External nutrient loads to San Francisco Bay

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i. Executive Summary

i.1 Background

San Francisco Bay (SFB) has long been recognized as a nutrient-enriched estuary (Jassby and Cloern, 2012). However, phytoplankton biomass and dissolved oxygen remain much lower and higher, respectively, in SFB than would be expected in an estuary having such high nutrient loads and ambient nutrient concentrations. Studies over the past 40 years in SFB have demonstrated that phytoplankton primary production and biomass accumulation are limited by a combination of factors, including strong tidal mixing, light limitation due to high turbidity, and grazing pressure by clams. 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 the Bay have experienced substantial increases in phytoplankton biomass (Cloern et al., 2007, 2010) and modest but statistically significant declines in DO concentrations (Cloern, 2011). An unprecedented red tide bloom in September 2004 (Cloern et al, 2005), and increased frequency of cyanobacteria blooms (Lehman et al., 2008) in the northern estuary also signal changes. Other recent studies have argued that the chemical forms of nutrients and their relative abundances (NH4:NO3, N:P) can influence phytoplankton productivity (Dugdale et al., 2007; Parker et al., 2012a,b; Dugdale et al., 2012) and community composition (Glibert et al., 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 (Water Board) 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, and identifying major data gaps, were identified as early priorities in the Nutrient Management Strategy.

This project was funded by the San Francisco Bay Regional Monitoring Program.

i.2 Main Goals and 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 analysis focused on loads from publicly-owned wastewater treatment works (POTWs), refineries discharges, stormwater runoff, efflux from the Sacramento-San Joaquin Delta, and oceanic exchange through the Golden Gate Bridge (addressed in a forthcoming section to be added to this report). 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

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

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 (NH4), nitrate (NO3), and ortho-phosphate (PO4) due to data availability. Total-N and Total-P are considered where possible.

i.3 Main Findings

i.3.a Bay-wide loads overview

The San Francisco Bay Area has 42 POTWs that service the Bay Area's 7.2 million people and discharge either directly to the Bay or to receiving waters in adjacent watersheds that drain to the Bay (not including discharges east of Suisun Bay that enter through the Delta). While several of these POTWs conduct nitrification or nitrification plus some forms of advanced treatment that remove a portion of nutrients prior to discharge, most POTWs carry out only secondary treatment ,which transforms nutrients from organic to inorganic forms, but generally does not remove much N or P. Bay-wide, POTWs discharged (annual average) 34400 kg d^{-1} NH4, 11800 kg d^{-1} NO3, and 4000 kg d^{-1} PO4. The 5 largest POTWs accounted for approximately 75% of NH4 loads, 50% of NO3 loads and 45% of PO4 loads of total POTWs Bay-wide. NH4 was the dominant form of DIN discharged Bay-wide, although NO3 was the dominant form for several POTWs who nitrify effluent prior to discharging. The 6 months of detailed effluent characterization data from POTWs currently available showed that 89% of total-N was discharged as dissolved inorganic nitrogen (DIN; DIN = NH4+NO3) and 78% of total-P was discharged as PO4. [DIN]:[PO4] 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 70 kg d^{-1} PO4.

Stormwater loads were estimated using a modeling tool that is under development for the Bay Area for other contaminants (Regional Watershed Spreadsheet Model; Lent et al 2011). The model quantifies annual runoff for 331 watersheds that ultimately drain to the Bay, based on rainfall, land-use, and slope, and combines 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 calibrate and validate models. Thus, the stormwater loads are highly uncertain, but nonetheless may serve as useful order of magnitude estimates for comparison with other sources that can be refined as needed with more sophisticated tools and additional data. Annual-average stormwater loads to the Bay were estimated to be 10000 kg d^{-1} DIN (mostly as NO3) and 1300 kg d^{-1} of PO4. The load magnitudes varied substantially on a seasonal basis and are best evaluated in that context. The calculated nutrient yields (kg d^{-1} m^{-2}) from individual watersheds also 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, especially DIN, came from watersheds draining into San Pablo Bay and Suisun Bay. Because of limited data and uncertainty around land-use specific nutrient concentrations used to compute loads (especially for watersheds with agriculturally-dominated land-uses), these stormwater loads need to be critically evaluated.

Flows emanating from the Delta deliver large amounts of nutrients to the Bay. Loads from the Delta were estimated using historic flow and concentration data at select locations near where the Delta transitions into Suisun Bay. Annual average loads were 5800 kg d^{-1} NH4, 10400 kg d^{-1} NO3, and 240 kg d^{-1} PO4, all of which exhibited strong seasonal and interannual variability (see Section i.3.b).

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

To evaluate the seasonal variability in the relative importance of different nutrient sources, monthly average loads were calculated for the period 2006-2011. In order to compare the relative importance of loads from different source types (POTWs, stormwater, Delta[2]) at spatial scales smaller than the entire Bay, SFB was segmented into subembayments using the Water Board's subembayment boundaries (see Figure 2). The use of these boundaries is intended as an initial approach, and does not indicate that they are the most hydrodynamically-meaningfully delineations for addressing management or science questions. Other boundaries were also considered, and, while moving the boundaries of course changed the segments to which some loads were assigned, the different boundaries did not appreciable influence the relative importance of sources (see Figure 21 and related text in Section 4.3.3; also discussed further in Section i.4).

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 PO4 year-round. While stormwater's contribution to DIN loads at the subembayment scale were minimal in these three subembayments, stormwater PO4 loads had the potential to be nontrivial during some months. In San Pablo Bay/Carquinez Straits, stormwater nutrient loads contributed much more substantially to total direct nutrient loads during wet months, owing to the relatively low direct POTW loads and relatively high DIN and PO4 loads (due to the higher proportion of agricultural landuse in the surrounding watersheds). Nutrient loads transported from Suisun Bay (which included loads entering from the Delta) to San Pablo Bay appear to have been an important, if not dominant, nutrient source throughout most of the year; The exchange estimates between Suisun Bay and San Pablo Bay need to further analyzed and refined through modeling. In Suisun Bay, load estimates suggest that the Delta was the largest source of NH4 for as much as half the year, but that direct POTW loads to Suisun Bay dominated NH4 loads during the rest of the year. The Delta contributed the largest loads of NO3 year-round to Suisun Bay, and the majority of PO4 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 loads (or load composition) over that period also need to be examined. Visual inspection of NH4 loads from some POTWs suggest that loads have increased substantially (30-40%) over the past 10-20

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[2] In general, this analysis did not include exchange between subembayments because of the Bay's complex hydrodynamics. The one exception was San Pablo Bay, for which nutrient loads transported from Suisun Bay (including loads from the Delta) were considered.

years. Others have remained relatively constant, or substantially decreased due to treatment upgrades. NH4 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 have been measuring multiple nutrient forms, for most POTWs only NH4 concentration data was readily available prior to 2012. For plants that do not nitrify, NH4 concentrations provide a reasonable surrogate for estimating total DIN loads. However, PO4 concentrations appear to be highly variable among POTWs (based on the 6 months of 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.

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 is based on a peer-reviewed approach that was applied for other compounds exiting the Delta (Jassby and Cloern, 2002), and is a reasonable and defensible approach for a first set of estimates. However the approach has limitations 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).

The stormwater load estimates in this report are highly uncertain. That said, the order-of-magnitude estimates suggest that stormwater loads have the potential to contribute substantially to DIN and PO4 loads in some subembayments during some times of the year. Furthermore, while stormwater loads may not be important at the subembayments scale in some subembayments, their importance at finer spatial scales (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 inherent model limitations and the fact that it 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. 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.

Finally, in this report, loads were combined and analyzed at subembayments spatial scales and at monthly time scales so that seasonal variation in the relative importance of sources could be evaluated. For these calculations, the Water Board's subembayments 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 et al., 2005; see Sections 2.2 and 4.3 of this report). 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 (Figure 21). 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 loads to and 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 (Jassby and Cloern, 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.

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 (Water Board) worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy[3], 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, and identifying major data gaps, 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.

This analysis focused on loads from publicly-owned wastewater treatment works (POTWs) discharges, refinery discharges, stormwater runoff, efflux from the Sacramento-San Joaquin Delta and oceanic exchange through the Golden Gate Bridge (addressed in a forthcoming section to be included in this report). Current annual loads and seasonal variations in loads were determined based on 2006-2011 data and recent POTW and refinery effluent characterization data that have 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 (NH4), nitrate (NO3), and ortho-phosphate (PO4) due to data availability. Total-N and Total-P are considered where possible.

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

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 the mixing, transport, or fate of nutrient loads once they enter SFB.

In general, data were most abundant for NH4, NO3 and PO4; total nitrogen (TN) and total phosphorous (TP) were considered when possible. Throughout this report, NH4 is used to refer to NH3 and NH4+. At typical pH values for SFB, nearly all ammonia is expected to be present as ammonium. 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 outfall 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 Water Board. To satisfy the first part of the order, dischargers submitted all available nutrient effluent data from 2004-2011. While 100% of dischargers monitored NH4 during this time because of numeric permit limits, far fewer measured NO3 (n=17) or PO4 (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 NH4, NO3, dissolved reactive phosphorous (PO4), and total N and total P.

Table 2 provides an overview of data availability. In some cases multiple POTWs discharge to SFB through combined outfalls (as noted in Table 2). Given that 2004-2011 data was not in a uniform format across all dischargers and was of variable completeness, a rigorous analysis of available 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 subembayment; 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 also estimated based on an approach described below.

Current loads were determined using both the 2012 and 2004-2011 datasets. The 2012 dataset, while complete in terms of the number of parameters measured, contained only 6 months of effluent characterization data, mostly collected during dry season months (July-December). Loads were calculated using this data, recognizing that while there was relatively low uncertainty for the months considered, there was considerable uncertainty about how well these loads applied to other time periods and other conditions. To address this uncertainty, loads were also computed using the 2006-2011 subset of the 2004-2011 data, which although less complete in terms of parameters, represented a longer record. Depending on data availability, estimates were made over the past 5 years in one of the following two ways:

1. For analytes measured during 2006-2011, paired flow and concentration data were combined to calculate loads:
$$\text{Load} = \text{Flow}_{date=i\,(2006-2011)} * \text{Concentration}_{date=i\,(2006-2011)}$$
This calculation was mainly limited to NH4, except for a few dischargers that also measured NO3 and PO4.
2. For analytes not measured during 2006-2011, average concentrations from the 2012 dataset were combined with actual flows during that time period:
$$\text{Load} = \text{Flow}_{date=i\,(2006-2011)} * \text{AverageConcentration}_{2012}\ .$$

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 been different at times during 2006-2011, either due to changes in operation (including changes in treatment or changes in flow due to water reuse or conservation) 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.

Loads from smaller dischargers were estimated as:
$$\text{Load} = {}^{2}/_{3}\, \text{Q}_{\text{design}} * \text{AverageConcentration}_{2012}$$
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 potential large for an individual 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; Lent 2011), which is under development by the San Francisco Estuary Institute (SFEI) and the Regional Monitoring Program (RMP) 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). 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 landuse-specific nutrient concentrations used were the geometric means of 1-5 literature values for each nutrient form within 5 landuse categories (residential, commercial, industrial, transportation, open and agriculture; Table 3). For both NH4 and NO3, agriculture runoff concentrations used were 3-10 times higher than those for other land-uses. The variance among the literature values was small (NO3 = 10, 7.3, 9.8 mg L^{-1}; NH4 = 1.3, 1.1 mg L^{-1}). Nonetheless, 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.

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

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 previously available. To address this data gap, we developed monthly time-series of NH4, NO3, and PO4 loads to Suisun Bay from the Delta, following an approach similar to the one 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[4]) and water quality data from nearby long-term monitoring stations (DWR[5], USGS[6]) to estimate nutrient loads (Figure 4). The exact stations used for water quality data changed over time based on which stations were active. A more detailed explanation of the method can be found in Appendix 2. NH4 and PO4 were measured at all water quality stations used in the calculations. For NO3, however, the reported data is actually nitrate + nitrite (NO2) for most dates. For dates when nitrite was also measured it accounted for <5% of NO3+NO2, so NO3 is assumed to be approximately equal to NO3+NO2. 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-analyzed results more accurately reflect the magnitude of the Delta loads relative to other loads (see below 2.2). Although the approach applied here is reasonable and defensible for developing a first set of estimates, it 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 mass loads) and due to gaps in that data. Uncertainty estimates are not included in this report, but are a necessary next step that would be best carried out with the help of a hydrodynamic/water quality model for the Delta.

2.1.4 Ocean Exchange

Nutrient exchange with the coastal ocean through the Golden Gate (GG) was also considered. The approach, results, and discussion for evaluating GG exchange will be described in a forthcoming section that will be included in this report (Largier and Stacey, in preparation).

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 5

[4] http://www.water.ca.gov/dayflow/
[5] http://www.water.ca.gov/bdma/meta/Discrete/data.cfm
[6] http://sfbay.wr.usgs.gov/access/wqdata/query/easy.html

subembayments based on discharge location. The subembayment boundaries used coincide with those used by Water Board (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 Water Board, the names assigned here for subembayments south of the Bay Bridge differ from the Water Board 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 et al., 2005) based on a statistical analysis of field data and expert opinion. The RMP also acknowledges that boundary locations may vary depending on the substance of interest or by season. We also applied the RMP boundaries, and found that while changing the boundaries of course 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 nutrient studies, and for evaluating nutrient-related impairment in SFB, 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 San Pablo Bay (see Section 3.2.4). To assess seasonal variability in POTW and refinery contributions, NH_4, NO_3, and PO_4 loads from all dischargers (both small and large) were averaged by month and combined by subembayment. For the larger POTWs, the 2006-2011 monthly 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 likely 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 are not sensitive to seasonally-varying nutrient abundance or nutrient leachability at the source (i.e.

differences in fertilizer application, tiling practices). Watersheds were assigned to Bay segments 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.

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 NH4 loads could be calculated during this period. For Delta efflux, sufficient data existed to develop load time series for NH4, NO3, and PO4 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 service the Bay Area's 7.2 million people and discharge 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 of these POTWs carry out nitrification or nitrification plus some forms of advanced treatment that remove a portion of nutrients prior to discharge, most POTWs perform only secondary treatment, which transforms nutrients from organic to inorganic forms but generally does not remove much N or P. Bay-wide, POTWs discharge (annual average) 34400 kg d^{-1} NH4, 11800 kg d^{-1} NO3, and 4000 kg d^{-1} PO4 (Table 6). Although SFB's large area, multiple subembayments, and complex hydrodynamics place practical limits on the meaningfulness 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 NH4 loads, 50% of NO3 loads and 45% of PO4 loads from all POTWs Bay-wide. NH4 was the dominant form of DIN discharged Bay-wide, although NO3 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 (NH4+NO3) and 78% of total-P was discharged as PO4. [DIN]:[PO4] was highly variable among POTWs.

When comparisons were possible, loads estimated from the 2006-2011 and 2012 datasets agreed reasonably well. The 2012 data was much more complete in terms of nutrient forms analyzed, and the weaker coverage of NO3 and PO4 in the 2006-2011 dataset limited the number of comparisons that could be made. Data was most plentiful for NH4. Loads agreed best when the dominant forms of N in effluent were compared (i.e., NO3 vs. NH4), and, not surprisingly, less well for the minor form of N. In some cases, the differences between the two estimates may reflect changes in POTW operation; however, an analysis of changes in treatment operations and effluent quality is beyond the scope of this report.

Bay-wide, NH4 accounted for approximately 75% of total DIN (in both the 2006- and 2012 datasets). On average, DIN comprised 89% ± 12% of TN loads and PO4 comprised 78% ± 16% of TP loads (based on 2012 dataset where TN and TP were measured by all plants). There was considerably less variability in % TN as DIN among plants than in %TP as PO4. Several plants reported more PO4 than TP in effluent (compared to only one plant that reported more DIN than TN in effluent). The instances in which DIN or PO4 represented greater than 100% of TN or TP were removed when calculating the above means and standard deviations.

[DIN]:[PO4] varied substantially among POTWs, and the variability was generally due to large differences in PO4 concentrations, as opposed to large variations DIN concentrations. Thus, historical PO4 loads estimates (e.g, based on best engineering estimates of either PO4 concentration or DIN:PO4) will likely 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} PO4. With few exceptions, current refinery loads were small compared to POTW loads. NO3 loads from Chevron refinery appear high relative to POTW NO3 load in San Pablo Bay/Carquinez; however, direct POTW NO3 loads are low compared to other subembayments. It is difficult to say if the relatively high NO3 effluent concentrations in 2012 (used to fill 2006-2011 data gap) are representative of typical plant operations, given the recent accident at this refinery and no historical data for comparison. PO4 concentrations tended to be lower than those of POTWs, while DIN concentrations were comparable to POTWs, leading to high DIN:PO4. DIN accounts for 82% ± 15% of TN loads, and PO4 accounts for 52% ± 30% of TP loads.

Annual-average stormwater loads to the Bay were estimated to be 10000 kg d^{-1} DIN (mostly as NO3) and 1300 kg d^{-1} of PO4 (Table 6). The load magnitudes varied substantially on a seasonal basis and are best evaluated in that 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.

Flows emanating from the Delta deliver substantial nutrient loads to the Bay. Annual average loads were 5800 kg d^{-1} NH4, 10400 kg d^{-1} NO3, and 240 kg d^{-1} PO4 (Table 6). As with stormwater, these loads exhibited strong seasonal and interannual variability and are best evaluated in that context (see Section 3.2.5).

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, the fate/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 PO4 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 NO3 (90%), as opposed to NH4, 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 PO4 loads accounted for up to 20% of the total annual PO4 load (Table 6).

Seasonal variability

Estimated stormwater loads varied seasonally because of the strong wet-dry season climate pattern in this region (Figure 7). DIN loads from POTWs also varied substantially. From the dry season to the wet season, NO3 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]:[PO4] in POTW loads did not show a consistent seasonal trend, but were overall higher than in stormwater loads (which were assumed to be constant, see Methods section and Figure A.1.1).

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 NO3 loads and ~35% of total PO4 loads to Lower South Bay (Figure 7)

3.2.2 South Bay

Annual averages

POTWs account for more than 90% of total DIN and PO4 loads to South Bay (Table 6). NH4 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 PO4 loads on an annual basis. Stormwater did contribute 30% of overall NO3 loads, but this was primarily because of the low POTW NO3 loads.

Seasonal variability

POTW loads did not exhibit strong seasonality in South Bay, neither in the magnitude of DIN and PO4 loads nor in the form of N (Figure 8). Similarly, [DIN]:[PO4] in POTW effluent did not systematically vary over the year but was approximately 5 times higher than calculated [DIN]:[PO4] in stormwater at all times of year (Figure A.1.2). Although stormwater loads were of limited importance on an annual basis, stormwater NO3 and PO4 loads have the potential to be nontrivial during certain months (e.g, stormwater accounted for 49% of NO3 and 28% of PO4 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, especially in the southern ~25% of South Bay, where exchange with the rest of South Bay is limited.

3.2.3 Central Bay

Annual averages

POTWs dominated nutrient loads to Central Bay, accounting for 98% and 93% of total DIN and PO4 loads, respectively (Table 6). NH4 accounted for 85% of DIN loads. Although some Central Bay POTWs are nitrifying (Table 4), the largest Central Bay dischargers are not, shifting the predominance toward NH4. Stormwater contributed less than 7% of each NO3, NH4, and PO4.

Seasonal variability

NH4 and DIN loads from POTWs remained fairly constant year-round, increasing approximately 10% from summer to winter months. However, NO3 and PO4 loads from POTWs showed strong seasonal variability, with higher loads during winter months (Figure 9). Although the difference between winter and summer NO3 loads appears large, it represents only ~5% of the DIN load. Stormwater contributed minimally to DIN loads, and even during the wettest month, stormwater contributed only 13% of PO4 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.

3.2.4 San Pablo Bay/Carquinez

Annual averages

As noted in the Methods, 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 PO4 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.

