	**842**	**7484**	**n/a**	**10555**	**324**	**60**	**623**	**n/a**	**1007**
Suisun	Jan avg	4903	386	774	11687	17750	1279	19	4023	18313	23634	6182	405	4797	30000	41384	430	2	576	1556	2564
	Jul avg	3892	4	3	2632	6531	1100	11	19	3443	4573	4992	15	22	6075	11104	303	1	2	231	537
	Annual avg	**4343**	**116**	**317**	**5808**	**10584**	**1275**	**14**	**1651**	**10376**	**13062**	**5618**	**130**	**1968**	**15930**	**23646**	**347**	**1**	**236**	**949**	**1533**
Bay-wide total		**34250**	**204**	**1797**	**5808**	**42059**	**11470**	**768**	**9023**	**10376**	**31637**	**45720**	**972**	**10820**	**16484**	**73996**	**3861**	**61**	**1280**	**949**	**6151**

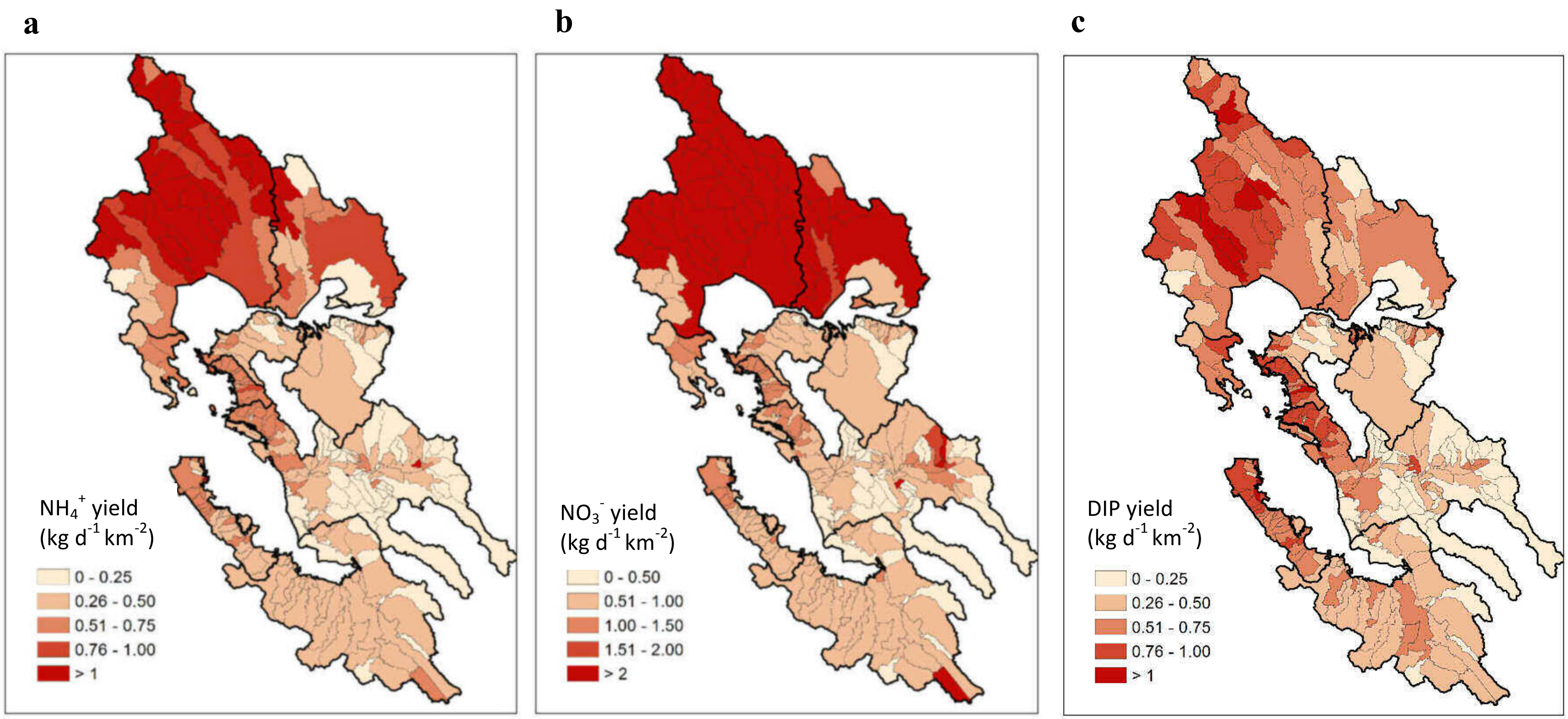

Figure 6 January stormwater nutrients yields for NH_4^+ (a), NO_3^- (b), and DIP (c) (load per km^2). January is the region's highest precipitation month when calculated stormwater loads are at a maximum. Note the different scale in Figure 6b.

3.2 Subembayment-scale loads across all sources

To evaluate seasonal and spatial variability in nutrient loads, load estimates across all sources (POTWs, refineries, stormwater, Delta) were combined and compared within 5 subembayments (Figure 2). These estimates are combined "end-of-the-pipe" loads, and do not consider mixing, or transformations of nutrients once entering the Bay, or loads due to exchange between subembayments (except for San Pablo Bay).

3.2.1 Lower South Bay

Annual averages

POTWs were the predominant source of DIN and DIP loads to Lower South Bay year-round, with SJSC accounting for ~60% of POTW loads (Table 4, Table 6). Unlike other subembayments, DIN loads from POTWs to Lower South Bay were predominantly in the form of NO_3^- (90%), as opposed to NH_4^+, because the POTWs there nitrify effluent prior to discharge (Sunnyvale's nitrification efficiency varies seasonally; see Section 4.2). Estimated stormwater DIN loads accounted for less than 10% of total DIN loads. However, stormwater DIP loads accounted for up to 20% of the total annual DIP load (Table 6).

Seasonal variability

Nutrient loads to Lower South Bay varied seasonally (Figure 7). Estimated stormwater loads varied seasonally, but a portion of the overall variability was also due to seasonal differences in POTW loads. From the dry season to the wet season, NO_3^- loads increased by as much as 50% at SJSC, and by as much as 300% at Sunnyvale because its nitrification efficiency increases in warmer summer months. [DIN]:[DIP] in POTW loads did not show a consistent seasonal trend, but was overall higher than in stormwater loads (which were assumed to be constant, see Methods section and Figure A.1.1). The degree of seasonality in total loads may be somewhat exaggerated because stormwater load estimates were distributed seasonally based on rainfall, and do not account for baseline streamflow during months with near-zero precipitation.

When considered on an annual basis, stormwater is not a major contributor to overall nutrient loads. However, in January, the region's wettest month, stormwater may contribute ~35% of total NH3 loads, ~15% of total NO_3^- loads and ~35% of total DIP loads to Lower South Bay (Figure 7).

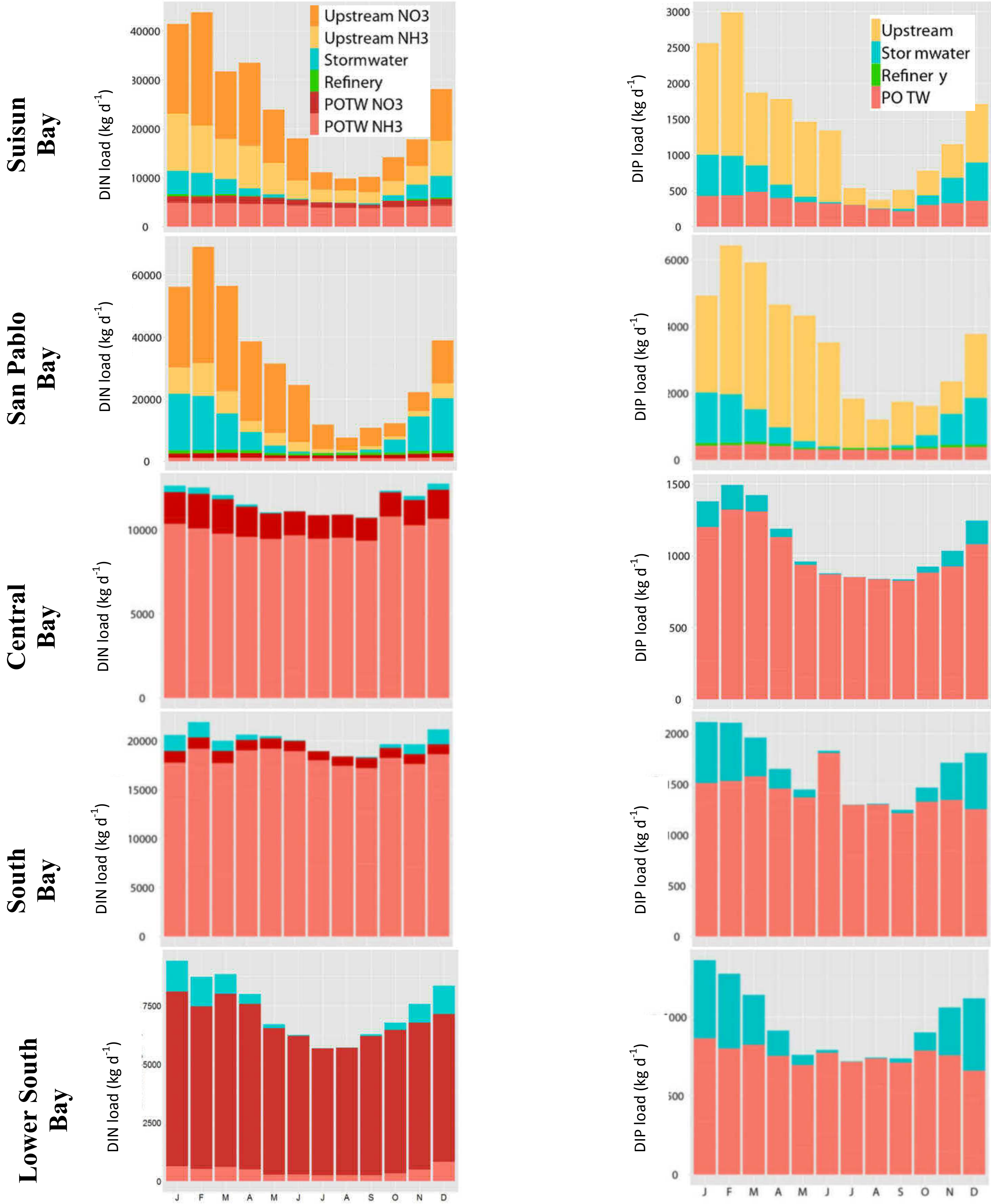

Figure 7 Average monthly DIN and DIP loads over the period 2006-2011 to each of the 5 subembayments. Colors indicate source (POTW, stormwater, refinery or upstream sources, i.e. the Delta to Suisun Bay). DIN loads from POTW and Upstream are broken down into NH_4^+ and NO_3^-, but total DIN loads is shown for refineries and stormwater.

3.2.2 South Bay

Annual averages

POTWs accounted for more than 90% of direct total DIN and DIP loads to South Bay (Table 6). NH_4^+ accounts for more than 95% of DIN discharged by POTWs, since none of the POTWs nitrify. Stormwater loads contributed ~3% and ~9% of overall DIN and DIP loads on an annual basis. Stormwater did contribute 30% of overall NO_3^- loads, but this was primarily because of the low POTW NO_3^- loads.

Seasonal variability

POTW loads did not exhibit strong seasonality in South Bay, neither in the magnitude of DIN and DIP loads nor in the form of N (Figure 7). Similarly, [DIN]:[DIP] in POTW effluent did not systematically vary over the year but was approximately 5 times higher than calculated [DIN]:[DIP] in stormwater at all times of year (Figure A.1.2). Although stormwater loads were of limited importance on an annual basis, stormwater NO_3^- and DIP loads have the potential to be nontrivial during certain months (e.g, stormwater accounted for 49% of NO_3^- and 28% of DIP loads to South Bay in January). Loads due to exchange from LSB to South Bay were not considered, and could contribute substantially to ambient nutrient concentrations in South Bay, especially in the southern quarter of South Bay, where hydrodynamic exchange with the rest of South Bay is muted.

3.2.3 Central Bay

Annual averages

POTWs dominated direct nutrient loads to Central Bay, accounting for 98% and 93% of total DIN and DIP loads, respectively (Table 6). NH_4^+ accounted for 85% of DIN loads. Although some Central Bay POTWs nitrify (Table 4), the largest Central Bay dischargers do not, shifting the predominance toward NH_4^+. Stormwater contributed less than 7% of each NO_3^-, NH_4^+, and DIP.

Seasonal variability

DIN loads from POTWs remained fairly constant year-round, increasing only 10% from summer to winter months (Figure 7). DIP loads, however, show strong seasonal variability, with approximately 50% higher loads during winter months. Stormwater contributed minimally to DIN loads, and even during the wettest month, stormwater contributed only 13% of DIP loads.

The Central Bay load estimates here do not consider net loads resulting from exchange with adjacent subembayments, which could be large during some times of the year. Furthermore, net nutrient loads from the coastal ocean during upwelling periods are not considered, but have the potential to contribute substantially under certain conditions (Largier and Stacey 2014).

3.2.4 San Pablo Bay/Carquinez

Annual averages

As noted in the Section 2.2, loads to Carquinez and San Pablo Bay have been combined in this analysis. San Pablo Bay/Carquinez Strait receives discharges from refineries as well as POTWs, and the refinery DIN and DIP contributions were 30% and 15% of the POTW contributions, respectively. A number of the POTWs that discharge to San Pablo Bay (or its watersheds) nitrify, and some also denitrify (Table 4).

Stormwater loads comprised a larger proportion of total subembayment loads in San Pablo Bay/Carquinez than in other subembayments (Table 6). In particular, stormwater loads exceeded direct POTW loads of both DIN and DIP on an annual basis. Stormwater loads' greater importance resulted from several factors. First, this region accounts for 32% of all watershed area Bay-wide, and a large portion of that area (33%) is classified as agriculture land use (Table 1, Figure 5). Although there is considerable uncertainty in the stormwater load estimates, these results suggest that San Pablo Bay's stormwater loads cannot be considered insignificant, and that additional efforts to refine estimates and reduce uncertainty may be needed. Second, direct POTW loads to San Pablo Bay were the smallest of all the subembayments (Table 6), allowing the stormwater contribution to play a relatively larger role. These annual average comparisons among sources in San Pablo Bay do not consider loads that enter from adjacent subembayments, which, more so than for any other subembayments, may be particularly important (see below).

Seasonal variability
Loads to San Pablo Bay exhibited strong seasonal variability, both in terms of total loads and in the predominant source. Both DIN and DIP loads from direct POTW discharge decreased by roughly 60% from winter to summer months due to summer discharge prohibitions on more than half of POTWs in this region. When loads derived from exchange between subembayments were not considered, stormwater loads dominated direct DIN and DIP inputs during the wet months, and, during dry months, POTWs/refineries became the dominant nutrient source (Figure 7). [DIN]:[DIP] from POTWs increased during dry summer months, but it was less than [DIN]:[DIP] from stormwater at all times of the year (Figure A.1.4). The [DIN]:[DIP] in stormwater loads was higher in San Pablo Bay/Carquinez than in any other subembayments, because of loading model assumptions and land-use characteristics (runoff nutrient concentrations used for agricultural land use had higher DIN:DIP than other land uses).

While exchange between subembayments was not considered for other subembayments due to complex hydrodynamics in many regions, exchange between Suisun Bay and San Pablo Bay/Carquinez was estimated and included in the analysis, both because of the potential importance of that transport load and because it was feasible to develop realistic estimates without sophisticated models (A detailed description of the approach can be found in Appendix 3). On average (2006-2011), loads from Suisun Bay to San Pablo/Carquinez were approximately 4000 kg d^{-1} NH_4^+, 17000 kg d^{-1} NO_3^-, and 2500 kg d^{-1} DIP, exceeding loads from any other source to San Pablo Bay by a factor of 3-4. For two-thirds of the year, loads from Suisun Bay to San Pablo Bay accounted for a large proportion of all nutrient forms (Figure 7). These Suisun export estimates are highly uncertain, and need to be better constrained; nonetheless they illustrate the potential importance of loads from up-estuary sources to San Pablo Bay. While loads from Suisun Bay appear to dominate throughout most the year, in winter and early spring, the estimated stormwater loads may still account for sizeable proportions of DIN and DIP loads.

3.2.5 Suisun Bay
Annual averages

On an annual-average basis, loads from the Delta to Suisun Bay exceed loads from other sources to Suisun Bay (Table 6). The majority of DIN coming from the Delta to Suisun was in the form of NO_3^-, but NH_4^+ loads were nonetheless still substantial. POTW discharges directly to Suisun Bay delivered DIN primarily in the form of NH_4^+ (Table 4). Stormwater loads to Suisun Bay were non-trivial; however, they were ultimately less than 10% of total DIN loads and less than 20% of total DIP loads due to the large contribution of Delta efflux loads. Refinery loads were non-zero, but small.

Seasonal variability

While POTW and refinery loads to Suisun Bay exhibited limited (DIN) to moderate (DIP) seasonal variability, the magnitude of Delta and stormwater loads, which comprised the majority of nutrient loads year-round, varied strongly between wet and dry seasons (Figure 7). Delta efflux dominated loads during winter months, contributing two thirds or more of NH_4^+, NO_3^- and DIP. Even during dry months, Delta efflux remained a large nutrient source, accounting for a minimum of ~50% of the total DIN load year round, and a smaller but still substantial portion of the DIP load. Stormwater loads peaked during January, when they contributed ~10% of DIN loads and ~20% of DIP loads.

As noted in Section 2.1.3 and Appendix 2, the stations used to estimate loads (both by Jassby and Cloern (2000) and also in this report) are between 10 and 30km upstream of the mouth of Suisun Bay. To explore the sensitivity of load estimates to station location, we calculated loads using both these upstream stations (D24 and D16) and one closer to the mouth of Suisun Bay (D4) for a period when data were available at both sites (1975-1995). DIN and DIP load estimates are relatively unchanged between these two locations. NH_4^+ transformations do appear to occur along this distance (Figure A.2.3), particularly during warmer summer months, but direct POTW NH_4^+ discharges already dominated over Delta efflux loads during these times (Figure 7). Therefore, while the estimated forms of N exported from the Delta to Suisun Bay are somewhat sensitive to station locations used in calculations, the overall conclusion that Delta loads of DIN and DIP are important remains reasonable.

4. Discussion

4.1 Relative importance of loading sources

4.1.1 Variability by subembayment

The relative importance of nutrient sources varied by subembayment. In Lower South Bay, South Bay and Central Bay, POTW effluent was the dominant source of all nutrient forms on an annual basis, with stormwater accounting for 5-10% of total nutrient loads to these regions. In San Pablo Bay/Carquinez Straits (Table 1, Figure 5), stormwater loads accounted for more than 50% of direct DIN and DIP loads on an annual basis. These stormwater loads may be artificially high due to limited data on land-use specific nutrient concentrations, and should be interpreted cautiously. When loads from Suisun Bay (including loads that originated from the Delta) to San Pablo Bay/Carquinez were included in the estimate, up-estuary sources were the dominant nutrient source to San Pablo Bay/Carquinez. In Suisun Bay, estimates indicate that Delta efflux loads were the dominant source of all nutrients on an annual basis, accounting for approximately two-thirds of total DIN loads and ~60% of total DIP loads to this subembayment.

The areal (i.e., area-normalized) DIN loads for each subembayment are presented in Table 7. Suisun Bay and Lower South Bay have the highest areal DIN loads, which are 4-5 times greater than the other three subembayments.

	DIN (kg d^{-1})	Bay surface area (km^2)	DIN (g $m^{-2}y^{-1}$)
Lower South Bay	7344	30	89
South Bay	20071	460	16
Central Bay	11826	200	22
San Pablo Bay/Carquinez	10555	310	12
Suisun Bay	23646	100	86
Bay-wide total	75938	1100	25

Table 7 Aerial DIN loads by subembayment. In absolute terms, Lower South Bay had the lowest DIN loads, but is also the smallest of all subembayments and therefore has the highest aerial loads. Surface area values were taken from Smith and Hollibough (2006).

4.1.2 Variability by season

To evaluate seasonal variability in the magnitude of loads and the relative importance of sources, monthly-averaged loads from all sources were combined and examined at the subembayment scale (Figure 7). POTW and refinery loads showed some, but relatively limited, seasonal variability Bay-wide, while stormwater and Delta efflux loads showed strong seasonal variation due to seasonal precipitation patterns.

Year-round, POTWs were the dominant DIN and DIP sources to Lower South Bay and South Bay. While stormwater contributed minimally to DIN loads in those subembayments, it did non-trivially influence loads of the minor nitrogen forms during wet months (NH_4^+ in LSB, and NO_3^- in South Bay). Wet-weather stormwater DIP loads accounted for up to ~30% of total DIP loads.

In San Pablo Bay/Carquinez Strait, there was strong seasonal variation in the importance of some sources. Exchange with Suisun Bay appears to have played a large if not dominant role in overall nutrient loadings to San Pablo Bay throughout most of the year. The RWSM estimates place stormwater loads as the second most important nutrient source to San Pablo Bay during wet months. During dry months, however, POTW loads have the potential to rival or exceed those sources in San Pablo Bay.

The importance of sources to Suisun Bay also shifted as a function of season. In Suisun Bay, POTW loads were the major DIN and DIP source during dry months. Estimated NH_4^+ loads from the Delta exceeded direct POTW loads for as much as half the year, but direct POTW loads were the largest source during the rest of the year. Much of the NH_4^+ entering and leaving the Delta originated from the Sacramento Regional County Sanitation District (SRCSD), which on average discharges ~15000 kg d^{-1} NH_4^+ to the Sacramento River approximately 70 km upstream of Mallard Island. The seasonal variation in the Delta NH_4^+ efflux load to Suisun Bay was probably due in large part to seasonal differences in *in situ* nitrification as SRCSD's effluent traveled along the Sacramento River (Foe 2010; Parker 2012a), and migrated through the Delta. The Delta was the largest source of NO_3^- year-round to Suisun Bay, and also contributed the majority of DIP during half the year. The Delta NO_3^- loads were likely due both to nitrified NH_4^+ (originally released by SRCSD) and NO_3^- from other sources (e.g., other POTWs upstream of and within the Delta; agriculture upstream of and within the Delta). Estimated stormwater DIN and DIP loads to Suisun Bay during wet months were comparable to direct POTW loads; however Delta loads during these times tended to exceed both stormwater and POTW loads combined.

4.2 Case study of long-term time-series

Long-term data was available for some POTWs, including most of the largest dischargers, and also for Delta efflux loads, allowing loading patterns over recent decades to be examined.

4.2.1 Lower South Bay

All POTWs in Lower South Bay nitrify effluent prior to discharging. SJSC made this transition to nitrification in 1979 and its NH_4^+ loads decreased by ~90% (Figure 8a). Palo Alto and Sunnyvale also upgraded to nitrification around this time, shifting the dominant form of DIN discharged to Lower South Bay from NH_4^+ to NO_3^- (Figure 8b).

In the late 1990's, SJSC implemented a step-feed biological nutrient removal (BNR) process that resulted in a ~35% reduction in DIN loads (Figure 8c). Current DIN loads are ~4000 kg d^{-1}, and there is substantial variability (±30-40%) around this central tendency value. Several treatment upgrades at SJSC over the past 20 years have also decreased DIP loads by ~75% (Figure 8d). Although NH_4^+ now represents only ~5% of SJSC's N load, there appears to have been a trend of increasing NH_4^+ over the past 10 years. This seems to be due to increases in effluent NH_4^+ concentrations (Figure 9b), since flows have actually decreased over this same time period (Figure 9a).

Like SJSC, the majority of N load from Palo Alto was in the form of NO_3^- (Figure 8b). NH_4^+ loads from Palo Alto have remained roughly constant since approximately 1995 with occasional spikes of higher NH_4^+ loads, including a prolonged period between approximately 2007 and 2010; during this 3-year period NH_4^+ loads nonetheless remained <5% of Palo Alto's DIN loads. Palo Alto's DIN loads have increased by approximately 30% since 1995. DIP loads increased by approximately 20% over that period, with evidence of a decrease (~20%) since 2009 that has returned DIP loads back to 1995 levels.

At Sunnyvale, both NH_4^+ and NO_3^- loads showed strong seasonality (Figure 8b). This is due to the fact that Sunnyvale uses oxidation ponds in secondary treatment and fixed growth reactors to nitrify, and the biological processes in these treatments are highly temperature dependent (T. Hall, EOA Inc., pers. comm.). DIN loads also exhibit strong seasonality, suggesting that denitrification occurs along Sunnyvale's treatment works. Although DIN loads varied by nearly 100% around the central tendency, average DIN loads appear to have decreased by 30-50% since 2000.

On an annual average basis, DIN loads to the entire subembayment have decreased by approximately 30% in the last two decades with a small increase in the last 5-10 years. These trends co-vary with those at SJSC, the largest DIN discharger to the region. DIP loads to Lower South Bay (based on SJSC and Palo Alto data) have decreased by approximately 50% in the last two decades due almost entirely to treatment upgrades at SJSC.

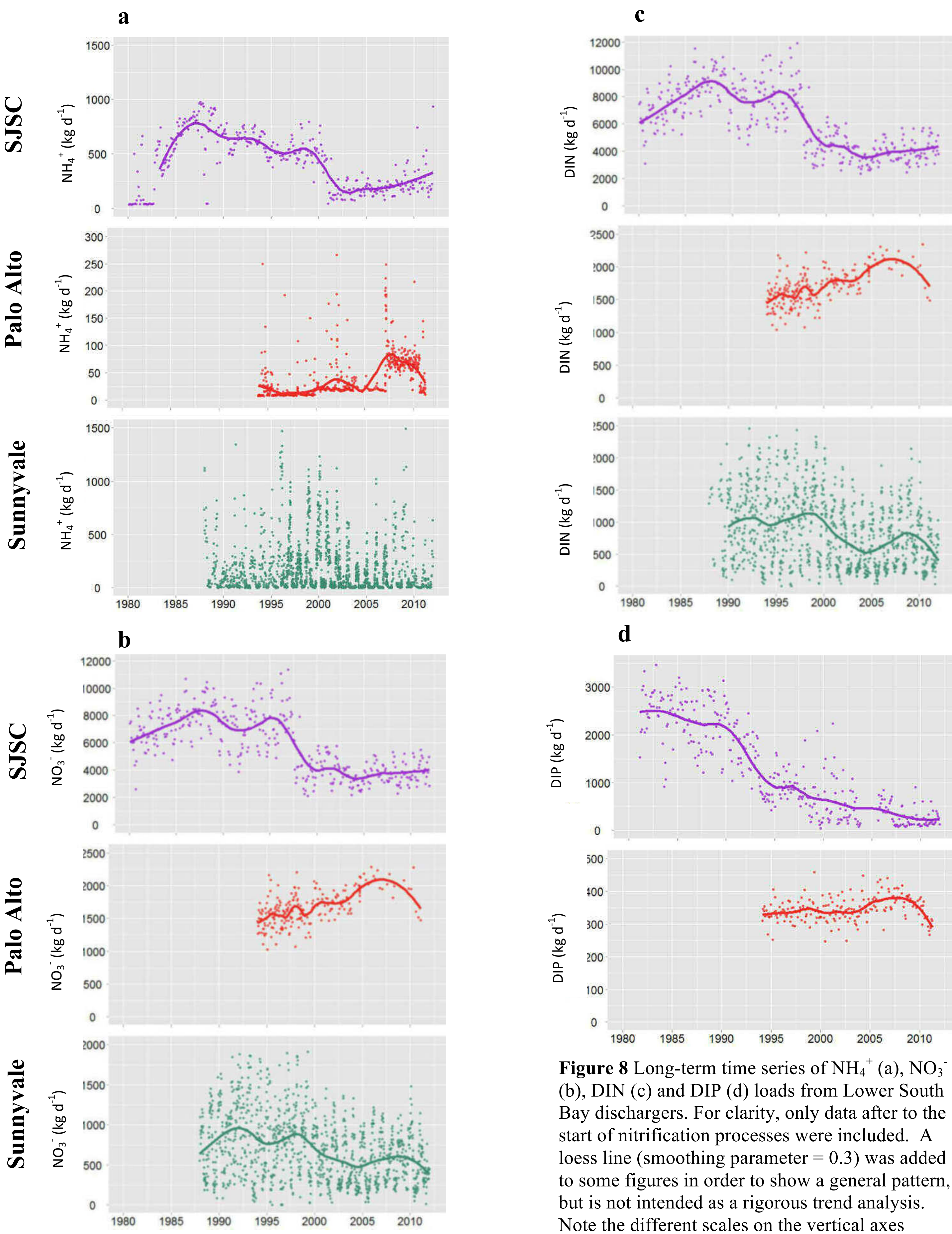

Figure 8 Long-term time series of NH_4^+ (a), NO_3^- (b), DIN (c) and DIP (d) loads from Lower South Bay dischargers. For clarity, only data after to the start of nitrification processes were included. A loess line (smoothing parameter = 0.3) was added to some figures in order to show a general pattern, but is not intended as a rigorous trend analysis. Note the different scales on the vertical axes

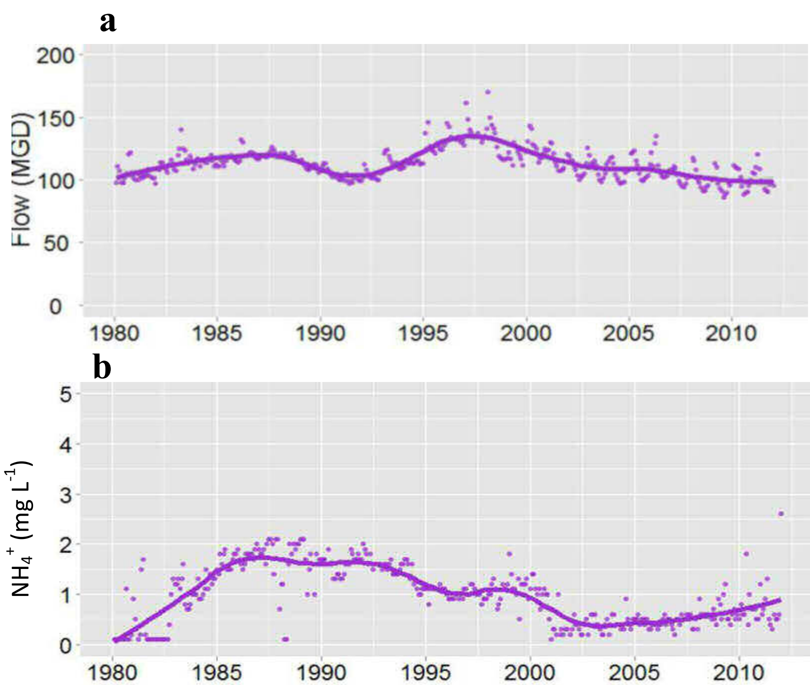

Figure 9 Long-term time series of flow (a) and NH_4^+ effluent (b) concentration from SJSC. NH_4^+ loads have increased at in the last decade (Figure 8a). For clarity, only data after to the start of nitrification processes were included. A loess line (smoothing parameter = 0.3) was added in order to show a general pattern, but is not intended as a rigorous trend analysis.

