Technical Memorandum 2: North San Francisco Bay Selenium Data Summary and Source Analysis

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ABBREVIATIONS

BASMAA	Bay Area Stormwater Management Agencies Association
cfs	cubic feet per second
mgd	million gallon per day
NDOI	Net Delta Outflow Index
NSFB	North San Francisco Bay
psu	Practical Salinity Unit
RMP	Regional Monitoring Program
SFEI	San Francisco Estuary Institute
SSC	Suspended Sediment Concentration
SWAMP	Surface Water Ambient Monitoring Program
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
TMDL	Total Maximum Daily Load
TSM	Total Suspended Particulate Material

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1. INTRODUCTION

North San Francisco Bay (NSFB) including Suisun Bay, Carquinez Strait, San Pablo Bay and Central Bay, shown in Figure 1-1, is listed as being impaired for selenium under section 303(d) of the Clean Water Act. This listing was based, in part, on elevated concentrations in white sturgeon and diving ducks in the 1980s and is more than a decade old. There is an ongoing effort by the San Francisco Bay Regional Water Board to prepare a TMDL for selenium in North San Francisco Bay with the most up-to-date information. This technical memorandum has been prepared in support of the TMDL development effort. The purpose of this memorandum is two-fold: provide a summary of relevant water and sediment selenium data in the North Bay and to develop a quantitative estimate of the sources of selenium to the waters of the North Bay. In addition to this document, two other technical memorandums are under preparation. The first of these assesses the scientific literature to develop recommendations for selenium toxicological endpoints in the North Bay, and the second presents a conceptual model of selenium behavior in the North Bay, with an emphasis on describing the biogeochemical processes relating selenium sources to concentrations in biological tissues. Information in these memorandums will support the development of a mechanistic model of selenium in NSFB linking sources to endpoints of interest in the TMDL.

There has been a long history of research on selenium sources, transport, and biological uptake in San Francisco Bay, the Delta, and in the Central Valley (e.g., Cutter, 1989; Cutter and San Diego-McGlone, 1990; Cutter and Cutter, 2004; Presser and Luoma, 2006; Meseck and Cutter, 2006). Starting in the mid-1980's, selenium concentrations have been monitored in the bay across the salinity gradient and in different seasons reflecting variations in freshwater flows. Major sources of selenium to the Bay-Delta identified in these previous studies include:

- San Joaquin River that receives discharge from agricultural drainage from the western San Joaquin Valley
- Selenium discharged from the effluents of North Bay refineries.
- Sacramento River, which is the dominant freshwater inflow to the Bay-Delta during the wet season.

This memorandum contains a summary of data and findings from past work, including an updated estimate of the selenium load contributions from various point and non-point sources. Over the past two decades, there have been major declines in refinery loads due to improved wastewater treatment installed in 1998; there is some evidence that San Joaquin River concentrations were lower in the late 1990s and beyond than in the 1980s, although this is not clear cut.

The data summary (Section 2) provides an overview of water and sediment data collected in and upstream of NSFB over the past two decades. Data on selenium in biota are discussed in the memo on toxicological endpoints (TM-3). The water and sediment data are presented in maps and plots to provide a visual summary and to identify major processes occurring in the North Bay. There are many ways to represent this large and complex data set. The broad objective of the data summary was to provide a reader with the spatial and temporal extent of the data collected to date, and to evaluate whether existing data could be used to address questions of interest to the TMDL. A more detailed evaluation of the data and underlying processes will be presented in the Conceptual Model (TM-4). These data will also serve as the basis for model calibration to be performed in the next step of the TMDL development. The majority of the data collected in the bay is focused on total selenium. Speciation, particularly the concentrations of selenate, selenite, and particulate selenium, determines how efficiently selenium enters higher aquatic food web (Presser and Luoma, 2006). To the extent available, speciation data on selenium are also described.

The goal of the source analysis (Section 3) was to use data on concentrations and flow volumes of each of the identified sources in NSFB, and to take a fresh look at estimating the relative magnitudes of the key point and non-point sources of selenium. The source estimates differ from previous work in the use of more recent data and the examination of a wider range of potential sources. Sources considered include: atmospheric deposition, urban and non-urban runoff, Delta inflows and the relative contributions of the Sacramento and San Joaquin Rivers, municipal wastewater effluents, petroleum refinery effluents, and inputs from the existing reservoir of selenium in the sediments of the North Bay. Accurate quantification of sources is a key input to selenium fate and transport modeling proposed for the bay. In the event that the TMDL finds that most recent data are consistent with selenium impairment in the North Bay, the source analysis is a means to identify the loads that need to be decreased to meet targets in the bay.

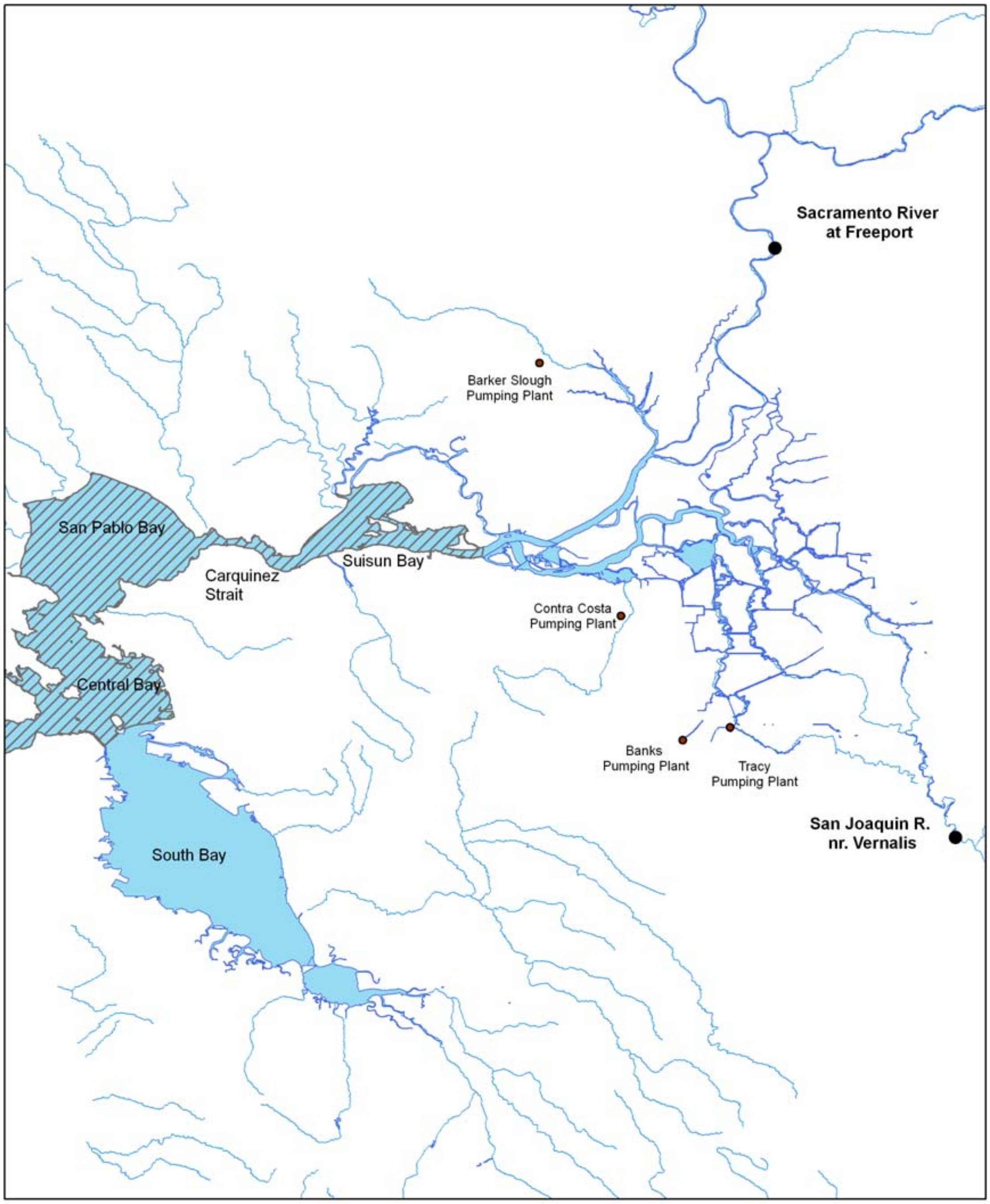


Figure 1-1 The San Francisco Bay estuary, Delta and Sacramento and San Joaquin Rivers. The cross-hatched area shows the area of interest for the North San Francisco Bay Selenium TMDL. The Sacramento River at Freeport and the San Joaquin River at Vernalis are the principal freshwater inflows into the Delta. A significant portion of the freshwater inflows are exported out of the Delta through the four pumping plants shown.

2. Selenium Concentrations in Bay Water and Bottom Sediments

2.1. Goals of Data Summary

A key objective of the data summary is to evaluate whether the following questions of relevance to the selenium TMDL in the NSFB can be addressed through the existing database:

- What is the distribution of selenium in the water column?
- What are the long term trends of selenium concentrations in water?
- What is the relative mix of dissolved and particulate selenium in the water column?
- How does selenium correlate with salinity and freshwater flows?
- What was the effect of refinery selenium load reduction in 1998?
- How does selenium correlate with suspended sediments and chlorophyll-a?
- What is the distribution of selenium in sediments?

In this section, the data sources used in this evaluation are first described, and plots and maps of the data are used to address each of the questions above.

2.2. Data Description

Selenium concentrations in the bay water column and bottom sediments have been collected by different entities since the 1980s. The major sources of data for selenium in the North Bay are: 1) data collected by the Regional Monitoring Program (RMP) since 1993; and 2) data collected by Dr. Greg Cutter's research group at Old Dominion University[1]. The RMP is a joint effort among San Francisco Estuary Institute (SFEI), the Regional Board, and local dischargers. All data collected by the Cutter research group from the mid-1980s onwards was made available to us electronically for the preparation of this and subsequent technical memorandums.\

The RMP was initiated in 1993 to sample contaminant concentrations in water, sediment and bivalves. Fifteen monitoring sites were located in the North Bay (out of 26 sites in the whole bay; Figure 2-1; Table 2-1). Samples were collected at a frequency of 2-3 times a year during high flow, intermediate flow and low flow periods. Starting in 2002, EPA's Generalized Random Tessellation Stratified (GRTS) sample design approach was utilized to monitor contaminants (SEFI, 2006). Thereafter, most of the long-term sites were discontinued except for five locations noted in Table 2-1. Since 2002, each year 12 randomly selected sites in the North Bay have been sampled for selenium in the water and 24 random sites have been sampled for selenium in sediments. Water samples were collected 1-2 feet below surface. Water samples were analyzed for total and dissolved (0.45 µm filtered) concentrations, with a detection limit of 0.02 µg/L. Sediment samples were

[1] Funded by the U.S. Bureau of Reclamation, CALFED (Grant 01WRPA0077), California Department of Water Resources, and National Science Foundation, Environmental Geochemistry and Biogeochemistry Initiative (Grant: OCE-9707946).

analyzed for dry weight concentrations with detection limit of 0.01 mg/kg. Sediment samples were taken from the top 5 cm of the sediment surface.

Dr. Cutter's research group used a different sampling design to sample dissolved and particulate selenium concentrations along the estuarine transect from the Golden Gate to the Sacramento (Rio Vista) and San Joaquin River (USGS Station 757), during 1980s and again during 1997-1999 (Cutter and Cutter, 2004; Doblin et al. 2006). Samples were taken along the salinity gradient at approximately equal salinity intervals and were analyzed for dissolved selenium and selenium species (selenate, selenite, and organic dissolved selenide) at detection limits of 1.6 ng/L. Because salinity varied according to the sampling year, the spatial locations varied slightly for individual sampling events. Locations for a sampling event during November 1999 are shown in Figure 2-1 along side RMP sampling stations. Samples were also analyzed for particulate selenium and its speciation (elemental selenium, selenite and selenate). Sampling depth is at 1-2 m below surface. The detection limit for particulate selenium was 0.4 ng/L. For the sediments, Dr. Cutter's research group sampled sediment cores at 23 locations in the Bay-Delta (Meseck, 2002). Sediment core profiles were taken from depths ranging from 5 cm to 20 cm at different locations. The cores were analyzed for total selenium, elemental selenium and selenite and selenate. Dr. Cutter's research group is the only one that has reported selenium speciation in the bay.

Table 2-1
RMP long-term sampling locations in the North Bay.

Site Code	Site Name	Sample Matrix	Period of data
BC10*	Central Bay/Yerba Buena Island	Water, sediment, bivalve	1993-2005
BC21	Central Bay/Horseshoe Bay	Sediment, bivalve	1993-2001
BC30	Central Bay/Richardson Bay	Water, sediment	1993-2001
BC41	Central Bay/Point Isabel	Water, sediment	1993-2001
BC60	Central Bay/Red Rock	Water, sediment, bivalve	1993-2001
BD15	San Pablo Bay/Petaluma River	Water, sediment, bivalve	1993-2001
BD20	San Pablo Bay	Water, sediment, bivalve	1993-2001
BD30*	San Pablo Bay/Pinole Point	Water, sediment, bivalve	1993-2005
BD40	San Pablo Bay/Davis Point	Water, sediment, bivalve	1993-2001
BD50	San Pablo Bay/Napa River	Water, sediment, bivalve	1993-2001
BF10	Suisun Bay/Pacheco Creek	Water, sediment	1993-2001
BF20*	Suisun Bay/Grizzly Bay	Water, sediment, bivalve	1993-2005
BF40	Suisun Bay/Honker Bay	Water, sediment	1993-2001
BG20*	Delta/Sacramento River	Water, sediment, bivalve	1993-2005
BG30*	Delta/San Joaquin River	Water, sediment, bivalve	1993-2005

*Sampling continued at these locations after 2002

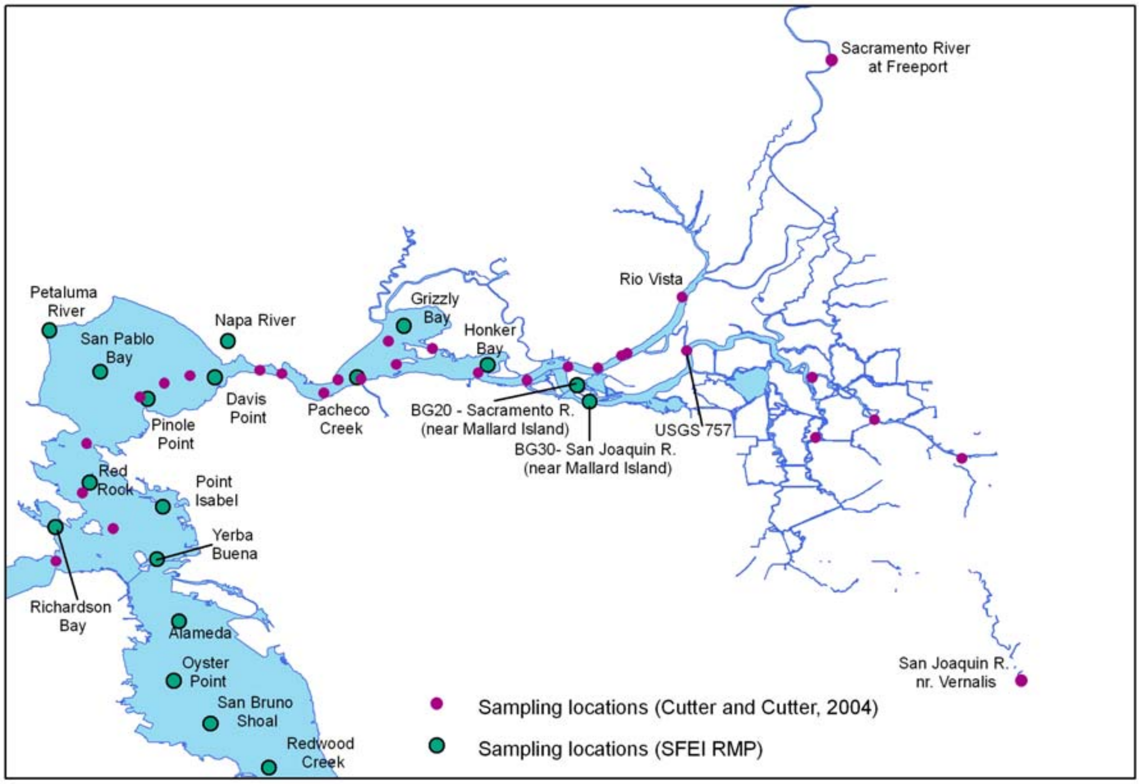


Figure 2-1 Locations of RMP long-term monitoring sites and sampling by Cutter and Cutter (2004) during November 1999.

2.3. WHAT IS THE DISTRIBUTION OF SELENIUM IN THE WATER COLUMN?

Selenium concentrations observed in the North Bay water column are generally low and mostly in the dissolved form. Over the period of 1993-2005, mean dissolved and total selenium concentrations averaged at each station were between 0.12-0.18 µg/L and 0.13-0.24 µg/L in the North Bay (Table 2-2 and Table 2-3). Particulate selenium (calculated as the difference between total and dissolved selenium) accounts for approximately 10% of the total. During the most recent sampling over 1999-2005, i.e., following improved wastewater control in the oil refineries in 1998 (Presser and Luoma, 2006), mean dissolved and total selenium concentrations pooled across all the long-term monitoring sites in North Bay were 0.10 µg/L (0.03-0.24 µg/L, n = 105) and 0.13 µg/L (0.04-0.45 µg/L, n = 100). In comparison, mean dissolved and total selenium concentrations for the period of 1993-1999 at these pooled long-term sites were 0.17 µg/L (range: 0.03-0.44 µg/L, n = 258) and 0.20 µg/L (0.02-0.5 µg/L, n = 230).

Spatially, total selenium concentrations are marginally higher in the mid-estuarine regions of Suisun and San Pablo Bays compared to the freshwater and marine portions (Figure 2-2). Total selenium concentrations in the Central Bay are lower, most likely due to ocean exchange and dilution. A few locations near the confluence of local tributaries (e.g., Petaluma and Napa River) show higher total selenium concentrations relative to the rest of the bay (Figure 2-2). The trends are most apparent when median values are considered.

Table 2-2
Summary of dissolved selenium concentrations in the water column for the period 1993-2005 for the North Bay (data source: RMP).

Site Code	Site Name	Mean (µg/L)	S.D. (µg/L)	Median (µg/L)	Count
BC10	Yerba Buena Island	0.14	0.08	0.11	27
BC20	Horseshoe Bay	0.14	0.10	0.10	23
BC30	Richardson Bay	0.14	0.10	0.13	23
BC41	Point Isabel	0.14	0.09	0.10	24
BC60	Red Rock	0.15	0.10	0.12	20
BD15	Petaluma River	0.18	0.07	0.17	21
BD20	San Pablo Bay	0.15	0.06	0.14	24
BD30	Pinole Point	0.16	0.06	0.15	24
BD40	Davis Point	0.17	0.06	0.16	25
BD50	Napa River	0.16	0.06	0.16	24
BF10	Pacheco Creek	0.17	0.08	0.15	24
BF20	Grizzly Bay	0.14	0.06	0.13	25
BF40	Honker Bay	0.12	0.05	0.11	22
BG20	Sacramento River (near Mallard Island)	0.13	0.09	0.12	29
BG30	San Joaquin River(near Mallard Island)	0.16	0.09	0.14	28

S.D. - Standard deviation

Table 2-3
Summary of total selenium concentrations in the water column for the period of 1993-2005 for the North Bay (data source: RMP).

Site Code	Site Name	Mean (µg/L)	S.D. (µg/L)	Median (µg/L)	Count
BC10	Yerba Buena Island	0.16	0.09	0.12	23
BC20	Horseshoe Bay	0.17	0.12	0.11	19
BC30	Richardson Bay	0.13	0.08	0.11	22
BC41	Point Isabel	0.14	0.07	0.12	20
BC60	Red Rock	0.18	0.08	0.15	16
BD15	Petaluma River	0.24	0.09	0.25	19
BD20	San Pablo Bay	0.18	0.07	0.17	23
BD30	Pinole Point	0.18	0.08	0.17	23
BD40	Davis Point	0.21	0.08	0.18	23
BD50	Napa River	0.20	0.05	0.19	22
BF10	Pacheco Creek	0.19	0.07	0.19	22
BF20	Grizzly Bay	0.17	0.07	0.17	23
BF40	Honker Bay	0.16	0.05	0.15	22
BG20	Sacramento River (near Mallard Island)	0.15	0.08	0.13	27
BG30	San Joaquin River (near Mallard Island)	0.18	0.09	0.16	26

S.D.- Standard deviation

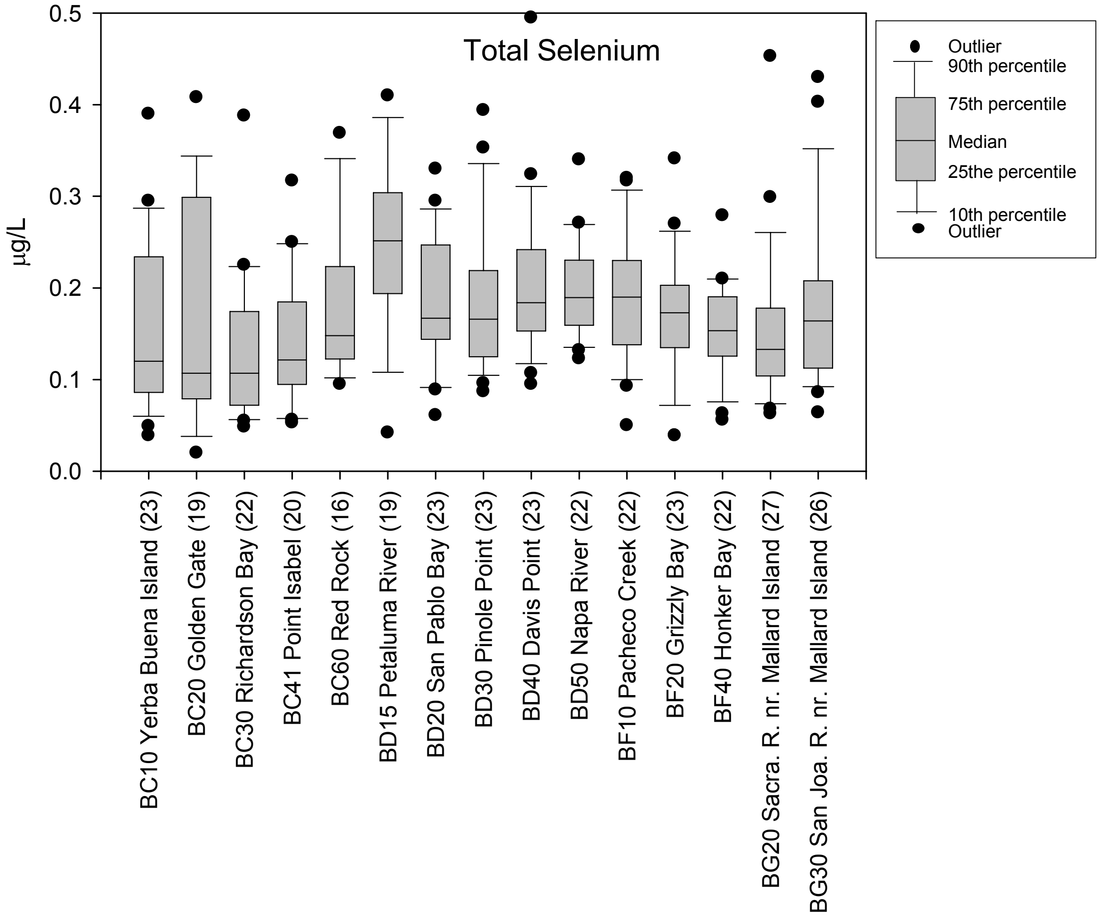


Figure 2-2 Total selenium concentrations at long-term monitoring sites for the period of 1993-2005. Values in parentheses are numbers of samples (data source: RMP).

Data from random sampling during 2002-2005 also indicated relatively low dissolved and total selenium concentrations, below 0.15 µg/L, with a whole North Bay average of 0.12 µg/L. Total selenium concentrations are higher in the upper estuary (Suisun Bay) than the San Pablo and Central Bays.

2.4. WHAT ARE THE LONG TERM TRENDS OF SELENIUM CONCENTRATIONS IN WATER?

Over the long-term, dissolved and total selenium concentrations show large temporal (both inter-annual and seasonal) variations (Figure 2-3 to Figure 2-6). For most stations in the North Bay, a weak negative correlation with time is noted, beginning in 1993. In most instances, the data show a general negative slope with time, and not an abrupt change in 1998 when refinery loads and concentrations were decreased. The temporal patterns in dissolved selenium closely resemble those in the total selenium.

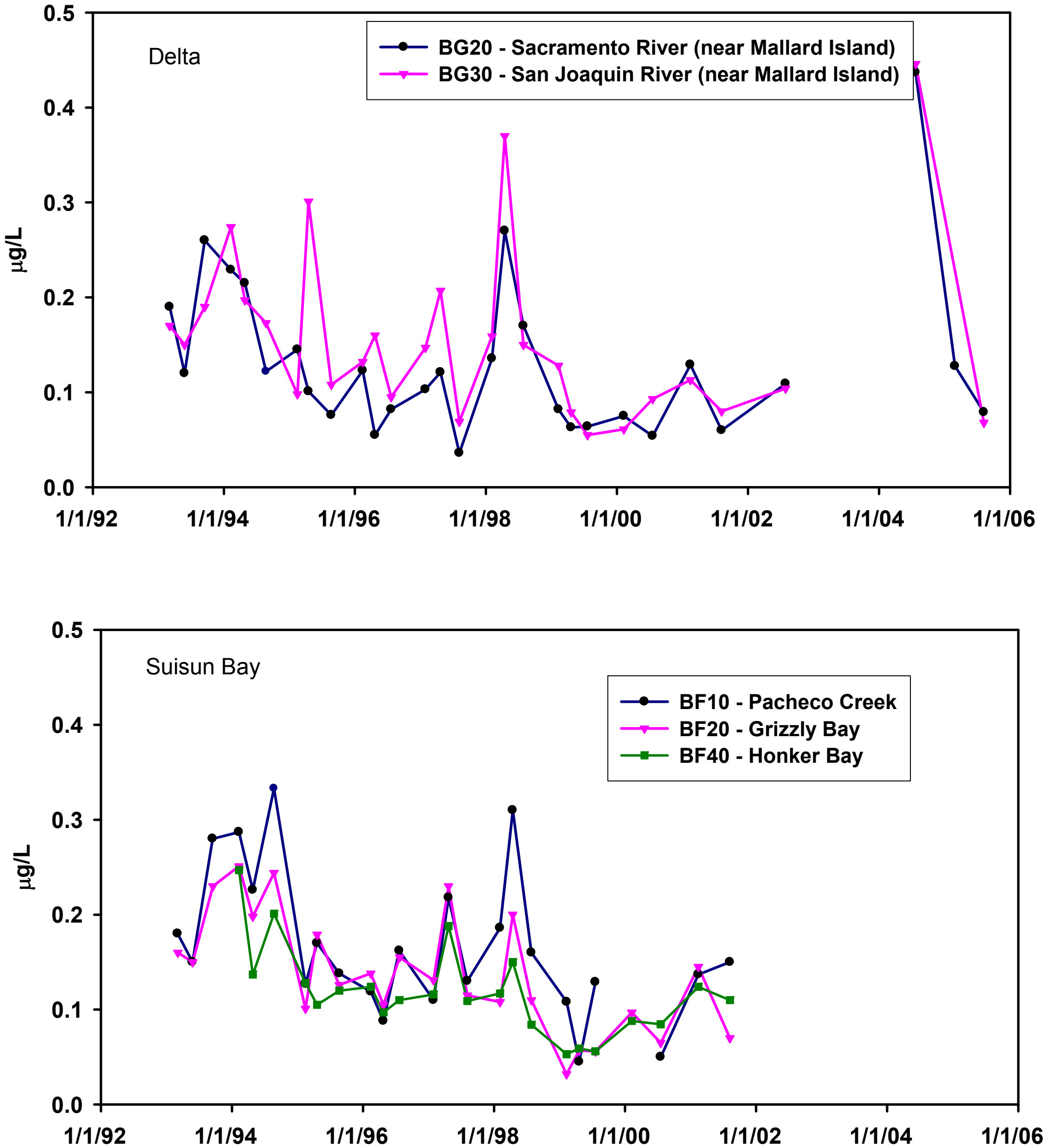
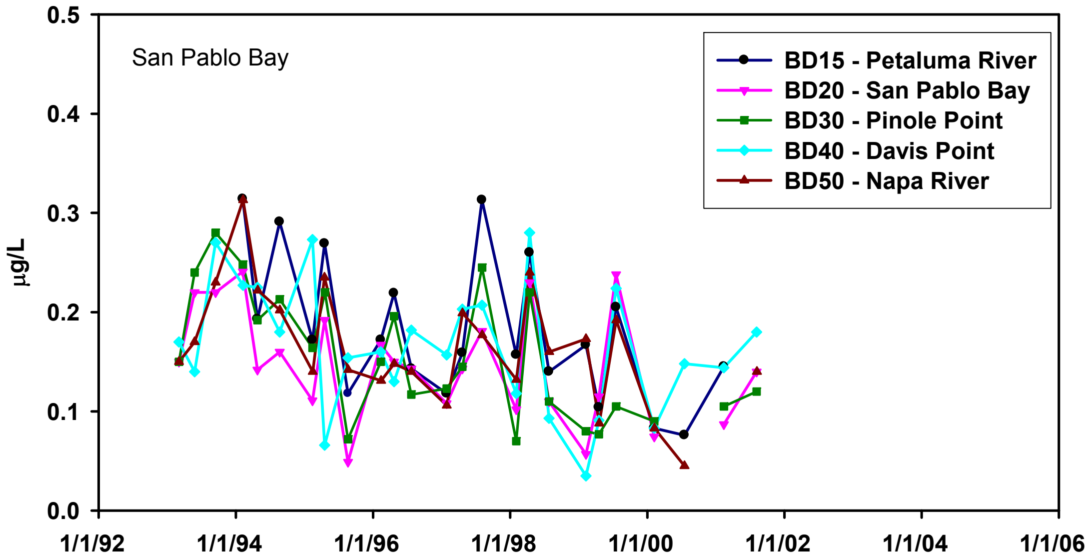


Figure 2-3 **Dissolved selenium concentrations as a function of time in stations near Mallard Island and in Suisun Bay (data source: RMP).**



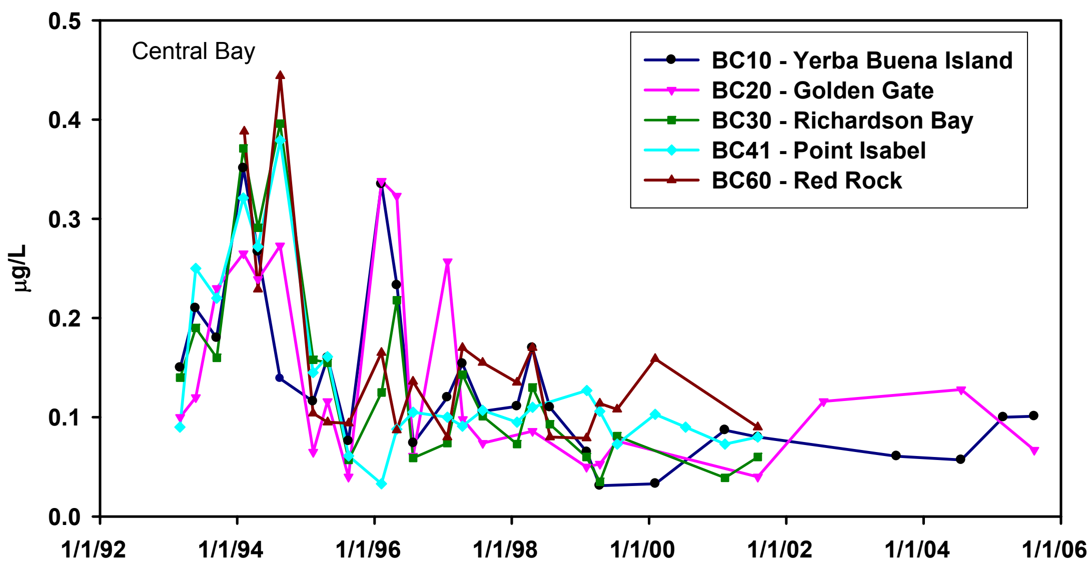


Figure 2-4 Dissolved selenium concentrations as a function of time in the San Pablo and Central Bay (data source: RMP).

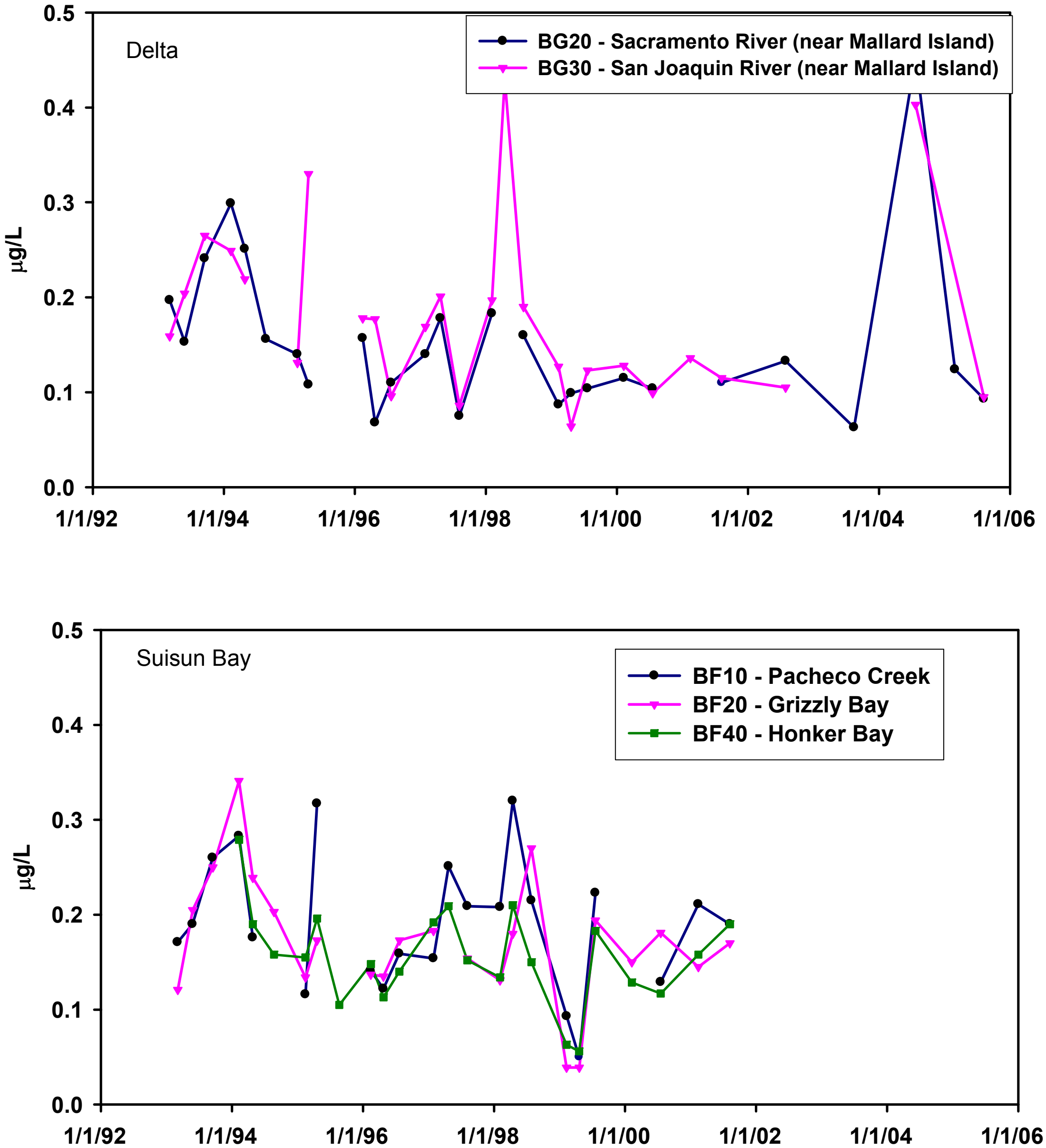
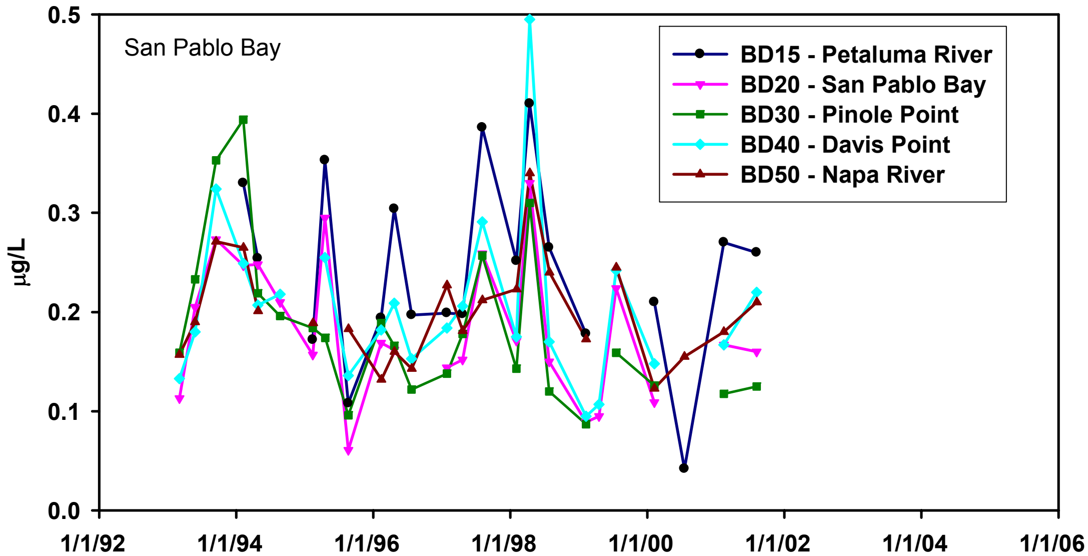


Figure 2-5 Total selenium concentrations as a function of time in stations near Mallard Island and in Suisun Bay (data source: RMP).



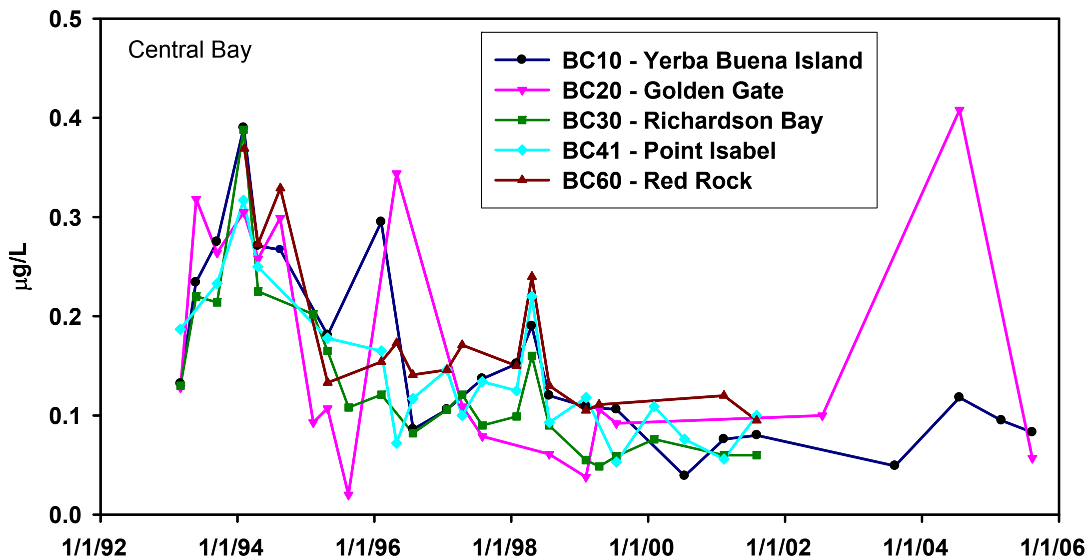


Figure 2-6 Total selenium concentrations as a function of time in the San Pablo and Central Bay (data source: RMP).

2.5. WHAT IS THE RELATIVE MIX OF DISSOLVED AND PARTICULATE SELENIUM IN THE WATER COLUMN?

Pooling all the data from the RMP monitoring indicates a close correlation between dissolved and total selenium (Figure 2-7), with the dissolved fraction representing more than two-thirds of the total selenium.

