Improved nutrient load estimates for wastewater, stormwater and atmospheric deposition to South San Francisco Bay (South of the Bay Bridge)

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Acknowledgements

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Introduction

Phytoplankton accounts about two thirds of the primary productivity of the Bay as a whole (Jassby et al., 2002; Guarini et al., 2002; Cloern and Dugdale, 2010) and therefore provides the majority of the fuel for the production of the invertebrates, zooplankton, small fish, and sportfish that wildlife and humans rely on for sustenance and recreation (Cloern et al., 2006). In the past, San Francisco Bay was considered a nutrient enriched low productivity system but recently, with increases in background phytoplankton production, the intensity of spring blooms, and the appearance of a fall bloom, the Bay has transformed to having primary production in a range more typical of other temperate latitude estuaries (Cloern et al., 2006). Based on an analysis of monthly trends, eight out of 12 months distributed across the whole year showed an upward trend in production (Cloern et al., 2007). Therefore, it is suggested that the resilience of the Bay to high nutrient loads may be decreasing (Cloern and Dugdale, 2010).

Nutrient availability influences primary production. Although there is evidence that ammonium concentration is one key factor limiting the rate of production and size of phytoplankton blooms in the North Bay and especially Suisun Bay (Dugdale et a., 2007), in the South Bay, for the most part, nutrients appear to play a stronger role in bloom termination when nutrients are depleted during larger blooms (Thompson et al., 2008). Thus San Francisco Bay is complex and does not support a simple model of nutrient and light limitation controlling phytoplankton growth and productivity. There are a number of hypotheses that together might explain the spatial complexity and trends such as changes to predation, water clarity, climate, and nutrient loads, however, at this time it is difficult to tease out the relative importance of each factor (Cloern et al., 2006; 2007; 2010). As such, changes in primary production cannot be predicted and there is growing concern for an increased propensity for periodic harmful algal blooms or low dissolved oxygen events into the future (Cloern and Dugdale, 2010).

Knowledge of nutrient loads is a key component data set for developing predictive models of estuarine productivity. A recent review of available data for San Francisco Bay highlighted a number of shortcomings in local data sets. These include a lack of temporal resolution in the available estimates (annual averages only), a lack of spatial resolution (whole Bay only), and limited and confusing information on speciation (McKee et al., 2011). In addition, loads data have not been updated in 15+ years since the paper by Smith and Hollibaugh (2006) which collated data from 1990-95. Yet since the 1990s there has been population, land use, and treatment technology trends that may have influenced speciation, timing and magnitude of loads (McKee et al., 2011). Given the recent interest to develop an *RMP Nutrient Strategy*, improved nutrient loads estimates would be timely, would support prioritization of work elements, and provide immediate critical information for improved water-quality-management in the Bay.

The objective of this effort therefore is to present new estimates of nitrogen loads for the South Bay, South of the Bay Bridge. To do this, recent data on dissolved inorganic nitrogen (nitrate+ nitrite+ ammonia/ium) concentrations in wastewater, stormwater and atmospheric deposition were collated and combined with water flow and climatic factors targeting the period 1991-2010 (20 years). Although ancillary to the main objective, we also present information on dissolved phosphate (PO_4) loads. Other sources, either positive or negative and likely seasonally unique, were not included in this analysis and include tidal boundary fluxes, net sediment-water boundary exchange, and transformations between inorganic forms (nitrogen only) and between organic and inorganic forms (nitrogen and phosphorus). In addition, there are industrial wastewater discharges to the Bay which have not been updated since the work of Davis et al. (2000). These may be justifiably considered in future efforts. Therefore the reader is encouraged to keep several important questions in mind while reviewing this report:

1. Would management decisions and future prioritization of data collection be better informed by sub-regional mass balance that could include fluxes between Bay segments, sediment-water interface fluxes, and transformation rather than the simple inventory of three significant sources as presented here?
2. Are the data sufficient to support the necessary water quality monitoring activities needed to suggest impairment?
3. How will future nutrient source-specific management activities be prioritized?

Physiography

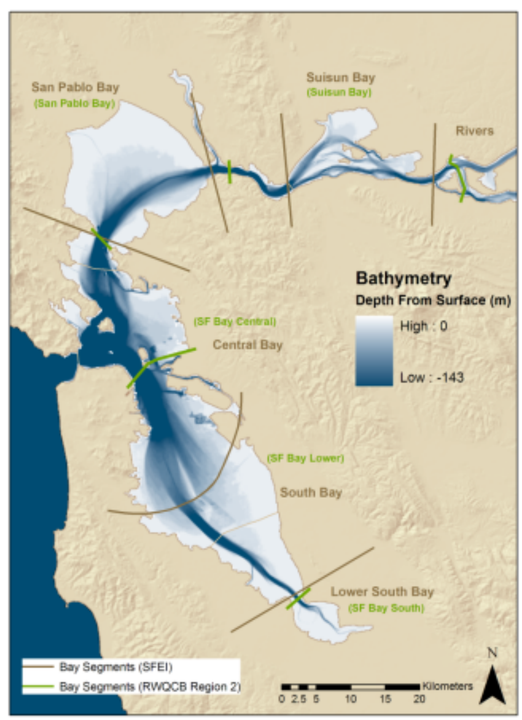
Broadly speaking, the Bay can be divided into two main regions, the North Bay (which includes SF Bay Central, San Pablo, and Suisun Bay) and the South Bay south of the Bay Bridge (Figure 1). The North Bay is a river dominated tidal estuary where spatial and temporal variability is driven by intra- and inter-annual variations in freshwater, sediment, and nutrient input from urban and agricultural sources within the Sacramento and San Joaquin River watersheds (Smith and Hollibaugh, 2006; Wilkerson et al., 2006; Cloern and Dugdale, 2010). The estimated average freshwater flushing time of the North Bay is 72 days (Engle et al., 2007). The South Bay, in contrast, acts more like a tidal lagoon with relatively low freshwater input relative to basin volume. It is dominated in the summer months by wastewater discharge (Cloern et al., 2000; Smith and Hollibaugh, 2006; Cloern and Dugdale, 2010). The average estimated freshwater flushing time of the South Bay is over 4,000 days (Engle et al., 2007). Within the South Bay there are several further geologically defined constrictions, most notably at the Dumbarton Bridge (Hwy 84) that defines the boundary between the South Bay and the Lower South Bay, and the second being the relatively abrupt change in the ratio of deep Bay habitat to shallow Bay habitat that occurs out from San Bruno shoals and forms the boundary between the Central Bay and the South Bay. For the purposes of the nutrient loads estimates presented here, the area of the Bay south of the Bay Bridge is lumped and referred to from here on as the South Bay. The loads presented here enter the Bay through its physical perimeter and are not based on a mass balance that would include fluxes through a tidal boundary, fluxes across the sediment-water interface (including groundwater), and nutrient transformations. The authors accept that material flux does occur in relation to these other sources and processes. Future analysis could include a thorough examination of the mass balance of each Bay segment as defined by management questions that may emerge out of a nutrient strategy for the Bay.

Wastewater Loading

Methods

Due to Stakeholder interest in the mounting evidence that the resilience of the South Bay to nutrients may be declining (see introduction section), nutrient loads to the North Bay, although important for an overall mass balance of the Bay, are not considered here. In the South Bay there are 12 wastewater treatment agencies discharging south of the Bay Bridge (Table 1). In the case of EBDA, six separate wastewater treatment facilities are part of the East Bay Dischargers Authority (EBDA): San Leandro WWTP, Oro Loma Sanitary District, Castro Valley Sanitary District, City of Wayward Treatment Facility, Dublin-San Ramon Services Wastewater Treatment Plant, and Livermore WWTP.

In order to calculate wastewater effluent loads, it was necessary to obtain data either for each of the plants or from a representative subset. Obtaining data for the wastewater treatment plants which provide service for the largest populations was given priority over the smaller facilities as it was assumed that quantification of the largest dischargers where high quality data existed would provide the best estimate of overall loads even if the smaller facilities had to be estimated by interpolation. Initially Johnson Lam (San Francisco Bay Water Board) was contacted because he had collated (in excel format) data received in relation to permit provisions from a number of the dischargers. Johnson Lam's data base contains data on daily discharge from January 2004 to April 2010 for a number of facilities in Region 2. Nutrient concentration data was most prolific for ammonium with only spot data for other nutrient



*Bathymetry data does not apply to ocean area.