4.2.2 Suisun

Suisun Bay receives large loads of NO_3^- and NH_4^+ from both direct POTW loads and from the Delta. Long-term data sets from CCCSD, and Delta efflux loads calculated as part of this effort, allowed us to evaluate trends in loads to Suisun Bay over the past 30-40 years. Data from FSSD were also available from 2004-2011, and data from DDSD were available intermittently between 1992 and 2011. While there were limited DIP data for Suisun Bay POTWs, TP data was available and was analyzed here. The concentration data from 2012 POTW effluent monitoring suggests that DIP was approximately 55% of TP at CCCSD and DDSD, and 90% of TP at FSSD. making TP a reasonable but imperfect proxy for TP..

Direct POTW DIN loads to Suisun Bay have increased by 40-50% over the last two decades. A wealth of effluent data, dating back 35 years, was available to assess trends in CCCSD loads (Figure 10). CCCSD experimented with trial periods of nitrification (intermittent between 1977 and 1988); for clarity, data from that period were omitted from the time series. In general, NH_4^+ has been the dominant form of DIN emitted from CCSD, and CCCSD's DIN loads have increased nearly 40% over the past 20 years (Figure 10a,c). The load increases appear to have been due to an increase in effluent NH_4^+ concentration (Figure 11b), rather than an increase in flow (Figure 11a). Aside from a short period of higher NO_3^- loads in the late 1990's, NO_3^- loads have stayed relatively constant over the same period (Figure 11b). FSSD nitrifies its effluents and discharges primarily NO_3^-. FSSD's DIN loads exhibited large fluctuations, and the average load appeared to nearly double over the period 2004-2011. Limited data availability makes it difficult to comment on long-term trends at DDSD. TP loads from CCCSD have been relatively constant in the last 15 years, after having decreased by approximately 75% in the early 1990s. TP loads from FSSD appear to have increased slightly since 2004. TP data from DDSD was too sparse to comment on long-term trends.

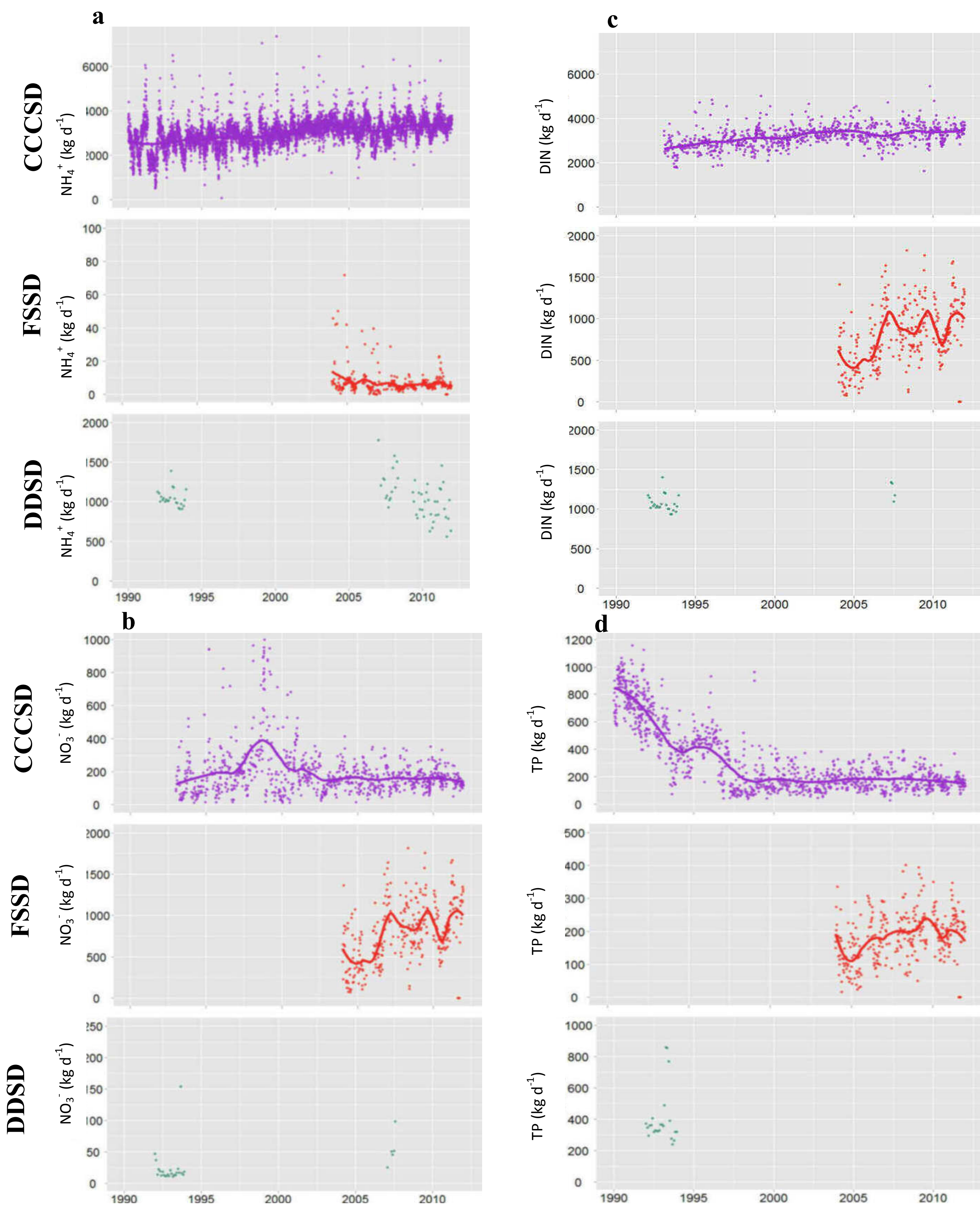

Figure 10 Long-term time series of NH_4^+ **(a)**, NO_3^- **(b),** DIN **(c)** and TP **(d)** loads from major POTWs in Suisun Bay. Historical DIP data was not available for any discharger. For clarity, periods of trial nitrification by CCCSD (pre-1990) were omitted. A loess line (smoothing parameter = 0.3) was added to some figures in order to show a general pattern, but is not intended as a rigorous trend analysis. Note the different scales on the vertical axes.

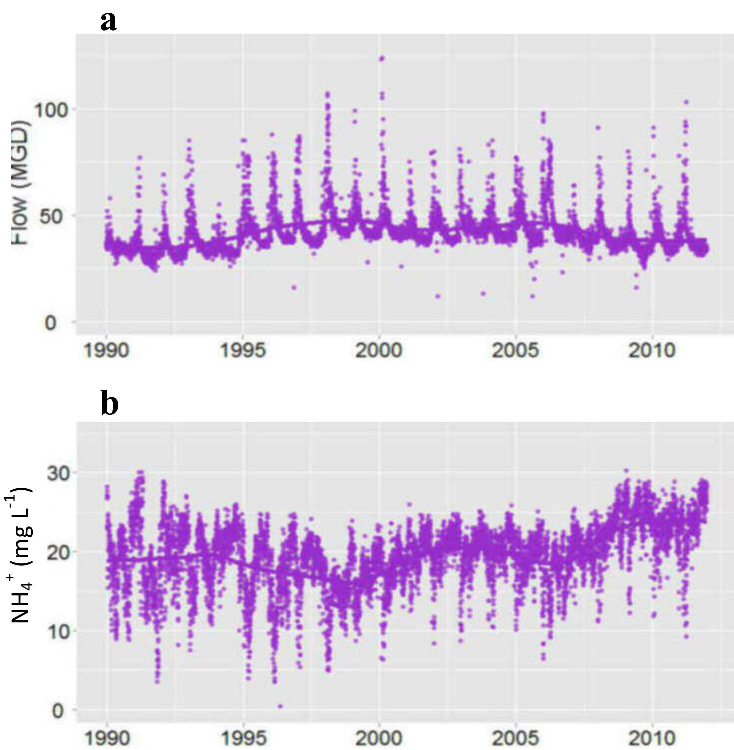

Figure 11 Long-term time series of flow (a) and NH_4^+ (b) effluent concentration from CCCSD. NH_4^+ loads from CCCSD have increased in the last decade (Figure 10a). For clarity, periods of trial nitrification (pre-1990) were omitted from figures. A loess line (smoothing parameter = 0.3) was added in order to show a general pattern, but is not intended as a rigorous trend analysis.

Delta efflux loads showed strong seasonal trends and large interannual variability (Figure 12), with the latter resulting from extreme conditions (drought vs. atypically wet) . NH_4^+ and NO_3^- loads during low flow months of the year (June-October) have typically been 4-5 times lower than wet season loads, likely due to a combination of transformation/losses (nitrification/denitrification) and lower agriculture-runoff-derived nitrate loads during the dry season (Figure 13a,b). In addition to this seasonal variation, NH_4^+ and NO_3^- loads have increased between 1975 and 2011. NH_4^+ loads have increased in all months throughout the year, sometimes by a factor of 2-3, with statistically significant increases in April-September and November-December (Figure A.1.6a). NO_3^- loads have also increased in some months between 1975-2011, with statistically significant increases only noted in June (Figure A.1.6b). Some of the increase in NH_4^+ load is likely explainable by the 2-3 fold increase in NH_4^+ loads from SRCSD since 1985 (Jassby 2008). SRCSD is located ~70 km upstream of Suisun Bay along the Sacramento River. A seasonally-varying portion of SRCSD's NH_4^+ load is nitrified en route to Suisun Bay (Parker 2012a). Planned treatment upgrades at SRCSD (nitrification, and biological nitrogen reduction) will both shift the form of N released and the total DIN load. The resulting overall decrease in load and composition shift from NH_4^+ to NO_3^- could make POTWs discharging directly to Suisun Bay the dominant NH_4^+ source, and perhaps the largest source of DIN during certain times of the year.

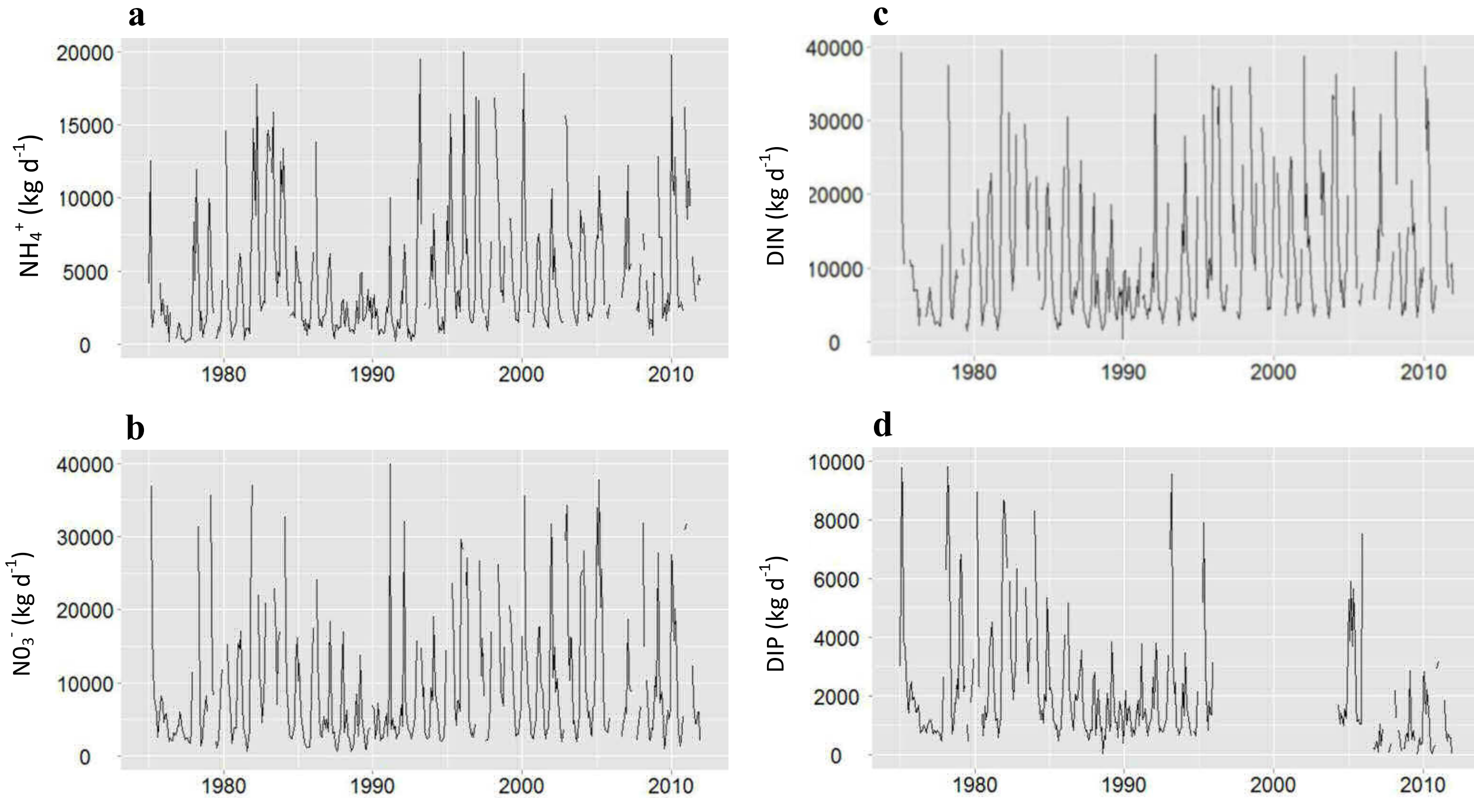

Figure 12 Long-term time series of NH_4^+ (a), NO_3^- (b), DIN (c) and DIP (d) loads from the Sacramento-San Joaquin Delta into Suisun Bay. Loads show considerable seasonal variability, and also an increase in baseline levels (see Figure 13). DIP loads could not be estimated between 1996 and 2005 because of gaps in water quality data at a key station used in calculations. Note the different scales on the vertical axes

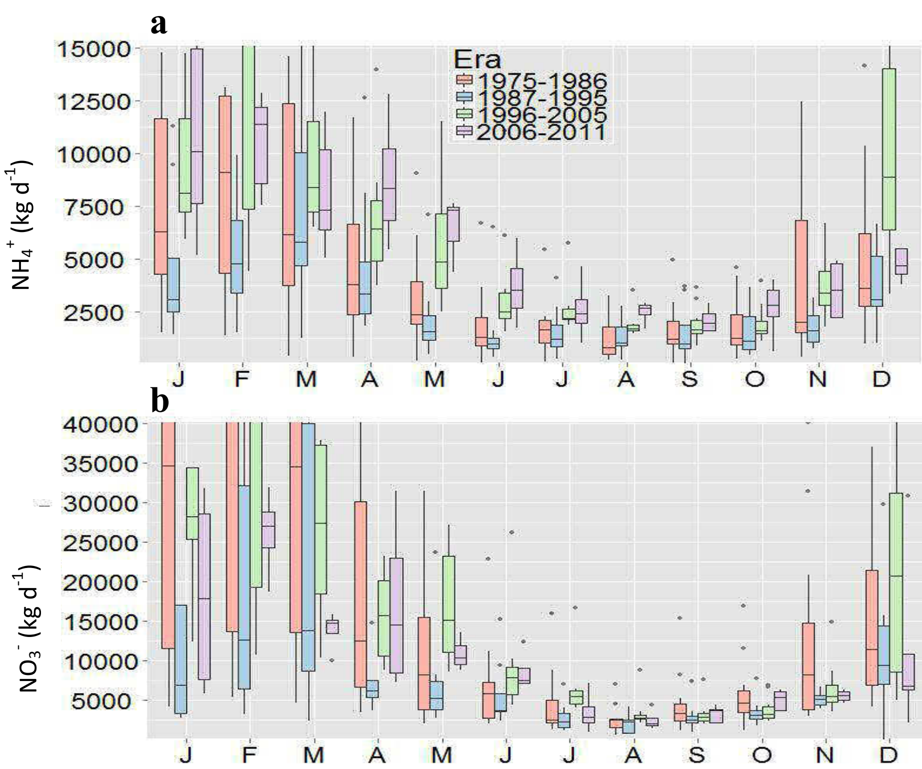

Figure 13 Seasonal and temporal variations in Delta efflux NH_4^+ (a) and NO_3^- (b) loads to Suisun Bay. Data were first aggregated into four eras (1975-1986, 1987-1995, 1996-2005 and 2006-2011), and then averaged by month within each era. Statistically significant increases (over the entire period, determined by Kendall-Tau test) in NH_4^+ loads occurred in April-September and November-December, and statistically significant increase in NO_3^- loads occurred in June (see Figure A.1.6)

4.2.3 Other large dischargers

Five dischargers to SFB account for roughly 60% of the total treated effluent flow. These dischargers include CCCSD and SJSC, which were discussed above, along with SFPUC, EBMUD, and the EBDA combined outfall.

Effluent data was available for SFPUC back to 1996. SFPUC does not nitrify, thus NH_4^+ is the primary DIN form it emits to the Bay. SFPUC's NH_4^+ loads have increased by ~50%, from 4000-5000 kg d^{-1} in 1996 to 7500 kg d^{-1} in 2011 (Figure 14a). NO_3^- loads were <10% of DIN loads (Figure 14b). SFPUC DIP loads have been highly variable but do not appear to have experienced substantial systematic changes since 1996.

Effluent flow rate and NH_4^+ concentration data are available from EBMUD back to 1998. EBMUD does not nitrify, so the majority of its DIN load should were in the form of NH_4^+. EBMUD's NH_4^+ loads have increased by ~50% since 2002 from 6000 kg d^{-1} to 9000 kg d^{-1} by 2011 (Figure 14a). This increase appears to be due primarily to increased NH_4^+ concentration, as opposed to increased flow (Figure 15). Some portion of the increases in EBMUD's NH_4^+ concentration and load is likely due to their waste to energy program, which involves accepting food waste to fuel methane production that is in turn used to produce electricity. Because of the N-rich composition of the food waste material, this practice augments N exports to the Bay. No DIP data for EBMUD prior to 2012 was available to determine whether DIP loads have also changed.

Flow and NH_4^+ data for the EBDA combined outfall were available back to 1999 (Figure 14). EBDA NH_4^+ loads varied by ±30% but with no systematic changes between 1998 and 2008. Between 2009-2011, loads appear to have increased by ~20%, corresponding to a period when flows decreased but NH_4^+ concentrations increased (Figure 15). The fact that the data series stops in 2011 makes it difficult to assess whether this apparent increase reflects a real trend.

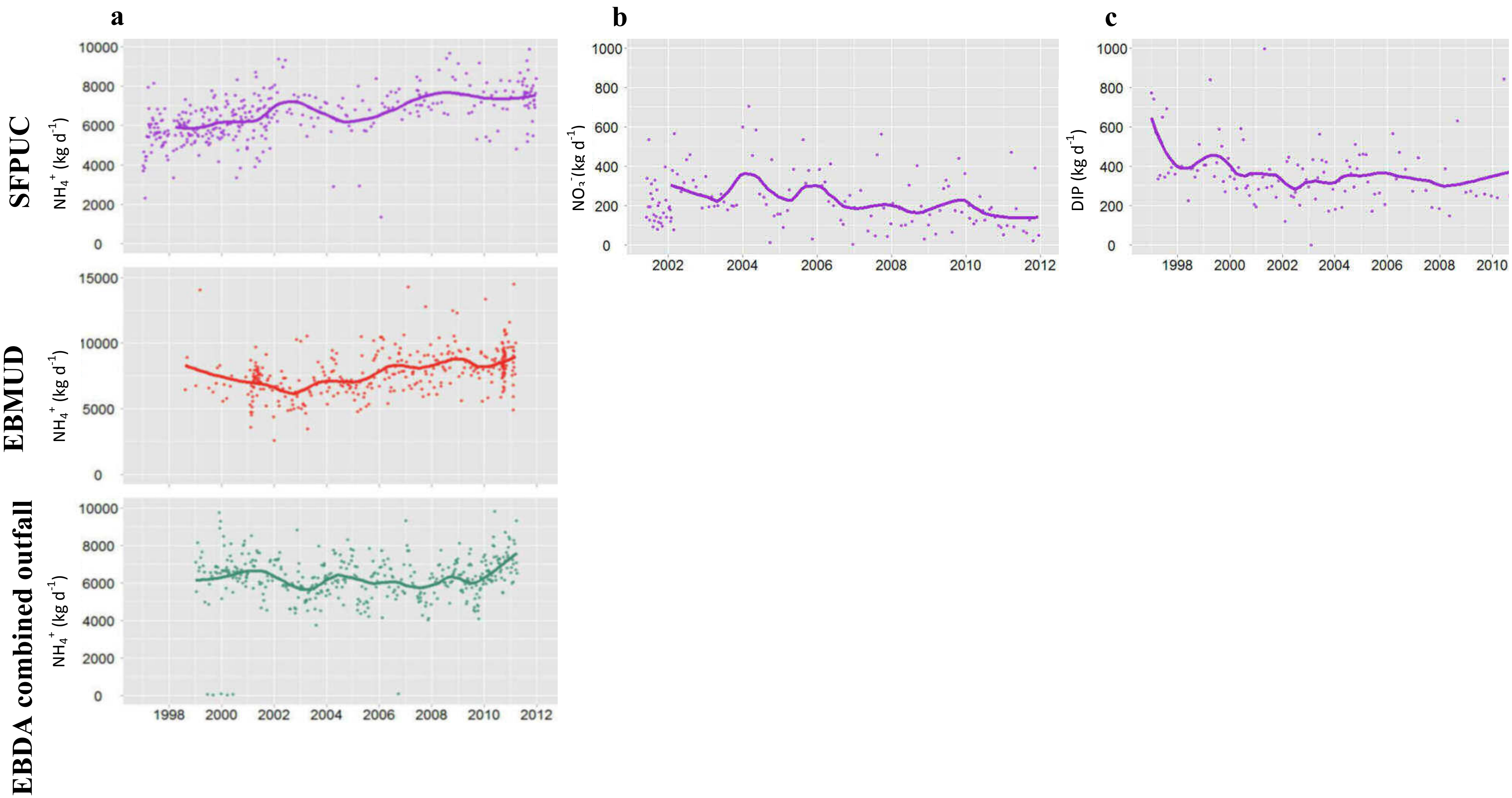

Figure 14 Long-term time series of NH_4^+ **(a)**, NO_3^- **(b)** and DIN **(c)** loads from the other large POTWs. Ample historical NO_3^- and DIP data was not available for any discharger except SFPUC. A loess line (smoothing parameter = 0.3) was added to some figures in order to show a general pattern, but is not intended as a rigorous trend analysis. Note the different scales on the vertical axes.

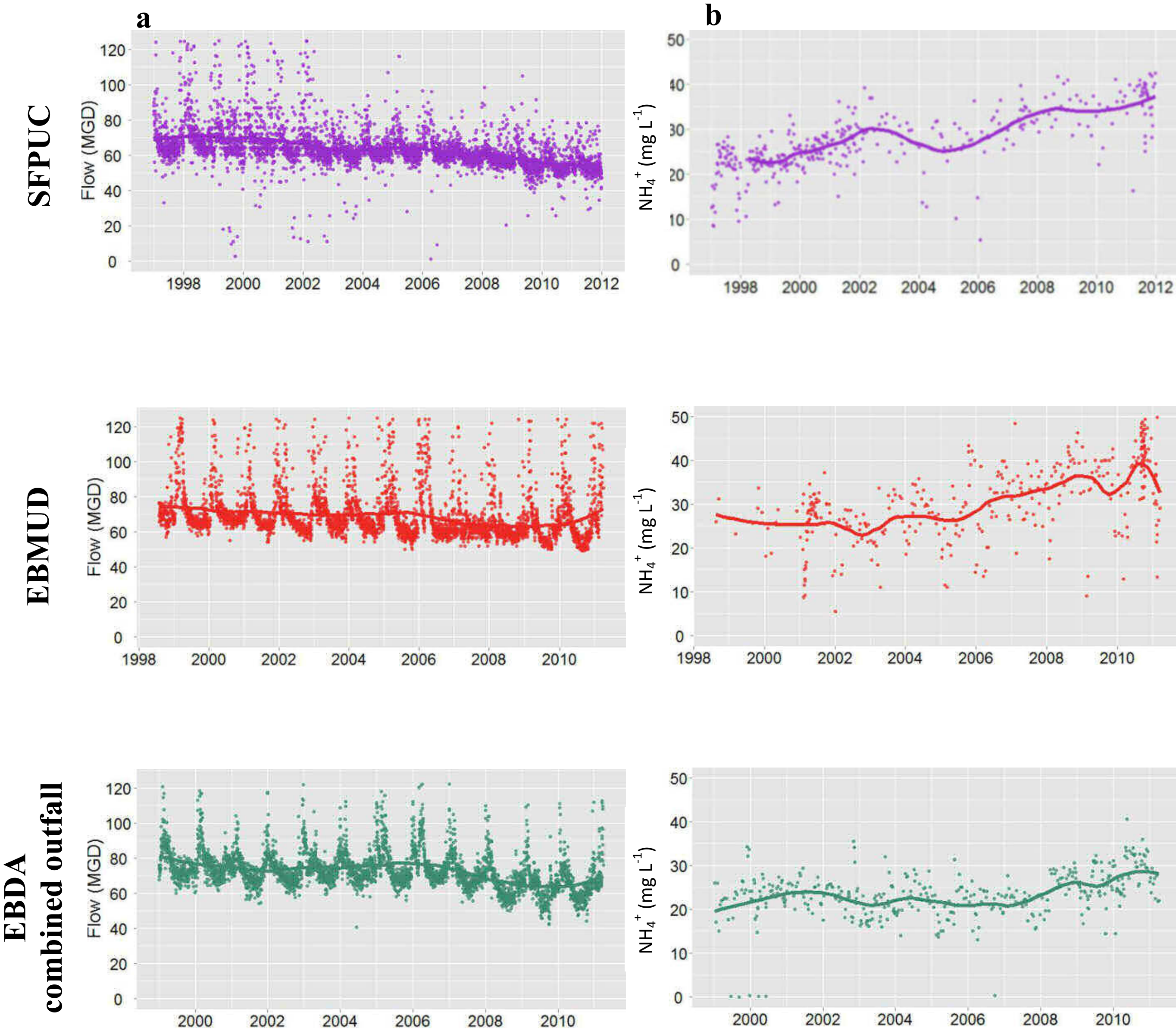

Figure 15 Long-term time series of flow (a) and NH_4^+ (b) effluent concentration from SFPUC, EBMUD and EBDA combined outfall. A loess line (smoothing parameter = 0.3) was added in order to show a general pattern, but is not intended as a rigorous trend analysis.