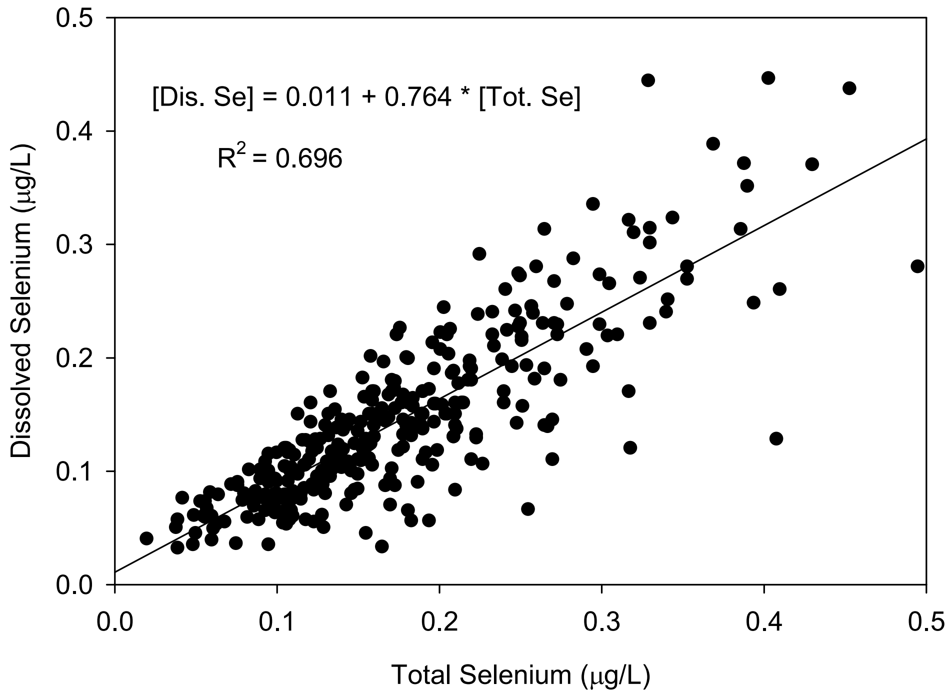


Figure 2-7 Correlation between dissolved and total selenium concentrations for long-term monitoring sites (data source: RMP).

2.6. HOW DOES SELENIUM CORRELATE WITH SALINITY AND FRESHWATER FLOWS?

Freshwater inflows from the Delta and from local tributaries, which are strongly seasonal, influence salinity and selenium concentrations in the bay. Measured dissolved selenium concentrations by RMP long-term monitoring were plotted as a function of salinity for the period before July 1998 and after July 1998, and for low flow and high flow periods (Figure 2-8 and Figure 2-9). The July 1998 cutoff represented periods before and after refinery load reductions. Transect sample data from Cutter and Cutter (2004) were also included for comparison. During low flow periods, dissolved selenium concentrations are low at salinity 0 psu, and increase in the middle of estuary (salinity 5-20 psu), and then decrease again with increase of salinity (> 25 psu). During high flow periods, selenium concentrations were generally higher at low salinity and decreased with increase of salinity or remain relatively constant (e.g. Feb 1999, Feb 2000). The observed patterns in the RMP data set agree well with the patterns observed by Cutter and Cutter (2004). Similar patterns for both low and high flow were observed for sampling dates after July 1998: during low flows, a mid-estuarine peak is more evident while concentrations were relatively constant during high flow (Figure 2-9).

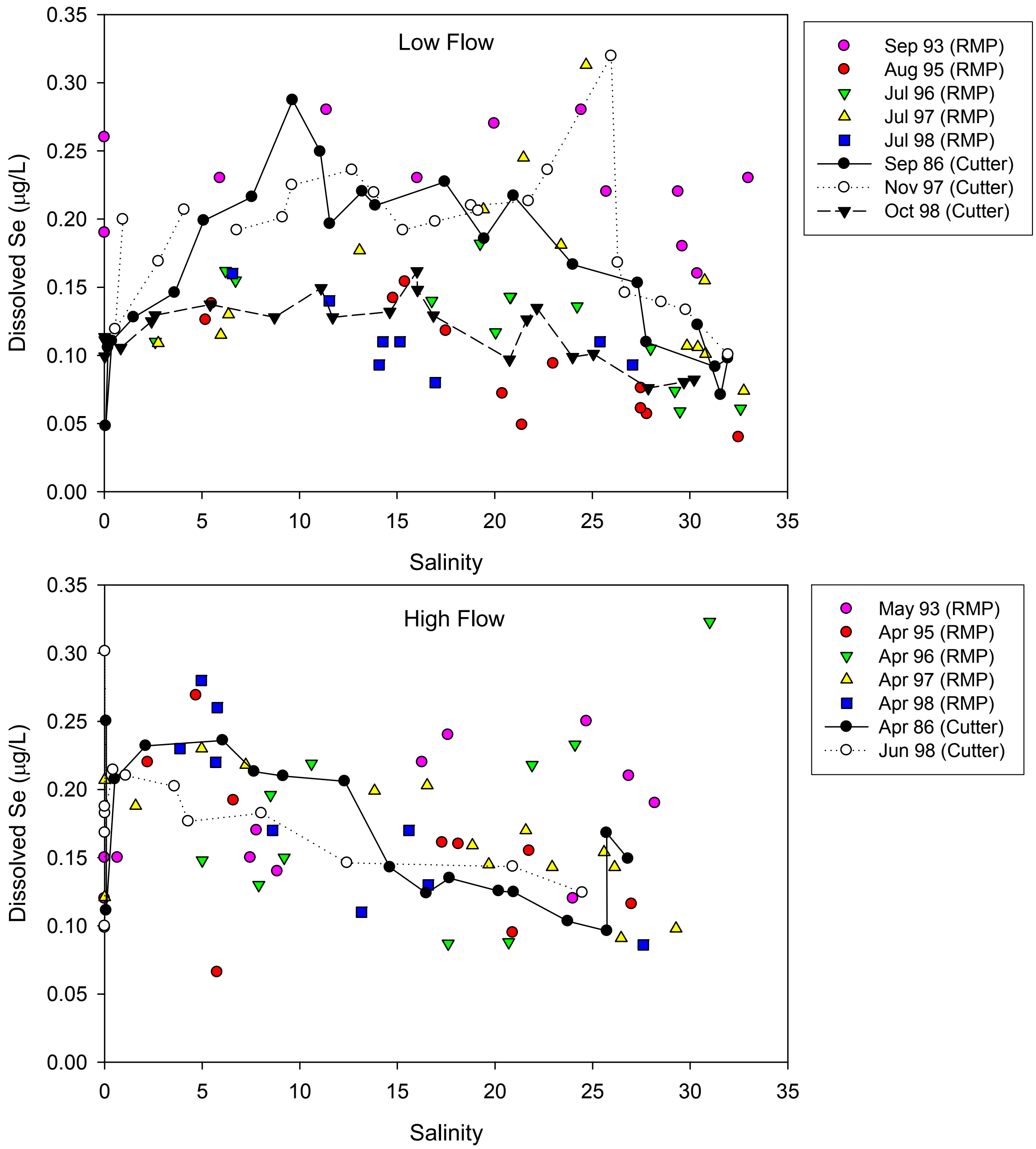


Figure 2-8 Dissolved selenium concentrations along salinity gradient during low and high flow sampling periods by RMP and Cutter and Cutter (2004) before 1999[2].

[2] Low flow and high flow for the RMP data set were defined based on sampling months: July-November (low flow), January-June (high flow). Low flow and high flow definition for the Cutter data set were the classification reported in Doblin et al. (2006): NDOI < 1.5 x 10^{10} l/d (low flow), NDOI > 8.5 x 10^{10} l/d (high flow) with October 1998 defined as low flow for simplification.

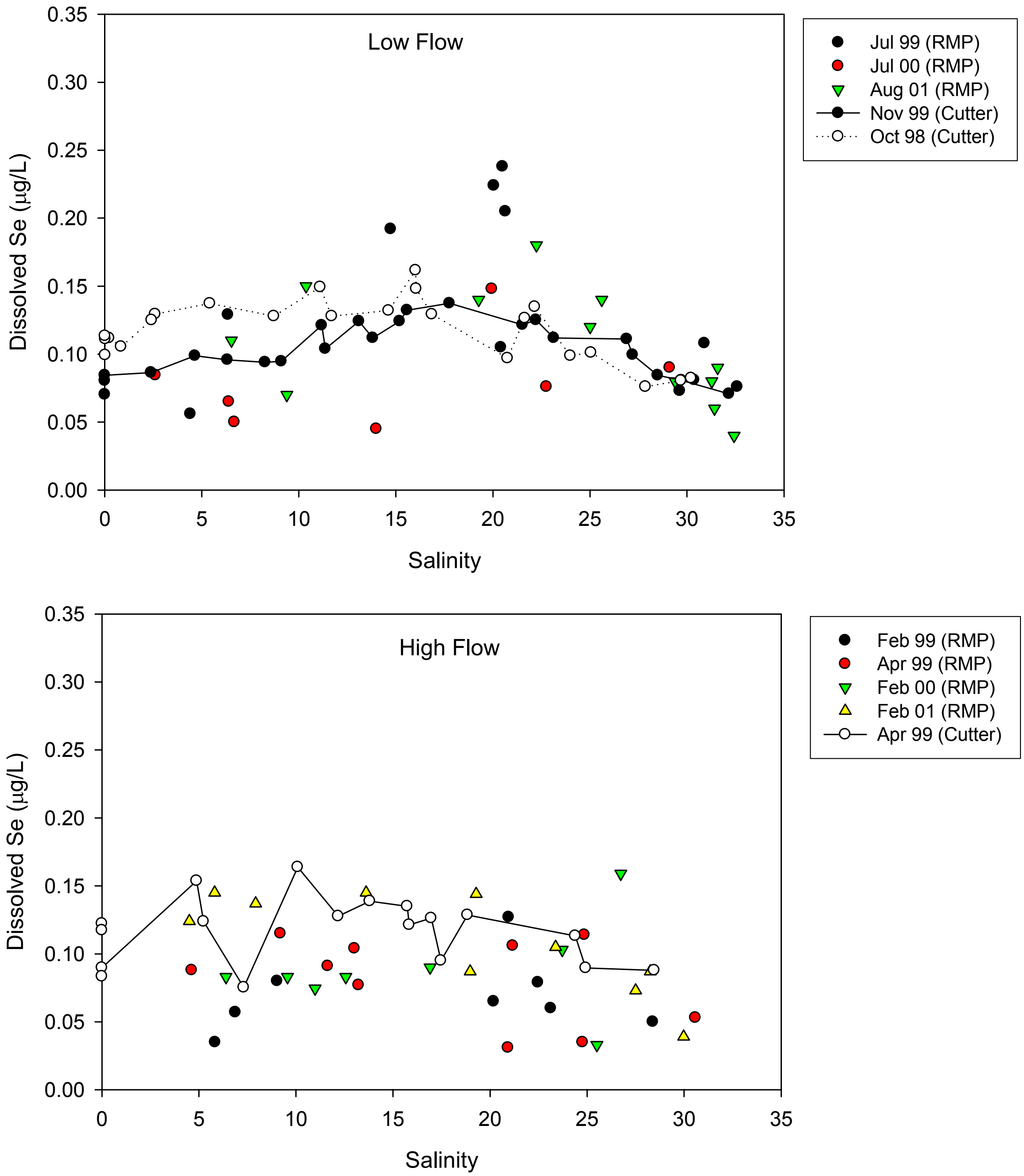


Figure 2-9 **Dissolved selenium concentrations as a function of salinity during low and high flow sampling periods by RMP and Cutter and Cutter (2004) from 1999 onwards.**

Selenium concentrations during the low flow period of a dry year (August 2001) indicated elevated concentrations in the Suisun Bay relative to the head of the estuary (Figure 2-10), suggesting local inputs of selenium. Maximum concentrations were observed in Suisun Bay near the Carquinez Strait. Concentrations in the San Pablo Bay remain relatively high compared to the head of estuary. Concentrations in Central Bay are lower. Salinity showed an increasing pattern from the head of estuary to the Golden Gate: from 0 to 10 psu in Suisun Bay, 25 psu in San Pablo Bay and above 30 psu in Central Bay.

During a wet period of the same year (February 2001), dissolved selenium concentrations were similar among the head of the estuary, Suisun Bay and San Pablo Bay stations (Figure 2-11). Lower concentrations were observed in the Central Bay. As expected, salinity during high flow is lower in Suisun and San Pablo Bay compared to the low flow period of the same year (August 2001).

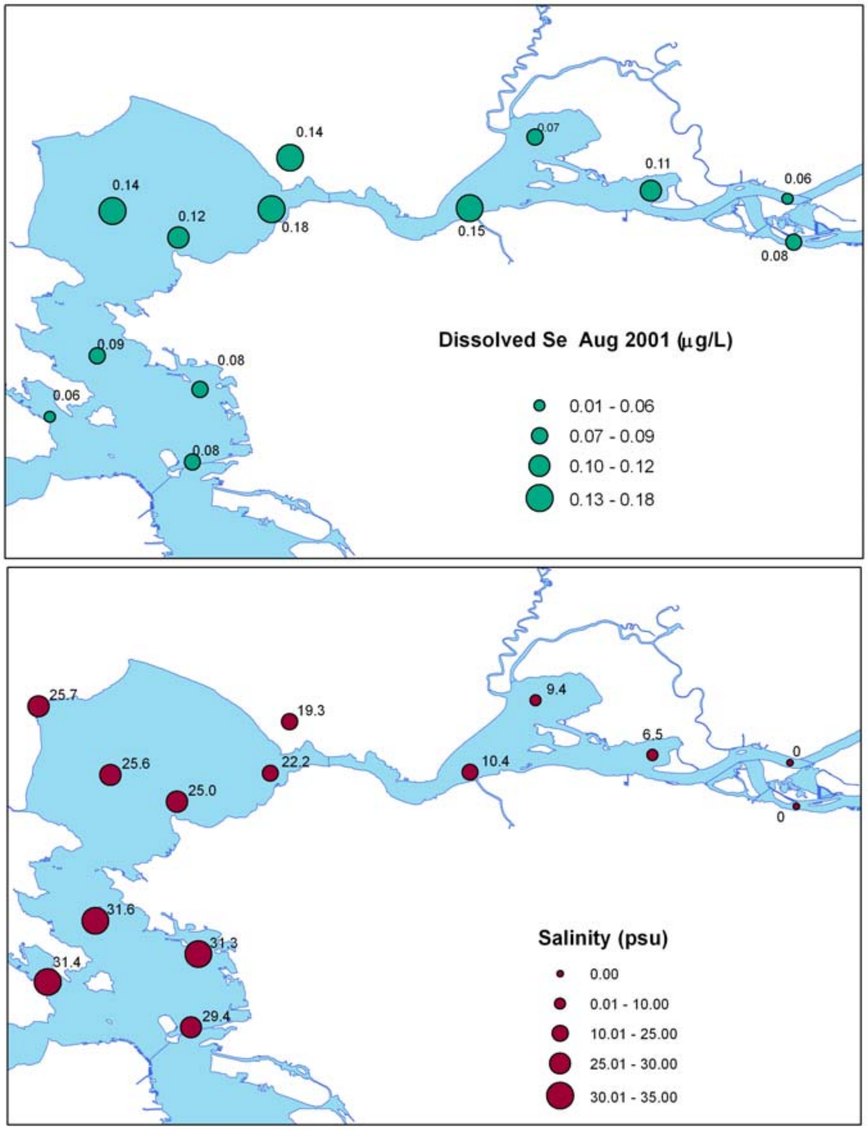


Figure 2-10 Spatial distribution of dissolved selenium and salinity during a sampling event in a dry period of a dry year (August 2001) by the RMP.

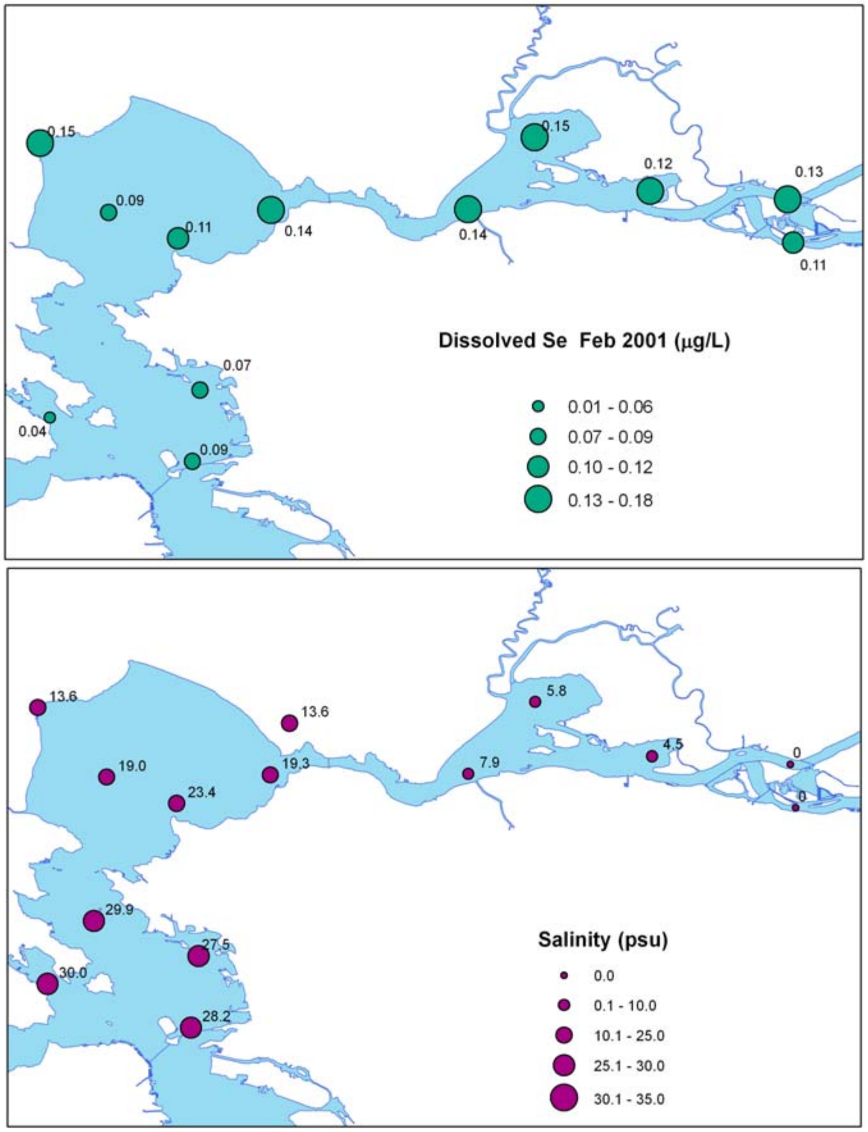


Figure 2-11 Spatial distribution of dissolved selenium and salinity during a sampling event in a wet period (February 2001) by the RMP.

During high flow periods, dissolved selenium concentrations along several salinity transects sampled by Cutter and Cutter (2004) suggested either a dilution pattern by seawater or were relatively constant throughout the bay (Figure 2-12). Dissolved selenium concentrations in April 1986 and June 1998 decreased with increase of salinity with some removal along salinity gradient, possibly due to phytoplankton uptake. Dissolved selenium concentrations were lower in April 1999 compared to April 1986 and June 1998. With the implementation of improved waste water treatment in the refineries in 1998, the most significant change in water column selenium was with respect to selenite (Cutter and Cutter, 2004). For both April 1986 and June 1998, selenite concentrations indicated an increase in the mid-estuary. In contrast, selenite concentrations for April 1999 remained low throughout the Bay (Figure 2-12). Selenate concentrations exhibited more conservative mixing behavior. Selenate concentrations in April 1999 were lower than in April 1986 and June 1998. Organic selenide concentrations showed some variability along the salinity transect although concentrations for the three high flow periods are similar.

Dissolved selenium concentrations during low flow sampling events indicated elevated concentrations in the mid-estuary (salinity 5-25 psu; Figure 2-13). Concentrations for October 1998 and November 1999 are generally lower than September 1986. However, total dissolved selenium concentrations are still slightly elevated in the mid-estuary. The most significant change is the observed decrease in selenite concentrations (Figure 2-13; Cutter and Cutter, 2004). Selenite concentrations for November 1999 are significantly lower than September 1986 and remain relatively constant throughout the Bay. Selenate concentrations were generally similar between the 1986 transect and October 1998 and November 1999 transects. Selenate concentrations show slightly elevated concentrations between salinity 10-20 psu. Organic selenide shows variable concentrations along the salinity transects.

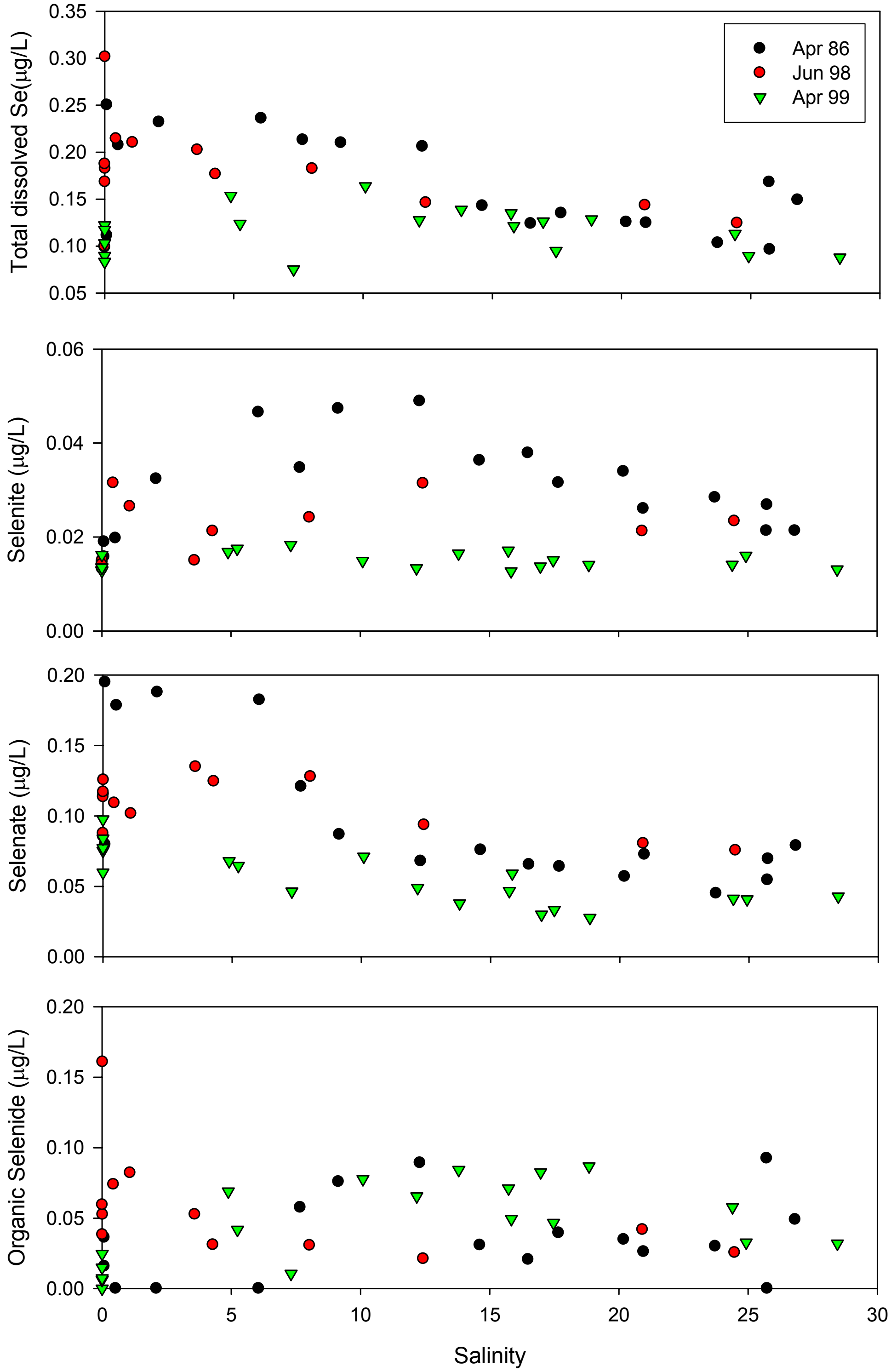


Figure 2-12 Transects of dissolved selenium, selenite, selenate, and organic selenide under high flow sampling periods (April 1986, June 1998, and April 1999; from Cutter and Cutter, 2004).

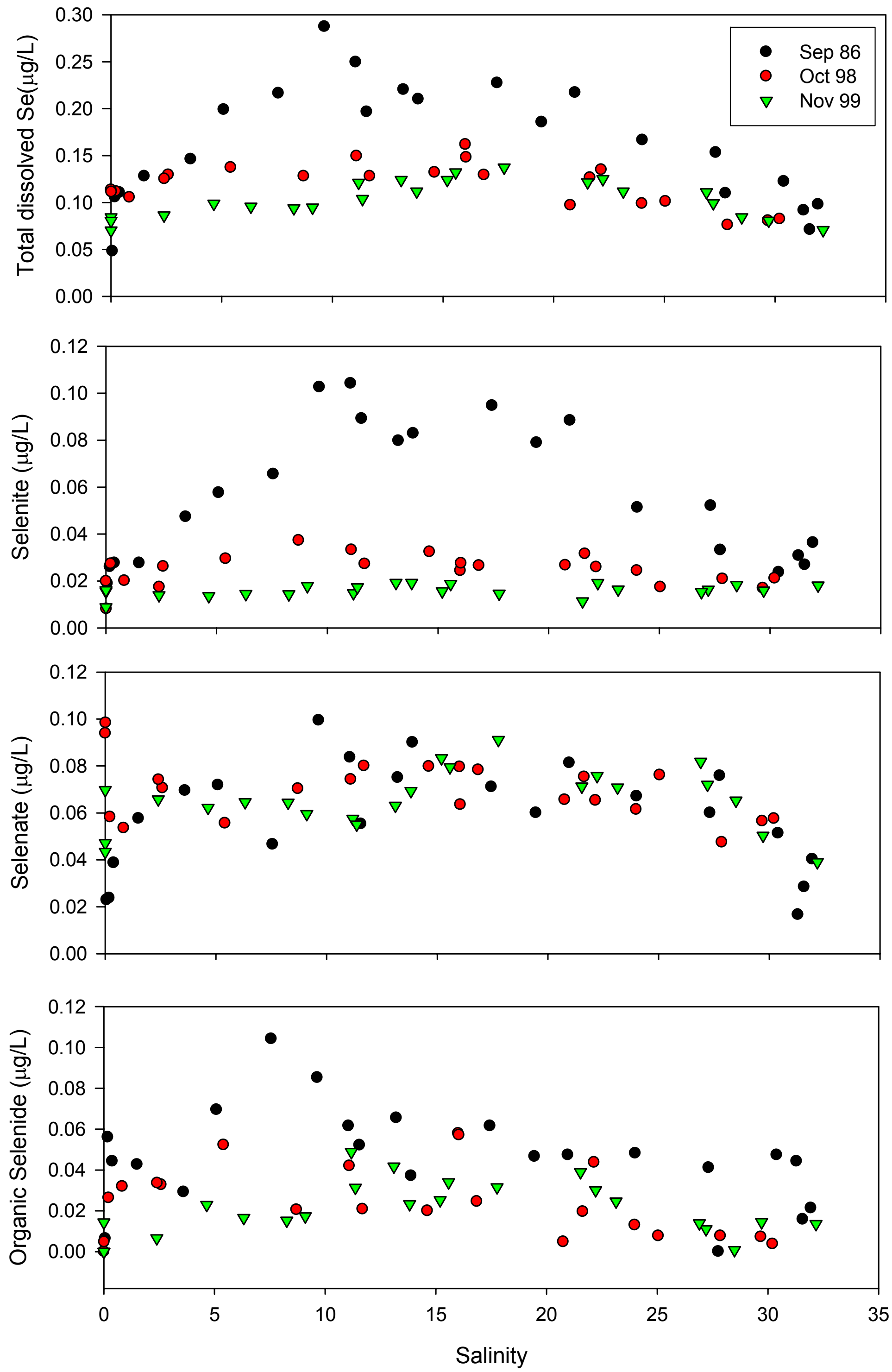


Figure 2-13 Transects of dissolved selenium, selenite, selenate and organic selenide under low flow sampling periods (September 1986, October 1998, and November 1999; from Cutter and Cutter, 2004).

2.7. WHAT WAS THE IMPACT OF REFINERY SELENIUM LOAD REDUCTIONS IN 1998?

Cutter and Cutter (2004) sampled the effluents of five refineries in the North Bay for three time periods during 1999-2000. Average dissolved selenium concentrations in the effluents of the refineries was 16.4 µg/L, a 66% decrease from average concentrations of 45.8 µg/L during 1987-1988 (Cutter and Cutter, 2004). The resulting decreases in selenium concentrations in the bay water are both evident for the low flow and high flow period (Figure 2-14).

Speciation of refinery effluent also changed dramatically after improved wastewater treatment. Average selenite concentrations at the five refineries changed from 28.2 µg/L (4.3 – 59.0 µg/L) from 1987 to 2.3 µg/L (0.3-5.0 µg/L) during the 1999-2000 (Cutter and Cutter, 2004).

Dissolved selenium speciation in the bay water column is dominated by selenate, followed by organic selenide and selenite (Table 2-4). Selenite averages 15% of total dissolved selenium in a low flow sampling event in November 1999, compared with 22% during a high flow sampling event in April 1999. Selenate was 64% and 56% of total dissolved selenium for November 1999 and April 1999, respectively. The changes in wastewater treatment at the refineries resulted in changes in speciation in the bay water column, most noticeably during low flow (Figure 2-15).

Table 2-4
Speciation of dissolved selenium in Bay water (Cutter and Cutter, 2004)

	Selenite		Selenate		Organic selenide		Total dissolved
	µg/L	% of total	µg/L	% of total	µg/L	% of total	µg/L
Apr 99 (high flow)	0.026 ± 0.006	22%	0.067 ± 0.010	56%	0.026 ± 0.017	22%	0.119 ± 0.024
Nov 99 (low flow)	0.016 ± 0.002	15%	0.067 ± 0.012	64%	0.022 ± 0.013	21%	0.105 ± 0.019
Apr 86 (high flow)	0.031 ± 0.010	19%	0.099 ± 0.094	59%	0.035 ± 0.055	21%	0.167 ± 0.062
Nov 86 (low flow)	0.057 ± 0.029	35%	0.058 ± 0.023	36%	0.047 ± 0.024	29%	0.162 ± 0.063

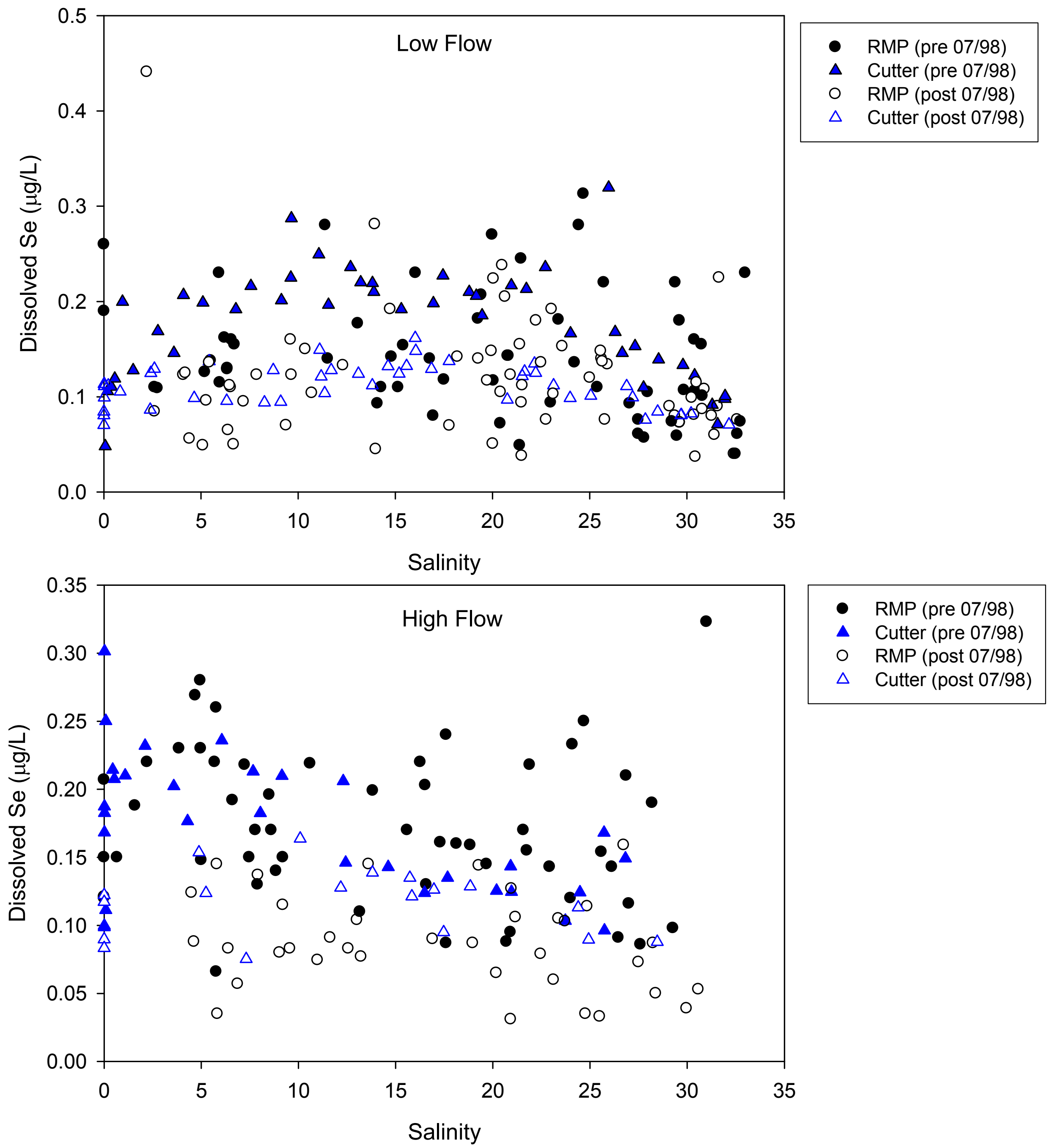


Figure 2-14 Dissolved selenium concentrations under low and high flow before and after July 1998 (data: RMP and Cutter and Cutter, 2004). The July 1998 cutoff date represents samples before and after improved wastewater treatment at the North Bay refineries.

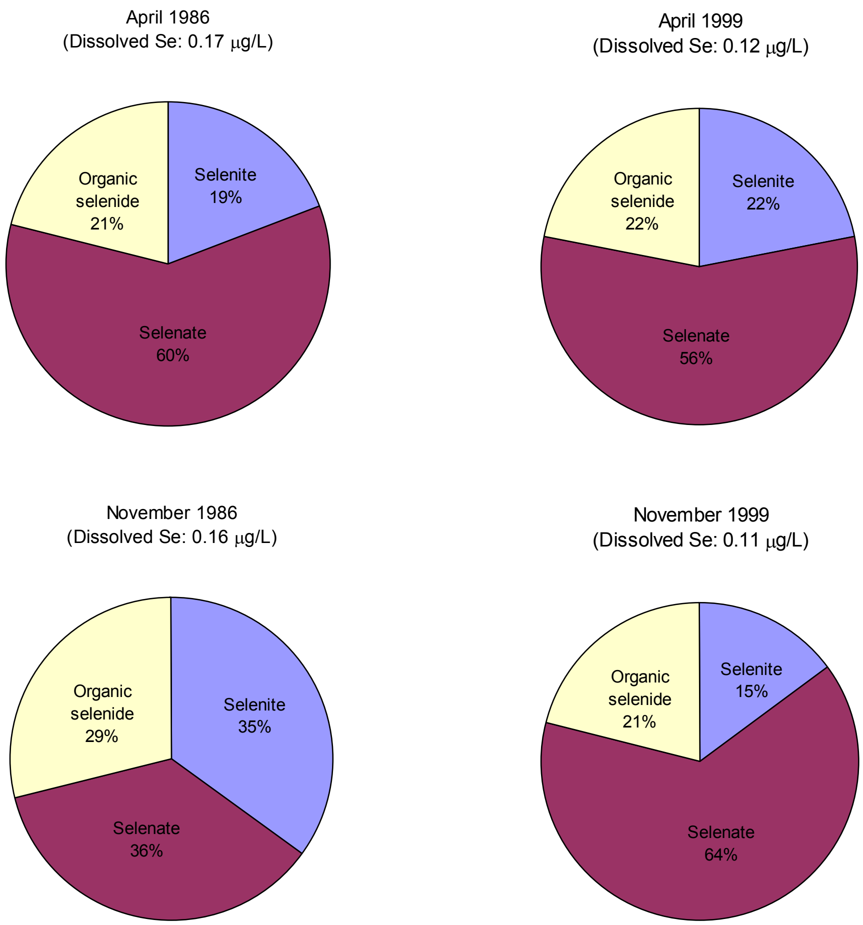


Figure 2-15 Speciation of dissolved selenium in Bay water column during different time periods (Data: Cutter and Cutter, 2004).

2.8. HOW DOES SELENIUM CORRELATE WITH SUSPENDED SEDIMENTS AND CHLOROPHYLL-A?

Doblin et al. (2006) reported the variation of total suspended particulate material (TSM),[3] and selenium on particles in San Francisco Bay. Particulate selenium content, including speciation, was measured directly using material collected on 0.4 µm filters. Particulate selenium was reported as mass of selenium per unit volume of water or as mass of selenium per unit mass of particles. The latter measure normalizes for the effect of changing TSM in water samples at different locations and times.

Particulate selenium concentrations along the salinity gradient generally track the pattern in TSM, and decrease along the salinity gradient during high flow (Figure 2-16). Chlorophyll-a concentrations show some occasional elevated values for the April 1986 transect. Selenium concentrations in particulate material are generally lower during high flow than low flow (Doblin et al., 2006), however, values as high as 1.6 µg/g were measured in the bay.

[3] TSM: total suspended particulate material, was determined by directly filtering 2l of water (out of 5l of sample water collected) through 142mm diameter, 0.4 µm polycarbonate membranes that were pre-weighted. The filters were dried at 40 ºC and weighed for TSM concentration (Doblin et al. 2006).

During low flow, TSM concentrations also decrease slightly with an increase in salinity (Figure 2-17). TSM concentrations show occasional increases in the middle of estuary, possibly due to resuspension. Particulate selenium concentrations track the patterns in TSM (Doblin et al. 2006), most evidently for the September 1986 and November 1999 transects. Selenium concentrations in particulate material exceed values measured during high flow and also show some increase with increase of salinity (up to 2.2 µg/g). For the October 1998 and November 1999 transects, chlorophyll-a concentrations are relatively constant throughout the bay with some increases in the Central Bay.