Figure 1. Physiography of San Francisco Bay illustrating bathymetry and Bay segments as defined by the Water Board (green lines across the Bay) and the Regional Monitoring Program for Water Quality (RMP) (brown lines).

forms (Table 1). The data base, although very informative, was missing some key daily flow data for five of the six larger facilities. San Jose/Santa Clara, EBMUD, EBDA, SF-Southeast, and Palo Alto provide wastewater service for approximately 86% of the population south of the Bay Bridge (Table 2). In addition, we were interested in obtaining discharge data back to 1991 since we were aware from the published paper by Smith and Hollibaugh (2006) that such data existed; although we were not able to determine the time interval of the data. As a general comment, the data input and sophistication of the calculation technique for wastewater was akin to the sophistication for stormwater; the data available for atmospheric deposition loads calculations was poor.

Table 1. Summary of data available from the Water Board (Johnson Lam).

Plant Name	Location relative to Bay Bridge	Daily flow (MGD)	NO3	NH3	Organic N	TKN	Total N	Nitrite	PO4
Burlingame	South	X		X					
EBDA	South	X		X					
EBMUD	South			X					
Milbrae	South	X		X					
North San Mateo	South			X					
Palo Alto	South		X	X	X			X	X
San Mateo	South			X					
SF - Southeast North Pt	South			X					
SJ/Santa Clara	South		X	X	X				X
SSF & San Bruno	South			X					
Sunnyvale	South	X	X	X	X			X	X
American Canyon	North	X		X					
Benicia	North	X		X					
Central Contra Costa	North			X					
Central Marin Sanitation	North			X					
Delta Diablo	North	X		X					
Dublin/ San Ramon	South	X		X					
Fairfield Suisun	North		X	X	X	X	X		X
Las Gallinas	North	X		X					
MVSD	North	X		X					
Petaluma	North	X		X					
Pinole/Hercules	North	X		X					
Sausalito	North	X		X					
Southern Marin	North	X		X					
Tiburon	North	X		X					
W. County/Richmond	North			X					
Pacifica Calera Creek	Coast		X						X
Rodeo	Coast	X		X					
SF - Oceanside	Coast			X					
SAM WWTP (Sewer Authority Mid-Coastside)	Coast	X		X					

Table 2. Wastewater discharge agencies, general characteristics of each facility and a summary of available data.

Treatment Plant	Treatment Level	Technology	Rated Capacity (mgd)	Average Discharge (MG y^{-1})	Population	Daily Flow Data	NOx	NH3	PO4	TP
San Jose/Santa Clara	Advanced	Biological nutrient removal (BNR) with filtration	167	38,104	1,365,000	X	X	X	X	X
EBMUD	Secondary	High Purity Oxygen	120	30,375	654,700	X	X	X	X	
EBDA (total combined)	Secondary	Activated sludge	77.1	26,204	636,000	X		X		
SF- Southeast	Secondary	Activated sludge + pure O2	85.4	26,854	556,000	X	X	X	X	X
Palo Alto	Advanced	AS+fixed film, dual media filters	39	9,019	228,500	X	X	X	X	
SBSA	Secondary	Trickling filter with activated sludge and Dual-Media filters	29		217,000					
San Mateo	Advanced	Act. Sludge (Nit.) with filtration	13.6		137,000					
Sunnyvale	Advanced	Ox ponds, fixed film reactor for N, dual media filtration	29.5	4,284	136,000	X		X		
Burlingame	Secondary	Activated sludge	5.5	1,426	37,000	X		X		
Millbrae	Secondary	Activated Sludge+hypo and effluent skimming	3	628	22,000	X		X		
Treasure Island	Secondary		2		2,400			X		
SF Airport	Secondary	Sequencing Batch Reactor	2.2		6414*			X		

Treasure Island permit: monthly discharge estimated from monthly average mgd (ex: 0.54mgd*30days); SF Airport permit: monthly discharge estimated from monthly average mgd (ex: 0.54mgd*30days). *SF-Airport population was estimated from data in Figure 3.

San Jose/Santa Clara WPCP: Data from the largest wastewater treatment plant, San Jose/Santa Clara WPCP, were obtained from James Ervin from the city of San Jose dating from January 1st 2003 to April 30th 2011. The San Jose/Santa Clara WPCP provides service for 1,365,000 people and conducts advanced level treatment through biological nutrient removal with filtration. Nutrient concentration data were provided for ammonium (NH3), nitrate (NO3), and phosphate (PO4). Loads were calculated by combining daily measured concentrations when available with daily flow data. Missing concentration data were estimated using concentration averaged for three flow classes (50-99, 100-150, and 150-200 MGD). Detection limits were used for data reported at below detection limits (not a common occurrence so no practical need to determine the effects of this on the resulting loads estimate). Loads for this plant for all nutrient forms are considered very high accuracy due to abundant concentration data.

EBMUD: Data from the second largest wastewater treatment plant, East Bay Municipal Utility District (EBMUD) was provided by Francois Rodigari at EBMUD. EBMUD provides service for 654,000 people and conducts secondary level treatment through high purity oxygen technologies. Daily flow data and semi-weekly nutrient concentrations for NH3 and nitrite (NO2) dating from June 1st 1994 to May 4th 2011 were provided. Daily flow data were spotty beginning July 1st 2001. From this date forward missing daily flow data were estimated to be equivalent to the monthly average flows. A limited amount of NO3 and PO4 data were also provided. Loads were calculated by combining daily flow data with measured concentrations on all days were there were data. For days without concentration data, concentrations were estimated as the average for four flow classes (0-99, 100-199, 200-299, 300-399 MGD). Loads for this plant for NH3 and NO2 are considered very high accuracy due to abundant concentration data. Loads for NO3 and PO4 are of medium accuracy.

EBDA: Six separate wastewater treatment facilities are part of the East Bay Dischargers Authority (EBDA): San Leandro WWTP, Oro Loma Sanitary District, Castro Valley Sanitary District, City of Hayward Treatment Facility, Dublin-San Ramon Services Wastewater Treatment Plant, and Livermore WWTP. EBDA provides service for 636,000 people and performs secondary level treatment utilizing activated sludge technology. Data for the EBDA daily combined discharge and weekly combined NH3 concentration dating from January 2004 to April 2010 were provided by Johnson Lam at the San Francisco Bay Regional Water Quality Control Board. NH3 concentration data from 2009 and 2010 were pulled from the monthly effluent reports posted on the EBDA website. Loads were calculated by combining daily flow data with measured concentrations on all days were there were data. For days without concentration data, concentrations were estimated as the average for four flow classes (30-59, 60-89, 90-119, and 120-150 MGD). No data were available for the other nutrient forms so the following estimates were applied (NOx=1 mg/L; PO4=4 mg/L) (Mike Falk, personal communication). Loads of NH3 for this plant are considered very high accuracy due to abundant concentration data. Loads for NO3 and PO4 are of moderate accuracy.

San Francisco Southeast WCPC: Data from San Francisco Southeast WCPC were provided by Kenneth Lee of San Francisco Water Power and Sewer. The San Francisco Southeast WCPC provides service for 556,000 people and conducts secondary level treatment through activated sludge plus pure O_2. Daily flow and semi-weekly nutrient concentrations for NH3, NO3, NO2, and PO4 were available dating from January 1st 1996 to June 11th 2011. Loads were calculated by combining daily flow data with concentrations estimated as the average for three flow classes (30-59, 60-89, and 90-120 MGD). Loads for this plant for all nutrient forms are considered very high quality due to abundant concentration data.

Palo Alto Regional WQCP: Data from the Palo Alto Regional WQCP were provided by Karin North at the city of Palo Alto. The Palo Alto Regional WQCP provides service for 228,500 people and conducts advanced level treatment through activated sludge, and fixed film, dual media filters. Daily flow and semi-weekly nutrient concentrations for NH3, NO3, NO2, and PO4 were available dating from January 1st 1994 to April 30th 2011. There were a few non-detects in the data set for ammonium – where encountered these were assigned the detection limit. Loads were calculated by combining daily flow data with measured concentrations on all days were there were data. For days without concentration data, concentrations were estimated as the average for four flow classes (10-24, 25-39, 40-54, and 55-70 MGD). Loads for this plant for all nutrient forms are considered very high quality due to abundant concentration data.