4.3 Major Data Gaps and Recommendations

4.3.1 POTW and refinery loads

Even though loads from POTWs and refineries were likely the best constrained of all the estimates made in this report, there were still substantial data gaps, especially regarding NO_3^- and DIP effluent concentrations and loads. Aside from several POTWs that have been monitoring for multiple nutrient forms, for most POTWs only NH_4^+ concentration data was readily available prior to 2012. For plants that do not nitrify, NH_4^+ concentrations provide a reasonable surrogate for effluent DIN concentrations and for estimating DIN loads. However, DIP concentrations appear to be highly variable among POTWs (based on 12 months of 2012 data). Furthermore, there is limited total N and total P data. The on-going POTW effluent characterization program will be valuable for addressing these gaps for current loads. To some extent that data may also help with filling historic gaps, if concentrations have not changed substantially. POTW and refinery load estimates will likely need to be updated as more data becomes available.

4.3.2 Stormwater loads

The stormwater load estimates in this report are highly uncertain. That said, they provide useful order-of-magnitude estimates for assessing the potential importance of stormwater contributions. These estimates suggest stormwater does not contribute substantially to loads at the subembayment scale in Lower South Bay, South Bay, and Central Bay. However, stormwater may contribute nontrivially to DIN and DIP loads in San Pablo and Suisun Bays during some times of the year. Furthermore, the importance of stormwater loads at spatial scales finer than the subembayment-scale (e.g., in shallow margin habitats) should not be ruled out. While the Regional Watershed Spreadsheet Model was the best available tool for estimating stormwater nutrient loads for this report, the nutrient load estimates it generated are highly uncertain due to it not being calibrated for nutrients, and due to inherent model limitations. In particular, loads from watersheds that have high proportions of agricultural land-use (primarily draining to San Pablo and Suisun Bays) need to be critically evaluated. Loads from agricultural land-use areas may have been overestimated because of the limited availability of land-use specific nutrient concentration input data, and the fact that agricultural practices may be quite different in Bay area watersheds than in those from which the small number of literature values were derived. Better constraining stormwater load estimates will require improved hydrological and loading models as well as additional field data to calibrate and validate those models.

4.3.3 Nutrient transport and fate

The results of this report suggest that Delta efflux loads have the potential to be a dominant source of nutrients to Suisun Bay (and potentially San Pablo Bay) during much of the year. The approach used for developing the time-series of monthly-average loads over the past ~35 years is based on a peer-reviewed approach applied for other compounds exiting the Delta (Jassby 2002), and a reasonable and defensible method for calculating a first set of estimates. However, as noted above, the method has limitations because it is an imperfect combination of historic data collected for other purposes (as opposed to flow and concentration specifically collected to quantify nutrient mass loads) and due to gaps in that data. Additionally, water quality data is limited during flood flow events, and therefore the Delta load estimates for high flow periods could be biased low. Hydrodynamic and reactive transport models need to be calibrated, validated, and applied to generate improved nutrient load estimates from the Delta to Suisun

Bay, including flood flow events, and to explore uncertainties and upstream factors that influence loads (e.g, flow routing, residence time, changes in nutrient loads and form from Sacramento Regional County Sanitation District). A hydrodynamic/nutrient modeling project for the Delta, which began in Q4 of 2013, should help refine these estimates and quantify uncertainties (Senn et al., funded by the CA Department of Water Resources through the Interagency Ecological Program, in preparation). Additional monitoring data may also be needed to refine load estimates, particularly during flood flow events.

Accurate estimates of nutrient loads at subembayment and finer scales need to consider nutrient exchange between subembayments. The need for such estimates is evident based on the potential importance of loads coming from Suisun Bay (and the Delta) to total loads in San Pablo Bay/Carquinez (Figure 7). Loads from South Bay and San Pablo Bay likely represent important and seasonally varying sources to Central Bay. In addition, direct POTW loads to Lower South Bay ultimately contribute to loads to South Bay through exchange between those two subembayments. Hydrodynamic and water quality models need to be directed toward addressing these gaps. In addition, the potential magnitude of exchange of nutrients between the coastal ocean and SFB needs to be evaluated with the help of models.

Finally, in this report, loads were combined and analyzed at subembayment spatial scales and at monthly time scales so that seasonal variation in the relative importance of sources could be evaluated. For these calculations, the SFBRWQCB's subembayments boundaries were used. However, other boundaries may be just as appropriate for such an analysis. For example, the RMP boundaries may better reflect hydrodynamics of the system during certain times of the year (Lowe 2005)(Figure 1), since the region north of the San Bruno Shoal is thought to exchange more readily with Central Bay, whereas the region south of San Bruno Shoal exchanges slowly with the rest of the Bay. Using the RMP boundaries shifts several POTWs and approximately 250 km^2 of watershed area from South Bay to Central Bay, substantially altering the magnitudes of the loads (Figure 16); however the relative importance of the sources (i.e., POTW vs. stormwater) is not sensitive to choice of boundaries. In reality, any set of boundaries that divides SFB into such large areas may be too coarse to meaningfully address management questions. More highly resolved longitudinal and lateral segmentation is likely needed, and hydrodynamic and water quality models will be essential for determining what levels of resolution are most appropriate depending on the management and science questions being addressed.

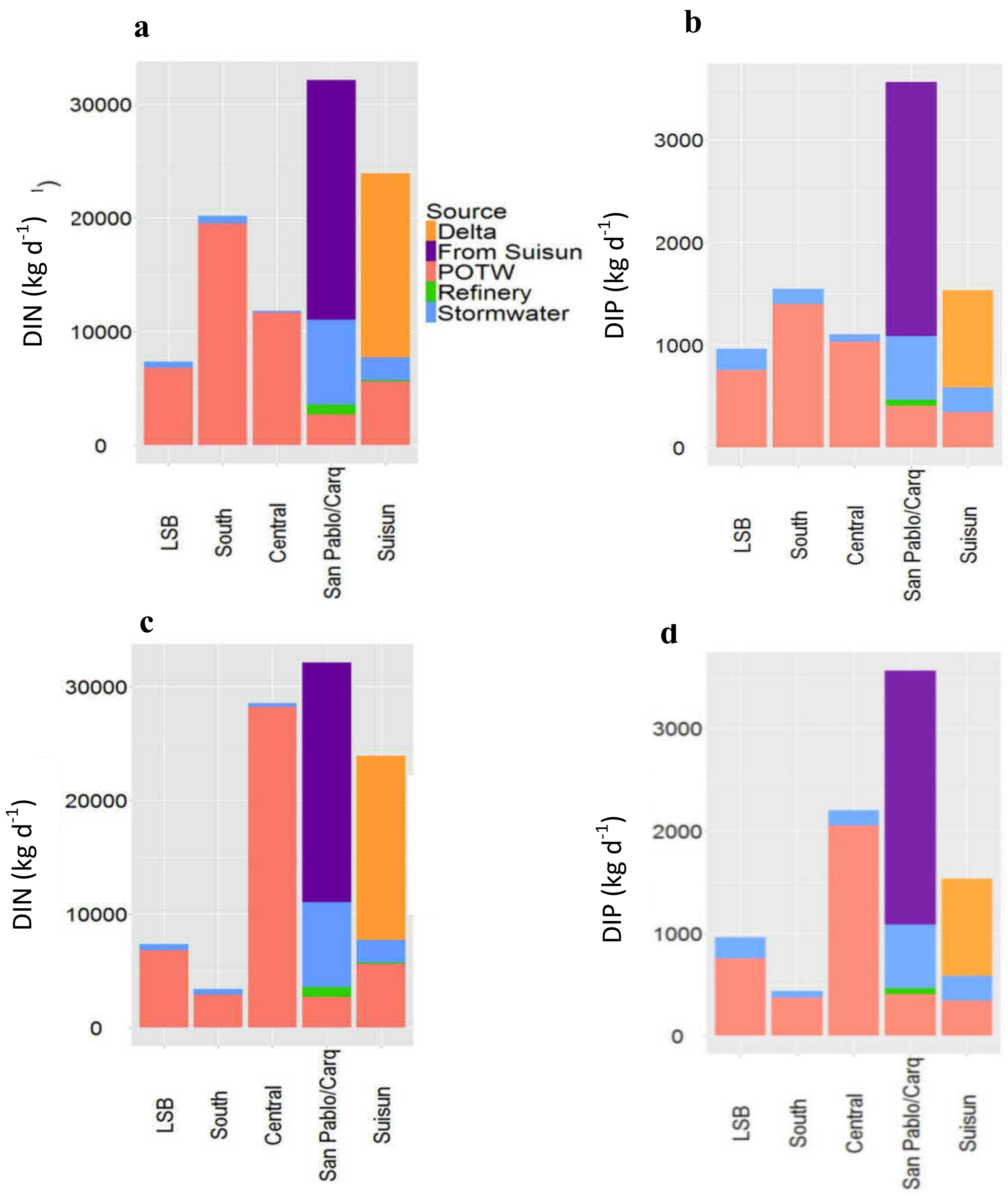

Figure 16 DIN and DIP loads by subembayment and source based on Water Board boundaries (Figures 16a and 16b) and based on RMP boundaries (Figures 16c and 16d). The Water Board divides South Bay from Central Bay at the Bay Bridge, while the RMP divides these two at the San Bruno shoals. All other subembayments are the same.

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Appendix 1: Additional Figures

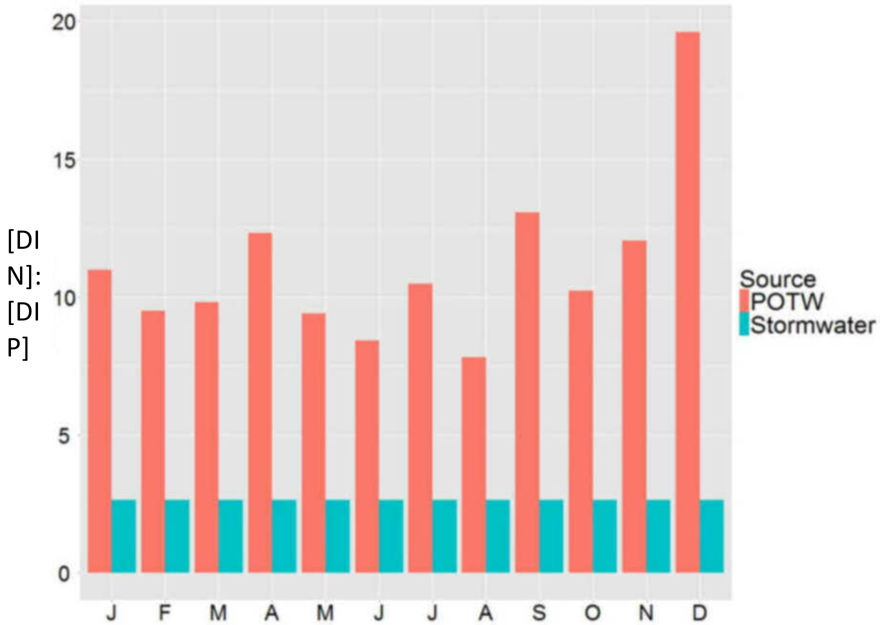


Figure A.1.1 Average **[**DIN]:[DIP] by source in Lower South Bay for 2006-2011. The Regional Watershed Spreadsheet Model, used to calculate stormwater loads, estimates loads on an annual basis and therefore [DIN]:[DIP] is assumed to be constant throughout the year. In reality, seasonal variability in fertilizer application and soil tilling (for example) could cause stormwater [DIN]:[DIP] to vary throughout the year.

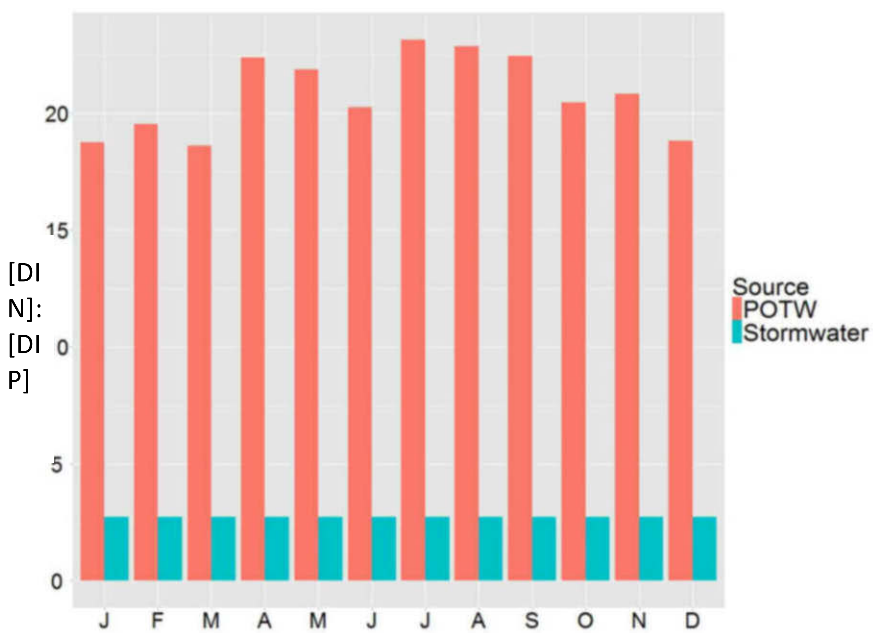


Figure A.1.2 Average **[**DIN]:[DIP] by source in South Bay for 2006-2011. See Figure A.1.1 for consideration of [DIN]:[DIP] in stormwater

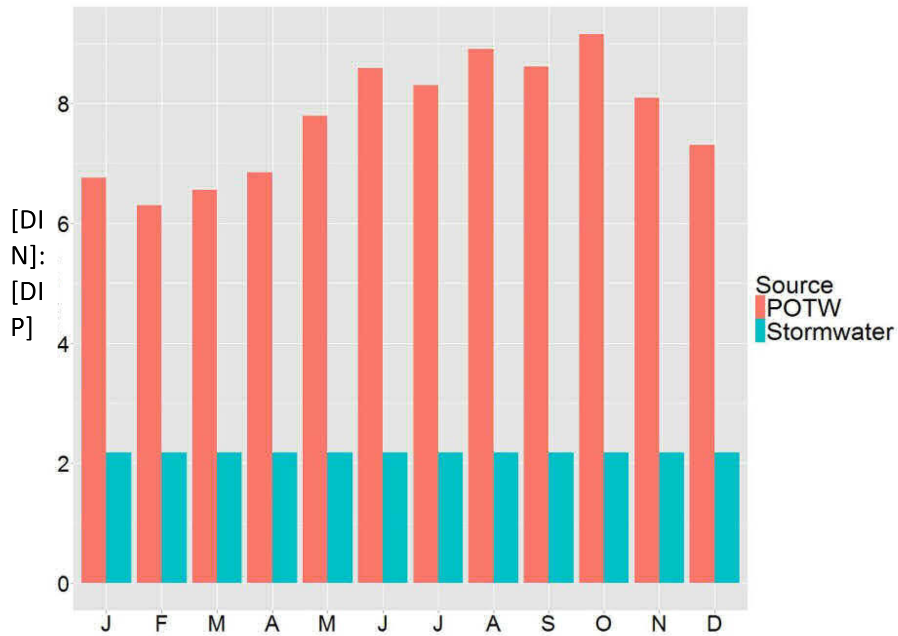


Figure A.1.3 Average **[**DIN]:[DIP] by source in Central Bay for 2006-2011. See Figure A.1.1 for consideration of [DIN]:[DIP] in stormwater

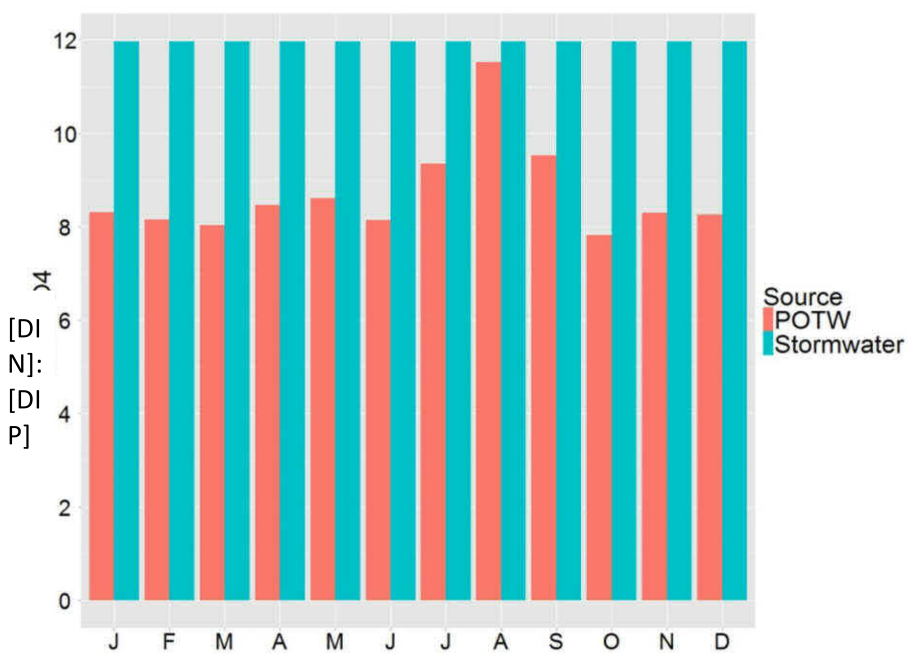


Figure A.1.4 Average **[**DIN]:[DIP] by source in San Pablo Bay/Carquinez Strait for 2006-2011. [DIN]:[PO4] in refinery discharge was exceedingly high (average of more than 50) and was omitted from this figure for clarity. See Figure A.1.1 for consideration of [DIN]:[DIP] in stormwater

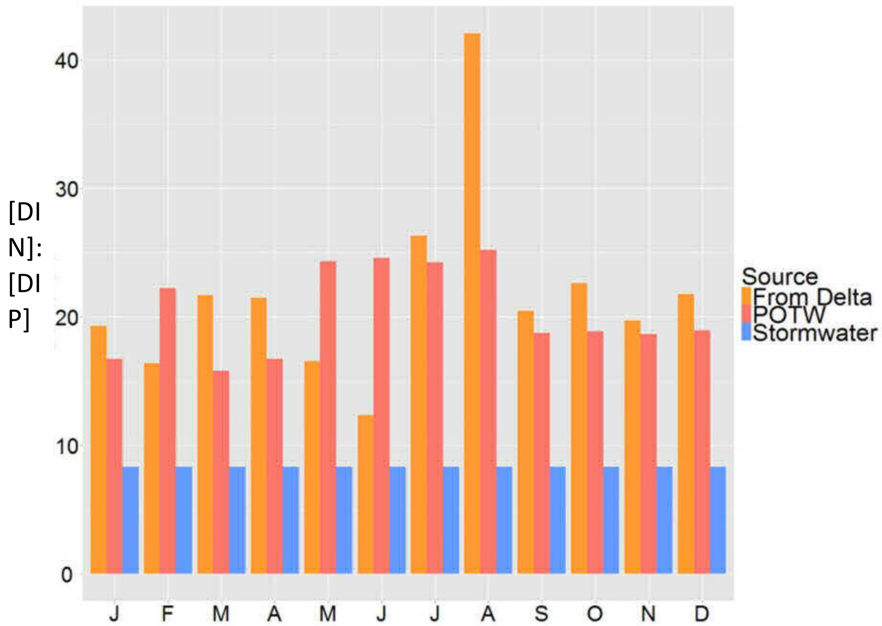
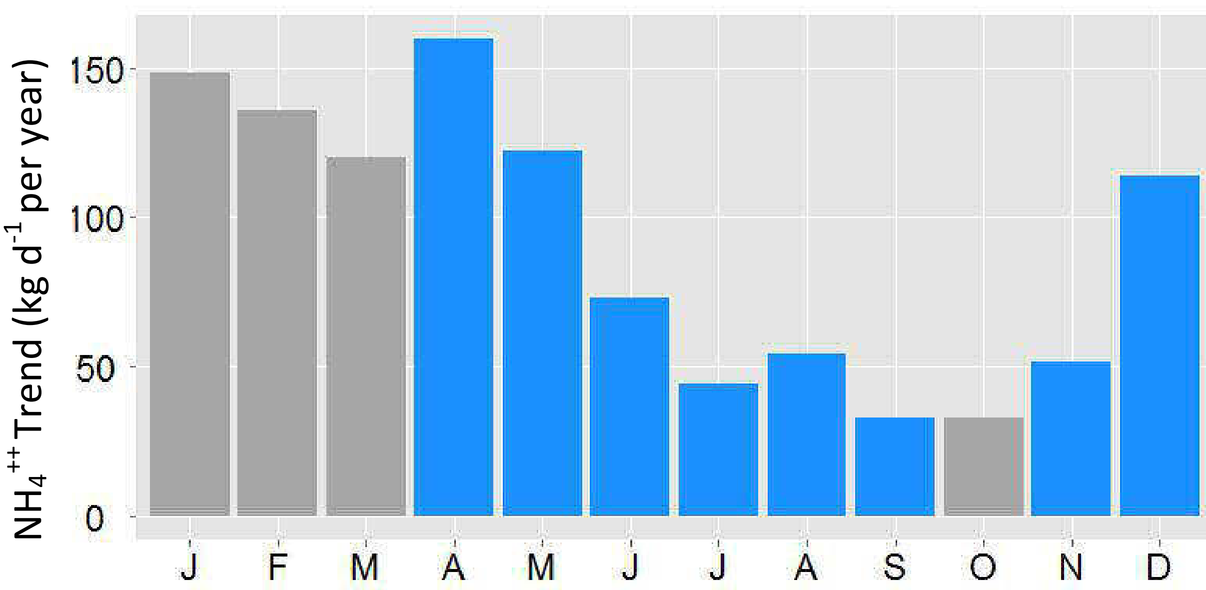


Figure A.1.5 Average **[**DIN]:[DIP] by source in Suisun Bay for 2006-2011. [DIN]:[DIP] in refinery discharge was exceedingly high (more than double that from any other source) and was omitted from this figure for clarity. The peak in [DIN]:[DIP] in Delta efflux is due to very low August DIP loads for the time period studied. See Figure A.1.1 for consideration of [DIN]:[DIP] in stormwater a



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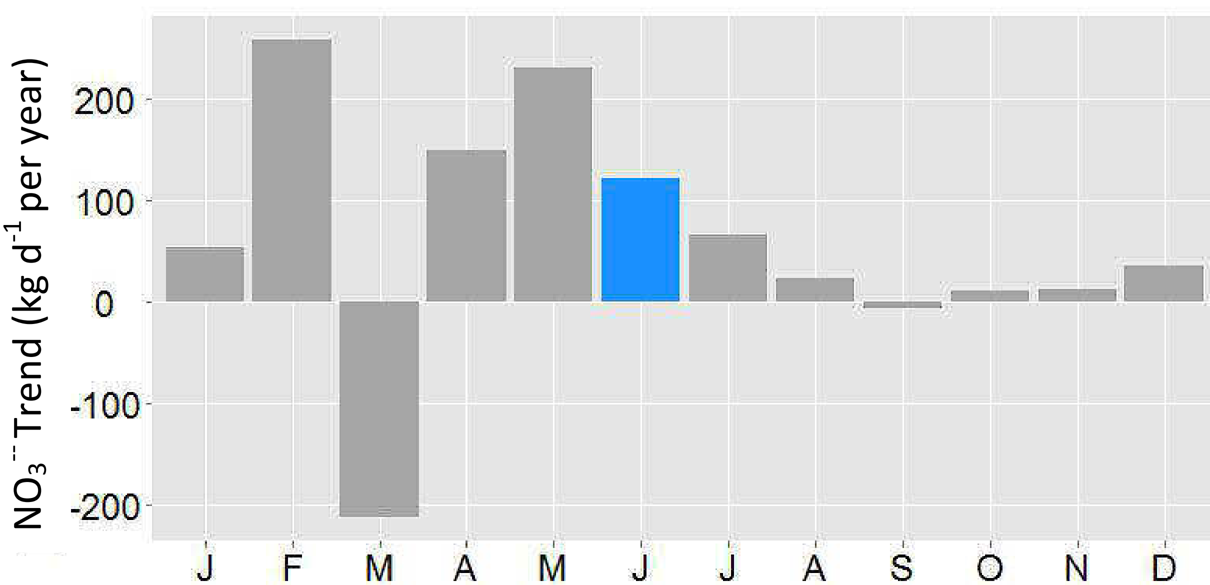


Figure A.1.6 Long-term variation in NH_4^+ loads **(a)** and NO_3^- loads **(b)** from the Delta into Suisun Bay, by month, for the period 1975-2011. Trend was characterized by the Theil slope, which is the median value of all possible slopes for a given month (between any two points). Blue bars indicate statistically significant trends, with $p<0.05$ as determined by the Kendall Tau test.

Appendix 2: Estimating Delta Efflux Loads

The approach for calculating nutrient loads from the Delta into Suisun Bay was adapted from an approach used by Jassby and Cloern (2000). We quantified loads past Rio Vista (representing flow originating in the Sacramento River, *Qrio*) and loads past Twitchell Island (representing flow originating in the San Joaquin River, *Qwest*), and combined these to estimate total load on a monthly average basis

$Load = Qwest Cwest + Qrio Crio$

Flow:

Flow values were taken from California Department of Water Resources (DWR) DAYFLOW records. Both Q_{west} and Q_{rio} are calculated values based on actual measured flows at gages throughout the Delta. Flow values were available daily, and we took a monthly average to calculate monthly average loads.

Qwest:

$$Q_{WEST} = Q_{SJR} + C_{SMR} + Q_{MOKE} + Q_{MISC} + Q_{XGEO} - Q_{EXPORTS} - Q_{MISDV} - 0.65\,(Q_{GCD} - Q_{PREC})$$

Qrio:

$$Q_{RIO} = Q_{SAC} + Q_{YOLO} - Q_{XGEO} - 0.28\,(Q_{GCD} - Q_{PREC})$$

Concentration:

DWR/IEP and USGS conduct monthly water quality monitoring in the Delta at stations that roughly coincide with the locations of *Qrio* and *Qwest*. We multiplied these concentrations (referred to as *Crio* and *Cwest*) by monthly-averaged flow produce monthly-averaged estimates of load. Stations used for *Crio* and *Cwest*) varied throughout the period of 1975-2011 because of changes in station operation (Table A.2.1). Between 1975 and 1975, DWR/IEP station D24 was used for *Crio* and DWR/IEP station D16 was used to represent for *Cwest*) . Unfortunately, monitoring at both of these stations ceased in 1995, and we were forced to substitute using stations whose monitoring continued past 1995. We performed multivariate linear regressions of D24 and D16 data from 1975-1995 against data from nearby stations from the same period in order to develop the substitutions that would be used post-1995. Starting in 2006, we made single-station substitutions for both *Crio* and *Cwest*) . At this time, nutrient monitoring intensified at DWR/IEP station D19 and began at USGS station 657, which is nearly collocated with DWR/IEP D24. Details on stations substitutions can be found in the table below. Locations of all stations used, as well as locations of *Qrio*and *Qwest*) , can be found in Figure A.2.2

Uncertainty:

Although this method should be reliable as order-of-magnitude estimates of Delta efflux loads, there some constraints in data availability that introduce uncertainty into our results. *Qwest* and *Qrio* are both calculated values, not directly measured by flow gages. Although the formula used to calculate these terms is frequently reviewed and revised by DWR (as recently as 2012), a calculated value will never be as accurate as one that is measured. The DWR/IEP and USGS stations used are not continuous over the entire period 1975-2011. There are stations with continuous data from 1975-1995 (D16 and D24), which are also nearly collocated with DAYFLOW locations of $Qwest$ and $Qrio$ however both of these stations were dropped in 1995. A USGS station (657) that is nearly identical to the location of station D24 began monitoring for nutrients in 2006, but there were gaps in the record from 1995-2006 (at the former station D24) and from 1995-2011 (at the former station D19). Multivariate linear regressions from nearby stations filled these gaps with varying levels of accuracy (see r^2 values in Table A.2.1), but this station substitution introduces additional uncertainty into these estimates. Additionally, all of these stations are located 10km to 30km upstream from the mouth of Suisun Bay, and it is possible for nutrient loads to change along this distance due to transformation or loss. To explore the sensitivity of load estimates to station location, we calculated loads using both these upstream stations (D24/D16) and one closer to the mouth of Suisun Bay (D4) for a period when data were available at both sites (1975-1995). On average, NH_4^+ load estimates decrease by ~30% (approximately 860 kg/d N) and NO_3^- load estimates increase by ~10% (approximately 850 kg/d N) between these two locations, but DIN and DIP loads are virtually unchanged. While NH_4^+ transformations along this distance are more significant during warmer summer months, direct POTW NH_4^+ loads already dominated over Delta efflux loads during these times. Therefore, while our exact estimates forms of N exported from the Delta to Suisun Bay are somewhat sensitive to station locations used in calculations, our overall conclusions, as well as overall DIN and DIP estimates, are reasonable. In spite of data gaps, the estimates made here are believed to be reliable as order of magnitude approximations and further modeling efforts in the Delta could help refine these estimates further.