Stormwater loads to San Pablo Bay/Carquinez were relatively more important in San Pablo Bay than other subembayments (Table 6), exceeding direct POTW loads of both DIN and PO4 on an annual basis. This result was driven by the size of the San Pablo Bay/Carquinez watershed and, more importantly, land-use within its watersheds region. This region accounts for 32% of all watershed area Bay-wide, and a large portion of that area (33%) is classified as agriculture landuse (Table , Figure 5). Although there is considerable uncertainty in the stormwater load estimates, these results suggest that stormwater loads to San Pablo Bay cannot be considered insignificant, and additional efforts to refine estimates and reduce uncertainty may be needed. These annual average comparisons among sources in San Pablo 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

Neither POTW nor refinery loads showed a consistent seasonal trend. Stormwater loads dominated direct DIN and PO4 inputs during the wet months, but during dry months, contributions from stormwater decreased and POTWs/refineries were the dominant source of nutrient loads (Figure 10). [DIN]:[PO4] from POTWs increased during dry summer months, but it was less than [DIN]:[PO4] from stormwater at all times of the year (Figure A.1.4). The [DIN]:[PO4] of stormwater loads was higher in San Pablo Bay/Carquinez than in any other subembayments, because of loading model assumptions and land-use characteristics (the runoff nutrient concentrations for agricultural land use had higher DIN:PO4 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 estimates were feasible. 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} NH4, 17000 kg d^{-1} NO3, and 2500 kg d^{-1} PO4, exceeding loads from any other source to San Pablo Bay by a factor of 3-4. For 2/3 of the year, loads from Suisun Bay to San Pablo Bay accounted for a large proportion of all nutrient forms (Figure 11). These Suisun export estimates are highly uncertain, and need to be better constrained; nonetheless they illustrate the potential importance of up-estuary loads 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 PO4 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 NO3, although NH4 loads were nontrivial. Direct POTW DIN loads to Suisun Bay were primarily in the form of NH4 (Table 4). Stormwater loads to Suisun Bay were non-trivial, especially relative to POTW loads; however, they were ultimately less than 10% of total DIN loads and less than 20% of total PO4 loads due to the large contribution of Delta efflux loads. Refinery loads were non-zero, but small.

Seasonal variability

POTW and refinery loads in Suisun Bay exhibited low (DIN) to modest (PO4) seasonal variability. However, Delta and stormwater loads varied strongly between wet and dry seasons (Figure 12). Delta efflux dominated loads to Suisun Bay during winter months, contributing 2/3 or more of NH4, NO3 and PO4. 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 PO4 load. Stormwater loads peaked during January, when they contribute 11% of DIN loads and 22% of PO4 loads to Suisun.

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 PO4 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, these up-estuary loads were the dominant nutrient source to San Pablo Bay/Carquinez. In Suisun Bay, estimates suggest 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 PO4 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.

4.1.2 Variability by season

Relying only on annual averages can obscure the fact that some nutrient sources account for a larger proportion of overall loads during certain months or seasons than would be evident from annual-average data. To assess seasonal variation, each subembayment's monthly averaged loads were examined (Figures 7-12).

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 precipitation patterns. Due to this, even though stormwater loads are not significant on an annual basis in Lower South Bay and South Bay, during certain rainy months, stormwater loads have the potential to be significant sources of NH4 to Lower South Bay and NO3 to South Bay.

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 load estimates from the RWSM suggest that stormwater loads were the second most important source to San Pablo Bay during wet months. During dry months, 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 PO4 sources during dry months despite POTWs not being dominant on an annually-averaged basis. Estimated NH4 loads from the Delta exceeded direct POTW loads for as much as half the year, but direct POTW loads dominated during the rest of the year. Much of the NH4 entering and leaving the Delta originated from the Sacramento Regional County Sanitation District (~15000 kg d^{-1}; SRCSD). The seasonal variation in the Delta NH4 efflux load to Suisun Bay was probably due in large part to seasonal differences in nitrification as the SRCSD's effluent traveled along the Sacramento River (Parker et al., 2012;

Foe, 2010) and migrated through the Delta. The Delta contributed the largest source of NO3 year-round to Suisun Bay, and the majority of PO4 during half the year. The Delta NO3 loads were likely due both to nitrified NH4 (originally released by SRCSD) and NO3 from other sources (e.g., other POTWs upstream of and within the Delta; agriculture upstream of and within the Delta). Estimated stormwater DIN and PO4 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 changes over recent decades in loading patterns to be examined. Since data analysis and modeling efforts in SFB will focus on investigating changes in ambient water quality and ecosystem response over the past few decades, changes in loads (or load composition) over that period also need to be assessed.

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 NH4 loads decreased by ~90% (Figure 13a). Palo Alto and Sunnyvale also nitrify, shifting the dominant form of DIN discharged to Lower South Bay from NH4 to NO3 (Figure 13b).

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 13c). Current DIN loads are ~4000 kg d^{-1}, and there is substantial variability (±30-40%) around this central tendency value. Several treatment upgrades at San Jose over the past 20 years have also decreased PO4 loads by ~75% (Figure 13d). Although NH4 now represents only ~5% of SJSC's N load, there appears to have been a trend of increasing NH4 over the past 10 years. This seems to be due to increases in effluent NH4 concentrations (Figure 14b), since flows have actually decreased over this same time period (Figure 14a).

Like SJSC, the majority of N load from Palo Alto was in the form of NO3. NH4 loads from Palo Alto have remained more or less constant since approximately 1995 with occasional spikes of higher NH4 loads, including a prolonged period between approximately 2007 and 2010; during this 3 year period NH4 loads remained <5% of its DIN loads. Palo Alto's DIN loads have increased by approximately 30% since 1995. PO4 loads increased by approximately 20% over that period, with evidence of a decrease (~20%) since 2009 that has returned PO4 loads back to 1995 levels.

At Sunnyvale, both NH4 and NO3 loads showed strong seasonality. This is apparently 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.). Beyond this seasonality there is no apparent trend in baseline NH4 loads from Sunnyvale. 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. PO4 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.

4.2.2 Suisun

Suisun Bay receives large loads of NO3 and NH4 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 long-term 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 was available intermittently between 1992 and 2011. While there was limited PO4 data for Suisun Bay POTWs, TP data was available and was analyzed here. The concentration data from 2012 POTW effluent monitoring suggests that PO4 was approximately 55% of TP at CCCSD and DDSD, and 90% of TP at FSSD. Trends in PO4 loads from the Delta were also assessed.

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 15). CCCSD experimented with trial periods of nitrification (intermittent between 1977 and 1988); for clarity, data from that period was omitted from the time series. In general, NH4 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 15a,c). The load increases appear to have been due to an increase in effluent NH4 concentration (Figure 16b), rather than an increase in flow (Figure 16a). Aside from a short period of higher NO3 loads in the late 1990's, NO3 loads have stayed relatively constant over the same period (Figure 16b). FSSD nitrifies its effluents and discharges primarily NO3. While FSSD's DIN loads exhibited large fluctuations in magnitude, over the period 2004-2011 their average load appears to have doubled. 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, although there was large fluctuation around this central value. TP data from DDSD was too sparse to comment on long-term trends.

Delta efflux loads showed strong seasonal trends and large interannual variability, with the latter resulting from extreme (drought vs. atypically wet) conditions (Figure 17). NH4 and NO3 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 less agriculture-runoff-derived nitrate during the dry season (Figure 18a,b). In addition to this seasonal variation, NH4 and NO3 loads have increased between 1975 and 2011. NH4 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). NO3 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 NH4 load is likely explainable by the 2-3 fold increase in NH4 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 NH4 load is nitrified en route to Suisun Bay (Parker et al. 2012). 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 NH4 to NO3 could make POTWs discharging directly to Suisun Bay the dominant NH4 source, and perhaps the largest source of DIN during certain times of the year.

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 NH4 is the primary DIN form it emits to the Bay. SFPUC's NH4 loads have increased by ~50%, from 4000-5000 kg d^{-1} in 1996 to 7500 kg d^{-1} in 2011 (Figure 19a). NO3 loads were <10% of DIN loads (Figure 22b). SFPUC PO4 loads have been highly variable but there do not appear to have been substantial systematic changes in loads since 1996.

Effluent flow rate and NH4 concentration data are available from EBMUD back to 1998. EBMUD does not nitrify, so the majority of its DIN load should be in the form of NH4. EBMUD's NH4 loads have increased by ~50% since 2002 from 6000 kg d^{-1} to 9000 kg d^{-1} by 2011 (Figure 19a). This increase appears to be due primarily to increased NH4 concentration, as opposed to increased flow (Figure 20). Some portion of the increase in EBMUD's NH4 concentration and load may be 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 additional material, this practice augments N exports to the Bay. No PO4 data for EBMUD prior to 2012 was available to determine whether PO4 loads have also changed.

Flow and NH4 data for the EBDA combined outfall were available back to 1999 (Figure 19). EBDA NH4 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 NH4 concentrations increased (Figure 20). The fact that the data series stops in 2011 makes it difficult to assess whether this apparent increase reflects a real trend.

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 with NO3 and PO4 effluent concentrations and loads. Aside from several POTWs that have been monitoring for multiple nutrient forms, for most POTWs only NH4 concentration data was readily available prior to 2012. For plants that do not nitrify, NH4 concentrations provide a reasonable surrogate for estimating total DIN loads. However, PO4 concentrations appear to be highly variable among POTWs (based on the 6 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, the order-of-magnitude estimates suggest that stormwater loads have the potential to contribute substantially to DIN and PO4 loads in some subembayments during some times of the year. Furthermore, while stormwater loads may not be important at the subembayments scale in some subembayments, their importance at finer spatial scales (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 stormwater load estimates it generates are highly uncertain due to inherent model limitations and the fact that it 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. 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 and Cloern, 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. Hydrodynamic and reactive transport models need to be calibrated, validated, and applied to generate improved nutrient load estimates from the Delta to Suisun Bay, 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, slated to begin in Q3 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). Additional monitoring data may also be needed to refine load estimates.

Accurate estimates of nutrient loads at subembayment and finer scales need to consider nutrient exchange between subembayments. The need for such estimates is evident through the potential importance of loads coming from Suisun Bay (and the Delta) to total loads in San Pablo Bay/Carquinez. Loads from South Bay and San Pablo Bay likely represent important and seasonally varying sources to Central Bay. In addition, direct POTWs 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 subembayments spatial scales and at monthly time scales so that seasonal variation in the relative importance of sources could be evaluated. For these calculations, the Water Board'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 et al., 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 21); 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.

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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 (% total flow Bay-wide)	Watershed area (sq. km)	% surface water[2]	% open[2]	% agriculture[2]	% commercial[2]	% industrial[2]	% residential[2]	% transportation[2]
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] Based on data from Association of Bay Area Governments (2000)

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 NH4, NO3 and PO4 (among other nutrients). See section 2.2 for a discussion of subembayment groupings.

			Flow		NH4		NO3		PO4	
			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
		City of Palo Alto	1994-2011	6326	1994-2011	845	1994-2011	220	1994-2011	204
		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	199-2011	411				
		City and County of SF-Southeast Plant (SFPUC)	1996-2011	5368	1996-2011	415	1996-2011	154	1996-2011	127
		South Bayside System Authority (SBSA)	1990-2011	8033	1990-2011	1005				
		City of San Mateo	1999-2011	2378	1996-1999 2008-2011	192 36				
		Cities of South SF and San Bruno (SSF-SB)[2]	2004-2011	2922	2004-2011	2215				
		City of Burlingame[2]								
		City of Millbrae[2]								
		San Francisco International Airport (SFO)[2]								
Central Bay	Large dischargers	East Bay Municipal Utility District (EBMUD)	1999-2011	4473	2007-2011	150				
		Central Marin Sanitation Agency (CMSA)	1998-2011	4932	1998-2011	708				
		West County/Richmond	2003-2011	2951	2008-2011	55				
	Small dischargers	Sewage Agency of Southern Marin (SASM)[3]	Loads estimated using design flow and 2012 concentrations							
		Sausalito-Marin City Sanitation District								
		U.S. Department of Navy - Treasure Island								
		Sanitary District of Marin County #5[3]								
San Pablo Bay/Carquinez	Large dischargers	Napa Sanitation District	200-2011	2311	2001-2011	149				
		Vallejo Sanitation and Flood Control District	2000-2011	1654	2000-2011	1652	2000-2011	136		
		Chevron, Richmond Refinery	2004-2009	1068	2004-2009	44				
		Shell Oil, Martinez Refinery	1998-2011	4563	2004-2009	135	2004-2009	47		
		Novato Sanitary District	2005-2011	878	2005-2011	272				
		Sonoma Valley County Sanitation District	1996-2011	5844	1996-2011	808	1996-2011	802		
		Conoco Phillips66 Rodeo Refinery	2004-2011	150	2004-2009	72	2007-2008	14		
		City of Pinole/Hercules[4]	2002-2011	104	2002-2011	62	2007-2009	26		
	Small dischargers	City of Petaluma	Loads estimated using design flow and 2012 concentrations							
		City of Benicia								
		City of American Canyon								
		Rodeo Sanitary District[4]								
		Valero, Benicia Refinery								
		Las Gallinas Valley Sanitary District								
		C&H Sugar Company								
		City of Calistoga								
		Town of Yountville								
		City of St. Helena								

[1] 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.

[2] Combined discharge location

[3] Combined discharge location

[4] Combined discharge location

Table 2 (continued)

			Flow		NH4		NO3		PO4	
			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							

Table 3 Land-use specific nutrient concentration values used in the Regional Watershed Spreadsheet model. Values used were the geometric mean of values from the indicated literature sources. No PO4 value was available for transportation, so TP was used.

	NH4		NO3		PO4	
	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] WCC (1991)
[2] Davis et al (2000)
[3] Ackerman and Schiff (2003)
[4] Sengupta (2013)
[5] Yoon and Stein (2007)
[6] Willardson (2008)

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)		NH4 (mg L^{-1})		NH4 (kg d^{-1})		NO3 (mg L^{-1})		NO3 (kg d^{-1})		DIN (kg d^{-1})		PO4 (mg L^{-1})		PO4 (kg d^{-1})		[DIN]:[PO4]		DIN/TN (%)	PO4/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%
Lower South Bay	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%
Lower South Bay	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%
South Bay	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%
South Bay	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%
South Bay	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%
South Bay	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%
South Bay	Burlingame	4		22.7		315		4.5		63		378		2.5		34		11		84%	46%
South Bay	Millbrae	2		39.2		297		0.1		1		298		2.6		20		15		94%	82%
South Bay	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%
Central Bay	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%
Central Bay	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%
Central Bay	SASM	2		3.7		34.0		15.8		144		178		4.4		40		4		89%	90%
Central Bay	Sausilito	1		8.8		40		12.2		56		96		3.6		16		6		90%	83%
Central Bay	Treasure Island	1		0.4		2		7.4		36		38		3.1		15		3		71%	137%
Central Bay	Marin District 5 (Tiburon)	1		21.0		52		0.5		1		53		2.5		6		9		91%	69%

[1] San Jose upgraded PO4 treatment in 2007 so historic analysis was limited to 2007-2011

[2] Sunnyvale dredged nitrification ponds in early 2012 and 2012 PO4 levels may be artificially high. PO4 loads were calculated using 2006-2011 flow, 2006-2011 TP and PO4: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 (continued)

		Flow (MGD)		NH4 (mg L^{-1})		NH4 (kg d^{-1})		NO3 (mg L^{-1})		NO3 (kg d^{-1})		DIN (kg d^{-1})		PO4 (mg L^{-1})		PO4 (kg d^{-1})		[DIN]:[PO4]		DIN/TN (%)	PO4/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)		NH4 (mg L^{-1})		NH4 (kg d^{-1})		NO3 (mg L^{-1})		NO3 (kg d^{-1})		DIN (kg d^{-1})		PO4 (mg L^{-1})		PO4 (kg d^{-1})		[DIN]:[PO4]		DIN/TN (%)	PO4/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} NH4, 17000 kg d^{-1} NO3 and 2500 kg d^{-1} PO4. See section 2.2 for a discussion of subembayment groupings.

		NH4					NO3					DIN					PO4				
		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	1111	47	11	n/a	1169	1082	690	75	n/a	1847	2193	737	86	n/a	3016	315	49	7	n/a	371
	Annual avg	**1270**	**88**	**1062**	**n/a**	**2420**	**1451**	**754**	**6422**	**n/a**	**8627**	**2721**	**842**	**7484**	**n/a**	**11047**	**406**	**60**	**623**	**n/a**	**1089**
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		**34371**	**204**	**1797**	**5808**	**42180**	**11841**	**768**	**9023**	**10376**	**32008**	**46212**	**972**	**10820**	**16484**	**74488**	**3943**	**61**	**1280**	**949**	**6233**

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).

	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	11047	310	13
Suisun Bay	23646	100	86
Bay-wide total	75938	1100	25

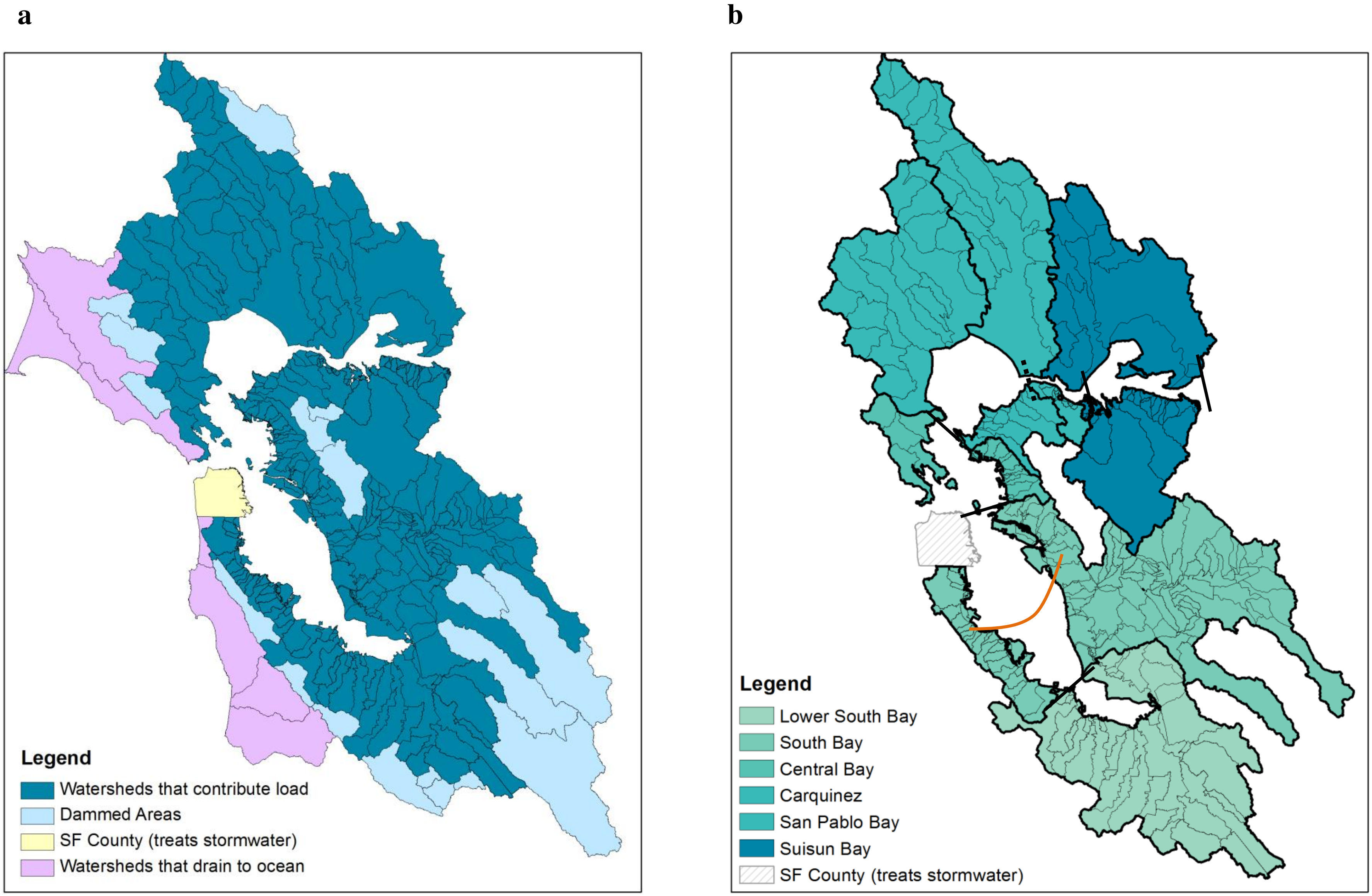


Figure 1 **(a)** A map of the entire Bay Area watershed, including watersheds that drain to the ocean (pink), watersheds that are dammed (light blue), San Francisco County (which treats stormwater along with wastewater, in yellow), and watersheds considered to contribute load to SF Bay (dark blue). **(b)** 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 Strait 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)