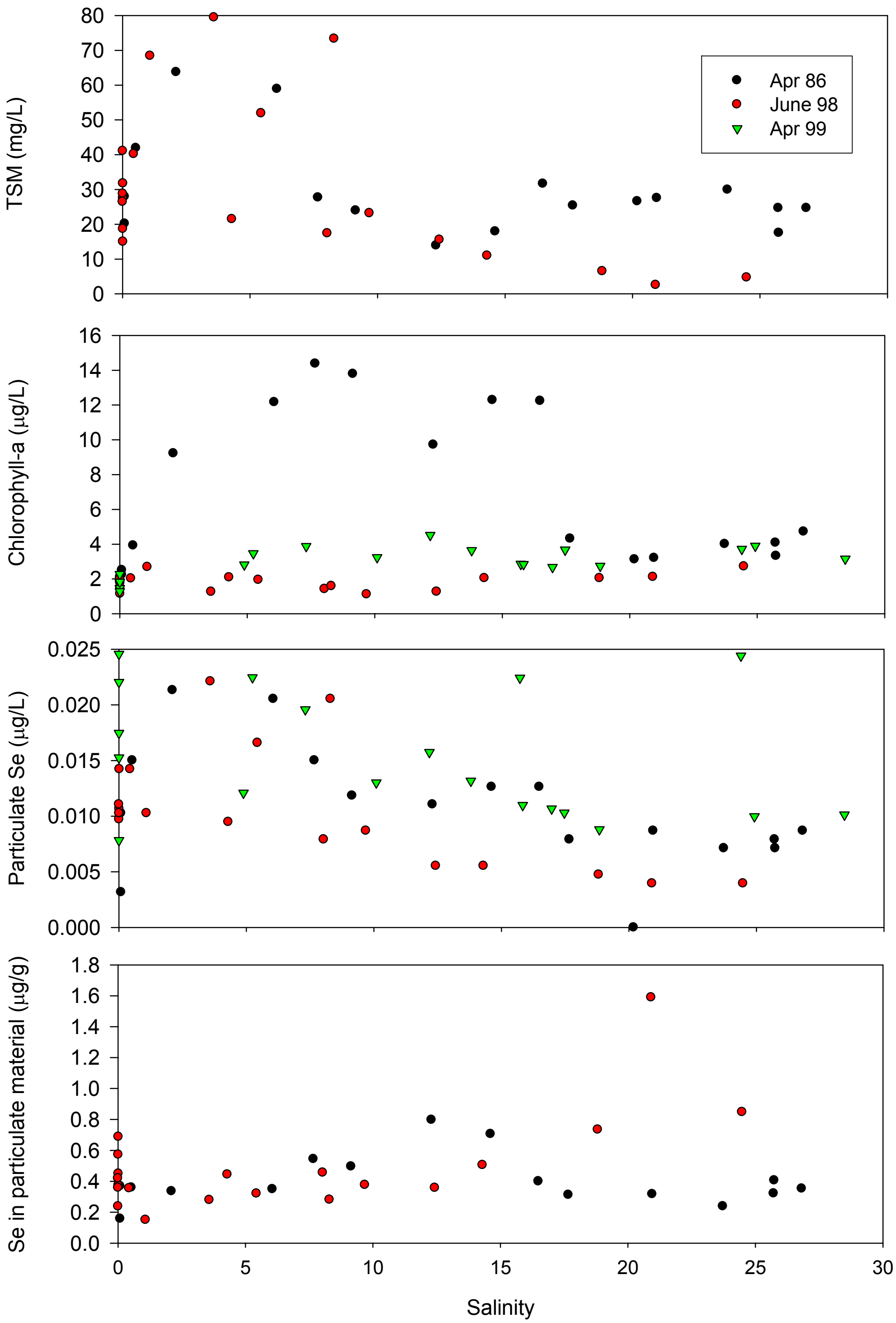


Figure 2-16 **Transects of TSM, chlorophyll-a, particulate selenium and selenium in particulate material under high flow (April 1986, June 1998 and April 1999; Doblin et al. 2006).**

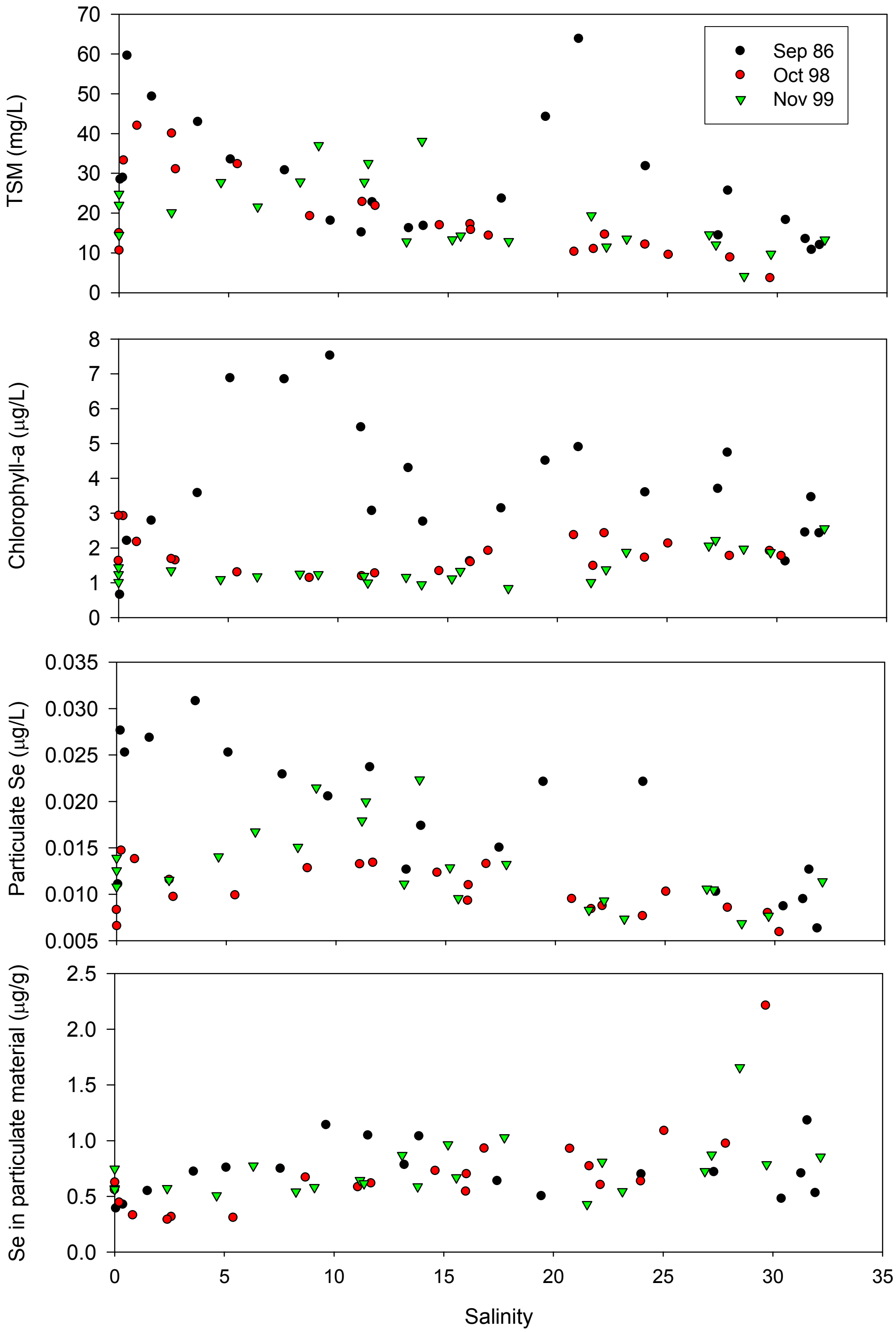


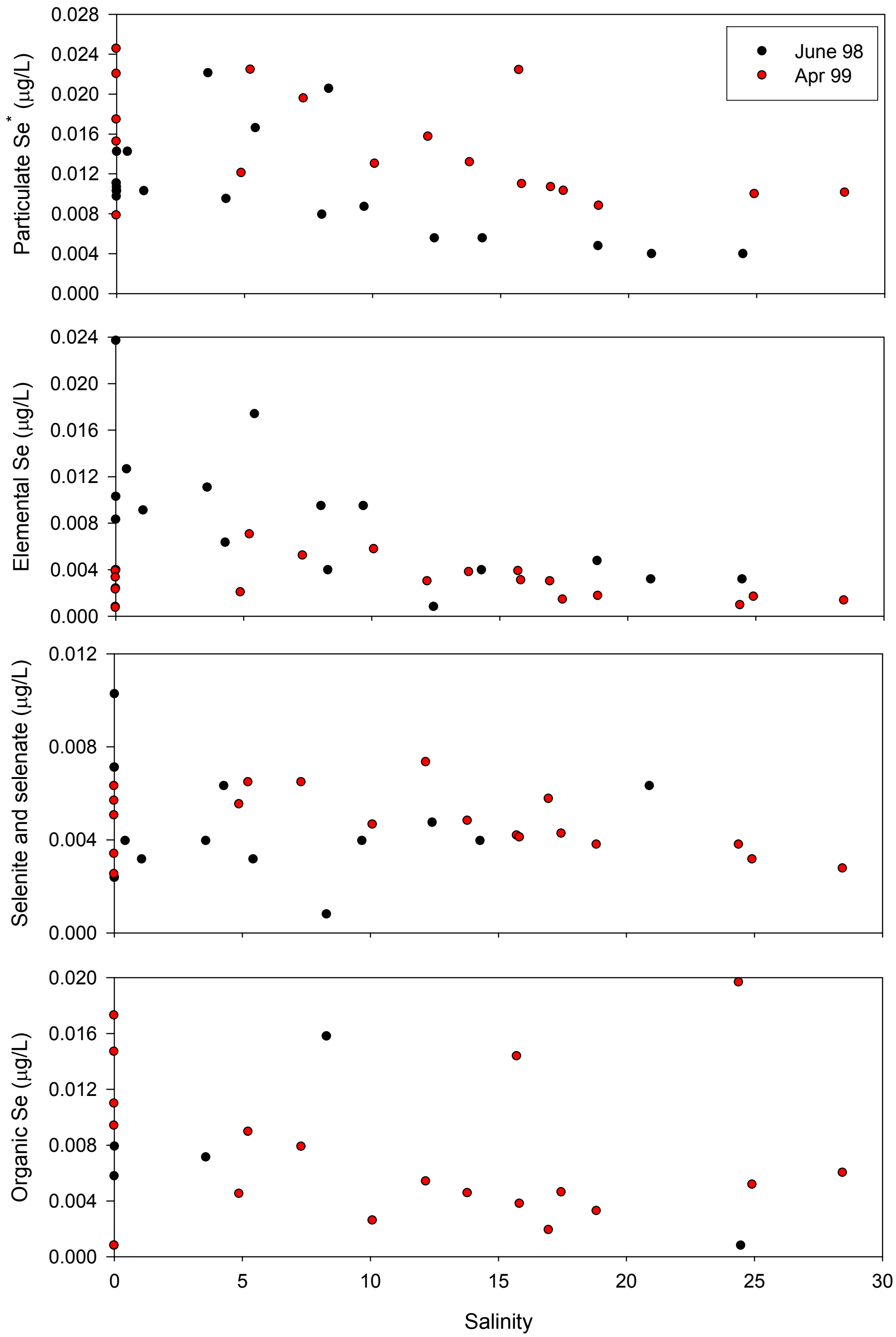
Figure 2-17 Transects of TSM, chlorophyll-a, particulate selenium and selenium in particulate material under low flow (September 1986, October 1998, and November 1999; Doblin et al. 2006).

Particulate selenium concentrations, expressed as µg/l, vary less over time than TSM (Table 2-5), although selenium content in suspended particles differs between low flow and high flow conditions. Low flow periods were found to have higher selenium content in suspended particles, most likely due to longer residence time and accumulation by phytoplankton and bacteria (Doblin et al. 2006). Selenium:Carbon ratios are higher during low flow. Selenium species on particulate material are dominated by organic selenide (45 ± 27%), followed by elemental selenium (35 ± 28%), and adsorbed selenite and selenate (20 ± 10%). The percentage of organic selenide is roughly similar during low and high flow periods. Speciation of particulate selenium along the five sampling transects are shown in Figure 2-18 and Figure 2-19.

Table 2-5
Summary of particulate concentrations during low and high flow periods (Doblin et al. 2006).

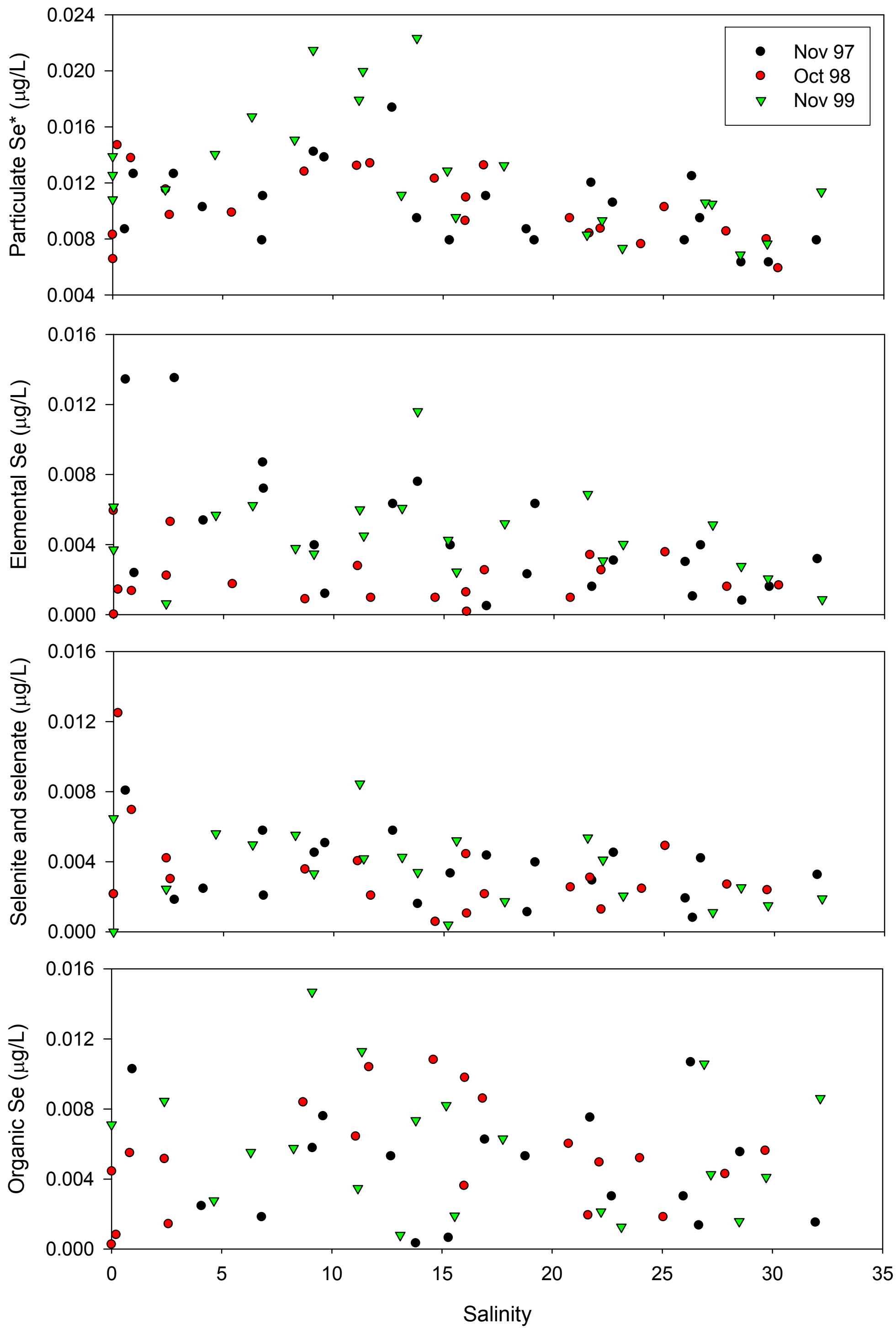
	Low Flow			High flow	
	Oct. 1998	Nov. 1999	Nov. 1997	June 1998	April 1999
TSM (mg/L)	19.1 ± 10.4	19.4 ± 8.8	13.1 ± 5.8	30.2 ± 22.0	31.2 ± 20.0
Particulate Se (µg/L)	0.010 ± 0.002	0.013 ± 0.004	0.010 ± 0.003	0.010 ± 0.005	0.015 ± 0.006
Se content in particulate (µg/g)	0.70 ± 0.41	0.73 ± 0.25	0.87 ± 0.30	0.49 ± 0.31	--
Se: C ratio (X 10^{-6})	4.7 ± 3.1	5.9 ± 2.7	6.5 ± 2.5	4.1 ± 2.0	3.0 ± 1.0

Particulate selenium concentrations are correlated with TSM (Figure 2-20). Particulate concentrations along the salinity gradient follow the pattern of TSM, which exhibit a linear decline along the salinity gradient due to mixing (Figure 2-21).



*include all adsorbed selenite and selenate, elemental and organic selenium

Figure 2-18 **Transects of total particulate selenium, particulate elemental selenium, particulate adsorbed selenite and selenate, and particulate organic selenium during high flow (June 1998 and April 1999; Doblin et al. 2006).**



*include all adsorbed selenite and selenate, elemental and organic selenium

Figure 2-19 **Transects of total particulate selenium, particulate elemental selenium, particulate adsorbed selenite and selenate, and particulate organic selenium during low flow (November 1997, October 1998 and November 1999; Doblin et al. 2006).**

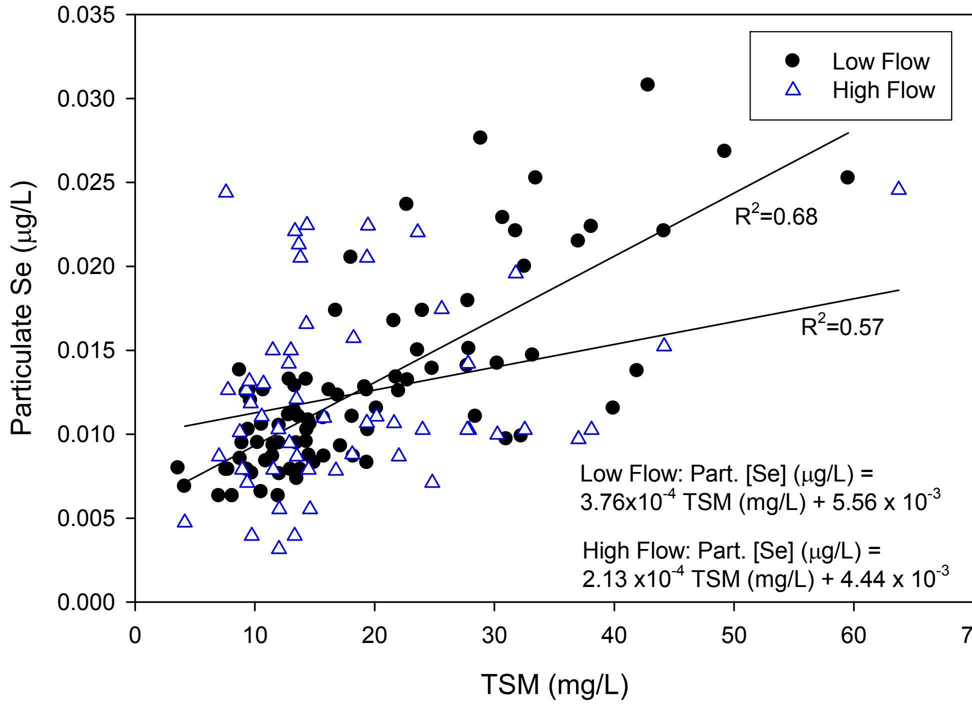


Figure 2-20 Correlation between particulate selenium and TSM under low and high flow (Data Source: G. Cutter, personal communication)

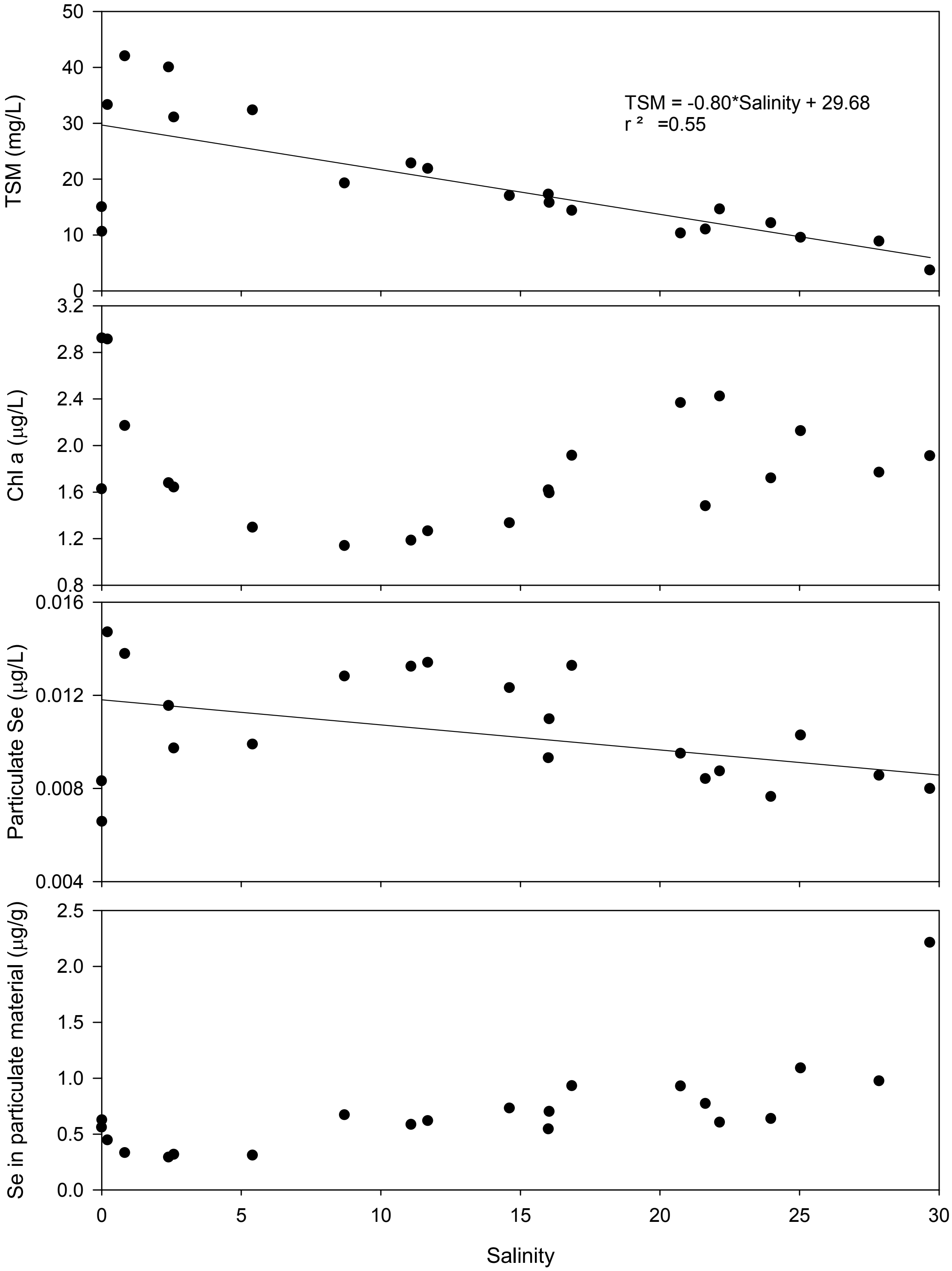


Figure 2-21 **Concentrations of TSM, Chl a, and particulate selenium and selenium content in particulates for a low flow sampling event of Oct. 1998 (Doblin et al. 2006).**

2.9. WHAT IS THE DISTRIBUTION OF SELENIUM IN SEDIMENTS?

Average selenium concentrations in bottom sediments of the North Bay show spatial variations at the RMP long-term monitoring sites although the total range of concentrations is not large (Figure 2-22). Sediment selenium concentrations are somewhat lower for the San Joaquin and Sacramento River stations near Mallard Island and the Central Bay stations (below 0.3 µg/g), whereas bottom sediments at sites in Grizzly Bay, San Pablo Bay and Napa River exhibit slightly elevated selenium concentrations (> 0.4 µg/g).

Sediment concentrations from RMP random sampling indicate somewhat larger spatial variation than the long-term sites because these are single point concentrations and not averages. The majority of the sediment samples have concentrations between 0.2 – 0.3 µg/g, while concentrations as high as 1.7 µg/g were also observed (Figure 2-23). The average for the whole North Bay is 0.25 µg/g. Generally, the sediment selenium concentrations observed are well below the ecological guideline of 1.5 µg/g established by SFBWQCB (1992). Selenium concentrations in seston however can reach 1.5 µg/g occasionally, as observed by Doblin et al. (2006).

Selenium concentrations in the bottom sediments are correlated to sediment grain size and organic carbon content. Sediment selenium concentrations were found to be highly related to percent fines < 0.00625 mm and percent total organic carbon (TOC) (R^2 = 0.78 and R^2 = 0.56; Figure 2-24; pooling all the data from long-term sites). Relationships between sediment selenium and percent fines and TOC are weaker for the random monitoring sites (Figure 2-25), however clear positive relationships are still observed. As illustrated in Figure 2-24, sites with low sediment selenium concentrations correspond to low percent fines in the sediments and vice versa. Meseck (2002) observed a similar strong relationship between sediment selenium and organic carbon concentrations (R^2 = 0.85).

Average selenium concentrations for sediment cores, 5-15 cm deep, collected by G. Cutter's research group range between 0.22-0.41 µg/g in the North Bay. Selenium in sediment cores is found to be dominated by elemental selenium (Meseck, 2002). Elemental selenium accounts for a median of 45% of the total selenium in the sediments across the sites, with selenite and selenate accounting for a median of 17%. The difference between total, elemental and selenite and selenate is the organic selenium. Selenium concentrations are generally uniform in the sediment cores, although some variations along the depth were observed (Cutter, unpublished data).

Long term data from the RMP indicated that despite sediment selenium concentrations showing inter-annual or seasonal variations, concentrations are generally stable at the monitoring sites except in early 1990s (Figure 2-26 and Figure 2-27).

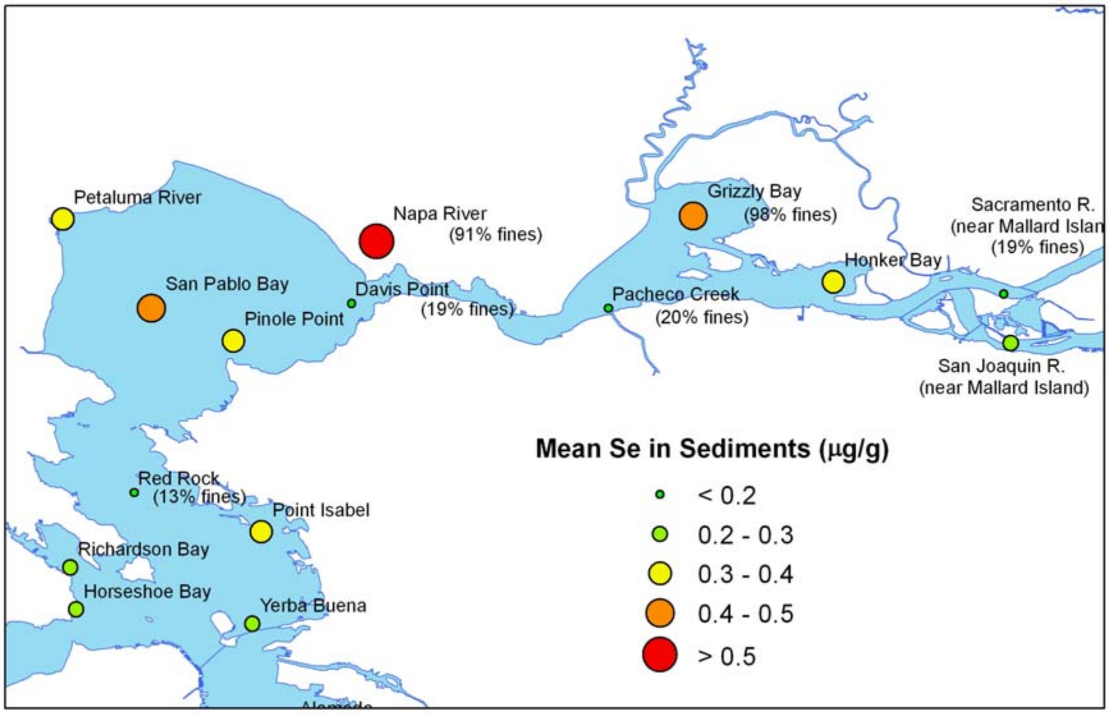


Figure 2-22 **Mean selenium concentrations in sediments for the period of 1993-2005 (data source: RMP).**

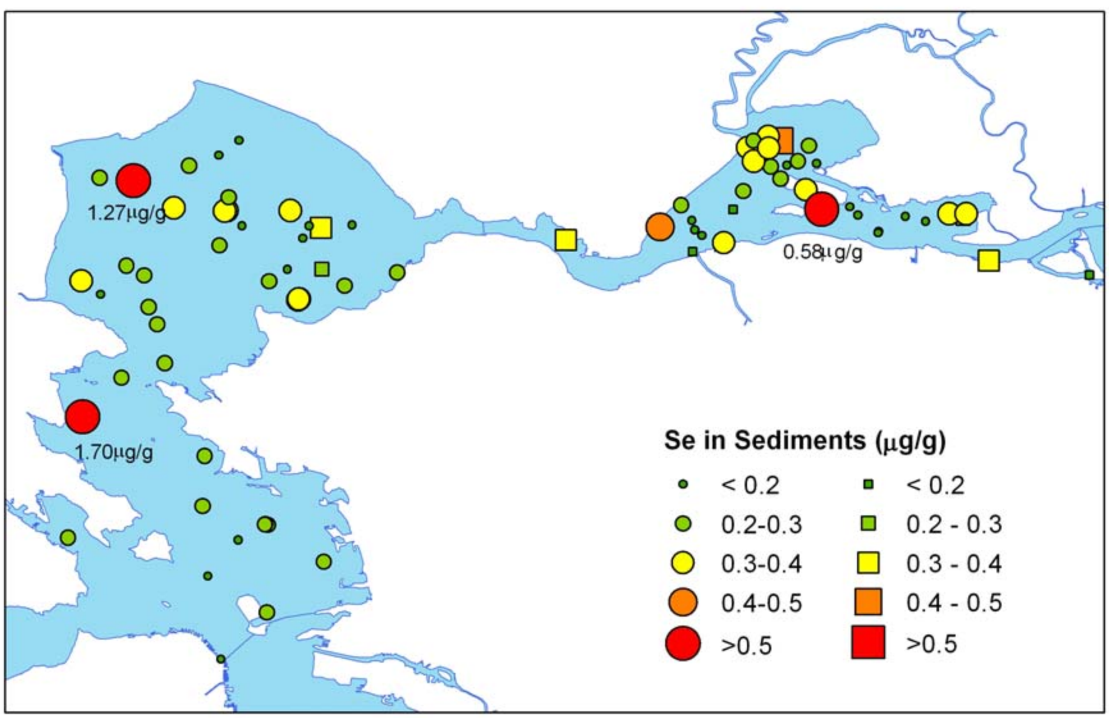


Figure 2-23 **Selenium concentrations in sediments with data from RMP random sampling sites (circles) and data collected by G. Cutter's research group (squares). Numbers shown are individual values from the sampling.**

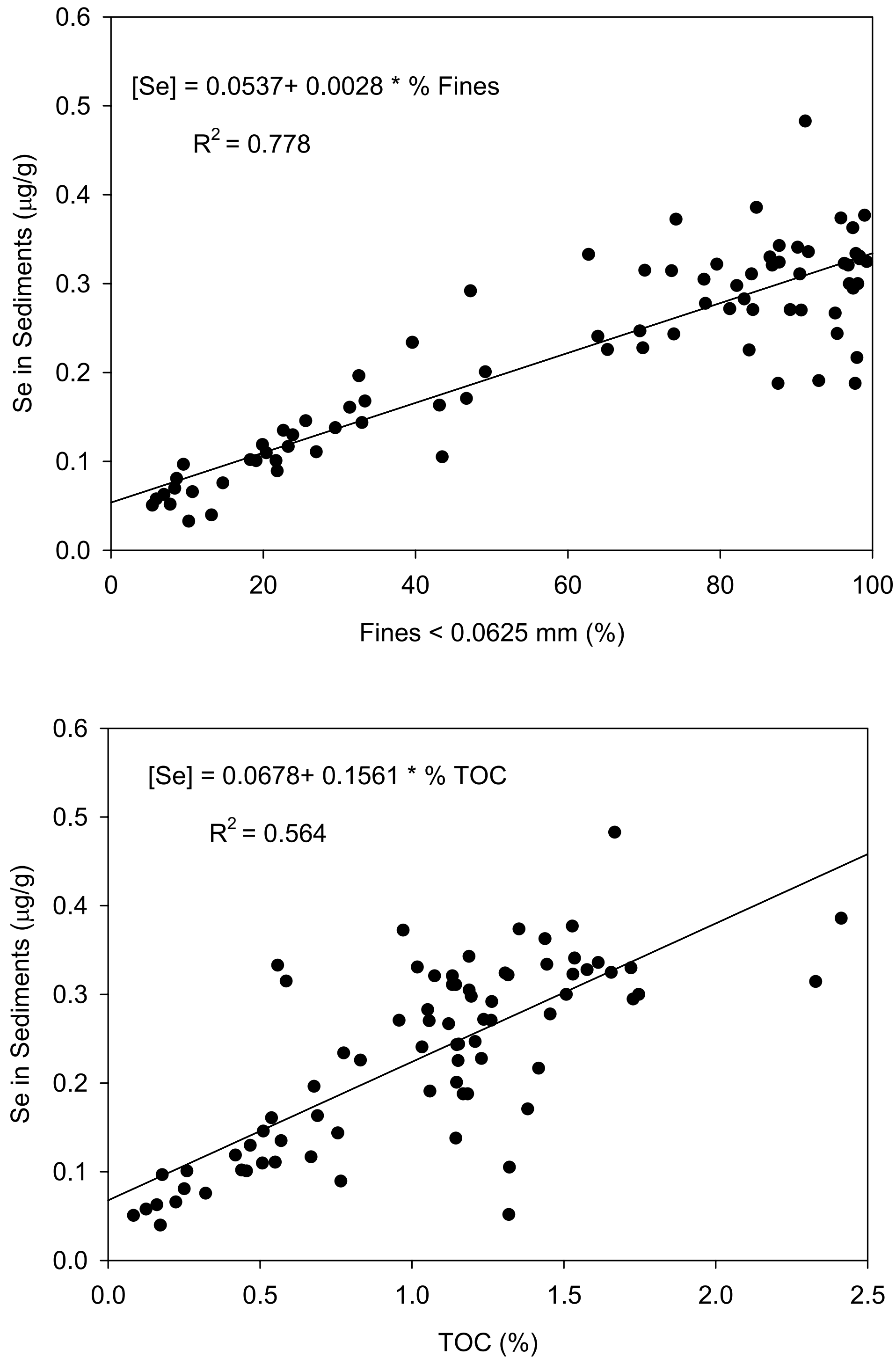


Figure 2-24 **Relationship between selenium concentrations in sediments and sediment characteristics at long-term sites (data source: RMP).**

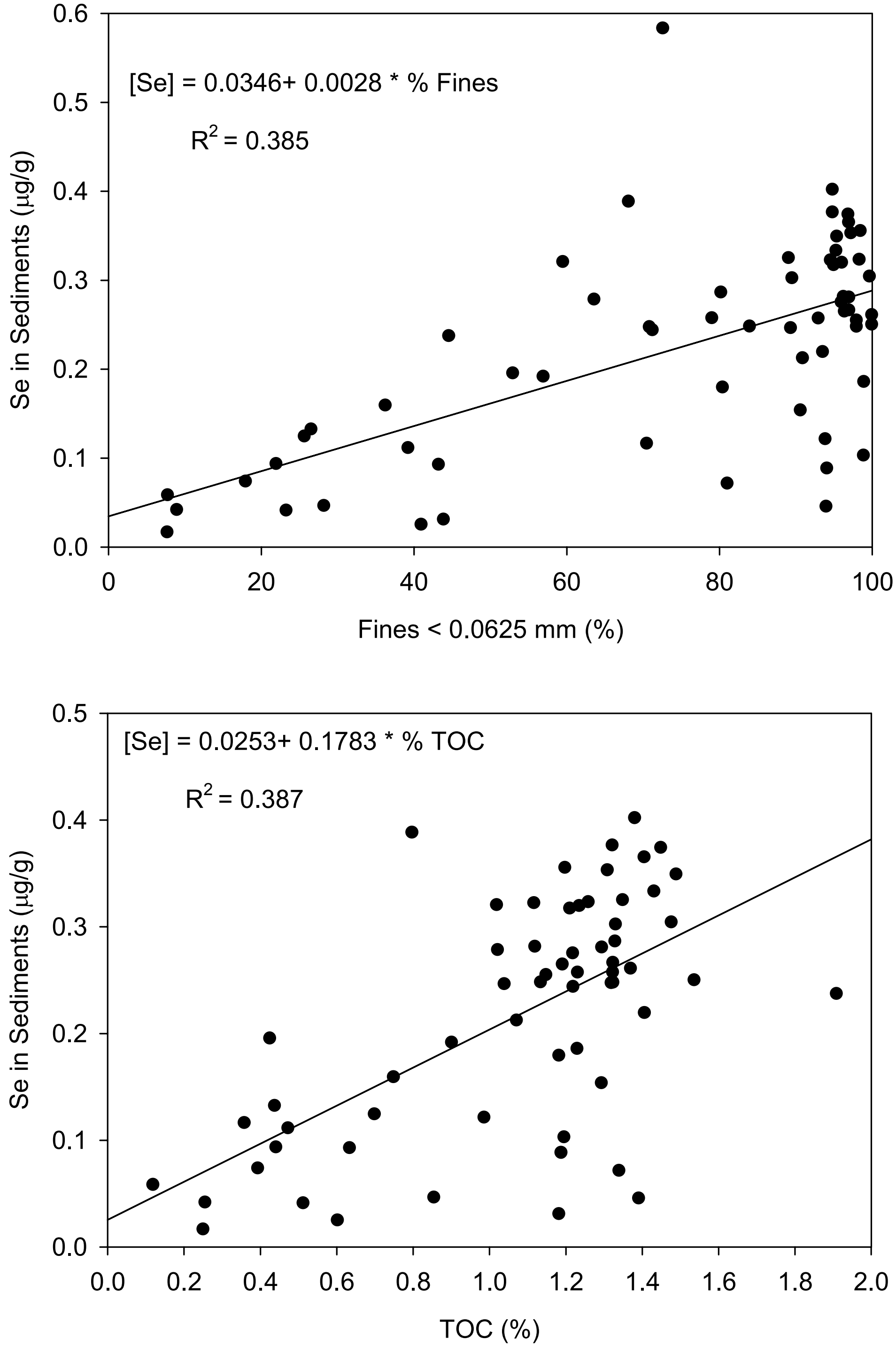


Figure 2-25 Relationship between selenium concentrations in sediments and sediment characteristics at random sampling sites (data source: RMP).

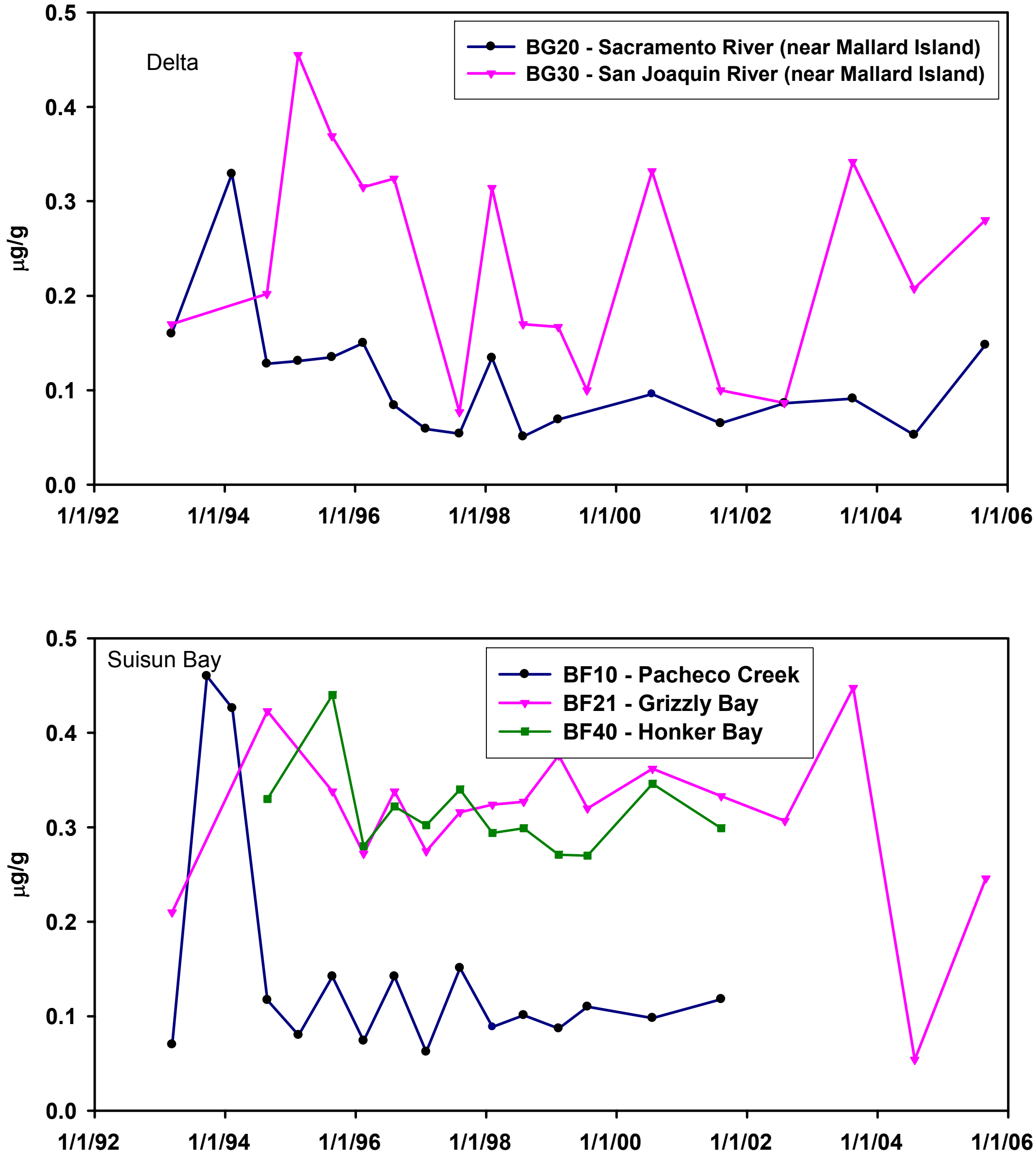


Figure 2-26 Selenium concentrations in sediments as a function of time in stations near Mallard Island and in Suisun Bay (data source: RMP).