References:

Jassby, A.D., and Cloern, J.E. (2000) Organic matter sources and rehabilitation of the Sacramento-San Joaquin Delta (California, USA). Aquatic Conservation: Marine and Freshwater Ecosystems 10: 323–352.

Tables and Figures:

		C_{west}	C_{rio}
1975-1995	NH_4^+	D16[1]	D24[1]
	$NO_3^- + NO_2^-$	D16[1]	D24[1]
1996-2005	NH_4^+	$0.311*D26+0.235*D28A+0.320*D4-0.001$ $r^2 = 0.77$	$0.165*C3+0.551*D4+0.022$ $r^2 = 0.52$
	$NO_3^- + NO_2^-$	$0.5305*D26+0.1613*D28A+0.3812*D4-0.020$ $r^2 = 0.93$	$0.200*C3+0.809*D4-0.023$ $r^2 = 0.85$
2006-2011	NH_4^+	D19 $r^2 = 0.81$	USGS 657[2]
	$NO_3^- + NO_2^-$	D19 $r^2 = 0.84$	USGS 657[2]

Table A.2.1 DWR/IEP and USGS water quality monitoring stations used in combination with DWR DAYFLOW values $Qwest$ and $Qrio$ to approximate Delta loads. After 1995, when both station D24 and D16 were dropped, there were gaps in the record that were filled by multivariate linear regression from nearby stations whose monitoring continued past 1995 (regression results are shown here).

[1]Stations used by Jassby and Cloern (2000)

[2]Regression against D24 not possible because data from these two stations never coexisted

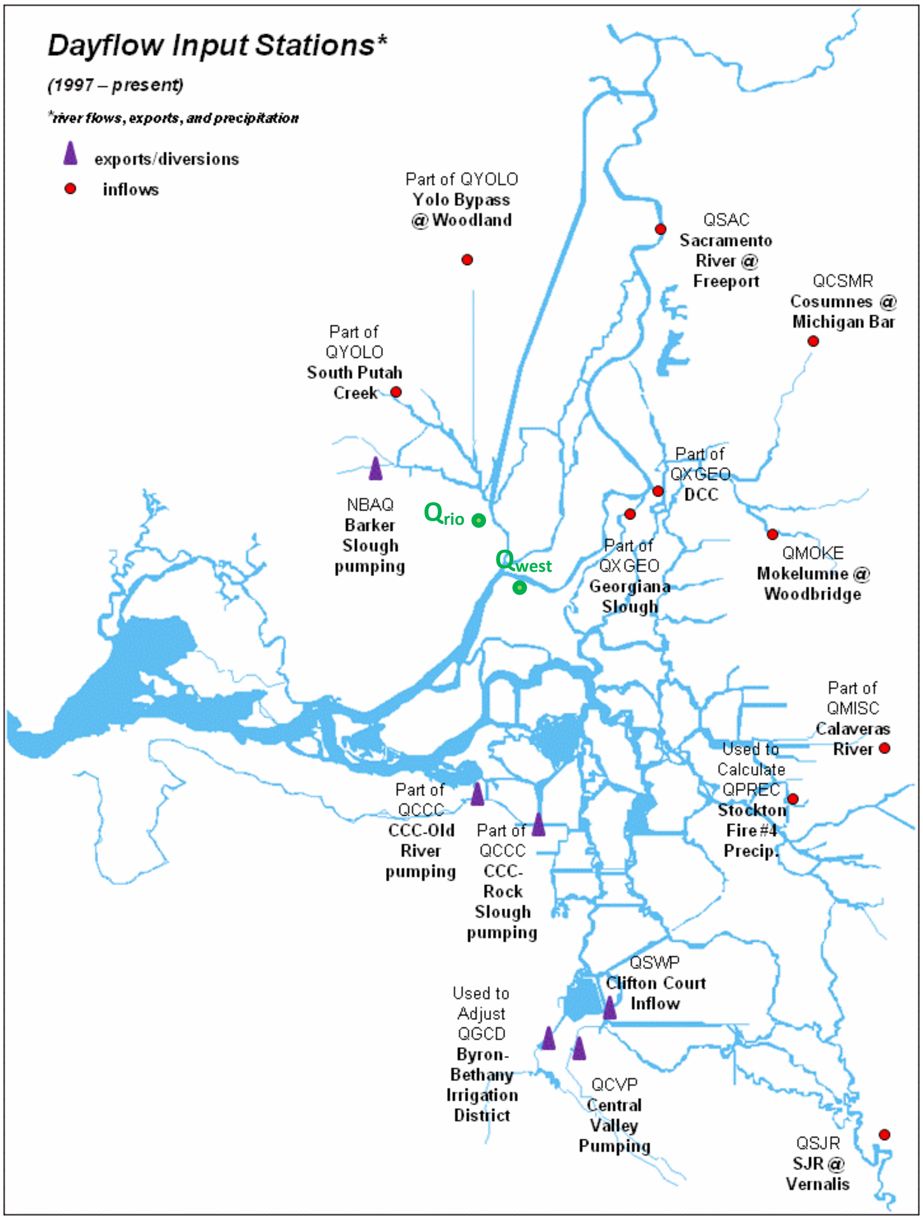


Figure A.2.1 Location DWR DAYFLOW gages (indicated by purple triangles). The values used in our estimation, $Qwest$ and $Qrio$ are calculated according to the following formulas and give approximation of flow past the points indicated above.

$Q_{WEST} = Q_{SJR} + C_{SMR} + Q_{MOKE} + Q_{MISC} + Q_{XGEO} - Q_{EXPORTS} - Q_{MISDV} - 0.65\ (Q_{GCD} - Q_{PREC})$

$Q_{RIO} = Q_{SAC} + Q_{YOLO} - Q_{XGEO} - 0.28\ (Q_{GCD} - Q_{PREC})$

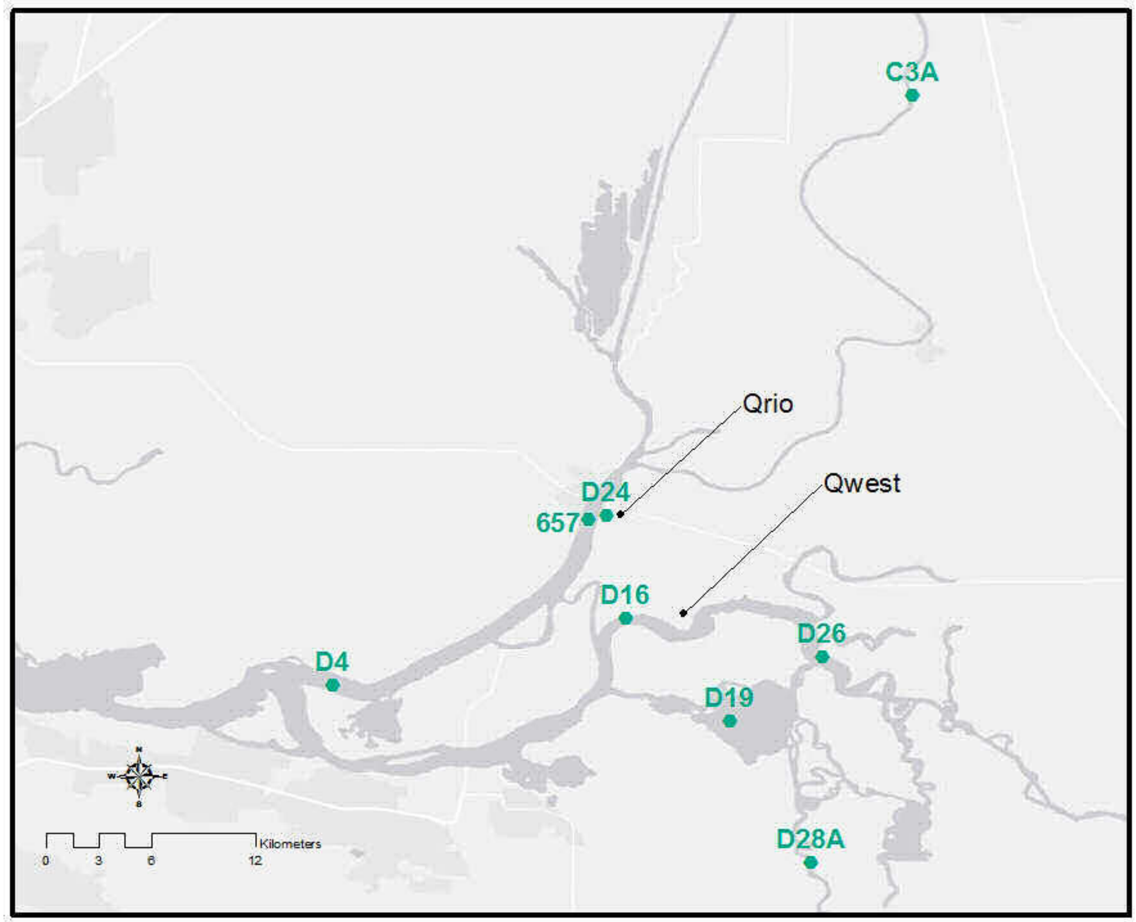


Figure A.2.2 Location of DWR/IEP and USGS water quality stations used in Delta loads estimate, as well as location of flow estimates.

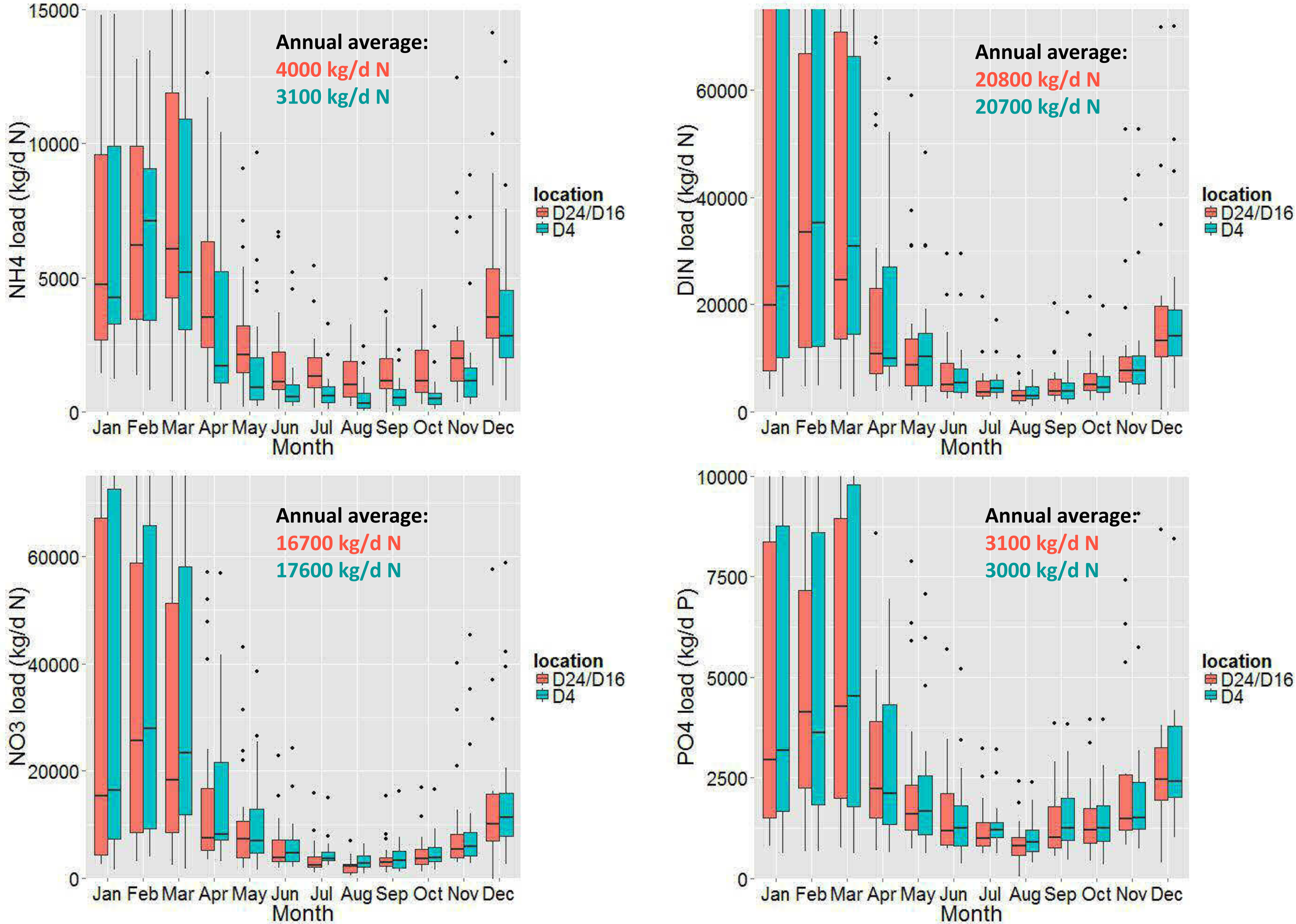


Fig A.2. 3 Comparisons of Delta efflux load estimates when stations D24/D16 are used in calculations (those used in Jassby and Cloern, 2000 and in this report) vs. when station D4 is used (closer to the mouth of Suisun Bay). While on average, the NH_4^+ load decreases by 30% (approximately 860 kg/d N) and the NO_3^- load increases by 10% (approximately 850 kg/d N) between these two locations, DIN loads change by less than 5%. Note the different scales on the y-axis.

Appendix 3

A.3.1: Estimating NH4+ loss in Suisun Bay with a 1-box model

In order to evaluate the role of Suisun Bay in transforming incoming NH_4^+ loads, we performed a 1-box mass balance using a well-mixed Suisun Bay as the control volume. We first performed a salinity balance in order to quantify tidal flows, and then performed a NH_4^+ balance to evaluate the residual transformation/loss term. Analyses focused on 2006-2011, when data from all load sources was most certain, and was limited to April-October, when residence time in Suisun Bay tends to be longest and when phytoplankton blooms have been historically observed. For these months, we assumed steady-state. Evaluation of assumptions is included in the description of each model.

Estimates of loads in and out were made using advective flow estimates from DWR DAYFLOW, tidal flow estimates from the salinity balance performed below, and concentration measurements from DWR/IEP and USGS monitoring stations. DAYFLOW measurements were extracted for the exact dates of DWR/IEP concentration measurements. The location of the flow and concentrations monitoring stations is shown in Figure A.3.1.1

<u>Salinity Balance</u>

To simplify our 1-box model, we made the following assumptions:

1. Treated Suisun as a well-mixed control volume
2. Steady state
3. Tidal dispersion on upstream side (exchange with D19, 657) considered negligible

The terms used in our mass balance were the following, and we solved for Q_{tide}:

1. S_{river} = flow-weighted average of S_{D19} and S_{657}
2. S_{su} = average(S_{D6}, S_{D7}, S_{D8})
3. $S_{sp} = S_{D41}$
4. $Q_{adv} = Q_{west}+Q_{rio}$
5. V_{su} = volume of Suisun Bay, 6.54e11 L

Further explanation of the terms and schematic for the salinity balance are given in Fig. A.3.1.2.

<u>Evaluation of assumptions</u>

Assumption #1 may introduce the greatest amount of uncertainty, since Suisun Bay is not particularly well-mixed with respect to salinity (Fig. A.3.1.3). In future modeling efforts, a multi-box model, using smaller well-mixed volumes, could improve estimates of Qtide. With regards to Assumption #2, although salinity is not truly steady state during April-October, the most rapid changes in salinity occur outside of these months and including non-steadiness in our model only changed the final k values by less than 7%. Assumption #3 appears to be the most valid. Salinity in the Sacramento and San Joaquin rivers is negligible and can be considered outside of tidal influence.

<u>NH_4^+ Balance</u>

We used the resulting value of $Qtide$: in an NH_4^+ mass balance, where the made the following assumptions:

1. Treated Suisun as a well-mixed control volume
2. Steady state
3. Tidal dispersion on upstream side (exchange with D19, 657) considered negligible
4. Assume loading from CCCSD mixes uniformly into Suisun Bay

We used the following terms on our model, and solved for $V_{su}k_{loss}C_{su}$(total losses, kg-d^{-1}) and k_{loss} (loss rate, d^{-1}):

1. C_{river}= flow-weighted average of C_{D19} and C_{657}
2. C_{su}= average(C_{D6}, C_{D7}, C_{D8})
3. C_{sp}= $= C_{D41}$
4. $Q_{adv} = Q_{west}+Q_{rio}$
5. V_{su} = volume of Suisun Bay, 6.54e11 L
6. $M_{discharge}$= M_{CCCSD}+ M_{FSSD}
7. Q_{tide} was solved for using the salinity balance

Further explanation of the terms and schematic for the NH_4^+ balance is given in Fig. A.3.1.4.

<u>Evaluation of Assumptions</u>

NH_4^+ concentrations at D6, D7 and D8 appear similar, supporting assumption #1 (Fig. A.3.1.5). However, this might be masking the influence of multiple NH_4^+ sources into Suisun Bay. We hypothesize that NH_4^+ concentrations actually decrease seaward from the Delta due to transformations/losses, but that CCCSD outfall just prior to D6 elevates concentrations to levels similar to those from Delta efflux. While the result corroborates our assumption of well-mixed Suisun, additional modeling on a finer spatial scale would likely reveal concentration gradients not captured by current monitoring. Regarding assumption #2, summertime NH_4^+ concentrations are less variable than they are at other times of the year. On average, concentrations between April and October vary by a factor of roughly 2, while concentrations on the entire year vary by a factor of 4. Assumption #3 has the potential to, if anything, underestimate the loading of NH_4^+ into Suisun Bay. If we included a tidal dispersion term on the upstream end, this would bring high-NH_4^+ waters from the Sacramento and San Joaquin rivers and would only increase the magnitude of observed losses in Suisun Bay. Lastly, assumption #4 may be overestimating the magnitude of NH_4^+ loads from CCCSD. In order to evaluate the importance of this assumption, we performed our calculations assuming 100%, 75%, 50% and 25% of CCCSD plume mixing in Suisun Bay prior to advection downstream. Loads in exceeded loads out for all months analyzed

(Figure A.3.1.6). On average, 75% of loads in are transformed or lost prior to flow out of Suisun Bay (either by advection or tidal flow)

Results

Loads in exceeded loads out for all months analyzed (Figure A.3.1.6). On average, 75% of loads in are transformed or lost prior to flow out of Suisun Bay (either by advection or tidal flow). First order loss rates were estimated at 0.1-0.3 d^{-1}, even when some of CCCSD effluent is considered lost downstream to advection prior to mixing into Suisun Bay.

We performed sensitivity analyses in order to evaluate the validity of some of our key assumptions. First, based on small variation of NH_4^+ concentrations in April-October (Figure A.3.1.5), we assumed steady state conditions. As a comparison, we did a non-steady model and our resulting values for k vary by less than 7%, indicating that our steady-state assumption is valid. Secondly, the most uncertain term in our mass balance is the tidal flow, which we calculated using a salinity balance that itself contained simplifying assumption. We performed a sensitivity analysis in order to evaluate the effect of this parameter on our overall results. We found that if our value for tidal flow was off by a factor of 5, the contribution of transformations/losses to the overall fate of NH_4^+ dropped from 75% to 60%, which would still be a significant contribution.

Figures and Tables

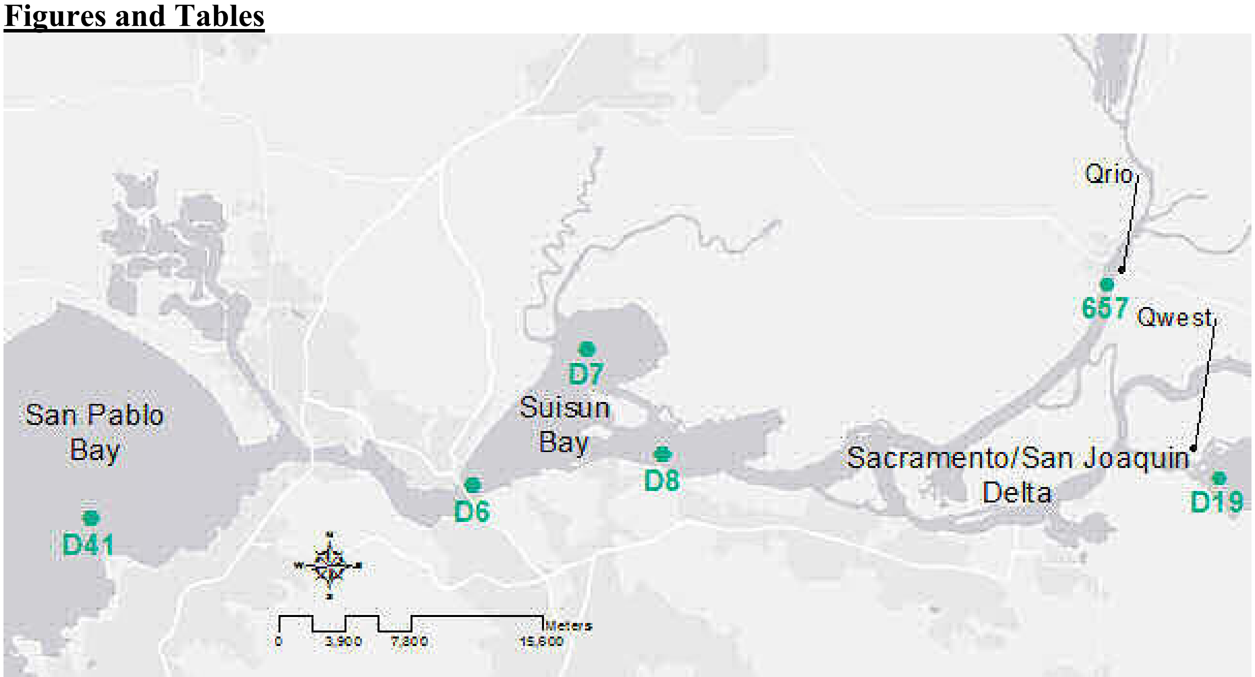
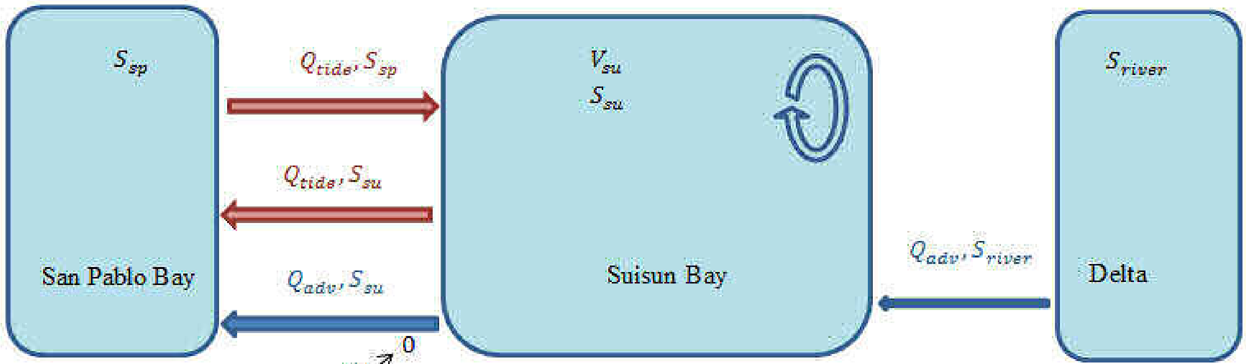


Figure A.3.1.1 Location of DWR/IEP and USGS monitoring stations (used as concentration terms) and DWR DAYFLOW stations (used as flow terms) in 1-box model for Suisun Bay. Tidal flows were estimated from a salinity balance (Fig. A.3.1.2).



$$\cancelto{0}{V_{su}\frac{dS_{su}}{dt}} = Q_{adv}S_{river} + Q_{tide}S_{sp} - Q_{adv}S_{su} - Q_{tide}S_{su}$$

$$Q_{tide} = \frac{-Q_{adv}(S_{river} - S_{su})}{S_{sp} - S_{su}}$$

Figure A.3.1.2 Salinity mass balance schematic used to approximate the magnitude of *Qtide*.

1. S_{river} = flow-weighted average of S_{D19} and S_{657}
2. S_{su} = average(S_{D6}, S_{D7}, S_{D8})
3. $S_{sp} = S_{D41}$
4. $Q_{adv} = Q_{west} + Q_{rio}$
5. V_{su} = volume of Suisun Bay, 6.54e11 L

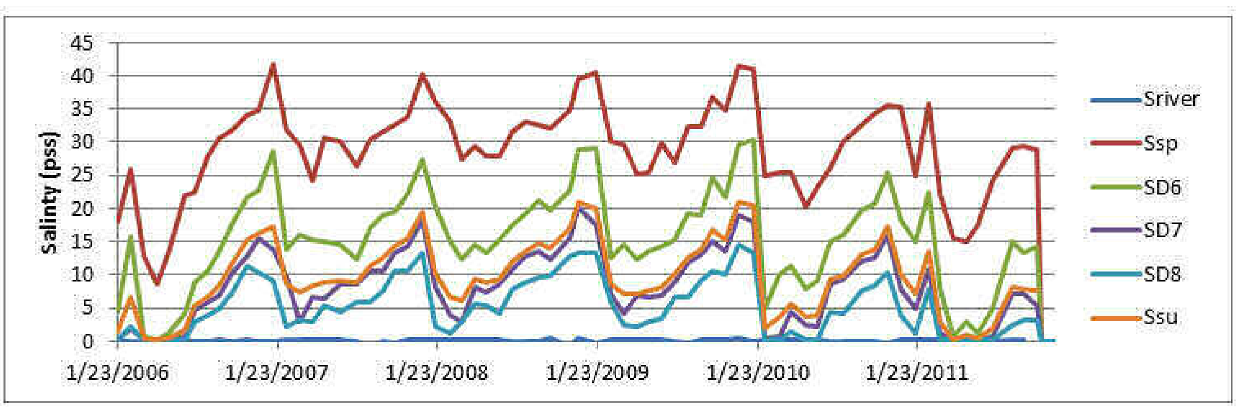
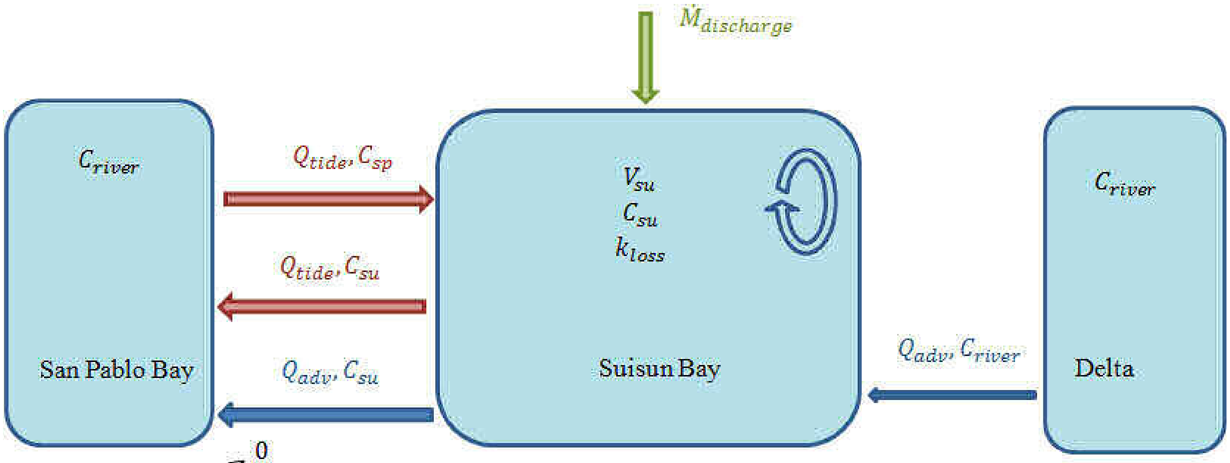


Figure A.3.1.3 Times series of salinity at locations used in mass balance (Only April-October were considered for the mode). *Sriver* is the flow weighted average of salinity at DWR/IEP D19 (San Joaquin River dominated) and USGS 657 (Sacramento River dominated), *Ssp* is salinity at DWR/IEP D41 and *Ssu* is the average of salinity at DWR/IEP D6, D7 and D8. This figure shows that Suisun Bay is not particularly well mixed with respect to salinity and making a well-mixed assumption may introduce uncertainty. *Sriver* was negligible and therefore we neglected tidal dispersion on the upstream end of Suisun Bay



$$\cancelto{0}{V_{su}\frac{dC_{su}}{dt}} = Q_{adv}C_{river} + Q_{tide}C_{sp} + \dot{M}_{discharge} - Q_{adv}C_{su} - Q_{tide}C_{su} - V_{su}k_{loss}C_{su}$$

$$V_{su}k_{loss}C_{su} = Q_{adv}(C_{river} - C_{su}) + Q_{tide}(C_{sp} - C_{su}) + \dot{M}_{discharge}$$

Figure A.3.1.4 Salinity mass balance schematic used to approximate the magnitude of NH_4^+ losses in Suisun Bay.