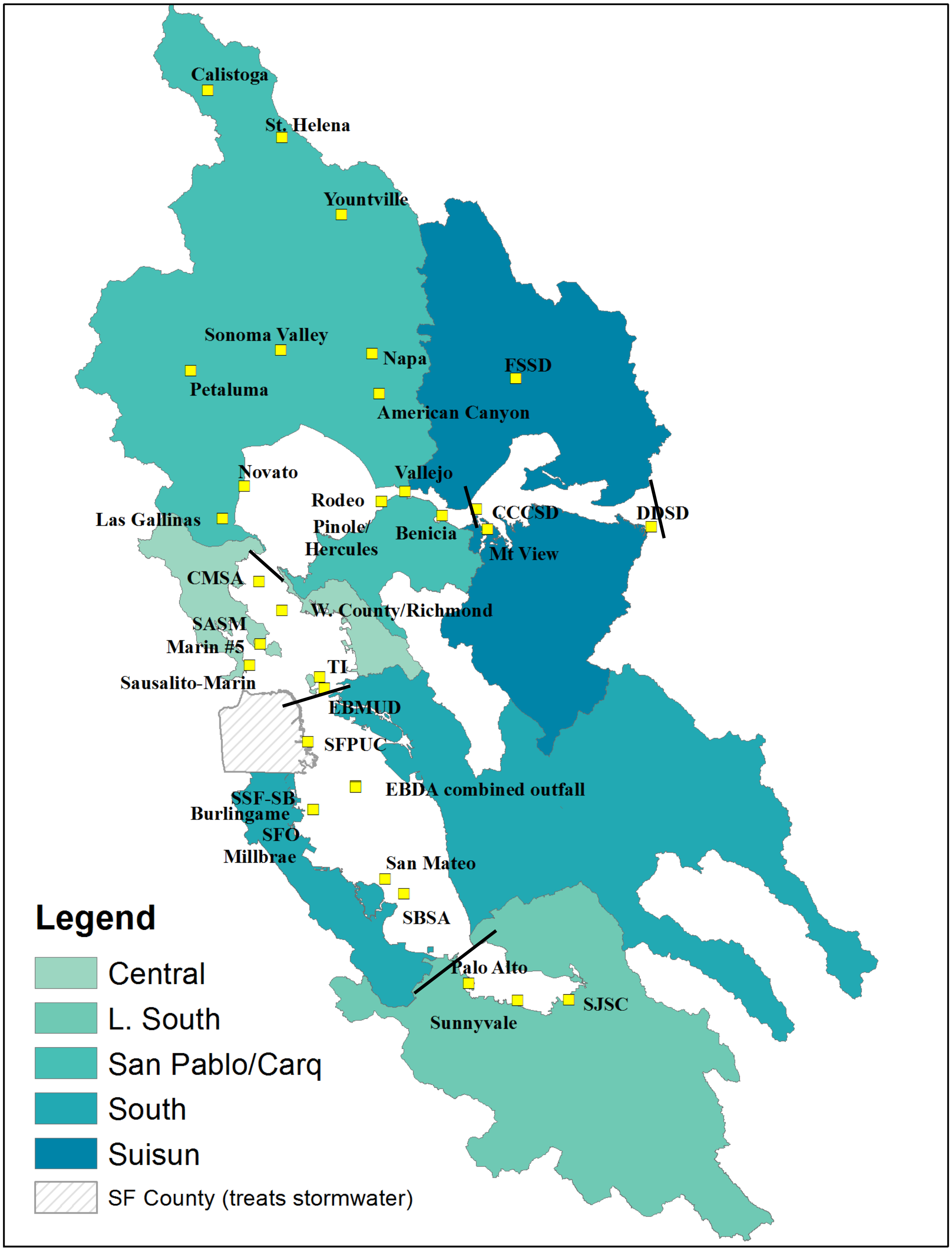


Figure 2(a) Location of POTW outfalls in San Francisco Bay. Colors indicate to which subembayment watersheds contribute load, based on the boundaries of the SF Regional Water Quality Control Board (shown in black). See section 2.2 for a discussion of subembayment groupings. SF County, which treats stormwater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

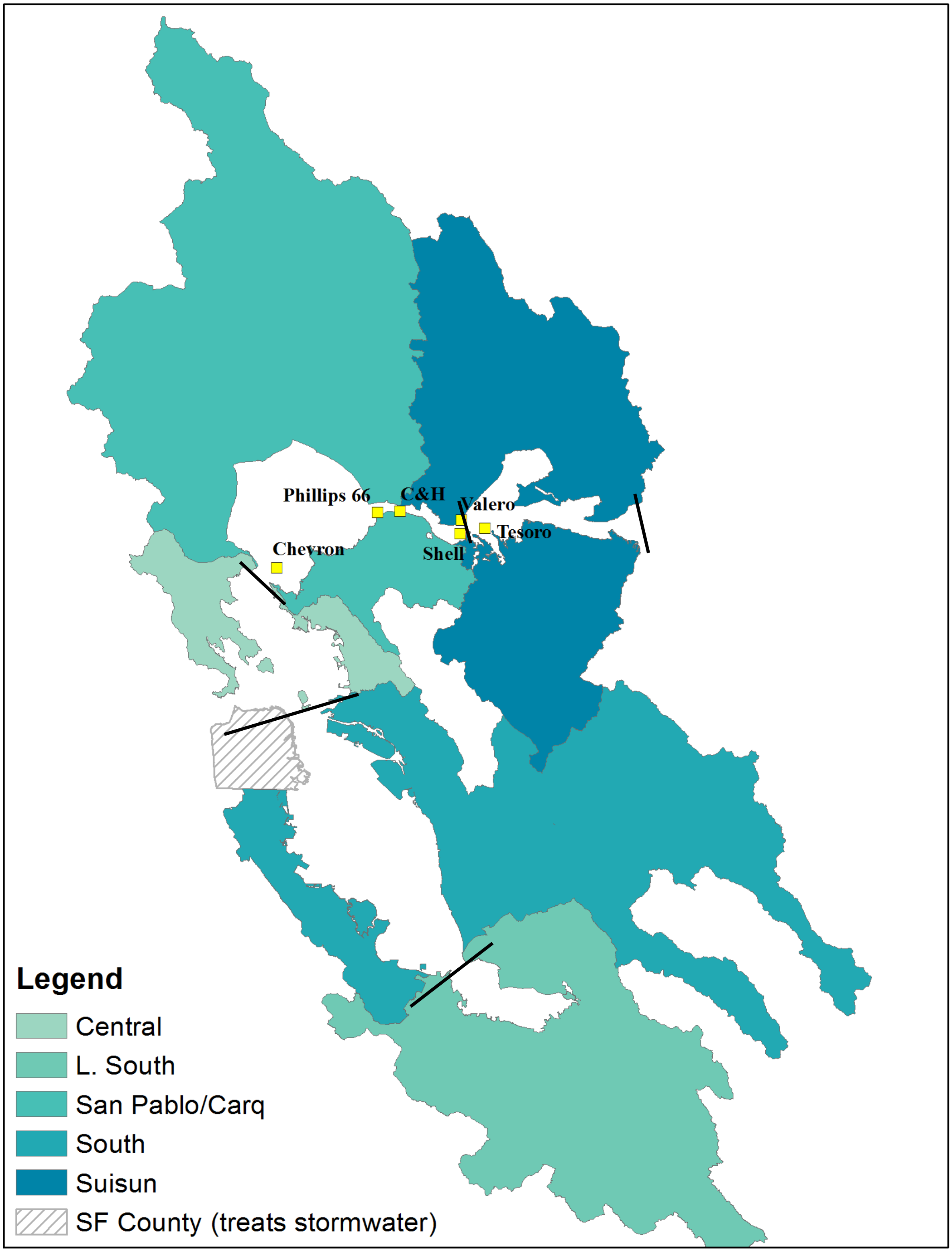


Figure 2(b) Location of refinery outfalls in San Francisco Bay. Colors indicate to which subembayment watersheds contribute load, and the boundaries that define them are shown in black (based on the boundaries of the SF Regional Water Quality Control Board). See section 2.2 for a discussion of subembayment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

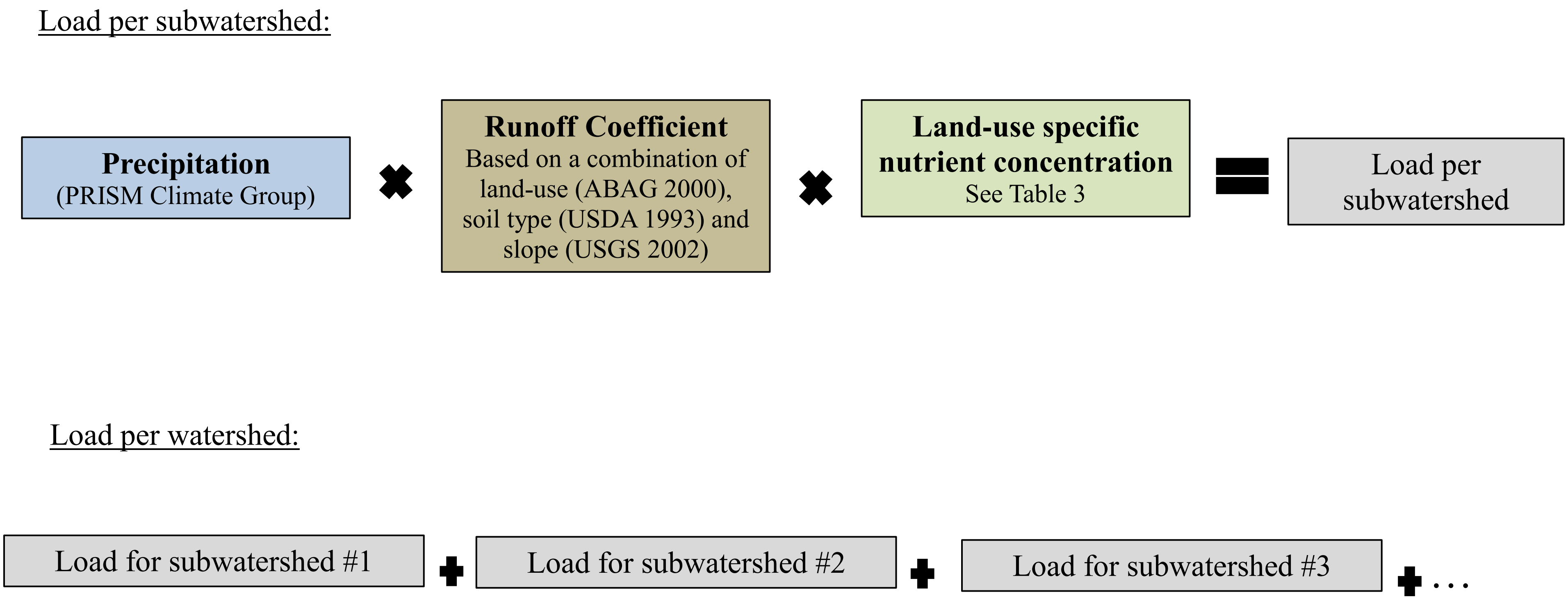


Figure 3 A schematic of the Regional Watershed Spreadsheet Model, the tool used to estimate stormwater nutrient loads. Several publicly available datasets were used as input variables to this model, including rainfall data from the PRISM Climate Group, land-use data from Association of Bay Area Governments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

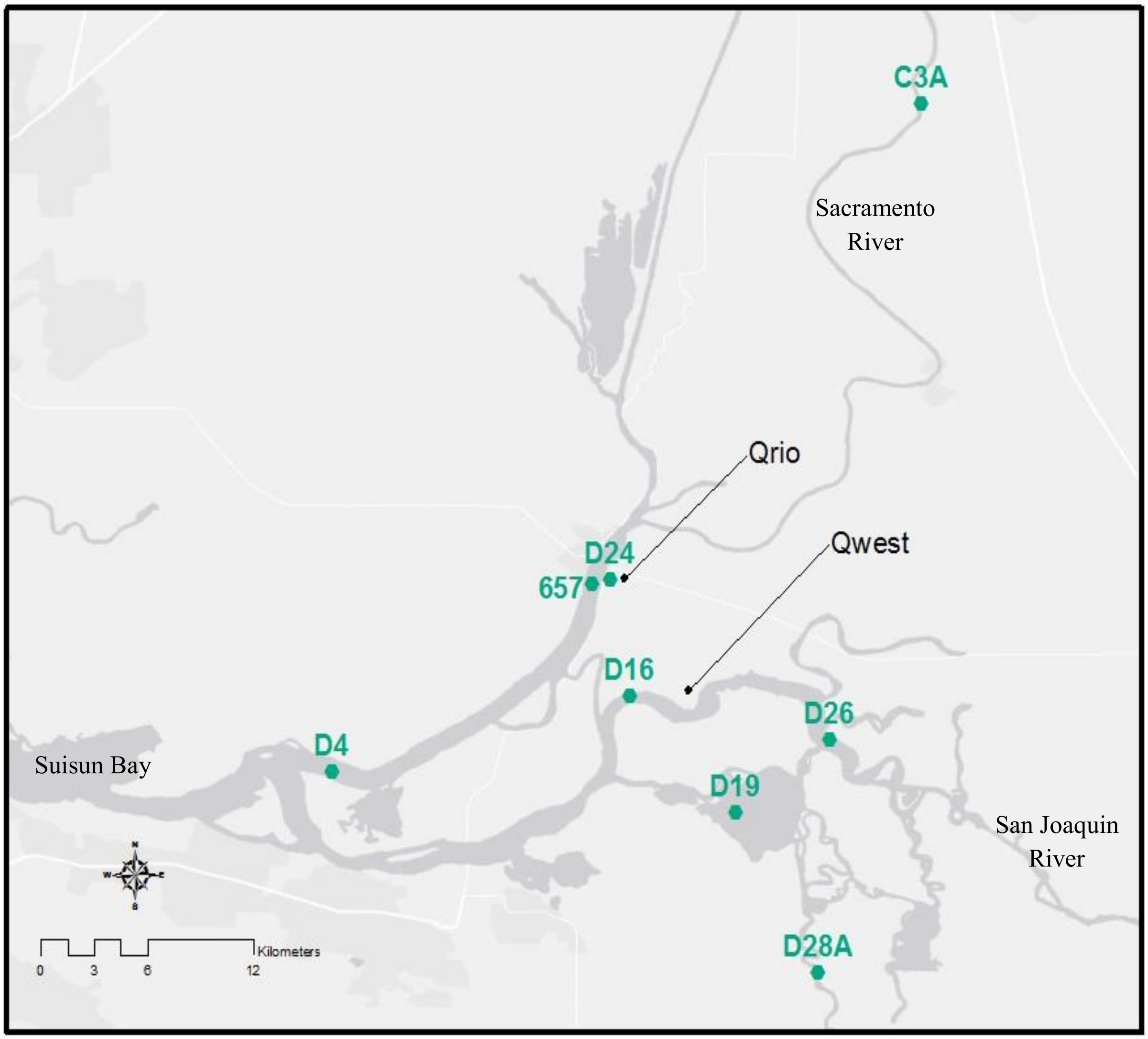


Figure 4 A schematic of the method used to calculate efflux loads from the Sacramento-San Joaquin Delta into Suisun Bay. Flow values (Q_{rio}, Q_{west}) were multiplied by water quality data from surrounding IEP or USGS monitoring stations (indicated by green dots) to estimate load. Detailed explanation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

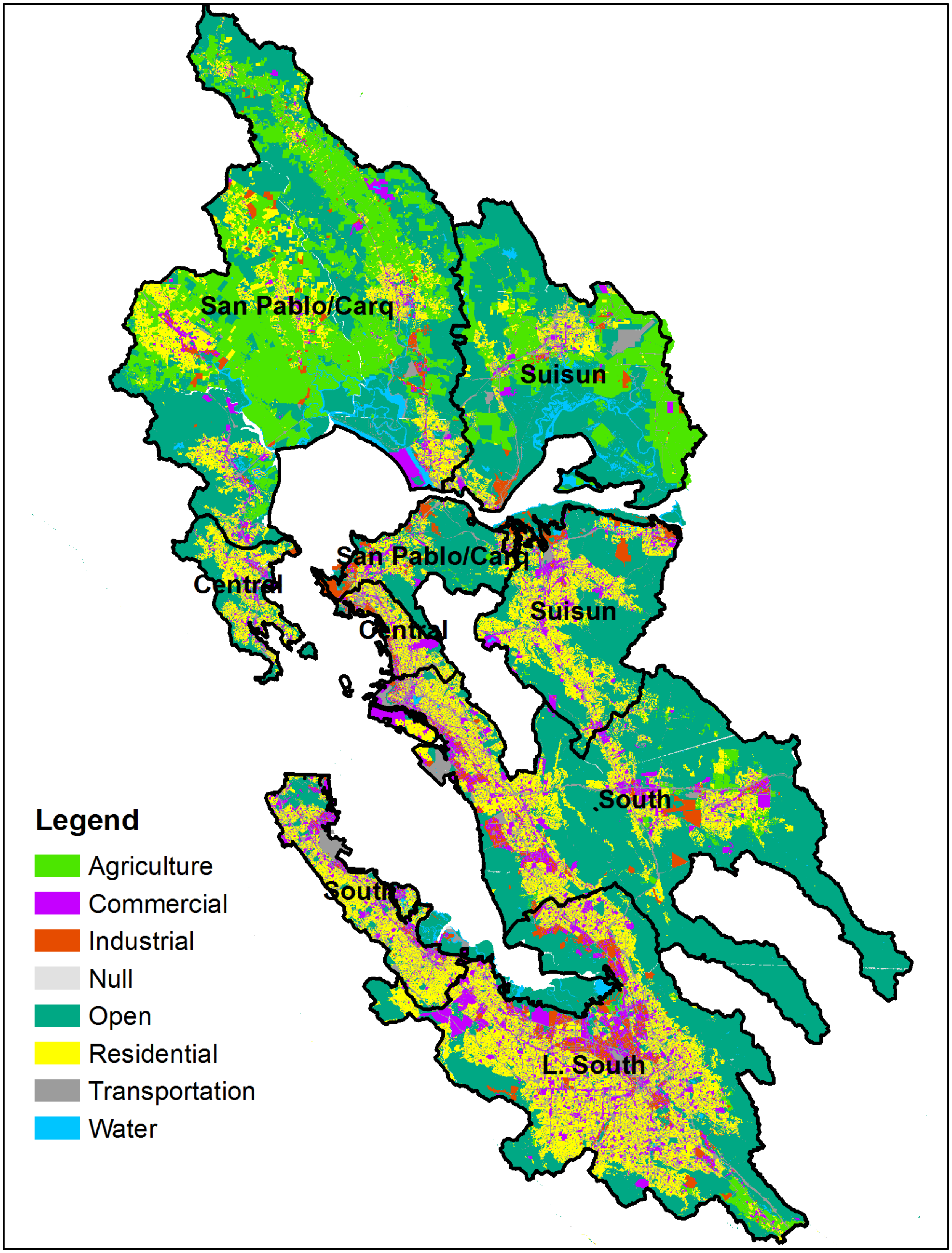


Figure 5 Land-use in watersheds that contribute load to San Francisco Bay, based on data from the Association of Bay Area Governments (2000). High frequency of agricultural activity in San Pablo Bay/Carquinez watersheds may explain high calculated stormwater loads for that region.