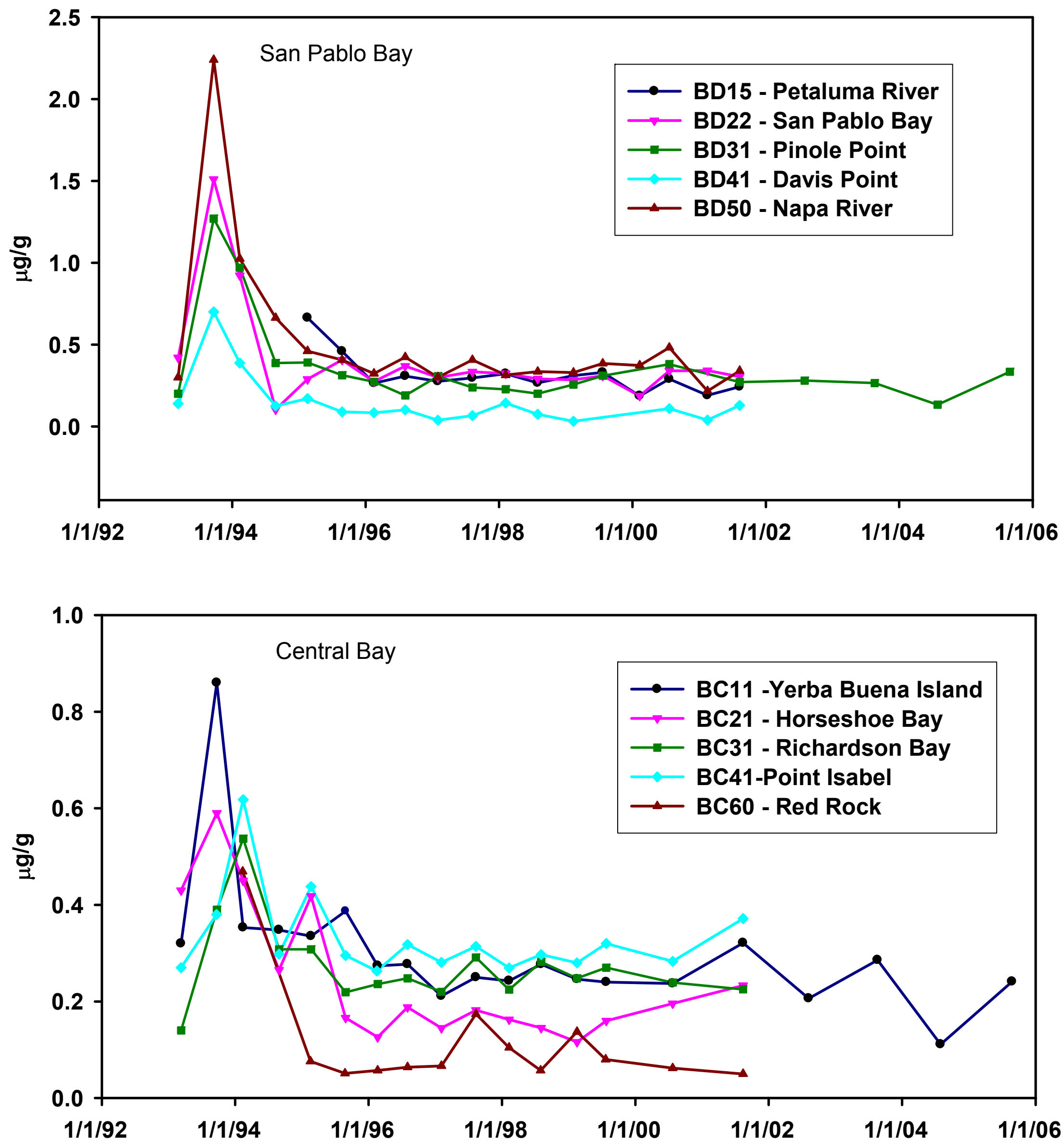


Figure 2-27 Selenium concentrations in sediments as a function of time in San Pablo and Central Bay (data source: RMP).

3. SOURCE CHARACTERIZATION

The goal of the source characterization is to quantify the various point and non-point sources that contribute selenium to North San Francisco Bay. The sources evaluated and their key features are listed below.

- Atmospheric deposition – includes both dry and wet deposition to the bay water surface, and is usually considered as a small selenium source
- Urban and non-urban runoff from local tributaries – includes both agricultural and urban stormwater runoff, and may be a significant source of selenium during the wet season
- Delta inflow – which consists of flow from both the San Joaquin and Sacramento Rivers, is the major source of selenium to the bay
- Municipal wastewater effluents – which generally have low concentrations of selenium
- Petroleum refineries – which were the major sources of selenium (in the form of selenite) in the 1980's and have decreased dramatically since 1999 because of improved wastewater treatment
- Input from bay sediment – net sediment erosion, resuspension, diffusion, and dredging activities can be potential internal sources of selenium to the bay water column

The magnitudes of the selenium loads associated with these sources are discussed in the subsequent sections. The dry season is a critical period for selenium bioaccumulation due to longer residence time, while wet season has larger flow volumes and can potentially contribute larger loads of selenium to the Bay. Therefore, for source categories with available flow information, both dry and wet season loads were calculated and compared. The relative contribution of loads may vary significantly between the dry and wet seasons.

3.1. OVERVIEW OF PREVIOUS SOURCE ESTIMATES

Presser and Luoma (2006) estimated annual selenium loads from San Joaquin River at Vernalis to be 1,614 – 7,819 kg/yr with an average of 4,440 kg/yr for the years of 1986-1998. Selenium loads from five agricultural sub-areas of western San Joaquin Valley were also estimated under different discharging scenarios by Presser and Luoma (2006).

Of special relevance to any long-term evaluation of selenium trends in NSFB is the reduction of loads from refineries that occurred because of major improvements in wastewater treatment in the late 1990s. Selenium loadings from oil refineries ranged between 928-2,116 kg/yr during 1987 and 1988 (Cutter and San Diego-McGlone, 1990) and 1,415-3,400 kg/yr during 1986-1992 (SFBRWQCB, 1993). Refinery discharge declined after July 1998 and selenium loads from five refineries were estimated to be 506 kg/yr in 1999 (Presser and Luoma, 2006).

Loads from the Sacramento River were calculated using an average concentration of 0.04 μg/L as a conservative estimate and were estimated to be 247 kg/yr during a critically dry year, 494 kg/yr for dry to critically dry year, 839 kg/yr for a median year and 1579 for a wet year (Presser and Luoma, 2006).

Abu-Saba and Ogle (2005) developed a conceptual model for selenium in the bay and estimated various sources including:

- Riverine fluxes via the Delta
- North Bay refinery effluent discharges
- Municipal wastewater, local tributaries, and urban runoff

Loading rates from the Delta were estimated by multiplying net freshwater discharge from the Delta and a "river end member concentration" estimated by flow weighting concentrations at the Sacramento and San Joaquin Rivers, measured by Cutter and Cutter (2004). Estimated loading rates from the Delta by Abu-Saba and Ogle (2005) for the period of November 1997-November 1999 were 282-9,570 kg/yr for dissolved selenium, and 47-686 kg/yr for particulate selenium. Oil refinery effluent discharge loading was calculated from effluent flow rates and selenium concentrations reported by Cutter and Cutter (2004) and ranged between 204-552 kg/yr. Urban and non-urban runoff and municipal wastewater loadings were estimated by some simple calculations (Abu-Saba and Ogle, 2005). Average annual runoff volume (both urban and non-urban) for the Bay Area is about 900 Mm^3 (McKee et al., 2002) and annual discharge volume from wastewater is at a similar volume of 866 Mm^3 (Grovhoug et al., 2004). Selenium concentration in local runoff and municipal wastewater effluents were thought to range from 0.1-1 µg/L, therefore Abu-Saba and Ogle (2005) estimated loadings from each of these sources to range between 90-900 kg/yr with uncertainty.

Cutter and Cutter (2004), based on data for five sampling events in 1997, 1998, and 1999, estimated riverine inputs from the Delta into the bay and inputs from refineries to the bay. Riverine inputs of dissolved selenium ranged between 773–26,195 g/day, with selenite inputs ranging between 110-2,446 g/day, selenate ranging between 497 – 17,121 g/day, and organic selenide ranging between 55 – 6,486 g/day. Refinery loadings were estimated to range between 1,515-6,328 g/day with selenite ranging between 379-2,414 g/day, selenate between 970-2,107 g/day and organic selenide ranging between 174-1,854 g/day. These data are described in daily load terms, as in the original work; the analysis below uses this information to compute annual loads. Because of the variability in daily flows and loads, the daily loads cannot be converted to annual loads simply by multiplying by 365. The computation needs assumptions or data on daily flows, as described for the loads calculations performed in the current study.

Subsequent sections present load estimates for all significant non-point and point-sources. These analyses build on previous work and include consideration of the most recent data, especially for point sources, tributaries, and the Delta.

3.2. DIRECT ATMOSPHERIC DEPOSITION

Atmospheric deposition of selenium occurs both as dry and wet forms. Selenium is emitted to the atmosphere naturally as volatile dimethyl selenide, or as selenium dioxide and elemental selenium from fossil fuel combustion (Cutter and Church, 1986). Deposition of selenium is part of a global cycle as gaseous selenium bound to particulate materials can be transported over long distances (EPA, 2002). Selenium in wet deposition consists of selenate, selenite, and elemental selenium. Rainwater samples from coastal California indicated that selenite is the major species in wet deposition for the region (Cutter, 1978). Dry deposition of selenium is mainly associated with fine particles (< 1 μm; Duce et al. 1976; Sweet et al. 1998) and gaseous forms.

Dry and wet deposition of selenium has not been measured in the San Francisco Bay and estimates were made using data from other studies. Atmospheric deposition of selenium is believed to represent only a small input to the water surface and the watershed in other studies (EPA, 2002). Reported concentrations of selenium in precipitation are 0.1 - 0.4 μg/L in urban areas (Mosher and Duce, 1989). Concentrations in precipitation measured in the Chesapeake Bay atmospheric deposition study are in the range of 0.07- 0.17 μg/L (EPA, 1996). To estimate the significance of wet deposition, a simple calculation was done by extrapolating concentrations in the literature to the North Bay. Given an approximate annual rainfall of 450 mm/yr (McKee et al. 2003) and a water surface of 434 km^2 in the North Bay, direct wet deposition of selenium is in the range of 13.7 – 78.1 kg/yr (assuming selenium concentrations of 0.07-0.4 μg/L). Wet deposition of selenium is relatively bioavailable as selenite is the major species.

Dry deposition was calculated from air-phase concentrations of selenium. Reported concentrations in the air exhibit a large variation from 0.3 to 2.4 ng/m^3. Concentrations measured in the Chesapeake Bay range from 1.4 – 1.8 ng/m^3 (EPA, 1996). Different deposition velocity values have been used to estimate dry deposition fluxes for the Great Lakes (0.1 cm/s, Sweet et al. 1998) and the Chesapeake Bay (0.26 cm/s low, 0.72 cm/s high, EPA, 1996). Selenium in the air is mostly associated with fine particles; therefore a lower deposition velocity is expected. Based on a concentration range of 0.3 – 2.4 ng/m^3 and deposition velocities of 0.1 cm/s and 0.26 cm/s, estimated dry deposition is in the range of 4.1 – 85.4 kg/yr.

Due to the lack of site-specific measurements of selenium deposition in the bay, the simple extrapolations from other sites are associated with large uncertainties. Nonetheless, these estimates provide a reference for comparison with other sources discussed below.

3.3. Urban and Non-urban Stormwater Runoff from Local Tributaries

Local tributaries, that is, streams that discharge directly into the North Bay and not into the Delta and/or the Sacramento and San Joaquin Rivers, can contribute elevated pollutant loadings due to the presence of urban and agricultural lands in their watersheds. Although local tributaries are only responsible for about 4% of the runoff to the bay, they were found to have a much higher sediment export rate than the Central Valley (~100 t/km^2 vs. ~14 t/km^2; McKee et al. 2003). With respect to selenium, relatively high selenium concentrations have been measured in tributaries around the Bay area, both in the wet and dry seasons. Total recoverable selenium concentrations observed in several watersheds in the South Bay during 2005-2006 ranged between 0.22–1.7 μg/L (median 0.38 μg/L) for the dry season and 0.56-9 μg/L (median 3.6 μg/L) for the wet season (EOA, 2006). Selenium concentrations observed in five tributaries of the North Bay in the Surface Water Ambient Monitoring

Program (SWAMP) study in 2001-2002 suggested high concentrations of 0.18-3.39 μg/L (median 0.94 μg/L) during the dry season and 0.39- 3.14 μg/L (median 0.90 μg/L) during the wet season (SFBRWQCB, 2007a). Total selenium concentrations as high as 1.7 μg/L and 4 μg/L during wet and dry seasons of 2003-2004 were observed in the Petaluma River (SFBRWQCB, 2007b). Selenium observed in the tributaries is mostly in the dissolved form. Little information is available on the speciation or bioavailability of selenium from local tributaries.

3.3.1 Review of Selenium Concentration Data in Tributaries

Selenium concentrations in local tributaries monitored for the SWAMP[4] study by the San Francisco Bay Regional Water Quality Control Board during 2001-2004 are listed in Table 3-1. SWAMP monitoring programs targeted both clean and polluted areas of the watershed. Therefore, many sampling sites are located in urban or agricultural areas. For each watershed, a number of stations along the tributaries were monitored with 2-4 stations measured for selenium. Among the watersheds monitored, Wildcat Creek/San Pablo Creek and Suisun Creek were sampled during 2001-2002. Kirker Creek, Mt. Diablo Creek and Petaluma River were sampled during 2003-2004. Three sampling events based on hydrological conditions were targeted for each monitoring year including wet (January to March), spring (April to May) and dry (June to October). Samples were analyzed for both total and dissolved selenium with a minimum detection limit (MDL) of 0.1 μg/L (SFBRWQCB, 2007b).

Relatively high total selenium concentrations were found for all seasons (Figure 3-1). The highest total selenium concentration was observed at an urban influenced site during the dry season (8.1 μg/L at KIR115-Kirker Creek Apartments). Average total selenium concentrations for the most downstream sites of all the North Bay watersheds are 1.57 μg/L for wet season, 1.03 μg/L for spring season and 1.95 μg/L for dry season (Table 3-1). The downstream sites were considered to be more representative of the watershed condition by integrating all the land uses and therefore only downstream sites were used in the calculations of loads to the bay. Note that the 8.1 μg/L value did not factor in the average because it was not the most downstream value on Kirker Creek. Due to the limited number of samples, for some sampling events, higher dissolved than total selenium concentrations were reported. For the purpose of the load calculations, estimates were made using total selenium concentrations.

The Bay Area Stormwater Management Agencies Association (BASMAA) has also sampled selenium concentrations from some local tributaries around the North Bay during 1988-1995 (BASMAA, 1996). The sampling sites for the North Bay are mostly located in the Alameda County with two sites located in the Contra Costa County. Selenium concentrations reported by BASMAA are lower than values reported in subsequent SWAMP studies (Figure 3-2). Variable detection limits are noted for the BASMAA dataset, with higher detection limit (at 0.2 μg/L) and higher percentage of non-detects in early period of the study (1988-1992). Lower detection limits (generally below 0.05 μg/L) were used for latter period of the study and most of the samples were above detection limits. Measured concentrations seem to vary

[4] Surface Water Ambient Monitoring Program, a statewide program to assess water quality conditions in surface water bodies.

with detection limits. Land uses for watersheds surrounding the sampling locations include open forests, industrial, residential and commercial. Median concentrations are 0.40 µg/L during dry weather (n = 7) and 0.33 µg/L for storm event sampling (n = 28). By land use, median concentrations are 0.29 µg/L, 0.35 µg/L and 0.30 µg/L for residential, open and industrial sites. For some of the BASMAA sampling sties, monitoring was continued for multiple years.

Table 3-1
Total and dissolved selenium concentrations observed at the SWAMP sites during wet, spring and dry seasons. Data for the most downstream location on each stream are shown. Data are individual values.

Creek	Site	Season	Year	Total µg/L	Dissolved µg/L
Kirker Creek	KIR020	Wet	2003-2004	1.26	1.21
		Spring	2003-2004	1.30	1.00
		Dry	2003-2004	2.50	2.00
Mt. Diablo Creek	MTD010	Wet	2003-2004	2.00	2.00
		Spring	2003-2004	0.40	0.30
Petaluma River	PET010	Wet	2003-2004	1.30	1.40
		Spring	2003-2004	0.20	0.50
	PET310	Wet	2003-2004	1.70	1.80
		Spring	2003-2004	1.30	1.50
		Dry	2003-2004	4.00	3.90
San Pablo Creek	206SPA020	Spring	2001-2002	2.74	2.57
		Dry	2001-2002	1.60	1.53
Suisun Creek	207SUI010	Spring	2001-2002	0.90	1.04
		Dry	2001-2002	0.32	0.17
Wildcat Creek	206WIL020	Spring	2001-2002	0.39	1.41
		Dry	2001-2002	1.33	1.11
	Average	Wet		1.57	1.60
		Spring		1.03	1.19
		Dry		1.95	1.74

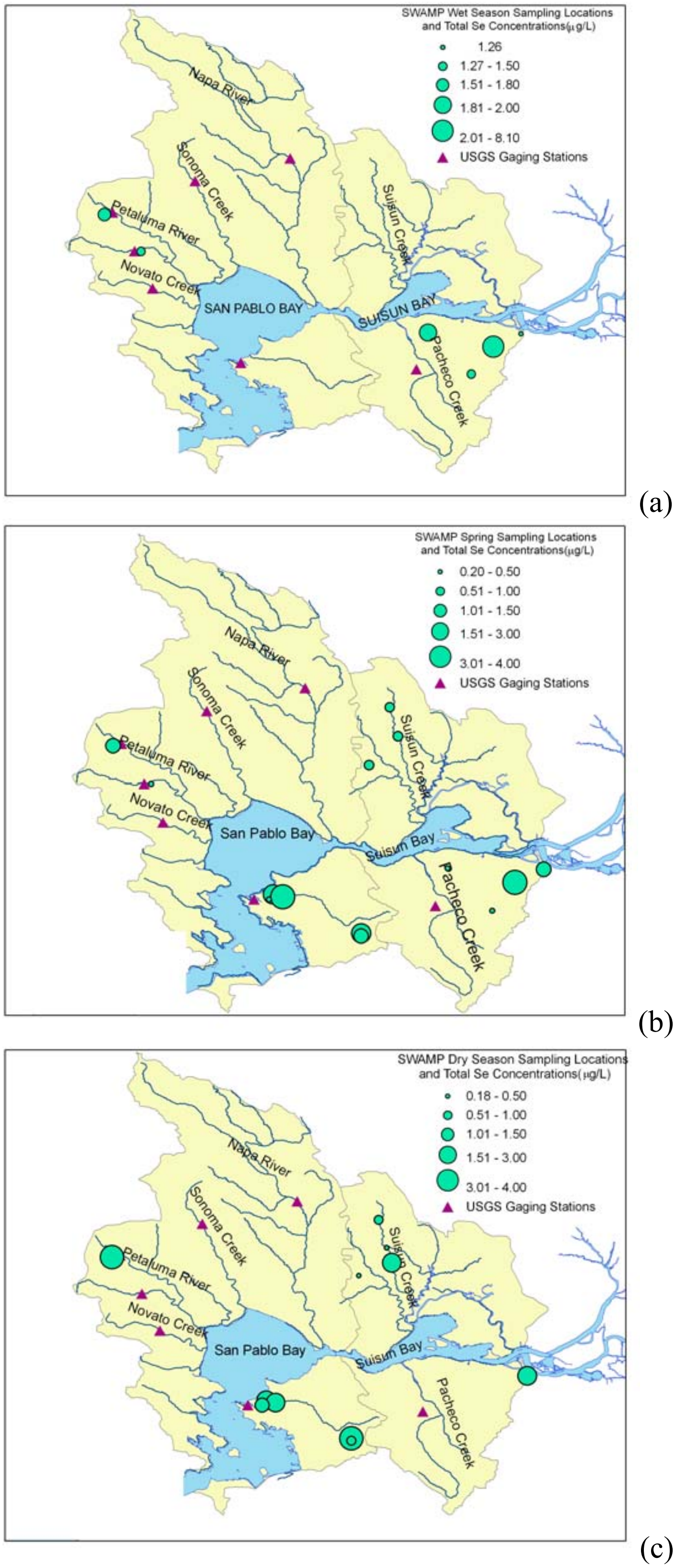


Figure 3-1 Total selenium concentrations in the wet (a), spring (b) and dry (c) seasons in local tributaries of the North Bay, sampled in the SWAMP program.

Three methods were used to estimate selenium loads from local tributaries based on two different methods of estimating runoff from local watersheds and selenium concentration data from SWAMP and BASMAA study.

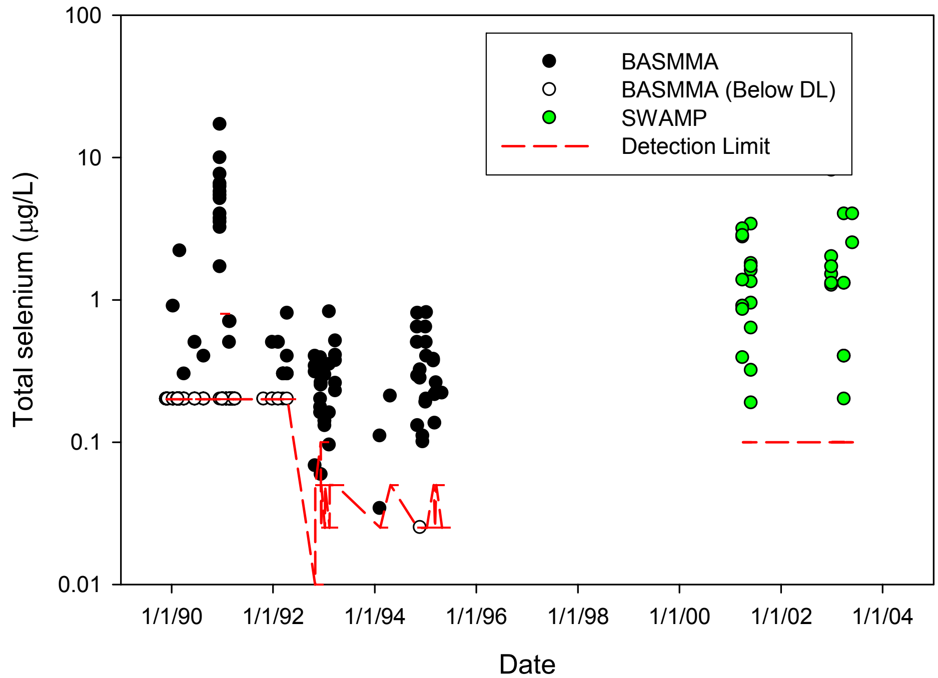


Figure 3-2 **Total selenium concentrations in tributaries of NSFB sampled during 1990–1996 and 2000–2003 (Source: BASMAA, 1996; SWAMP data from SFBRWQCB, 2007a, b).**

3.3.2 Method 1: Modeled Estimates of Runoff in Tributaries and Using SWAMP Concentrations

Total annual runoff from local watersheds has been computed using a simple model by Davis et al. (2000). The predicted runoff compared reasonably well to the limited observed data (r2 = 0.62-0.89). We used the Davis et al. (2000) runoff estimates and concentrations measured in the SWAMP study to estimate loadings from each of the watersheds surrounding the North Bay (Table 3-2). A map of these local watersheds (hydrological areas) is shown in Figure 3-3. The average annual loadings of total selenium from local tributaries to the North Bay were estimated to be 913.9 kg/yr, with the Napa River and Fairfield watersheds being the largest sources. Higher selenium loads from these watersheds are most likely due to larger watershed areas and high annual runoff.

Runoff in the Bay area shows large year-to-year variation. Therefore, loadings from local tributaries are expected to vary greatly with climate conditions. Watersheds in the Bay area show inter-annual variation with coefficient of variation (CV) ranging from 0.65 to 1.01 (McKee et al. 2002). The 10th and 90th percentiles of rainfall in the Bay area for the record period of 1961-1990 were summarized previously in Davis et al. (2000). Assuming constant runoff concentrations under different climate conditions, 10th and 90th percentiles of the selenium loadings were calculated to be 522.8 kg/yr and 1367.2 kg/yr, respectively.

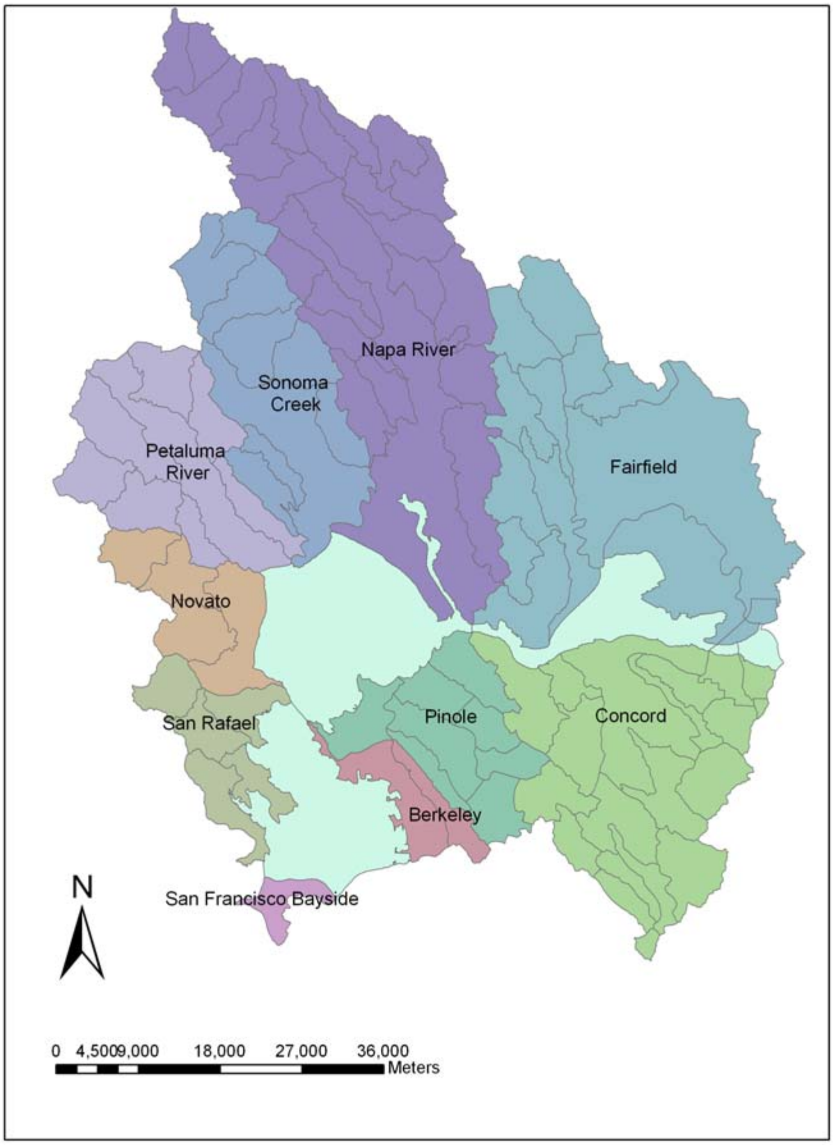


Figure 3-3 Hydrological areas surrounding NSFB. Source: San Francisco Estuary Institute

Table 3-2
Runoff and selenium loadings from local watersheds to the North Bay

Hydrologic Area	Total Annual Runoff (Mm^3/yr)[1]	SWAMP Sampling Station	Mean total selenium concentrations (μg/L)[2]	Total selenium loadings (kg/yr)
San Rafael	56		1.57	87.6
Berkeley	25		1.57	39.1
San Francisco-Bayside	8.8		1.57	13.8
Novato	47		1.57	73.6
Petaluma River	60	Petaluma River	1.5	90
Sonoma Creek	68		1.57	106.4
Napa River	180		1.57	281.7
Pinole	35	Wildcat, San Pablo	1.57	54.8
Fairfield	129	Suisun Creek	0.9	116.1
Concord[3]	106	Mt. Diablo Creek	0.4	42.4
Concord[4]	6.7	Kirker Creek	1.26	8.4
Total	721.5			913.9

[1]Davis et al. (2000)
[2]SFBRWQCB (2007a, b), 1.57 μg/L is the wet season mean concentration for all the most downstream sites in the North Bay watersheds sampled (n = 4).
[3]Subunits of the Concord hydrologic area (ID: 220731, 220732, and 220733)
[4]A subunit of the Concord hydrologic area (ID: 220734)

3.3.3 Method 2: Measured Flow in Selected Tributaries and Using SWAMP Concentrations

The second method is based on USGS flow data in the Bay area to estimate selenium loading from local tributaries. Daily flow records from several USGS gaging stations for some major North Bay tributaries are available for different periods (Table 3-3 and Table 3-4). Long-term average monthly flow at these stations suggested that the majority of the flow is discharged during the wet season (defined as Oct 1st to Apr 30th). Flow during the dry season (defined as May 1st to September 30th) comprises only a very small portion of the wet season flow (0.2 – 3.5%) except Walnut Creek (13.1%) and Pinole Creek (5.8%). Many of the stations have relatively short flow records and contain values prior to 1990. Flow records at these stations may not fully reflect the current hydrologic regime of the watershed.

The long-term average monthly flow and the seasonal concentrations measured by the SWAMP study were used to estimate long-term average selenium loadings at these gaging stations for each month. Loadings were estimated by multiplying flow and concentrations of the same river. For tributaries without observed selenium concentrations, the overall average concentration for all the North Bay downstream sites was used. The estimated loadings are shown in Figure 3-4. Following the pattern in flow volumes, total selenium is mainly delivered to the bay in wet season. Dry season loadings average 0.2 – 3.0% of wet season loadings for 6 of the 8 stations (Table 3-5). An annual areal loading was also estimated for each of the tributary, based on total annual selenium loading and the drainage area. The estimated areal loadings were used to scale up loading estimates of the entire hydrological area (e.g. Novato Creek at Novato was scaled up for the whole Novato hydrological area). For hydrological areas without data (e.g., San Rafael), areal loading from a nearby watershed was used.

Estimated total selenium loadings for the North Bay area by hydrological area are summarized in Table 3-6 and Figure 3-5. Total selenium loadings from local tributaries using the method above were estimated to be 1,511 kg/yr, higher than the estimates from Method 1. A large portion of the loadings were estimated to originate from Napa and Sonoma hydrological areas. Due to the lack of selenium concentrations for these two areas in the SWAMP dataset, an overall mean concentration of the whole North Bay tributaries were used and therefore the estimates are subject to large uncertainty. Flow records for the Napa and Sonoma rivers also suggested higher runoff from these two areas compared to the rest of the North Bay (337 and 422 mm/yr for Napa and Sonoma, compared to ~200 mm/yr for the other tributaries), contributing to the high estimated selenium loadings.

Table 3-3
Major USGS gaging stations in North Bay watersheds (Source: USGS)

Station Name	Station Number	Latitude	Longitude	Drainage Area (mi^2)	Flow Period
Novato Creek at Novato	11459500	38 06’28’’	122 34’44’’	17.6	1946-current
San Antonia Creek Nr Petaluma	11459300	38 10’57’’	122 36’55’’	28.9	1975-1981
Petaluma River at Petaluma	11459000	38 15’40’’	122 39’35’’	30.9	1948-1963
Sonoma Creek at Agua Caliente	11458500	38 19’24’’	122 29’36’’	58.4	1955-current
Napa River nr. Napa	11458000	38 22’06’’	122 18’08’’	218	1929-current
Wildcat Creek at Richmond	11181400	37 57’41’’	122 21’33’’	8.69	1964-1975
Walnut Creek at Concord	11183600	37 56’43’’	122 02’55’’	85.2	1968-1992
Pinole Creek at Pinole	11182100	37 58'21"	122 14'43"	10	1938-1977

Table 3-4
Long-term average monthly flow (in cfs) at USGS gaging stations in North Bay watersheds for the record period (Source: http://waterdata.usgs.gov/nwis)

	USGS11459500 (Novato Creek at Novato)	USGS11459300 (San Antonia Creek nr. Petaluma)	USGS11459000 (Petaluma River at Petaluma)	USGS11458500 (Sonoma Creek at Agua Caliente)	USGS11458000 (Napa River nr. Napa)	USGS11181400 (Wildcat Creek at Richmond)	USGS11183600 (Walnut Creek at Concord)	USGS11182100 (Pinole Creek at Pinole)
Jan	46.79	82.47	58.75	244.85	695.67	22.06	112.55	11.97
Feb	46.56	70.48	64.11	216.32	710.04	11.78	132.28	11.23
Mar	26.92	30.69	28.38	124.3	486.98	10.09	108.15	7.94
Apr	10.50	5.35	14.00	70.74	198.32	6.20	52.33	5.44
May	1.65	0.72	0.49	16.44	59.26	0.89	19.13	1.23
Jun	0.82	0.17	0.03	5.12	18.46	0.61	12.32	0.59
Jul	0.66	0	0	1.81	5.72	0.27	9.52	0.29
Aug	0	0	0	0.98	2.51	0.01	8.27	0.16
Sep	0	0	0	0.77	1.95	0.03	8.77	0.13
Oct	0.69	0.01	0.96	6.28	10.26	1.01	14.33	0.53
Nov	3.01	0.63	2.24	24.26	68.85	4.06	32.47	0.53
Dec	16.81	13.84	37.69	159.32	335.17	7.73	52.05	3.81
Dry season (cfs)	3.9	0.9	0.5	25.1	87.9	1.8	58.0	2.4
Wet season (cfs)	151.3	203.5	206.1	846.1	2505.3	62.9	504.2	41.5
Dry as wet %	2.59	0.45	0.25	2.97	3.51	2.88	11.51	5.79
Runoff (mm/yr)	249.8	200.3	189.4	422.5	336.9	211.0	186.9	124.2

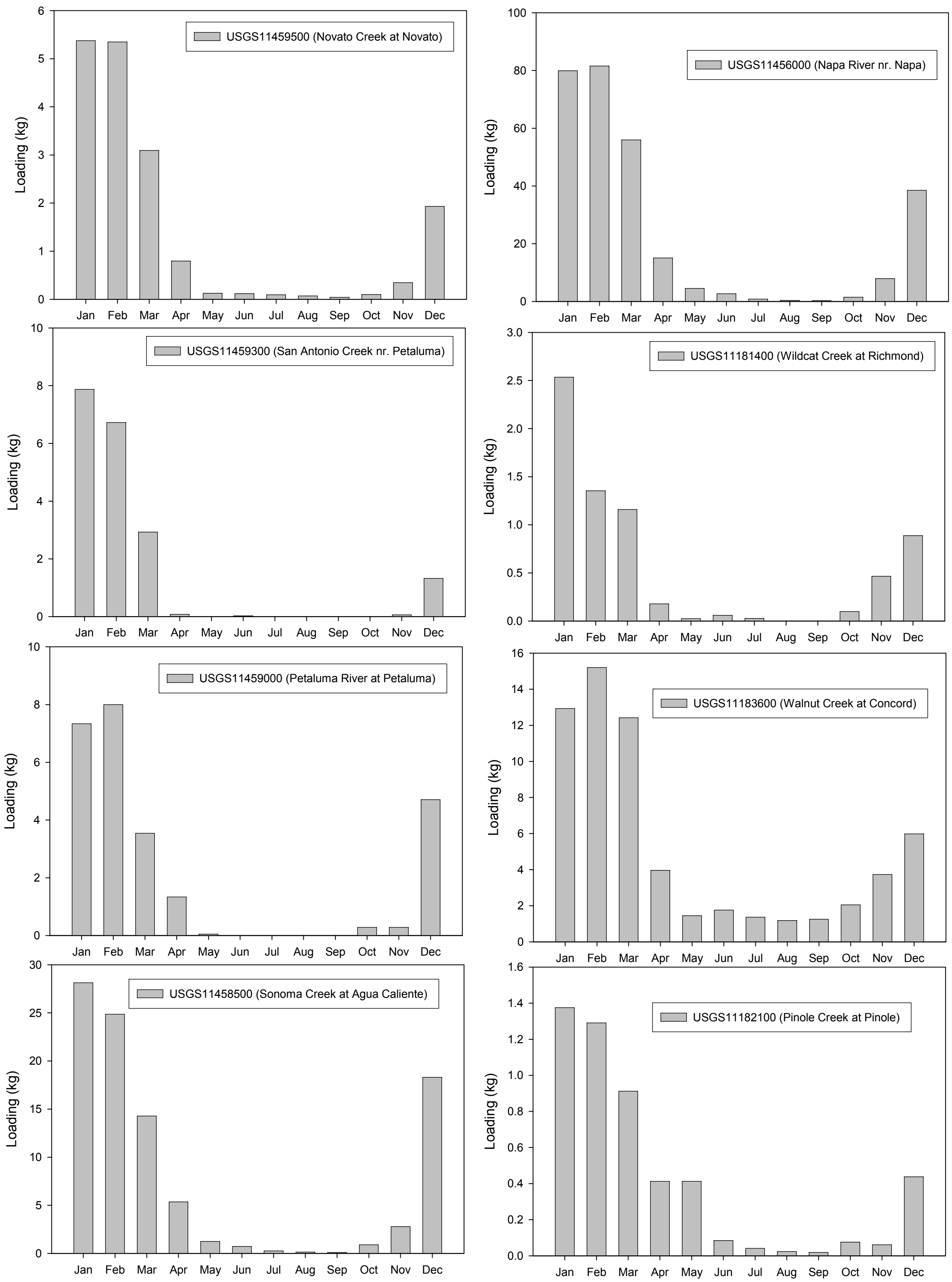


Figure 3-4 **Estimated long-term average monthly selenium loadings at gaging stations of local tributaries.**

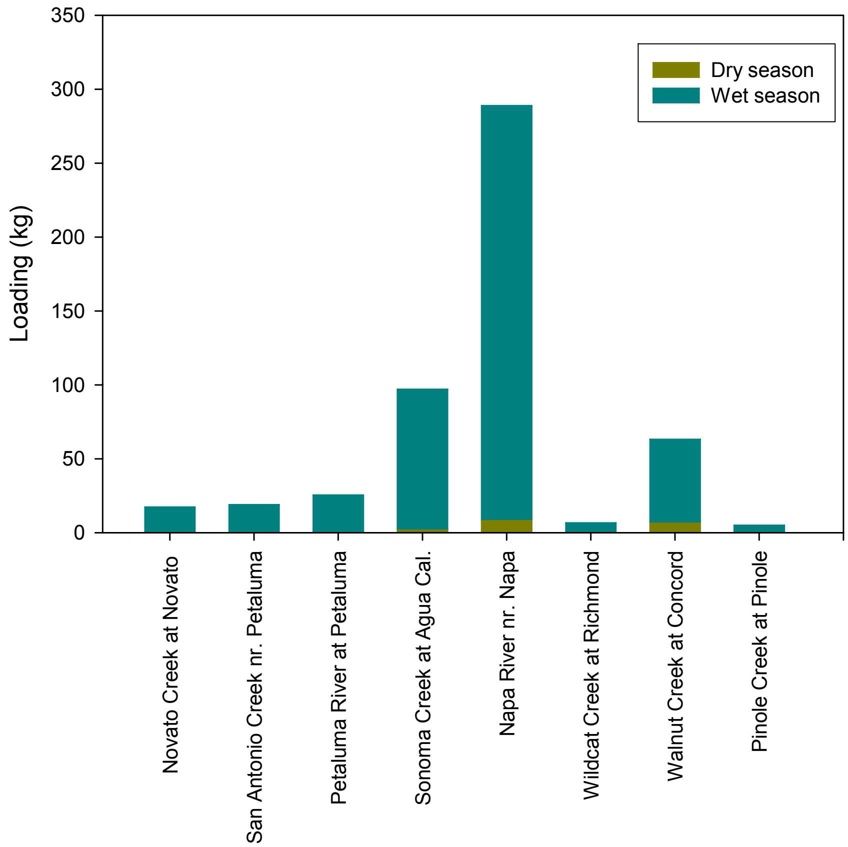


Figure 3-5 Comparison of dry and wet season selenium loadings for tributaries in the North Bay.

Seasonal selenium concentrations from the SWAMP data set were also used in conjunction with the daily flow at Napa River near Napa to estimate daily selenium loadings for 1991-2007. The estimated daily loadings were accumulated to estimate seasonal loading for all the years. As a result of variations in hydrological conditions, total selenium loading in Napa River near Napa vary largely across the years (Figure 3-6). Total selenium loadings can be greater than 700 kg/yr during wet year (1995) versus less than 100 kg/yr during a dry year (1994). The dry and wet year notation was based on the classification system for San Joaquin and Sacramento River by the Department of Water Resources (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST). Wet and above normal years are classified as wet years. Dry, below normal and critically dry years are classified as dry years. Dry season is defined as May 1st to September 30th. The wet season is defined as October 1st to April 30th.