1. C_{river}= flow-weighted average of C_{D19} and C_{657}
2. C_{su}= average(C_{D6}, C_{D7}, C_{D8})
3. C_{sp}= $= C_{D41}$
4. $Q_{adv} = Q_{west}+Q_{rio}$
5. V_{su} = volume of Suisun Bay, 6.54e11 L
6. $M_{discharge}$= M_{CCCSD}+ M_{FSSD}
7. Q_{tide} was solved for using the salinity balance

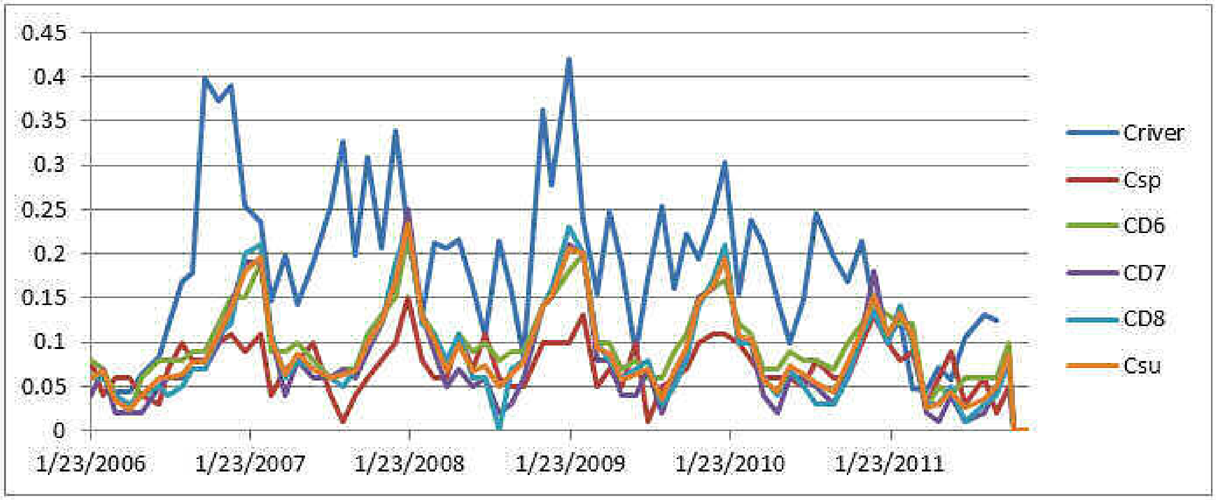


Figure A.3.1.5 NH_4^+ concentrations at locations used in mass balance. *Criver* is the flow weighted average of NH_4^+ at DWR/IEP D19 (San Joaquin River dominated) and USGS 657 (Sacramento River dominated), *Csp* is NH_4^+ at DWR/IEP D41 and *Csu* is the average of NH_4^+ at DWR/IEP D6, D7 and D8. NH_4^+ is reasonably well-mixed with respect to salinity. In our calculation, we neglected upstream dispersion in Suisun Bay (see Figure A.3.1.3), however given the high concentrations of NH_4^+ in the rivers, if anything this omission underestimates NH_4^+ loads to Suisun Bay and therefore underestimates the magnitude of NH_4^+ losses.

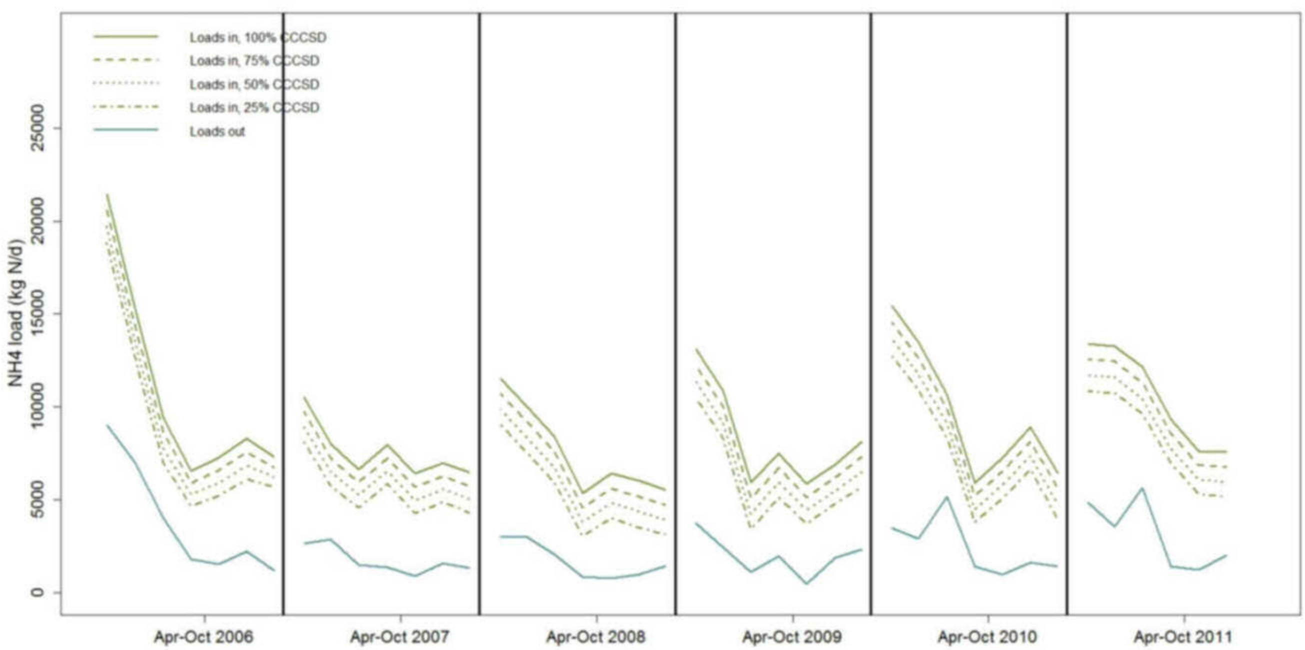


Figure A.3.1.6 Differences between NH_4^+ loads into Suisun Bay (including advective loads, tidal downstream tidal loads and discharger loads assuming various amounts of CCCSD effluent mixing; green line) and NH_4^+ loads out of Suisun Bay (including advective loads and downstream tidal loads). The difference between loads in and loads is an estimate of the magnitude of NH_4^+ losses in Suisun Bay (kg d^{-1}). Even when only 25% of CCCSD plume was allowed to mix into Suisun Bay prior to advecting downstream, loads in always exceeded loads out by as much as 2-3 times. First-order loss rates are presented in Fig. A.3.1.7.

A.3.2: Estimating exchange between subembayments

Exchange between subembayments was not broadly considered in this report because of complex hydrodynamics in many regions, however exchange between Suisun Bay and San Pablo Bay was relatively easy to approximate. Based on the results of the 1-box model for NH_4^+, on average advection accounted for approximately 95% of all loads from Suisun Bay to San Pablo Bay/Carquinez and therefore tidal loads were omitted from estimates of exchange.

Loads exchanged from Suisun Bay to San Pablo Bay/Carquinez Strait accounts for both loads coming into Suisun Bay from the Delta and POTW loads directly discharged into Suisun Bay, and were calculated in the following way:

$$Load = Qadv \times Csu$$

where

$$Qadv = Qwest + Qrio$$

$$Csu = average(CD6, CD7, CD8)$$

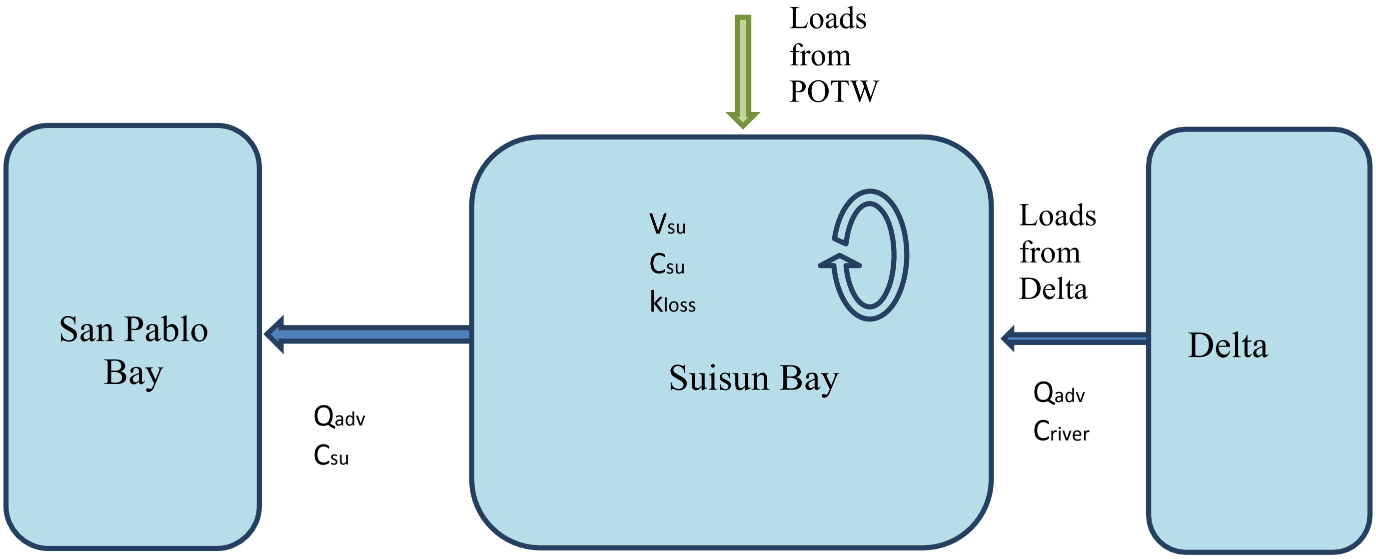


Figure A.3.2.1 Schematic for estimating loads exchanged from Suisun Bay to San Pablo Bay, including both loads into Suisun Bay from the Delta and direct POTW discharges to Suisun Bay. Only advective loads were considered, which account for 95% of overall transport (based on the 1-box model described in section A.3.1.

Appendix 4: Analysis of Year 1 effluent data

To: BACWA and San Francisco Bay Regional Water Quality Control Board staff
From: David Senn and Emily Novick
Date: October 8 2013
Re: Year 1 Effluent Nutrient Data - Initial Observations

1. Introduction

At the request of BACWA and Regional Board staff, SFEI reviewed a subset of the Year 1 POTW effluent characterization data whose collection was required under the 13267 Letter[1] issued by the Regional Board in 2012.

The review was motivated by two questions that have been raised by the discharger community:

1. How will the monitoring data be used, in particular through modeling?

2. Based on the Year1 effluent characterization data, and the anticipated data uses, could some analytes be dropped during Year 2, either because they are unlikely to be used in modeling, or because they provide limited additional information given the other analytes?

To explore these questions, we analyzed effluent data from July 2012-June 2013 from the 8 largest POTWs (based on flow rate) and two additional POTWs with somewhat unique discharge requirements and advanced treatment (Napa and Sunnyvale). In addition to being among the largest contributors of nutrient loads to the Bay, these POTWs also represent a wide range of treatment processes and are geographically well-distributed throughout the region. Typical estuarine water quality model input requirements were also considered and compared with the analyte list. Although evaluating data quality was not the primary purpose of this effort, we do comment in a limited way on some issues that became evident during data analysis. For completeness, Year 1 data from all POTWs that participated in the effluent characterization study is briefly summarized in Table A.4.3.

This report is intended as a broad-brushstroke overview. It aims to describe general trends and identify seasonal and inter-POTW differences in effluent composition and relative importance of N and P forms that will help address the two questions above.

2. Data and Approach

Table A.4.1 identifies the ten wastewater treatment plants that were selected. Each of these dischargers was required to sample and analyze effluent 1-2 times per month for the analytes noted in Table A.4.2.

In evaluating the first year's effluent data, the main considerations were:

[1] Link to 13267 Letter

1. How consistent was effluent composition (concentrations) within individual POTWs over the course of the year?
2. How large were the inorganic vs. organic forms of N, and dissolved vs. particulate organic forms of N? How much did their proportions vary over the year?
3. How large were the particulate vs. dissolved forms of P, and the "reactive" vs. non-reactive forms of dissolved P? How much did their proportions vary over the year?
4. For any parameters, do analytical and other uncertainties substantially limit the utility of the results?

To explore these issues, we evaluated the concentrations of measured analytes, and also several calculated parameters (Table A.4.2). Since urea is not being measured in Year 2, urea data was not considered in this report.

3. Main Observations

Flows and loads of N and P are shown in the upper left panel of Figures 1-10 and 11-20, respectively. The upper right panels in Figures 1-10 and 11-20 present concentrations of N and P species, respectively. The bottom left panels in each figure present the proportion of N in organic and inorganic forms (Figures 1-10) and the proportion of P in dissolved and particulate forms (Figures 11-20). Finally, the bottom right-hand panels in Figures 1-10 and 11-20 present the concentrations of TON and DON, and the proportions of TDP present as DIP and DUP, respectively.

3.1 Typical water quality model load input requirements, and limitations of laboratory measurements

Many widely used estuarine water quality models consider multiple nutrient parameters, both in terms of external loads, and as nutrient forms in the water column or in the sediments:

1. NH_4^+ or NH_3
2. NO_3^- + NO_2^- (typically these are combined as opposed to considered separately)
3. ortho-phosphate or DIP
4. PON
5. DON
6. POP
7. DOP
8. reactive phosphorous complexed by mineral particles such as iron oxides

Some water quality models also consider a range of reactivities, or labilities, for PON, DON, POP, and DOP. The reactivities are typically not determined from monitoring data, but rather through experimentation, literature estimates, or through model calibration.

The current set of effluent characterization analytes (Table A.4.2) are either the actual input parameter required by models, or are parameters that are needed to indirectly estimate (e.g., by subtraction) an input parameter. For example, in POTWs effluent:

$PON = TON - DON = (TKN-NH_4^+) - (SKN-NH_4^+) = TKN - SKN$

and

POP = TP - TDP (assuming that non-organic forms of particulate P are negligible)

and

DOP = TDP - DIP

Uncertainties about the actual chemical form being measured can be nontrivial, especially when the measured value is sensitive to sample preparation or when a parameter is actually calculated from two or more analytes. Many chemical measurements are actually "operationally-defined", in the sense that they are the best estimate or approximation of the target chemical form. In the case of NO_3^- or NO_2^-, the measured value is likely to be a good estimate of the true concentration in the sample, because both NO_3^- and NO_2^- are 100% dissolved and responsive to the analytical reagents, and the analytical techniques are well-established. However, the value measured for TN or TP may vary depending on the sample pretreatment method used, and how completely that pretreatment liberates N or P. For so-called "dissolved" analytes that can be present in both dissolved and particle-complexed forms (e.g. P), a sample is first passed through a filter. The pore size of the filter used, and the sharpness of its cutoff, can influence what gets counted as dissolved or particulate, both because of the presence of small particles (colloids) that pass through the filter, and because the effective pore size of filters can decrease as more sample is filtered (due to filter clogging). In the end, when determining what measurements to do, there is reason to consider the accuracy and uncertainties of the measurements (and any subsequent calculations), the relative importance or sensitivity of the modeling results to a particular loading parameter, and the cost.

3.2 Flows and N & P loads

- Several POTWs exhibited strong seasonal variability in flows and/or loads, with 20-40% higher flows and loads common during wet months compared to drier months.
  - Sunnyvale loads of N and P were 3 and 1.5-2 times higher, respectively, in wet/winter months than dry weather months
  - San Jose loads of N and P were ~1.5 and 5 times higher, respectively, in wet/winter months than dry weather months.
- The load increases at some POTWs during wet winter months are likely due in large part to a combination of shorter residence time and lower temperature (resulting in lower biochemical removal efficiency), since any water that infiltrated into sewer lines and caused higher flows would have had relatively low N and P concentrations.

3.3 Nitrogen

3.3.3 Inorganic N

- As expected, dissolved inorganic nitrogen (DIN) dominated total N at all POTWs (bottom left panel in Figures 1-10).
- Also as expected, all POTWs, with the exception of Sunnyvale and Napa, exhibited a strong dominance of either NO_3^- or NH_4^+ (top right panel in Figures 1-10), with the other form being a minor constituent. During winter months, Sunnyvale effluent contained NO_3^- and NH_4^+ at comparable concentrations because of the well-documented decreased efficiency of nitrification in its effluent ponds. A mixture of NO_3^- and NH_4^+ was also observed in Napa effluent at several time points .
- In all POTWs, NO_2^- represented only a minor portion of DIN (generally <5%) (top right panel in Figures 1-10). During several sampling events in December, NO_2^- concentrations

increased in San Jose effluent and comprised as much as 25% of DIN, but returned to low levels by January, and continued to be low thereafter.

- DIN concentration varied widely among POTWs. DIN was lowest at San Jose (10-15 mg L^{-1}) and Napa (10-15 mg L^{-1}), and during a few warm months at Sunnyvale (~15 mg L^{-1}). San Jose and Napa have advanced treatment for N removal, and denitrification occurs at seasonally-varying rates in Sunnyvale's effluent ponds. DIN concentrations were highest in effluent from EBMUD (35-45 mg L^{-1}, with one very low value during high flows), SFSE (generally 30-40 mg L^{-1}, with a few lower values), and South Bayside (30-45 mg L^{-1}), and were greater than rule-of-thumb estimates for DIN (20-30 mg L^{-1}) in secondary treated effluent (BACWA, 2011). The elevated values at EBMUD were expected (because of animal waste additions), but the reason for the relatively high concentrations at South Bayside and SFSE are not known. In the case of SFSE the DIN concentrations measured during 2012-2013 are consistent with earlier data included in the recent draft loading study (Novick and Senn, 2013). Even the somewhat lower levels observed at EBDA (~30 mg L^{-1}), Fairfield-Suisun (several months ≥ 30 mg L^{-1}), and Palo Alto (highly variable with several months ≥ 30 mg L^{-1}) were consistently at or above the upper end of the rule-of-thumb range for DIN.

3.3.4 Organic N, and Particulate vs. Dissolved Organic N

- TON ranged between 10-20% of TN at most POTWs. Fairfield-Suisun and Palo Alto were exceptions, where TON was ≤ 5% of TN. At Sunnyvale, the TON proportion appeared to vary seasonally, comprising nearly 20% in warm months and ~10% in winter months.
- Both TON and DON are calculated parameters (TKN - NH_4^+ and SKN - NH_4^+, respectively). In cases when most of the DIN is present as NH_4^+, the calculated TON and DON values represent small difference between between two relatively large numbers, each of which has analytical uncertainty and sample-related uncertainty (if measurements were conducted on different samples). For that reason, of all the analytes, TON and DON might be expected to have the largest relative uncertainty (e.g., standard deviation / mean). This uncertainty needs to be taken into account when comparing the magnitudes of TON and DON in a given sample, and when considering the variability in their concentrations over time.
- Of all the N forms, TON and DON exhibited the greatest relative variability (Figures 1-10, bottom right panel). Much of this variability likely owes to them being calculated by difference (see bullet above). Note also, though, that the y-axis scales for the TON and DON graphs.
- In general, TON concentrations were comparable to or less than rule-of thumb concentrations for plants that do not nitrify effluent (~5 mg L^{-1}). Overall, TON for the POTWs investigated in this report fell between 2-5 mg L^{-1}, with a few being consistently lower than 2 mg L^{-1} (Fairfield-Suisun, Palo Alto, San Jose), and EBMUD frequently exceeding 5 mg L^{-1}.
- Despite the variability and uncertainty, TON was generally greater than DON, as would be expected if particulate organic nitrogen (PON) was present. At some POTWs PON represented as much as 50% of TON, and was on the order of 1-3 mg L^{-1}. While 50% is a relatively large proportion of TON, PON nonetheless remained a small percentage of TN (<5-10%). At POTWs that perform filtration, PON should be even smaller. On average, PON

does appear to be lower in San Jose effluent than at several of the other large POTWs (e.g., EBMUD, CCCSD, EBDA). However, San Jose also has lower TN due to biological nitrogen removal, and the observed lower PON may be due to both N removal and filtration.

3.3 Phosphorous

3.3.1 Total Phosphorous

- In general, TP showed considerable inter-monthly or seasonal variability within individual POTWs (e.g., ±50% or more; upper right panel in Figures 11-20). EBDA was an exception, where TP was still variable but over a relatively narrow range (±20%).
- While at most POTWs TP variations were not obviously systematic or seasonal, pronounced seasonality was evident at Fairfield-Suisun, San Jose (10-fold higher concentrations in winter than summer), Sunnyvale, and Palo Alto.
- TP concentrations differed substantially among POTWs. Lowest values were measured at CCCSD (<1.5 mg L^{-1}) and Napa (<1.5 mg L^{-1}), and during warm-weather months at San Jose (<0.5 mg L^{-1}). Highest concentrations were seen at Sunnyvale (up to 6-8 mg L^{-1}), Fairfield-Suisun (up to 4-5 mg L^{-1}), Palo Alto (up to 4-5 mg L^{-1}), and EBMUD (up to 4-5 mg L^{-1}). With the exception of Sunnyvale during some months, the observed concentrations were comparable to or considerably lower than rule-of-thumb TP concentrations for secondary treatment (4-6 mg L^{-1}).

3.3.2 Dissolved vs. Particulate P

- In general, >80% of TP was measured in the dissolved phase across most POTWs (bottom right panels in Figures 11-20). At some POTWS, TP was >95% in the dissolved phase. Some POTWs (Fairfield-Suisun, Palo Alto, Sunnyvale, and occasionally San Jose). The proportion of dissolved P occasionally dipped as low as 60% at CCCSD; the relatively larger swings may be due in part to its already low TP.
- Apparent analytical or reporting issues with SFSE and Napa P data make it difficult to interpret their reported levels.

3.3.3 Reactive vs. unreactive dissolved P

- The proportions of reactive (DIP) vs. unreactive (DUP) dissolved phosphorous were highly variable among POTWs. For example, >90-95% of TDP was present as DIP in effluent from Palo Alto and Sunnyvale. At other POTWs (e.g., CCCSD and EBMUD), DIP ranged from 60-90% of TDP.
- Like DON and PON, DUP is a calculated value and a small difference between two relatively large values. DIP in many cases was comparable to TDP; in some cases the values were likely indistinguishable given their individual analytical uncertainties (this is evident from the number of DIP proportions that exceed 1). In other cases, there seems to be a clear systematic difference between TDP and TRP (e.g., EBMUD, CCCSD, EBDA).

4. Recommendations

- Overall, the nutrient-related analytes (i.e. Table A.4.2) defined in the 13267 letter are a reasonable list for characterizing effluent the Year 1 program and for continued measurement in Year 2, both with respect to limited amount of historic data on effluent composition and likely data usages.
- Based on a preliminary analysis of effluent characterization and load data from Year 1, an additional year of effluent characterization, based on this list of parameters, appears justified. Seasonal variability in composition and loads, inter-POTW variability, and analytical uncertainty were all substantial enough in Year 1 that an additional year of data collection would help better define N and P loads and the abundance of major and minor nutrient forms. The need for additional data is particularly true considering that, at a number of POTWs, little historic data was available prior to the current monitoring effort on most forms of P, organic N, and speciation of inorganic N.
- Calculated PON represents a fairly small percentage of TN. For that reason, it may seem that distinguishing between TON, PON, and DON is unnecessary, and that one parameter (i.e., SKN) could be dropped from the analyte list. However, PON has a different fate than DIN and DON once entering receiving waters; PON will tend to settle and accumulate in sediments. Before a decision can be made about whether a parameter like SKN can be dropped from the analyte list, the relative importance of PON and its fate needs to be considered. For example, assume: on an annual basis only 10% of DIN that enters the Bay is converted into phytoplankton biomass; some percentage of that newly produced phytoplankton biomass (e.g., 50%, probably a high number) settles and accumulates in the Bay sediments (the remainder is recycled in the water column or transported out of the Bay as phytoplankton biomass); in this example, the 5-10% of TN that leaves POTWs in the form of PON would be comparable in magnitude to settling phytoplanktonas a PON source to the Bay's sediments. For this reason, alongside the uncertainty in the concentrations (in part due to the short time-series and data quality issues), continuing to measure both TKN and SKN seems justified.
- Of all the parameters, 2-3 may warrant further discussion as to whether they are high value and essential, or could potentially be dropped. That decision might be better made after an additional year of data. The cost of doing these measurements needs to be considered relative to the potential gains in terms of the data (or lack there of) would be used.
    - Given the analytical uncertainty and close correspondence between TDP and TRP, it may be reasonable to argue that only one of these parameters needs to be measured.
    - A case could also be made that NO_2^- is not necessary. However NO_2^- is probably among the least expensive measurements (and depending on the measurement technique is obtained anyway during NO_3^- analysis (if measured by ion chromatography)), and may provide useful diagnostic information about treatment plant operation.
    - A case might also be made that the analytical uncertainties are large enough that PON and DON can not be realistically distinguished. More detailed analysis of current data (and QA/QC data, such as replicates, analytical precision, etc.) would be needed to make the case that SKN might be a candidate for dropping.

- A coordinated data QA/QC plan is needed. Over the first year of sampling (July 2012 - June 2013) individuals from the BACWA Permits Committee and Regional Board staff reviewed data on a quarterly basis, and again at the close of the year. Those data checks proved essential for catching errors either in reporting or laboratory analyses. Nonetheless, there appear to be some remaining issues. Detailed QA/QC of the data was not among this reports goals. Some immediate action may be needed based on apparent data quality issues with some POTWs reported data, so that any analytical issues can be addressed early in Year 2 to ensure usable data for some problematic parameters. A first step along would be a coordinated review of Year 1 data.
- In addition, an on-going data analysis plan needs to be established, and become of regular monitoring program data analysis and reporting. This plan also needs to consider eventual data usage.

Table A.4.1 POTWs considered for detailed analysis in this report.