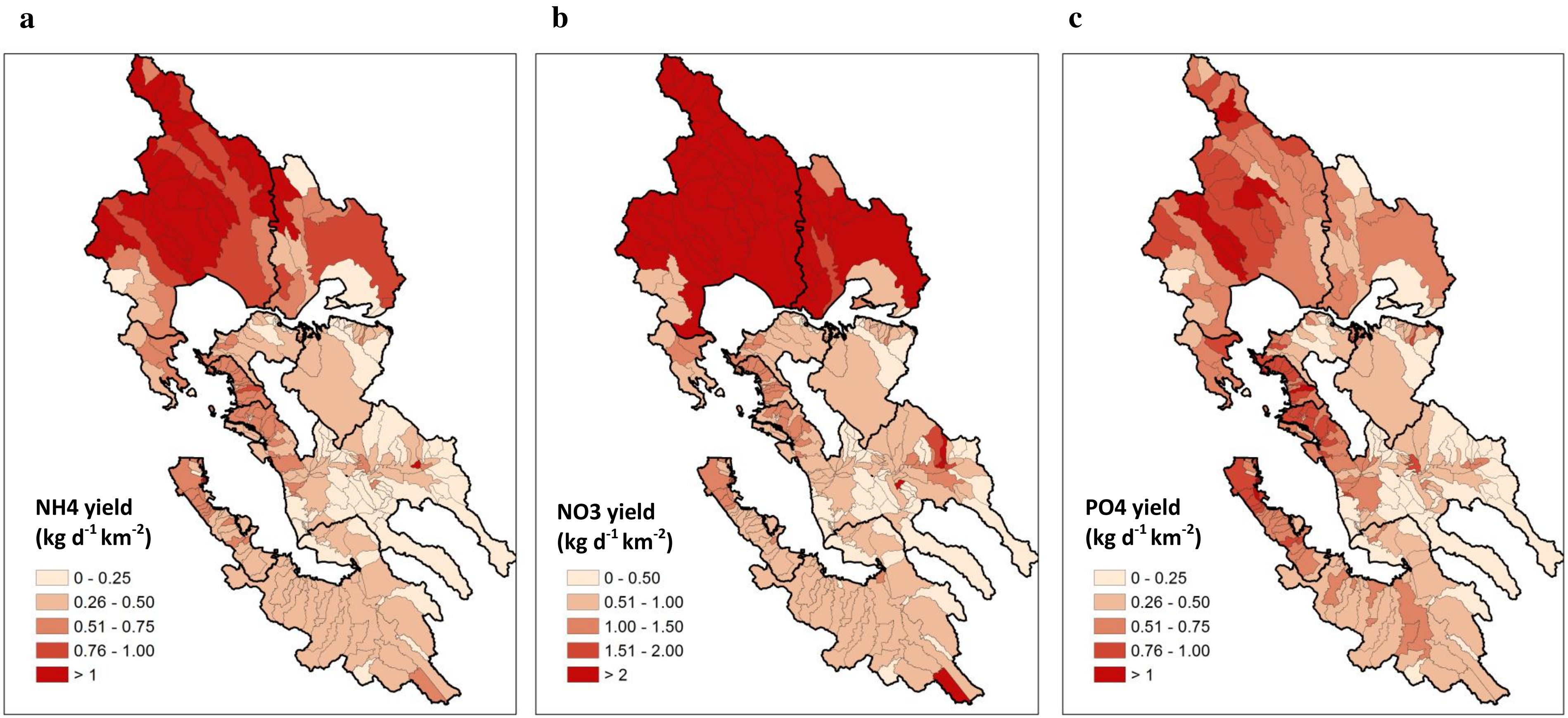


Figure 6 NH4 (**a**), NO3 (**b**), and PO4 (**c**) yields (load per km^2) for January, the region's highest precipitation month when calculated stormwater loads are at a maximum. Note the different scale in Figure 7b.

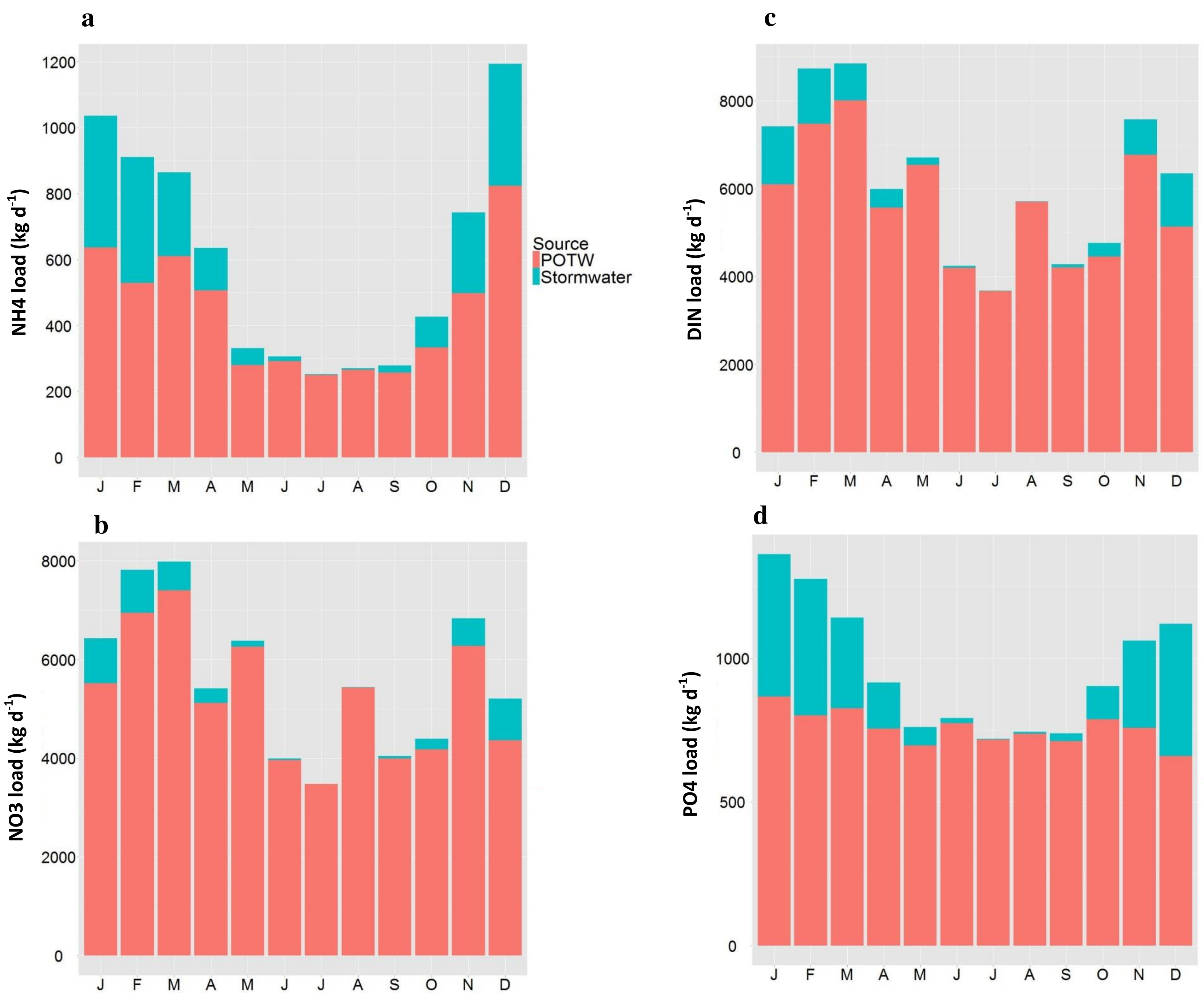


Figure 7 Average NH4 (**a**), NO3 (**b**), DIN (**c**) and PO4 (**d**) loads by month (for the period 2006-2011) from POTWs and stormwater into Lower South Bay. Note the different scales on the vertical axes.

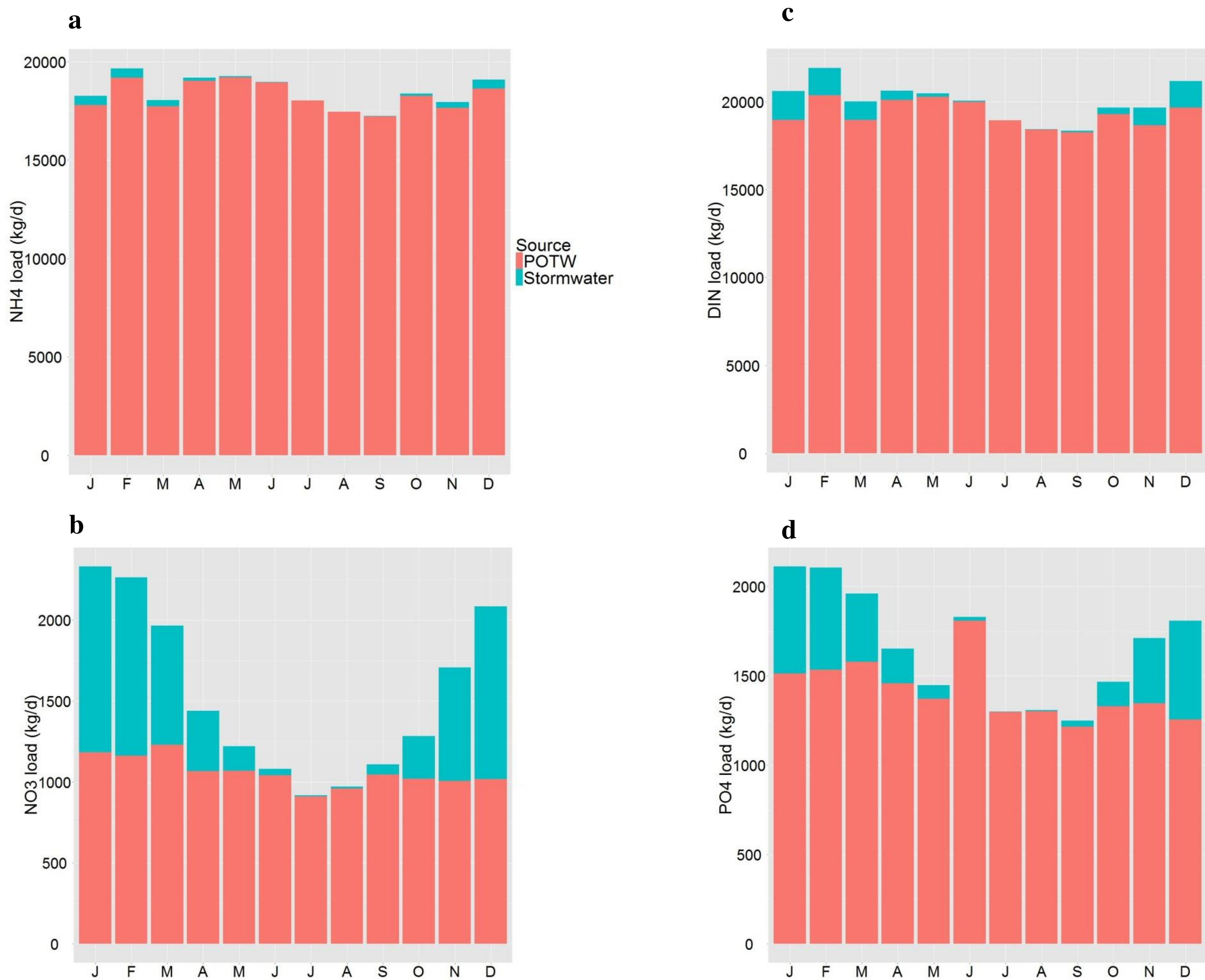


Figure 8 Average NH4 (**a**), NO3 (**b**), DIN (**c**) and PO4 (**d**) (for the period 2006-2011) from POTWs and stormwater into South Bay. Note the different scales on the vertical axes.

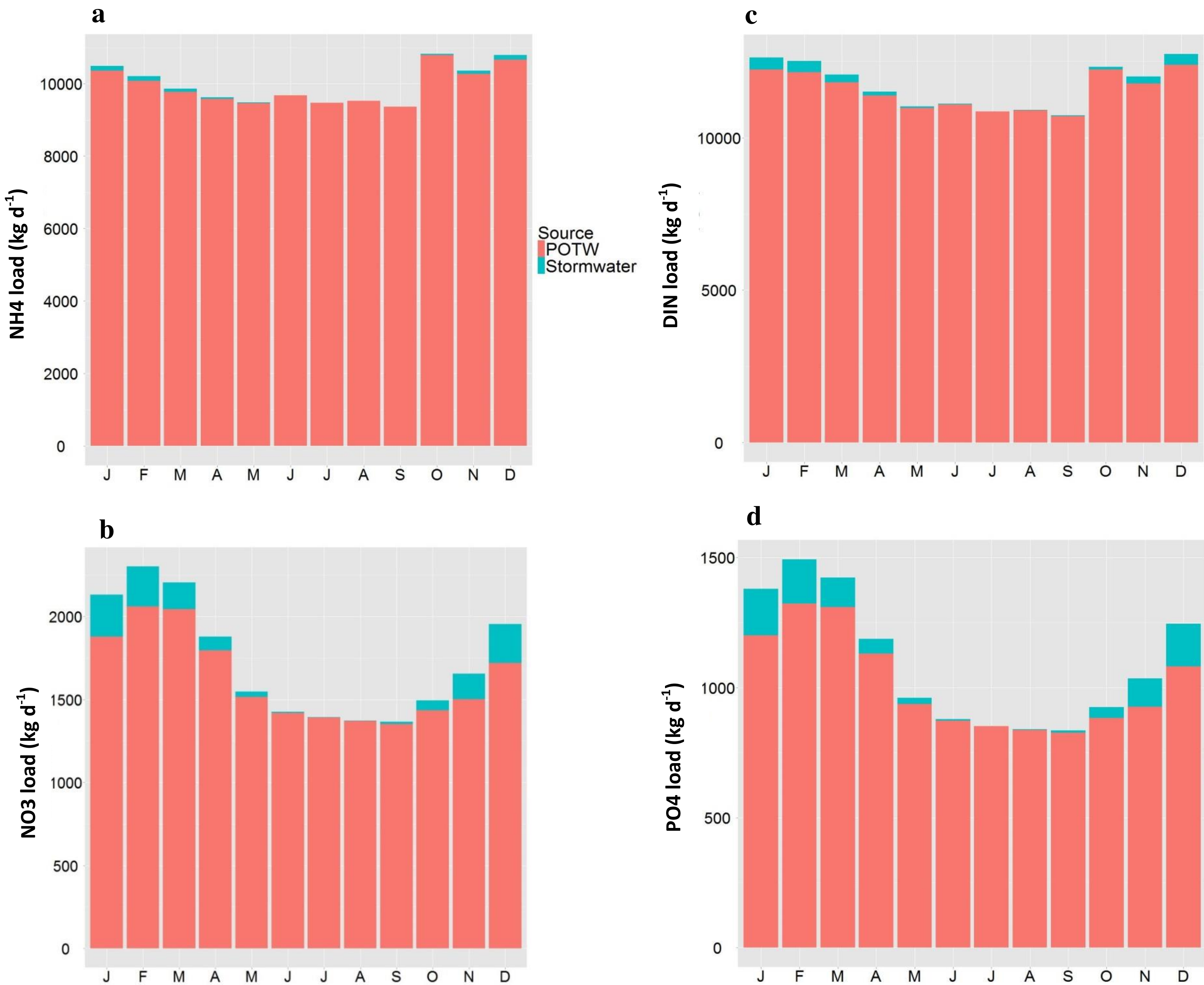


Figure 9 Average NH4 **(a)**, NO3 **(b)**, DIN **(c)** and PO4 **(d)** loads by month (for the period 2006-2011) from POTWs and stormwater into Central Bay. Note the different scales on the vertical axes.

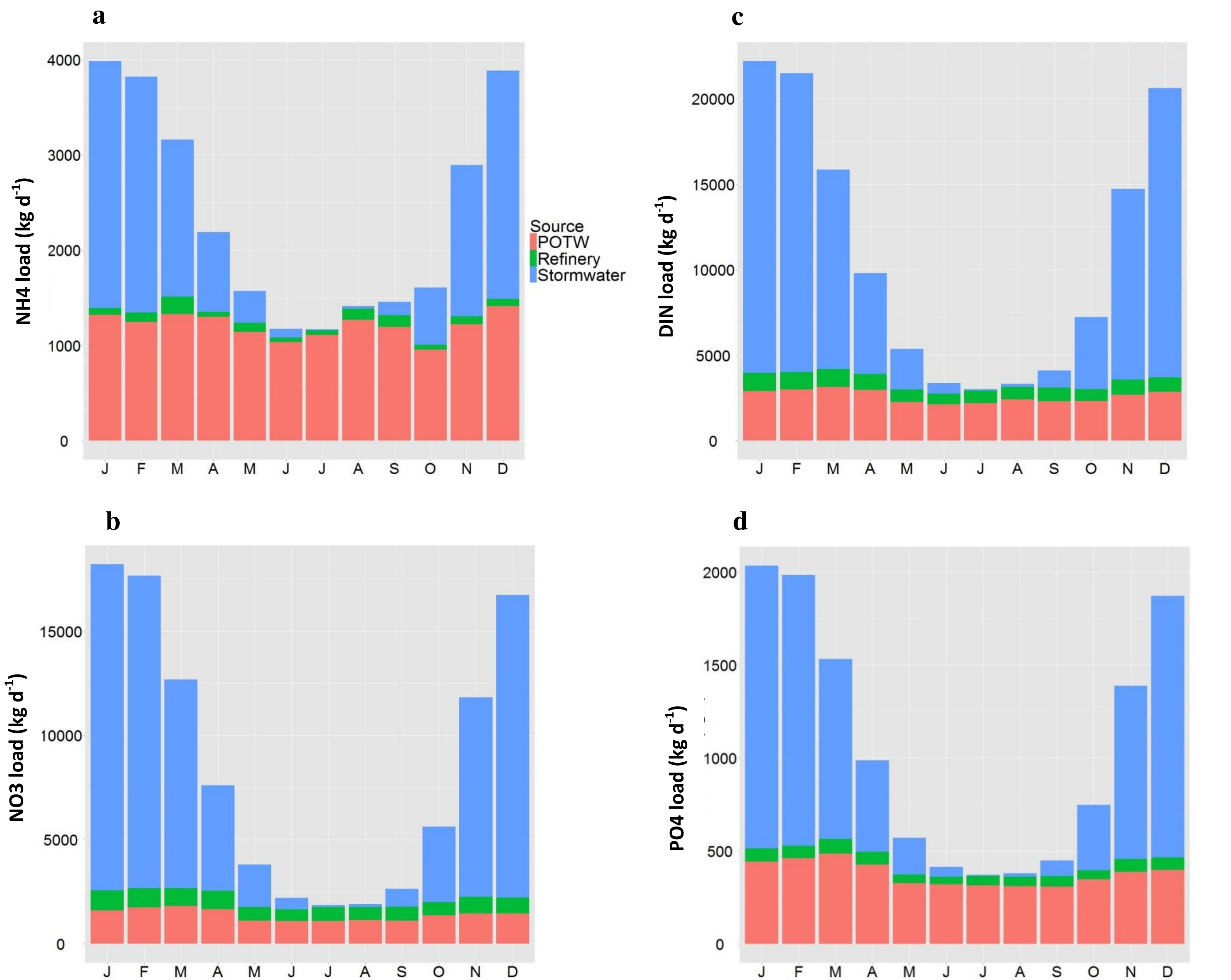


Figure 10 Average NH4 (**a**), NO3 (**b**), DIN (**c**) and PO4 (**d**) loads by month (for the period 2006-2011) from POTWs, refineries stormwater into the combined San Pablo Bay/Carquinez Strait region. Note the different scales on the vertical axes.