Table 3-5
Estimated long-term average monthly total selenium loadings (kg/month) to the gaging stations.

	USGS11459500 (Novato Creek at Novato)	USGS11459300 (San Antonia Creek nr. Petaluma)	USGS11459000 (Petaluma River at Petaluma)	USGS11458500 (Sonoma Creek at Agua Caliente)	USGS11458000 (Napa River nr. Napa)	USGS11181400 (Wildcat Creek at Richmond)	USGS11183600 (Walnut Creek at Concord)	USGS11182100 (Pinole Creek at Pinole)
Jan	5.37	7.87	7.33	28.13	79.92	2.53	12.93	1.38
Feb	5.35	6.73	8.00	24.85	81.57	1.35	15.20	1.29
Mar	3.09	2.93	3.54	14.28	55.94	1.16	12.42	0.91
Apr	0.80	0.08	1.34	5.36	15.04	0.18	3.97	0.09
May	0.13	0.01	0.05	1.25	4.49	0.03	1.45	0.41
Jun	0.12	0.02	0.01	0.73	2.64	0.06	1.76	0.08
Jul	0.09	0.00	0.00	0.26	0.82	0.03	1.36	0.04
Aug	0.07	0.00	0.00	0.14	0.36	0.00	1.18	0.02
Sep	0.04	0.00	0.00	0.11	0.28	0.00	1.26	0.02
Oct	0.10	0.00	0.28	0.90	1.47	0.10	2.05	0.08
Nov	0.35	0.06	0.28	2.79	7.91	0.47	3.73	0.06
Dec	1.93	1.32	4.70	18.30	38.50	0.89	5.98	0.44
Annual total (kg/yr)	17.4	19.0	25.5	97.1	288.9	6.8	63.3	4.8
Areal loading (kg/mi^2)	0.99	0.66	0.83	1.66	1.33	0.78	0.74	0.48
Dry season (kg)	0.45	0.04	0.06	2.49	8.59	0.12	7.01	0.26
Wet season (kg)	16.99	18.99	25.47	94.61	280.35	6.68	56.28	4.56
Dry as wet %	2.65	0.21	0.22	2.63	3.06	1.73	12.46	5.71

Table 3-6
Estimated annual total selenium loadings for the hydrological areas in the North Bay.

Hydrological Areas	Drainage Area (Mm^2)	Area (mi^2)	Loadings (kg/yr)	Dry (kg)	Wet (kg)
Novato	183.98	71.03	70.4	1.8	68.6
San Rafael	157.66	60.87	60.3	1.6	58.8
San Francisco Bayside	28.76	11.11	11.0	0.3	10.7
Berkeley	87.59	33.82	26.4	0.4	26.0
Pinole	152.43	58.85	28.4	1.5	26.9
Concord	648.27	250.30	185.9	20.6	165.3
Fairfield	877.89	338.96	251.8	27.9	223.9
Napa	937.89	362.12	480.0	14.3	465.7
Sonoma	429.77	165.93	275.9	7.1	268.6
Petaluma	377.64	145.81	120.5	0.3	120.2
Total			1510.6	75.8	1434.8

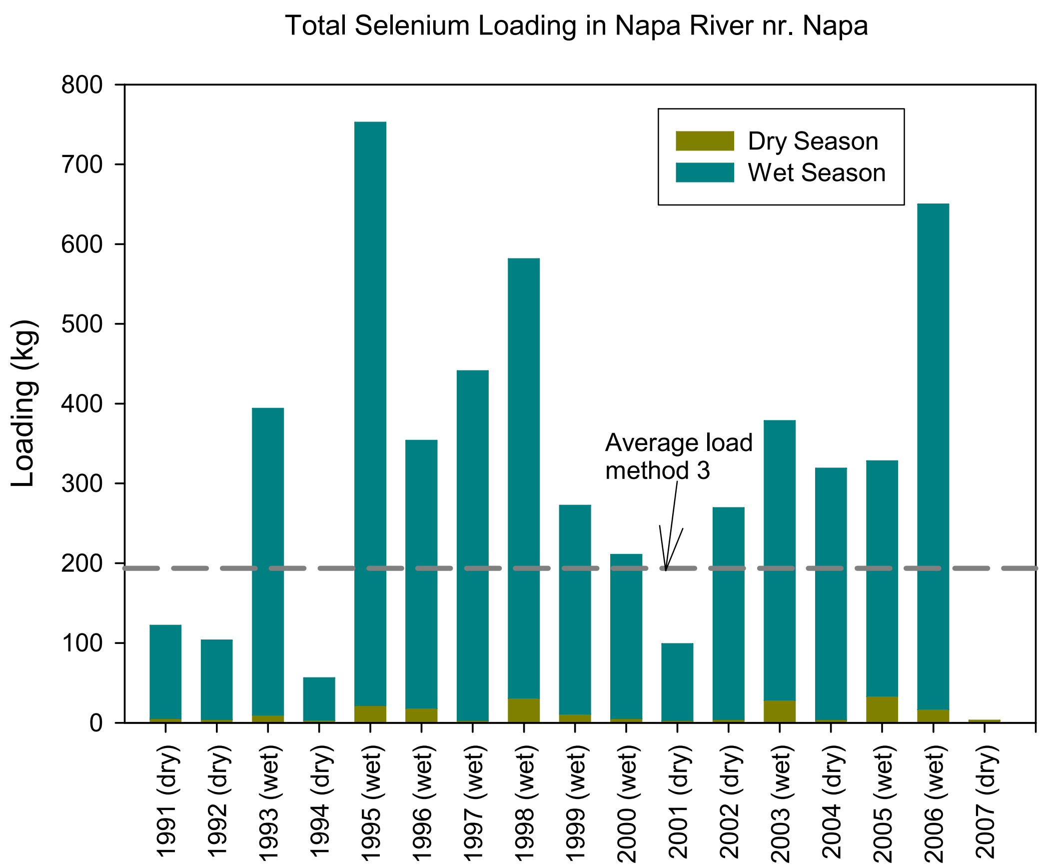


Figure 3-6 **Dry and wet season selenium loadings by water year at Napa River near Napa.**

3.3.4 Method 3: Modeled Estimates of Runoff with BASMAA and SWAMP concentrations for Calculating Land Use-Specific Loads

To estimate stormwater loads of selenium from urban areas, a previously published approach was used (Davis et al., 2000). This approach has been used in estimating urban loads of PCBs in the San Francisco Bay PCB TMDL (KLI, 2002; SFBRWQCB, 2007c). Loads are estimated from five broad categories of land use (agricultural, open space, industrial, commercial and residential) based on estimated runoff from each land use type and land-use specific concentrations. Urban lands are defined as a group and include industrial, commercial and residential lands.

Land uses for each hydrological area were previously determined by Davis et al. (2000; Table 3-7). Best estimates of runoff coefficient for each land use type were also derived by Davis et al. (2000; Table 3-7). KLI (2002) sampled stormwater concentrations of PCBs and Hg in the Bay area, however selenium was not sampled in this effort. For selenium, land use specific concentrations were derived from BASMAA (1996) and SWAMP study (SFBRWQCB 2007a, b). BASMAA (1996) sampling stations include sites that are mostly residential and sites that are more dominated by forests/open area. Therefore, overall mean concentrations for sites with dominant land use of residential, open, and industrial were calculated. Concentrations for agricultural land use were assumed to be the same as open area. When concentrations were reported as below detection limits, half of the detection limit was used. Mean selenium concentrations from the BASMAA study are similar across land uses (Table 3-8). Stations from the SWAMP study are generally located in the urban areas, with Suisun Creek stations located in agriculture-dominated areas. Therefore values from Suisun Creek were used to derive concentrations for the agricultural areas. Due to the differences in concentrations reported in two programs, values from BASMAA were used as lower bound of concentrations from local tributaries, while SWAMP data were used as an upper bound (Table 3-8). Overall, Method 3 results in a somewhat lower estimate of loads than the prior two methods, with loads ranging from 354.3 to 838.7 kg/yr.

Table 3-7
Summary of drainage areas and land use for each hydrologic area of NSFB (Davis et al. 2000; KLI, 2002)

Hydrological areas (HA)	Drainage Area (Mm^2)	Residential (%)	Commercial (%)	Industrial (%)	Agricultural (%)	Open (%)	Rainfall
Berkeley	87.59	57	16	18	0	9	21
Concord							
Concord (220731)	283.96	25	10	7	9	49	17
Concord (220732)	212.54	44	4	1	1	50	21
Concord (220733)	121.72	39	6	7	0	47	21
Concord (220734)	30.05	46	9	26	6	12	17
Fairfield							
Fairfield (220721)	226.20	12	1	5	12	70	25
Fairfield (220722)	131.69	0	0	0	13	86	29
Fairfield (220723/26)	410.25	8	6	2	48	36	21
Fairfield (220724/25)	109.76	0	0	0	1	99	19
Napa River	937.89	10	3	1	24	62	31
Novato	183.98	23	7	1	13	56	33
Petaluma River	377.64	14	1	2	35	48	27
Pinole	152.43	33	5	12	0	49	23
San Francisco Bayside	28.76	58	39	2	0	1	21
San Rafael	157.66	50	8	1	0	41	39
Sonoma Creek	429.77	8	1	1	36	54	29

Table 3-8
Land use specific runoff coefficient and mean selenium concentrations

	Residential	Commercial	Industrial	Agricultural	Open	Source
Runoff coefficient (best estimate)	0.35	0.9	0.9	0.1	0.25	Davis et al. (2000)
Selenium concentration (low end) $\mu g1^{-1}$	0.36	0.58	0.58	0.50	0.50	BASMAA (1996)
Selenium concentration (high end) $\mu g1^{-1}$	1.55	1.55	1.55	0.85	0.85	SWAMP

Table 3-9
Estimated total selenium loadings (kg/yr) by land use from hydrological areas draining NSFB by land uses

Hydrological area	Residential	Commercial	Industrial	Agricultural	Open	Total (kg/yr)
Berkeley	14.4	10.4	11.7	0.0	0.9	37.5
Concord	60.7	30.5	24.6	1.1	31.6	148.5
Fairfield	18.8	20.3	16.1	11.5	67.0	133.8
Napa River	40.1	30.9	10.3	15.1	97.3	193.6
Novato	19.2	15.1	2.2	1.7	18.4	56.5
Petaluma River	19.7	3.6	7.2	7.7	26.4	64.6
Pinole	15.9	6.2	14.9	0.0	9.3	46.3
San Francisco Bayside	4.8	8.3	0.4	0.0	0.0	13.6
San Rafael	42.4	17.4	2.2	0.0	13.6	75.6
Sonoma Creek	13.7	4.4	4.4	9.7	36.3	68.6
Total (kg/yr)-SWAMP	249.8	147.2	94.1	46.8	300.8	838.7
Lower bound estimates (kg/yr) - BASMAA	58.4	54.8	35.0	27.7	178.4	354.3
Urban loads[1] (kg/yr)						491.1 (148.2 lower bound)

[1]Urban loads are the sum of residential, commercial, and industrial land uses.

Estimated stormwater runoff from urban areas surrounding the NSFB is 316.8 Mm^3/yr, about 44% of the total runoff. Estimated loads from urban areas based on the SWAMP concentrations are at 491.1 kg/yr, about 58.6% of loads from all land use types. Because a lower concentration in the agricultural areas compared to other urban land uses was used (0.85 µg/L versus 1.55 µg/L), estimated total selenium loads from all land uses are slightly lower than load estimates in Method 1. Also note for Napa River watershed, because a large portion of the land uses is agricultural, using a lower selenium concentration for agricultural area resulted in lower estimates of selenium loads for the whole hydrological area (193.6 kg/yr versus 281.7 kg/yr in method 1). Estimated loads from urban areas based on the BASMAA concentrations are at 148.2 kg/yr, about 43% of loads from all land use areas.

3.3.5 Tributary Load Summary

Three, somewhat overlapping methods were used to compute tributary loads. Using the SWAMP selenium data from the tributaries, loads were computed using flow from different sources: modeled annual flows from a recent study (Davis et al., 2000) and measured flows from USGS gage stations. The modeled flows were used because of the limited availability of measured flow data. Loads from urban and non-urban areas were also estimated based on modeled runoff and land use specific concentrations derived from BASMAA and SWAMP concentration data. Loads from urban areas generally account for 43% or 59% of total loads from tributaries, depending on the concentrations used.

Driven in large part by relatively high concentrations in the tributaries in both the wet and dry seasons, the average annual loads from the tributaries can be up to 1,511 kg/year depending on the methods used for the load estimation. Much of this load (greater than 95%) is delivered to the bay in the wet months, consistent with the timing of flows, as shown in the calculation using the USGS gage data. The largest single sources of loads are the Napa River, Sonoma Creek, and the Concord hydrological area. Note that selenium is a naturally occurring trace element, and is found even in runoff from open areas. A significant portion of these loadings is associated with natural sources.

On average, the tributary concentration data are generally higher than Sacramento River concentrations, which are more typical of a low background in the region. Although the high average concentrations are not driven by one or two measurements, it is nonetheless clear that the load estimates above are based on a limited amount of data. Furthermore, the SWAMP and BASMAA concentrations differ: lower mean concentrations were observed in BASMAA dataset. However, the range of concentrations (0.06 – 0.90 µg/L after 1/1/1992) indicates that higher concentrations than 0.1 µg/L were not uncommon in local tributaries. Given the underlying data limitations and uncertainty in flows, and the year-to-year variability, estimated loads from tributaries can be as low as 354 kg/yr using BASMAA concentrations and modeled runoff, 834 or 914 kg/yr based on SWAMP concentrations and modeled runoff, and 1511 kg/yr based on SWAMP concentrations and measured flow. For the purpose of this analysis, we go forward with the relatively wide range of 354-834 kg/yr, with about half originating in urban runoff.

Particulate selenium loads from local tributaries were estimated based on previous estimates of total suspended sediment (TSS) loads for different hydrological areas in the Bay Area by Davis et al. (2000). Estimates of TSS loads by Davis et al. (2000) were based on SIMPLE model estimates of runoff multiplied by available TSS concentrations. Data on particulate selenium concentrations are limited from local tributaries. Therefore selenium concentrations in particulates measured for the Sacramento River (0. 62 ± 0.21 µg/g; n =5) by Doblin et al. (2006) were used in the calculation. TSS loads estimated by Davis et al. (2000) are 1.91×10^8 kg/yr for the North Bay watersheds. With a particulate selenium concentration of 0.62 µg/g, estimated particulate selenium loads from local tributaries are 118.2 kg/yr.

3.4. Inputs from San Joaquin and Sacramento Rivers via the Delta

Although selenium inputs from the Central Valley via the Delta are expected to be a significant source to the North Bay, accurately estimating these loads is difficult due to the role of the Delta and tidal influences from the bay. Loads upstream of the Delta can be estimated from measurements at Freeport (on the Sacramento River) and at Vernalis (on the San Joaquin River) (Figure 3-7). Inflow originating from the San Joaquin River has high selenium concentrations due to inputs from agricultural drainage (0.68 ± 0.20µg/L dissolved selenium) and the Sacramento River has much lower selenium concentrations (0.07 ± 0.02 µg/L) (Cutter and Cutter, 2004). However, flows in the San Joaquin River at Vernalis are usually much smaller: 10 to 15 percent of inflow from Sacramento River at Freeport (Figure 3-7). Therefore, on an annual basis loads from both rivers to the Delta are significant. However, selenium processes in the Delta are not well characterized. Besides the normal processes of settling and mixing, a large portion of the water in the Delta is also exported for agricultural and urban uses in other parts of California. The relative contribution of the Sacramento and San Joaquin Rivers to the overall export from the Delta to the North Bay changes with tidal cycles and season. The contribution from the San Joaquin River can potentially increase during drier months of September to November (Figure 3-7 and Presser and Luoma, 2006). In this section, available flow and concentration data are used to make the best possible estimates of the selenium load contributions of the Delta and the two major rivers to the North Bay.

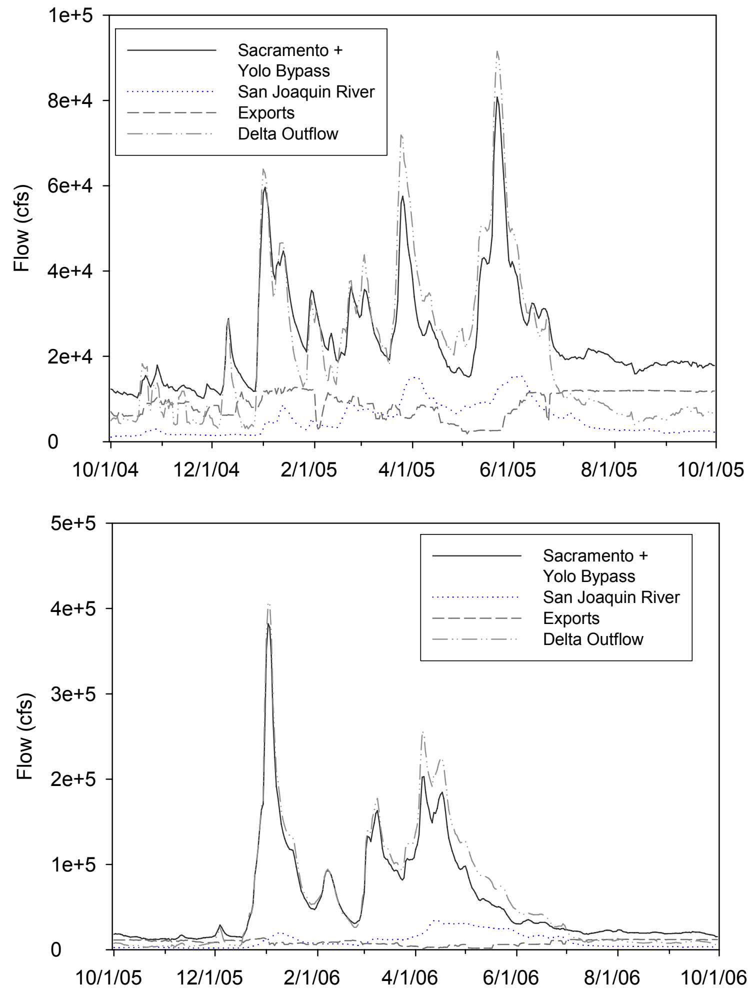


Figure 3-7 Flow from Sacramento River, San Joaquin River, compared to Delta exports (diversions of Central Valley Project, State Water Project, Contra Costa Water District Diversions and North Bay Aqueduct) and outflow to Delta for a dry year (water year 2004) and a wet year (water year 2005) (Data source: IEP).

Selenium data have been collected as part of the RMP just above Mallard Island at the BG20 (Sacramento River) and BG30 (San Joaquin River) stations. Observed total selenium concentrations at these stations (0.15 and 0.18 µg/L, respectively) are more representative of Delta concentrations than of the individual rivers. The concentrations are higher than in the Sacramento River at Freeport (0.07 µg/l, noted above), and substantially lower than in the San Joaquin River at Vernalis (0.68 µg/l), indicating mixing between the two sources, and possibly tidal influences from the bay during low flow periods. Concentrations observed at BG20 and BG30 also correlate well ($R^2 = 0.59$) possibly due to mixing of common sources. In a separate study, selenium concentrations were found to decrease by 60-80% during transport from the San Joaquin River at Vernalis into the estuary at Antioch (Cutter unpublished data; Meseck and Cutter, 2006).

Different methods have been used in previous studies to calculate riverine inputs of various pollutants through the Delta to the Bay. Davis et al. (2000) used average concentrations at two RMP monitoring stations in the Delta (BG20 and BG30) to estimate loads of different pollutants from Central Valley to the Bay. Leatherbarrow et al. (2005a) and McKee et al. (2006) used continuous monitoring data of SSC at Mallard Island to estimate loads of sediments, mercury and organics to the Bay. With respect to selenium, Presser and Luoma (2006) estimated loads from the two rivers (Sacramento River at Freeport and San Joaquin River at Vernalis) separately to estimate selenium inputs to the Bay. Cutter and Cutter (2004) and Abu-Saba and Ogle (2005) used the approach of flow weighting concentrations from the two rivers to calculate a riverine concentration and multiplied this by the net Delta outflow to estimate loads from the Delta to the bay. Meseck (2002) applied a “Delta removal constant” to the riverine loads to take into account the possible selenium sink in the Delta in her modeling analysis.

Here we used three different approaches to estimate the selenium loadings from Central Valley via Delta to the bay based on the available data. The first approach is the simple approach similar to Davis et al. (2000), which uses average concentration of two RMP stations in the Delta and multiplies it by the net Delta outflow. The second approach uses selenium loadings from the Sacramento and the San Joaquin Rivers separately based on data from Cutter and Cutter (2004) and applies a “Delta removal constant” similar to Meseck (2002) to account for the possible selenium loss in the Delta. The third approach is independent of the prior two, in which the loadings from Central Valley to the bay were estimated as the difference between inputs from the two rivers minus the export through aqueducts. The third method can be used to estimate the relative selenium load contribution of the two rivers to the bay.

3.4.1 Method 1. Loadings Based on the RMP data and Tidally Corrected Delta Outflows

For the first approach, tidally corrected outflow data from the Delta were obtained from the Interagency Ecological Program (IEP) (http://www.iep.ca.gov/dayflow/index.html). Outflows from the Delta show large year-to-year variations (Figure 3-8). Concentrations measured at BG20 and BG30 also show year- to-year variations, and no correlation with the Delta outflow and no clear pattern in wet versus dry seasons were observed.

Daily selenium loadings were estimated by multiplying daily Delta outflow with the average concentrations at BG20 and BG30 of the dry and wet seasons of each year. The estimated daily loadings were summed to compute annual loadings. Estimated annual loadings are highly variable (by a factor of 12) depending on the volume of outflow from the Delta (Table 3-10 and Figure 3-9). Water year 1998 was an exceptionally wet year. Excluding 1998, estimated annual loadings vary by a factor 6 among the years. Loadings from the Delta are more significant in the wet season than the dry season (Figure 3-9). An average load of 3,962 kg/year from the Delta to the North Bay was estimated (1994-2006).

There is some limited evidence that the Delta load may be higher than computed using this method and using BG-20 and BG-30 concentrations from the RMP. Selenium concentrations have been measured in the outflow from the Delta (Mallard Island) during the storm events of 2005 - 2006 (0.46 ± 0.13 µg/L; L. McKee, personal communication), and separate from the RMP data. Higher concentrations observed at Mallard Island during storm events suggest potential of higher loadings during these periods. Total recoverable selenium concentrations during storm events are a function of daily flow, suggesting a dilution behavior (Figure 3-10). Nonetheless, the relationship was used to estimate total selenium loadings during high flow. The result indicates a potential of 16-56% underestimate of total selenium loadings using BG20 and BG30 concentrations (e.g. 1,059 kg/yr vs. 1,590 kg/yr for a dry year 2001 and 5,078 kg/yr vs. 21,000 kg/yr for wet year 2006). However, the storm selenium concentration data are very limited at this point, and the more complete RMP data record is recommended for calculation of long term Delta loads.

Leatherbarrow et al. (2005a) used concentrations measured at Mallard Island to estimate loads of PCB (polychlorinated biphenyls), PAH (polycyclic aromatic hydrocarbons), OC (Organochlorine) pesticides, and Hg from the Delta to the Bay. Contaminant loads were estimated based on relationships between contaminants and SSC, and the estimated sediment loads using available flow information and continuous SSC concentrations measured at Mallard Island. In quantifying loads of sediment from Mallard Island to the Bay, both the advective and dispersive loads were estimated. The relative contributions of the advective and dispersive load were estimated using point velocity and concentration measured during water year 1994 and 1996 (McKee et al. 2006). During a wet period (mean discharge = 2116 m^3/s), dispersive point-load averages about 11% of the advective point load. Due to the tidal influence at Mallard Island, dispersive loads (most commonly landward) can be a significant portion of total load during low flow period. Estimated dispersive load for a low flow period (April 15, 1994-June 4, 1994) was 49% of advective point load at surface and 52% at mid-depth (McKee et al. 2006). Overall the dispersive loads of sediment were estimated to be 0.24 Mt/yr or 20% of the total loads for the 9 year period of 1995-2003. There is limited applicability of this method for total selenium loadings because most selenium (at least two-thirds, and often more) is in the dissolved form. However, the sediment load estimates are used to estimate particulate loads of selenium from the Delta to the bay. The calculation appears at the end of this section.

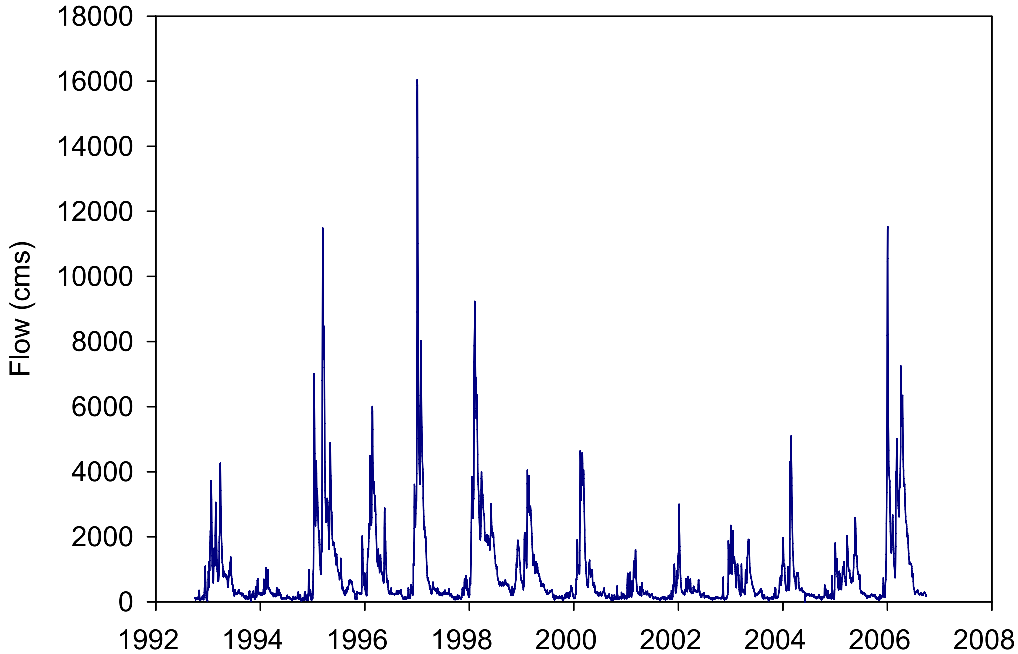


Figure 3-8 Daily Delta outflow for water years 1992-2006 (Data source: IEP)

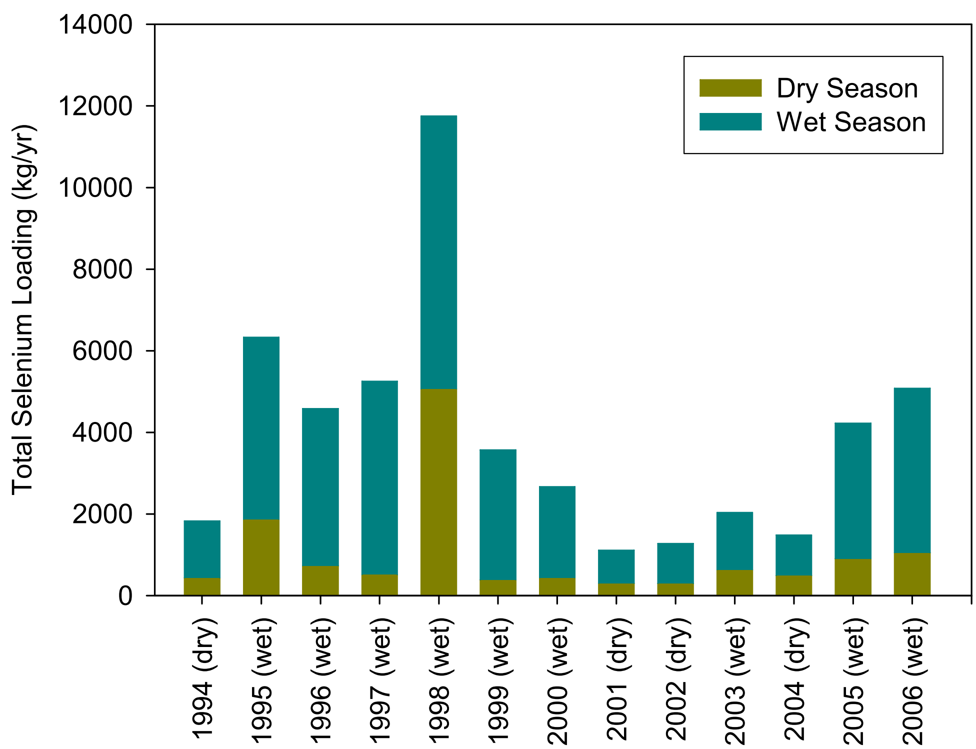


Figure 3-9 Estimated wet and dry season total selenium loadings from Delta to the Bay by water year.

Table 3-10
Estimated total and dissolved selenium loadings from the Delta

Year	Delta outflow m^3	Loadings (total) kg/yr	Loadings (dissolved) kg/yr
1994	7.42E+09	1,831	1,647
1995	4.11E+10	6,859	6,159
1996	2.56E+10	4,355	2,818
1997	4.23E+10	5,252	4,399
1998	5.36E+10	11,752	9,736
1999	2.78E+10	3,572	3,292
2000	2.24E+10	2,666	1,495
2001	8.56E+09	1,110	882
2002	1.13E+10	1,276	814
2003	1.73E+10	2,037	1,797
2004	1.84E+10	1,485	2,259
2005	1.90E+10	4,228	4,337
2006	5.40E+10	5,078	3,970
Average	2.68E+10	3,962	3,354

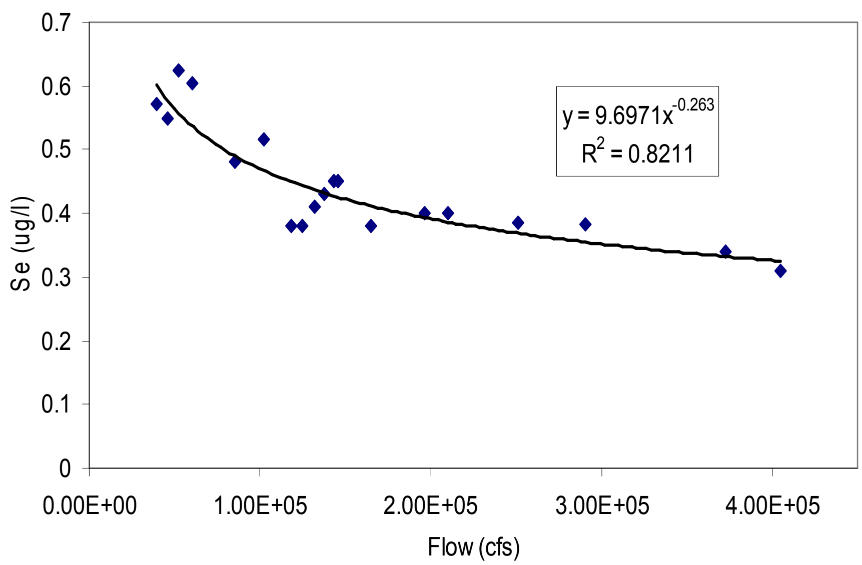


Figure 3-10 Relationship between total selenium concentrations and flow at Mallard Island (Data source: L. McKee).

3.4.2 Method 2: Loadings Based on Riverine Loads to the Delta, and Assumption of Delta Removal Constant

Dissolved selenium concentrations in the Sacramento River at Freeport sampled by Cutter and Cutter (2004) on biweekly or monthly bases indicated relatively small changes from 1984 to 2000 (Figure 3-11). Dissolved selenium concentrations in the Sacramento River (at

Freeport) range between 0.01-0.13 µg/L, with an average of 0.07 ± 0.02 µg/L for the period of 1999-2000. Dissolved selenium concentrations in the San Joaquin River at Vernalis may be 10 times higher. Concentrations for the San Joaquin River at Vernalis range between 0.14 - 4.69 µg/L for entire period of record. A significant decrease in selenium concentrations was observed for 1999-2000 compared to the 1980s sampling. Mean dissolved selenium concentration for the period of 1999-2000 is 0.68 ± 0.20 µg/L.

Concentrations during 1999-2000 show some variations both in the Sacramento and San Joaquin River (Figure 3-12). For the Sacramento River, higher concentrations were observed for the months between April to July. For the San Joaquin River, no clear seasonal pattern was observed. Concentrations in relation to flow are shown in Figure 3-13. For the Sacramento River, no clear relationship between flow and concentrations was observed for the recent years, consistent with findings in Cutter and Cutter (2004). Cutter and Cutter (2004) reported a poor correlation between river discharge and any dissolved selenium forms for the Sacramento River. For San Joaquin River, a negative relationship between concentrations and flow was observed, possibly due to the dilution of selenium discharge by natural flow.

For the Sacramento River, due to the weak relationship between dissolved selenium concentration and flow, monthly concentrations were used to calculate the daily loadings. For the San Joaquin River, the flow and concentration relationship derived was used to estimate daily concentrations based on flow. The daily loading was then estimated based on daily flow and estimated daily concentration. Daily flow for the Sacramento River at Freeport (USGS 11447650) and the San Joaquin River at Vernalis (USGS 11302500) were obtained from the USGS website (http://waterdata.usgs.gov/nwis/dv/?referred_module=sw). The estimated daily loadings were summed to calculate the seasonal loadings. The wet season was defined as Oct 1st to Apr. 30th and the dry season was defined as May 1st to Sep 30th (Tetra Tech, 2006).

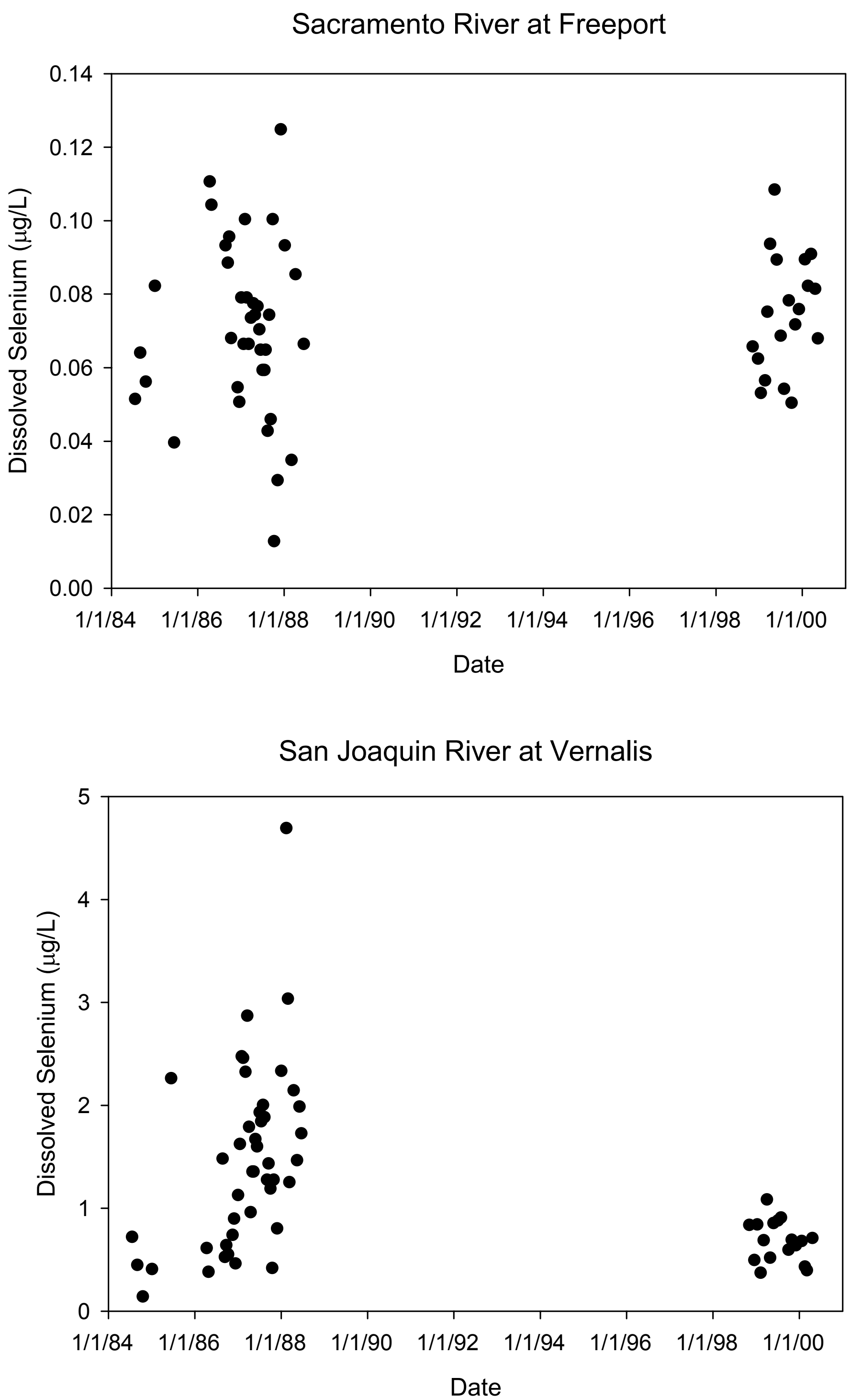
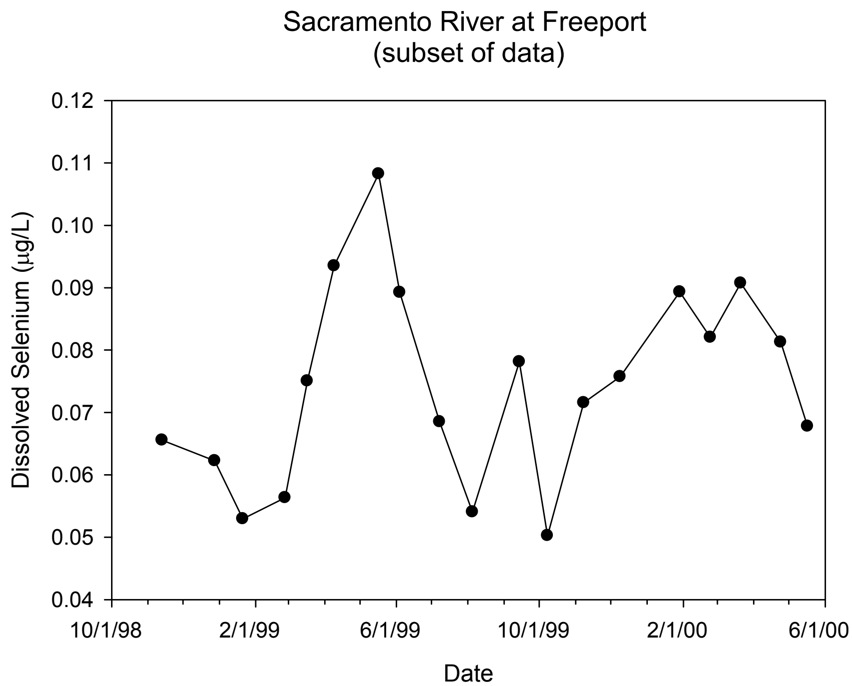


Figure 3-11 Dissolved selenium concentrations in Sacramento River at Freeport and San Joaquin River at Vernalis during 1984-1988 and 1998-2000, sampled by Cutter and Cutter (2004).