POTW	Average Flow (MGD)
Central Contra Costa Sanitation District (CCCSD)	38
EBDA	63
EBMUD	60
Fairfield-Suisun	14
Napa	11
Palo Alto	21
San Jose	93
San Francisco Southeast (SFSE)	58
South Bayside	13
Sunnyvale	11

Table A.4.2 Analytes and calculated concentrations

Parameter	Measured or calculated	Calculation
NO_3^- - nitrate	measured	
NO_2^- - nitrite	measured	
NH_4^+ - ammonium	measured	
TKN - Total Kjeldahl Nitrogen	measured	
SKN - Soluble Kjeldahl Nitrogen	measured	
TN = Total Nitrogen	calculated	TN = TKN + NO3 + NO2
TDN = Total Dissolved Nitrogen	calculated	TDN = SKN + NO3 + NO2
TON - Total organic N (TON), the total amount of organically-complexed N in the sample, including both particulate and dissolved forms,	calculated	TON = TKN - NH_4^+
DON - Dissolved organic nitrogen (DON), he amount of organically-complexed nitrogen that passes through a specified filter pore size (often 0.4 µm),	calculated	DON = SKN - NH_4^+
PON - particulate organic nitrogen	calculated	PON = TON - DON
TP - total phosphorous	measured	
TDP - total dissolved phosphorous	measured	
DIP - dissolved inorganic phosphorous	measured	
TPP - total particulate phosphorous, which would include particualte organic phosphorous (POP) + any mineral-complexed P, which would be expected to be small.	calculated	TPP = TP - TDP
DUR - dissolved non-reactive phosphorous, an approximation for dissolved organic P (DOP)	calculated	DUR = TDP - DIP

Table A.4.3 A comparison POTW effluent concentrations and loads for select nutrients between the first 6 months (Q3/Q4 2012) and full first year of data.

		Flow		NH_4^+ (mg/L)		NH_4^+(kg/d)		NO_3^- (mg/L)		NO_3^-(kg/d)		DIN (kg/d)		**Change in DIN loads**	DIP (mg/L)		DIP (kg/d)		**Change in DIP loads**
		Q3/4 2012	Yr 1 avg	Q3/4 2012	Yr 1 avg	Q3/4 2012	Yr 1 avg	Q3/4 2012	Yr 1 avg	Q3/4 2012	Yr 1 avg	Q3/4 2012	Yr 1 avg		Q3/4 2012	Yr 1 avg	Q3/4 2012	Yr 1 avg	
Lower South Bay	SJSC	92	93	0.8	0.8	277	288	11.3	12.4	3929	4359	4451	4832		0.4	0.8	159	287	
	Palo Alto	22	21	0.1	0.1	12	12	26.4	28.5	2157	2261	2184	2282	**6%**	4.2	4.2	339	331	**10%**
	Sunnyvale	10	11	7.2	6.2	371	334	18.3	17.7	629	640	1042	1018		6.7	5.3	244	199	
South Bay	EBDA	62	63	28.0	28.7	6584	6843	2.3	2.6	548	623	7512	7873		1.7	1.8	396	441	
	SF Southeast	54	58	34.5	33.3	7032	7267	1.8	1.9	357	421	7583	7822		1.4	1.1	291	236	
	SBSA	13	13	40.1	38.1	2036	1893	0.6	1.1	30	54	2081	1965		4.0	3.6	202	177	
	San Mateo	11	11	29.2	29.6	1160	1234	1.6	1.8	79	86	1296	1372	**3%**	2.6	2.5	106	104	**-2%**
	SSF-SB	9	9	28.3	23.8	971	809	1.9	3.7	65	123	1093	1010		3.0	3.2	101	109	
	Burlingame	3	3	24.0	27.5	263	314	2.7	4.8	33	55	302	372		6.2	6.8	71	78	
	Millbrae	2	2	39.2	40.1	222	230	0.1	0.1	1	1	224	233		2.6	2.3	14	13	
	SFO	1	1	37.7	51.0	155	215	3.9	3.9	16	16	177	238		1.6	2.7	7	12	
Central Bay	EBMUD	65	60	35.2	36.8	8073	8066	4.5	4.4	1074	1002	9482	9351		2.9	2.9	695	652	
	CMSA	9	8	32.2	30.2	825	751	2.9	3.2	90	89	936	861		3.3	3.2	111	93	
	W. County/Richmond	9	8	20.9	22.0	643	653	3.2	3.0	148	120	795	776		1.6	1.5	53	47	
	SASM	2	2	3.7	5.4	29	46	15.8	19.5	128	167	161	216	**-1%**	4.4	4.4	35	37	**-7%**
	Sausilito	2	2	8.8	9.7	49	56	12.2	12.9	80	76	135	138		3.6	3.7	21	21	
	Treasure Island	0	0	0.4	0.6	1	1	7.4	7.5	9	9	10	10		3.1	3.0	4	4	
	Marin District 5	1	1	21.0	19.4	49	41	0.5	6.2	1	12	54	57		2.5	3.2	6	6	
San Pablo and Carquinez	Napa	16	11	2.2	2.2	137	114	6.3	7.8	371	286	521	408		1.1	0.9	63	44	
	Vallejo	11	10	9.6	10.6	378	396	7.3	8.2	304	314	714	744		2.8	2.9	109	106	
	Novato	5	5	0.2	0.6	4	11	11.0	11.7	193	210	199	225		0.4	1.2	7	23	
	Sonoma	6	4	0.2	0.3	5	4	13.5	8.1	190	104	194	108		2.6	3.2	44	40	
	Pinole-Hercules	3	3	22.8	21.4	243	217	7.0	8.3	74	82	334	321		3.2	2.7	34	28	
	Petaluma	7	7	0.4	0.3	10	7	1.0	1.1	32	35	42	43		2.4	1.8	63	46	
	Benicia	2	2	25.0	22.5	230	193	0.9	1.4	7	10	266	229	**-5%**	2.8	2.7	25	23	**-8%**
	American Canyon	2	2	0.3	0.3	2	2	9.5	9.2	63	59	65	61		5.0	3.8	31	23	
	Rodeo	1	1	2.5	2.3	5	5	11.2	13.0	30	32	36	38		3.8	3.8	9	9	
	Las Gallinas	2	3	2.7	2.0	27	20	20.3	23.3	185	229	213	250		3.6	3.6	33	35	
	Calistoga	1	1	2.8	7.1	16	22	11.0	7.2	47	30	66	55		2.2	1.6	9	6	
	Yountville	1	0	6.3	4.1	13	7	13.0	10.5	23	15	37	22		3.0	2.4	6	4	
	St. Helena	1	1	8.3	10.7	29	56	0.03	2.0	0.1	12	29	73		3.1	3.8	11	20	
Suisun Bay	CCCSD	37	38	25.1	25.2	3435	3549	1.0	1.4	155	206	3664	3823		0.5	0.6	72	79	
	Fairfield Suisun	14	14	0.03	0.03	2	2	27.1	25.9	1404	1296	1410	1299	**1%**	3.8	3.9	193	192	**1%**
	Delta Diablo	7	7	27.8	29.0	693	774	36.3	34.2	895	876	1644	1693		0.8	0.7	20	17	
	Mt View	2	1	0.5	0.4	7	4	21.3	24.3	130	126	137	131		2.8	3.2	16	16	

N

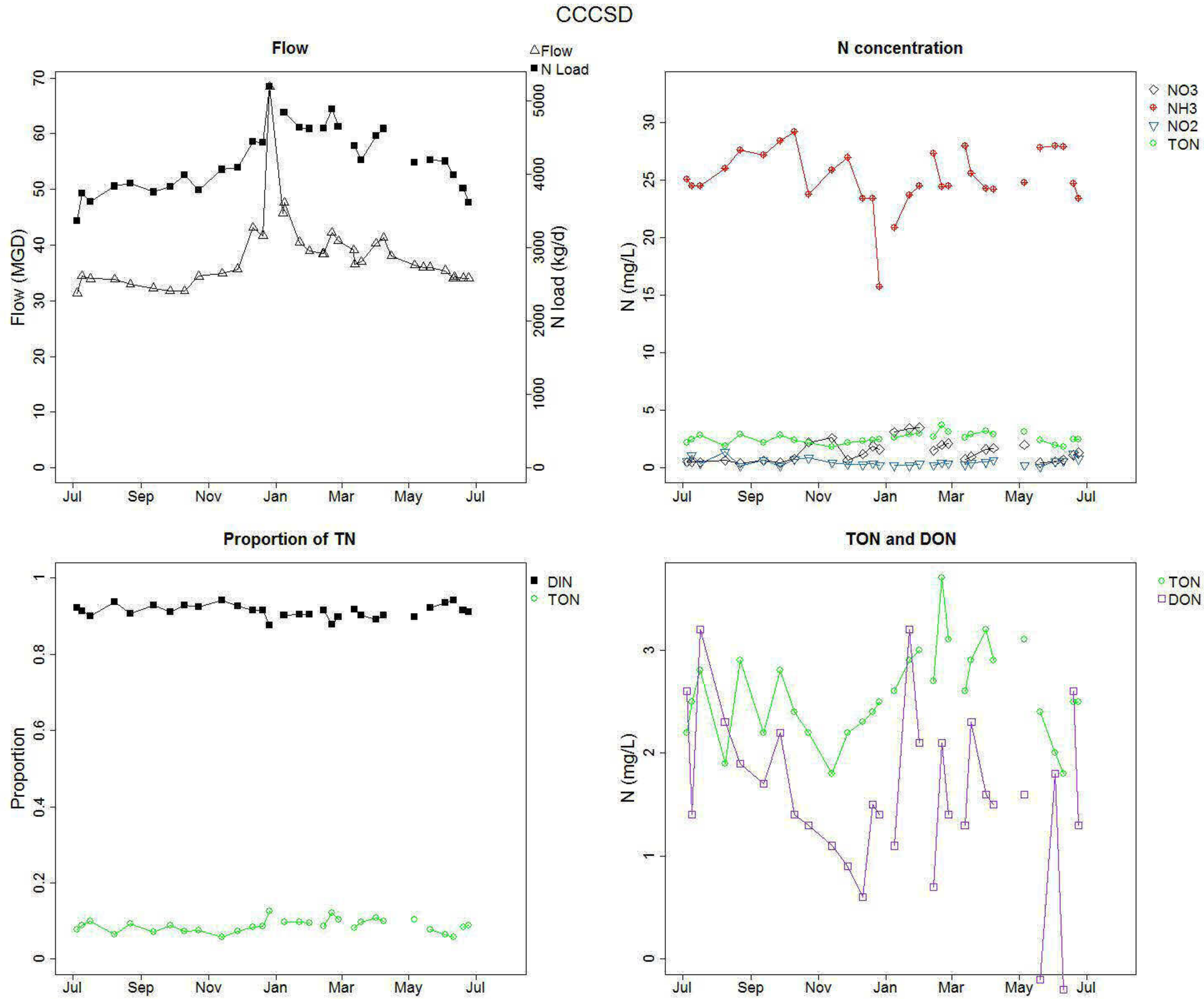

CCCSD
Flow
Flow
N Load
Flow (MGD)
N load (kg/d)
N concentration
NO3
NH3
NO2
TON
N (mg/L)
Proportion of TN
DIN
TON
Proportion
TON and DON
TON
DON
N (mg/L)
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 1

N

EBDA

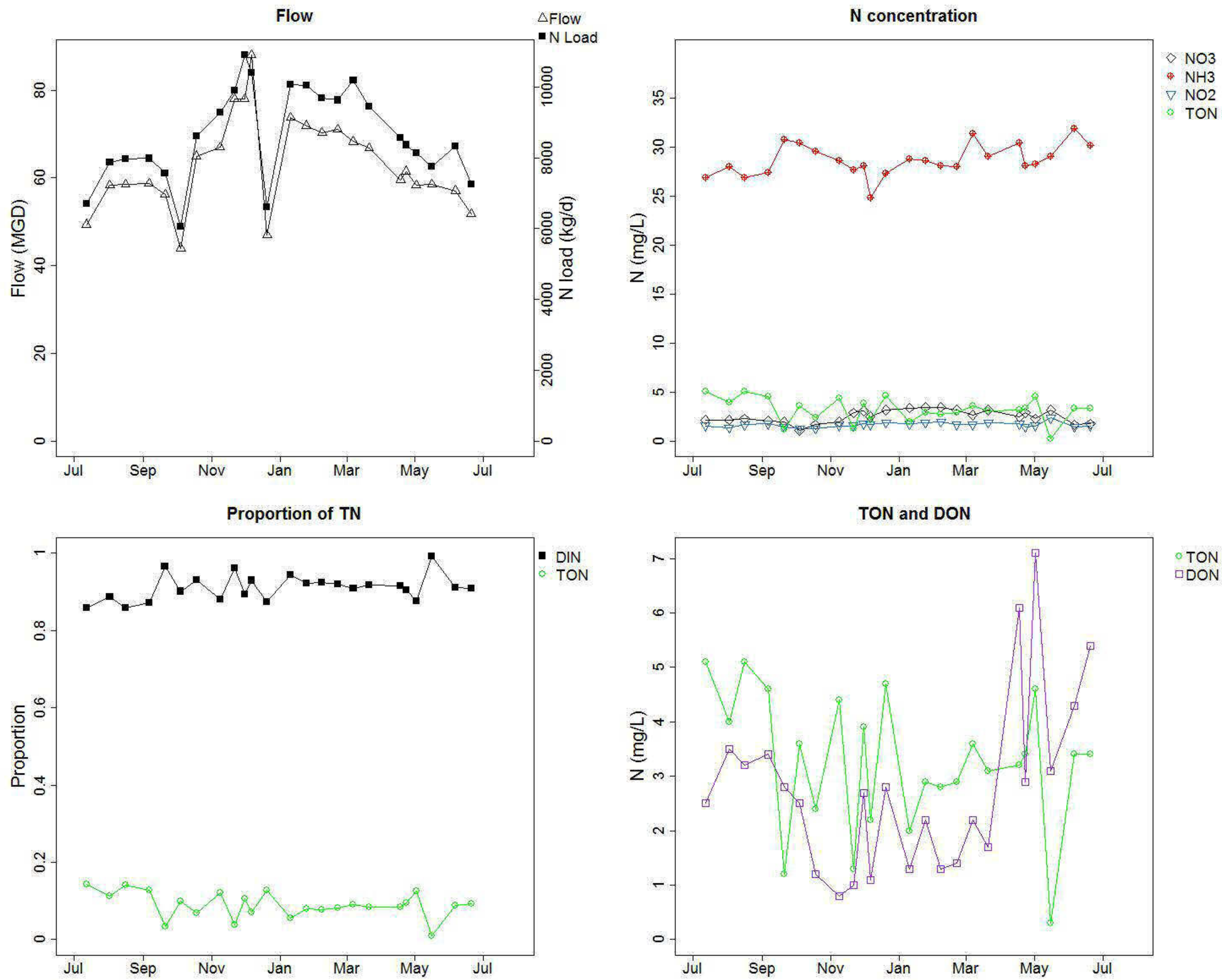


Figure 2

N

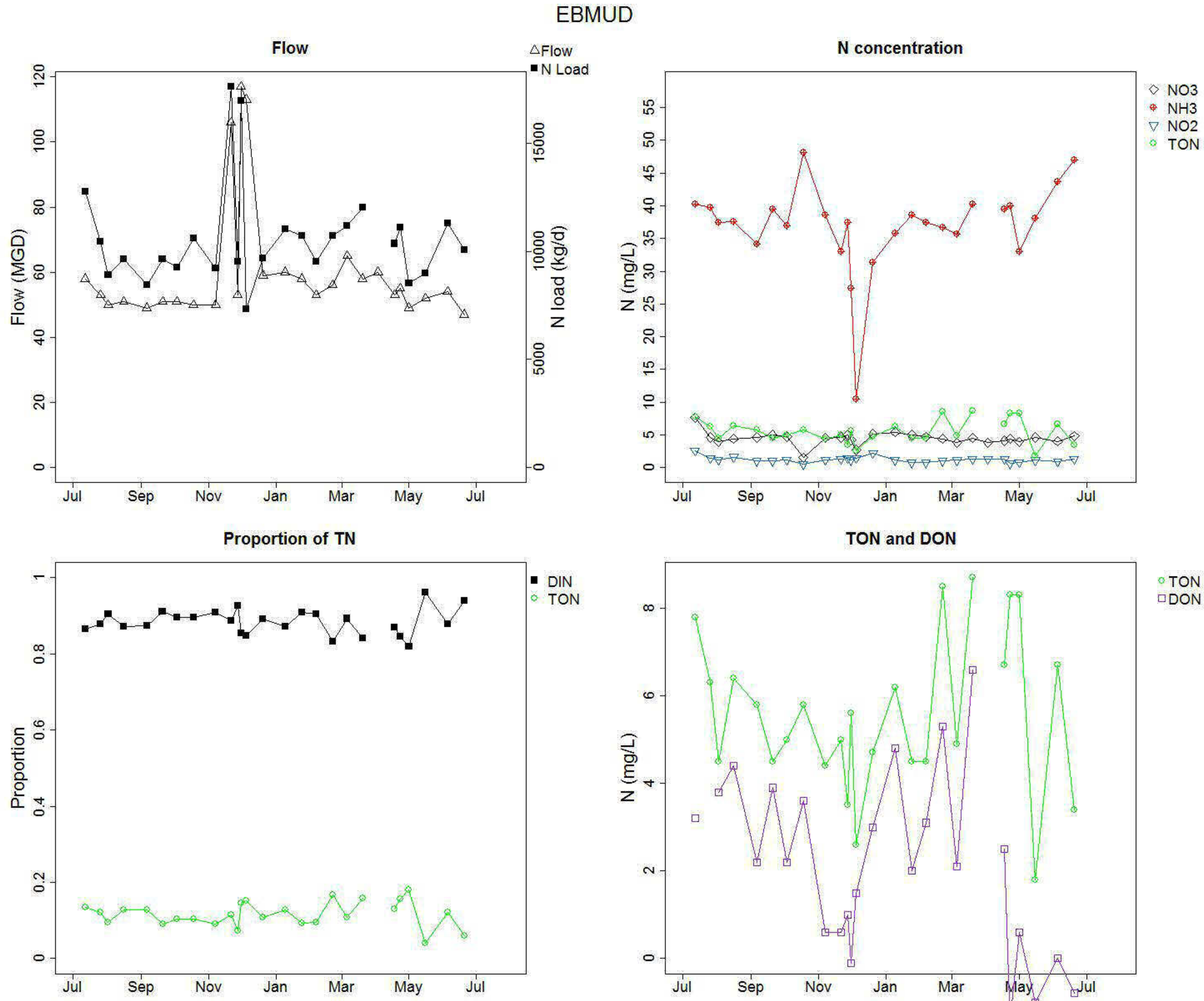
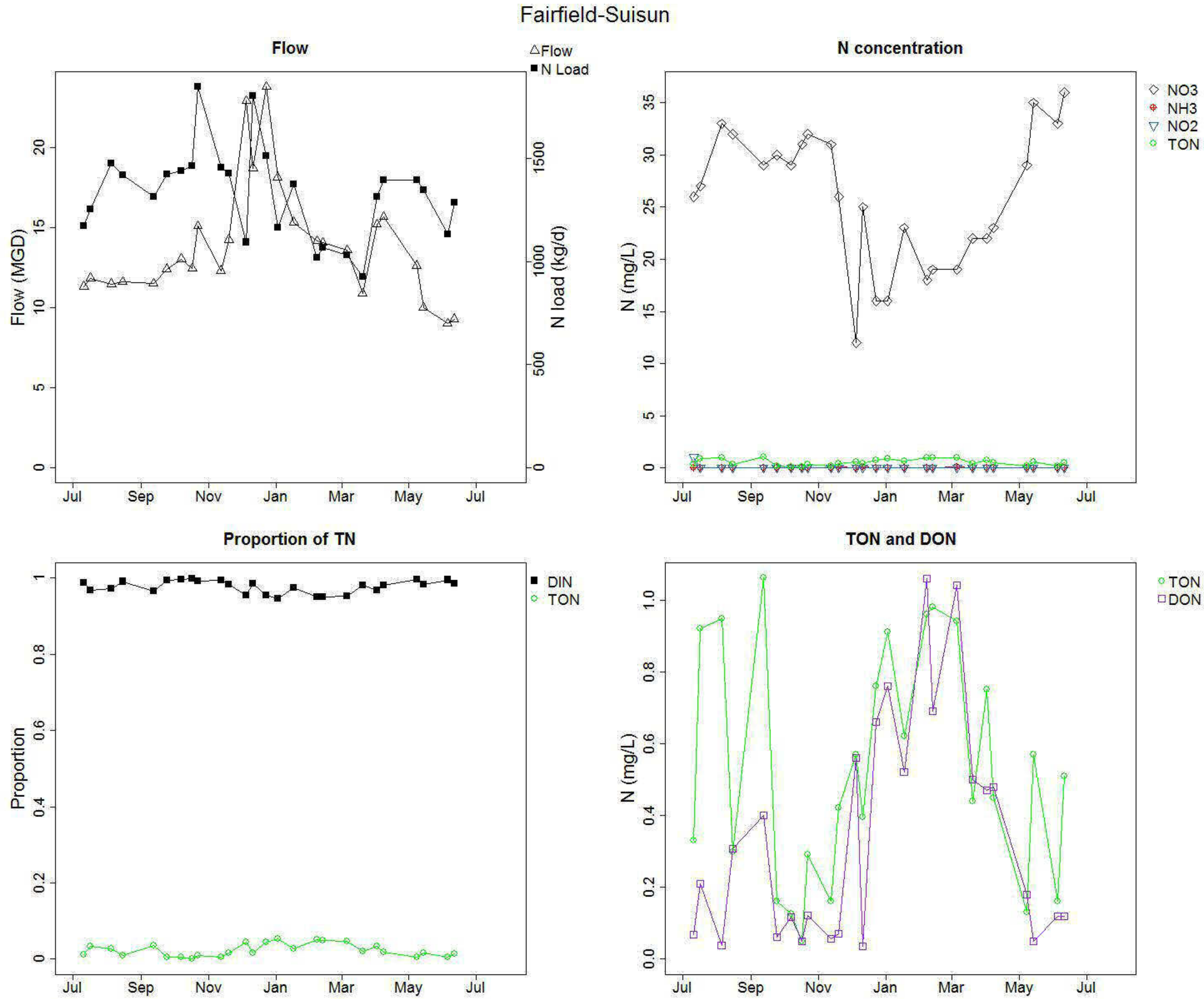

EBMUD
Flow
Flow
N Load
Flow (MGD)
N load (kg/d)
0
20
40
60
80
100
120
0
5000
10000
15000
Jul
Sep
Nov
Jan
Mar
May
Jul
N concentration
NO3
NH3
NO2
TON
N (mg/L)
0
5
10
15
20
25
30
35
40
45
50
55
Proportion of TN
DIN
TON
Proportion
0
0.2
0.4
0.6
0.8
1
TON and DON
TON
DON
N (mg/L)
0
2
4
6
8

Figure 3

N



Fairfield-Suisun
Flow
Flow
N Load
Flow (MGD)
N load (kg/d)
N concentration
NO3
NH3
NO2
TON
N (mg/L)
Proportion of TN
DIN
TON
Proportion
TON and DON
TON
DON
N (mg/L)
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 4

N

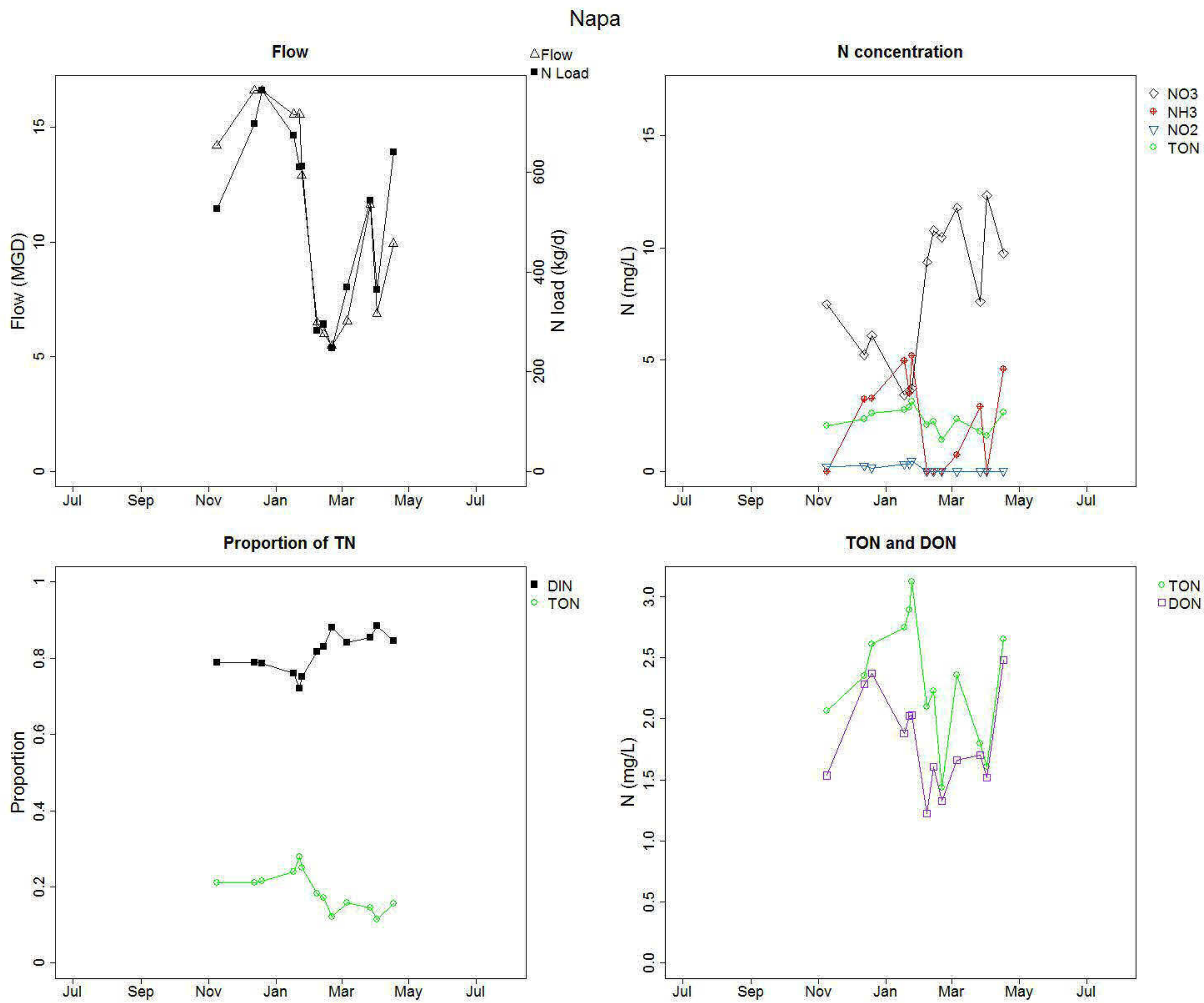

Napa
Flow
Flow (MGD)
N load (kg/d)
Flow
N Load
N concentration
N (mg/L)
NO3
NH3
NO2
TON
Proportion of TN
Proportion
DIN
TON
TON and DON
N (mg/L)
TON
DON
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 5