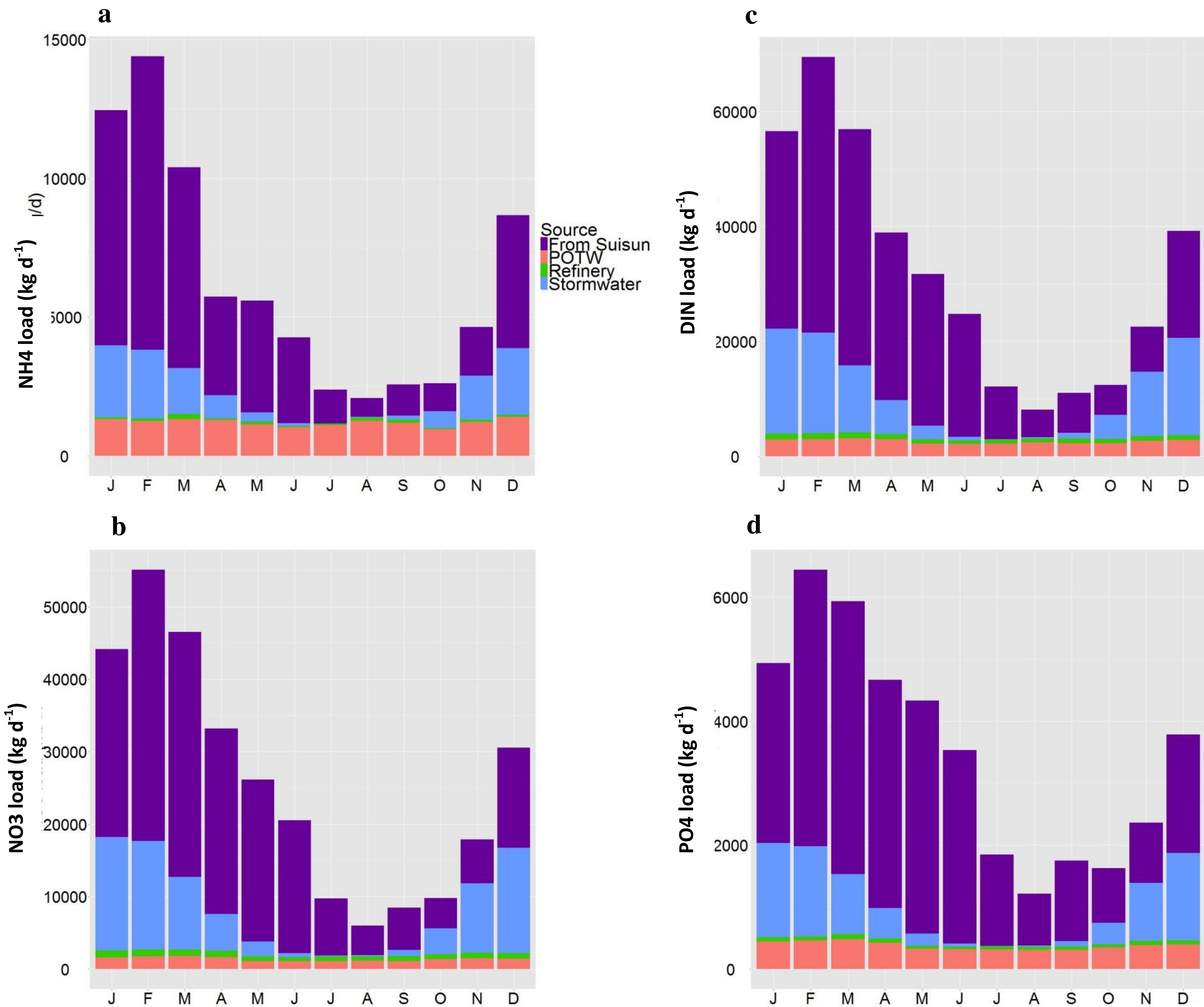


Figure 11 Average NH4 **(a)**, NO3 **(b)**, DIN **(c)** and PO4 **(d)** loads by month (for the period 2006-2011) into the combined San Pablo Bay/Carquinez Strait region, now considering loads exchanged from Suisun Bay. This includes both Delta loads advecting through Suisun Bay and POTW loads directly discharged to Suisun Bay and advecting downstream (see Appendix 3 for details of calculation). Note the different scales on the vertical axes.

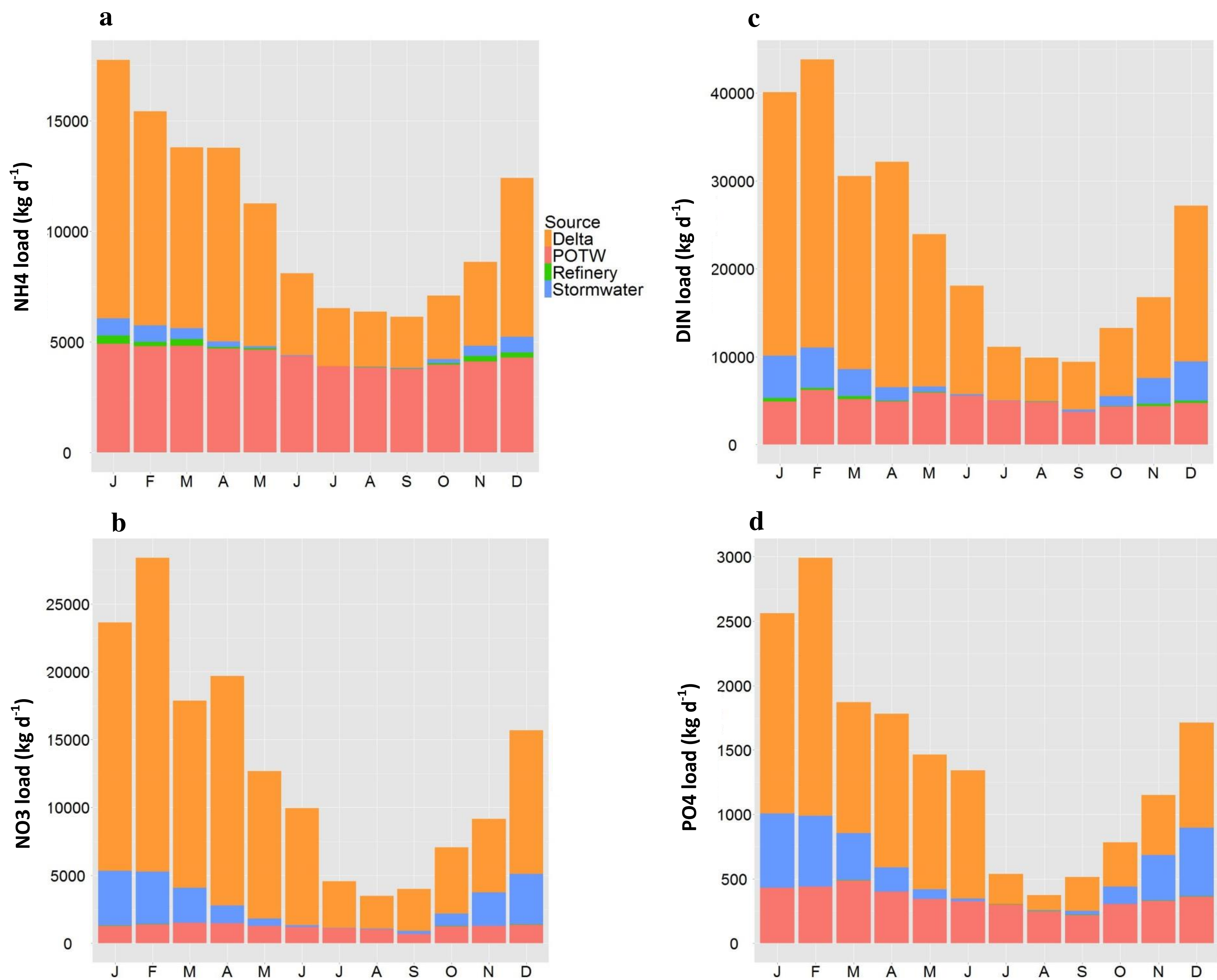


Figure 12 Average NH4 (**a**), NO3 (**b**), DIN (**c**) and PO4 (**d**) loads by month (for the period 2006-2011) from the Delta, POTWs and stormwater into Suisun Bay. One outlier was removed from the NO3 and DIN figures (February 2008) and one outlier was removed from the PO4 figure (April 2011). Note the different scales on the vertical axes.

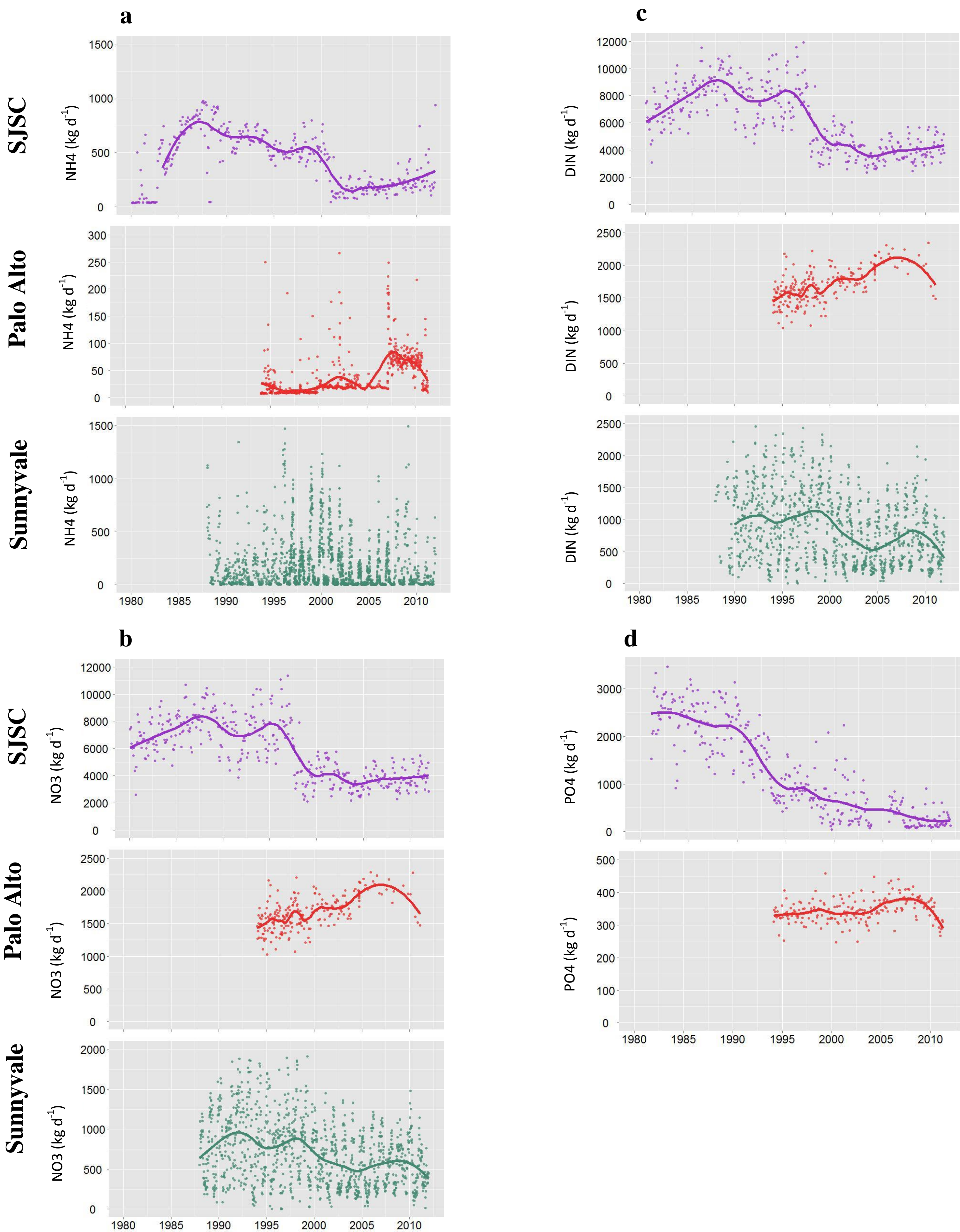


Figure 13 Long-term time series of NH4 (**a**), NO3 (**b**), DIN (**c**) and PO4 (**d**) loads from all POTWs in Lower South Bay. For clarity, only data after to the start of nitrification processes were included. A loess line (smoothing parameter = 0.3) was added to some figures in order to show a general pattern, but is not intended as a rigorous trend analysis. Note the different scales on the vertical axes.

a

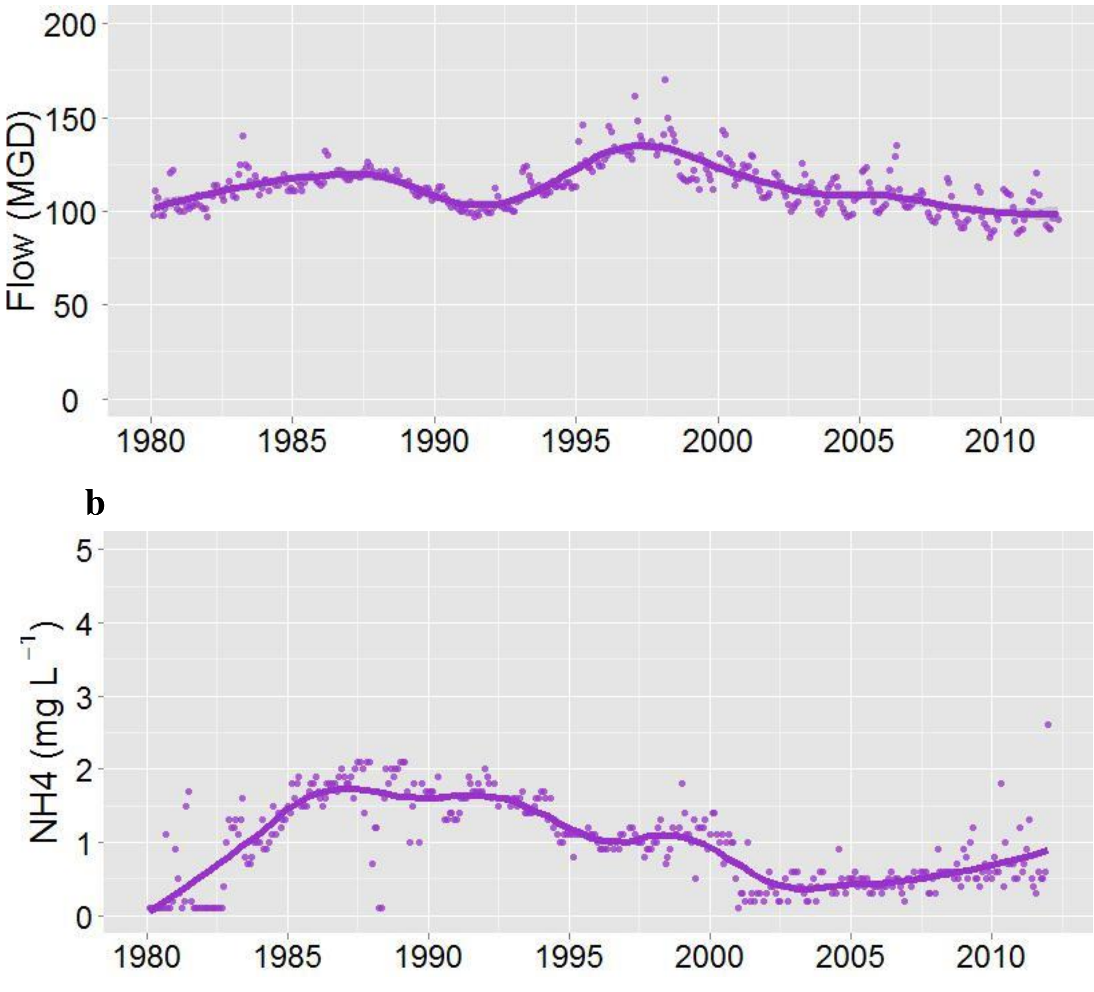


Figure 14 Long-term time series of flow **(a)** and NH4 effluent **(b)** concentration from SJSC. NH4 loads have increased at in the last decade (Figure 13a). For clarity, only data after to the start of nitrification processes were included. A loess line (smoothing parameter = 0.3) was added in order to show a general pattern, but is not intended as a rigorous trend analysis.

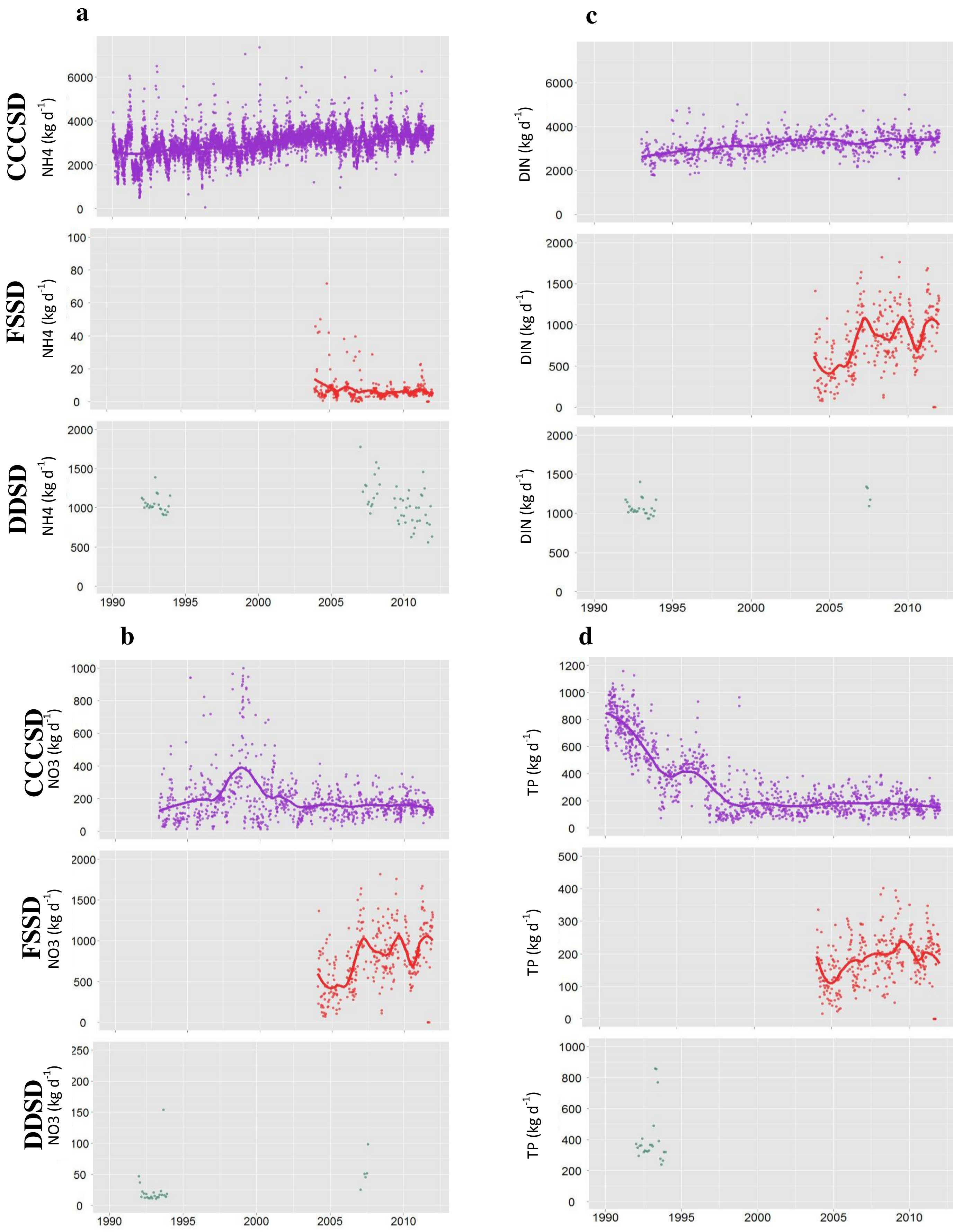
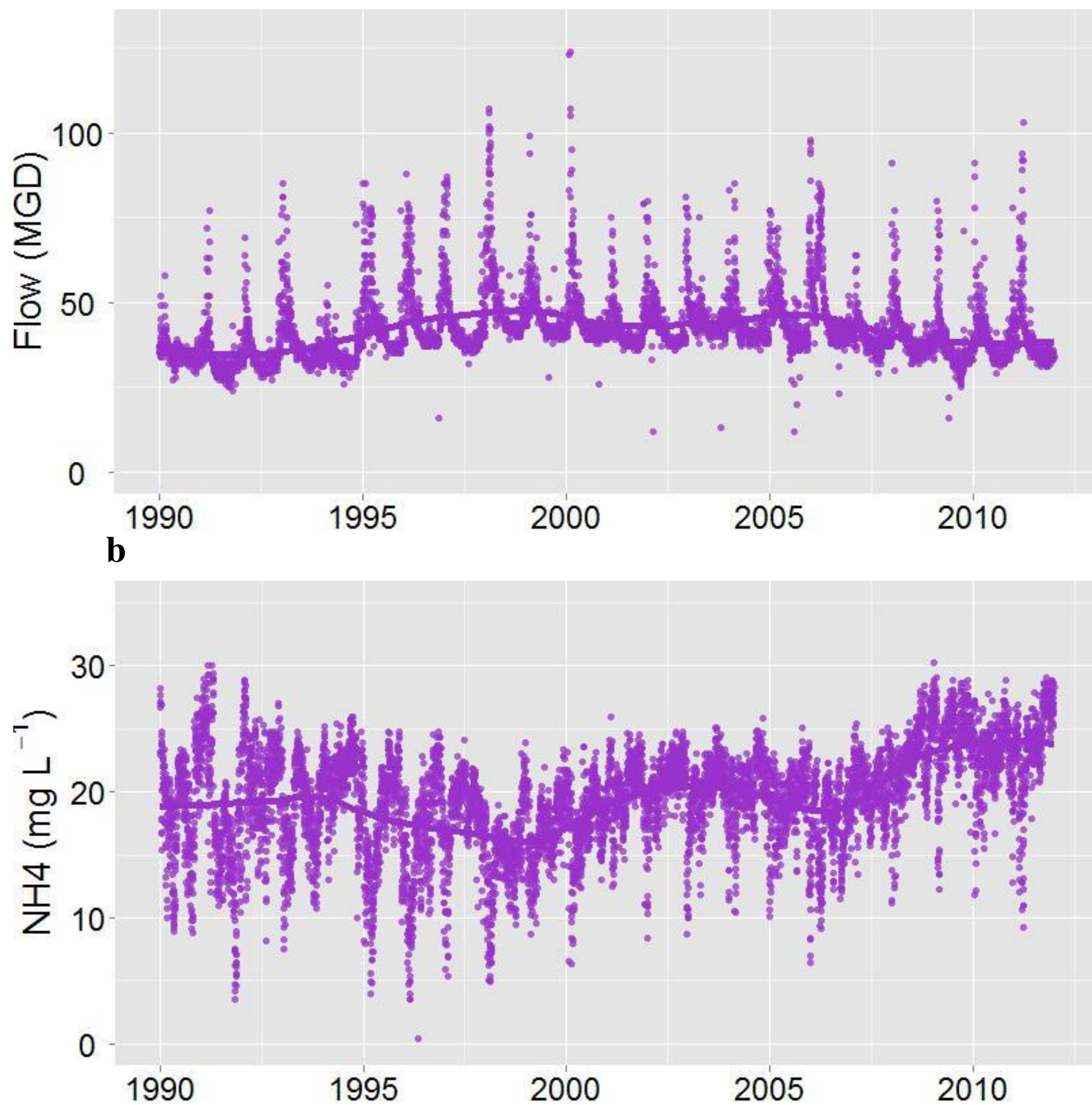


Figure 15 Long-term time series of NH4 **(a)**, NO3 **(b),** DIN **(c)** and TP **(d)** loads from major POTWs in Suisun Bay. Historical PO4 data was not available for any Suisun Bay discharger. For clarity, periods of trial nitrification by CCCSD (pre-1990) were omitted from figures. A loess line (smoothing 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.

a



b

Figure 16 Long-term time series of flow **(a)** and NH4 **(b)** effluent concentration from CCCSD. NH4 loads from CCCSD have increased in the last decade (Figure 15a). 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.