Sunnyvale WWTP: Data for the Sunnyvale WWTP were provided by Johnson Lam at the San Francisco Bay Regional Water Quality Control Board. Daily discharge was available from January 1st 2004 to April 30th 2010 and ammonia concentrations were available for a number of days. Loads were calculated by combining daily flow data with measured concentrations on all days were there were data. For days without concentration data, concentrations were estimated as the average for four flow classes (0-5.9, 6-11.9, 12-17.9, 18-24MGD). No data were available for the other nutrient forms so the following estimates were applied (NOx=10 mg/L; PO4=4 mg/L) (Mike Falk, personal communication). Loads of NH3 for this plant are considered very high accuracy due to abundant concentration data. Loads for NO3 and PO4 are of moderate accuracy.

Burlingame: Data for daily discharge for the Burlingame facility were available from January 1st 2004 to April 30th 2010 and provided by Johnson Lam at the San Francisco Bay Regional Water Quality Control Board. NH3 data were limited to just 2009 and 2010. Loads were calculated by combining daily flow data with measured concentrations on all days were there were data. For days without concentration data, concentrations were estimated as the average for four flow classes (0-5.9, 6-11.9, 12-17.9, 18-24MGD). No data were available for the other nutrient forms so the following estimates were applied (NOx=10 mg/L; PO4=4 mg/L) (Mike Falk, personal communication). Loads of NH3 for this plant are considered high accuracy rather than very high accuracy due to abundant but only recent concentration data. Loads for NO3 and PO4 are of moderate accuracy.

Millbrae: Data for daily discharge for the Millbrae facility were available from January 1st 2004 to April 30th 2010 and provided by Johnson Lam at the San Francisco Bay Regional Water Quality Control Board. Ammonia data were limited to just 19 measurements (average = 38 mg/L) but these did not cover the full range of flows at the plant. No other nutrient data were available. Loads for this facility were not calculated directly.

Daily loads calculations: Daily loads for the period January 1st 2004 to April 30th 2010 for wastewater discharge south of the Bay Bridge were therefore calculated for the five largest facilities and several of the smaller ones. Calculation of the total loads was done by scaling up the daily loads estimates for advanced plants (San Jose/Santa Clara, Palo Alto, and Sunnyvale) that cover a total population of 1,729,500 persons to the advanced facilities not directly qualified (San Mateo) that service a population of 137,000; the resulting scaling factor was 1.08 Similarly, the loads from secondary facilities that were quantified (EBMUD, EBDA, SF-Southeast, and Burlingame) that together service a population of 1,883,700 persons were scaled by a factor of 1.13 to cover those facilities that were not qualified directly (Millbrae, Treasure Island and SF Airport) that together service a population of 24,400 (SF Airport population was estimated to be 6,414 persons on average from the data in Figure 2 below).

Results

On average for the facilities in Region 2 where data are available, measured annual average flow is 67% of the rated capacity of the facilities (Figure 2). Thus, nutrient concentrations estimated from an understanding of the treatment process could be combined with the rated discharge of the facility and multiplied by a factor of 0.67 to estimate an planning level annual average effluent load to the Bay. On average, 94 gal of water per day is consumed per person in the Bay Area and discharged through our wastewater facilities (Figure 3).

Nutrient concentrations in wastewater discharges are influenced by the treatment technology at each facility and weather conditions (Table 3). As seen, the local data for amonium is comparible to the “rules of thumb” provided by Mike Falk that are based on professional experience and knowledge of influent concentrations and treatment processes. For example, the ammonium concentrations observed in secondary effluent at EBMUD, EBDA, and SF-Southeast all fall in the lower part of the Falk ranges during dry weather flow (Table 3). However, the local nitrate and nitrite data (when summed to NOx) apppear to be a little higher than the Falk estimates and the phospate data for secondary seem to be a little lower than the Falk estimates. For advanced treatment the local data seems to conform with the Falk estimates but again the nitrate+nitrate and phosphate concentrations appear to be plant specific.

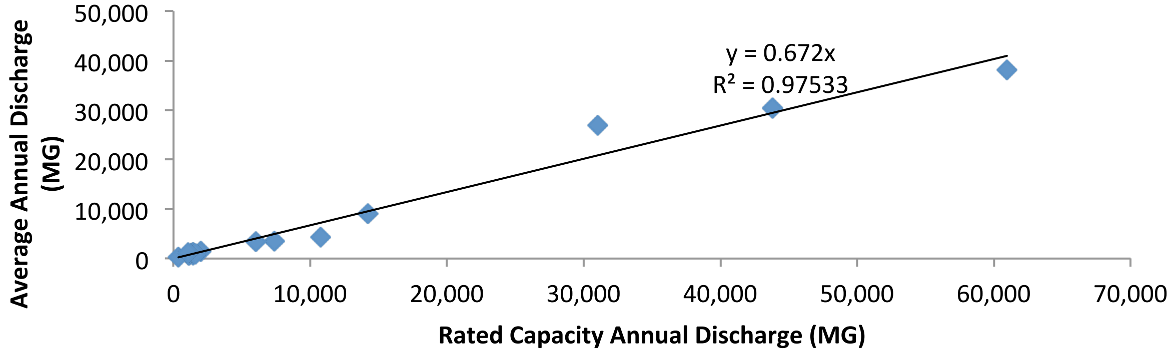


Figure 2. The rated capacity discharge in millions of gallons per year versus the average annual discharge for 16 wastewater treatment plants in the San Francisco Bay Area. On average, the average annual discharge is 67% of the rated capacity. The intercept has been forced through zero and it is not statistically significant from the non-forced regression.

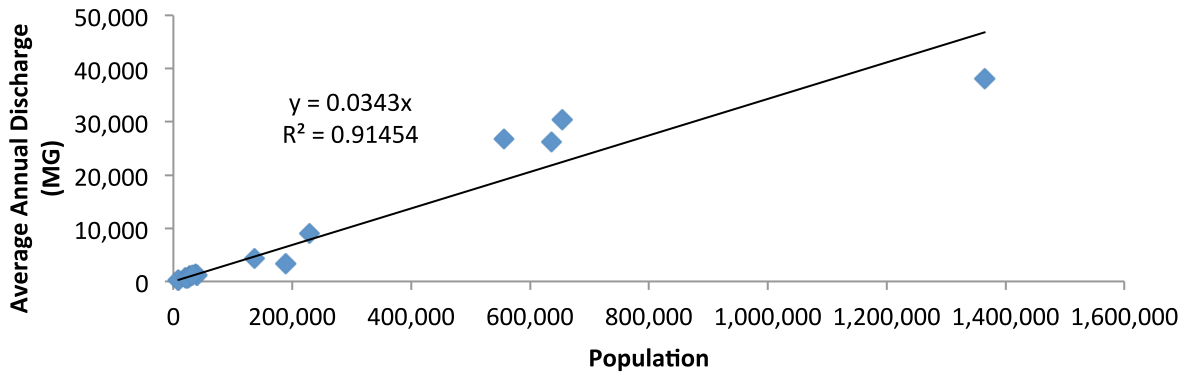


Figure 3. The service population of the wastewater treatment plant versus the average discharge (million gallons per year) for the corresponding plant. The data that makes up this graphic suggests that the per capita consumption discharged through wastewater facilities in the Bay Area is 94 gal per person per day.

It is also seen that there are strong climatic influences in the data that appear to differ slightly between treatment technolgies (or at least between our facitities). In many cases there is a strong dilution effect on ammonium concentrations during rainfall (e.g. EBMUD, EBDA, SF-Southeast) but in other cases flow augmentation by stormwater causes an increase in concentrations (Burlingame, Sunnyvale). The patterns are similarly variable between plants for nitrite, nitrate and phosphate. It is the preservation of this climatic signal and speciation that provides a further indication for a very high level of confidence in the overall total loads and timing of those loads entering the Bay south of the Bay Bridge.

Table 3. Average nutrient concentrations in wastewater treatment facilities South of the Bay Bridge and a comparison to "rules of thumb" (last five table rows) provided by Mike Falk (HDR, Folsom California).