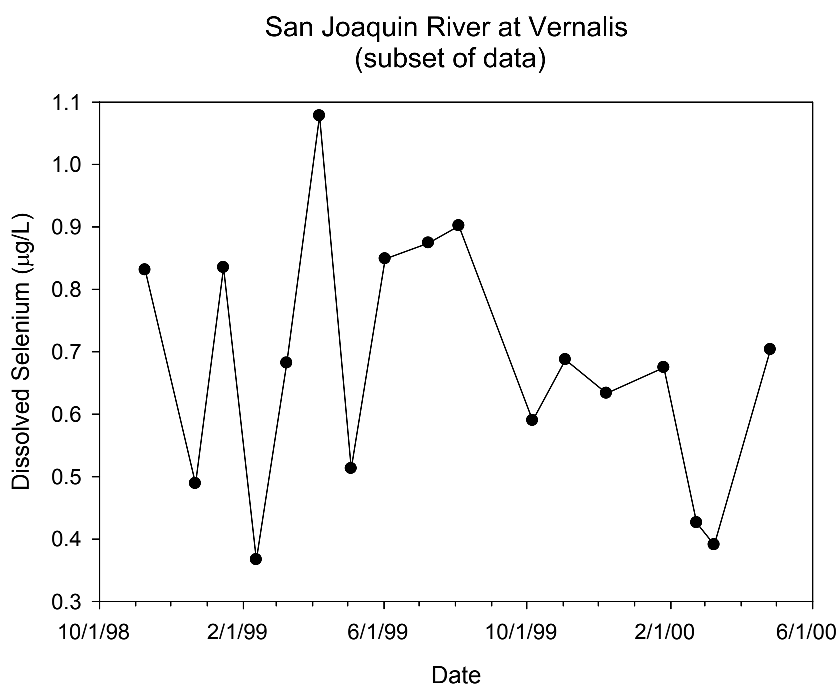
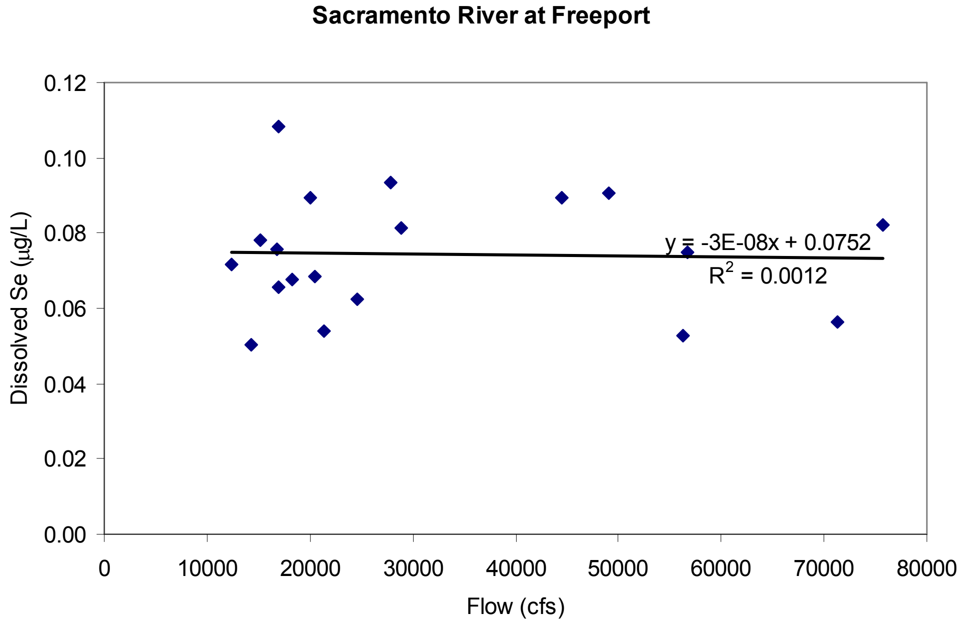


Figure 3-12 Dissolved selenium concentrations at Sacramento River at Freeport and San Joaquin River at Vernalis during 1998-2000, sampled by Cutter and Cutter (2004).



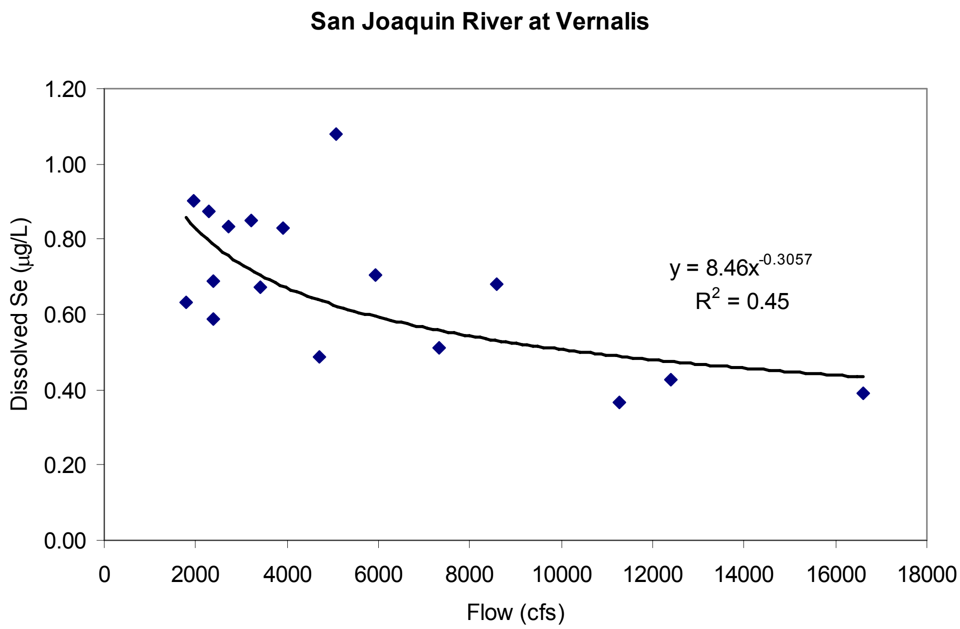


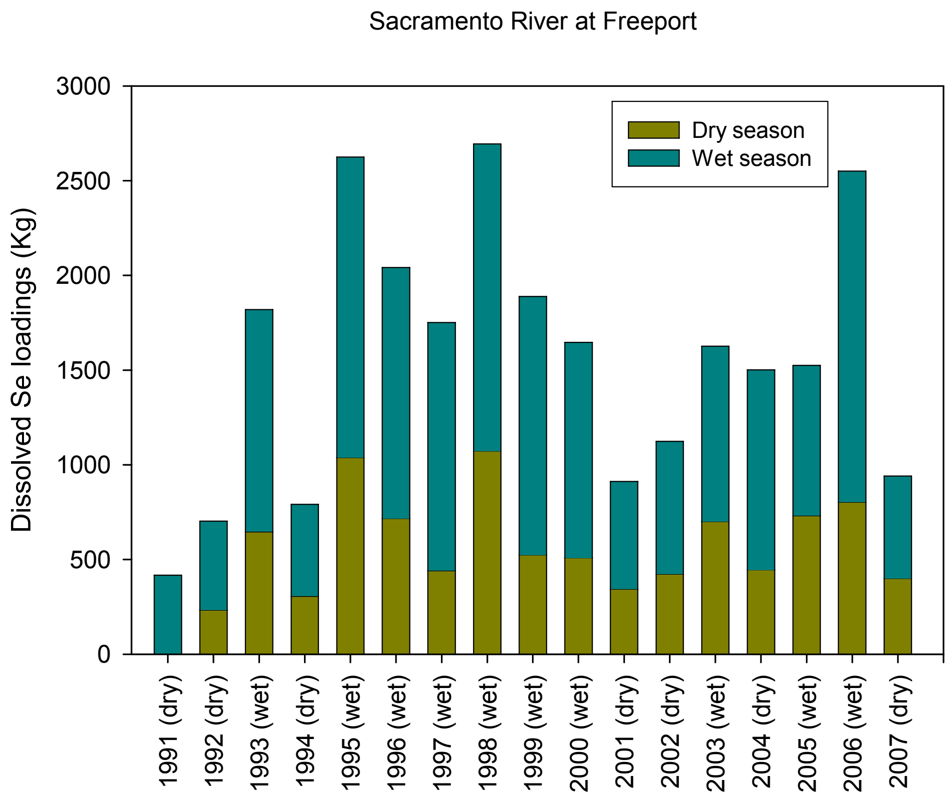
Figure 3-13 Relationship between dissolved selenium concentrations and daily flow for Sacramento River at Freeport and San Joaquin River at Vernalis for the period of 1998-2000 (data source: Cutter and Cutter, 2004). Note that dissolved selenium concentrations show no correlation with flow rate for the Sacramento River.

The estimated annual dissolved selenium loadings range between 703 – 2,693 kg/yr for the Sacramento River at Freeport and 867 – 4,710 kg/yr for the San Joaquin River at Vernalis. Estimated dry season loadings range between 234 – 1,074 kg/yr for the Sacramento River (at Freeport) and 261-2,097 kg/yr for the San Joaquin River (at Vernalis). Estimated wet season loadings range between 417- 1,748 kg/yr for Sacramento River and 552- 3,048 kg/yr for San

Joaquin River. On average, dry season loadings are generally lower and represent 58% and 60% of the wet season loadings for the Sacramento River (at Freeport) and the San Joaquin River (at Vernalis), with only one exception (San Joaquin River in 1995).

Estimated annual dissolved selenium loadings vary with water years (Figure 3-14). Annual loadings can be as high as 2,600-2,700 kg/yr during wet years for the Sacramento River (at Freeport) and approximately 750 – 1,000 kg/yr during dry years. Annual loadings for the San Joaquin River (at Vernalis) also vary with hydrological conditions. Annual loadings can be greater than 4,000 kg/yr during wet years and less than 1,000 kg/yr during dry years. Overall, average dissolved selenium loadings are higher for the San Joaquin River (at Vernalis) than the Sacramento River (at Freeport) (2,380 kg/yr vs. 1,634 kg/yr during 1990-2007).

Total selenium concentrations were also measured by the SWAMP program at San Joaquin River at Vernalis (Airport Way) on a weekly basis by Central Valley Water Quality Control Board(http://www.waterboards.ca.gov/centralvalley/water_issues/water_quality_studies/surface_water_ambient_monitoring/). The observed total selenium concentrations were higher during the 1980s and early 1990s compared to recent years (Figure 3-15). Dissolved selenium concentrations for the same period measured by Cutter and Cutter (2004) agree relatively well with the total selenium concentrations observed in the SWAMP study but were slightly lower (Figure 3-16). This is to be expected as dissolved selenium usually accounts for 80-95% of total selenium measured. The observed decreases of selenium concentration at Vernalis most likely resulted from the implementation of the Grassland Bypass Project in 1996, which has led to a 60% decrease in selenium loads from the Grassland Drainage Area from pre-project conditions (www.sfei.org/grassland/reports/). However, the magnitudes of the decrease were more significant just below the Grassland Bypass Project area (at Crows Landing). With transport downstream, the change in concentration was smaller, likely due to inflow from other tributaries (Figure 3-17). Concentrations are generally lower during the wet years (1996 and 2006) and a negative correlation between flow and concentrations was noted (Figure 3-18). The weekly total selenium concentrations measured by SWAMP were extrapolated to daily concentrations for the week and multiplied by daily flow to estimate daily total selenium loadings for the San Joaquin River. Estimated daily loadings were summed up to calculate seasonal and annual loadings (Figure 3-19). Estimated annual loadings for total selenium based on SWAMP dataset are generally comparable to although slightly higher than loadings of dissolved selenium estimated from the Cutter and Cutter (2004) data (Figure 3-20) except for water years 1998 and 2006, when larger discrepancies between the two methods were observed.



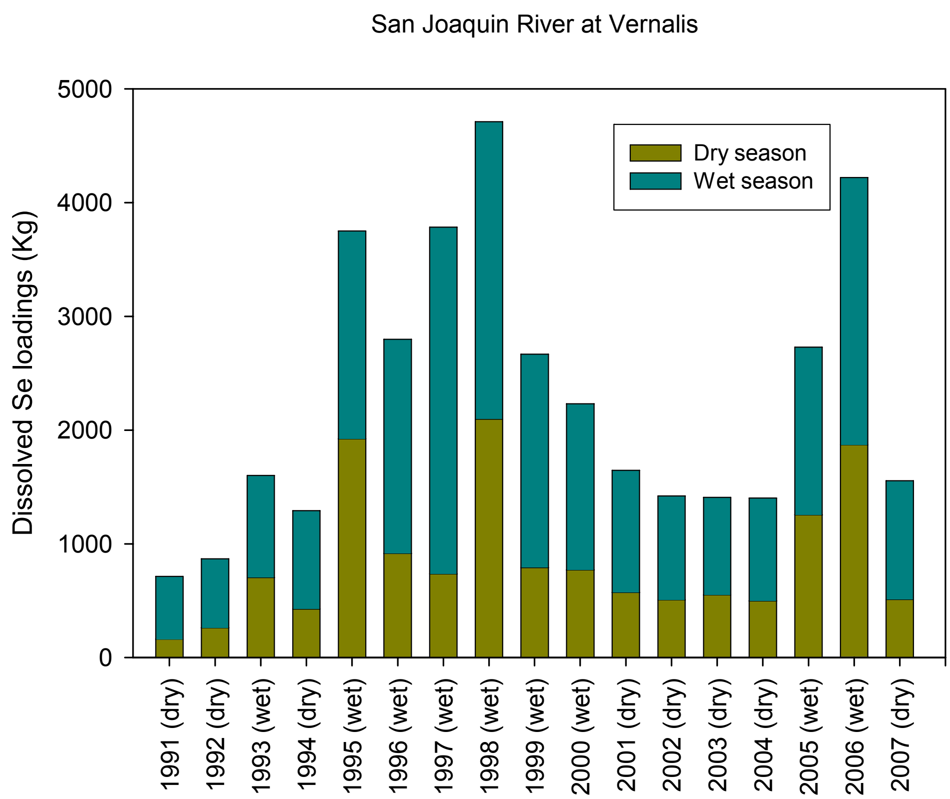


Figure 3-14 Dry and wet season dissolved selenium loadings at Sacramento River at Freeport and San Joaquin River at Vernalis for 1991-2007.

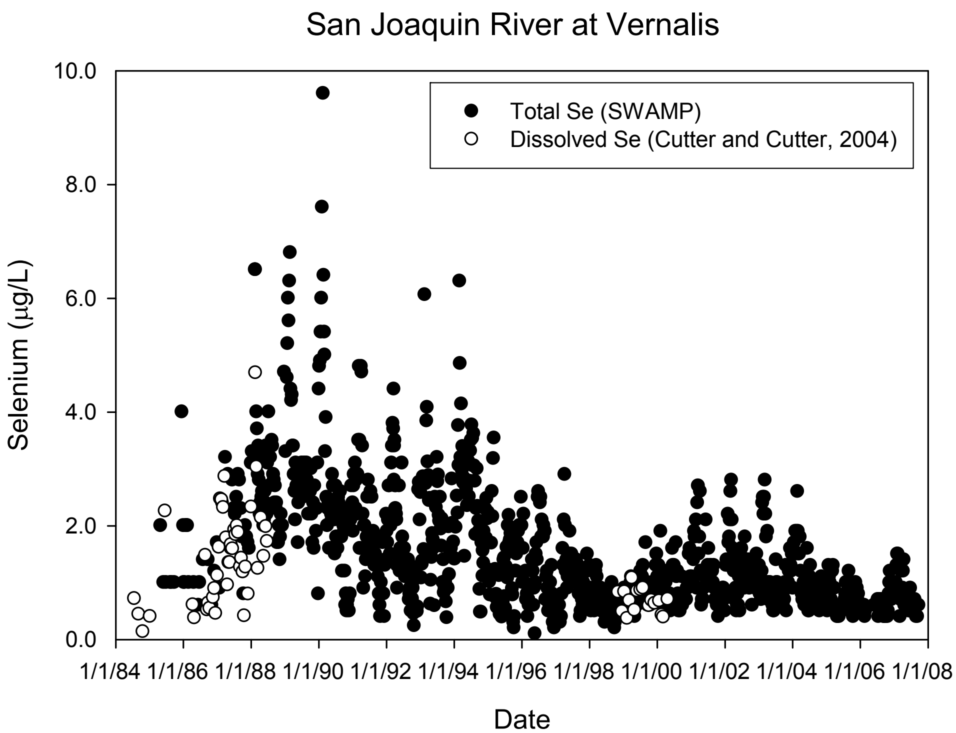


Figure 3-15 **Dissolved selenium concentrations sampled by Cutter and Cutter (2004) at San Joaquin River at Vernalis compared to total selenium concentrations observed in SWAMP study.**

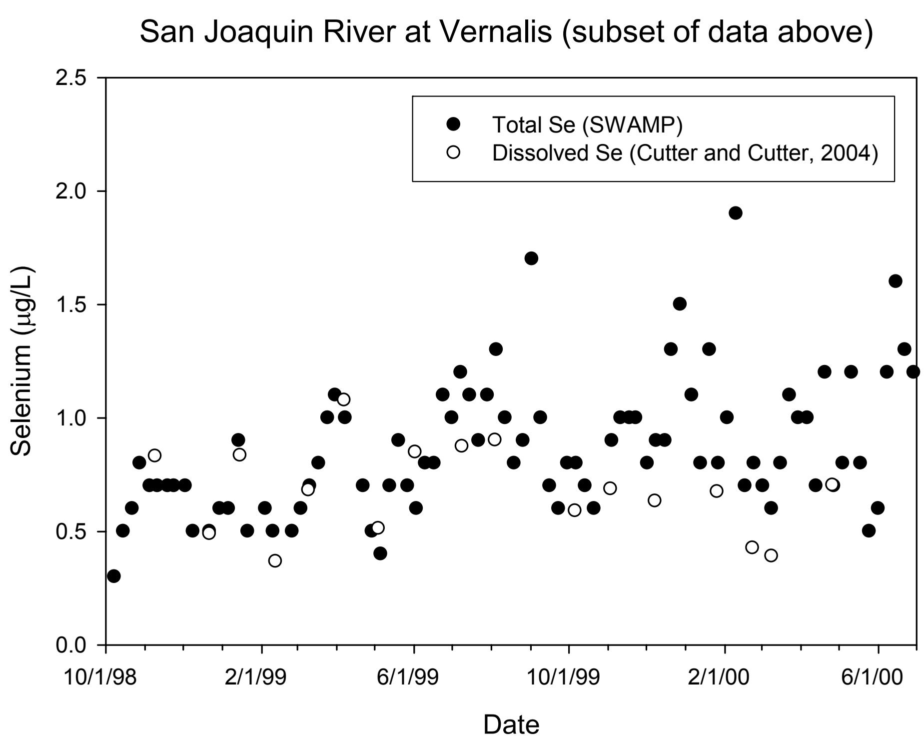


Figure 3-16 **A subset of dissolved selenium concentrations sampled by Cutter and Cutter (2004) compared to total selenium concentrations from SWAMP.**

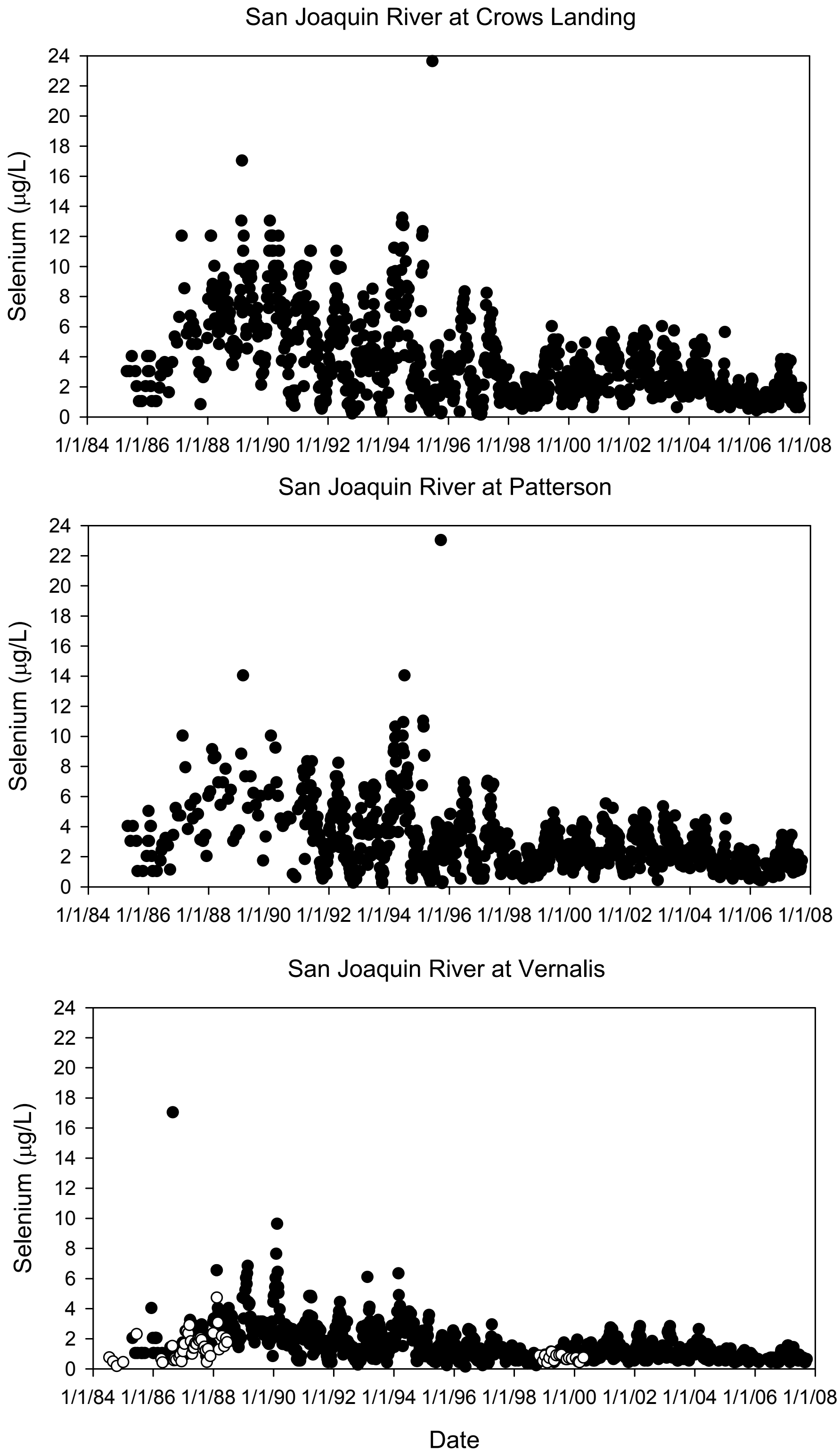


Figure 3-17 Total selenium concentrations along main stem of San Joaquin River at Crows Landing (below grassland bypass project), at Patterson, and at Vernalis (Data Source: Central Valley RWQCB)

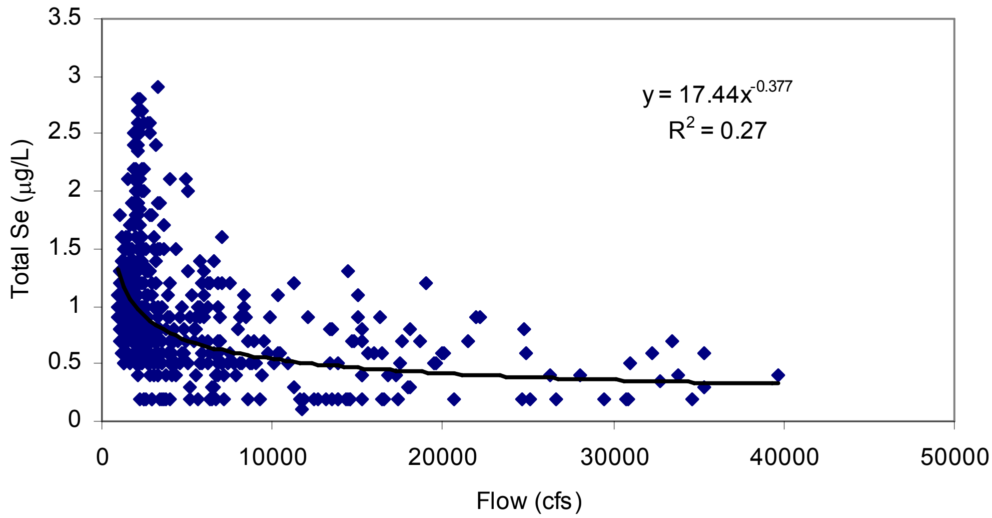


Figure 3-18 **Relationship between total selenium and flow at San Joaquin River at Vernalis (Data source: Central Valley Regional Water Quality Control Board SWAMP study and USGS).**

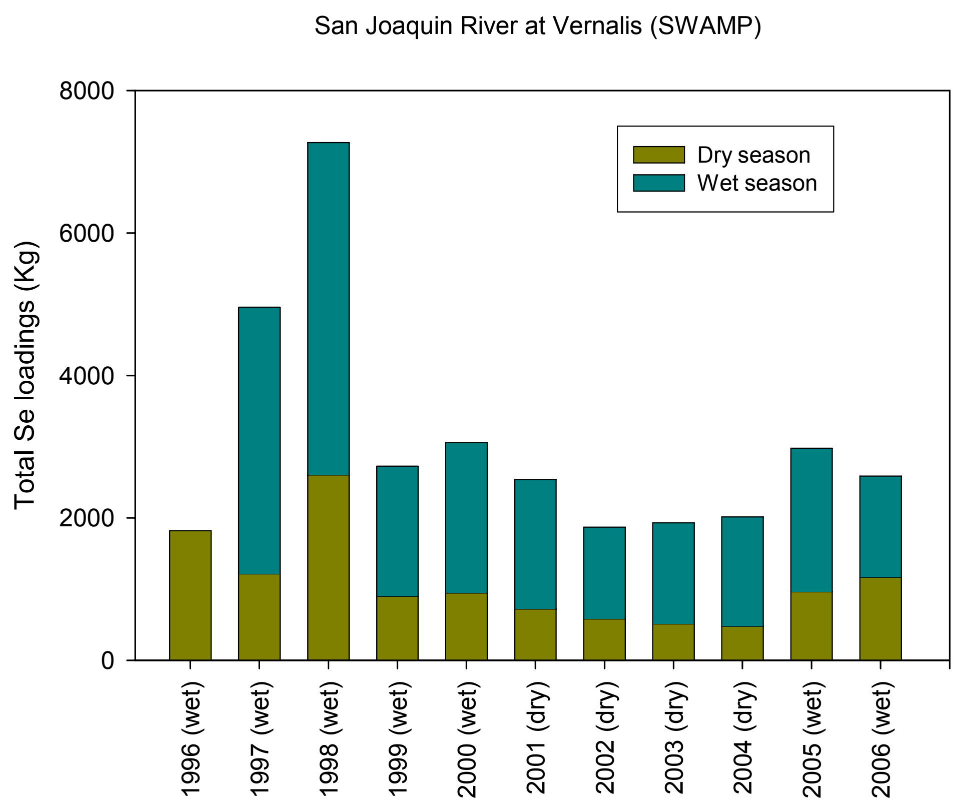


Figure 3-19 **Dry and wet season total selenium loadings at San Joaquin River at Vernalis, estimated from concentrations from SWAMP study.**

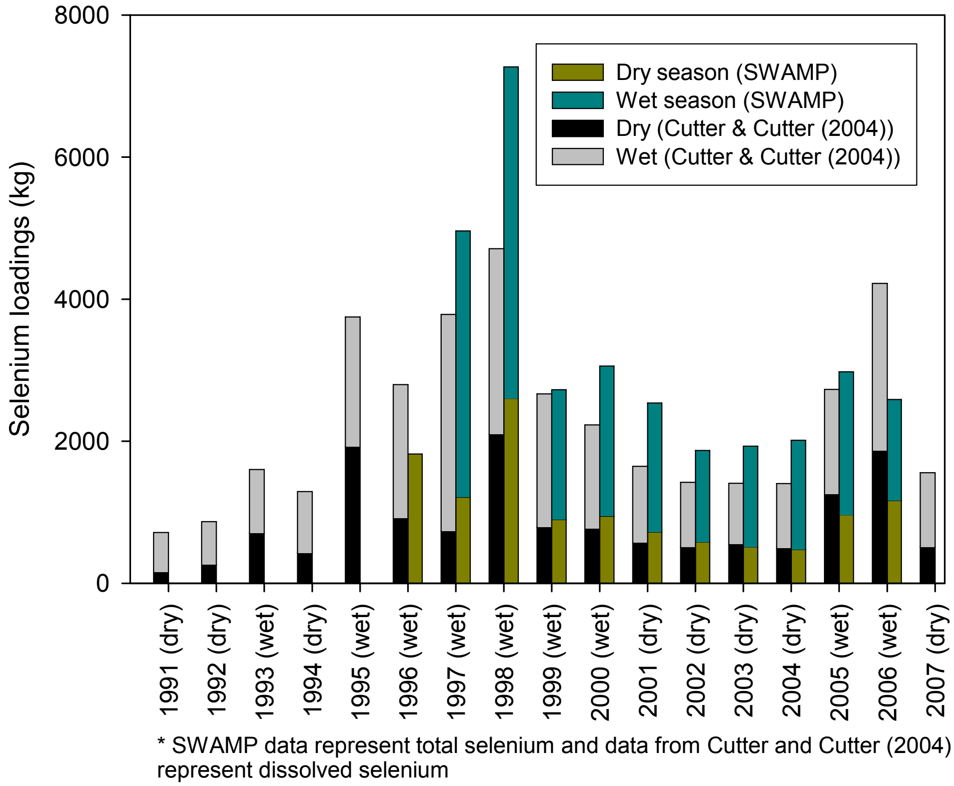


Figure 3-20 Comparison of selenium loadings at San Joaquin River at Vernalis estimated from Cutter and Cutter (2004) data and data from SWAMP study.

Biogeochemical processes in the Delta could potentially serve as a mechanism to remove high selenium concentrations originated from the San Joaquin River. As shown in Figure 3-21, during two low flow sampling events, dissolved selenium concentrations were high in close proximity to the San Joaquin River and decrease through the Delta. Dissolved selenium concentrations at the head of estuary were much lower than the concentrations observed close to the river.

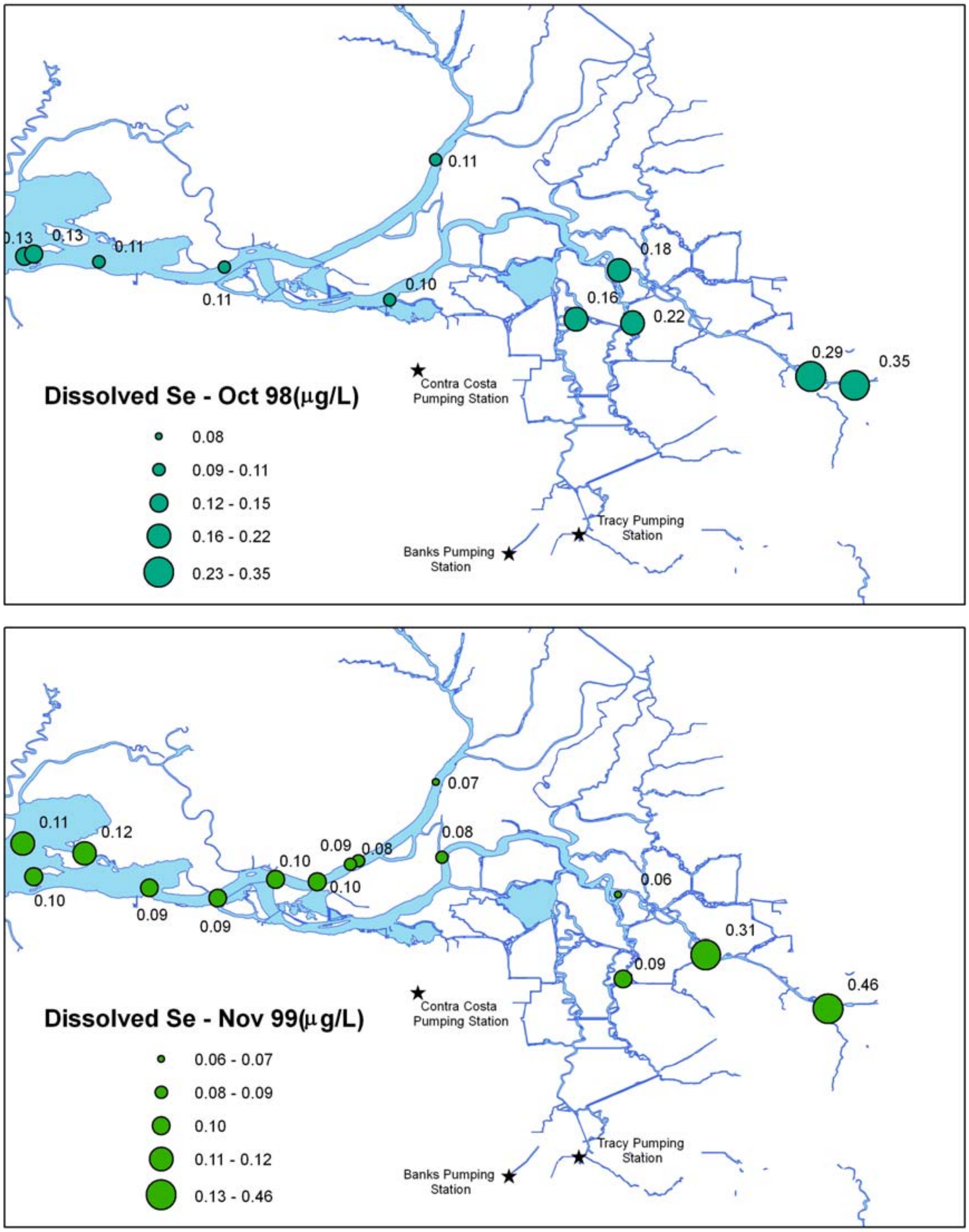


Figure 3-21 Dissolved selenium concentrations at various locations of the Delta and North Bay in October 1998 (NDOI = 4.27×10^{10} L/d) and November 1999 (NDOI = 1.07×10^{10} L/d) sampling (Cutter and Cutter, 2004).

Meseck (2002) fitted sine wave equations to selenium data from the Sacramento and San Joaquin Rivers, and used the fitted functions to estimate riverine loads. Based on samples collected during fall 1998 and summer 2000, selenium concentrations at Vernalis are reduced by 60-80% after being transported through Delta into the estuary at Antioch.

Therefore, Meseck (2002) applied a "Delta removal" constant of 60% to predict actual input of selenium at Antioch from the San Joaquin River.

Using the approach described by Meseck (2002), if a removal constant of 60% was applied to the San Joaquin River inputs, resulting dissolved selenium loading based on estimated river loadings varies between 1,005- 4,578 kg/yr (Figure 3-22). The estimated loadings were compared to Method 1, above, for each year. The percent absolute difference between the two methods for each individual year ranges between 6.3-51.9% except for 1998, an unusually wet year. For 1998, previous method estimated a significantly higher loading of 9,736 kg/yr compared to 4,578 kg/yr using the second approach.

For this method, an average load of 2,493 kg/yr for 1991-2007 from Delta to the Bay was estimated. Average load at Sacramento River at Freeport is 1,577 kg/yr. Average load at San Joaquin River at Vernalis is 2,289 kg/yr.

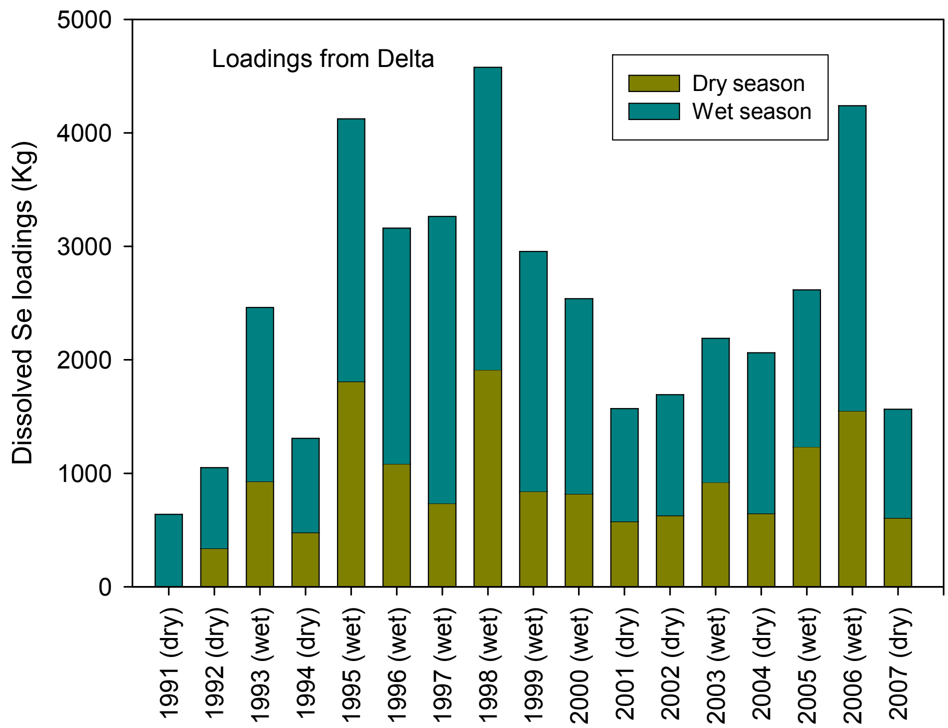


Figure 3-22 Estimated selenium loadings from the Delta to the bay as a result of inputs from Sacramento River at Freeport and San Joaquin River at Vernalis, assuming a "Delta Removal Constant" of 0.60.

Both Methods 1 and 2 have limitations in estimating selenium loads from the Delta. The previous method based on RMP monitoring dataset at BG20 and BG30, has the potential issue of overestimating loads during dry season due to tidal influence. The second method, through applying a "Delta removal constant" cannot account for the varying impacts of Delta on the selenium inputs to the Bay. As discussed next, an alternative is to consider outflow data from the Delta through aqueducts, and the estimated selenium concentrations in these outflows, to evaluate the net loads delivered to bay.

3.4.3 Method 3. Calculate selenium loadings to bay by accounting for export through aqueducts

Average export of water from Delta through aqueducts was 6.82 ± 0.90 × 109 m3/yr during 1994-2006. Flow at pumping plants is mostly dominated by Sacramento River water. During some periods, San Joaquin River water can also dominate. Assuming equal volume mixing of the two rivers, the selenium concentration in pumping plants is approximately 0.4 µg/L (0.07 µg/L at Sacramento River at Freeport and 0.68 µg/L at San Joaquin River at Vernalis). Assuming a concentration range of 0.1 µg/L (low end, when Sacramento River dominates) to 0.4 µg/L, the export of selenium through aqueducts is likely to range between 700- 2,700 kg/yr. For critically dry years during 1986-1998, Presser and Luoma (2006) estimated an aqueduct export of 1,557 kg/6 months, a value comparable to the higher end of this estimated range.

A more detailed computation of the riverine contribution to exports can also be performed. The contribution of the Sacramento and San Joaquin Rivers or other relatively minor inflows to State Water Project (SWP) pumping plant at Banks was previously modeled using a hydrodynamic model (Delta Simulation Model, Version 2, or DSM2) by the California Department of Water Resources (DWR). Results from DSM2 simulations indicated that during dry years or in the dry season, Sacramento River is the major source of flow at Banks pumping plant (DWR 2004; Figure 3-23). During wet years or in wet seasons, San Joaquin River can contribute a large portion of the flow. Results from these DSM2 fingerprinting simulations were used to estimate selenium concentrations at the pumping plant based on concentrations from the Sacramento and San Joaquin Rivers, and selenium loads exported through aqueducts.

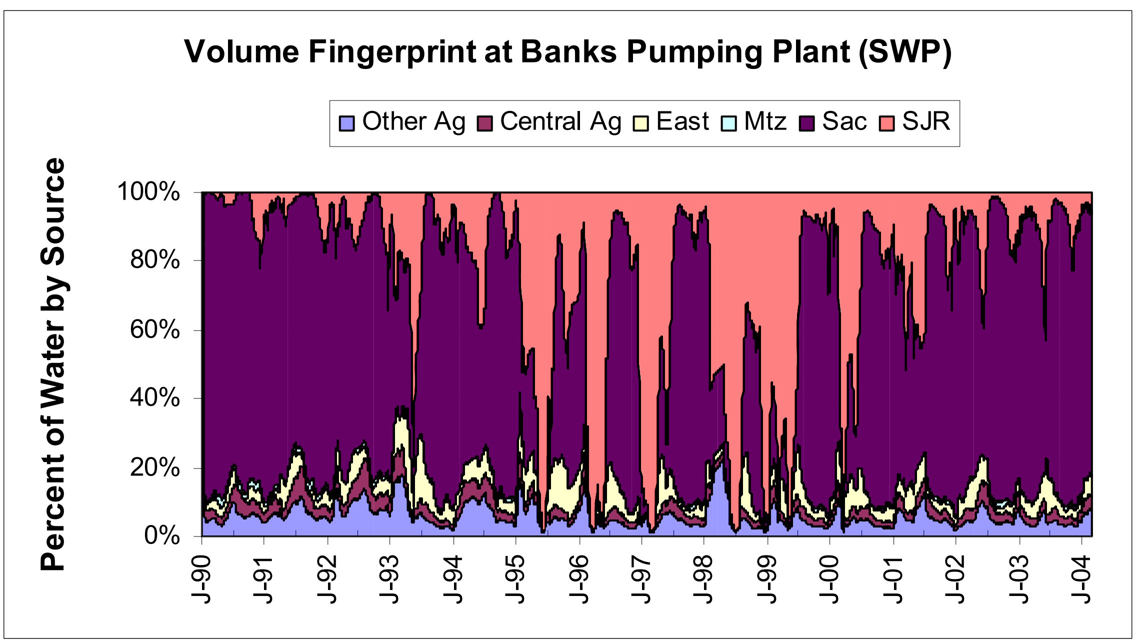


Figure 3-23 Long-term percentage contribution of flows at the Banks Pumping Plant (data provided by DWR; Tetra Tech, 2006).