N

Palo Alto

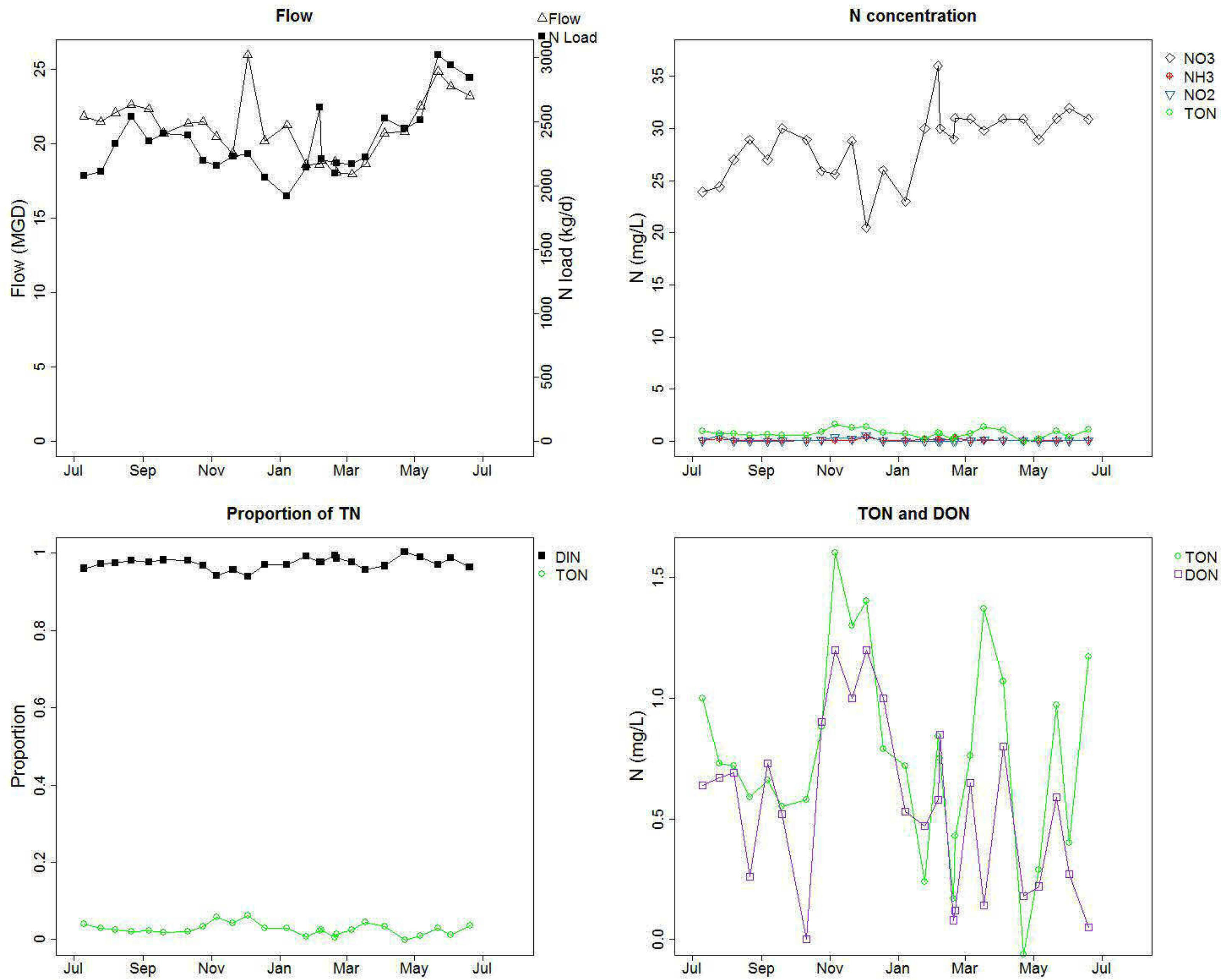


Figure 6

N

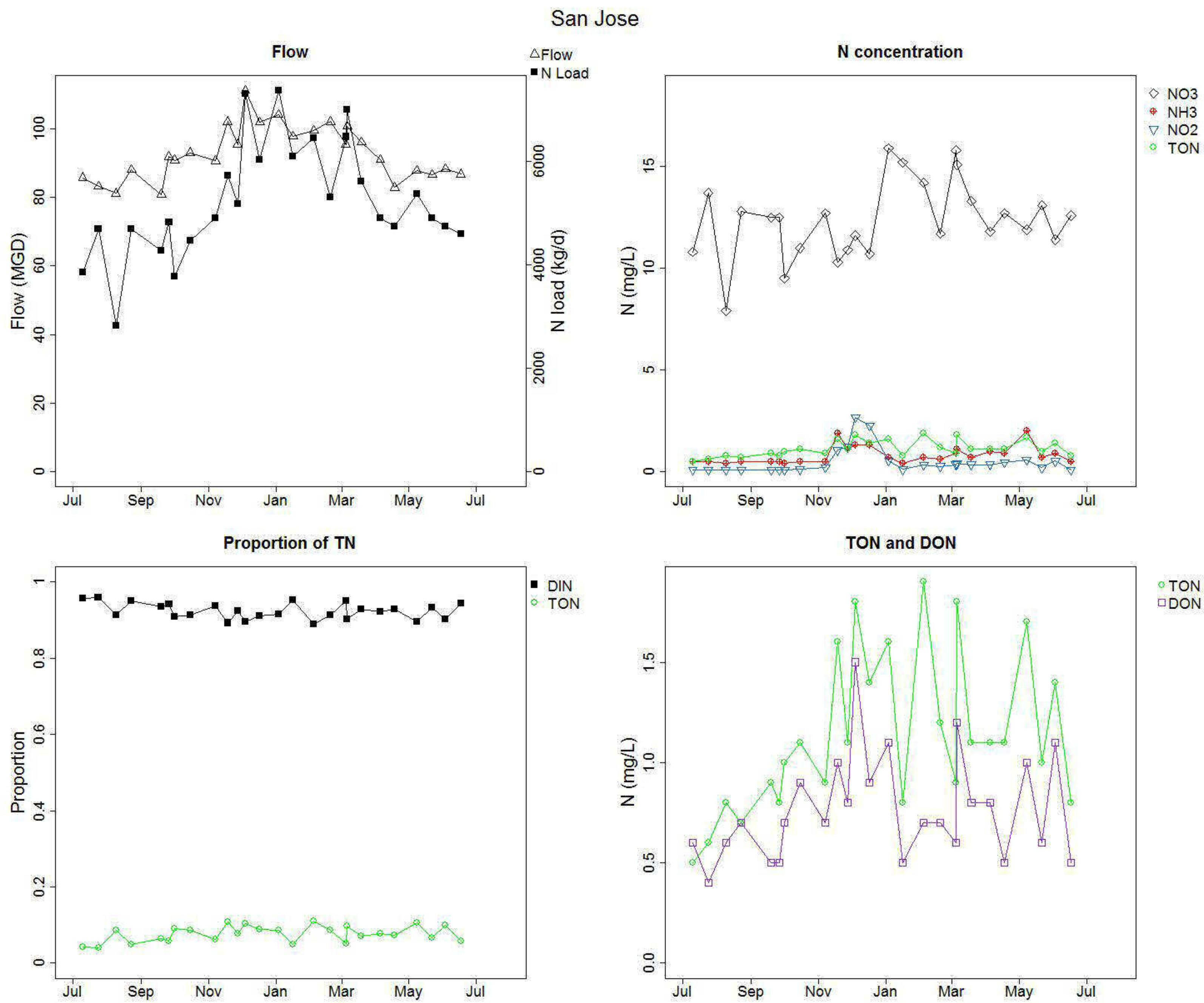

San Jose
Flow
△Flow
■N Load
Flow (MGD)
N load (kg/d)
N concentration
NO3
NH3
NO2
TON
N (mg/L)
Proportion of TN
DIN
TON
Proportion
TON and DON
TON
DON
N (mg/L)
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 7

N

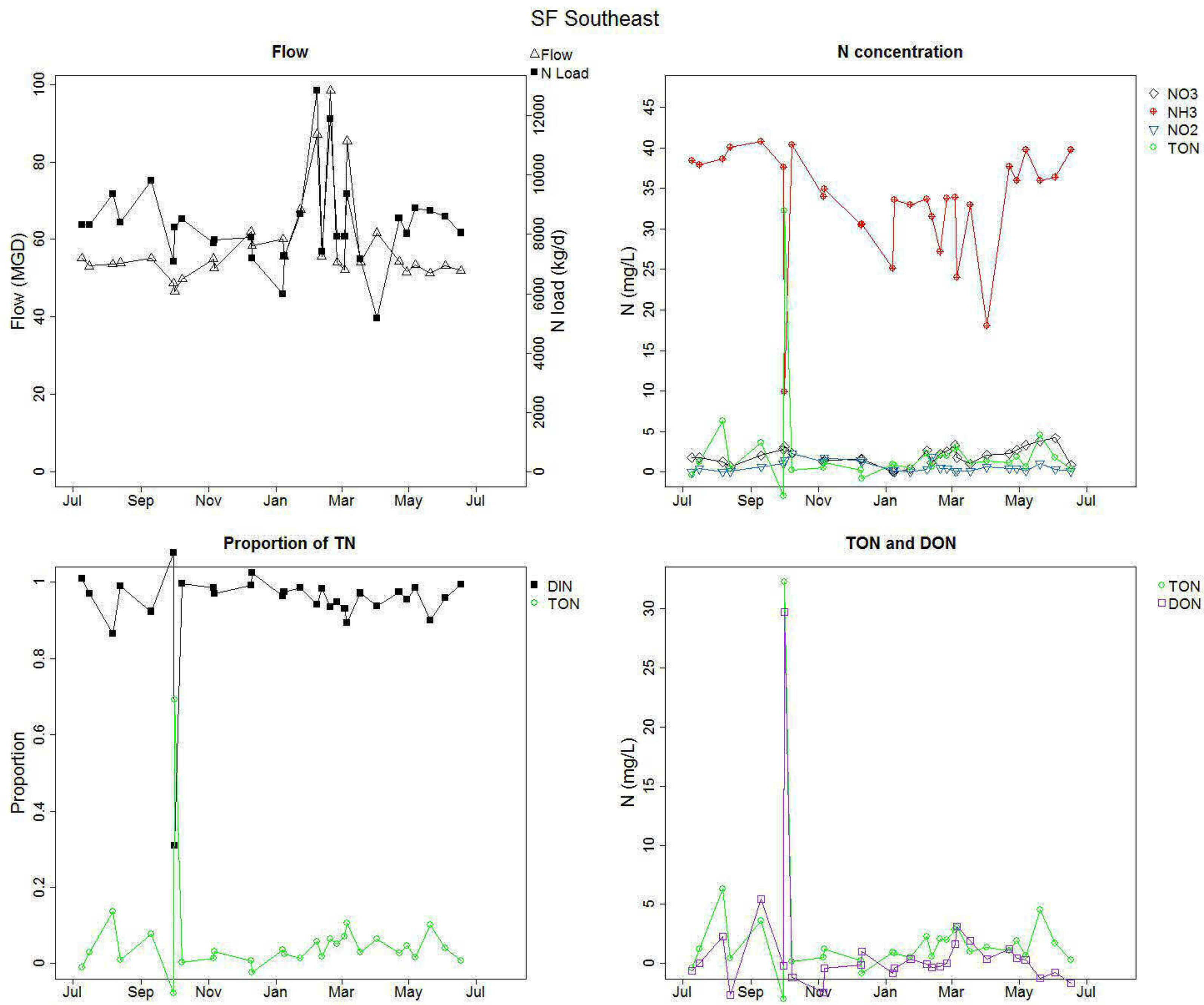

SF Southeast
Flow
△Flow
■ N Load
Flow (MGD)
N load (kg/d)
N concentration
NO3
NH3
NO2
TON
N (mg/L)
Proportion of TN
DIN
TON
Proportion
TON and DON
TON
DON
N (mg/L)
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 8

N

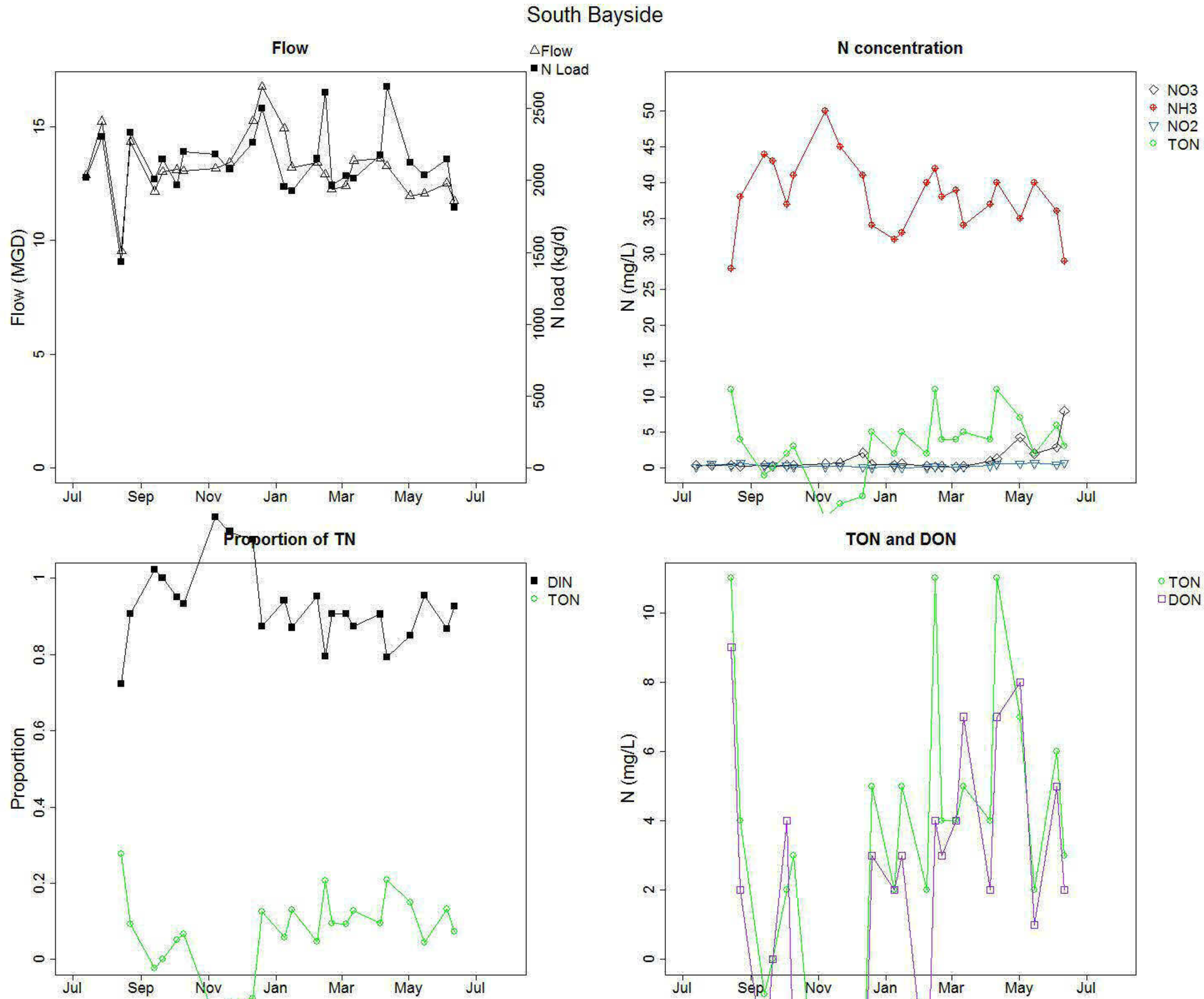
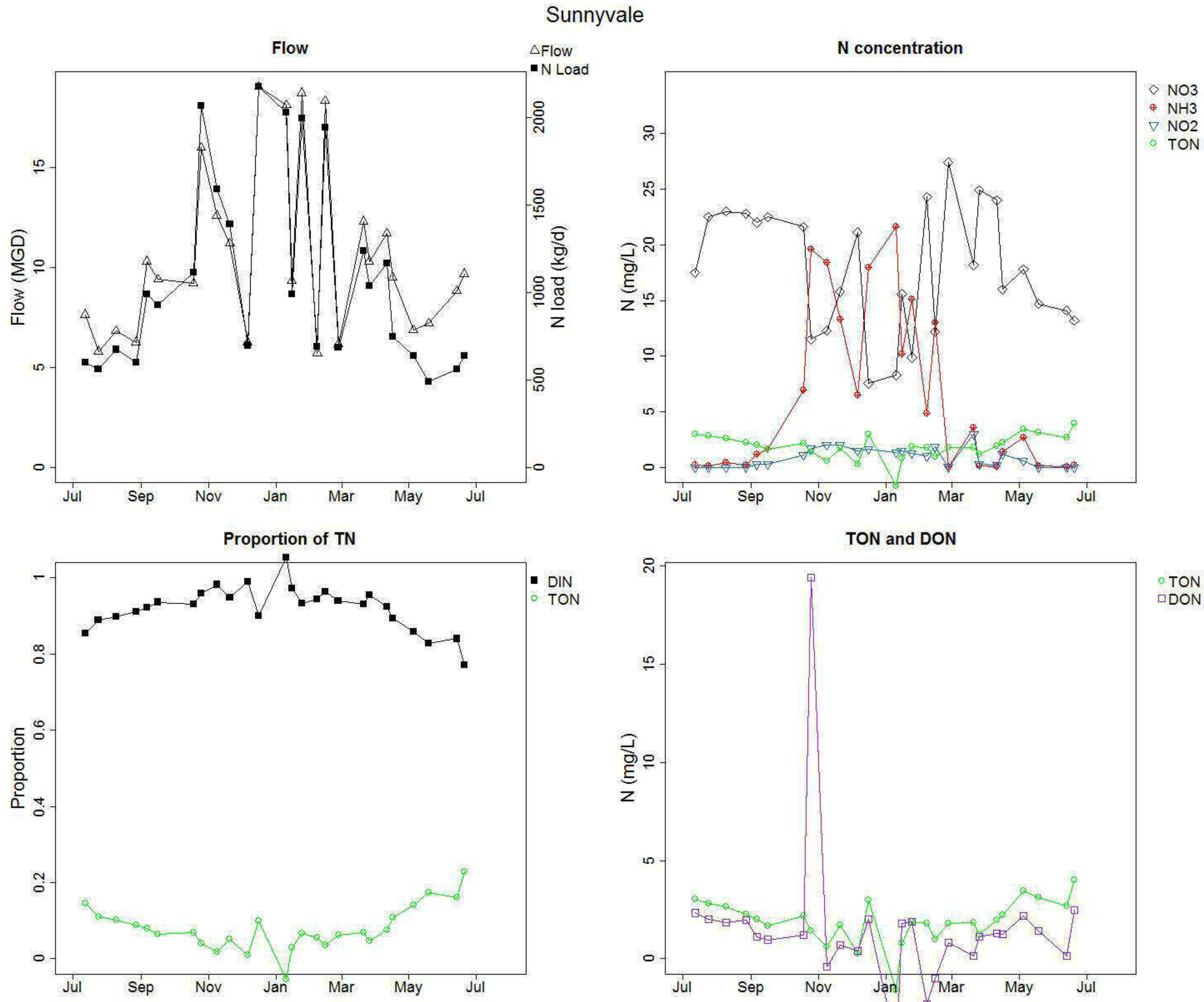

South Bayside
Flow
Flow
N Load
Flow (MGD)
N load (kg/d)
N concentration
NO3
NH3
NO2
TON
N (mg/L)
Proportion of TN
DIN
TON
Proportion
TON and DON
TON
DON
N (mg/L)
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 9

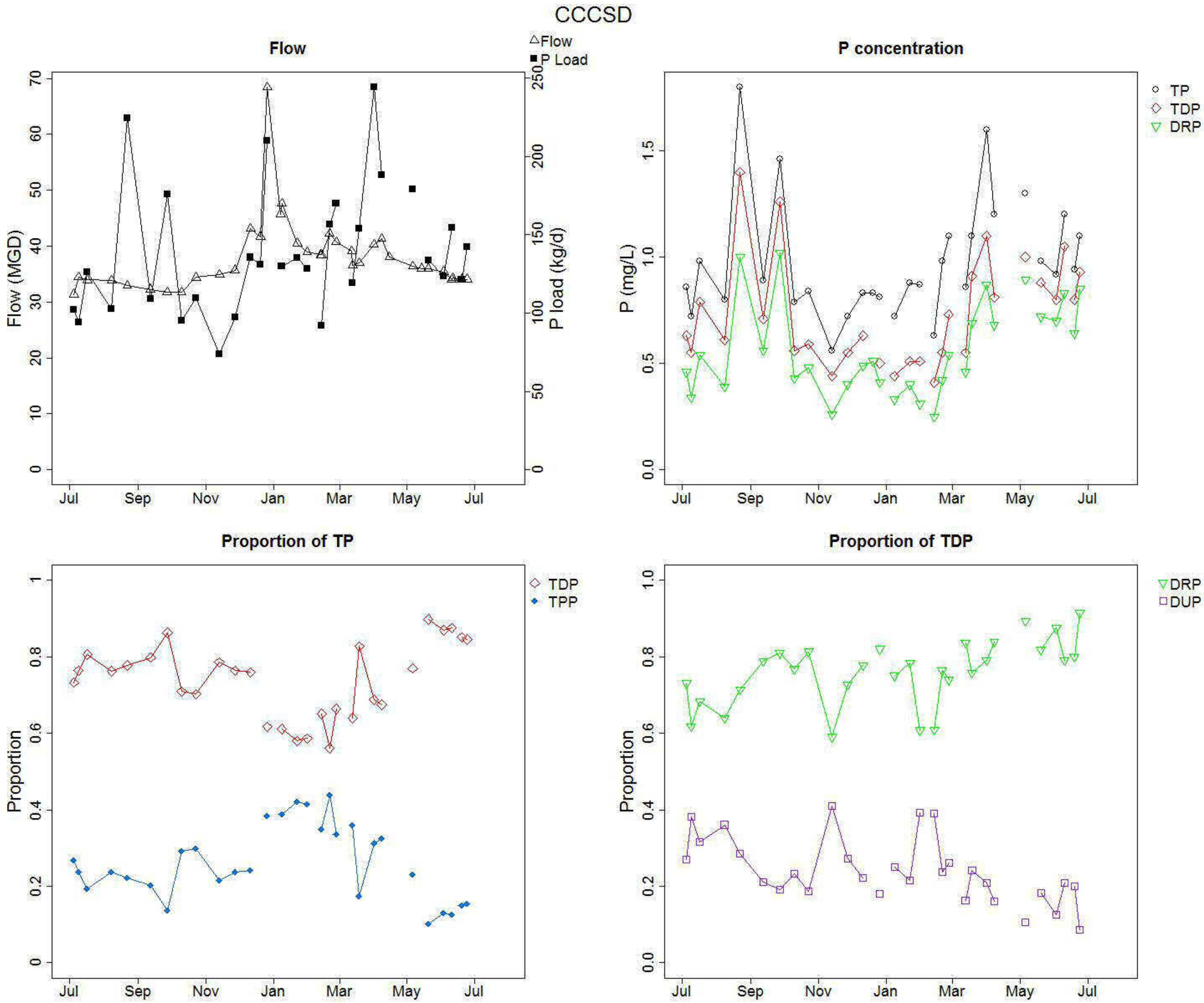
N



Sunnyvale
Flow
Flow
N Load
Flow (MGD)
N load (kg/d)
N concentration
NO3
NH3
NO2
TON
N (mg/L)
Proportion of TN
DIN
TON
Proportion
TON and DON
TON
DON
N (mg/L)
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 10