Treatment Plant	Treatment Level	Treatment Technology	Flow class (MGD)	Ammonia (mg N/L)	Nitrite (mg N/L)	Nitrate (mg N/L)	Phosphate (mg P/L)	Total Kjedahl Nitrogen (ammonia + Org N) (mg N/L)	Nitrite + Nitrate (mg N/L)	Total Nitrogen (mg N/L)
EBMUD	Secondary	High Purity Oxygen	0-99	25.1	2.43	0.15	2.64	-	-	-
			100-199	17.2	1.74	-	-	-	-	-
			200-299	9.3	0.36	-	-	-	-	-
			300-399	3.9	0.13	-	-	-	-	-
			Count (n)	836	700	4	3	-	-	-
EBDA (total combined)	Secondary	Activated sludge	30-59	26.9	-	-	-	-	-	-
			60-89	23.3	-	-	-	-	-	-
			90-119	18.2	-	-	-	-	-	-
			120-150	13.1	-	-	-	-	-	-
			Count (n)	203	-	-	-	-	-	-
SF- Southeast	Secondary	Activated sludge + pure O2	30-59	28.1	0.2	1.1	1.4	-	-	-
			60-89	25.0	0.2	1.0	1.6	-	-	-
			90-110	13.6	0.6	1.8	1.7	-	-	-
			Count (n)	375	374	144	120	-	-	-
Burlingame	Secondary	Activated sludge	2-4.9	16.6	-	-	-	-	-	-
			5-7.9	27.9	-	-	-	-	-	-
			8-10.9	39.7	-	-	-	-	-	-
			11--14	45.1	-	-	-	-	-	-
			Count (n)	304	-	-	-	-	-	-
Millbrae	Secondary	Activated Sludge+hypo and effluent skimming	-	-	-	-	-	-	-	-
Treasure Island	Secondary		-	-	-	-	-	-	-	-
SF Airport	Secondary	Sequencing Batch Reactor	-	-	-	-	-	-	-	-
San Jose/Santa Clara	Advanced	Biological nutrient removal (BNR) with filtration	50-99	0.68	-	9.45	2.15	-	-	-
			100-150	0.56	-	9.65	3.11	-	-	-
			150-200	0.50	-	9.30	3.65	-	-	-
			Count (n)	127	-	102	217	-	-	-
Palo Alto	Advanced	AS+fixed film, dual media filters	10--24	0.50	0.016	18.7	12.4	-	-	-
			25-39	0.38	0.012	16.5	10.5	-	-	-
			40-54	0.20	0.013	13.0	6.6	-	-	-
			55-70	0.10	0.007	-	-	-	-	-
			Count (n)	845	221	220	204	-	-	-
SBSA	Advanced	Trickling filter with activated sludge and Dual-Media filters	-	-	-	-	-	-	-	-
San Mateo	Advanced	Act. Sludge (Nit.) with filtratio	-	-	-	-	-	-	-	-
Sunnyvale	Advanced	Ox ponds, fixed film reactor for N, dual media filtration	0-5.9	0.5	-	-	-	-	-	-
			6-11.9	1.1	-	-	-	-	-	-
			12-17.9	2.6	-	-	-	-	-	-
			18-24	4.3	-	-	-	-	-	-
			Count (n)	762	-	-	-	-	-	-
Influent				25				35	<1	35
Secondary Treatment Effluent				25-30			6	25-30	<1	30
"Garden Variety" Nutrient Removal Plants (e.g., San Jose)				<1			6	1--3	10	13
Advanced Nutrient Removal Plants (those around Chesapeake Bay)				<1			6	1--3	3	6
Limit of Technology (barring RO)				<1			<1	1--3	<1	3

For illustrative purposes, several of the longest records of effluent flow are provided in addition to the record from EBDA with shows an interesting pattern (Figure 4). The first is from EBMUD. The change in the look of the data in 2001 is associated with the change from daily to monthly flow. In the case of Palo Alto there is an interesting uptrend in the summertime flows during the middle years of the record. It is these examples of long term flows that are the basis for very excellent loads calculations. In the case of EBDA, there appears to be a down trend in flow perhaps associated with water reuse, which has an influence on the estimate of NOx and PO4 loads trends since the Mike Falk estimate of concentration were used for this facility.

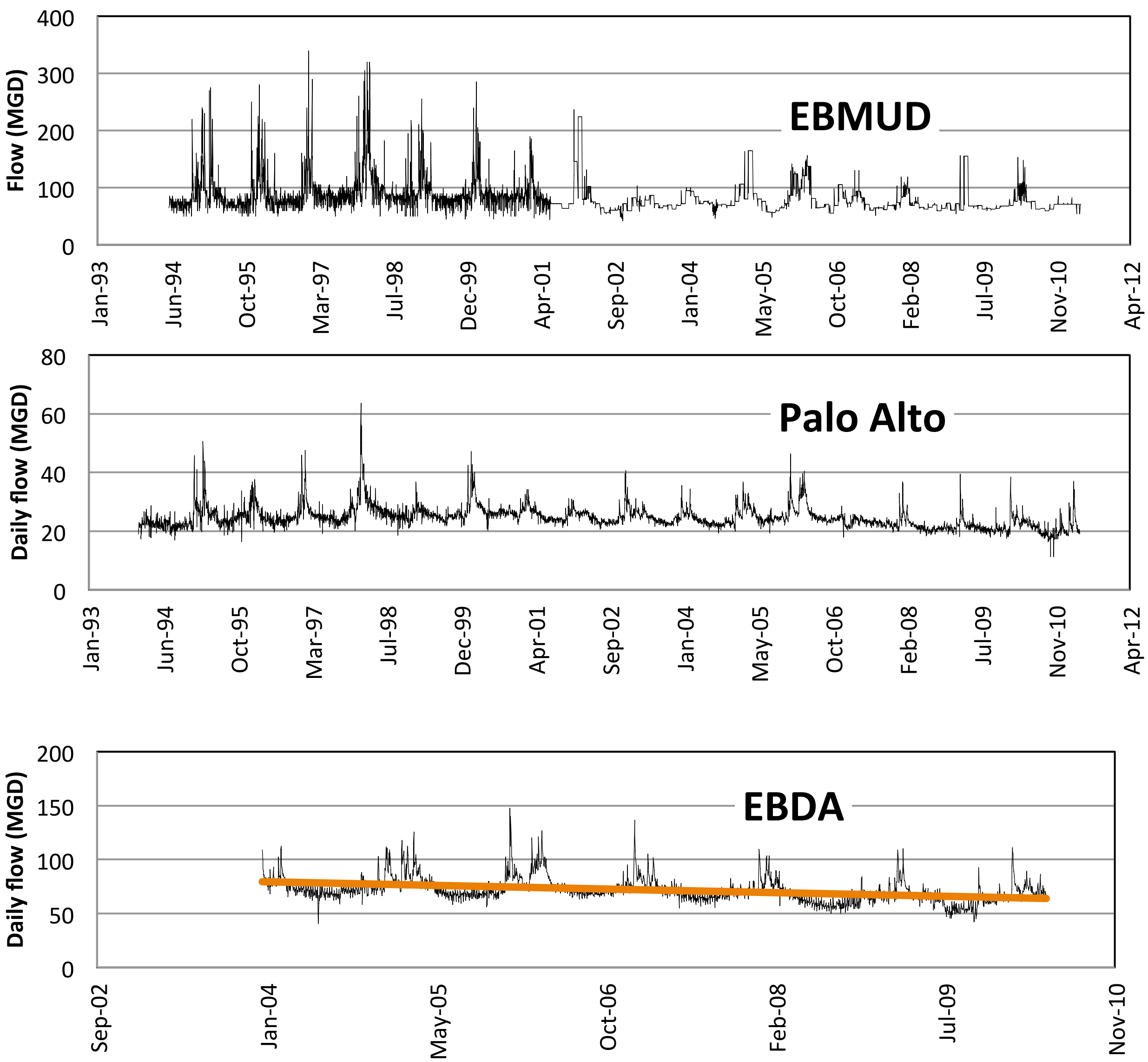


Figure 4. Examples of long flow records for South Bay Wastewater treatment facilities. Note the change in the data for EBMUD from daily to mainly monthly for EBMUD in 2001 and the apparent trend in the discharge data from EBDA.