Concentrations at pumping plants were estimated as:

$$Cexp = (Qsac * Csac + Qsjr * Csjr) / Qexp \quad (1)$$

Where Cexp is daily concentration in the aqueduct, Qsac is export flow originating from the Sacramento River, Csac is daily selenium concentration at the Sacramento River at Freeport (estimated from monthly concentrations from Cutter and Cutter, 2004), Qsjr is export flow originating from the San Joaquin River, Csjr is daily selenium concentration at the San Joaquin River (estimated previously based on relationship between flow and concentrations using data from Cutter and Cutter, 2004), and Qexp is total flow through the aqueducts (includes the Central Valley Project, State Water Project, Contra Costa Water District, and North Bay Aqueduct). We made the assumption that the flow composition from the two rivers at Banks pumping plant is the same as the other pumping plants.

Estimated concentrations in the aqueduct were multiplied by the export flow (obtained from DAYFLOW) to calculate selenium loads lost from the Delta through aqueducts. The seasonal loads were calculated by adding the daily loads. Estimated loads exported through aqueducts for the years between 1993-2003 range between 883 – 1,985 kg/yr (Figure 3-24). Dry season loads are comparable to wet season loads, largely because aqueduct exports are less variable than riverine flows over the course of the year. For a few years dry season loads exceed wet season loads (e.g. 1995, 1998). The range of annual exported loads using this approach is similar to what was determined previously, i.e., 700-2,700 kg/yr.

Contribution of loads to aqueducts from the two rivers was also estimated based on modeled contribution of flow from the two rivers and concentrations at each river. The results indicated that the San Joaquin River is the major, but not the only, source of selenium to the aqueducts. Estimated selenium loads from the Sacramento River are significantly lower ranging between 193- 486 kg/yr for 1993-2003, compared to 600-1,780 kg/yr from the San Joaquin River. Although the Sacramento River dominates in terms of flow in the aqueducts most of the time, due to higher selenium concentrations, San Joaquin River contributes more selenium loads to aqueducts.

Assuming other losses are small, loads from the Delta to the bay can be estimated as the difference between total loads from the two rivers and the export through aqueducts. Estimated loads from the Delta to the bay show large variations among the years (1993-2003; Figure 3-25). Loads for dry years are approximately 1,000 kg/yr (e.g. 1994, 2001). Loads in wet years can be much larger (nearly 6,000 kg/yr in 1998). Contribution of loads from the two rivers to the Delta outflow was estimated as the difference between loads from the rivers and the export through aqueducts. Estimated loads from the two rivers to the Delta are generally comparable. Annual selenium loads from the San Joaquin River are normally below 1,000 kg/yr. However during wet years larger loads can originate from the San Joaquin River (exceeding loads from the Sacramento River). Dry season loads from San Joaquin River to the Bay normally range between 200-300 kg. However for a few wet years, dry season loads from the San Joaquin River are approximately 1,000 kg. An average dissolved selenium load of 2,696 kg/yr from the Delta to the bay for 1993-2003 was estimated using this method.

Observed selenium concentrations at Delta-Mendota Canal near Tracy Headworks (Milepost 3.50) obtained from U.S. Bureau of Reclamation are higher than the estimated selenium concentrations in the aqueducts using the flow-weighted method described above (Figure 3-23). Note the observed concentration at Delta-Mendota Canal has a high detection limit of 0.4 µg/L. Estimated loads in Delta-Mendota Canal near Tracy Headworks by Bureau of Reclamation are at 792-1279 kg/yr for water year 2002-2006. Given approximately equal export volume in the CVP and SWP, exported loads in aqueducts can range between 1580-2560 kg/yr. The range of loads is at the higher end of our estimates of 700- 2700 kg/yr.

Selenium concentration data from the State Water Project (SWP) aqueducts have been reported using relatively high detection limits. The SWP publishes data from monthly grab samples at the Banks Pumping Plant (http://wwwomwq.water.ca.gov/GrabSamplePage/GrabSampleTables/index.cfm) with a detection limit of 0.001 mg/L or 1 µg/L, with most samples being below detection limits. These data were not used in the calculations.

3.4.4 Summary of Delta load calculations

Although loads from the Central Valley are a major source of selenium to NSFB, the estimation of these loads is not straightforward because of tidal influences at the edge of the Delta and the bay, and because of complexities caused by mixing and water export from the Delta. The load estimates are more difficult because of the limited data in the Delta and the aqueducts.

Our approach in this section was to apply three different methods to compute loads, and to compare these values. Note that for the second and third methods, data was available to compute only the dissolved selenium loads and not the total load.

- The first approach used average concentration of two RMP stations in the Delta and multiplies it by the net tidally corrected Delta outflow. This resulted in an annual average load estimate of 3,962 kg/yr of **total selenium** from the Delta to the NSFB (1994-2006).
- The second approach used selenium loadings from the Sacramento and the San Joaquin Rivers separately based on data from Cutter and Cutter (2004) and applied a "Delta removal constant" similar to Meseck (2002) to account for the possible selenium loss in the Delta. These concentrations were reported only as dissolved selenium, not total selenium. This resulted in an annual average load estimate of 2,493 kg/yr of **dissolved selenium** (1993-2003).
- The third approach was independent of the prior two: the loadings from Central Valley to the bay were estimated as the difference between inputs from the two rivers minus the export through aqueducts, and assuming minimal loss processes in the Delta. This resulted in an annual average load estimate of 2,696 kg/yr of **dissolved selenium** (1993 to 2003).

Given the simplifications and assumptions employed in these load calculations, and given that some loads are in terms of dissolved selenium, the range of annual averages is small, and the methods are supportive of one another. Because the data used in the analysis was most abundant for Method 1, and both total and dissolved data were available, and because the flow volumes used in load calculation are tidally corrected, it is recommended that this method be used for describing Delta loads, resulting in an average Delta to bay export of 3,962 kg/yr.

Particulate selenium loads from the Delta to the Bay were estimated based on previously estimated TSS loads by Leatherbarrow et al. (2005a) or McKee et al. (2006) at Mallard Island. McKee et al. (2006) based on continuous monitoring data of SSC at Mallard Island to estimate TSS loads for water year 1995-2003. Reported TSS loads at Mallard Island vary greatly with water years ranging from 0.26 ± 0.08 Mt/yr (2001) to 2.6 ± 0.8 Mt/yr (1995). Particulate selenium concentrations average 0.62 ± 0.21 µg/g (n =5) at the Sacramento River and 0.66 ± 0.42 µg/g (n =5) at the San Joaquin River (Doblin et al. 2006). Therefore an average concentration of 0.64 µg/g was used in the calculation for all years. As a result, estimated particulate selenium loads from Delta range between 151 – 1,510 kg/yr for 1995-2003 (mean: 698 kg/yr). The estimated loads are higher than those estimated by Abu-Saba and Ogle (2005) for November 1997 to November 1999 (47-686 kg/yr).

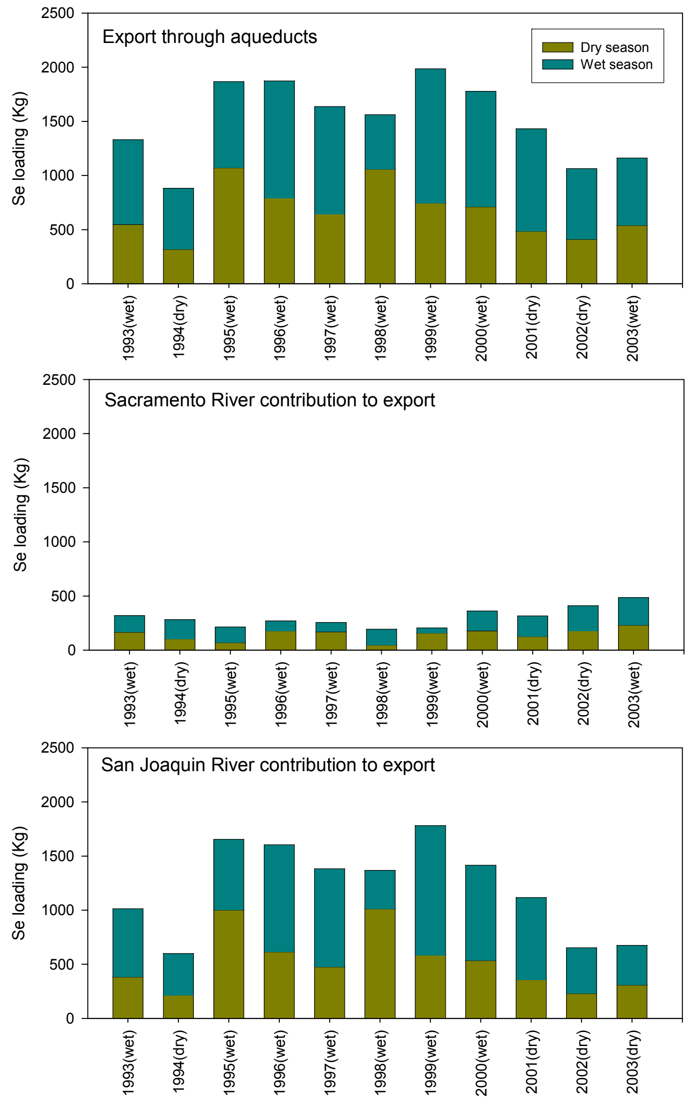


Figure 3-24 **Estimated selenium loadings through the aqueducts and contributions from the Sacramento River and the San Joaquin River.**

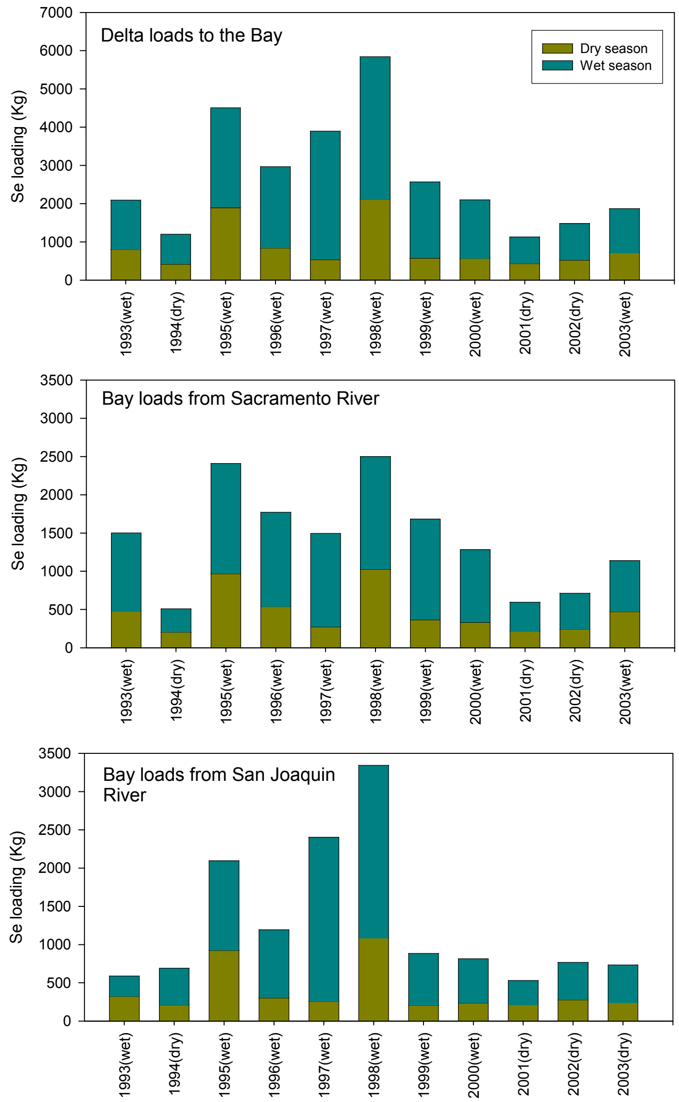


Figure 3-25 Estimated selenium loadings from the Delta to the Bay as the difference between loads from the Rivers and export through aqueducts, as well as contributions attributed to the Sacramento River and the San Joaquin Rivers individually.

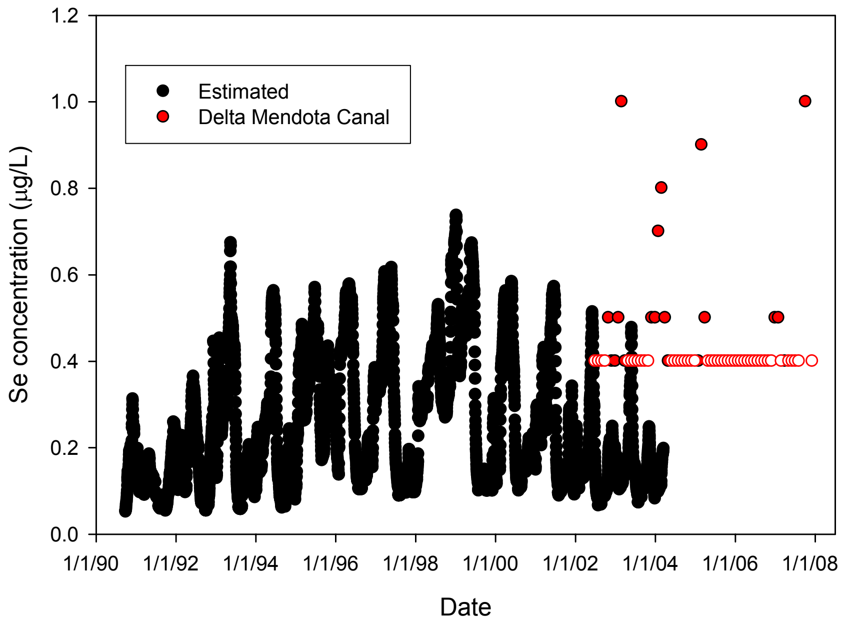


Figure 3-26 **Estimated selenium concentrations in the aqueducts using flow weighted method compared to observed concentrations in Delta Mendota Canal near Tracy Headworks (MP 3.50) (Open circles indicates values below detection limit of 0.4 µg/L).**

3.5. MUNICIPAL AND INDUSTRIAL WASTEWATER DISCHARGERS

Currently there are a total of 17 Publicly Owned Treatment Works (POTWs) located in the North Bay (Figure 3-27). Most of these facilities receive secondary treatment with a few with advanced treatment (i.e., City of American Canyon, Napa Sanitation District). Dry weather flows from these facilities range from 1 to 120 mgd.

Flow at five largest municipal dischargers in the North Bay is shown in Figure 3-28. Flow at municipal discharges generally follows a seasonal pattern of higher concentration during wet season, most likely due to storm water runoff. Concentrations in effluents of municipal dischargers generally are below 1 µg/L, with many samples below detection limit (Figure 3-29).

Effluent total selenium concentrations at a monthly interval are reported for these facilities. Total selenium concentrations in the effluents are generally near 1 µg/L (Table 3-11). Effluent concentrations at two facilities with the largest discharges (i.e., East Bay Municipal Utility District, EBMUD and Central Contra Costa Sanitation District, CCCSD) average 0.34 ± 0.19 µg/L and 0.34 ± 0.50 µg/L. Reported concentrations compared well to the dissolves selenium concentrations observed by Cutter and San Diego-McGlone (1990) during 1987-1988 sampling (24-hour composite sample at monthly intervals; CCCSD: 0.53 ± 0.11 µg/L, EBMUD: 0.37 ± 0.10 µg/L). No relationship between flow and concentrations in the effluent were observed. Therefore, no flow-concentration correlation was used in the load estimates.

Two methods were used in calculating daily loadings from POTWs. In the first method, the overall average daily maximum concentration was multiplied by overall average daily flow. In the second method, daily loadings were estimated based on flow and reported concentrations for all the available dates and an overall average of daily loadings was calculated. For concentrations reported as below the detection limit, concentrations were assumed to be half of the detection limit. Some non-detect data were reported with very high detection limits (e.g. 5 µg/L); in these cases data were disregarded. Estimated daily loadings show large temporal variations (Figure 3-30) related to the flow variability.

Estimated annual selenium loadings from POTWs in the North Bay are 230-234 kg/yr (Table 3-12). The loadings are roughly half of values previously estimated by Cutter and San Diego-McGlone (1990) for the entire bay (1.08 kg/day or 394 kg/yr).

Effluents from municipal dischargers are dominated by selenate (60%), followed by selenite (25%) and organic and elemental selenium (15%; Cutter and San Diego-McGlone, 1990).

The second method used for POTWs was also used to calculate loadings from the industrial facilities in the North Bay. Loadings from industrial facilities are minor compared to other sources (Table 3-13).

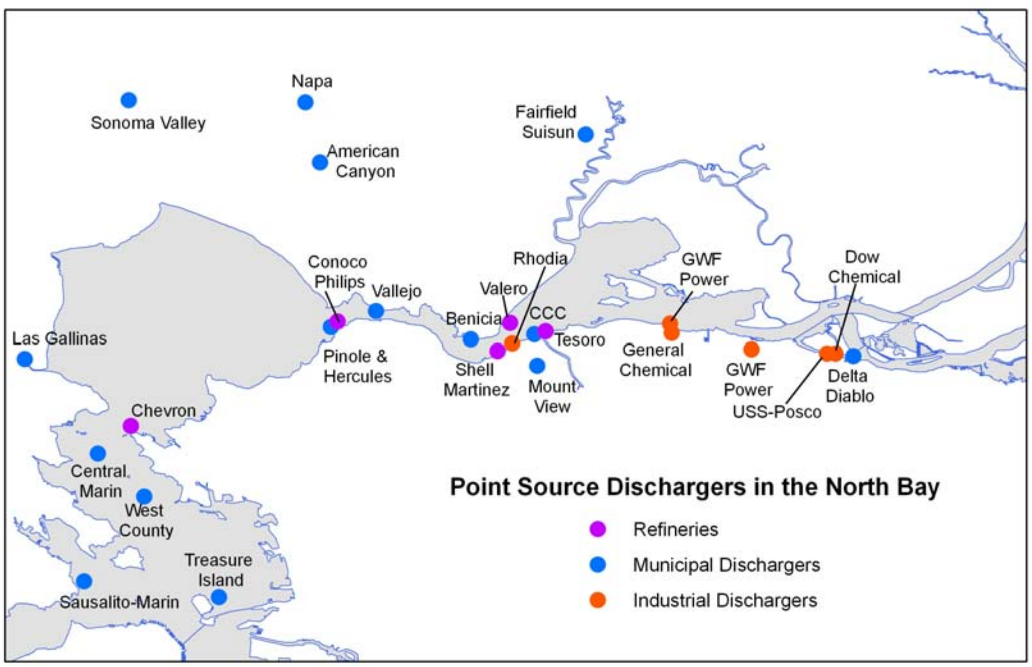


Figure 3-27 Point source dischargers in the North Bay (source: SFBRWQCB).

Table 3-11
Summary statistics of daily maximum effluent concentrations at the municipal dischargers

Municipal dischargers	Mean[1]	S.D.	Min	Max	Count
American Canyon	1.16	0.59	0.2	2	32
City of Benicia	0.81	0.51	<0.3	5	97
Central Contra Costa	0.34	0.50	<0.05	4	99
Central Marin Sanitation Agency	0.75	0.68	0.17	6.4	98
Delta Diablo	4.21	7.54	<1	37	100
EBMUD	0.34	0.19	<0.2	1.6	294
Fairfield-Suisun Sewer District	0.75	0.38	0	2	95
Las Gallinas Valley SD Permit	0.64	0.17	0.5	0.97	10
Mount View Sanitary District	0.62	0.60	<0.02	5	37
Napa Sanitation District (dry)	0.57	0.21	<0.5	1	13
Napa Sanitation District (wet)	0.27	0.25	0	<1	26
Petaluma Permit	0.65	0.23	0.35	1.4	60
Pinole-Hercules	0.91	0.66	<0.1	4	47
Rodeo Sanitary District Permit	0.80	0.61	<0.1	3	30
Sausalito-Marin Sanitary District Permit	1.36	0.91	0.5	17.5	85
Sonoma Valley Permit	<5.00	0.00	<5	<5	27
US Navy Treasure Island Permit	0.29	0.17	<0.25	8.96	46
Vallejo San & Flood Control District	0.84	0.52	<0.7	10.6	79
West County/Richmond Permit	1.40	0.97	0.25	9	60

1. For values below detection limit, half of the detection limit was used in mean calculation.

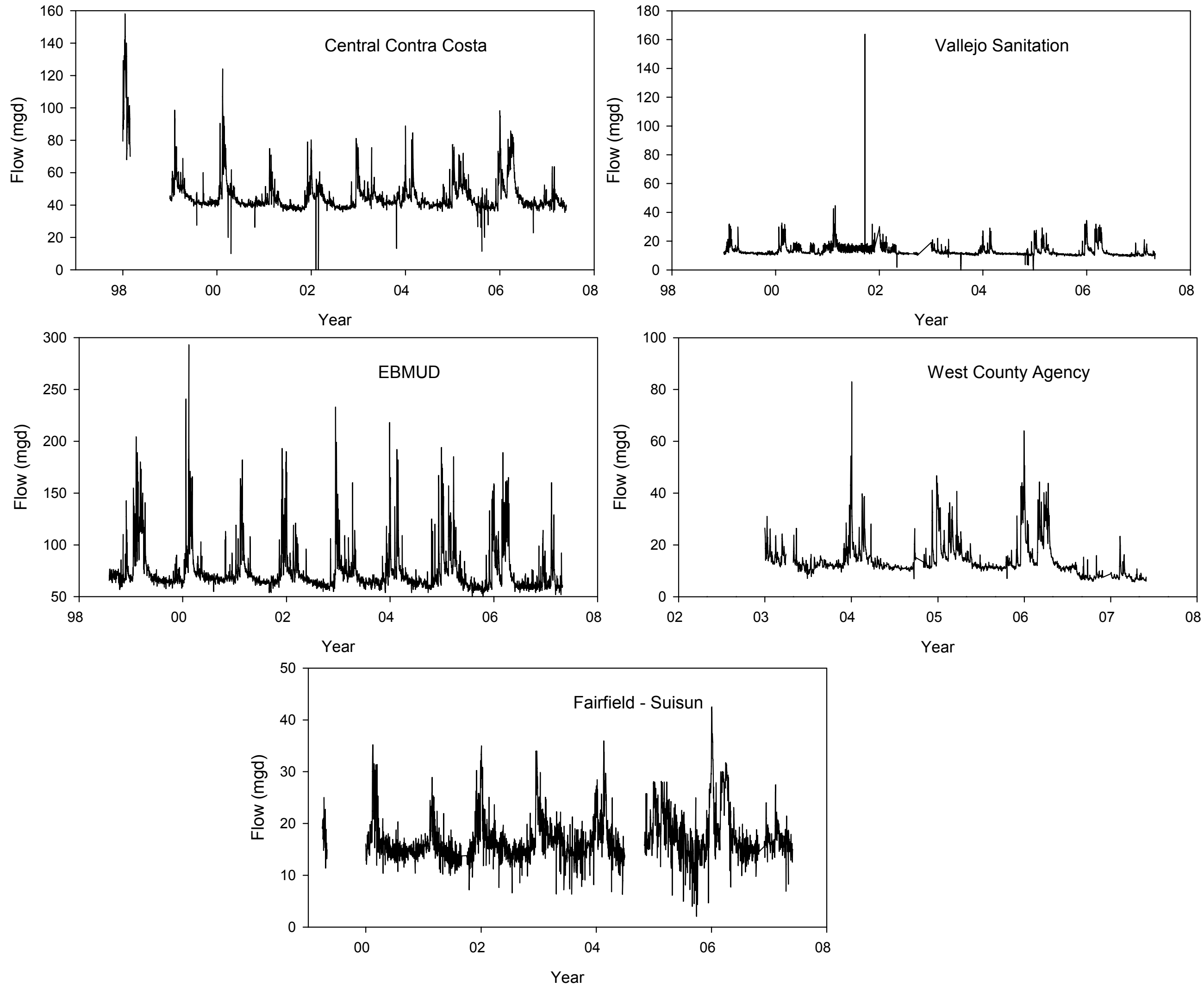


Figure 3-28 Daily effluent average flow at five largest dischargers in North Bay.

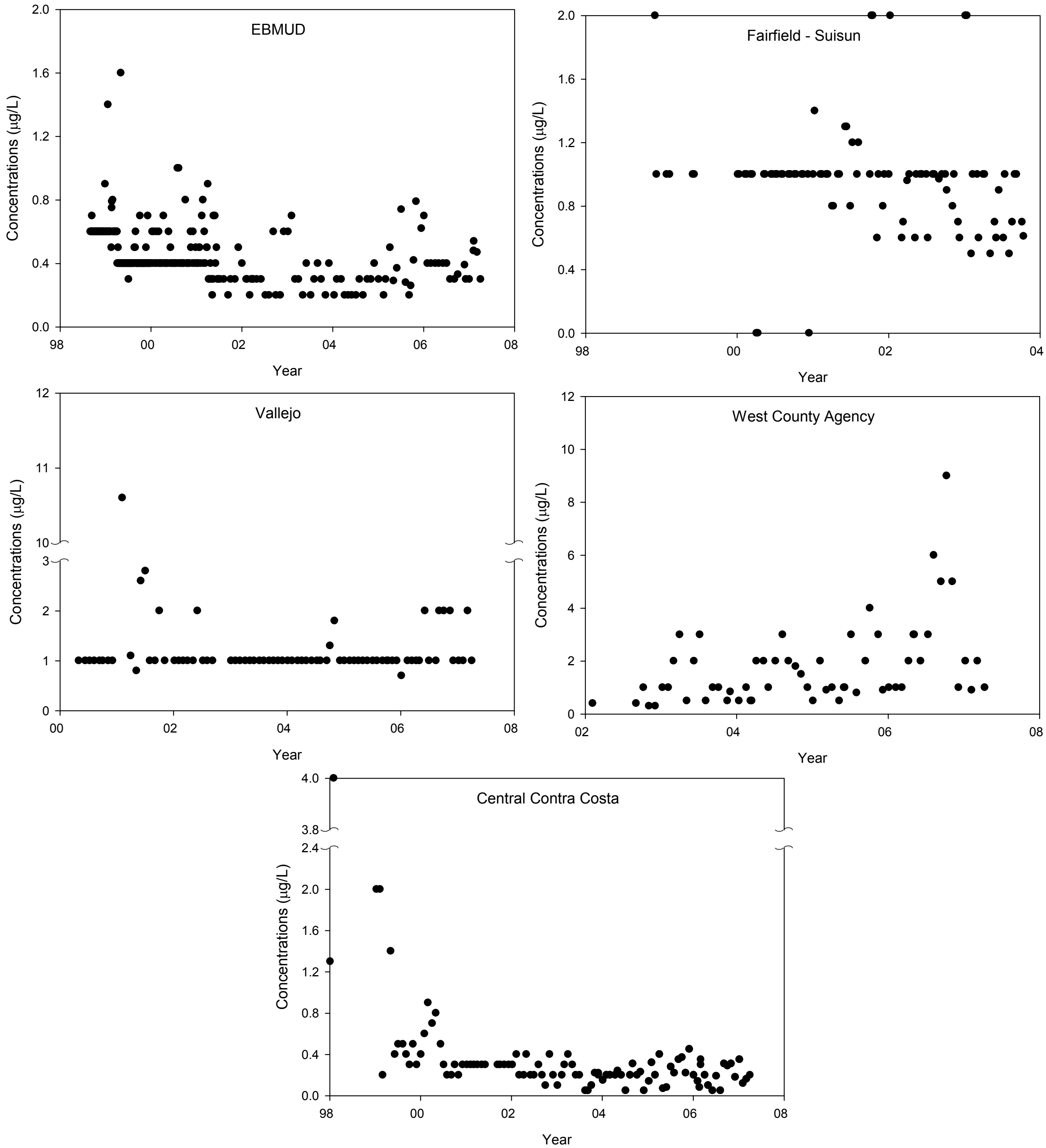


Figure 3-29 Effluent maximum concentrations at the five largest dischargers in the North Bay.

Table 3-12
Estimated total selenium loadings from POTWs in the North Bay

POTW Facility Name	Average flow (mgd)	Estimated Se Loadings[1] (kg/yr)	Estimated Se Loadings[2] (kg/yr)
City of American Canyon	0.9	2.1	1.5
City of Benicia	3.0	3.5	3.4
Central Contra Costa S.D.	74.6	21.8	15.0
Central Marin Sanitation A.G.	11.0	12.3	10.7
Delta Diablo	11.46	66.6	64.1
East Bay MUD	74.6	34.8	36.9
Fairfield Suisun Sewer Dist.	17.0	17.5	16.8
Las Gallinas Valley S.D.	3.5	3.3	4.0
Mount View S.D.	2.0	2.3	1.5
Napa S.D.	8.9	8.2	14.1
City of Petaluma	7.6	11.2	8.3
Cities of Pinole & Hercules	3.2	4.0	4.2
Rodeo S.D.	0.8	0.9	0.9
Sausalito-Marin City S.D.	1.6	2.3	4.9
Sonoma Valley County S.D.	7.4		High DL (5 µg/L) [3]
U.S. Navy Treasure Island	0.5	0.4	0.25
Vallejo Sanitation & Flood Control	13.2	19.7	16.7
West County Agency WCA	14.1	19.5	30.7
Total	243.9	230.4	234.0

1 - Estimated based on overall average concentration and average daily flow

2 - Estimated based on flow and concentrations on all available dates

3 - Due to high detection limit of 5 µg/L, reported concentrations were below detection limit and therefore these data were not used in the load calculation.

Table 3-13
Estimated selenium loadings from industrial wastewater dischargers in the North Bay

Industrial Facilities	Daily loading (g/day)	Annual loading (kg/yr)
Dow Chemical	6.5	2.4
General Chemical	4.8	1.8
GWF (I)	1.05	0.4
GWF (V)	0.4	0.1
USS-Posco	31.0	11.3
Total	43.7	16.0

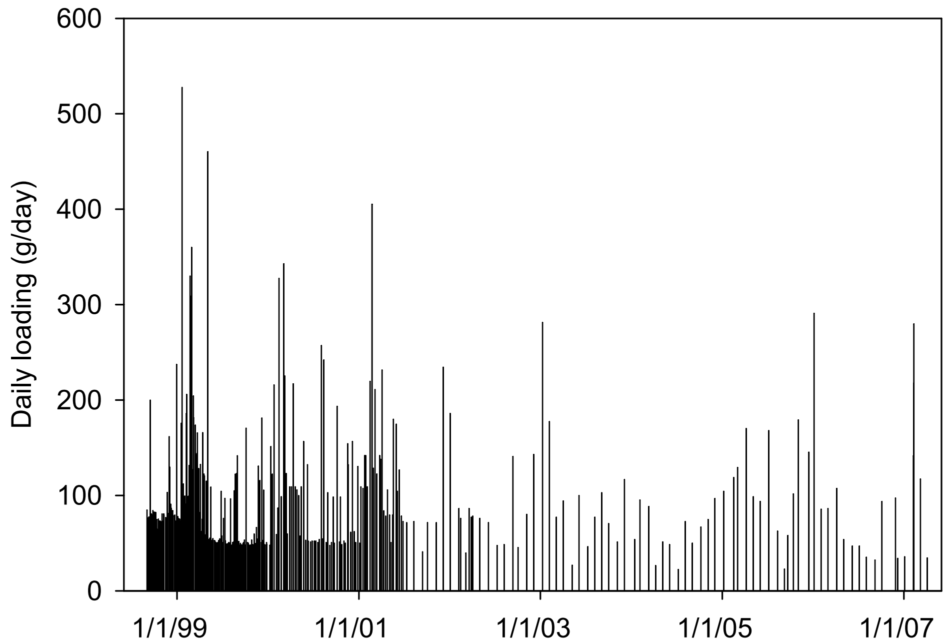


Figure 3-30 Estimated daily total selenium loadings from EBMUD.

3.6. PETROLEUM REFINERIES

Mean selenium concentrations at the refineries range between 11.9 – 27.7 µg/L (Table 3-14). Concentrations show relatively large variations over time (Figure 3-31). Daily flow measurement at the refineries indicates some seasonal high flows, probably due to storm water runoff (Figure 3-32). Concentrations generally show no correlation with flow (Figure 3-33).

For the five petroleum refineries located in the North Bay, daily loadings were estimated based on the continuous daily flow data and the reported effluent daily maximum concentrations on a weekly basis. Mean daily maximum concentrations for the refineries range between 12 – 28 µg/L. No relationship between concentrations and flow were observed. The annual loadings were calculated by summing the daily loadings. The estimated total daily loading from these refineries is 1.47 kg/day or an average of 537 kg/yr during 1999-2007 (Table 3-15). Current loadings are significantly lower than the previous years (1,407 – 3,382 kg/yr in 1986 – 1992) following the improvement in waste water treatment practices at the refineries (Presser and Luoma, 2006).

To calculate seasonal loads, daily loads were calculated by multiplying daily flow with weekly concentration extrapolated to the week and then adding up for dry and wet season. Wet season was defined as Oct. 1st to Apr. 30th. The dry season was defined as May 1st to Sep. 30th. Estimated annual selenium loadings are relatively constant throughout the years (Figure 3-34). Average dry season loadings are generally 62-78% of the average wet season loadings at four of the refineries. Average dry season loadings at Tesoro are only 35% of the wet season loadings.

The effluents are dominated by selenate (56%) and organic selenide (30%), with selenite accounting for only 14% on average (compared to 64% in 1987-1988, Cutter and Cutter, 2004). The speciation in refineries is similar to that in municipal wastewater effluents.

Table 3-14
Summary statistics of daily maximum effluent concentrations at the refineries

Refineries	Median	Mean	Standard deviation	Min	Max	Count
Chevron	11.2	12.1	5.9	2.3	48.0	308
ConocoPhillips (at Rodeo)	14.0	15.5	8.5	1.0	49.0	448
Shell Martinez	27.0	27.7	9.4	4.0	82.0	266
Tesoro	11.0	11.9	5.1	1.0	41.0	367
Valero	26.1	26.6	7.4	8.0	50.0	447

Table 3-15
Estimated total selenium loadings from petroleum refineries in the North Bay

Refinery	Flow (mgd)	Mean daily loading[1] (kg/day)	Mean daily loading[2] (kg/day)	Annual loading[1] (kg/yr)	Annual loading[2] (kg/yr)
Chevron	7.1	0.31	0.33	112.6	120.7
Conoco Philips	2.3	0.16	0.16	57.9	58.0
Shell Martinez	5.8	0.61	0.59	224.1	214.9
Tesoro	4.1	0.19	0.19	70.2	69.3
Valero	2.0	0.20	0.20	71.9	75.1
Total	21.3	1.47	1.47	536.7	538

1 – Calculated as continuous daily flow times weekly concentrations extrapolated to the rest of the week

2 – Calculated based on daily flow and concentrations on sampling dates only

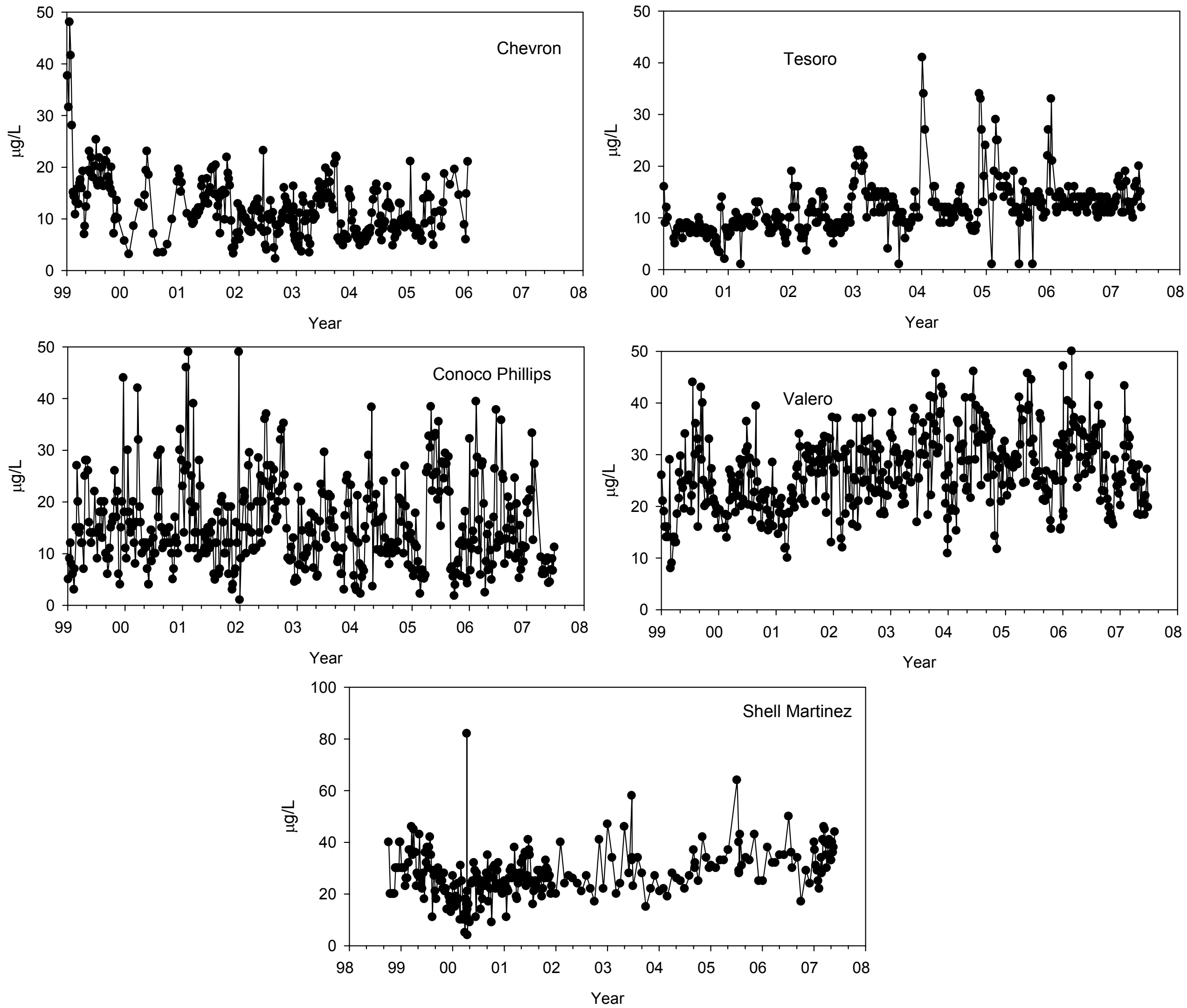


Figure 3-31 Effluent daily maximum selenium concentrations for the refineries in the North Bay.

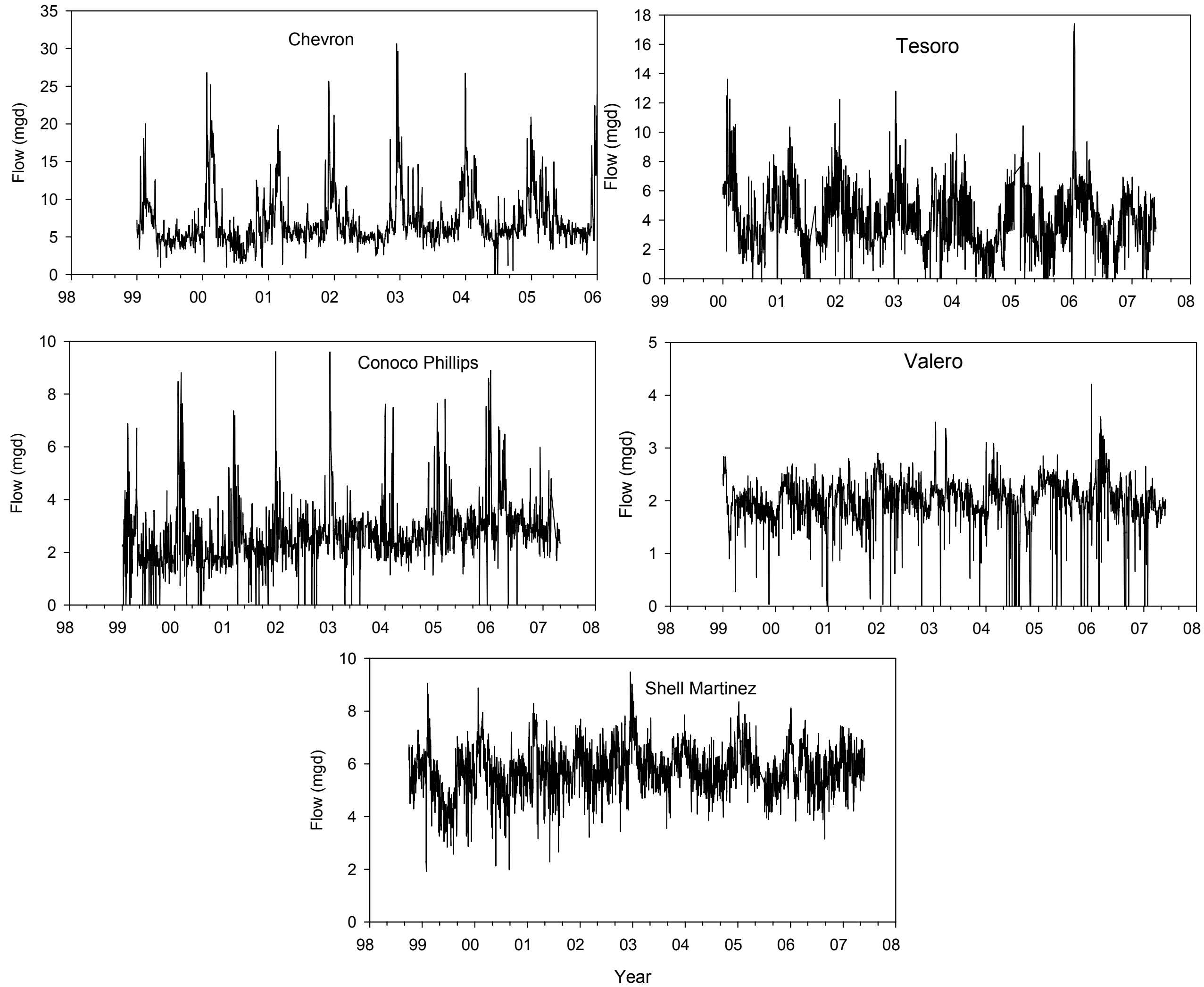


Figure 3-32 Daily average effluent flow rate from the refineries.