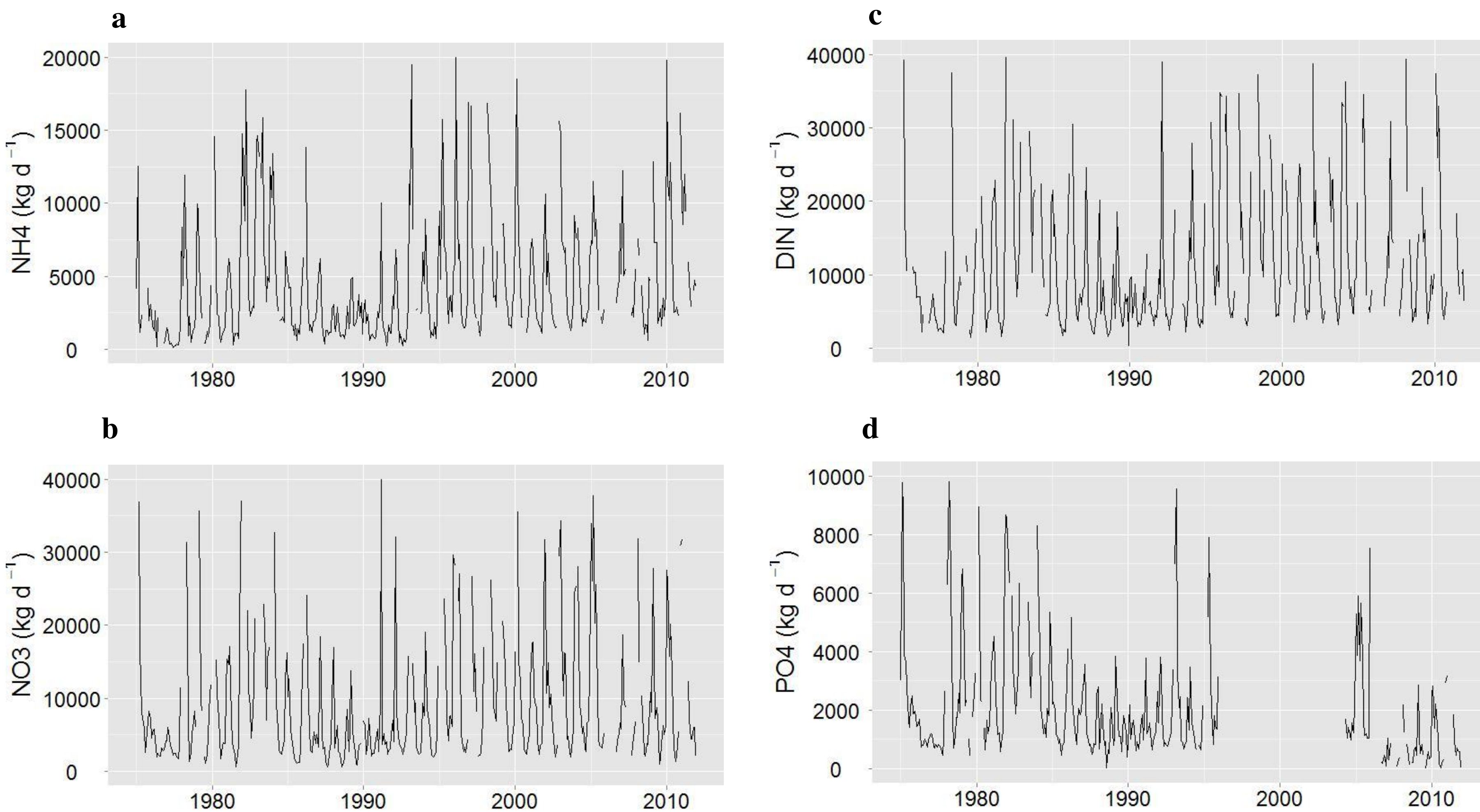


Figure 17 Long-term time series of NH4 (**a**), NO3 (**b**), DIN (**c**) and PO4 (**d**) loads from the Sacramento-San Joaquin Delta into Suisun Bay. Loads show considerable seasonal variability, and also an increase in baseline levels (see Figure 18). PO4 loads could not be estimated between 1996 and 2005 because of gaps in water quality data at a key station used in calculations. More detail on estimation methods can be found in Appendix 2. Note the different scales on the vertical axes.

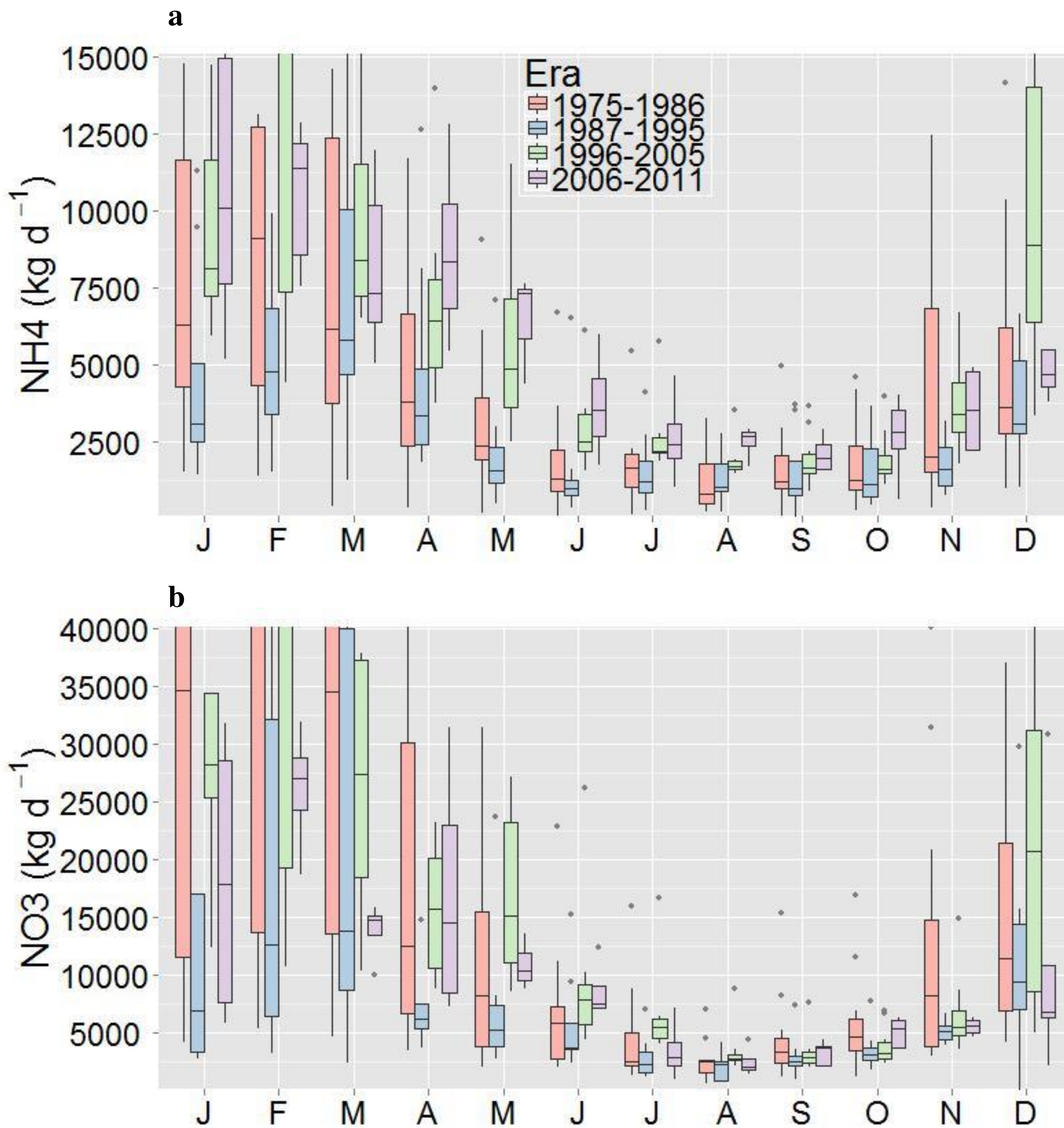


Figure 18 Seasonal and temporal variations in Delta effluxNH4 **(a)** and NO3 **(b)** loads to Suisun Bay. Data were first aggregated into four eras (1975-1986, 1987-1995, 1996-2005 and 2006-2011), and then averaged by month within each era. Statistically significant increases (over the entire period) in NH4 loads over this occurred in April-September and November-December, and statistically significant increase in NO3 loads occurred in June. Statistical significance was determined by the Kendall-Tau test (see Figure A.6)

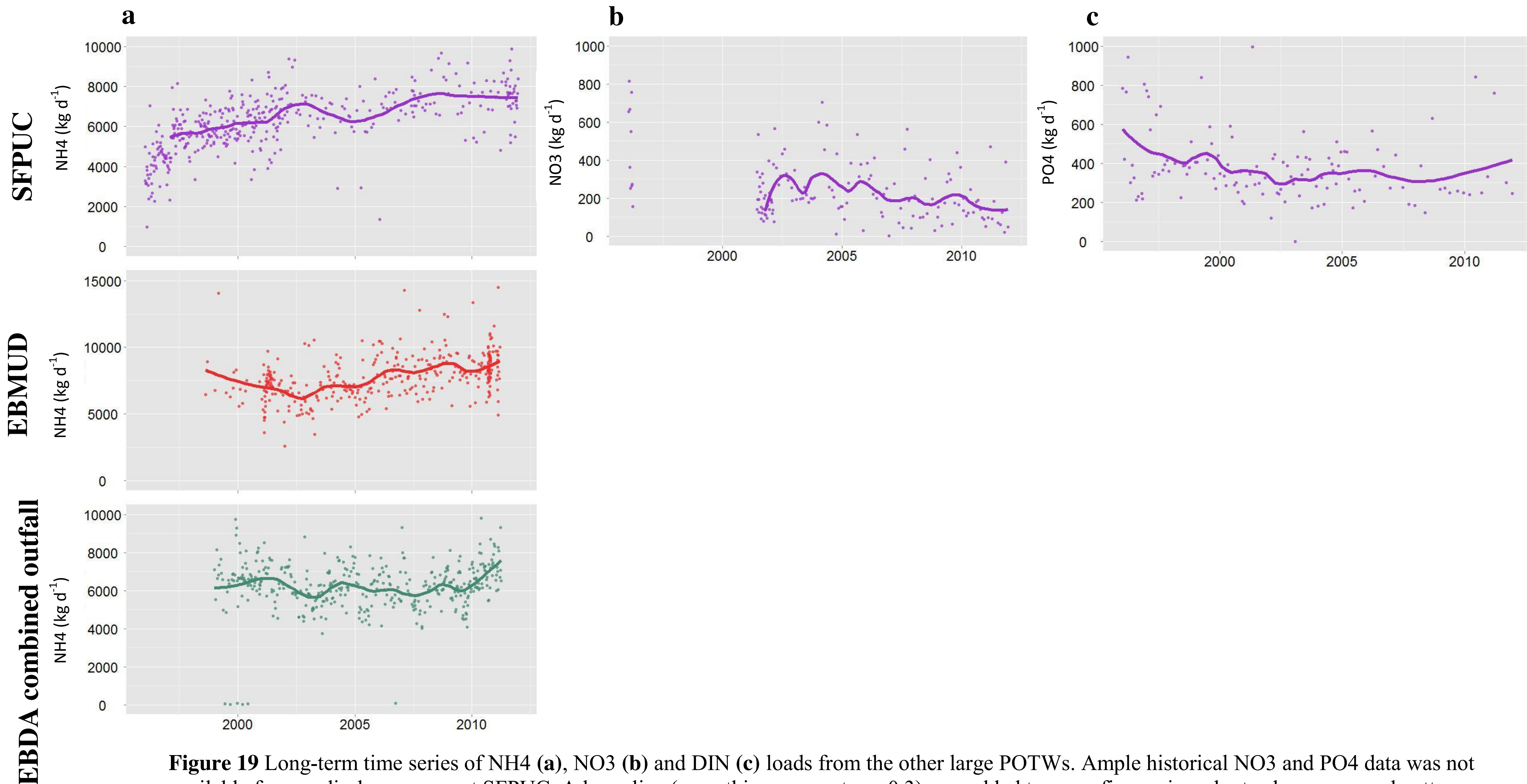


Figure 19 Long-term time series of NH4 **(a)**, NO3 **(b)** and DIN **(c)** loads from the other large POTWs. Ample historical NO3 and PO4 data was not available for any discharger except SFPUC. A loess line (smoothing parameter = 0.3) was added to some figures in order to show a general pattern, but is not intended as a rigorous trend analysis. Note the different scales on the vertical axes.

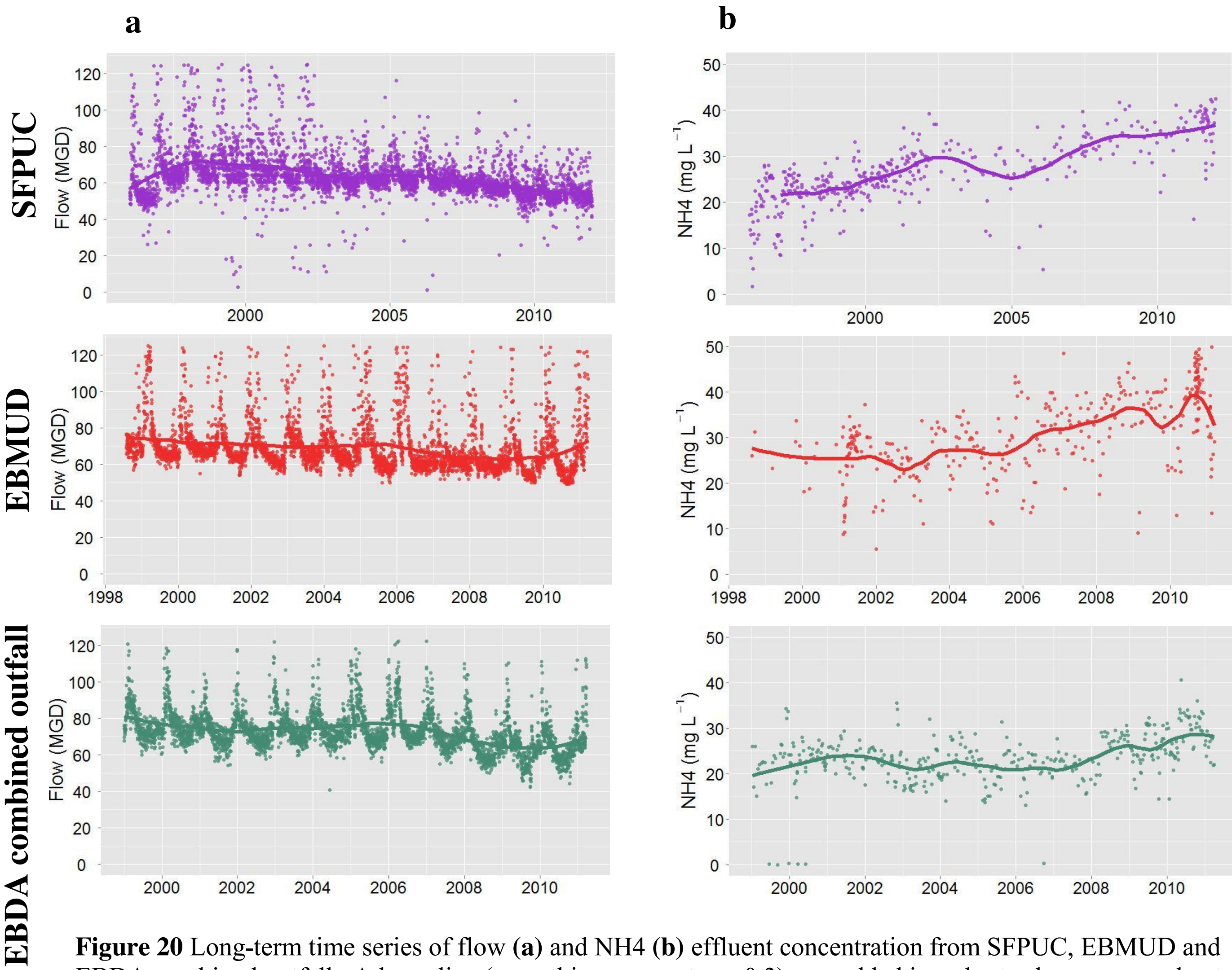


Figure 20 Long-term time series of flow **(a)** and NH4 **(b)** effluent concentration from SFPUC, EBMUD and EBDA combined outfall. A loess line (smoothing parameter = 0.3) was added in order to show a general pattern, but is not intended as a rigorous trend analysis.