Very reliable daily loads were calculated for seven out of the 12 facilities in the south of the Bay Bridge covering both secondary and advanced treatment. For illustrative purposes, the loads are summarized on an annual basis (Table 4). Loads do not vary substantially from year to year, and vary between 85-119% of the annual average load when the average of all facilities with measurements is considered together (Note this contrast with stormwater – see next section of the report for details). Loads of nitrogen from secondary treatment facilities is dominated by ammonium at an average ratio of 14:1 NH4:NOx, whereas for advanced treatment, the ratio is 15:1 NOx:NH4 favoring NOx. Given the best quality data for both flow volume and concentrations were available for a shorter period for these seven facilities for just seven years (WY 2004-2010), it was these data that were used to estimate total loads to the Bay south of the Bay bridge (Table 5). Overall on average, 11,198 t of dissolved inorganic nitrogen (DIN) is estimated to enter the Bay south of the Bay Bridge. Ammonium dominates the load comprising 76% at an average ratio of 2.9:1 NH4:NOx. On average, an estimated load of 1,861 t of phosphate (PO4), often referred to as dissolved inorganic phosphorus (DIP), is discharged to the Bay south of the Bay Bridge.

Table 4. Calculated annual loads (metric t) for wastewater treatment facilities south of the Bay Bridge, San Francisco Bay for facilities where high quality data for daily flow and concentrations were available. Note a Water Year runs October 1st to September 30th where the date is denoted by the end date.

	EBMUD			EBDA			Burlingame			SF-Southeast			San Jose/ Santa Clara			Palo Alto			Sunnyvale		
Water Year	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)
1995	2,757	224	333	-	-	-	-	-	-	-	-	-	-	-	-	14.1	606	394	-	-	-
1996	2,768	209	319	-	-	-	-	-	-	-	-	-	-	-	-	13.8	615	400	-	-	-
1997	2,810	297	341	-	-	-	-	-	-	2,291	139	154	-	-	-	13.9	620	402	-	-	-
1998	2,754	340	391	-	-	-	-	-	-	3,104	253	248	-	-	-	13.7	655	414	-	-	-
1999	2,571	343	329	-	-	-	-	-	-	2,563	170	184	-	-	-	14.1	610	395	-	-	-
2000	2,745	337	336	-	-	-	-	-	-	2,587	177	187	-	-	-	14.1	639	404	-	-	-
2001	2,707	273	306	-	-	-	-	-	-	2,507	164	177	-	-	-	15.3	621	399	-	-	-
2002	2,462	245	323	-	-	-	-	-	-	2,452	168	176	-	-	-	16.9	606	392	-	-	-
2003	2,453	252	259	-	-	-	-	-	-	2,089	102	124	85	1,434	444	14.8	617	398	-	-	-
2004	2,622	268	275	2,356	102	410	105	5.6	22	2,075	100	124	86	1,414	424	14.9	609	394	25	156	62
2005	2,593	271	300	2,369	107	426	133	6.3	25	2,505	168	177	87	1,457	448	15.2	618	400	32	172	69
2006	2,692	278	317	2,364	107	429	130	6.2	25	2,446	163	170	87	1,483	430	15.4	644	414	38	175	70
2007	2,568	262	277	2,288	100	400	93	5.2	21	2,243	123	136	81	1,353	380	18.9	599	395	31	151	60
2008	2,537	256	264	2,223	93	373	93	5.0	20	2,279	124	135	87	1,340	354	16.7	569	375	45	165	66
2009	2,436	249	268	2,165	89	358	77	4.4	17	2,261	127	134	88	1,278	327	16.2	554	366	43	154	62
2010	2,462	253	266	2,225	94	378	103	5.0	20	2,207	131	133	87	1,315	351	16.0	561	369	43	177	71
2011	2,419	249	255	-	-	-	-	-	-	-	-	-	87	1,418	417	13.5	526	345	-	-	-
Minimum	2,419	209	255	2,165	89	358	77	4	17	2,075	100	124	81	1,278	327	13	526	345	25	151	60
Maximum	2,810	343	391	2,369	107	429	133	6	25	3,104	253	248	88	1,483	448	19	655	414	45	177	71
Average	2,609	271	304	2,284	99	396	105	5.4	22	2,401	151	161	86	1,388	397	15	604	392	37	164	66

Table 5. Estimate total average annual loads (metric t) of ammonium, nitrate+nitrite (NOx) and phosphate (PO4) entering the Bay south of the Bay Bridge. See methods section above for a more detailed explanation of how the total loads were estimated. Note a Water Year runs October 1st to September 30th where the date is denoted by the end date.

	A			B			C			D			E		
	Secondary treatment (measured)			Secondary treatment (A multiplied by 1.13 to account for facilities without measurements)			Tertiary treatment (measured)			Advanced treatment (C multiplied by 1.08 to account for facilities without measurements)			Estimate total for all facilities (Sum of B and D)		
Water Year	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)	NH3 (t)	NOx (t)	PO4 (t)
2004	7,158	476	831	8,089	538	939	126	2,179	880	136	2,353	951	8,225	2,892	1,890
2005	7,600	552	928	8,587	623	1,049	135	2,246	917	146	2,426	990	8,733	3,049	2,039
2006	7,632	554	940	8,624	626	1,062	140	2,302	914	151	2,487	987	8,775	3,113	2,049
2007	7,192	490	834	8,127	554	943	131	2,103	835	142	2,272	902	8,268	2,825	1,844
2008	7,132	478	793	8,059	541	896	148	2,075	795	160	2,241	859	8,220	2,781	1,755
2009	6,938	469	777	7,840	530	878	148	1,986	754	159	2,145	814	8,000	2,675	1,692
2010	6,996	484	798	7,905	547	902	146	2,053	791	158	2,217	854	8,063	2,764	1,755
Average	7,235	501	843	8,176	566	953	139	2,135	841	150	2,306	908	8,326	2,871	1,861

At this time there are limited data available for total nitrogen and total phosphorus in the concentration data sets provided by the wastewater treatment managers. However, based on the "rules of thumb" provided by Mike Falk (see last five rows of Table 3), it appears that organic forms may add an additional 20% to the load and perhaps an additional 30% in advanced systems. Thus as a first estimate, total nitrogen loads for the South Bay south of the Bay Bridge might be 125% x (8,326+2,871) = 13,996 metric t. Similarly, a first estimate for total P might be made by increasing the load of phosphate by a factor of 6/4 or 50% based on Mike Falk's rule of thumb of phosphate in effluent at 4 mg/L and total phosphorus at 6 mg/L for all plant types. Data from the San Jose / Santa Clara Plant indicates that on average total P is 113% of dissolved phosphate. Total phosphorus load to the South Bay might therefore be as high as 1,861 x 150% = 2,792 metric t per year.

Stormwater Loading

Methods

Here we define stormwater loading as all wet and dry weather flow entering the Bay from small tributaries that drain the nine-county Bay Area. These include all (more) natural rivers and creeks, and engineered above and below ground storm drain facilities. In order to make estimates of loads from small tributaries to the Bay south of the Bay Bridge, an estimate of flow was needed. This was done by developing an index of flow based on data from as many gauged watersheds as possible. Gauging records were available for the period Water Year 1971-2010 (40 years) for the following USGS gauging stations: Dry Creek at Union City (11180500), Alameda Creek at Niles (11179000), Guadalupe River at Hwy 101 (11169025), San Francisquito

Creek at Stanford University (11164500), and Saratoga Creek at Saratoga (11169500). Thus it was possible to build a 5-station index. We realize reservoirs will have a variable influence on flow (especially during rare events when capacity may be exceeded) and the influence likely differs between reservoirs depending on design specifications and operation rules. However, for this exercise we assumed that, for all reservoirs and for all storms, watershed area upstream from reservoirs did not contribute flow. Excluding the area upstream from reservoirs, these five gauges represent an area of 1,255 km^2 or 40% of the total area of small tributaries draining to the Bay south of the Bay Bridge (3,109 km^2). The daily sum of flow data from these tributaries was then scaled up using the calibrated and verified annual time step rainfall-runoff model recently developed by the Regional Monitoring Program for Water Quality (RMP), Sources, Pathways, and Loadings Workgroup (SPLWG) (Lent and McKee, 2011). Based on this approach, very high accuracy daily flows were generated for wet season months; the dry weather flow months are considered moderate accuracy because irrigation overflows and other non-groundwater urban sources many not be perfectly accounted.