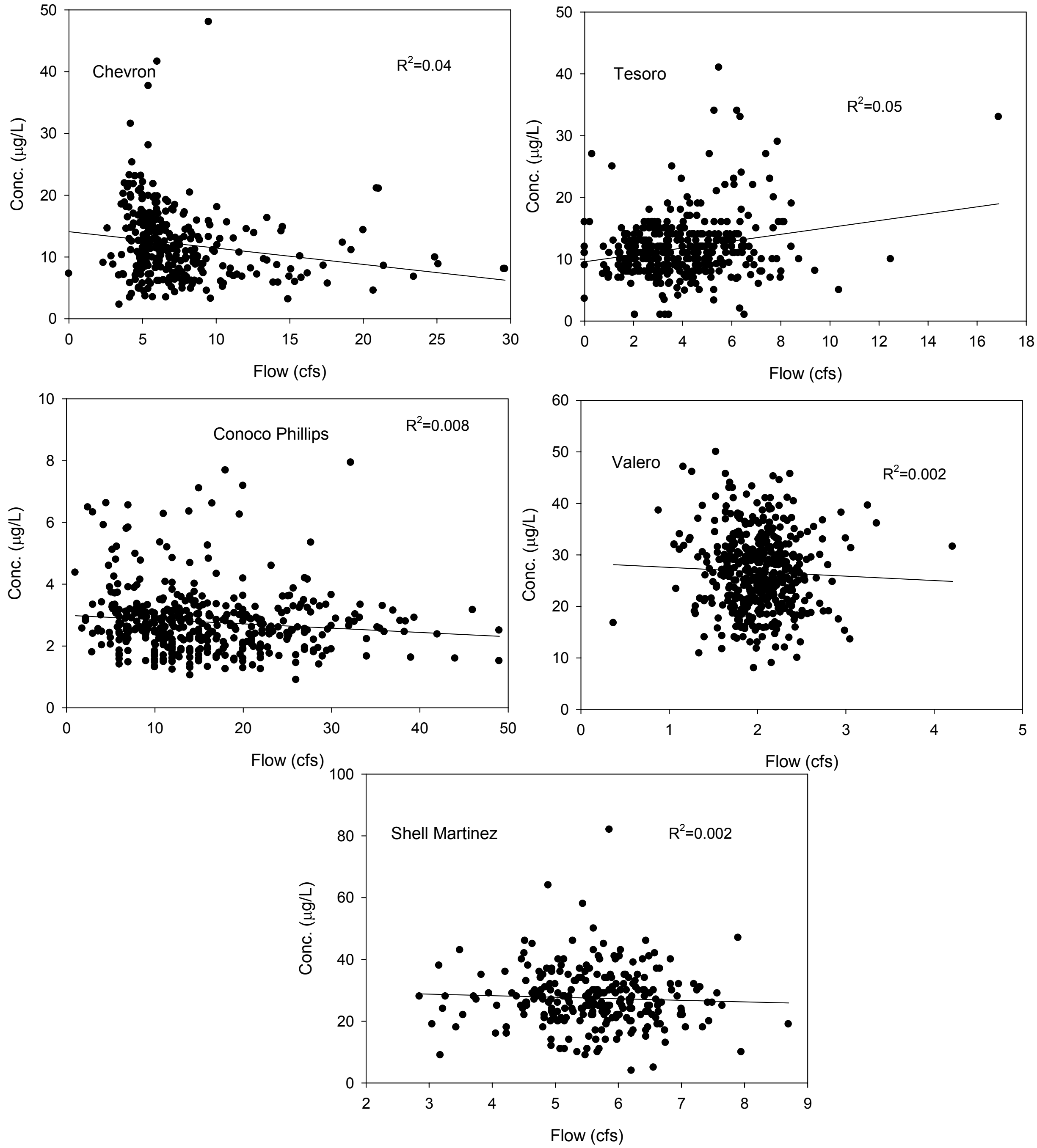


Figure 3-33 Concentrations and flow for the refineries in the North Bay. No meaningful correlations were found; the regression lines in the plots are to illustrate the lack of a relationship between flows and concentrations.

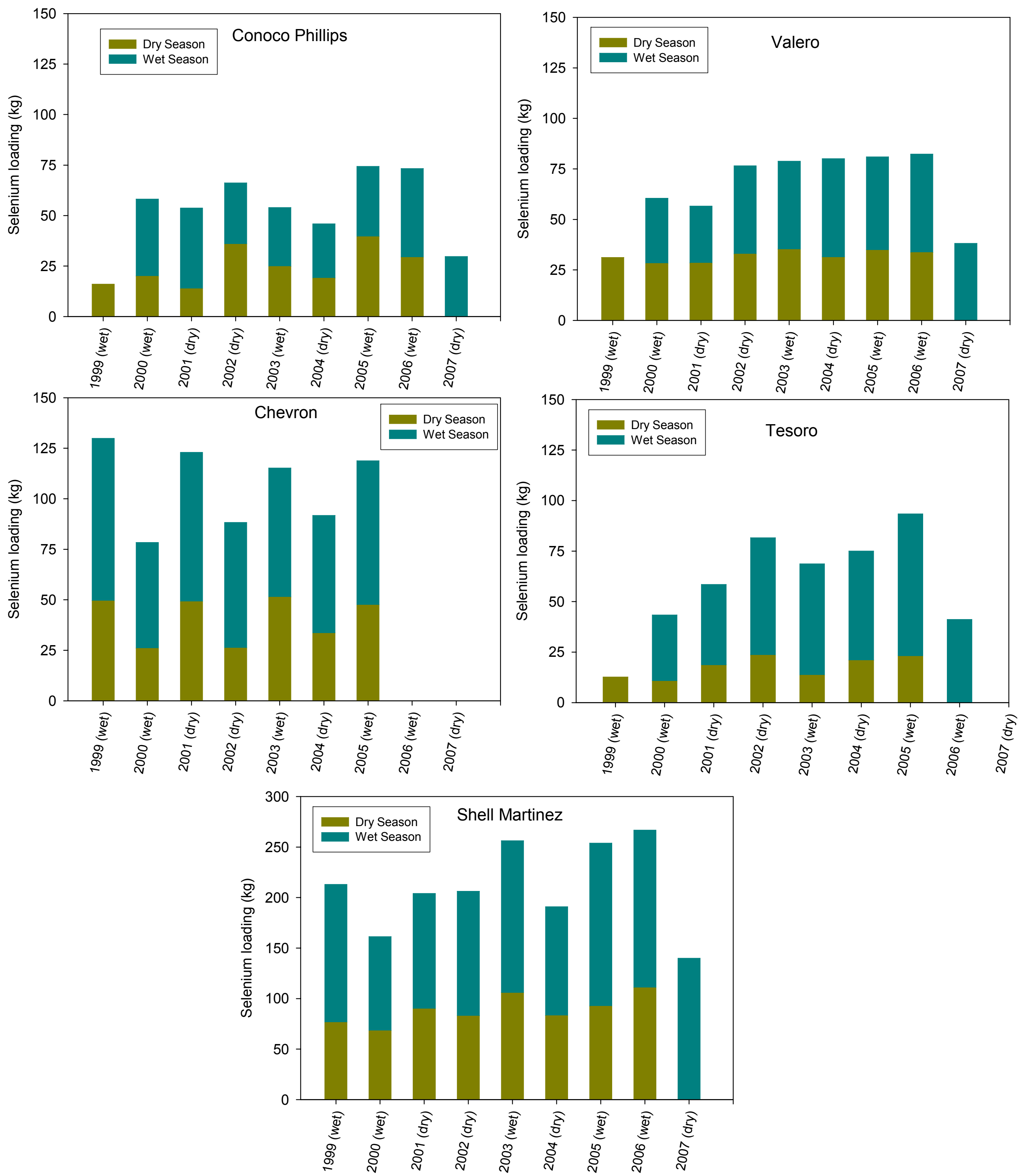


Figure 3-34 Dry and wet season selenium loadings from refineries for the years of 1999-2007.

3.7. Internal Sources - Sediment Erosion

Sediments in the North Bay represent a large reservoir of selenium (Abu-Saba and Ogle, 2005). A review of sediment processes in the San Francisco Bay indicated an active sediment mixing layer of 15 cm (Leatherbarrow et al. 2005b). Given the sediment mass for the upper 15 cm of the whole bay (1.4×10^{11} kg; Davis (2003), cited in Abu-Saba and Ogle, 2005) and mean selenium concentrations of 0.25µg/g, the selenium in the upper layer of sediments of North Bay is about 20,000 kg.[5]

Selenium in bottom sediments can be mobilized to the water column through resuspension, erosion, diffusion and bioturbation. Resuspension rates in the San Francisco Bay were found to be 2 to 5 times greater than the accumulation rates, indicating sediment is resuspended 2 to 5 times before settling (Leatherbarrow et al. 2005b). Previous studies indicated sediment residence time in the water column of 5 ± 3 days in San Pablo Bay. It was suggested that during summer low flow months, wind generated and tidal driven resuspension redistributes sediments to a wider area. Localized sediment erosion also occurs due to decreases in sediment supply from the surrounding watersheds. Net sediment erosion was found to occur both in the Suisun Bay and San Pablo Bay. For San Francisco Bay, the abundance of organisms has been found to potentially enhance mobilization of sediments to the water column. Diffusion of dissolved selenium from the sediment porewater to the water column has been found to be a small source, estimated at 18.2 kg/yr for the North Bay (Meseck, 2002). Direct biotic uptake of particulate selenium in bottom sediments by consumer organisms is another pathway of selenium mobilization, but this has not been quantified for the source analysis.

Selenium in sediments can also undergo a series of transformations (Meseck and Cutter, 2006). In deeper layers of sediment, selenate and selenite can be converted to elemental selenium due to microbial reduction. As a result, elemental selenium comprises a large portion of selenium in the sediments and the presence of elemental selenium in bay water can be an indicator of origin from bottom sediments. Organic selenide in surface sediment can also be oxidized to selenite and selenate or methylated by microbes.

Studies in San Pablo and Suisun Bay indicated that more erosion than burial is occurring in these two areas in the recent years (USGS 2001a, b). In Suisun Bay, net sediment erosion was 1-2 Mm^3/yr from 1887 to 1990 (USGS 2001a). During 1942 to 1990, Suisun Bay experienced a net loss of 61 Mm^3 of sediment, with a net loss of 1.27 Mm^3/yr at an erosion rate of 1.2 cm/m^2/yr. Erosion in San Pablo Bay is at a slower rate and only occurred after 1950s. San Pablo Bay lost approximately 7 Mm^3 of sediments between 1951 and 1983 at a rate of 0.22 Mm^3/yr (USGS 2001b). This net loss of sediments can be a potential source of selenium from sediments to the water column. Average selenium concentration in surface sediment is at 0.25 µg/g. Sediment loss of Suisun and San Pablo Bay is estimated to be around 1,100 M kg/yr (SFBRWQCB, 2004). This results in selenium loadings due to sediment erosion of 275 kg/yr.

[5] Assuming North and Central Bay area of 434 km^2 and 214 km^2, over the total area of 1133 km^2 for the whole Bay (Tsai et al. 2001).

Loss of tidal mudflats occurs both in fringe areas of Suisun Bay and San Pablo Bay (1000 acres in Suisun Bay during 1887 - 1990 and 125 acres/yr in San Pablo Bay). Loss of tidal mudflats may introduce contaminants previously deposited in these areas to the Bay (Marvin-DiPasquale et al., 2003).

Sediment dredging from navigation channels and disposal in locations inside and outside the bay can also influence sediment selenium pool. On average, in each year 1.8 million cubic yards of sediments were disposed in the bay and 2.4 million cubic yards were disposed out of the bay. Assuming a mean concentration of 0.25 μg/g, this represents a net loss of 82.5 kg/yr of selenium from the Bay (Table 3-16). In-bay disposal was estimated to be 248 kg Se /yr, while ocean disposal and upland/wetland reuse are 142.5 kg Se/yr and 225 kg Se/yr respectively. The dry mass of selenium was calculated assuming a particle density of 2.65 kg/L and a 50% solid per unit mass sediment, similar to assumptions used in the recent PCB TMDL for San Francisco Bay (SFBRWQCB, 2007c).

Table 3-16
Estimated selenium mass associated with dredge material disposal (2001-2005)[1]

Disposal site	Total volume 2001-2005 (m^3)	Average volume (m^3/yr)	Average annual estimated Se dry mass (kg/yr)
In-bay disposal	6,800,000	1,380,000	248
Ocean (SF-DODS) disposal	2,900,000	580,000	-142.5
Upland/wetland reuse	6,190,000	1,220,000	-225
Net loads			-82.5

[1]Source of data for volume of dredge material is from SFBRWQCB, 2007c.

3.8. LOADS FROM THE SOUTH BAY

Water in the South Bay and Central Bay is subject to mixing near the Bay Bridge. As a result, selenium loads can enter the Central Bay from South Bay or vice versa. The net inflow of water is assumed to be equal to river flow from the South Bay (Smith and Holibaugh, 2006). To estimate the net effect of exchange between two the two portions of the bay on selenium loads, we assumed selenium concentrations at a station near the boundary of the two bays (BC10 Yerba Buena Island) to be representative of net inflow concentration from the South Bay. Estimated freshwater inputs from local watersheds of South Bay are 664 Mm^3/yr (Davis et al. 2000). With the mean selenium concentration of 0.16 μg/L at Yerba Buena Island (Table A-3), estimated selenium inputs from South Bay to the Central Bay is at 106.2 kg/yr. The estimated load is relatively small compared to other selenium sources to the North Bay.

One of the tributaries in the South Bay, the Guadalupe River can be a major source of selenium to the South Bay because of high concentration. Observed average total selenium concentration at Guadalupe River (BW15) by RMP is at 4.76 μg/L. With the annual flow of 39.9-141.9 cfs for 2003-2007 (USGS11169025), selenium loads from this tributary alone can be 169.6-603.2 kg/yr. Therefore, the estimated 106.2 kg/yr load from South Bay may be at the lower bound of the loads entering from South Bay or suggests that significant removal of selenium via deposition may be occurring in the South Bay.

3.9. COMPARISON OF SELENIUM CONCENTRATIONS AND LOADS FROM DIFFERENT SOURCES

A comparison of total and dissolved selenium concentrations from several sources of interest is summarized in Table 3-17. In terms of concentrations, the refineries have the highest selenium concentrations compared to other sources such as Delta outflow, atmospheric deposition, municipal wastewater and the bay water, followed by local tributaries.

A comparison of relative importance of loadings from various sources is listed in Table 3-18. Input from Delta represents the largest source of total selenium and exhibits large variation depending on flow. Local tributaries and refineries are other two important sources. Loadings from atmospheric deposition and municipal wastewater are smaller. Bay sediment erosion contributes a notable portion of the particulate selenium loadings.

Table 3-17
Representative selenium concentration in different sources

	Source	Total (µg/L)	Dissolved (µg/L)
Atmospheric deposition	Mosher and Duce (1989)	-	0.1-0.4
Local tributaries (data for individual tributaries)	SFRWCB, 2007a,b	0.4-4.0[1]	0.3-3.9
	BASMAA (1996)	0.46	
Municipal wastewater	Data provided by SFBRWQCB	<1	-
Refineries	Data provided by SFBRWQCB	12-28[2]	12-28
Mallard Island (outflow from Delta) Storm Values	L. McKee, personal communication	0.46	-
San Joaquin River @ Vernalis (1999-2000)	Cutter and Cutter (2004)		0.68
Sacramento River @ Freeport (1999-2000)	Cutter and Cutter (2004)		0.07
San Joaquin River near Mallard Island (BG30)	RMP	0.18	0.16
Sacramento River near Mallard Island (BG20)	RMP	0.15	0.13
Bay water (1993-2005)	RMP	0.18	0.15

1. Mean of downstream sites in North Bay (SFRWCB, 2007a, b),

Table 3-2
2. Mean concentrations at individual refineries listed in Table 3-1.

Table 3-18
Relative importance of loadings from different sources

	Total (kg/yr)	Dissolved (kg/yr)	Particulate (kg/yr)	Uncertainty
Sources:				
Atmospheric deposition	17.8-163.5	13.7 – 78.1	4.1-85.4	High
Local tributaries	354 -1511 (354-834 best estimate)	-	118.2[1]	High
Municipal and industrial wastewater	250	-	-	Low
Refineries	538	-	-	Low
Input from Delta	1,110-11,752 (mean:3,962)	814-9,736 (mean: 3,354)	151-1,509[2] (mean: 698)	Moderate
Sacramento River at Freeport		670-2,693 (mean: 1,577) for 1991-2007		Moderate
San Joaquin River at Vernalis	760-7,270[5] (mean: 2,972) for 1994-2007	838-4,711 (mean: 2,289) for 1991-2007		Moderate
Sediment	293	18.2[4]	275	Moderate
South Bay	106			High
Sinks:				
Outflow	4500[3]	3750[3]	750[3]	Moderate
Sediment Dredging	82.5	82.5		Moderate

[1]Based on TSS loadings by Davis et al. (2000), times selenium content in particulate material of Sacramento River
[2]Based on TSS loadings by McKee et al. (2006) and mean selenium content in particulate material of Sacramento and San Joaquin Rivers
[3]Based on average Delta outflow of 25000 Mm^3. Outflow only includes loads contributed by the northern reach.
[4]Sediment diffusion rate estimated by Meseck (2002).
[5]Based on SWAMP dataset

A comparison of dry and wet season loadings from different sources (Table 3-19) indicates that during the dry season, the major source of selenium loadings is from the Delta. The local tributary contribution during the dry season is minimal. During the wet season, the Delta outflow and local tributaries are the main selenium sources to the Bay. Refineries have a relatively steady input during both dry and wet seasons.

Table 3-19
Summary of dry and wet season selenium loading from major sources

	Dry season (kg)	Wet season (kg)	Annual total (kg)
Delta (Total, RMP data)	1,007.4	2,930.7	3,938.2 (total)
Delta (Dissolved, assuming 60% removal of San Joaquin River load)	909.5	1,583.1	2,492.6
Sacramento River at Freeport	564.1	1,012.7	1,576.9
San Joaquin River at Vernalis	863.4	1,426.0	2,289.4
Export through aqueducts	664.5	841.7	1,506.1
Delta (dissolved, difference between river loads and export through aqueduct)	855.5	1,840.4	2,595.9
Tributaries[1]	75.8	1,434.8	1,510.6
Refineries	204.2	322.2	526.4

[1] Estimates from Method 2

The estimated selenium loads from different sources were compared to previous studies of Presser and Luoma (2006), Meseck and Cutter (2006) and Abu-Saba and Ogle (2005) (Table 3-20). Selenium loads from refineries compared well to loads estimated by Presser and Luoma (2006) and Abu-Saba and Ogle (2005). Loadings from the Delta on an annual basis were also comparable to estimates of Presser and Luoma and in the same range of Abu-Saba and Ogle (2005), principally because the estimated range is wide. However, dry season Delta to bay loads in this work are substantially higher than previous estimates by Presser and Luoma (2006): over 1,000 kg compared to 200 kg. Loadings from local tributaries were higher than estimates by Abu-Saba and Ogle (2005), most likely due to higher selenium concentrations and runoff values used in the calculation.

Table 3-20
Comparison of alternative total selenium loadings estimates to North San Francisco Bay.

Source Category	Presser and Luoma (2006)	Meseck and Cutter (2006)	Abu-Saba and Ogle (2005)	This report
All loads in kg				
Refineries: Prior to improved wastewater treatment in 1998, kg/yr	1,850	2,890	610-1,660	No estimate
Refineries: Subsequent to improved wastewater treatment in 1998, kg/yr	620[1]	1,100	204-552	526
Delta loads, kg/yr	200 kg/6 months, critically dry season; 4,500 kg/6 months, high flow season	No estimate reported; value embedded in model calculations.	330-10,200 (Nov 1997- Nov 1999)	3,946 annual average; 1,007 dry months and 2,930 wet months
Selenium inventory in sediment bed, kg	No estimate	No estimate	50,000 in upper 15 cm of entire San Francisco Bay	20,000 kg in top 15 cm in North San Francisco Bay
Sediment erosion	No estimate	No estimate	No estimate	293
Local tributaries and waste water to North San Francisco Bay, kg/yr	No estimate	No estimate	90-900 (to all San Francisco Bay)	Local watershed runoff: 354-834
POTWs	No estimate	No estimate	90-900	Wastewater, other than refineries: 250
Atmospheric deposition, kg/yr	No estimate	No estimate	No estimate	18-164

[1]From the value illustrated in Figure 26 (p93) of Presser and Luoma (2006). The number 506 kg/yr on page 1-1 was from Table 10 (p35) of Presser and Luoma (2006) where the actual loads were estimated for 1999.

3.10. LOW FLOW VS. HIGH FLOW CONCENTRATIONS

Selenium loadings and concentrations in water column and the suspended particulate material can vary with flow conditions. Under high flow, high loadings from Delta combined with short residence time can result in selenium concentrations in the bay that are similar to those in Delta inflows. During low flow periods, local sources from point dischargers may become a larger source. Under low flow, also due to the longer residence time and warmer temperature, selenium is more likely to accumulate in phytoplankton and bacteria. Zooplankton selenium concentrations have been found to be highest during low flow period (Pukerson et al. 2003). Therefore the low flow season is a critical time period for selenium bioaccumulation. The hydraulic residence time in NSFB can vary from 2 days during high flow to an average of 160 days during low flow (Cutter, 1989).

To forecast the expected selenium concentrations in water column and suspended particulate material, a simple, completely-mixed, one-box model similar to Presser and Luoma (2006) was used to estimate possible concentrations in the bay under several flow conditions: high flow in a wet year (2006), low flow in a wet year (2006), and low flow in a critically dry year (2001). Loadings from various sources estimated in previous sections were used.

Partition coefficient between dissolved and particulate selenium were derived from data of Doblin et al. (2006).

Several processes besides outflow to ocean that may contribute to the selenium removal: methylation to form dimethylselenide followed by volatilization, influx of dissolved selenium into sediments, reduction followed by adsorption and settling, phytoplankton uptake, and settling of suspended sediment. Previous study has indicated that diffusion into and out of the sediment is negligible (Meseck, 2002). Due to the oxic water, reduction of selenium is less likely to occur in the water column. Sediments in Suisun and San Pablo Bay are erosional, therefore net deposition into sediments are unlikely to be an important removal mechanism. More details of the one-box model are provided in the Appendix.

Predicted mean selenium concentrations using zero removal rates under high flow are generally similar to the observed concentrations from the RMP random sampling during 2002-2005 (0.14 µg/L; Table 3-21), suggesting relatively conservative behavior during high flow. Predicted maximum selenium concentration under low flow of a critically dry year is at higher concentration of 0.36 µg/L. RMP sampling during a representative period in August 2001 indicated a North Bay average of 0.15 µg/L. Because the observed concentrations during this period are significantly lower than predictions with removal rates set to zero, removal process may indeed be significant during these periods. The one-box modeling described here is a preliminary effort to assess the data and will be refined in subsequent work on the conceptual model and detailed mechanistic model.

Table 3-21
Estimated selenium concentrations under different flow conditions (more detailed calculation listed in Appendix A).

	Delta outflow (Mm3/day)	Delta loadings (kg/day)	Loadings from other sources* (kg/day)	Predicted total selenium concentrations (µg/L)	Concentrations in suspended particulate material** (µg/g)
High flow, wet year (2006)	202.2	19.0	9.6	0.14	0.94
Low flow, wet year (2006)	73.0	6.9	3.2	0.14	0.92
Low flow, critically dry year (2001)	14.2	2.0	3.2	0.33	2.20

*includes loadings from refineries, POTWs, local tributaries (proportional to delta outflow), and bed erosion.

**based on average K_d of 7.4 L/g (Cutter and Cutter, 2004).

4. SUMMARY

In this analysis selenium concentrations in water column and sediment were examined to provide a baseline for future modeling to be performed as part of the selenium TMDL in North San Francisco Bay. Major sources of monitoring data are the RMP and Prof. Greg Cutter's research group at Old Dominion University. The RMP has obtained selenium data at regular intervals at fifteen stations in the North Bay between 1993 and 2002, at 12 random stations for water concentrations and at 24 stations for sediment concentrations between 2002 and 2005. Selenium concentrations are generally low in the Bay water column with a whole North Bay average of 0.12 µg/L. Selenium concentrations in sediments are generally below 0.3 µg/g. Concentrations are lowest near the Golden Gate Bridge, with higher concentrations at lower salinities. More focused data sets that spanned a longer time frame and contained speciation data were also evaluated (Cutter, personal communication, 2007). The data show that there have been significant decreases in dissolved selenium concentrations and selenite in the North Bay since the mid-1980s, particularly in the low-flow season, following the implementation of more stringent controls on refinery discharges. Much of the selenium in the waters of the bay is in dissolved form, and consists of selenate, selenite, and organic selenide.

The quantification of selenium loadings from different point and non-point sources including Sacramento River and San Joaquin River inputs through Delta, local refineries, POTWs, tributaries and sediments, during both dry and wet season, was another major component of this analysis. The results indicated that annual loadings from the Central Valley through the Delta are the largest source of selenium with high variability depending on total flow through the Delta. Concentrations from the RMP stations are weakly correlated to Delta outflows to the bay, and therefore loads in high flow years are estimated to be more than ten times higher than in low flow years. The average Delta load is estimated to be 3,962 kg/yr. Local tributaries draining both urban and non-urban areas are also a large source of selenium (estimated average load of 354-834 kg/yr). Refineries are now estimated to be the third largest source of selenium to the North Bay (538 kg/yr), although these loads may have been higher prior to the late 1990s when wastewater controls were installed. Sediment resuspension/erosion and diffusion (293 kg/yr), other wastewater discharges (250 kg/yr), and atmospheric deposition (18-164 kg/yr) are other, smaller contributors of total selenium load. The point source loads (the refineries and the POTWs) contribute relatively uniform loads over the year, although the non-point source loads (the Delta and the local tributaries) contribute substantially more load in the wet season than in the dry season.

Although numerical values of load estimates are provided here for comparison, it should be acknowledged that this process contains significant uncertainty, and more than one estimation method may be applied, sometimes leading to different answers as described below. This is particularly true of non-point source load estimates. These alternative values are described below for completeness.

Selenium loads at Sacramento and San Joaquin River were estimated based on data collected by Cutter and Cutter (2004). Sacramento River at Freeport was estimated to have an average annual dissolved selenium loading of 1,577 kg/yr for 1991-2007. San Joaquin River at Vernalis has an average of dissolved selenium loading of 2,289 kg/yr for 1991-2007.

We applied three different methods to compute loads, from the Delta to the bay, depending on available data:

- The first approach used average concentration of two RMP stations in the Delta and multiplies it by the net tidally corrected Delta outflow. This resulted in an annual average load estimate of 3,962 kg/yr of **total selenium** from the Delta to the NSFB (1994-2006).
- The second approach used selenium loadings from the Sacramento and the San Joaquin Rivers separately based on data from Cutter and Cutter (2004) and applied a "Delta removal constant" similar to Meseck (2002) to account for the possible selenium loss in the Delta. These concentrations were reported only as dissolved selenium, not total selenium. This resulted in an annual average load estimate of 2,493 kg/yr of **dissolved selenium** (1993-2003).
- The third approach was independent of the prior two: the loadings from Central Valley to the bay were estimated as the difference between inputs from the two rivers minus the export through aqueducts, and assuming minimal loss processes in the Delta. This resulted in an annual average load estimate of 2,696 kg/yr of **dissolved selenium** (1993 to 2003).

In addition to these loads, the average particulate load was estimated as 698 kg/yr, based on loads of sediment from the Delta to the bay and by application of a constant selenium content in the sediments.

Given the simplifications and assumptions employed in these load calculations, and given that some loads are in terms of dissolved selenium, the range of annual averages is small, and the methods are supportive of one another. Because the data used in the analysis was most abundant for Method 1, and both total and dissolved data were available, and because the flow volumes used in load calculation are tidally corrected, it is recommended that this method be used for describing Delta loads, resulting in an average Delta to bay export of 3,962 kg/yr.

Using the SWAMP selenium data from the tributaries, loads were computed using flow from different sources: modeled annual flows and measured flows from USGS gage stations. The modeled flows were used because of the limited availability of measured flow data. Driven in large part by relatively high concentrations in the tributaries in both the wet and dry seasons, the average annual loads from the tributaries can range from 354 kg/year to 1,511 kg/year depending on the methods used for the load estimation. Much of this load (greater than 95%) is delivered to the bay in the wet months, consistent with the timing of flows, as shown in the calculation using the USGS gage data. The largest single sources of loads are the Napa River, Sonoma Creek, and the Concord hydrological area.

Although the tributary concentration data are different between two datasets (SWAMP and BASMAA), the high average concentrations are not driven by one or two measurements. It is nonetheless clear that the load estimates above are based on a limited amount of data. Furthermore, the SWAMP concentration data are not independently corroborated. Given the underlying data limitations and uncertainty in flows, and the year-to-year variability, the wide range in the load estimates are not entirely surprising. For the purpose of this analysis, we recommend using a range of load estimates for the next stage of the analysis of 354-834 kg/yr.

5. Key Findings and Implications for Model Development

The analysis presented here is an important first step in the modeling to be performed for the selenium TMDL. Key findings from this analysis, including uncertainties and data gaps, that will carry forward to the next steps are listed below:

- More than two-thirds of the selenium in bay waters is present in the dissolved form, with the majority in the selenate form.
- Selenium concentrations vary according to the freshwater flows moving through the bay, and are highest in the in the mid-estuarine regions in the driest periods of the year.
- Sediment selenium concentrations from the RMP data set, averaged over several years of sampling at fixed stations, vary over a narrow range 0.2 to 0.5 µg/g, with a few exceptions. These concentrations correlate well with TOC and percent fines. Almost all sediment data have been collected near the surface (15 cm deep or less). No data are available to estimate natural background levels of selenium in the bay sediments.
- Refinery load reductions are consistent with reductions in selenium concentrations in NSFB in both wet and dry seasons. Concentrations of selenite, a major component of refinery discharges in the past, show dramatic declines from 1998.
- Local tributary selenium concentrations are high (i.e., closer to San Joaquin River values than Sacramento River values) and result in significant loads to the NSFB, although more than 95% of this load is delivered in the wet months. The data used in this calculation have been collected by the SWAMP program and have not been corroborated by other monitoring programs. The Napa River was estimated to be the largest tributary load contributor. A sediment sample in the bay near the mouth of the Napa River showed significantly elevated concentrations.
- Selenium loads in NSFB are dominated by non-point sources, and therefore correlated with runoff. Because of the region's climate, with distinct seasonal patterns of rainfall, and significant variability from year to year, the non-point loads are highly variable both on a seasonal and annual basis.
- Load estimates of the rivers to the bay showed that both San Joaquin and Sacramento Rivers are significant contributors of selenium to the NSFB. Their load contributions are of similar magnitude and occur in both wet and dry seasons.
- The large Central Valley selenium sources are transported through the Delta, but data within the Delta are limited, and understanding of its role in the removal and/or export of selenium is based on a small amount of data.
- Point source loads (refineries, POTWs, and other industrial dischargers) are among the best characterized loads into NSFB because both flow and concentration are

measured simultaneously. These loads are also less variable through the year and the wet season and dry season loads similar. This contrasts with Delta loads and tributary loads which are far larger in the wet months. On an annual basis, point source loads are relatively small; on a seasonal basis, point source loads are significant during the dry months.

- POTW discharge concentrations of selenium are much smaller than refinery wastewater concentrations. However, because their flows are larger, on a load basis, POTW loads are about a third of the refinery loads.

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APPENDICES

Table A-1
Parameters and inputs of one-box model

Category	Value	Unit	References
Water depth (mean)	6.1	m	Conomos et al. 1985
Surface area			
North Bay	434	km^2	Tsai et al. 2001
Central Bay	214	km^2	Tsai et al. 2001
Volume			
North Bay+ Central Bay	3953	Mm^3	Calculated
Delta outflow			
Wet year (2006), wet season average	202.2	Mm^3/day	http://iep.water.ca.gov/dayflow/
Wet year (2006), dry season average	73.0	Mm^3/day	http://iep.water.ca.gov/dayflow/
Critically dry year (2001), dry season	14.2	Mm^3/day	http://iep.water.ca.gov/dayflow/
Delta loads			
Wet year (2006), wet season	19.0	kg/day	Average of daily loads
Wet year (2006), dry season	6.9	kg/day	Average of daily loads
Critically dry year (2001), dry season	2.0	kg/day	Average of daily loads
Refineries loads (wet season)	1.53	kg/day	
Refineries loads (dry season)	1.36	kg/day	
Bed erosion	0.75	kg/day	
Local tributaries (wet)	6.80	kg/day	
Local tributaries (dry)	0.57	kg/day	
Local tributaries (dry, 2001)	0.14	kg/day	Scaled from Napa 2001 dry season loads
Wastewater	0.50	kg/day	
Residence time			
Wet year (2006), wet season	19.5	day	Calculated
Wet year (2006), dry season	54.2	day	Calculated
Critically dry year (2001), dry season	278.4	day	Calculated
Predicted mean concentrations (total)			
Wet year (2006), wet season	0.14	µg/L	
Wet year (2006), dry season	0.14	µg/L	
Critically dry year (2001), dry season	0.33	µg/L	
Concentrations in particulates			
Wet year (2006), wet season	0.94	µg/g	
Wet year (2006), dry season	0.92	µg/g	
Critically dry year (2001), dry season	2.2	µg/g	

Equations: Assuming completely mixed and steady state:

(1). C = W/a, where W: loadings from all sources, a: assimilation coefficient, C: concentration

(2). a = Q + kV+ vAs, where Q: outflow, k: degradation/reaction coefficient, v: settling velocity, As: surface area. For simplicity, k and v are assumed to be 0.

(3) Cs = Kd*Cw, where Cs: concentration in particulate, Kd: partition coefficient, Cw: dissolved concentration. Cw is assumed to be 90% of C.

Table A-2
Summary of dissolved selenium concentrations in water for the period of 1993-2005 for the whole Bay (data source: RMP).

Site Code	Site Name	Median (µg/L)	Mean (µg/L)	Standard Deviation	Count
BA10	Coyote Creek	0.37	0.43	0.21	21
BA20	South Bay	0.33	0.32	0.12	23
BA30	Dumbarton Bridge	0.25	0.26	0.09	28
BA40	Redwood Creek	0.17	0.18	0.05	24
BB15	San Bruno Shoal	0.15	0.16	0.07	20
BB30	Oyster Point	0.13	0.16	0.09	24
BB70	Alameda	0.12	0.16	0.18	19
BC10	Yerba Buena Island	0.11	0.14	0.08	27
BC20	Horseshoe Bay	0.10	0.14	0.10	23
BC30	Richardson Bay	0.13	0.14	0.10	23
BC41	Point Isabel	0.10	0.14	0.09	24
BC60	Red Rock	0.12	0.15	0.10	20
BD15	Petaluma River	0.17	0.18	0.07	21
BD20	San Pablo Bay	0.14	0.15	0.06	24
BD30	Pinole Point	0.15	0.16	0.06	24
BD40	Davis Point	0.16	0.17	0.06	25
BD50	Napa River	0.16	0.16	0.06	24
BF10	Pacheco Creek	0.15	0.17	0.08	24
BF20	Grizzly Bay	0.13	0.14	0.06	25
BF40	Honker Bay	0.11	0.12	0.05	22
BG20	Sacramento River (near Mallard Island)	0.12	0.13	0.09	29
BG30	San Joaquin River (near Mallard Island)	0.14	0.16	0.09	28
BW10	Standish Dam	1.40	1.36	0.63	16
BW15	Guadalupe River	4.72	4.21	2.10	13
C-1-3	Sunnyvale	0.82	1.03	0.59	23
C-3-0	San Jose	0.91	0.86	0.33	23

Table A-3
Summary of total selenium concentrations in water for the period of 1993-2005 for the whole Bay (data source: RMP).

Site Code	Site Name	Median (µg/L)	Mean (µg/L)	Standard Deviation	Count
BA10	Coyote Creek	0.39	0.47	0.25	17
BA20	South Bay	0.33	0.35	0.15	21
BA30	Dumbarton Bridge	0.26	0.28	0.12	29
BA40	Redwood Creek	0.19	0.20	0.06	20
BB15	San Bruno Shoal	0.16	0.17	0.08	19
BB30	Oyster Point	0.14	0.16	0.08	21
BB70	Alameda	0.16	0.19	0.16	19
BC10	Yerba Buena Island	0.12	0.16	0.09	23
BC20	Horseshoe Bay	0.11	0.17	0.12	19
BC30	Richardson Bay	0.11	0.13	0.08	22
BC41	Point Isabel	0.12	0.14	0.07	20
BC60	Red Rock	0.15	0.18	0.08	16
BD15	Petaluma River	0.25	0.24	0.09	19
BD20	San Pablo Bay	0.17	0.18	0.07	23
BD30	Pinole Point	0.17	0.18	0.08	23
BD40	Davis Point	0.18	0.21	0.08	23
BD50	Napa River	0.19	0.20	0.05	22
BF10	Pacheco Creek	0.19	0.19	0.07	22
BF20	Grizzly Bay	0.17	0.17	0.07	23
BF40	Honker Bay	0.15	0.16	0.05	22
BG20	Sacramento River (near Mallard Island)	0.13	0.15	0.08	27
BG30	San Joaquin River (near Mallard Island)	0.16	0.18	0.09	26
BW10	Standish Dam	1.70	1.65	0.82	14
BW15	Guadalupe River	5.59	4.76	2.58	12
C-1-3	Sunnyvale	1.02	1.14	0.58	23
C-3-0	San Jose	1.10	0.97	0.38	22

Table A-4
Summary of selenium concentrations in sediments for the period of 1993-2005 for the whole Bay (data source: RMP)

Site code	Site Name	Median (μg/g)	Mean (μg/g)	Standard Deviation (μg/g)	Count
BA10	Coyote Creek	0.32	0.31	0.10	16
BA21	South Bay	0.34	0.44	0.25	16
BA30	Dumbarton Bridge	0.33	0.35	0.10	16
BA41	Redwood Creek	0.32	0.33	0.16	20
BB15	San Bruno Shoal	0.30	0.28	0.07	14
BB30	Oyster Point	0.29	0.33	0.13	16
BB70	Alameda	0.30	0.34	0.11	14
BC11	Yerba Buena Island	0.28	0.30	0.15	20
BC21	Horseshoe Bay	0.19	0.25	0.14	16
BC32	Richardson Bay	0.25	0.27	0.09	16
BC41	Point Isabel	0.30	0.33	0.09	16
BC60	Red Rock	0.07	0.11	0.11	13
BD15	Petaluma River	0.29	0.31	0.12	14
BD22	San Pablo Bay	0.32	0.41	0.32	18
BD31	Pinole Point	0.28	0.36	0.27	20
BD41	Davis Point	0.11	0.15	0.17	16
BD50	Napa River	0.38	0.52	0.47	18
BF10	Pacheco Creek	0.11	0.15	0.12	16
BF21	Grizzly Bay	0.33	0.50	0.68	20
BF40	Honker Bay	0.31	0.38	0.20	14
BG20	Sacramento River (near Mallard Island)	0.10	0.14	0.13	19
BG30	San Joaquin River (near Mallard Island)	0.30	0.29	0.16	20
BW10	Standish Dam	0.51	0.49	0.17	10
BW15	Guadalupe River	0.53	0.54	0.09	8
C-1-3	Sunnyvale	0.31	0.33	0.19	15
C-3-0	San Jose	0.33	0.33	0.11	15