P



CCCSD
Flow
△Flow
■P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 11

P

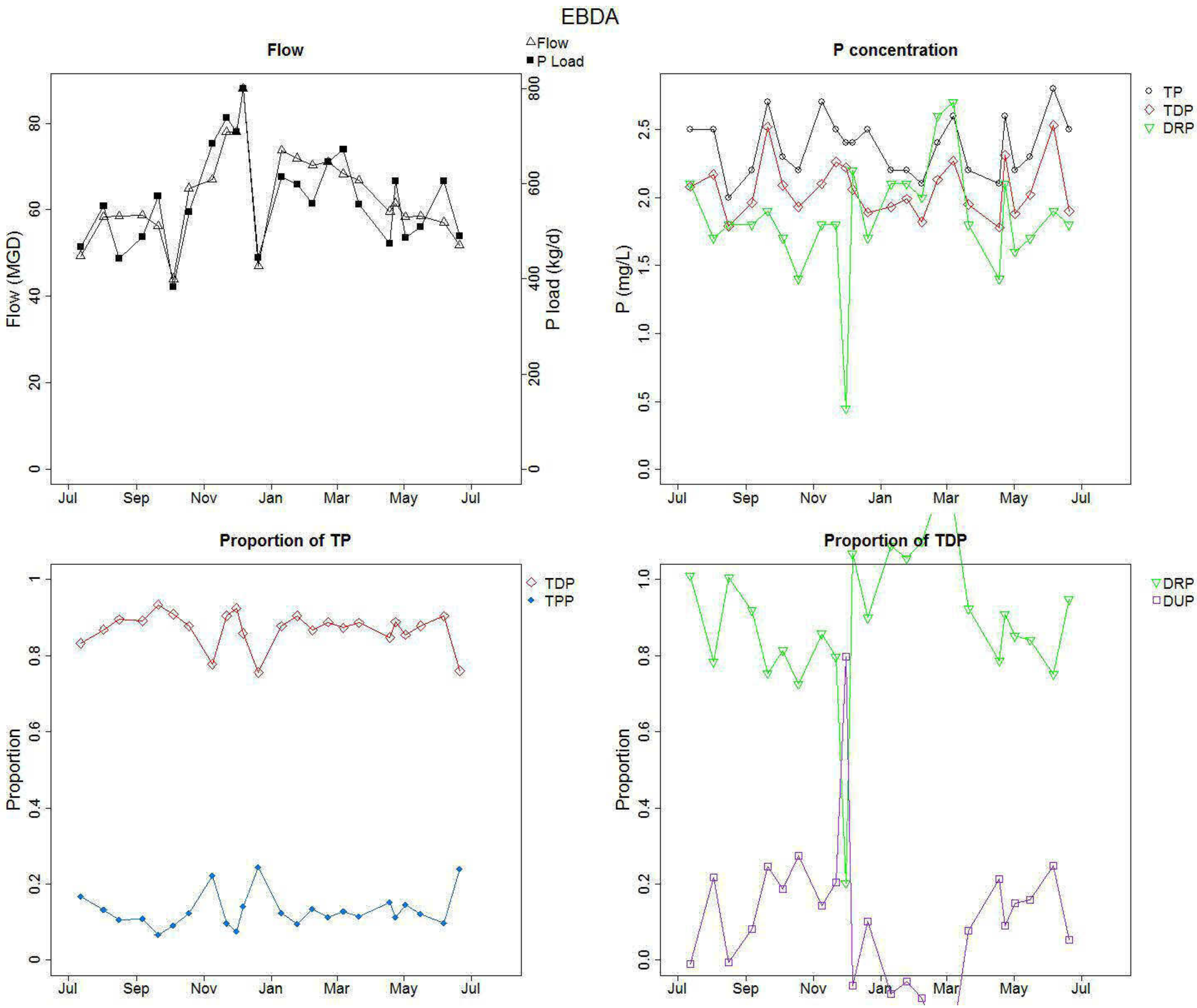

EBDA
Flow
Flow
P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 12

P

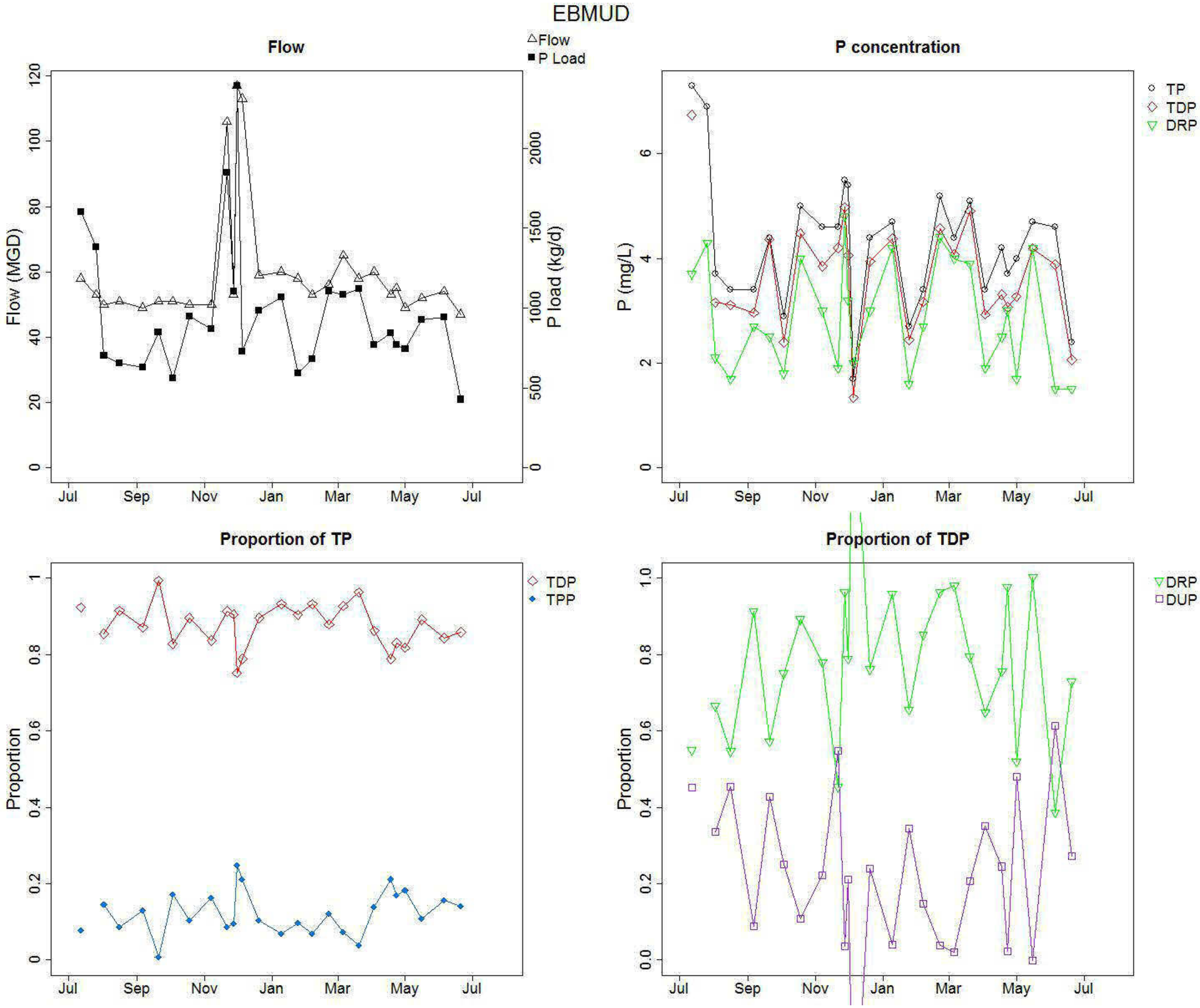

EBMUD
Flow
△Flow
■P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 13

P

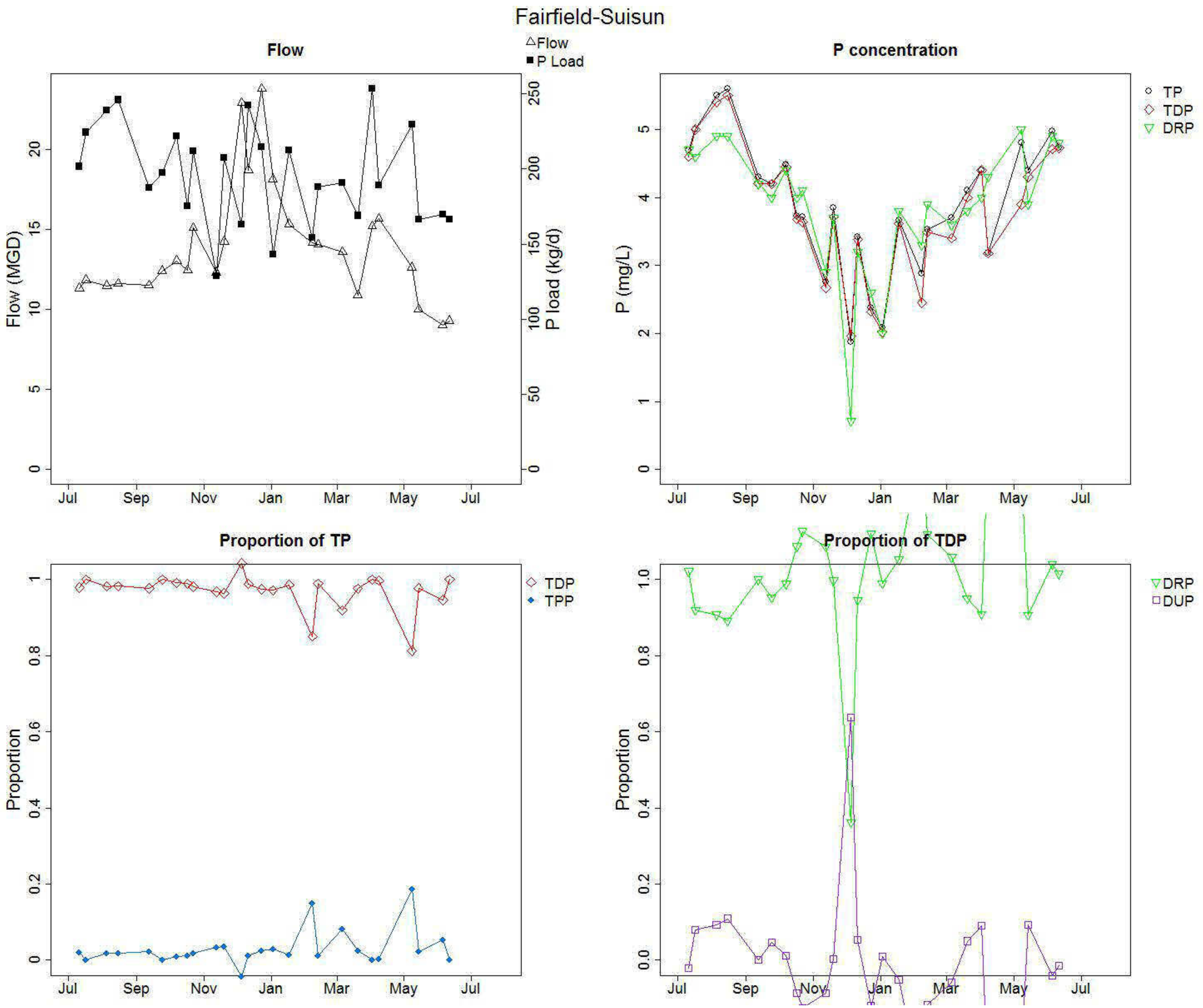

Fairfield-Suisun
Flow
Flow
P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 14

P

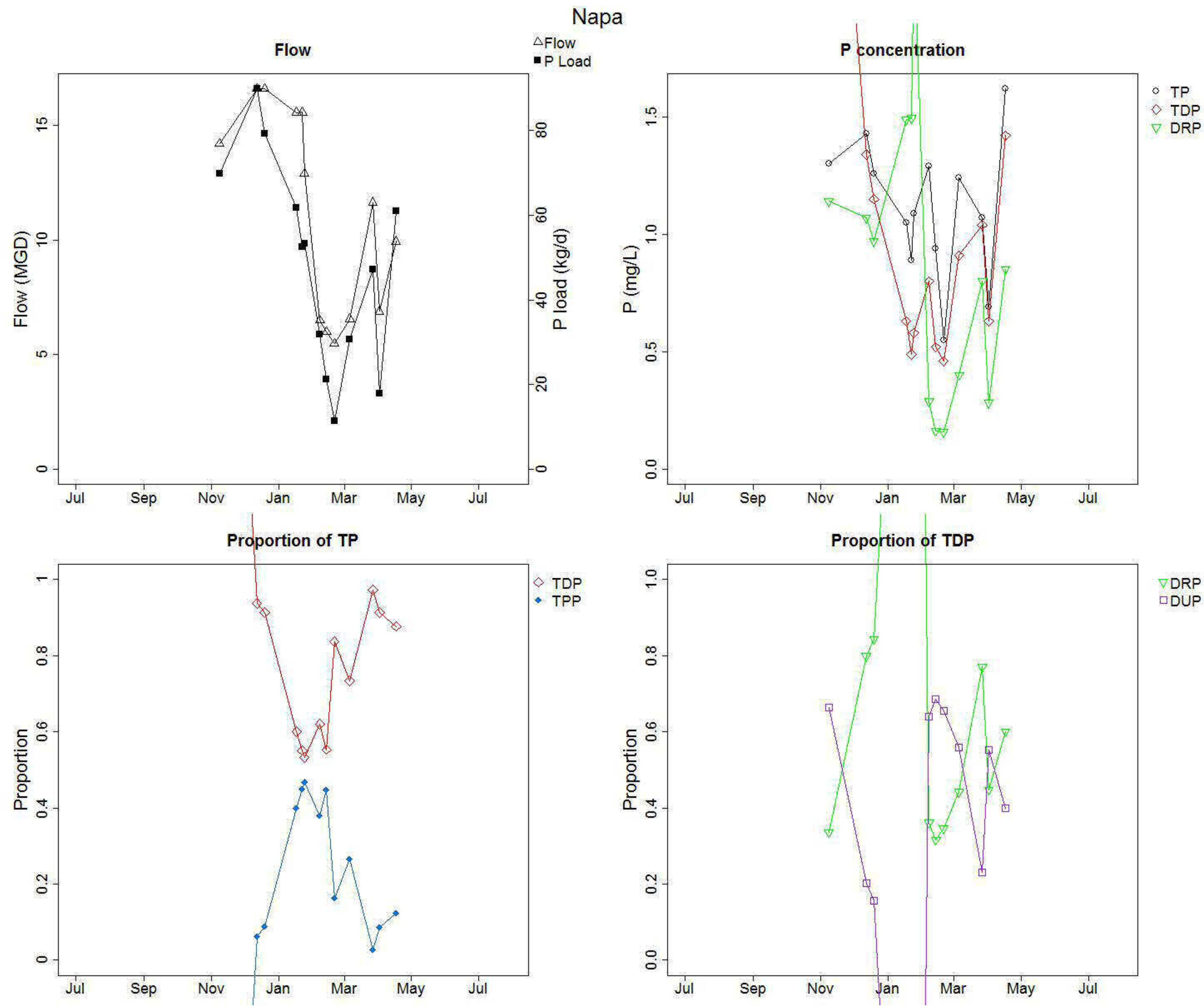

Napa
Flow
Flow
P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul Sep Nov Jan Mar May Jul

Figure 15

P

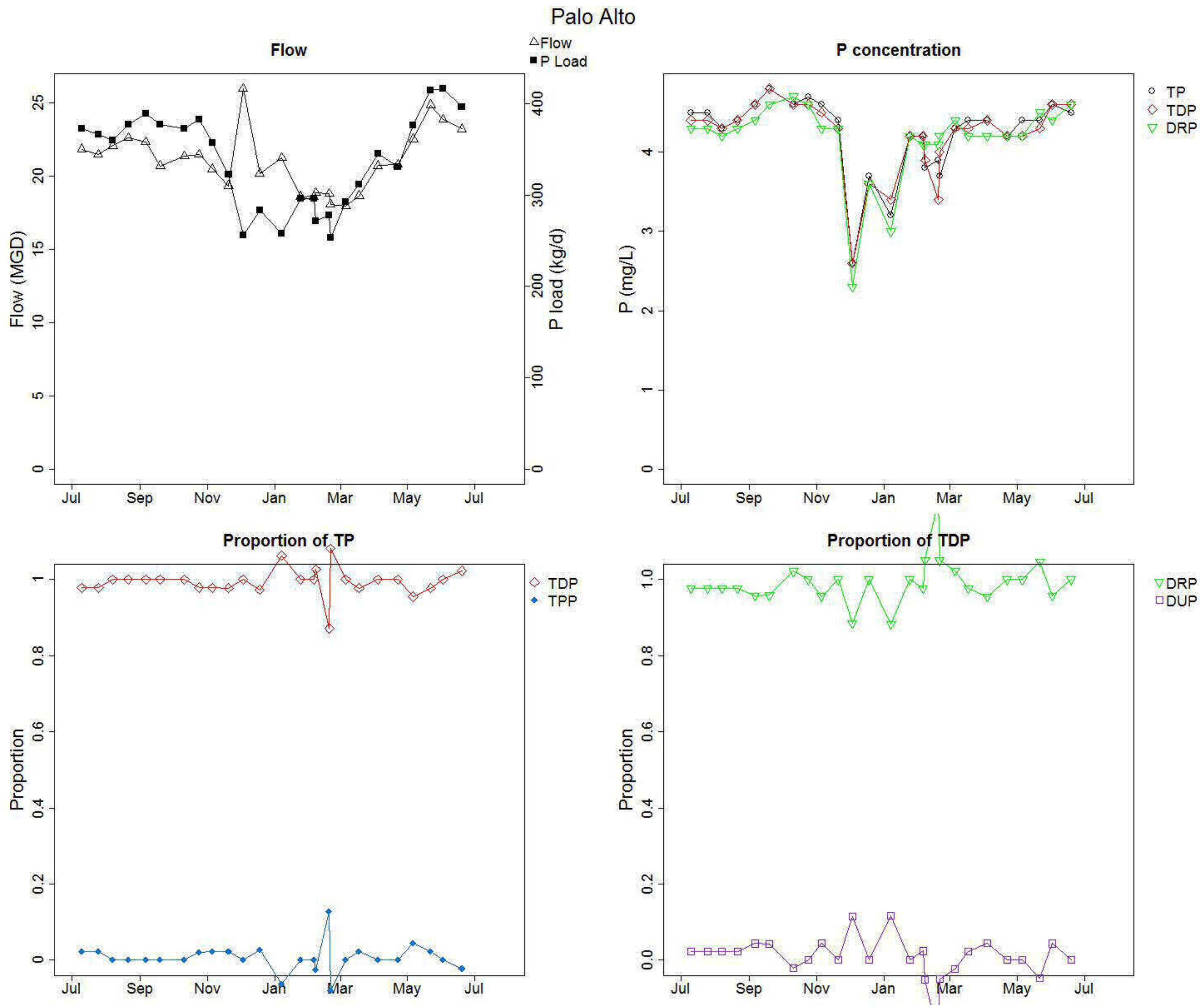
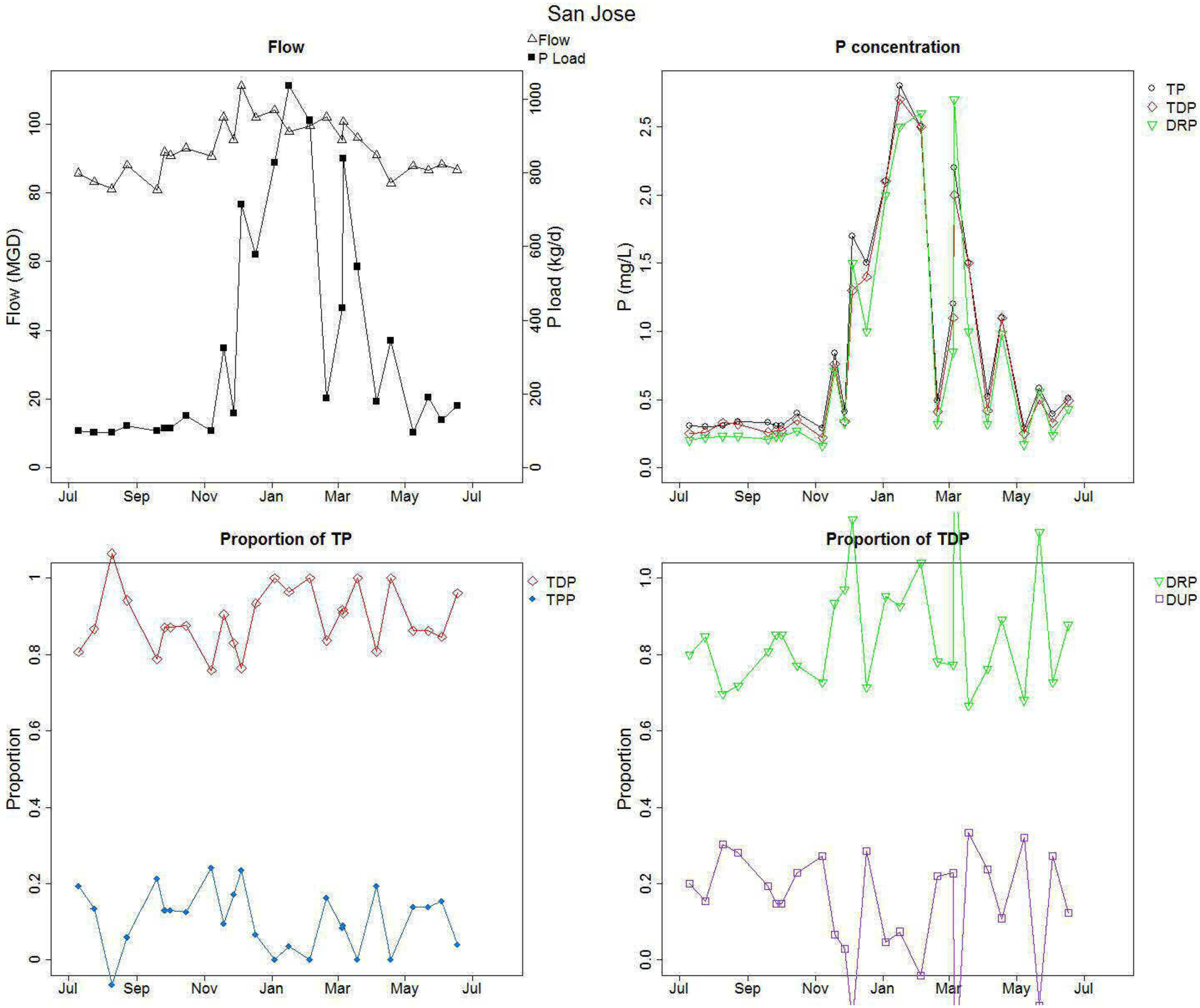

Palo Alto
Flow
Flow
P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 16

P



San Jose
Flow
△Flow
■P Load
Flow (MGD)
P load (kg/d)
P concentration
P (mg/L)
TP
TDP
DRP
Proportion of TP
Proportion
TDP
TPP
Proportion of TDP
DRP
DUP
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 17

P

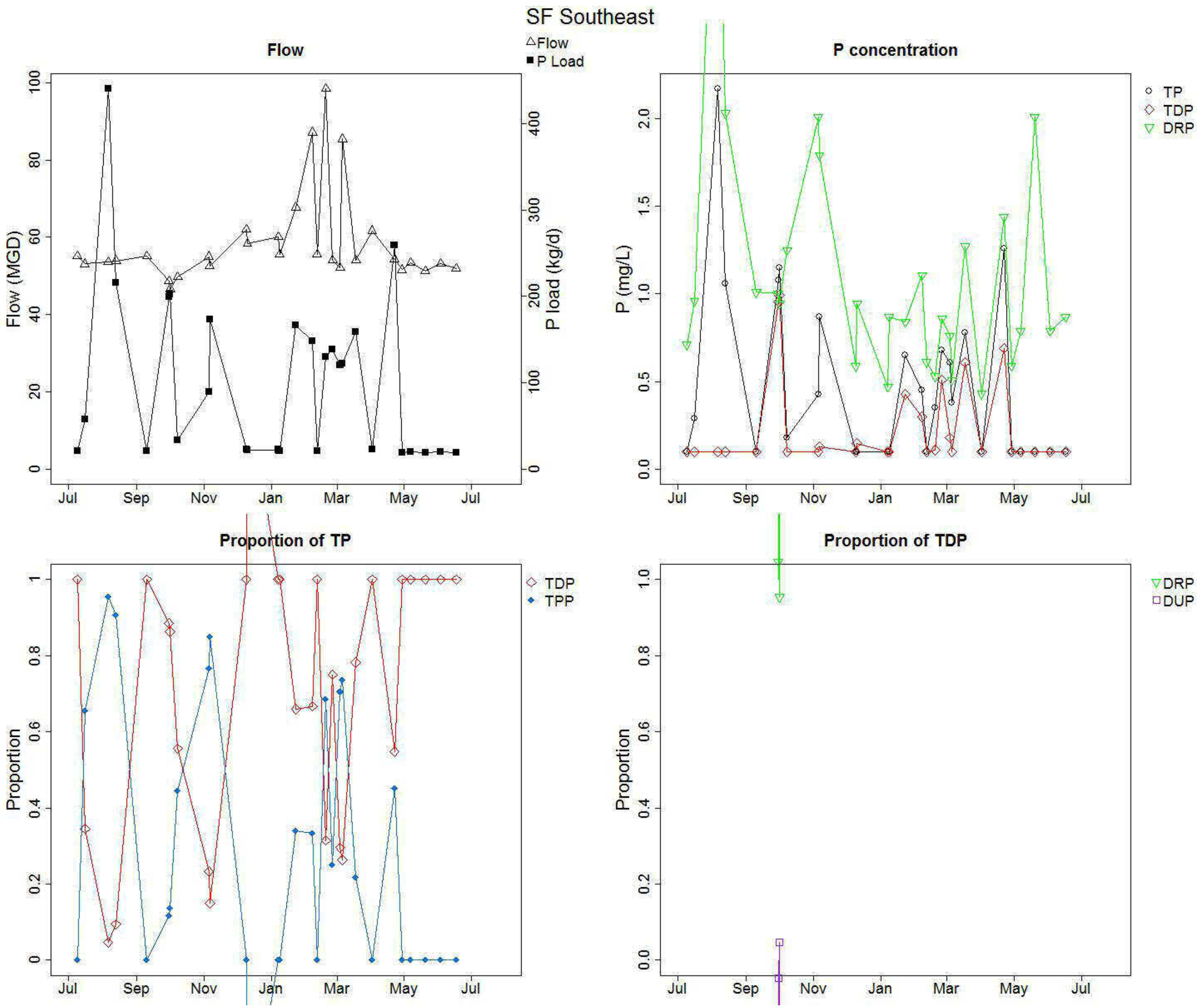

SF Southeast
Flow
P Load
Flow
Flow (MGD)
P load (kg/d)
P concentration
P (mg/L)
TP
TDP
DRP
Proportion of TP
Proportion
TDP
TPP
Proportion of TDP
Proportion
DRP
DUP
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 18

P

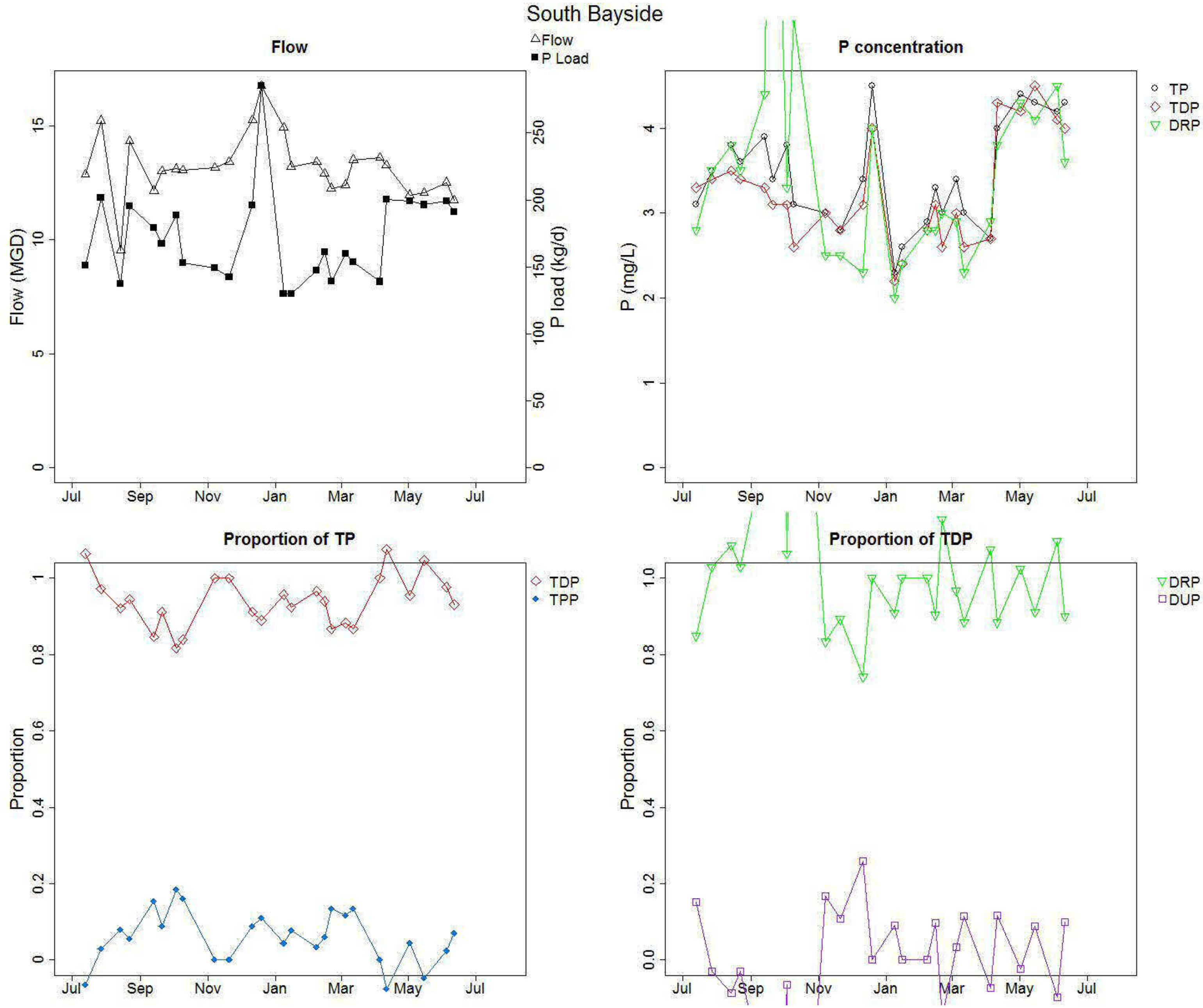
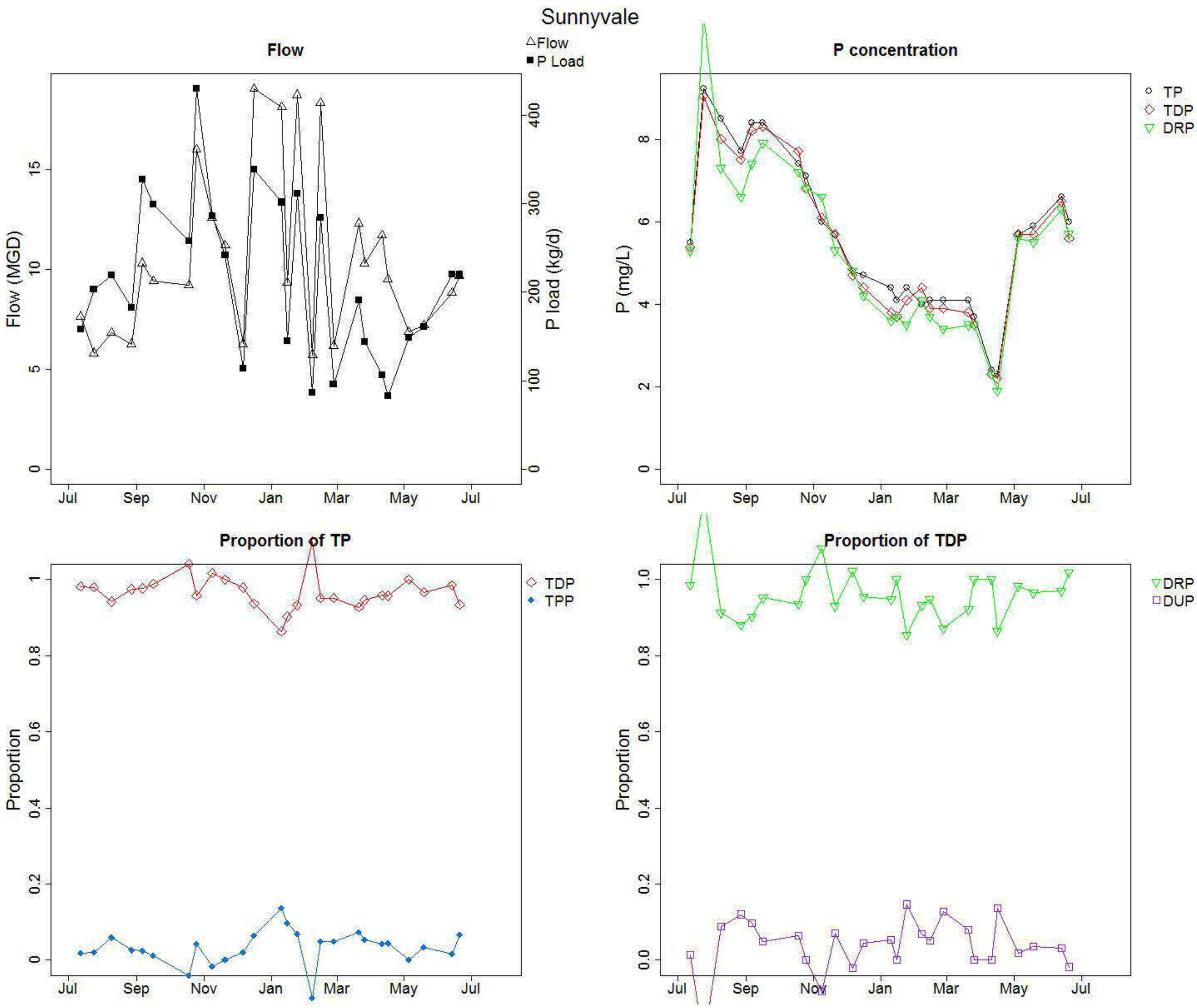

South Bayside
Flow
△Flow
■P Load
Flow (MGD)
P load (kg/d)
P concentration
P (mg/L)
TP
TDP
DRP
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 19

P



Sunnyvale
Flow
△Flow
■P Load
Flow (MGD)
P load (kg/d)
P concentration
TP
TDP
DRP
P (mg/L)
Proportion of TP
TDP
TPP
Proportion
Proportion of TDP
DRP
DUP
Proportion
Jul
Sep
Nov
Jan
Mar
May
Jul

Figure 20