Nutrient concentration data are sparse for stormwater during high flow in the Bay Area. Data were collated for eight locations (Table 6). These data were (with the exception of Z4LA) not collected for the purpose of loads calculations and were generally bias towards low flow rather than high flow when the majority of loads would be transported. These data to not show systematic patterns with flow as would normally be expected. As such loads were estimated by combining average nutrient concentrations with daily flow estimates. Thus at present, we consider the estimate of daily loading to the Bay from small tributaries draining to the Bay south of the Bay Bridge to be of low accuracy and likely bias low. This might be especially true for NOx and PO4 as (by the author's experience) these typically show higher concentrations at high flow. The bias may be as high as 2x for NH4 and 3x or even 4x for NOx and PO4. As a general comment, although the loads are perhaps bias low (because of nutrient data availability), the sophistication of the calculation technique for stormwater was akin to the sophistication for wastewater and superior to atmospheric deposition.

Table 6. Watersheds with nutrient data that was used for the estimation of stormwater loads.

	Ammonium (NH4)	Nitrate+Nitrite (NOx)	Phosphate (PO4)	Source
Z4LA	X	X	X	Lester McKee, SFEI
El Cerrito Creek	X	X	X	Francois Rodigari at EBMUD
Ettie Street Pump stn	X	X	X	Francois Rodigari at EBMUD
Matadero Ck	X			Karin North at the City of Palo Alto
San Francisquito Ck	X	X		Karin North at the City of Palo Alto
Napa River	X	X	X	Lester McKee, SFEI
Sonoma Creek	X	X	X	Lester McKee, SFEI
Pinole Creek	X	X	X	Lester McKee, SFEI

Results

Annual flow from the small tributaries south of the Bay Bridge has varied from 84-2,419 million m^3 for the period Water Year 1971-2010 (40 years), a variation on the annual scale of 29 times.

Daily flows have varied from 0.016 million m^3 during the driest of dry seasons to a maximum estimate daily flow of 120.7 million m^3 on February 19th, 1986 (Figure 5) a variation of over 7,500 times. Thus it can be seen that we have a very advanced understanding of the timing of flows. In addition, this magnitude of variation sets up the possibility that even though on average wastewater loads of nutrients to the Bay dominate, during some years and some months of each year, stormwater flow and loads will dominate.

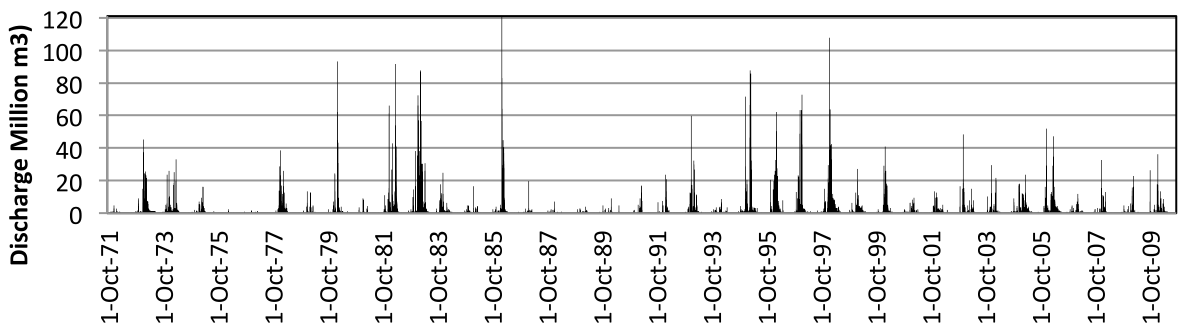


Figure 5. Daily flow from the local tributaries in the nine-county Bay Area to the South Bay south of the Bay Bridge based on an 5 station index (Dry Creek at Union City, Alameda Creek at Niles, Guadalupe River at Hwy 101, San Francisquito at Stanford University, and Saratoga Creek at Saratoga) adjusted to the annual average flow (586 million m^3) for water years 1971-2000 (Lent and McKee, 2011).

Nutrient concentration data are highly variable between watersheds (Table 7). Data for Ettie Street pump station were particularly remarkable for ammonium, with highly variable and high concentrations. Available data were sorted for month and then summarized as averages for the wet season (October – April) and dry season (May to September). Since the data that we have indicated that nitrite is very small compared to nitrate, all data were used for the averages in the NO3/NOx column of the table. Ammonium concentrations were greater in the dry season compared to the wet season for five out of seven watersheds. This was not expected and is likely due to an artifact of bias to low flow in all data regardless of wet or dry season. Similarly, phosphorus results were unexpected. In contrast, NO3/NOx concentrations were greater in the wet season for four out of five watersheds. Thus it was decided to use these separate wet and dry season average concentrations to calculate loads despite concerns that the data are not likely representative of the wet weather transport processes and concentrations. It is interesting to note that the data in Table 7 are remarkably similar to the averages derived from the "SWAMP dataset" collected by the Water Board with the exception of NH3 which shows the same wet to dry pattern but concentrations are lower overall (Table 8).

Table 7. Average nutrient concentrations (mg/L) for selected watersheds in the Bay Area.

	NH3	NO2	NO3	NO3/NOx	PO4
Wet season					
Z4LA	0.100	0.014	0.194	0.208	0.092
El Cerrito Creek	0.440		1.137	1.137	0.042
Ettie Street Pump stn	0.864		0.906	0.906	0.066
Matadero Ck	0.230				
San Francisquito Ck	0.353		1.479	1.479	
Napa River	0.014	0.0037	1.161	1.165	0.042
Sonoma Creek	0.010	0.0019	1.272	1.274	0.063
Pinole Creek	0.022	0.0088	0.919	0.927	0.273
Dry Season					
Z4LA					
El Cerrito Creek	0.304		1.111	1.111	
Ettie Street Pump stn	1.260		2.995	2.995	
Matadero Ck	0.302				
San Francisquito Ck	0.410				
Napa River	0.016	0.0021	0.284	0.287	0.045
Sonoma Creek	0.015	0.0026	0.271	0.274	0.063
Pinole Creek	0.013	0.0028	0.086	0.088	0.468
Average wet season	0.254	0.0071	1.010	1.014	0.096
Average dry season	0.332	0.0025	0.949	0.951	0.192
Average all data	0.290	0.0051	0.985	0.987	0.128

Table 8. A summary of "SWAMP" data collected by the Water Board during selected months between September 2001 and February 2006 (inclusive). All concentrations are in mg/L. NOx=NO2+NO3; TN = TKN+NOx. Raw data source: California Environmental Data Exchange Network (CEDEN): http://www.ceden.us/AdvancedQueryTool (SFBRWQCB 2007a; SFBRWQCB 2007b; SFBRWQCB 2008)

	NH3	NO2	NO3	NOx	TKN	TN	PO4	TP
Average wet season	0.106	0.017	0.974	0.992	0.439	1.430	0.100	0.128
Average dry season	0.140	0.016	0.794	0.811	0.521	1.331	0.169	0.189
Average all data	0.115	0.017	0.927	0.944	0.464	1.408	0.118	0.145
Count	170	184	249	-	234	-	249	231

As an illustration of the variation of daily loads estimate, data are shown for ammonium for the target period (Water Year 1991-2010; 20 years) (Figure 6). Daily loads of ammonia have varied from an estimated 0.006-27.3 metric t. Similarly, NOx and PO4 loads are estimated to have varied from 0.018-109 metric t and from 0.002-10.4 metric t respectively. Annual loads are estimated to have varied for NH3, NOx, and PO4 from 45-467 metric t, from 167-1,814 metric t, and from 19-186 metric t respectively (Table 9).

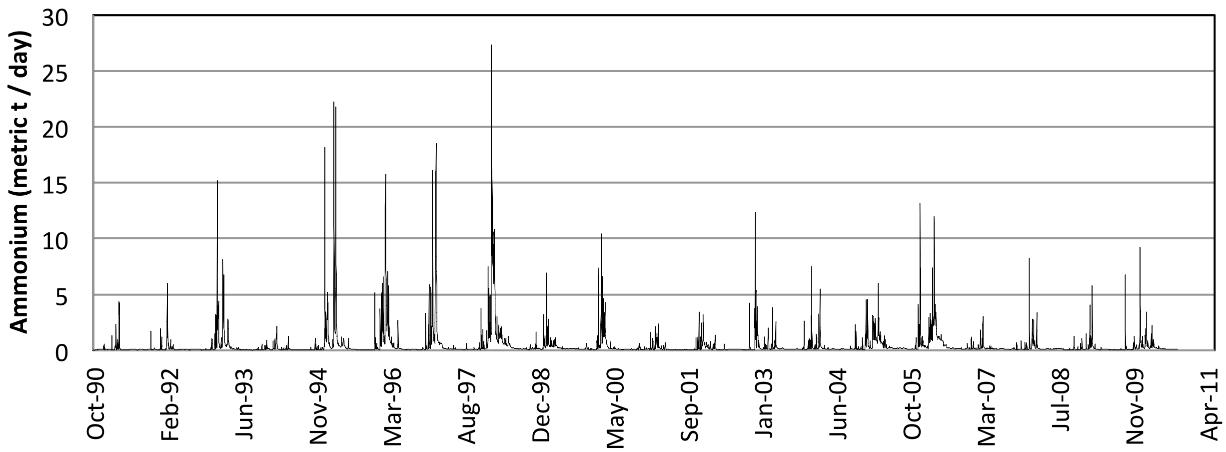


Figure 6. Estimated daily variation in ammonium load to the Bay south of the Bay Bridge.