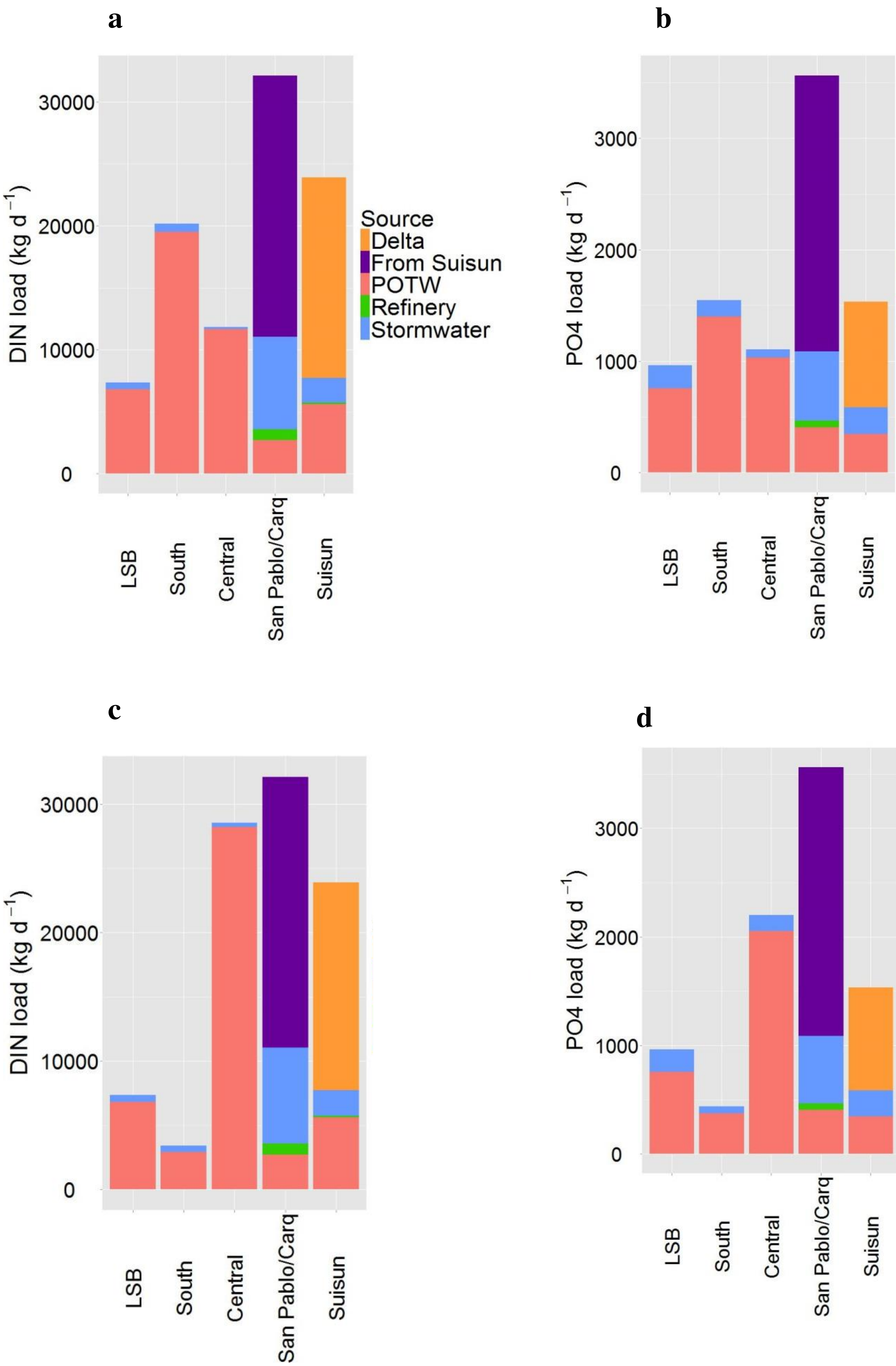


Figure 21 DIN and PO4 loads by subembayment and source based on Water Board boundaries (Figures 21a and 21b) and based on RMP boundaries (Figures 21c and 21d). The Water Board divides South Bay from Central Bay at the Bay Bridge, while the RMP divides these two at the San Bruno shoals. All other subembayments are the same.

Appendix 1: Additional Figures

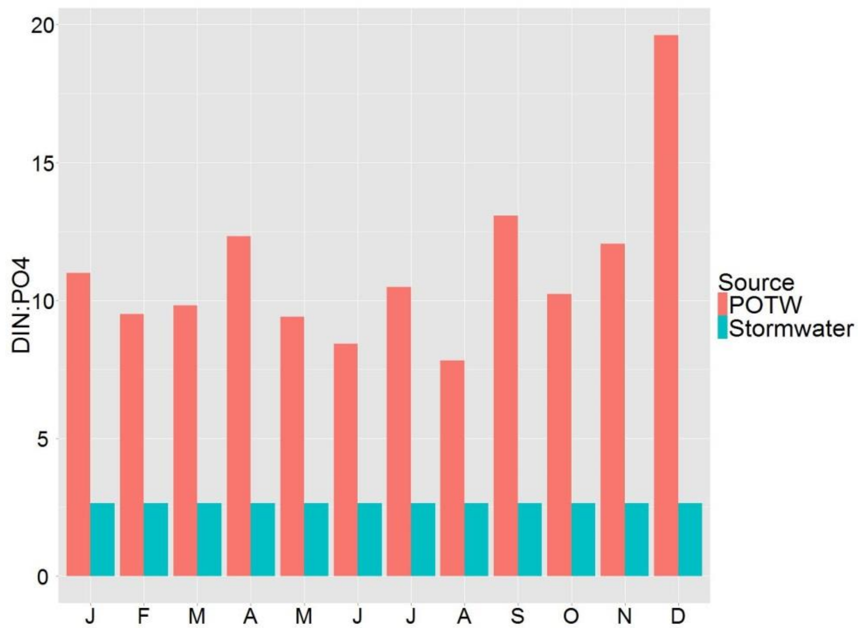


Figure A.1.1 Average [DIN]:[PO4] by source in Lower South Bay for 2006-2011. The Regional Watershed Spreadsheet Model, used to calculate stormwater loads, estimates loads on an annual basis and therefore [DIN]:[PO4] is assumed to be constant throughout the year. In reality, seasonal variability in fertilizer application and soil tilling (for example) could cause stormwater [DIN]:[PO4] to vary throughout the year.

Figure A.1.2 Average [DIN]:[PO4] by source in South Bay for 2006-2011. See Figure A.1.1 for consideration of [DIN]:[PO4] in stormwater

Figure A.1.3 Average **[**DIN]:[PO4] by source in Central Bay for 2006-2011. See Figure A.1.1 for consideration of [DIN]:[PO4] in stormwater

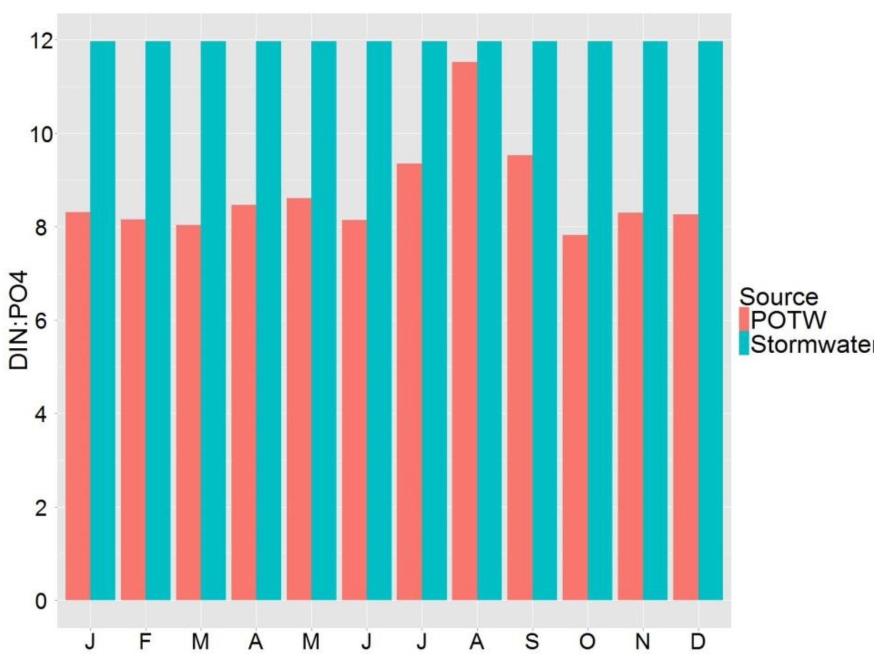


Figure A.1.4 Average **[**DIN]:[PO4] by source in San Pablo Bay/Carquinez Strait for 2006-2011. [DIN]:[PO4] in refinery discharge was exceedingly high (average of more than 50) and was omitted from this figure for clarity. See Figure A.1.1 for consideration of [DIN]:[PO4] in stormwater

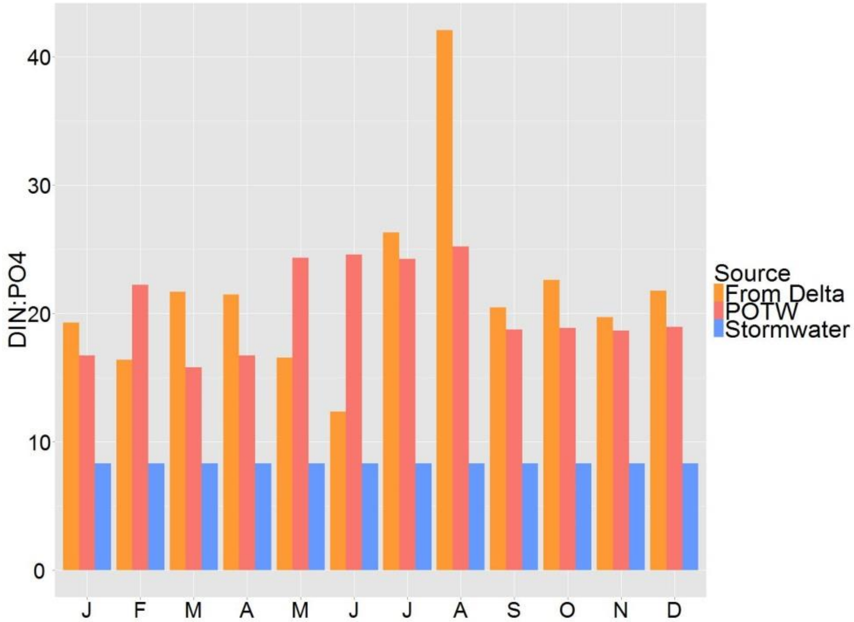


Figure A.1.5 Average **[**DIN]:[PO4] by source in Suisun Bay for 2006-2011. [DIN]:[PO4] in refinery discharge was exceedingly high (more than double that from any other source) and was omitted from this figure for clarity. The peak in [DIN]:[PO4] in Delta efflux is due to very low August PO4 loads for the time period studied. See Figure A.1.1 for consideration of [DIN]:[PO4] in stormwater

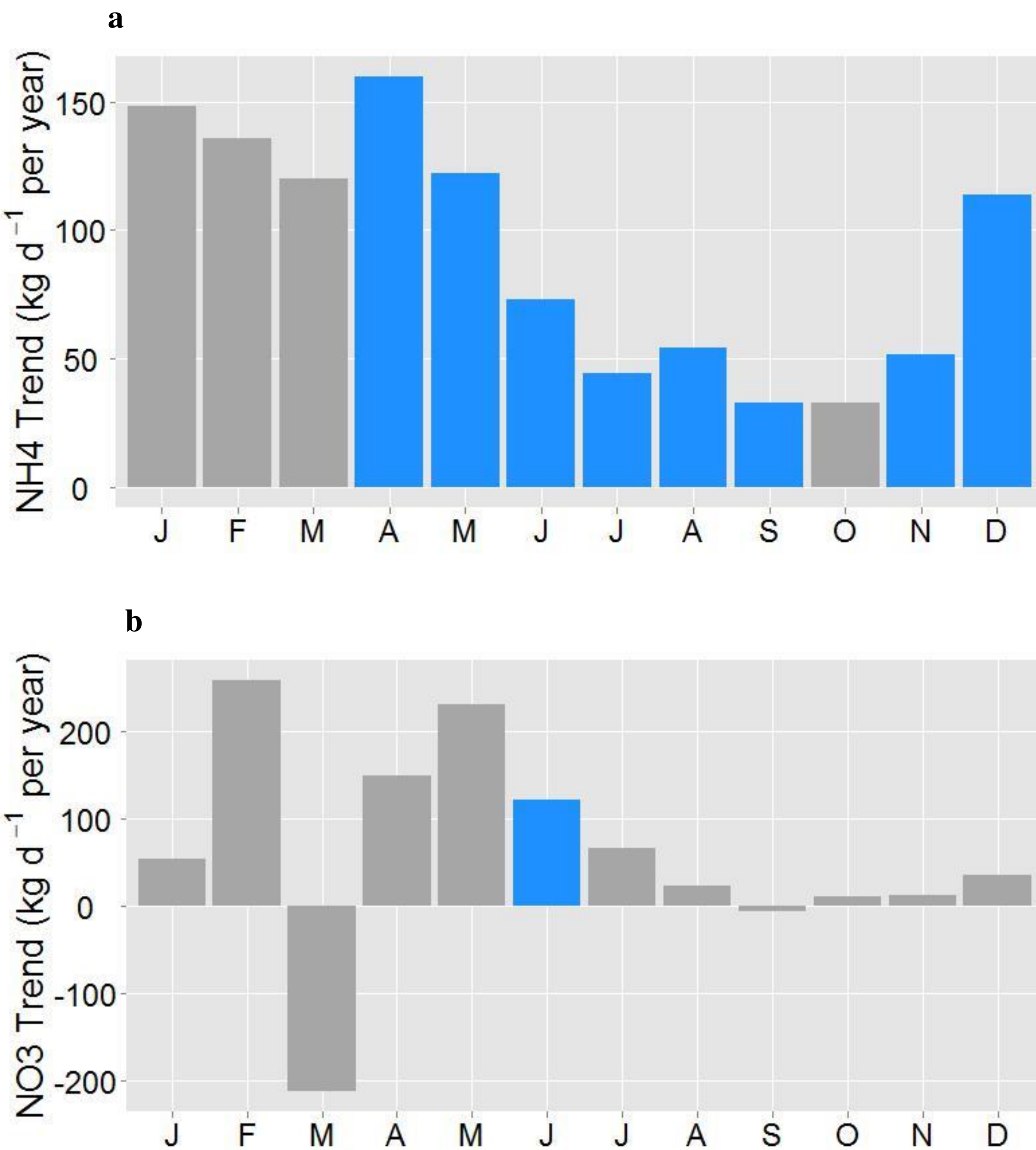


Figure A.1.6 Long-term variation in NH4 loads **(a)** and NO3 loads **(b)** from the Delta into Suisun Bay, by month, for the period 1975-2011. Trend was characterized by the Theil slope, which is the median value of all possible slopes for a given month (between any two points). Blue bars indicate statistically 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, Q_{rio}) and loads past Twitchell Island (representing flow originating in the San Joaquin River, Q_{west}), and combined these to estimate total load on a monthly average basis

$$Load = Q_{west}C_{west} + Q_{rio}C_{rio}$$

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.

Q_{west}:

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

Q_{rio}

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

Concentration:

DWR/IEP and USGS conduct monthly water quality monitoring in the Delta at stations that roughly coincide with the locations of Q_{rio} and Q_{west}. We multiplied these concentrations (referred to as C_{rio} and C_{west}) by monthly-averaged flow produce monthly-averaged estimates of load. Stations used for C_{rio} and C_{west} 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 C_{rio} and DWR/IEP station D16 was used to represent for C_{west}. 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 C_{rio} and C_{west}. 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 Q_{rio} and Q_{west}, 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. Q_{west} and Q_{rio} 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 Q_{west} and Q_{rio}, 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. In spite of these 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	NH4	D16[1]	D24[1]
	NO3+NO2	D16[1]	D24[1]
1996-2005	NH4	$0.311 * D26 + 0.235 * D28A + 0.320 * D4 - 0.001$ $r^2 = 0.77$	$0.165 * C3 + 0.551 * D4 + 0.022$ $r^2 = 0.52$
	NO3+NO2	$0.5305 * D26 + 0.1613 * D28A + 0.3812 * D4 - 0.020$ $r^2 = 0.93$	$0.200 * C3 + 0.809 * D4 - 0.023$ $r^2 = 0.85$
2006-2011	NH4	D19 $r^2 = 0.81$	USGS 657[2]
	NO3+NO2	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 Q_{west} and Q_{rio} 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 (the resulting linear equation and r^2 values 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

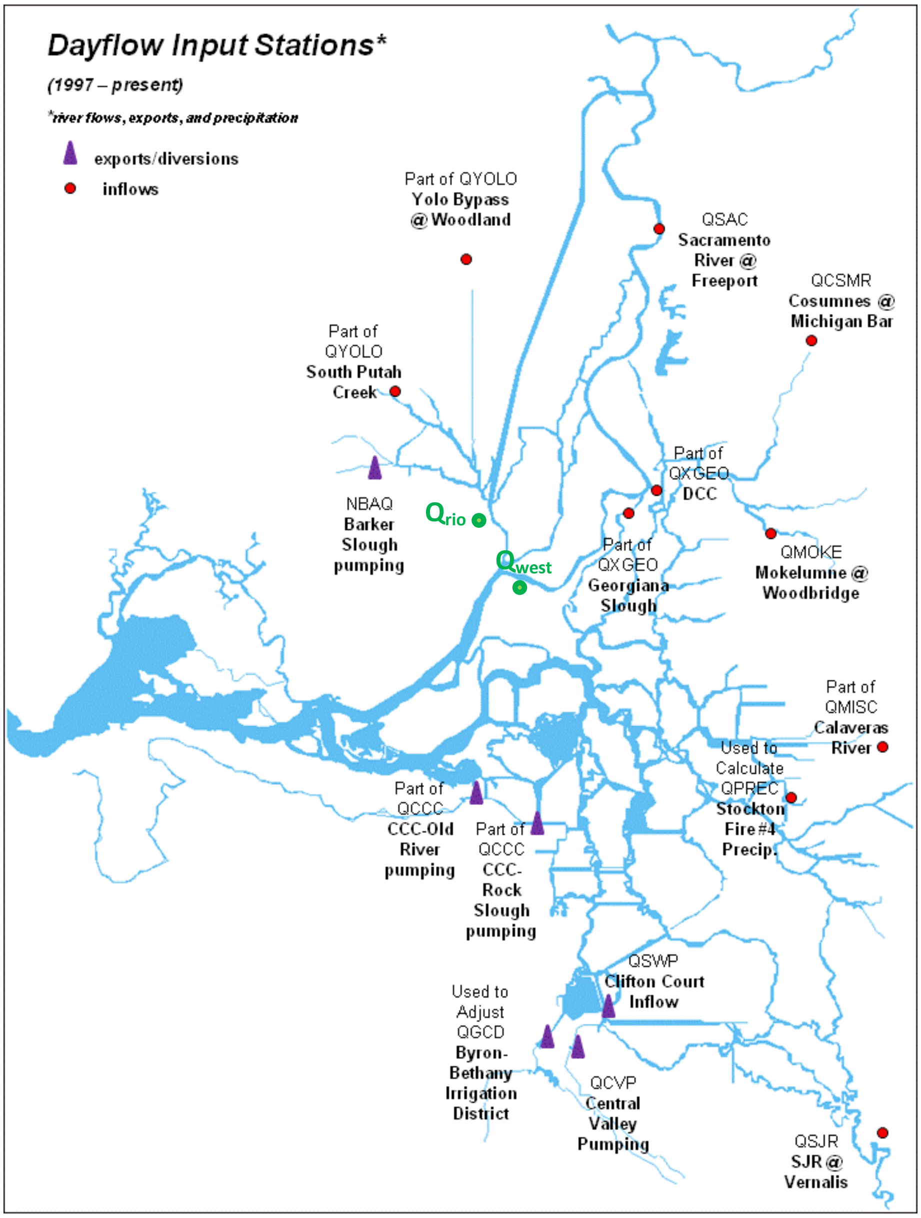


Figure A.2.1 Location DWR DAYFLOW gages (indicated by purple triangles). The values used in our estimation, Q_{west} and Q_{rio}, are calculated according to the following formulas and give approximation of flow past the points indicated above.