Table 9. Annual estimated nutrient loads to the Bay south of the Bay Bridge for the last 20 water years (Water year runs October 1st to September 30th with the year denoted as the end date).

Water Year	Flow (Million m3)	NH3 (metric t)	NOx (metric t)	PO4 (metric t)
1991	197	53	198	23
1992	238	64	239	27
1993	689	178	696	70
1994	167	45	167	19
1995	1,263	328	1,274	130
1996	1,036	268	1,046	106
1997	1,080	278	1,092	109
1998	1,798	467	1,814	186
1999	435	116	436	49
2000	583	152	588	61
2001	228	60	229	25
2002	304	81	305	33
2003	456	122	458	52
2004	353	94	354	40
2005	720	191	723	80
2006	1,091	292	1,094	123
2007	254	70	254	31
2008	351	94	352	39
2009	277	73	278	30
2010	468	124	471	51
Minimum	167	45	167	19
Maximum	1,798	467	1,814	186
Average	599	158	603	64

At this time there are limited data available for total nitrogen and total phosphorus local stormwater data sets with the exception of the SWAMP data (SFBRWQCB 2007a; SFBRWQCB 2007b; SFBRWQCB 2008). It appears that on average TN is 1.33 times larger than the sum of NH3+NOx) and TP is 1.22 times larger the PO4. Thus as a first estimate, total nitrogen loads in stormwater entering the Bay South Bay south of the Bay Bridge might be TN = (158+603) x 1.33 = 1012 metric t. Similarly TP = 64 x 1.22 = 78 metric t.

Atmospheric Deposition

Methods

Searches were done for relevant peer-reviewed literature in addition to reviewing data generated by the Bay Area Air Quality Management District (AQMD) and the Air Resources Board (ARB). Neither of these departments yielded. Los Angeles County data was collected from the National Atmospheric Deposition Program (NADP) website. There are several west coast locations that are part of the National Trends Network that collect precipitation chemistry data, however, the sites predominantly are located away from urban areas and point sources of pollution. No other suitable data were found. As a general comment, the data input and sophistication of the calculation technique for atmospheric deposition was poor compared to wastewater and stormwater.

Results

Russell et al. (1980) estimated an annual wet and dry deposition of total nitrogen and total phosphorus of 980 and 120 metric t respectively; however they did not disclose the source of data or methods for their calculations. Normalizing their data to the whole area of the Bay (1,200 km^2), Russell et al.'s estimates are equivalent to 817 and 100 kg/km^2/year (Table 10). Comparison of these measurements to those in Lake Tahoe provided by Jassby et al. (1994) (562 kg N/km^2/y and 32.6 kg P/km^2/y) suggest that the estimates of Russell et al. (1980) might be reasonable. Recently, estimates were made for the Central Valley of 413-1,243 kg N/km^2/y (Kratzer et al., 2011). The Los Angeles County data from NADP seems to be close in comparison to the data provided by Russell et al., 1980. The data from the other NADP sites are lower, but that is expected due to their increased distance to urban areas.

Applying these deposition rates to the south Bay yields a range of loading estimates (Table 11). The estimates generated using Los Angeles data may be the most applicable for nitrogen species, but that said, the lack of local recent data still remains a concern. There remains an even more unsatisfying situation with a lack of data for phosphorus; we are left to fall back on the high quality but outdated work of Jassby et al., (1994) for Lake Tahoe. Overall atmospheric deposition loads may be considered to be low accuracy. More work needs to be done to properly interpret available data sets and resolve reliable loading estimates and temporal variability.

Table 10. The annual average rates of wet and dry deposition for the San Francisco Bay and several west coast locations. National Atmospheric Deposition Program-National Trends Network. http://nadp.sws.uiuc.edu/NTN/ntnData.aspx

Location	Source	Range of Years	NH4 (kg/km^2)	NO3 (kg/km^2)	Inorg. N (kg/km2)	TN (kg/km^2)	TP (kg/km^2)
San Francisco Bay, CA	Russell et al., 1980	1978				817	100
Lake Tahoe, CA	Jassby et al., 1994	1993				562	32.6
Central Valley, CA	Kratzer et al., 2011					413-1,243	
Los Angeles County, CA	NADP	1982-2009	124.3	528.3	216.0		
Mendocino County, CA	NADP	1979-2009	41.0	197.2	76.3		
San Benito County, CA	NADP	1999-2009	15.5	68.5	27.5		
Benton County, OR	NADP	1979-2007	27.8	176.2	61.4		
Benton County, OR	NADP	1983-2009	65.3	170.8	89.5		
Jefferson County, WA	NADP	1980-2009	47.2	271.9	98.0		

Table 11. Estimated atmospheric loads of nutrients entering the Bay south of the Bay Bridge via direct deposition to the Bay surface assuming an area of 480.7 km^2. The loads estimates enclosed with the thicker lines may be reasonable.

Location	Source	Range of Years	Ammonium (NH4) (metric t)	Nitrate (NO3) (metric t)	Total nitrogen (metric t)	Total Phosphorus (metric t)
San Francisco Bay, CA	Russell et al., 1980	1978	-	-	393	48
Lake Tahoe, CA	Jassby et al., 1994	1993	-	-	270	16
Central Valley, CA	Kratzer et al., 2011	Low	-	-	199	-
		High	-	-	598	-
Los Angeles County, CA	NADP	1982-2009	60	254	-	-
Mendocino County, CA	NADP	1979-2009	20	95	-	-
San Benito County, CA	NADP	1999-2009	7	33	-	-
Benton County, OR	NADP	1979-2007	13	85	-	-
Benton County, OR	NADP	1983-2009	31	82	-	-
Jefferson County, WA	NADP	1980-2009	23	131	-	-

Synthesis

New nutrient loads have been generated for treated wastewater discharged to the Bay south of the Bay Bridge. Wastewater loads estimates are based on a considerable amount of data and are thought to be very reliable. New estimates of loads from stormwater (including rivers, creeks and engineered storm drains), although temporally revolved with high confidence, are presently considered moderate accuracy due to poorer dry weather flow data and likely bias low by a factor of 1.5 x to perhaps 3 x due to the lack of rainstorm nutrient concentration data. Atmospheric loads remain uncertain. These things noted, it is interesting to compare the data generated at a variety of time scales. Daily loads of wasterwater ammonium on average exceeded stormwater loads by a factor of 155 times; during dry weather this factor went as high as 591 times and during wet weather winter conditions the factor was as low as 2.2 times (Figure 7). Similarly, the factors for PO4 ranged between 1.6 times during the winter and 242 times during the summer with an average condition of 77 times. In contrast, NOx loads during the winter months could sometimes exceed wastewater input by a factor of 5 times but during the dry season wastewater still dominated up to a factor of 40 times.