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

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

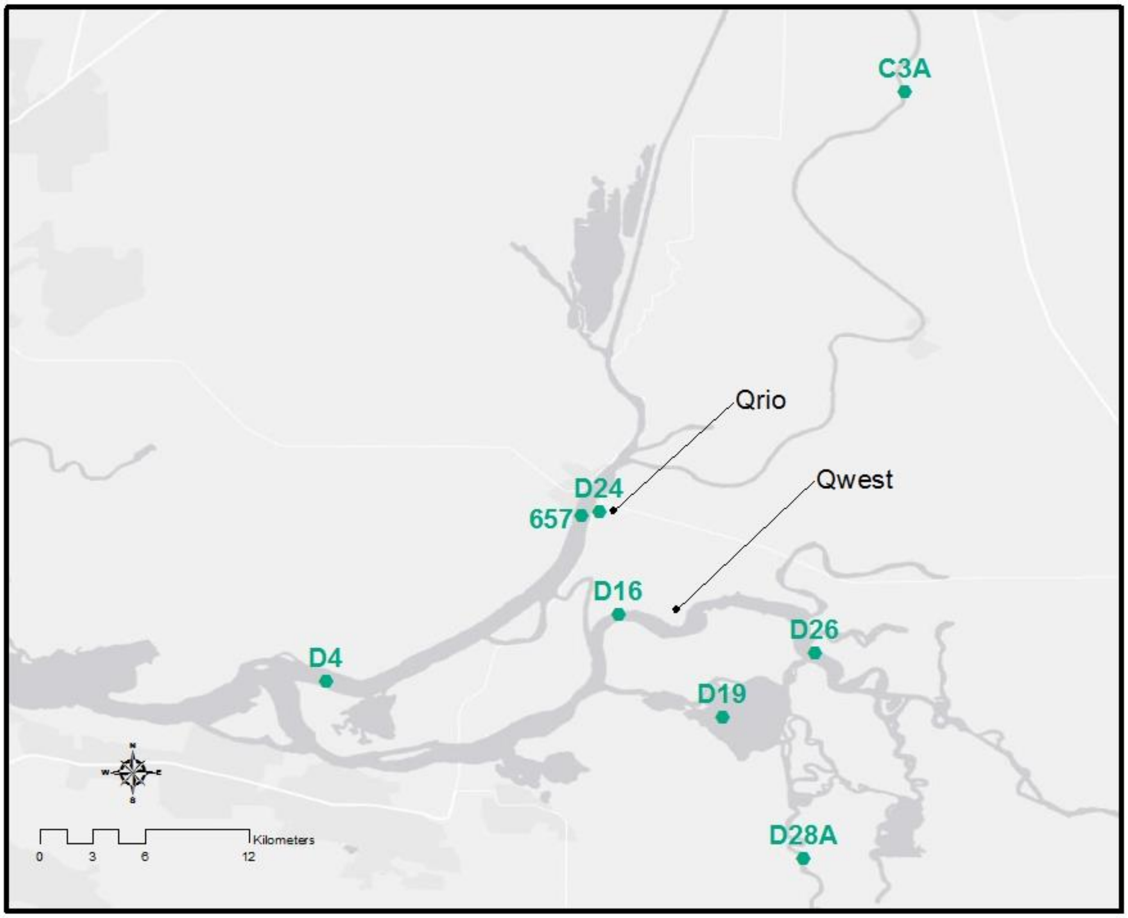


Figure A. 2.2 Location of DWR/IEP and USGS water quality stations used in Delta loads estimate, as well as location of flow estimates.

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 NH4 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 NH4 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

Salinity Balance

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.

Evaluation of assumptions

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.

NH4 Balance

We used the resulting value of Q_{tide} in an NH4 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. $\dot{M}_{discharge}$= $\dot{M}_{CCCSD}$+ $\dot{M}_{DDSD}$
7. Q_{tide} was solved for using the salinity balance

Further explanation of the terms and schematic for the NH4 balance is given in Fig. A.3.1.4.

Evaluation of Assumptions

NH4 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 NH4 sources into Suisun Bay. We hypothesize that NH4 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 NH4 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 NH4 into Suisun Bay. If we included a tidal dispersion term on the upstream end, this would bring high-NH4 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 NH4 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)

(Figure 6.20). 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 NH4 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 NH4 dropped from 75% to 60%, which would still be a significant contribution.

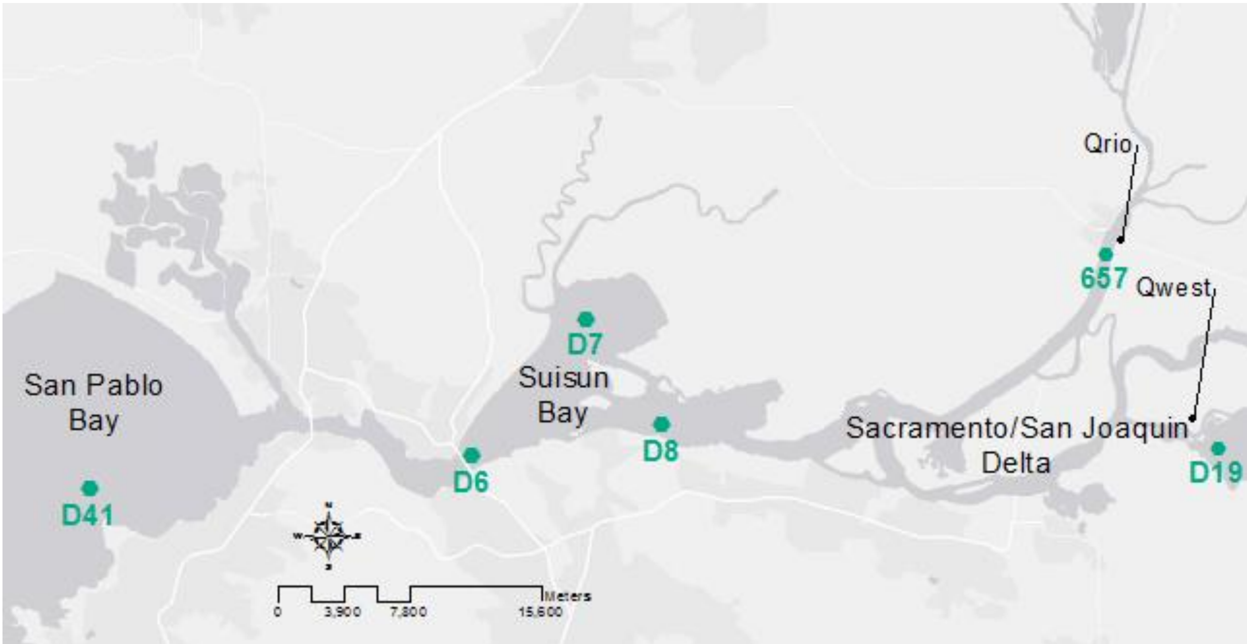
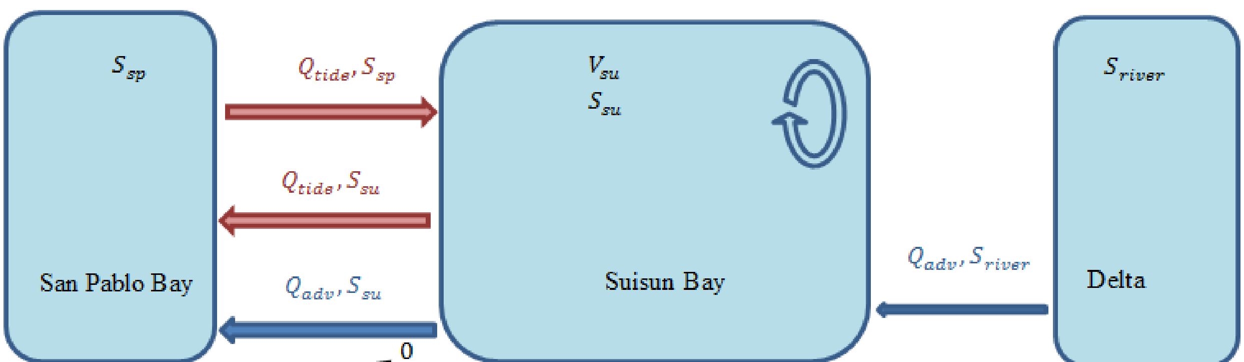


Figure A.3.1.1 Location of DWR/IEP and USGS monitoring stations (used as concentration terms) and DWR DAYFLOW stations (used as flow terms) in 1-box model for Suisun Bay. Tidal flows were estimated from a salinity balance (Fig. A.3.1.2).



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

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

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

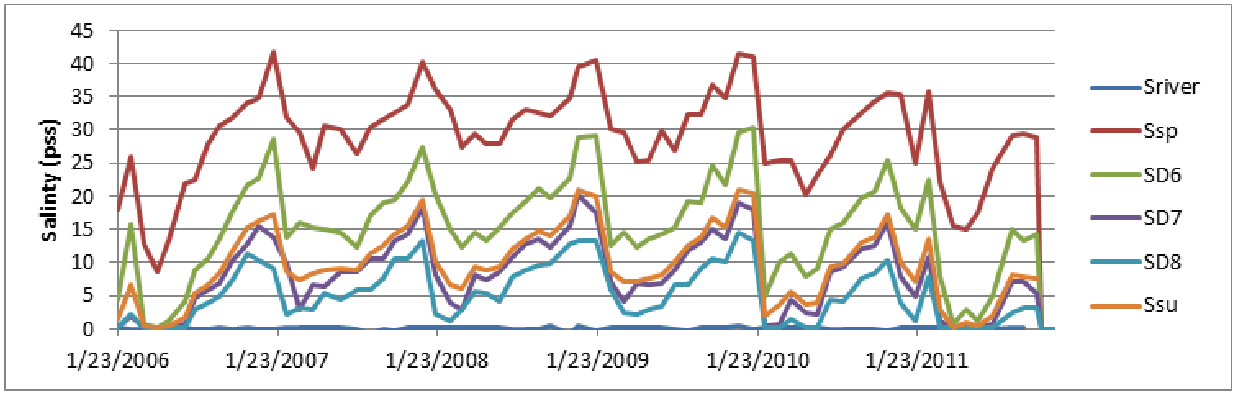
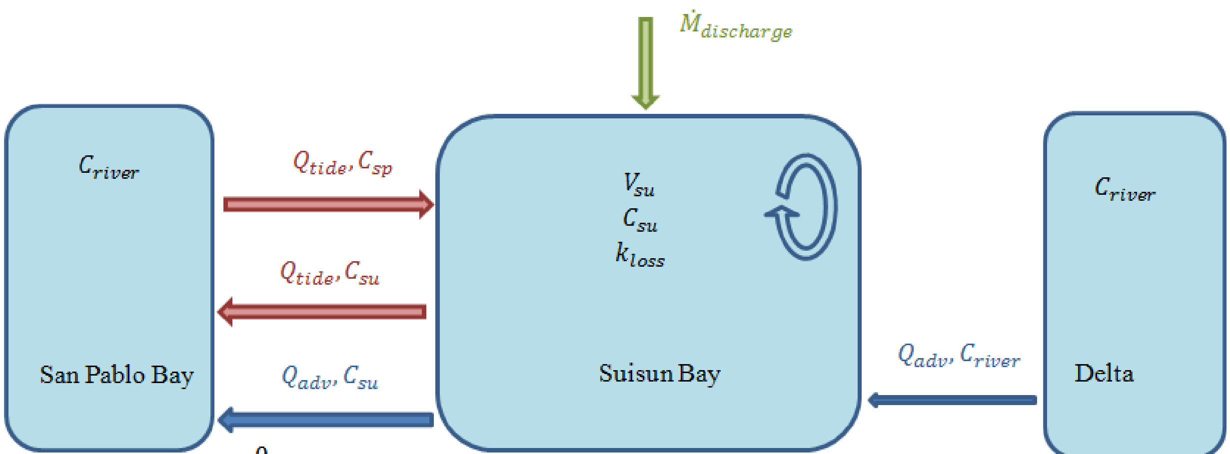


Figure A.3.1.3 Times series of salinity at locations used in mass balance (Only April-October were considered for the mode). S_{river} is the flow weighted average of salinity at DWR/IEP D19 (San Joaquin River dominated) and USGS 657 (Sacramento River dominated), S_{sp} is salinity at DWR/IEP D41 and S_{su} 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. S_{river} was negligible and therefore we neglected tidal dispersion on the upstream end of Suisun Bay



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

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

Figure A.3.1.4 Salinity mass balance schematic used to approximate the magnitude of NH4 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. $\dot{M}_{discharge}$= $\dot{M}_{CCCSD}$+ $\dot{M}_{DDSD}$
7. Q_{tide} was solved for using the salinity balance

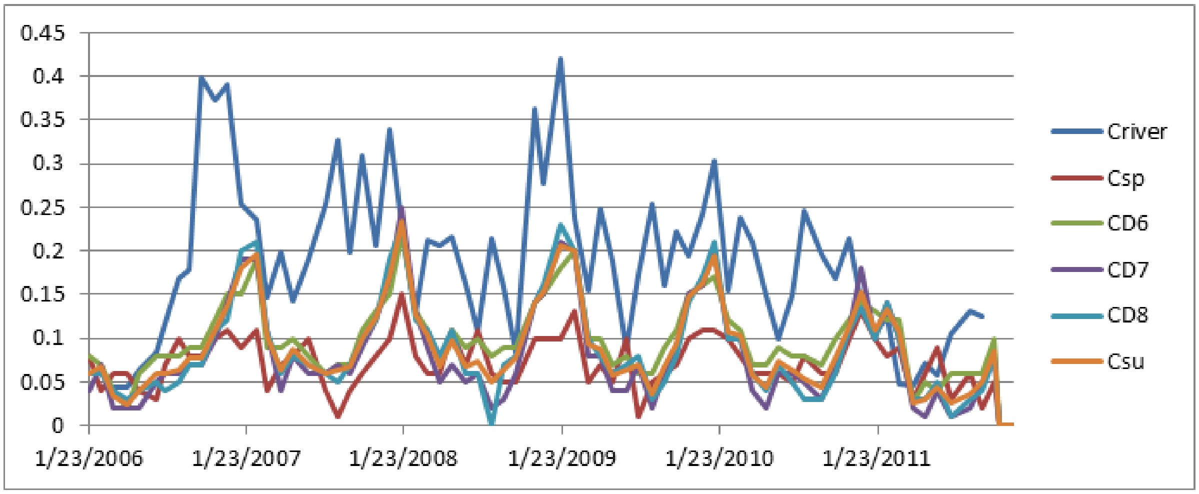


Figure A.3.1.5 NH4 concentrations at locations used in mass balance. C_{river} is the flow weighted average of NH4 at DWR/IEP D19 (San Joaquin River dominated) and USGS 657 (Sacramento River dominated), C_{sp} is NH4 at DWR/IEP D41 and C_{su} is the average of NH4 at DWR/IEP D6, D7 and D8. NH4 is reasonably 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 NH4 in the rivers, if anything this omission underestimates NH4 loads to Suisun Bay and therefore underestimates the magnitude of NH4 losses.

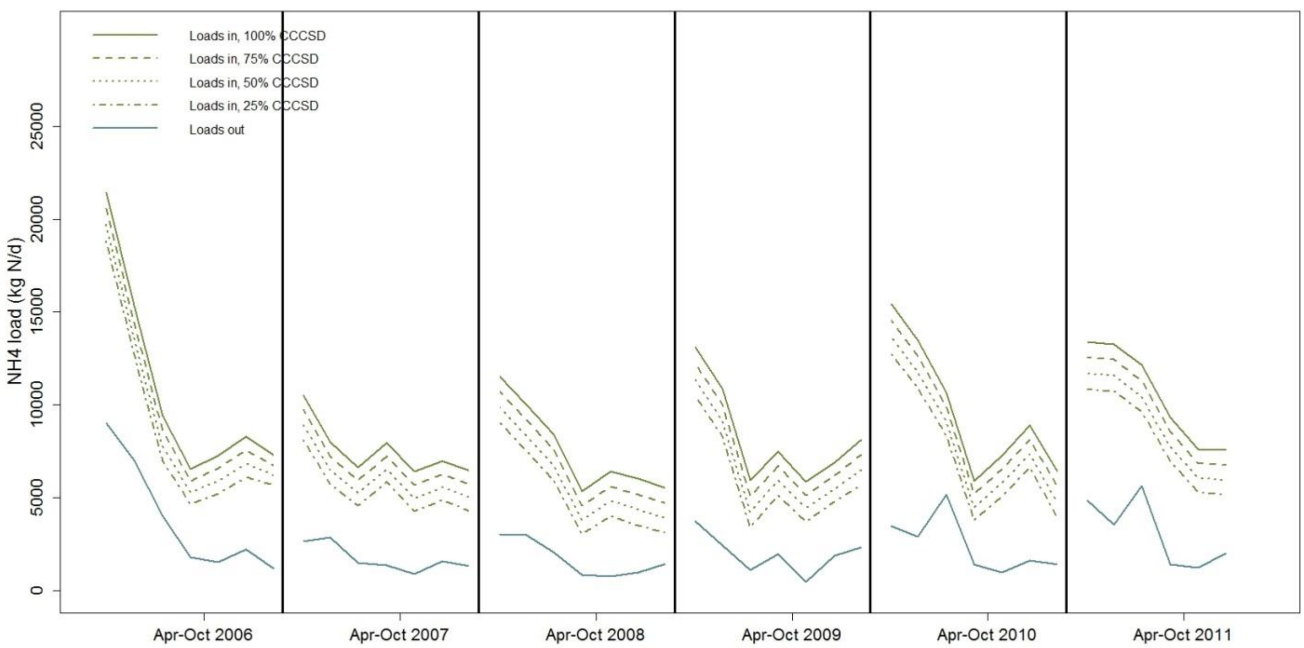


Figure A.3.1.6 Differences between NH4 loads into Suisun Bay (including advective loads, tidal downstream tidal loads and discharger loads assuming various amounts of CCCSD effluent mixing; green line) and NH4 loads out of Suisun Bay (including advective loads and downstream tidal loads). The difference between loads in and loads is an estimate of the magnitude of NH4 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 NH4, 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:

$$Load = Q_{adv} \times C_{su}$$

where

$$Q_{adv} = Q_{west} + Q_{rio}$$
$$C_{su} = average(C_6, C_7, C_8)$$

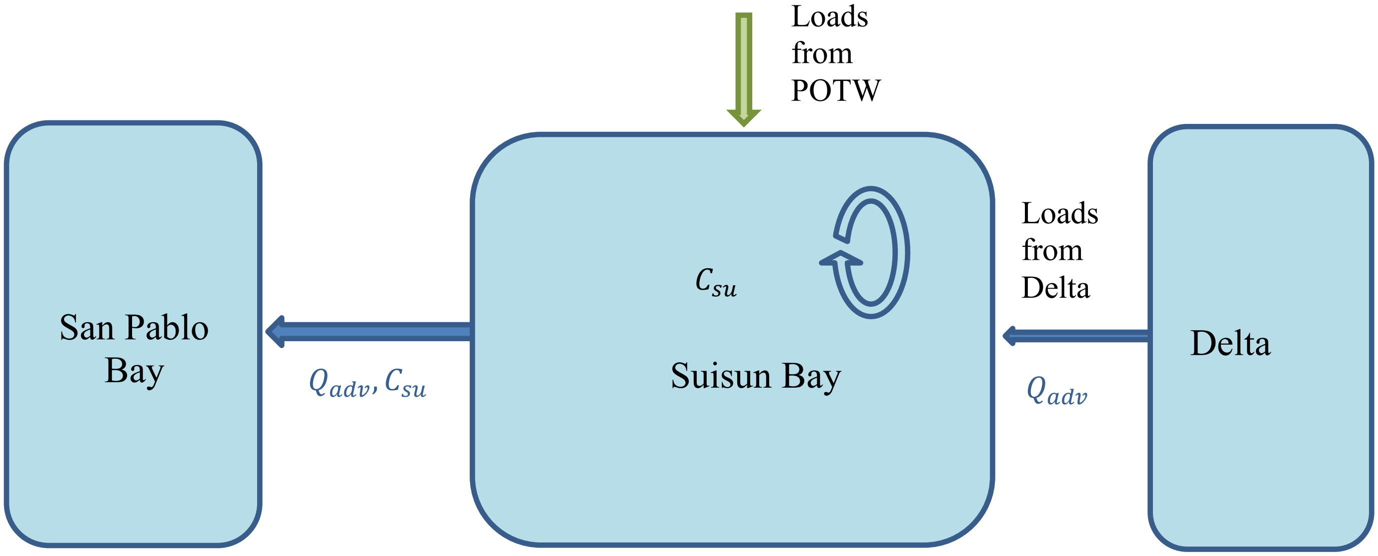


Figure A.3.2.1 Schematic for estimating loads exchanged from Suisun Bay to San Pablo Bay, including both loads into Suisun Bay from the Delta and direct POTW discharges to Suisun Bay. Only advective loads were considered, which account for 95% of overall transport (based on the 1-box model described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