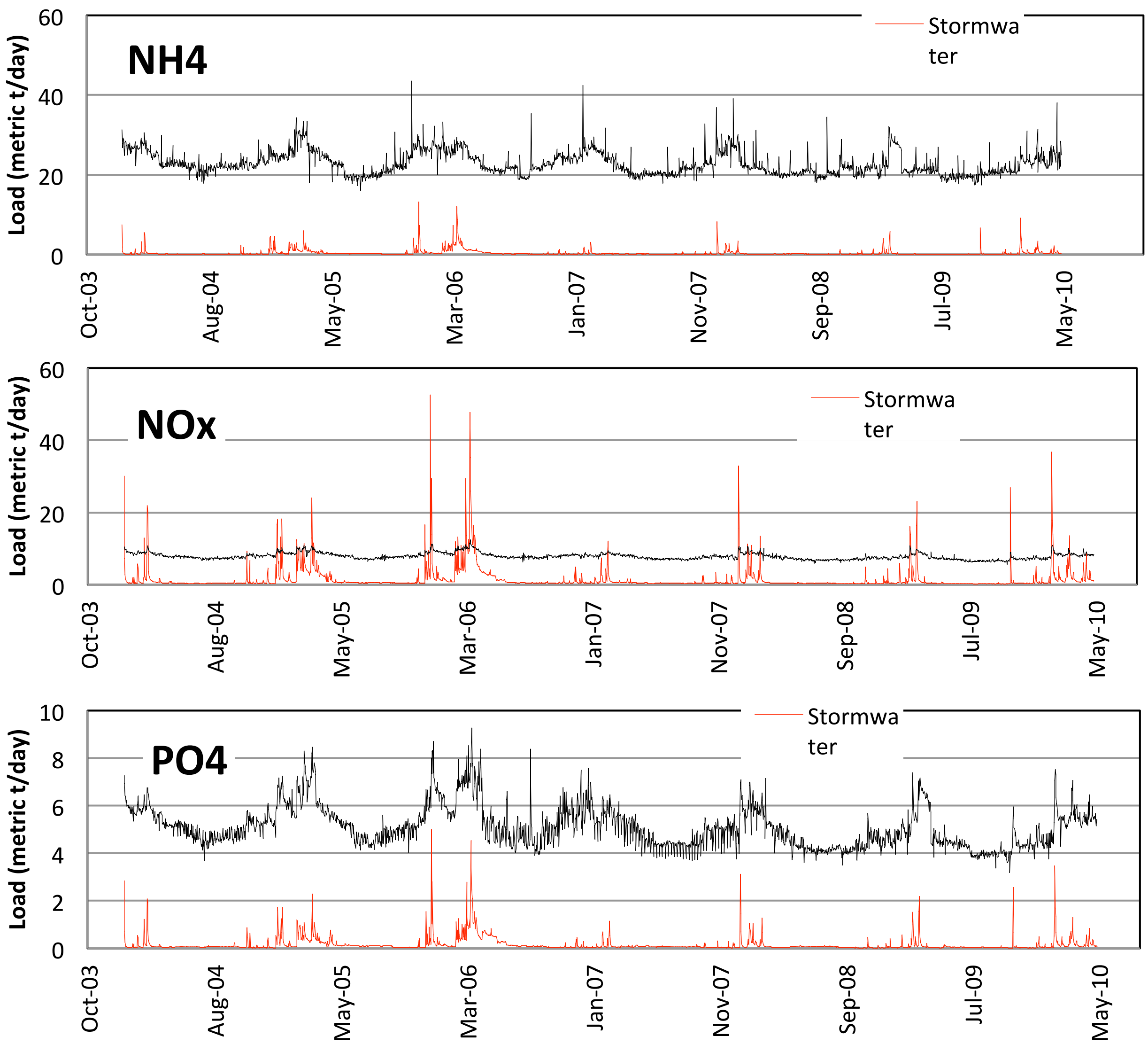


Figure 7. Comparison of daily loads for wastewater against daily loads of stormwater.

On an annual average basis, wastewater loads appear to dominate for ammonia based on the calculations presented here (Figure 8a). Even if we assume stormwater ammonium loads are underestimated by a factor of 1.5 times (see discussion in stormwater methods section above), this would be the case. Similarly, no matter how bias low the PO4 stormwater loads data are, it appears wastewater would dominate. The magnitude of NOx loads from stormwater and atmospheric deposition is of more interest and may approach that of wastewater load if quantified more accurately (Figure 8B).

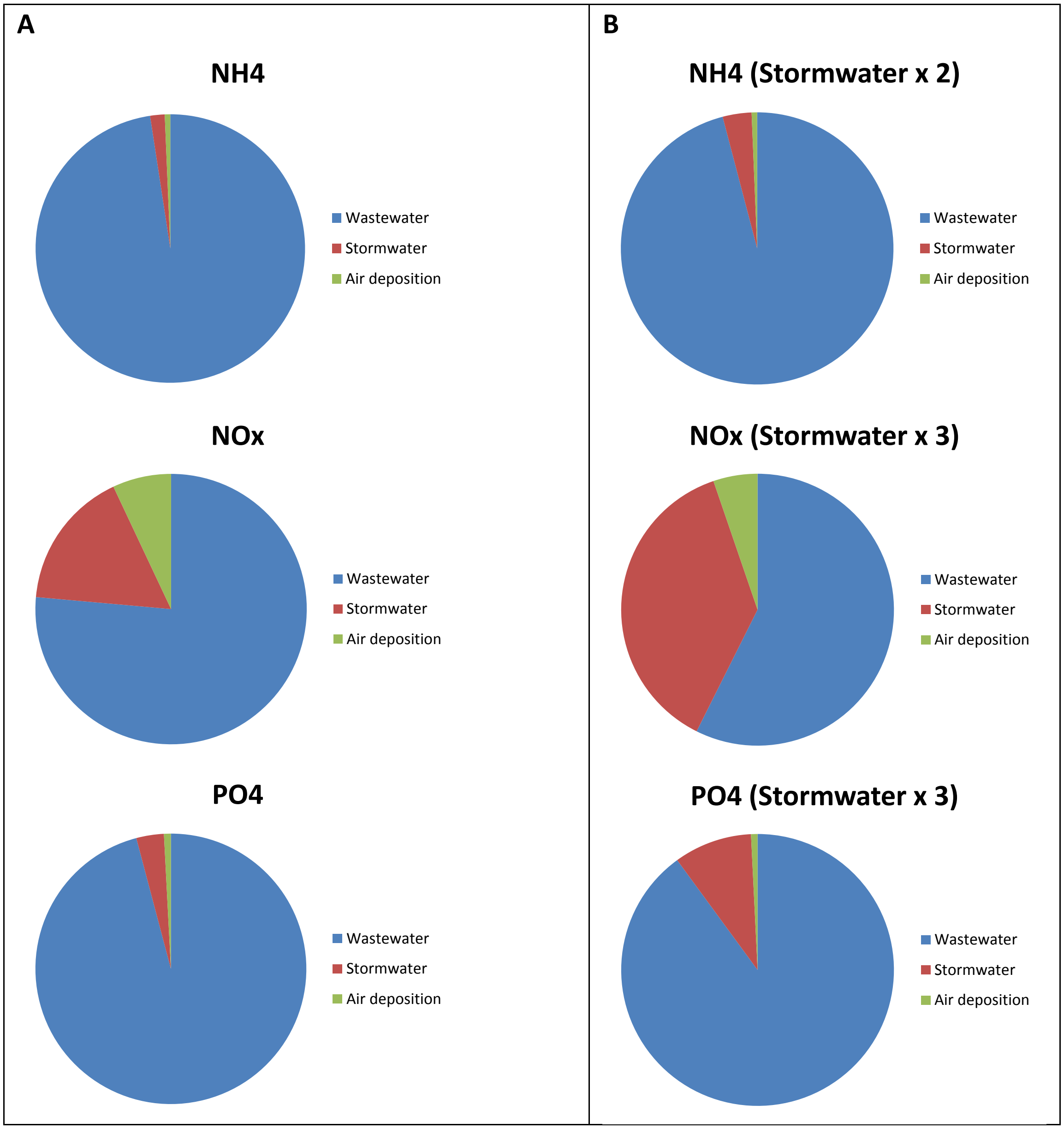


Figure 8. Comparisons of annual average loads from wastewater, stormwater, and atmospheric deposition. The reader is reminded that these are not the only sources of nutrients to the Bay. Other sources, either positive or negative and likely seasonally unique, include tidal boundary fluxes, net sediment-water boundary exchange, and transformations between inorganic forms (nitrogen only) and organic forms (nitrogen and phosphorus). In addition, there are industrial wastewater discharges to the Bay that are relatively small compared to other sources (McKee et al., 2011). Panel A shows the estimated loads based on the work presented in this report. Panel B shows the estimated loads if we were to assume stormwater loads estimates are bias low by a factor of 2 times for ammonium, and 3 times for NOx and PO4 (see stormwater methods section for rationale).

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